GAUSS FUSION

Conceptual Design Report

Executive Summary

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December 2025

Foreword

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Fusion: Europe's moment to lead

The Conceptual Design Report (CDR) for Gauss Fusion's GIGA power plant design presented in this document constitutes Europe's first full design for a commercial fusion power plant. Developed with partners from across five European countries, it translates scientific progress into an industrial plan. As the first comprehensive conceptual blueprint of its kind, it defines the technologies, partnerships, and financing required to turn fusion into a deployable source of power for Europe. This report marks a pivotal moment for Europe and for fusion energy. A moment where Europe can move from research to engineering, and from vision to delivery.

Europe stands at an inflection point. Global competition for energy sovereignty is intensifying. The United States – in pursuit of global energy dominance – and China, have each committed tens of billions to commercial fusion programmes, enabling their industrial supply chains to start scaling as a result. If Europe does not act now, our suppliers, materials, and engineering talent will soon be fully committed to serve U.S. and Chinese commercial fusion projects rather than our own.

Across the continent, momentum is building. Governments right across Europe are signalling a clear intent to integrate fusion into their future energy strategies. Europe has the scientific foundations, the industrial capacity and a growing political will. What our CDR provides is one more crucial element on the journey to making fusion a reality: a commercially grounded design and plan for delivery.

Achieving fusion on an industrial scale will require Europe to move past inherited limitations and long-standing conventions. It will require a collective embrace of the bold leadership needed to accelerate progress. Fusion is not only an answer to the energy transition, it is a pillar of strategic autonomy. In a world of fragile supply chains and rising geopolitical tension, mastery of fusion technology is as vital to Europe's future as its aerospace and defence industries once were. Energy security is Europe's first line of defence. Fusion will not only decarbonise our power mix, it will strengthen the resilience of our economies and the sovereignty of our continent.

For Europe to realise this opportunity, leadership must be collective, coordinated and ambitious. Europe's strength lies in its unity, as no single nation can win the fusion race alone. Europe can lead globally, but it must act together.

Gauss Fusion: Engineering Europe's fusion future

Gauss Fusion was founded in 2022 by leading European industrial firms to turn the promise of fusion into a practical, commercial technology. We are engineering-led, building on Europe's scientific excellence to deliver a system that can be built, maintained, and operated safely at scale.

Our team brings deep experience across high-technology sectors, supplying components and delivering services to major scientific, commercial and defence programmes. We apply systems engineering and concurrent design principles drawn from aerospace, to manage complexity, accelerate development and integrate disciplines from materials science to robotics. This approach enables us to move fusion from laboratory to industrial reality.

Our purpose is clear: to design, build and deliver Europe's first fleet of gigawatt-scale stellarator fusion power plants. We have a mission to supply clean, secure electricity to more than one million European homes, with no carbon emissions and no long-lived radioactive waste.

To deliver on this promise, we have built partnerships with Europe's foremost research institutions and a supply chain that already spans Germany, France, Italy, Spain, Denmark, the Netherlands and the UK. What unites us is a shared belief that if we coordinate as one, Europe can lead the global fusion industry of the future and deliver at the industrial scale required.

A Eurofighter for Fusion: Europe's next great industrial project

The CDR contained within this document marks a decisive shift in Europe's fusion journey – from research to engineering, and from vision to execution. It represents Europe's most comprehensive and practical plan yet developed for a commercial fusion power plant, with a clear pathway from first-of-a-kind (FOAK) installation to a full fleet deployed across the continent.

But the CDR is more than a technical milestone. It sets out a vision for a "Eurofighter for Fusion" – a model of collaboration across European governments, industry and research. Just as the Eurofighter programme united Europe's aerospace industry to secure its independence in the skies, our "Eurofighter for Fusion" programme will unite Europe's energy and technology base to secure our continent's independence in power generation. Energy supply is now an integral part of Europe's defence strategy. Ensuring access to clean, sovereign power is as vital as ensuring our territorial security. Europe's future prosperity will not be secured by caution but by courage.

The project will begin as a public–private partnership (PPP) to secure a strong, coordinated launch, with private capital progressively taking the lead as the technology matures. This model captures the essence of successful European industrial policy: governments provide the framework, credibility, and long-term strategic direction, while industry delivers innovation, speed, and scale. Each nation contributes its expertise, from superconducting magnets to robotics, and from materials science to advanced manufacturing.

The result? A shared European capability greater than the sum of its parts. A project of this calibre will draw national and European public investment, alongside global private investors,

ultimately opening the path to an IPO once commercial deployment begins. This will ensure that Europe retains both technological sovereignty and economic leadership in this emerging field.

With this approach, we avoid duplication, strengthen supply chains, and ensure that fusion remains a European technology built by European companies. It also provides political resilience: a European-wide project stands a far better chance of continuity and stability than any single-nation effort.

Yet a project of this scale cannot succeed through diffuse effort alone. Europe needs frontrunners willing to take responsibility for pace, ambition and risk. Leadership within a collective framework is essential: when first-movers act with conviction, others gain the confidence and direction to follow. Europe's industrial renewal will require the willingness to challenge conventions and pursue solutions that have never been attempted before. By thinking big, we can transition from ambition to reality and deliver the technologies Europe has long aspired to, but not yet achieved.

Germany and Italy are best positioned – and most compelled – to lead this effort. Both countries face an urgent need for a secure, competitive energy solution and a revitalisation of their industrial base, particularly following the structural shocks experienced by sectors such as automotive and manufacturing. Their ability to mobilise industry, scale complex technologies and coordinate large supply chains gives them a decisive role in setting the pace for the rest of the continent.

From blueprint to power plant

The CDR sets out a three-phase roadmap from concept to commercial power generation:

- **Phase 1 (2022–2025): Conceptual design (Completed)**
  Definition of the plant architecture, selection of key technologies, and identification of remaining R&D gaps. This phase culminates with the delivery of this CDR – a fully integrated concept for Europe's first commercial fusion power plant.
- **Phase 2 (2026–2032): Engineering design**
  Development of detailed designs, prototyping and qualification of major systems, including magnets, tritium fuel cycle and remote-handling robotics. This is the phase where European supply chains will be fully mobilised and where PPPs with national governments and industry will take shape to industrialise technology.
- **Phase 3 (2032–2044): Construction and commissioning**
  Civil works, manufacturing and assembly of the FOAK power plant, followed by staged commissioning and integration into the grid. The goal is to achieve first plasma in 2040 and full power generation in the mid-2040s.

Each phase is designed to broaden participation and progressively diversify funding. The five-step funding model begins at a national level, expands to European private financial investors, then to EU institutions, international private capital, and ultimately to public markets through an eventual IPO.

This structure ensures that governments act as catalysts for private investment, rather than carrying it. Early public commitments signal confidence, and with that, private capital will

follow. This is how Europe will attract the €20 billion co-investment needed to launch such an ambitious infrastructure programme. And in return, this programme promises to deliver significant long-term economic benefits stemming from technology exports, power-plant licensing and more.

The economic case strengthens over time. The FOAK plant will require an estimated €15–18 billion, but costs are expected to fall by 50% through economies of scale, learning effects, and supply-chain maturity. This will bring the cost of subsequent plants down in line with today's large-scale power plant projects. Across Europe, fusion could create hundreds of thousands of high-quality jobs, following the same pattern seen in fission: every 100 jobs in the sector generates around 200 additional jobs across the wider economy. In Italy alone, reintroducing nuclear technologies is expected to create around 117,000 new jobs, and in the UK each £1 invested in the sector contributes nearly £4 to the national economy. Fusion represents not just clean energy, but the foundation of a new industrial renaissance for Europe.

We aim to begin construction of the first commercial fusion power plant in the early 2030s and deliver power to the grid by the mid-2040s. From there, replication and cost reduction will turn fusion from a scientific triumph into a new industrial sector for Europe. This will create growth, resilience, energy security and provide clean, dependable baseload power for generations to come.

The moment to act is now

Fusion must be part of our continent's energy future, and this CDR demonstrates that European industry is ready to deliver on that commitment. The choice for Europe is now strategic, not scientific. Do we continue to fund new experimental machines, or do we take the decisive next step towards industrial realisation?

This CDR provides a complete foundation for that decision to be made. It sets out how a commercial fusion power plant can be delivered – technically, economically, and through a credible European partnership model. It defines the technologies to be industrialised, the roadmap to bring them to market, the framework for financing, and the governance that will enable success.

If we act now, fusion can do more than power Europe, it can power Europe's next industrial age.

Through European collaboration, leadership and ambition, we can move from research to reality, and from vision to power. Together, we can ensure that the world's first generation of fusion power plants carries a European signature, is built on European soil, and serves European citizens.

Industry is ready. Europe is ready. The time to act is now.

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1. Introduction to the GIGA Fusion Power Plant concept development

The Conceptual Design Report (CDR) details Gauss Fusion's plan to develop GIGA[1], Europe's first commercial fusion power plant. To deliver the GIGA Power Plant, Gauss Fusion (GFG) is developing critical strategic fusion technologies that enable efficient operation, robust safety and reduced maintenance costs. Breakthroughs being delivered in technologies such as plasma control, demountable superconducting coils, Tritium Breeding Blanket (TBB), divertor, remote robotics will change the game for fusion and be instrumental building blocks in commercialising fusion. The innovative approach being applied to developing GIGA will deliver systematic modularity, facilitating scale and widespread robotic maintainability, which will enhance the commercial viability of the design. Another key technology area under development is the fuel cycle technology, the successful delivery of which will ensure that GIGA can be economically operated and replicated as a fleet of fusion power plants across Europe.

Gauss Fusion focuses on developing these key enabling technologies in-house, while partnering strategically across Europe for system integration, testing, and component development. Our core technology stack includes:

- Blanket and fuel cycle technology
  - Helium-cooled gas loops for sustainable, efficient thermal management
  - Modular and scalable breeding blankets
  - Advanced ceramic breeders for high tritium productivity and resilience
  - Novel tritium extraction, permeation control, and accountancy systems
- Demountable and re-mountable superconducting coils
  - Enabling modular assembly, simplified maintenance, and scalability
- Stellarator divertor and first wall architecture
  - Integrated with the fuel cycle to optimally manage plasma exhaust, a modular, high-performance cassette design tailored to the stellarator magnetic island structure
- Integrated remote maintenance robotics
  - Development of a vacuum vessel that enables access for internal component replacement and simplifies remote handling
  - Remote maintenance approach taking advantage of demountable coils, allowing large ports and use of casks to maintain tritium barrier, unique for stellarators

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[1] GIGA: one GW electrical (3 GW thermal) Fusion Power Plant

- o End-to-end plant architecture that incorporates maintainability from the outset to reduce downtime and lower lifecycle costs

Gauss Fusion pursues an active IP strategy focused on developing enabling technologies within our clear freedom to operate - particularly in areas that are not yet widely addressed in the fusion sector, such as blanket systems and modular plant architecture. Our approach is to commercialise these innovations through licensing to other fusion companies, applying them in adjacent industries, and offering high-value consulting services to support integration. In parallel, we will deploy these technologies in our own power plant to maximize performance, maintainability, and cost-effectiveness. Figure 1.1 presents an overview of the Technology Readiness Level (TRL) for various fusion technology systems under development.

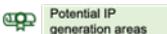| Main components	Components	TRL	
Design	Stellarator	~	IP
Magnets & Plasma	Plasma **core**	~	
	Plasma **exhaust**	~	
	Magnet technology / demountable superconducting coils	✓ / ~	IP
Vacuum vessel	**Vacuum** vessel	~	
	Plasma-facing component technology	~	IP
Tritium Breeding Blanket	**Breeding blanket** technology	✗	IP
	Fuel cycle	✗	IP
Divertor	**Plasma-facing** component technology	~	IP
Cryostat	Materials	~	
Supporting systems	**Power** conversion (Water / Helium)	✓ / ~	
	Remote **maintenance**	✗	IP
	Materials	~	IP

✓ Technically feasible / Demonstrated TRL 7-9	~ Concepts / Solutions exist TRL 4-6	✗ Ideas exist / No solutions / Path forward not clear TRL 1-3	IP Potential IP generation areas

Figure 1.1: Overview of Technology Readiness Level achieved in magnetic fusion and areas of innovation focus by Gauss Fusion

Gauss Fusion is undertaking development of the full Fusion Power Plant at Concept Phase, accounting for all system requirements from plasma through to electricity generation and site services. Through the Engineering Phase, those Technology Systems being developed from fundamentally new technology will be qualified along their TRL scales, whilst those mature technology systems will undergo a product design cycle in parallel.

A best-in-class Systems Engineering approach is employed across the development suite that concurrently develops Manufacturing Readiness Level (MRL) to enable rapid industrialization of the modular FPP architecture, in accordance with our GIGA timeline. With Systems Engineering principles at the core of our technology development programs we ensure that our execution delivers high-impact technologies at a speed and performance quality that supports our roadmap to safe, commercial fusion by the 2040s.

This Executive Summary outlines the technology development approach, the industrialisation approach and the operational approach being implemented by Gauss Fusion to deliver GIGA by 2042. The FPP system architecture and the innovative technology systems that underpin it are outlined here and presented in further detail through the CDR.

1.1. Stellarator Concept Introduction

The stellarator is a toroidal plasma confinement and control device, based on careful design of the magnetic fields to provide steady-state, quiescent confinement with no external current drive required to maintain the configuration. Multiple options exist; Gauss Fusion uses a quasi-isodynamic (QI) variation which aims to balance the internal plasma currents in order to produce no net toroidal self-driven current, meaning that the plasma shape does not vary much with changing plasma pressure and providing consistent divertor strike positions.

Magnetic-confinement fusion is attractive as a fast path to fusion energy as the efficiencies of the supporting systems and economics of fuel preparation make it considerably easier to achieve a reasonable power plant design with net electricity output and reasonable availability. Basing the design on a stellarator rather than a tokamak leads to a further improvement in economics from the intrinsic steady-state performance and ability to avoid a drop in plant output from the need to create a constant current in the plasma. The cost of these benefits is a more complex design process, which must solve three particular issues: finding a configuration of coils which achieve a target plasma while maintaining sufficient stand-off distance to fit sufficient blanket and shielding to allow them to be lifetime components; capturing in that coil configuration real engineering limitations on shape, manufacturing, assembly, and tolerances such that the coil set can actually be built to the requirements; and identifying a maintenance approach for in-vessel components which have a shorter lifetime than the vacuum vessel and coils which allows them to be efficiently and rapidly replaced.
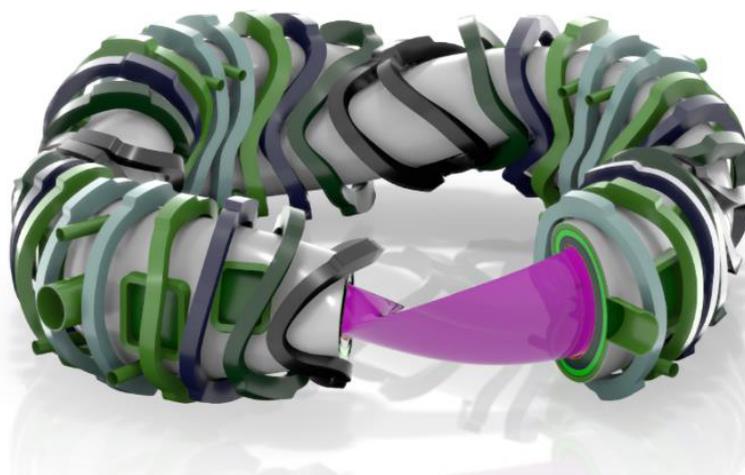

Figure 1.2: A view of the Gauss Fusion stellarator, showing coils, vacuum vessel, and plasma

Stellarators can be designed with multiple poloidal and toroidal coil sets, but the state-of-the-art is to use a "modular" approach in which one set of coils provides both the toroidal and poloidal field elements. This avoids large-diameter, helical, and interlinked coils – all of which are complex to build and move to site – but results in complex non-planar shapes which require accurate positioning to achieve the target performance. Experimental installations such as the Helically Symmetric Experiment (HSX) in the USA, the Wendelstein stellarators (W7-AS and W7-X) at the Institut für Plasmaphysik in Germany, and the Chinese First Quasi-symmetric Stellarator in China demonstrate that such a device can be built, albeit at a smaller scale and with more forgiving materials.

1.2. Gauss Fusion GIGA FPP

Fusion's greatest promise lies in its extraordinary energy density: it releases immense amounts of energy from just a tiny amount of fuel. This enables compact power plants like GIGA to deliver a full gigawatt of electricity occupying only about 100 hectares -comparable to the footprint of a coal or fission plant, and dramatically smaller than the sprawling areas required for solar or wind.
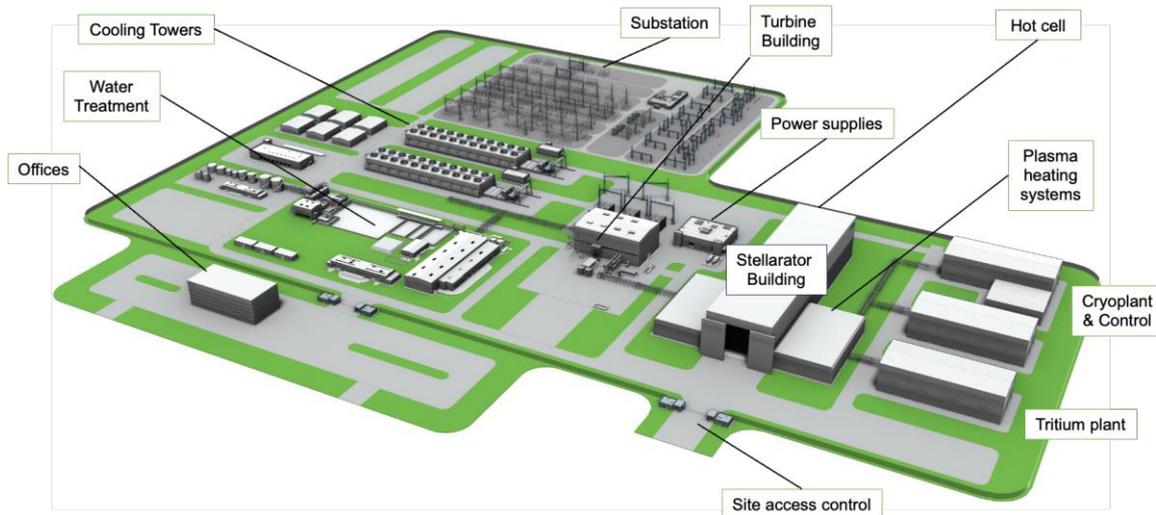

Figure 1.3: Gauss Giga Power Plant Layout

Every major subsystem can be manufactured in close collaboration with existing European suppliers of precision engineering works, specialty steels, superconductors, and remote-handling robotics, anchoring a high-value industrial chain inside the Union. The Gauss Fusion technology approach is focused on developing technologies and designs for the fastest possible construction of a Gigawatt class fusion power plant.

The plan for the design and construction of the Gauss Fusion FPP is divided in three main phases:

Phase 1: Conceptual Phase

In the pre-concept development, all parts of the FPP were considered with the aim of selecting the right technologies for each plant sub-system and defining a well-founded R&D programme to deliver solutions in areas where gaps remain. Phase 1 concludes with this Conceptual Design Report (CDR). Further development needs have been identified within this first phase, with plans produced for each technology system to qualify it through to FOAK operation.

Phase 2: Engineering Phase

The Engineering Phase will produce all the required specifications to build the GIGA FPP. This phase will end with the production of the Technical Design Report (TDR). Through this phase, risk management with mitigation and contingencies will be defined for the construction and assembly phase. By the end of 2027, GFG will also select the GFG FPP site location in collaboration with local and national authorities. This is paramount to obtaining the required

licensing and installation permissions before the beginning of the Construction and Assembly phase.

This phase also includes prototyping, qualification, and manufacturing tests for long lead-time items, such as blanket modules, magnets, and the vacuum vessel; this requires close engagement and partnerships with European industries to ensure that components are ready for delivery during the assembly phase.

Phase 3a: Construction and Assembly Phase

Once all the technical specifications are completed within the Engineering phase, the last phase will cover the Construction and Assembly of the FPP. Civil works can be parallelized with Phase 2 once the site location is selected.

Phase 3b: Staged Commissioning

GFG will implement a streamlined staged commissioning approach for the GFG FPP. This approach will be key to early demonstration of the correct performance of the machine prior to the D-T cycle operation and fully closed D-T loop, as well as to implementing and demonstrating the maintenance and upgrade strategy of the machine from early stages. The modular architecture of the stellarator will enable and facilitate the implementation of the staged approach and the required upgrade of the device. This approach, apart from reducing risks on the way to an operating FPP, also allows decoupling the device timeline from specific technologies and materials, which can be tested and commissioned in a staged manner along the different stages of the plant.

1.3. GIGA Architecture and requirements

The GIGA power plant system is developed as a multi-level architecture that incorporates the stellarator, power conversion and all the auxiliary systems required to ensure safe and efficient operation. A set of stakeholder requirements has been developed at the GIGA level, to meet the expectations of customers, regulators, investors, etc. and propagated through the technology architecture levels.

GIGA architecture

The architecture developed to address the GIGA requirements is shown in Figure 1.4. Ten Level 01 elements were proposed. Also shown is an additional architectural level, developed at Level 02 to address the requirements developed for the Level 01 system.

GIGA requirements

Safety and commercial viability are at the core of the GFG FPP technology development philosophy. A competitive LCOE over the life of the plant means that the FPP, along with achieving a low capital cost, must also have high availability, a long life and low maintenance cost. A technology philosophy that develops materials and systems that are economically replaceable at reasonable preventative maintenance intervals is critical. Larger, more expensive systems must maintain lifelong operation to ensure viability. The GIGA design strikes this balance.
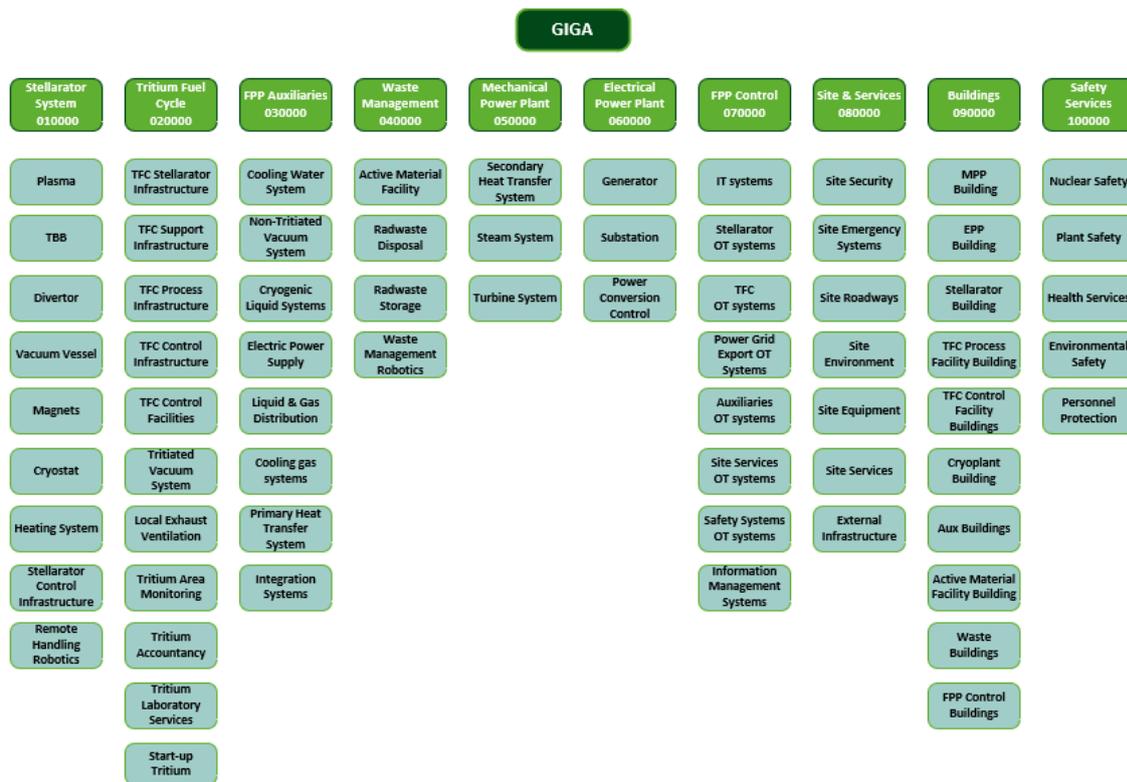
Figure 1.4: GIGA FPP Architecture described at Level 01, Level 02 and Level 03.

Safety is essential and GFG are developing a Safety Case for the FPP to ensure that the plant operates safely in all lifecycle stages, in adherence to the IAEA General Safety Requirements.

The set of Stakeholder Requirements for GIGA that captures technical, commercial, safety and regulatory expectations is presented in Section 2 of the CDR.

GFG Fusion Technology

The core of technology development for Gauss Fusion is in the stellarator. Consideration of the full power plant ensures that we capture all interfacing functions and develop the Stellarator such that ultimately the integrated power plant performance meets expectations. Development of the Tritium Fuel Cycle (TFC) technology facilitates commercial operation of GIGA and its viable expansion to a fleet of Fusion Power Plants. The performance of the GIGA plasma arises from the 3D shape of the magnetic field given by the coils and is optimized for energy and particle confinement and position of the divertor strike points. It is therefore important to account for uncertainties and tolerances in the design process and anticipate methods for ensuring and/or recovering magnetic field accuracy during and after construction, and after maintenance interventions, in order to ensure device performance over its lifetime.

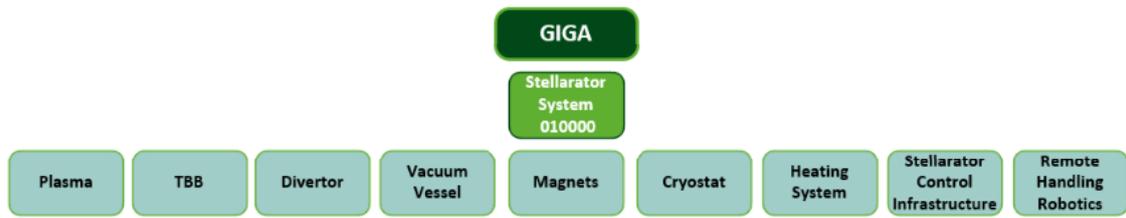The system breakdown structure for the stellarator is shown in Figure 1.5.

Figure 1.5: Stellarator architecture to Level 02 subsystems

1.4. Enabling Technologies

The enabling technologies being developed by Gauss Fusion are a significant differentiator within the Fusion landscape. Our focus is on developing a commercially viable power plant system. This focus pervades the high-level GIGA requirements that in turn direct our subsystem technology development philosophies, resulting in key enablers for commercial fusion. This section summarises some of the main areas of GFG technology development during the Concept Phase.

Modular Coils

Gauss Fusion pursues demountable superconducting coils because they transform stellarator economics: the ability to insert joints converts each coil into two lift-out halves, so that the complex magnetic cage no longer poses a daunting obstacle to assembly or maintenance of the device. Figure 1.6 depicts a coil being demounted from the stellarator. Cryostat ports facilitate access to the magnets and the in-vessel components. These coils also dramatically reduce the complexity of assembling the device in the first place.

Figure 1.6: Demounting operation for a stellarator coil

Breeding Blanket Technology

Within the architecture of fusion power plants – regardless of whether driven by laser or enabled by magnets – the breeding blankets play a key role. By capturing the emerging neutrons from the fusion plasma, they generate tritium while also capturing heat to produce electricity. Figure 1.7 shows a schematic of general layout for a TBB in a magnetic confinement device.

The GFG solution for the fusion power plant blankets consists of an innovative gas-cooled pebble bed blanket improving longevity and recyclability and addressing critical sustainability issues. By developing prototypes for large-scale testing and refinement, we ensure practical and effective solutions.
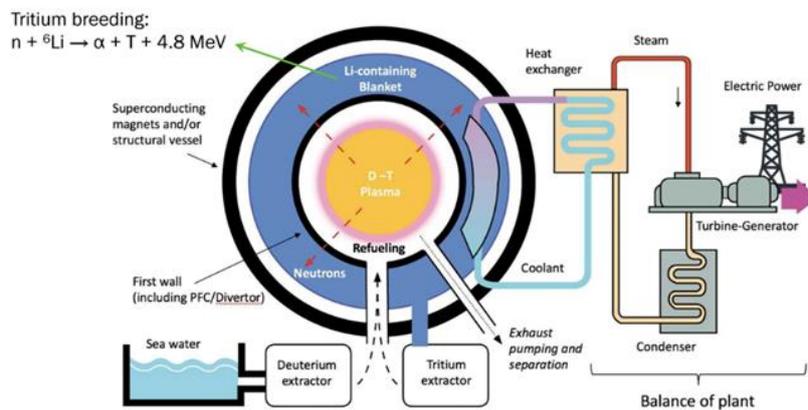
Figure 1.7: Schematic of the blanket and fusion fuel cycle

Qualification of tritium breeding technology is an important challenge that we plan to address under two different scenarios depending on the available devices and will drive the evolution of the technology readiness of this component.
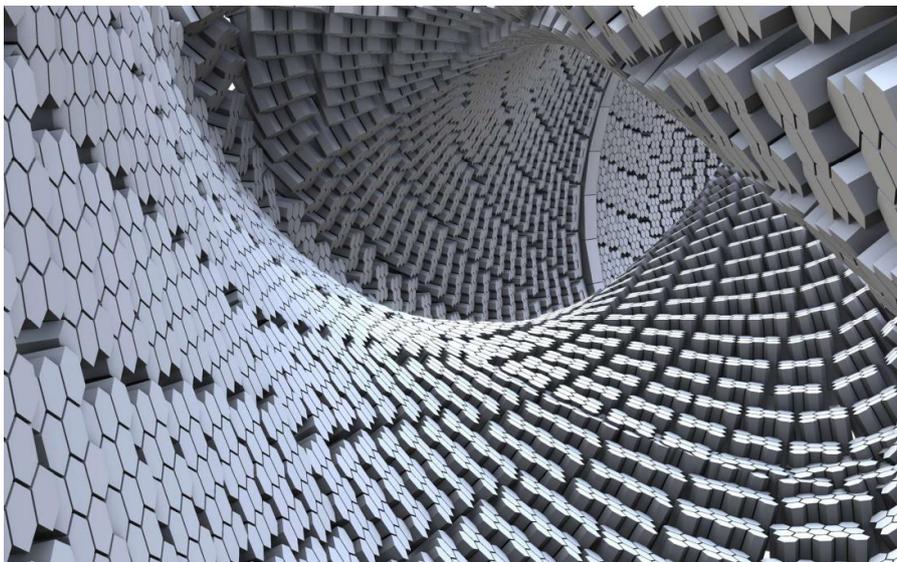

Figure 1.8: Tritium Breeding Blanket coverage in the reactor

Our approach builds on the development work carried out for EU-DEMO. It is more efficient and safer than alternative water-based cooling systems, allowing us to maintain optimal operating conditions while reducing the overall footprint of the plant. Recovering tritium effectively from the blanket and from the stellarator exhaust is crucial to keep inventories low and safety high. Figure 1.8 presents an image of the GFG TBB coverage in the reactor. Clearly visible are the TBB pins and their arrangement into modules around the stellarator wall.

Divertor Design, Technology and Vessel Integration

Divertor design, technology and vessel integration form the third pillar of Gauss Fusion's strategy to turn the stellarator from an elegant physics device into a commercially viable power plant. The divertor is the portion of the plasma-facing wall dedicated to managing

plasma–wall interactions. The role of the divertor is multi-fold, as it interfaces directly with the edge magnetic topology to intercept exhaust heat and particles, strongly influences pumping efficiency and detachment behaviour for wall integrity, and provides a critical contribution to neutron shielding and thermal protection of the vacuum vessel. Figure 1.9 shows analysis imagery of the GFG plasma structure and the divertor interaction at the four magnetic islands.
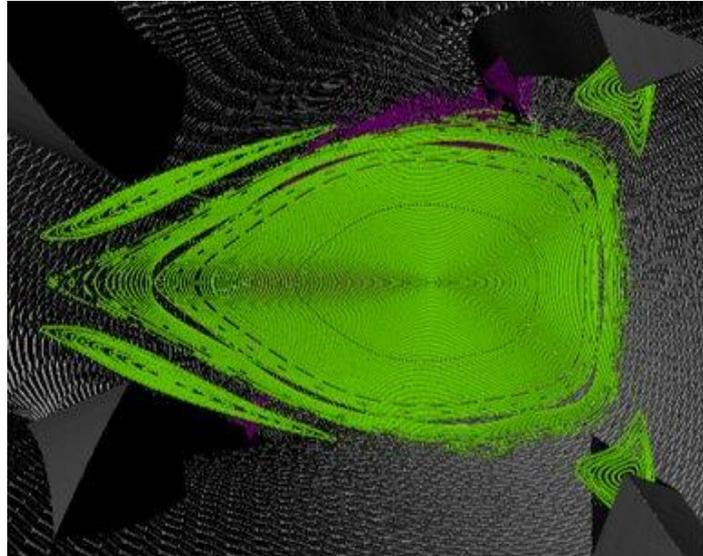

Figure 1.9: A Poincaré plot of the GIGA plasma, showing the magnetic structure including the four islands, two of which intersect the divertor structures

Gauss Fusion's approach begins from first principles: aligning the 4/4 magnetic island structure with toroidally continuous, hydraulically segmented cassettes that ensure both thermal decoupling and manufacturability. With up to 10 MW/m^2 peak transient heat fluxes expected, tungsten monoblocks with CuCrZr cooling channels form the plasma-facing units, backed by a water-cooled grade-91 steel cassette body that guarantees both structural integrity and shielding mass. Heat deposition from both plasma and neutron irradiation is modelled to verify operational headroom and avoid failure modes across monoblocks, pipe, and support interfaces. By adopting a co-optimization strategy, the divertor is engineered in tandem with blanket and coil geometry to enforce toroidal alignment, neutronic shielding, and remote access. Figure 1.10 shows the Gauss Fusion divertor concept with integrated cooling channels and pumping ducts to maintain safe operation of the plasma-facing units and cassette body. A complementary patent has just been filed on a mechanism to dramatically improve the exhaust pumping efficiency, an issue for stellarators in particular.

Complementing the divertor, the vacuum vessel and cryostat form the structural and thermal backbone of the fusion core and are essential enablers of system integration, maintainability, and nuclear safety. The vacuum vessel is conceived not just as a containment shell, but as a multifunctional interface that must accommodate intense mechanical loads, neutron and gamma radiation, and spatial constraints from both magnet geometry and remote maintenance operations.
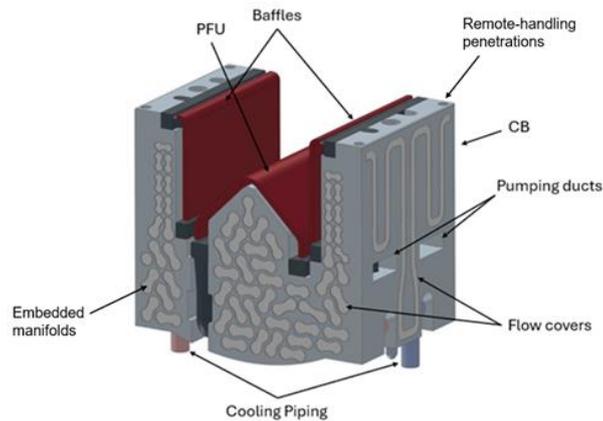
Figure 1.10: Conceptual design of the representative divertor cassette with labelled sub-systems

Surrounding the vacuum vessel, the cryostat provides the necessary thermal insulation for the superconducting magnet system and maintains the operating conditions required for the LTS or HTS conductors. Gauss Fusion's approach emphasizes manufacturability and modularity, with cryostat segments prefabricated off-site and assembled via high-precision welds or bolted flanges.

Taken together, the divertor, vacuum vessel, and cryostat define the "device" core of Gauss Fusion's power plant and are the linchpin for its commercial viability. By designing these systems from the outset to be modular, manufacturable, and serviceable, Gauss Fusion is not only addressing the technical challenges of stellarator architecture but also unlocking a path to series production. The ability to assemble, maintain, and upgrade these subsystems with minimal disruption to plant operations is a cornerstone of our economic model. It reduces downtime, extends component lifetimes, and ensures that the stellarator moves beyond laboratory demonstration into the realm of continuous, high-availability power generation. In doing so, Gauss Fusion establishes a new industrial benchmark for integrated fusion plant design in Europe.

Tritium Fuel Cycle (TFC)

Most fusion concepts are built around the reaction between the hydrogen isotopes: deuterium (2 proton, 1 neutron) and tritium (1 proton, 2 neutrons). These two isotopes are reacted in equal molar quantities, with GIGA anticipated to consume ~450g of tritium (and ~300g of deuterium) per operational day.

Tritium occurs naturally only in trace amounts in the stratosphere. It must therefore be produced artificially in the breeder blankets and injected into the plasma to fuel the fusion reaction.

The nature of magnetic confinement devices means they do not confine injected matter indefinitely. Instead, the DT fuel injected into the plasma core (where fusion occurs) is typically confined on the order of seconds, before it diffuses to the cooler plasma edge and must be pumped away. As a result, only ~1% of the injected DT gas undergoes fusion, with the remaining ~99% lost to the exhaust.

Given the radiological nature, scarcity, and high value of tritium, this unused inventory cannot be discharged to the environment. Instead, it must be recovered and recycled for reinjection into the reactor. The Tritium Fuel Cycle manages the capture and processing of Tritium throughout the FPP. Gauss Fusion is developing Fuel Cycle system technology to operate optimally with Stellarator based power plant. The Fuel Cycle compliments the TBB function in ensuring that surplus Tritium is captured to facilitate the fuelling of further GIGA power plants and ultimately fuelling the expansion to a suite of GIGA FPPs.

GIGA TFC Architecture

The tritium fuel cycle predominately concerns the fuelling and reprocessing architecture, alongside several supporting functions. The architectural concept for the GIGA TFC is presented in Figure 1.11. Eleven sub-systems will support the operation of the TFC.

Figure 1.11: TFC Stellarator architecture to Level 02 subsystems

DT fusion devices can be broadly divided into one of four categories with a corresponding TFC architecture. Batch-Mode Single-Loop, Semi-Continuous Mode Single-Loop, Semi-Continuous Mode Multi-Loop, and Continuous Mode Multi-Loop fuel cycles.

The GIGA TFC is the next evolution of the DEMO-like TFC to yield a continuous-mode multi-loop architecture. While a few other Stellarator endeavours are considering their own fuel-cycles, within the limits of the public domain, these mostly appear focused on using DEMO architecture with no significant stellarator-centric new architecture development, and GIGA is at the forefront of TFC architecture development. Figure 1.12 presents an overview of the TFC system under development for GIGA.
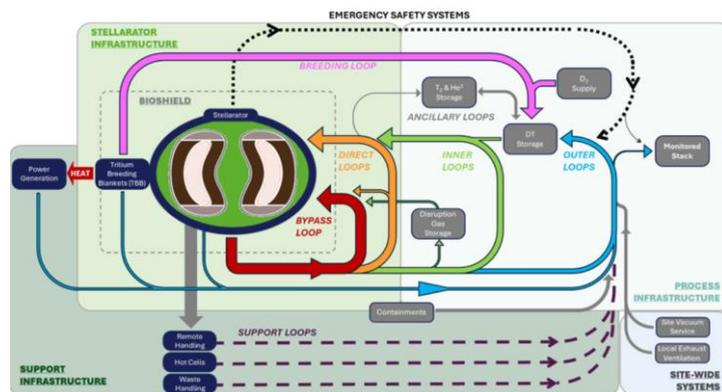

Figure 1.12: Simplified TFC multi-loop infrastructure for GIGA, indicating the different infrastructure zones

1.5. Systems Engineering approach

Systems engineering (SE) has been adopted and advanced for use across many industries such as automotive, medical equipment, and nuclear energy. It provides a disciplined, interdisciplinary approach to developing complex engineering systems, focusing on a system's entire lifecycle to ensure it meets stakeholder needs.

Defining stakeholder needs and addressing them through formulation of a 'System of Systems' architecture is an important early step in the process. Other key aspects of SE include requirements management, interface management, trade studies, and risk management, all integrated through continuous communication and feedback loops to achieve a successful outcome.

Figure 1.13, illustrates the link between a system's development phases and its corresponding qualification activities, ensuring verification and validation are undertaken throughout the entire technology lifecycle.

Within each product design cycle, a Concurrent Engineering approach is being adopted to ensure rapid development through an astute approach to parallelisation of engineering activities across multifunctional design teams.

Concurrent Engineering is a process, again widely used in the aerospace industry, focused on optimising engineering design cycles, which complements the traditional sequential design-flow by integrating multidisciplinary teams that work collectively and in parallel, with the objective of performing the design in the most efficient and consistent way as possible, right from the beginning.
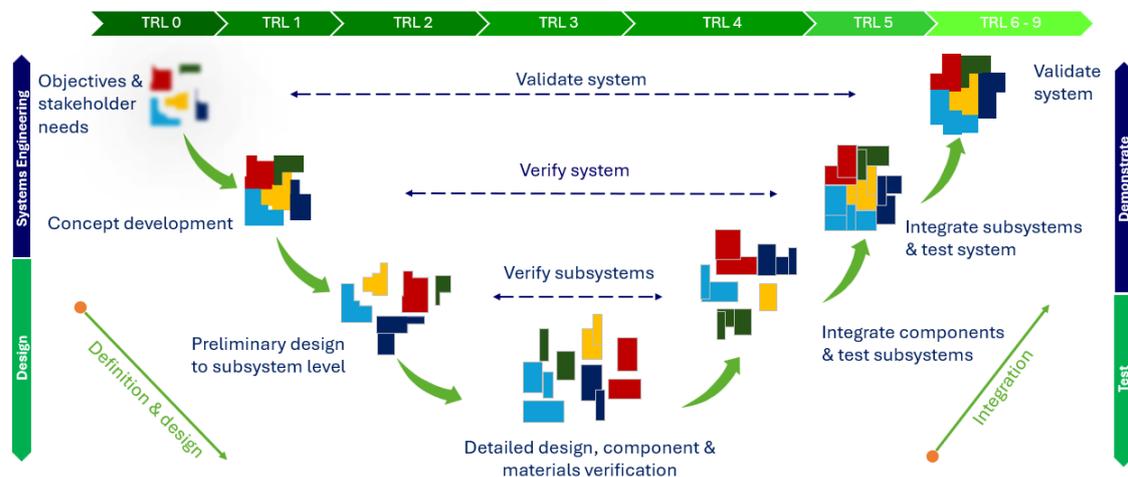
Figure 1.13: Typical V-diagram qualification represented against TRL definitions

Risk Assessment

Technology risk management is a critical component of a Systems Engineering approach and was adopted across the technology systems for Concept Phase. A qualitative Failure Modes and Effects Analysis (FMEA) risk assessment approach was undertaken with a focus on operational risk. The outcome of the exercise was a clear definition of the functional risks and the technical controls in place to manage and mitigate their occurrence.

Adopting this best-in-class approach to risk management puts Gauss Fusion in a position to facilitate regulatory authorities to expedite the licensing process through provision of a robust safety case for GIGA.

1.6. Technology Qualification Plan

Concept Phase qualification has culminated in the release of this GIGA Conceptual Design Report. One of the CDR outcomes is definition of the Qualification Plan. The Qualification Plan for each technology system covers its development over the next two phases and reflects its own TRL roadmap and developmental requirements. All the technology system plans are aligned to the corporate roadmap and converge on delivery of commercially mature technology systems to the final design of GIGA.

Engineering Phase outline

The Engineering Phase (Phase 2) will commence in 2026 and conclude in 2032, progressing technology systems' maturity through to TRL 6. The Engineering Phase will comprise of numerous design review gates; the System Integration Review in 2026, followed by a series of Technical Design Reviews through the remainder of Phase 2. Supply Chain will also be fully developed through this stage. The outcome of Phase 2 will be the Technical Design Report and Engineering Specification for the entire GIGA FPP and progression to Phase 3: Construction and Commissioning.

Depending on the maturity level of the system, its development in Phase 2 may take the course of a product/system design development cycle or that of a new technology development and qualification cycle, progressing on its TRL scale. For either approach in defining the development, the ultimate corporate timeline is identical. Figure 1.14 presents the design review milestones through the Engineering Phase.

Figure 1.14: Engineering Phase timeline and milestones

For those Technology Systems being developed from fundamentally new technology, typically reaching TRL 2-3 at Concept Phase, Phase 2 will progress the technology maturity through to TRL 6-7, depending on availability of appropriate system testing facilities. Some TRL 7 testing may be considered as part of the FOAK Commissioning in Phase 3.

Each technology system is different. The Qualification Plans map out the TRL stages against the timeline to 2032, detailing the specific technical outcome achieved at each stage and through what qualification means this will be achieved. To develop the Qualification Plans, an assessment of the resource needs for analysis, prototyping and testing has been performed covering both the internal GFG facilities along with team and external collaboration resources. The needs and availability of testing facilities have been considered for all systems.

Engineering Phase Milestones

1. System Integration Review (SIR) Q4 2026

Global integration review for interface consistency across FPP Systems with full system baselined for Intermediate Design stage.

2. Intermediate Technical Design Review 1 (ITDR-1) (2029)

The objective of the ITDR-1, which covers intermediate technical design, is to finalise verification development/design (high-fidelity system TRL 6 prototyping, or manufacturing prototypes for long lead time items), issuing final L02 system prototype drawings for construction, and moving into detailed technical design towards the ITDR-2 milestone.

Manufacturing equipment development with Tier One suppliers for long lead time items will be developed in this stage. Supply chain and procurement strategy progressed significantly with preferred suppliers developed (audited, ranked, framework agreements, manufacturing technology co-development projects established, where required).

Level 02 technology system verification should be at TRL4+ to close ITDR-1. Technology qualification status will be assessed against performance requirements, cost, manufacturability and safety/regulatory requirements.

Design specifications will be complete for progression to detailed technical design.

3. Intermediate Technical Design Review 2 (ITDR-2) (2031)

The objective of ITDR-2 is to close the detailed technical design and full-scale technology development, progressing to the TDR phase which covers final design.

Technology development will deliver TRL 5-6 to all fundamental technology development programs.

Manufacturing prototypes and processes will be qualified demonstrating manufacturability.

4. Technical Design Review (TDR) (Q4 2032)

The TDR comprises the final design review to close technical design, issue for construction (IFC) and call for tender (CFT). Comprehensive technology qualification review, System/Integration review, Design Review, Manufacturing readiness review, Regulatory & Safety review will be undertaken. Phase 2 review will be completed with the release of the final Technical Design Report.

Engineering Phase Costing

The cost evaluation of the Engineering Phase incorporates both internal headcount and external expenditures, covering all activities related to engineering design, prototyping, testing, and including a preliminary contingency allowance.

Given the high level of technical uncertainty and complexity inherent to the development of the GIGA power plant, this cost assessment relies on the convergence of two complementary approaches:

- a bottom-up estimate, derived from detailed planning and resource assessment, and

- a top-down estimate, used as a benchmark to validate the overall magnitude of costs.

The bottom-up evaluation for Phase 2 is presented in the GIGA Program Baseline document and provides an overall cost estimate around 900 M€.

In parallel, the top-down estimate, developed using industry benchmarks (e.g. ITER, LHC, ESS), provides an order-of-magnitude range of 0.9–1.5 B€. This range serves as a reference to guide the ongoing refinement of the bottom-up planning. In this approach the development cost is taken as a fraction of the final projected system, with a larger fraction used for lower TRL & MRL (technology & manufacturing readiness level) systems.

System	Bottom-up Cost (M€)	Top-Down Cost (M€)	TRL/ MRL
Site and buildings	90	100	High
Stellarator (without Magnets)	400	800	Low
Magnets system	160	200	Medium
Balance of plant (thermal and power supplies)	82	103	High
Vacuum systems	10	10	High
RM systems	50	100	Low
Tritium plant	100	200	Low
I&C	5	5	High
Misc plant	3	3	High
Total	900	1520	

Table 1.1: Indicative ROM breakdown for Phase 2 costs

Construction and Commissioning Phase

Construction and Commissioning of GIGA will proceed from 2032 to 2044, when full power production output will be achieved. As shown in Figure 1.15, Phase 3 is broken into two stages, Phase 3a - Construction and Assembly, and Phase 3b – Commissioning of the reactor.

Figure 1.15: GFG Corporate timeline through Phase 3

A staged approach, to commissioning the reactor, as outlined in Figure 1.16, will be undertaken to manage risk and facilitate technology validation in the FOAK GIGA. The staged commissioning approach will be key to early demonstration of the correct machine performance prior to D-T cycle operation and operating the fully closed D-T loop, as well as demonstrating the maintenance and upgrade strategy of the machine from early stages.

The modular architecture of the Stellarator will enable and facilitate the implementation of the staged approach and the required upgrading of the device. This approach, apart from

reducing risks on the way to an operating FPP, also allows decoupling the device timeline from specific technologies and materials, which can be tested and commissioned in a staged manner along the different stages of the plant.

An example of this could be the tritium breeding blankets or the divertor.

Figure 1.16: Outline of staged commissioning approach for GIGA

The machine could initially run in D-D mode with ferritic blanket mock-ups to check coolant performance etc., and with a non-fusion-rated divertor to tune divertor heat deposition and pumping, which could then be replaced through remote maintenance demonstration/test with the full blanket version when ready.

Construction and Commissioning Costing

There are many previous examples of estimating the costs of a magnetic fusion power plant in which the reactor and power plant systems – including site land area and buildings – are described parametrically and scaled to match the output of the plant based on assumptions about the physics and technology performances. The model then calculates a cost for each system based on the scaling of masses or volumes of steel, concrete, other materials, etc. and a baseline ersatz for the cost of those materials as-manufactured in a similar industrial system. For example, data is available on the costs of building fission reactor pressure vessels, and these can be used as an ersatz for the cost-per-tonne of a fusion vacuum vessel. Superconducting magnets in MRI scanners, or for projects such as CERN, can be used to provide a scaling for the magnets in a fusion reactor. Nuclear buildings for fission power plants provide a baseline for the fusion reactor hall. Depending on the complexity of the model, additional charges to represent interest costs, project management and contingency costs, and reductions in nominal costs due to Nth-of-a-kind industrial efficiencies can also be considered.

Using this approach, with the caveats that estimates remain uncertain for the reasons explained above, we can break the estimated costs down broadly by system as shown in Table 1.2. Here we have also broken out project management and contingency costs – overheads which are often ignored in such cost projections.

In this table the fusion-specific systems at low manufacturing readiness level (MRL) are marked in bold. They represent €10bn – over half – of the total cost. With scale-up of production and improved manufacturing from experience, it is reasonable to expect this cost to reduce by at least half in the long-term, benefiting from learning factors and improved

supply chains. This then puts the cost of an Nth-of-a-kind fusion plant competitive with an EPR. Further optimisation of design, from operational experience and the ability to test and refine components in a true fusion environment, will allow further cost reductions.

System	Cost (M€)
Site and buildings	2000
Stellarator (excluding Magnets)	4000
Magnets system	4000
Balance of plant (thermal and power supplies)	1050
Vacuum systems	200
RM systems	500
Tritium plant	2000
I&C	100
Misc plant	50
Project management	2000
Contingency	2000
Total	17900

Table 1.2: Estimated costs breakdown for the FOAK fusion power plant. Fusion-specific (currently low MRL) systems are in bold

1.7. Building a Fusion Industry

Building a robust industrial ecosystem for fusion energy is not something that can happen overnight. It must be cultivated gradually—through the progressive adaptation of existing industrial capabilities, the right incentives, and clear market signals. While past experimental programs like ITER have laid important groundwork, particularly by initiating the development of a European-level supply chain, these efforts have not yet reached the scale or continuity required for full industrialization. Today, fusion still lacks mature, dedicated supply chains. Even with a fully developed fusion power plant design in hand, initiating its production today would prove out of reach. The necessary industrial infrastructure, specialized tooling, and coordinated supply chains to build such a plant at scale simply do not exist yet.

The real catalyst for industrial growth will come when a credible first reactor, such as GIGA, enters the advanced stages of engineering and procurement. Only then will industry players feel confident enough to invest capital into dedicated production lines. Yet a key challenge remains: suppliers are unlikely to commit unless they foresee a steady stream of repeat orders, ensuring fleet-level continuity. This means early-stage fusion projects must be prepared to shoulder the initial costs, co-develop specialized tooling with suppliers, and provide guarantees of future demand. This is where governments have a critical role to play in de-risking these early phases and helping bridge the gap—through targeted funding mechanisms and policy frameworks that actively encourage industrial participation. Ultimately, supply chains evolve when companies believe that a first-of-a-kind reactor will be followed by a second, a third, and many more.

During the Engineering Phase of its development program, Gauss Fusion will actively develop the fusion supply chain by engaging Tier One suppliers in the co-development of manufacturing and qualification equipment routes for long-lead time components. This

structured approach ensures that supply chain partners are not only technically prepared but also strategically aligned with the timeline and scale of the First-of-a-Kind (FOAK) reactor.

By closing the Intermediate Technical Design Review 1 in 2029, progressing toward TRL 6 through the detailed design activity supporting Intermediate Technical Design Review 2 in 2031, and finalizing the design for the Technical Design Review milestone by 2032, Gauss Fusion will lay the foundation for a robust, scalable, and repeatable industrial ecosystem— one capable of supporting fleet-level deployment and long-term market growth. The roadmap presented in Figure 1.17 further summarises cost and schedule considerations in realizing GIGA.

Industrialising Fusion will combine efforts across technology development, supply chain development, workforce development and financing. The Gauss Fusion approach manages risk throughout a credible delivery roadmap that facilitates development of strategic commercial factors in parallel with our technology qualification and delivery.
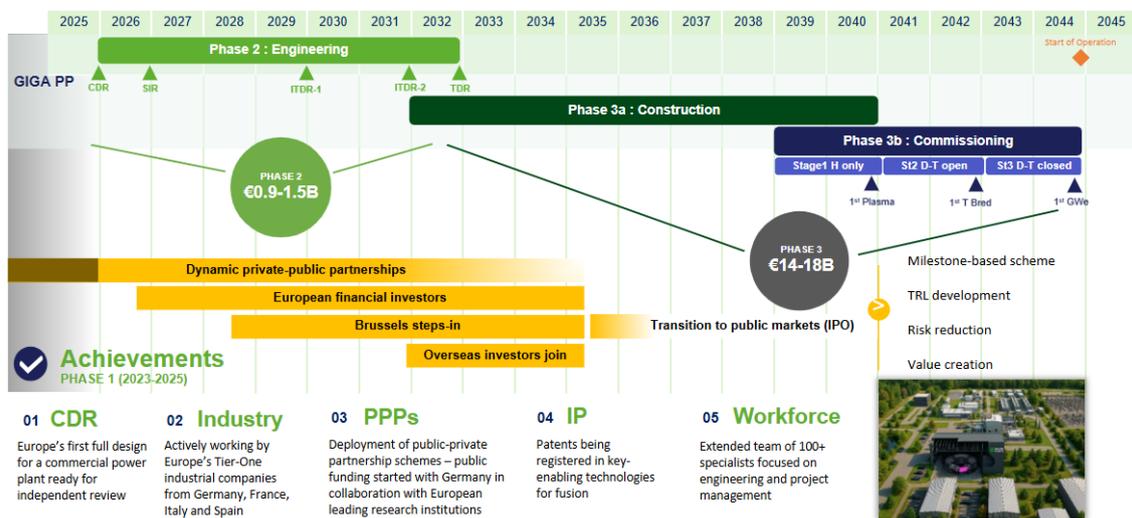

Figure 1.17: Building the path to Fusion Energy. Phases, funding and key achievements on the road to commercial power

The plan presented in this CDR and its execution through our systems engineering and risk-controlled development philosophy will ensure the reliability, safety, and rapid industrialization of our cutting-edge technologies, positioning Europe to lead the global transition to commercially viable, carbon-free fusion energy. Stellarator System

1.8. General Requirements

While the steady-state nature of the stellarator avoids frequent thermal and stress fluctuations on all components, the cost of these benefits is a more complex design process, which must solve three particular issues: designing a plasma shape that achieves the target plasma performance and a supporting configuration of coils which maintain a stand-off distance to fit sufficient blanket and shielding to allow the vacuum vessel and coils to be lifetime components; capturing in that coil configuration real engineering limitations on shape, manufacturing, assembly, and tolerances such that the coil set can actually be built to the requirements; and identifying a maintenance approach for in-vessel components which

have a shorter lifetime than the vacuum vessel and coils which allows them to be efficiently and rapidly replaced. Multiple options for a stellarator exist; Gauss Fusion uses a multi-objective optimized plasma configuration which aims to balance the internal plasma currents to produce no net toroidal self-driven current, meaning that the plasma shape does not vary much with changing plasma pressure and providing consistent divertor strike positions.

Moreover, tritium confinement during operation, shielding of (and maintenance of) vulnerable and lifetime components from neutron damage, are essential considerations. With a plasma temperature of 100 million K, wall operating temperatures of 500-1200 K, and superconducting coils at 4-20 K, thermal control of, and insulation between, different elements and considerations of differential thermal expansion are important. The whole device will need to be encased in a cryostat to prevent environmental heat reaching the coils, and a biological shield for radiation protection of personnel will be needed outside that.

Extrapolations from existing devices are, admittedly, large. GIGA is four times as large as W7-X in linear dimensions, with a plasma volume of 1500 m^3 rather than 30 m^3, and a magnetic field twice as large. Using physics developments and access to more advanced computing and optimisation techniques than were available to W7-X, additional optimisation of the plasma to improve turbulent losses, plasma stability, and fast ion confinement has been applied. For effective steady-state operation and an efficient fuel cycle, new divertor concepts which improve neutral compression and exhaust pumping must be developed; these can be tested on existing devices, within limitations on other experimental programmes. A final major difference is the need to include tritium breeding and shielding structures between the plasma and vacuum vessel, pushing the coils further from the plasma and bringing ferritic materials into the gap. However, no showstopper has been identified which would prevent a fusion power plant based on the stellarator from being successful.

The overall TRL of the stellarator (from a current assessment of TRL 2, accounting holistically for the readiness of subsystems) can be rapidly increased through development and validation of the individual subsystems, mock-ups and prototypes of specific interfaces such as the maintenance access, and integrated modelling. However, integrated operation and nuclear performance cannot be verified without operation of an integrated, nuclear device, meaning that the final overall TRL at build is unlikely to exceed 6; this implies a robust commissioning process and in-operation surveillance to collect the necessary validation data. Fundamentally, this will be true of any power-plant-scale fusion reactor of any design, not just GIGA. There is no bulk fusion-spectrum neutron source, suitable for large-scale component qualification, foreseen to be available before procurement of GIGA components is underway, and certainly nothing capable of fully qualifying components under operational conditions. Nor is any such facility is planned at this time in any research programme. Moreover, such a facility would be of the scale, complexity, and cost of the GIGA power plant, and require effective tritium breeding and extraction due to constraints on external tritium supply. For these reasons GIGA must, as first-of-a-kind, be its own test environment and must be designed and operated to collect relevant data to provide regulatory submissions for full-lifetime operation, optimise component performance for future generations of fusion power plants, and obtain accurate FMEA and lifetime data for in-vessel components. It must do this without sacrificing safety principles or operational targets. There are thus currently

unmitigable risks based on the performance of the tritium breeding systems and fuel cycle, which are the lowest TRL subsystems.

One consequence of this lack of a testing facility is that the port plugs, acting as feedthroughs for the plasma heating systems, will also incorporate materials irradiation functionality, with samples intended to be removable with a minimum of shutdown time (i.e. without breaking vacuum or depowering magnets). Post-irradiation components, removed to the hot cell, will need inspection facilities.

High-level requirements are:

- The stellarator will produce 3 GW of fusion power, with thermal extraction of the heat at a suitable coolant temperature for conversion to electricity at good efficiency
- The stellarator will breed its own tritium supply with sufficient tritium breeding ratio (TBR) to achieve self-sufficiency and a tritium doubling time of 5 years
- The stellarator will support the Fusion Power Plant operational lifetime of 40 years, with a planned maintenance (PM) schedule of 4.5 yrs operation and 6-month maintenance duration

At this level the development for the next engineering phase revolves around controlled integration of design elements as the system designs mature. In particular, the integration of magnetic field design to provide a suitable plasma, while meeting engineering and shielding requirements for the magnets, requires at least one further iteration, and the cascade of stellarator requirements to subsystems must be managed to achieve consistent integration.

The implementation of strong systems engineering approaches and configuration control for stellarator systems will be critical to the success of the GIGA project. Qualification of suppliers for major systems such as the magnets and vacuum vessel needs to start during Phase 2 and prototyping activities need to be representative enough of final designs to give confidence in manufacturability and performance. Overall, the major design elements must be fixed early in the design phase to allow detailed engineering to proceed with confidence and clear requirements. Because of the FOAK nature and scale of these systems, certain design choices must inevitably be made which can foreseeably be descoped in the future with more direct experience of operational performance in a fusion environment.

In addition, a fusion facility operating at a new scale will always have some unknowns in operation; even the best modelling is not wholly predictive. There is therefore envisioned a staged commissioning process (outlined in the Concept of Operations Manual) to bring operational systems online as rapidly as possible while maintaining safety and capital protection. This is designed to ensure full confidence in plasma performance and control is achieved before the reactor is contaminated with tritium.

2. Stellarator

2.1. Plasma

Purpose and Function of the Plasma

The plasma is the primary reaction volume for the deuterium and tritium fuel and the source of neutrons and heat in the stellarator power plant. A plasma is a charged gas resulting from the heating of a gas to the point where collisions between atoms strip the electrons from atoms. Being composed of charged particles, plasmas experience the full force of electric and magnetic fields, and it is with these magnetic fields that we can confine a plasma by forming a torus. In heating the deuterium and tritium fuel to the point they undergo nuclear fusion, a plasma is formed. Thus, the plasma can be considered an emergent property from a system engineering perspective, resulting from the interactions of the magnetic field coils, heating systems, and fuelling system. However, because the shape of the magnetic field encodes how well the plasma is confined, the plasma's shape is usually defined first, with the design of the magnetic coils being focused on achieving the desired plasma shape. Fundamentally the plasma is the source of neutrons and heat of the power plant.

In magnetically confined fusion, the goal is to fuse isotopes of hydrogen by heating them to high temperature thereby creating a plasma which is confined with magnetic fields. The primary reaction of interest is between deuterium (^{2}H) and tritium:

$$(^3\text{H}): {}^2H + {}^3H \xrightarrow{yields} {}^4He(3.52\ MeV) + n(14.06\ MeV)$$
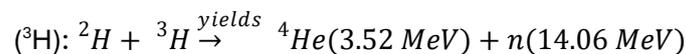
where the resultant products are an energetic neutron and an energetic alpha particle (^{4}He). The deuterium and tritium fuel will be in a fully ionized state as temperatures higher than 10 keV are required for fusion to occur in significant quantities. The resulting energetic helium, if confined, will transfer its energy through collisions to the electrons, which is turn will transfer energy to the ions via collisions as well. At which point the helium will achieve thermal equilibrium with the other species, becoming helium ash. The design challenge is to confine alphas long enough to transfer their heat to the electrons and to confine the plasma thermal energy long enough to maintain the temperatures necessary for fusion to occur.

The plasma itself is confined using toroidal magnetic fields. The most basic motion of charged particles in a magnetic field is such that the particles stream along magnetic field lines while tracing helical trajectories as they do so. Thus, we would like to construct a magnetic bottle where magnetic field lines close on themselves forming a racetrack like layout within which the particles will stay confined.

The Poincaré-Hopf theorem tells us that given a smooth vector field (such as the magnetic field) we can achieve this with a toroidal configuration. However, the curved nature of the resulting toroidal magnetic fields introduces cross-field drifts in the motion of the charged particles.
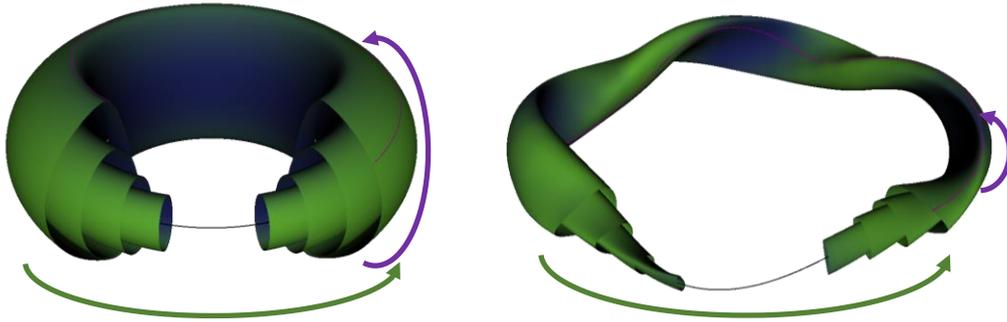
Figure 2.1: Tokamak (left) and stellarator (right) flux surfaces. The magnetic axis is depicted as a black line while a field line has been depicted as a purple line. Color contours indicate strength of magnetic field. Green arrows indicate toroidal direction while the purple arrows indicate poloidal direction.

This not only deconfines the particles but causes charge separation with the ions and electrons moving in opposite directions. To fix this we must also twist the magnetic field lines in the poloidal direction (short way around the doughnut). This results in the inward drift of particles on the inboard side of the torus compensating the outward drift on the outboard side. This effective twist of the magnetic field is called rotational transform, which is related to the enclosed poloidal and toroidal flux of a given toroidal magnetic field line ($\iota = d\chi \backslash d\Psi$). Thus it is possible to create toroidal magnetic field lines which trace out a set of nested toroidal magnetic surfaces, flux surfaces, thereby confining the plasma (Figure 2.1). In a tokamak, the twist of the magnetic field is achieved by driving a current in the plasma. In a stellarator, the twist is achieved by deforming the shape of the flux surfaces as we move toroidally around the torus. We define the confinement of a given magnetic field by a confinement time which is simply the ratio of the total energy (or particles) divided by the input power (or fuelling):

$$\tau_E = W_{plasma}/P_{heating}.$$

In the equilibrium problem we seek to determine the magnetic field which gives rise to a certain flux surface shape including the currents arising from the plasma. Traditionally, this is done under the assumption of a continuous set of nested flux surfaces. The common methodology to solve the ideal MHD equations is via an energy minimization method where the pressure is a function of the radial grid (as is the prescribed current) and the surfaces are represented by a double harmonic Fourier series.

The perturbative study of these equilibrium magnetic fields is the domain of stability theory. Many types of instability mechanisms are studies in the framework of ideal MHD. Highly localized perturbations in the presence of a pressure gradient give rise to an instability known as a ballooning mode. The study of toroidal perturbations and their coupling give rise to kink (or finite-n) stability. These are just a few possible modes. General concepts like the presence of a magnetic well and Mercier condition help to provide compact expressions for assessing stability of a given ideal MHD equilibrium. This is important as the presence of such modes in tokamaks can be destructive, while in stellarators they can degrade plasma confinement. However, experimental evidence from stellarators suggest that such limits are soft, with

second stability (stability past a given stability limit) being reached. This is one of the key motivations for selection of the stellarator as the GIGA magnetic confinement concept.

Once a stable equilibrium magnetic field is found, confinement of said fields is not perfect due to collisions and the presence of temperature and density gradients. The way charged particles diffuse from high temperature (or density) to lower temperature (or density) regions in a straight magnetic field is known by the term classical transport. The inclusion of curved magnetic fields and gradients in field strength result in some charged particles becoming trapped in magnetic wells. These wells are regions of low magnetic field strength bounded by high magnetic field strength along a give magnetic field line. The study of the collisional behaviour of such particles is known by the term neoclassical transport. This mechanism gives rise to a self-generated toroidal current (bootstrap current), for stellarators a radially electric field, and was responsible for early stellarators having poor transport as compared to equivalent tokamaks, essentially resulting in large radial diffusions of heat and particles in stellarators. Minimization of such transport through careful tailoring of the magnetic field has been an enabling achievement in stellarators towards the goal of fusion energy.

In addition to collisional particle orbits resulting in radial diffusion, density and temperature perturbations give rise to turbulent transport. In the simplest terms, small perturbations of density and temperature which drift along a flux surface perturb the underlying force balance resulting in growth of the perturbation and ultimately heat and particle transport. Experimentally this type of transport is often referred to as 'anomalous' transport, due to the complex theoretical underpinnings required to predict its behaviour. The theoretical model starts with the 5-dimensional (three positions, two velocities) phase space of the plasma. Through various orderings of terms and geometrical assumptions, different driving mechanisms for turbulence can identified (ion temperature gradient, trapped electron mode, kinetic ballooning modes, etc.). While computation of the non-linear heat flux can be quite computationally expensive (extending to the exa-scale regime), much work has been conducted in the past 25 years to understand how shaping magnetic fields can minimize such transport. Moreover, experimental evidence suggests that some low level of turbulence may be beneficial in aiding fuelling and expelling impurities from the core of the plasma.

Design Basis

The design of the GIGA plasma involves optimization of the plasma shape to achieve a set of desired physical properties. Based on the history of stellarator design and experimentation a plasma with low neoclassical transport, low bootstrap current, high fast ion confinement, MHD stability, reduced turbulent transport, and divertor compatible rotational transform is desired. This must all be achieved at reactor relevant temperatures and densities, meaning reactor relevant pressures. The process by which the plasma shape is varied to achieve such parameters is known as stellarator optimization. A variety of software for this purpose has been developed over 40 years, but the arguably most advanced of these is the STELLOPT package. Central to this package is the ideal MHD equilibrium code VMEC.

The STELLOPT code performs a multi-objective chi-squared minimization of a user definable set of target functionals. The user is free to define the varies quantities (x-vector), the target functionals (f-vector), inverse weights (σ), and the algorithm for the chi-squared minimization. The minimized function takes the form

$$\chi^2(\vec{x}) = \sum_m \frac{\left(F_m(\vec{x}) - F_m^{target}\right)^2}{\sigma_m^2}$$

here the summation is over the number of desired target values. The chi-squared function can be minimized using Levenberg-Marquardt, differential evolution, and particle swarm optimization methods, in addition to the techniques available in the MANGO package. In the context of our problem the *x*-vector is composed of the boundary harmonics representing the equilibrium along with the enclosed toroidal flux. Meanwhile, the target functionals (*F*) are the magnetic field on axis, total bootstrap current, magnetic field symmetry,
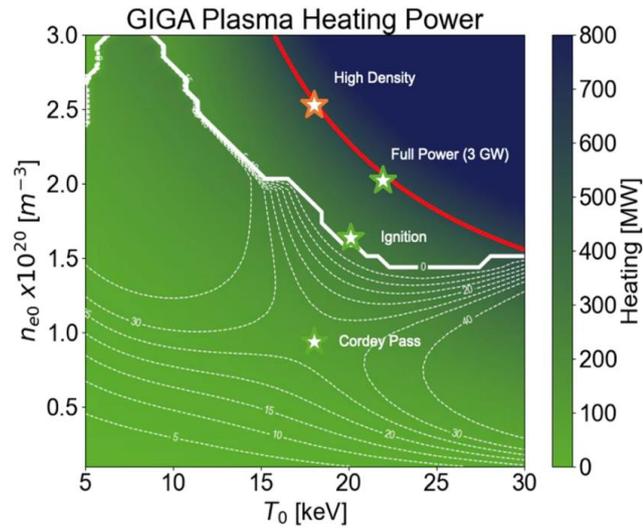

Figure 2.2: POPCON plot showing the startup, ignition (white solid line), and full power (red solid line) operating states. Dashed lines indicate required auxiliary heating power to sustain the plasma. Representative scenarios are shown as stars.

neoclassical transport, MHD stability, fast ion confinement, turbulent transport, and rotational transform. The plasma volume is held fixed at 1500 m³ through a renormalization of the plasma boundary every time the VMEC code is run. Through this multi-objective optimization, a plasma shape is found which meets the physics requirements of our design objective.

The zero-dimensional scaling study in addition to helping understand sensitivities to parameter variations, has also been used to identify operating scenarios for the plasma. Figure 2.2 shows the POPCON plot for the GIGA device with our four reference scenarios labelled. The Cordey Pass denotes a saddle point in the required auxiliary heating necessary to support the plasma. This is the minimum auxiliary heating needed to achieve an ignited state in GIGA. The ignition point defines a point just beyond the line of ignition. Beyond this point the plasma is fully supported by the alpha particle heating (assuming 95% alpha energy confinement). Two full power scenarios are identified at different density points. It should be noted that this study indicates that GIGA requires an energy confinement time slightly less than ITER at plasma core temperatures less than ITER.

The control of the plasma is the subject of the Stellarator Control Infrastructure system (SCI). This system is responsible for plasma startup, parameter control and control of the total fusion power output. This is achieved by controlling the auxiliary heating system and fuelling systems. A set of robust diagnostics provide state measurements of the plasma. The development of this system is considered a separate L2 system of GIGA.

The GIGA plasma reliability can be considered relatively high compared given the stellarator concept adoption. Stellarators are intrinsically steady-state by nature. In the fully ignited state, the plasma will continue to burn so long as fuel is supplied to maintain a given density. As no large toroidal current is required, disruptions and their associated phenomena are not present. A density limit does exist for stellarators but is related to an edge density radiative limit (the Sudo limit). Experimental evidence suggests this is a soft limit with many stellarator

reactor designs exceeding the limit by factors of two. Using the empirical W7-X density limit scaling, it is found that GIGA is well below the density limit even for large impurity contents. Should a radiative limit be hit the decay time for the plasma will be on the order of 100 ms, with about 3% of the magnetic energy being lost. While not ignorable, such changes do not impose significant structural issues for the stellarator. Such events mostly affect the tritium breeding blankets and divertor as an impulsive photon load (thermal).

Figure 2.4: The optimized GIGA_v515 VMEC equilibrium depicting the magnetic field strength on the plasma boundary.

Concept Definition

The stellarator plasma being developed for GIGA is a 4-field period, 6 T, 1500 m^3 device, producing 3 GW of fusion power (Figure 2.4). The design of the GIGA stellarator starts from a rescaled W7-X high-iota high mirror configuration. This serves as the starting point for plasma optimization with STELLOPT.

Reasonable assumptions about achievable plasma temperature and density profiles were chosen to reach the target 3 GW of fusion power.
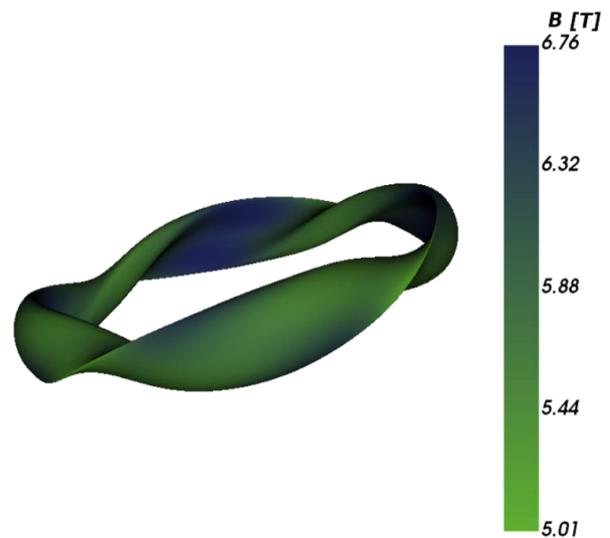

Figure 2.3: Comparison of turbulent fluxes between GIGA_v515, W7-X, and Type-One Infinity Two. The W7-X and GIGA simulations are electrostatic (STELLA) while those of Infinity Two are electromagnetic (GX code).

Various direct and proxy targets are used in the optimization. The rotational transform and magnetic field on axis targets are directly computed from the VMEC equilibria. A transformation to straight magnetic field line coordinates (Boozer coordinates) is performed to evaluate the quasi-poloidal symmetry and quasi-isodynamic nature of the magnetic field. The COBRAVMEC code is used to compute ballooning stability at radial locations across the plasma. The neoclassical transport is minimized in the $1/\nu$ regime via the effective helical ripple as computed by the NEO code at mid radius. The Γ_C metric is employed at mid radius to improve energetic particle confinement. The $g_{\theta\theta}$ metric (prox1d) is used to minimize turbulent transport as generated by the ion temperature gradient (ITG) mode. Finally, the total

bootstrap current is minimized by computation with the BOOTSJ code. These targets define the multi-objective functional.

The optimization is performed using successive applications of the differential evolution algorithm. At each stage a ±10% bound on the boundary coefficient is applied to the search space. Between 10 and 20 generations are utilized with a population of approximately 1000 members. Successive application of this optimization with changes to weight were performed to achieve the plasma shape (GIGA_v515). Preliminary analysis of this configuration found it to meet all the requirements of the conceptual design. Although not directly targeted the plasma was found to maintain the magnetic well feature of the initial equilibrium indicating some level of MHD stability.

Qualification Record

While many physical properties of the plasma are directly targeted through the optimization process, others are proxies which require more detailed analysis. Analysis of various physical quantities of the plasma are analysed through the lens of the four previously defined scenarios. The MHD stability, fast ion confinement, neoclassical transport, and turbulent transport were all evaluated. This analysis culminated in development of a 1D transport model showing access to the 3 GW fusion power operating point with 50 MW of applied ECRH heating.

The minimization of the bootstrap current was verified by the coupled DKES+PENTA codes. The BOOTSJ simulations found a vanishing small total bootstrap current for the GIGA_v515 equilibrium, where zero toroidal current was assumed in the equilibrium calculation. Simulations with the THRIFT (DKES+PENTA used) current evolution code showed that not only was BOOTSJ underestimating the total bootstrap current, but that self-consistency between equilibrium toroidal current and bootstrap current were required for accurate computation. Still the changes to the rotational transform were small at the plasma boundary and affected the plasma core. Continued reduction of bootstrap is taken as an open point for further plasma optimization.

The stability analysis of the plasma involved computation of the ballooning stability, finite toroidal mode stability, and Alfvén gap structure of the plasma. The plasma was found to be ballooning stable at all plasma radii for the four configurations considered. All configurations also showed both Mercier stability and magnetic well. The n=0, n=1, and n=2 mode families of stability were analysed with the TERPSICHORE code. Some level of instability was found but was usually localized to the core or edge. Studies of the effect of toroidal current suggest that even small reductions in the bootstrap would stabilize these plasmas. The Alfvén continuum was computed (STELLGAP) for the configurations and no large gap in the mode families were found.

Neoclassical transport analysis shows significantly reduced neoclassical transport in the $1/\nu$ regime. This suggests significant improvement in confinement in the collision less regime. This is confirmed through use of the DKES and PENTA codes (Figure 2.5). However, we note that the effective collisionality,

$$\nu^* = (\nu/v_{th})(R_0/\iota)$$

is in the range of 0.001 to 0.8 over the entire plasma at full power. This suggests that while the ions may be in the $1/\nu$ regime, the electrons are in the plateau. This confirms the notion that BOOTSJ, which is only valid in the very low collisionality limit may not be applicable for these plasmas. The radial electric field for these plasmas was in the ion root.

Nonlinear electrostatic flux tube simulations of turbulent transport (STELLA code) were conducted indicating significantly reduced turbulent transport as compared to simulations performed for W7-X. Figure 2.3 depicts the GIGA_v515 turbulent heat fluxes as compared to work performed for W7-X and the Infinity Two concept (Type One Energy). For all densities gradients the electrostatic simulations show heat fluxes on par with Infinity Two and lower than W7-X. The W7-X and GIGA_v515 simulations are electrostatic flux tube simulations while the Infinity Two work is electromagnetic. Generally, it is thought that electrostatic simulations provide an upper bound on turbulent transport. While this is not universally true, this work does suggest that GIGA has reduced turbulent transport as compared to W7-X, showing that the proxy function-based optimization appears to have been fruitful. A database of such simulations was created for different radial locations, density gradients, and temperature gradients to provide a lookup-table for transport.

Monte-Carlo simulations of fast ion confinement using alpha birth profiles confirmed adequate fast ion confinement. Assessment with the 0D model suggest at least 85% of the alpha power would need to be deposited in the plasma for ignition to be achieved before reaching 3 GW of fusion power. Around 88% of the total fusion power is in fact confined by the plasma with 20% of that power going directly to the ions (Figure 2.6). Simulations of trapped orbits show that optimization with the Γ_c metric did reduce trapped losses.

Figure 2.6: Lost alpha particle power as a function of time in ASCOT5 simulations.

Combining the results of neoclassical transport, turbulent transport, and fast ion simulations one dimensional transport equations were solved for the GIGA device. Transport in these models use neoclassical terms as determined by solving the drift-kinetic equations. Using the aforementioned turbulence simulations, coefficient characterizing stiffness and critical temperature gradient were determined. These coefficients were then implemented in the same equations used to model ion temperature clamping as seen in the W7-X
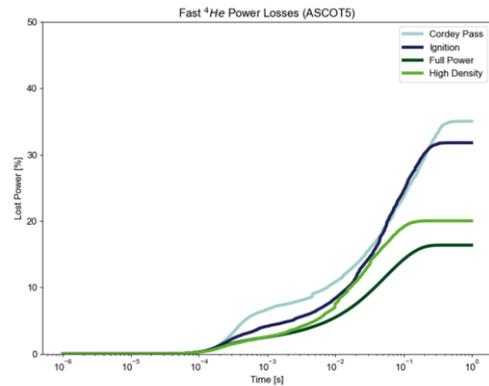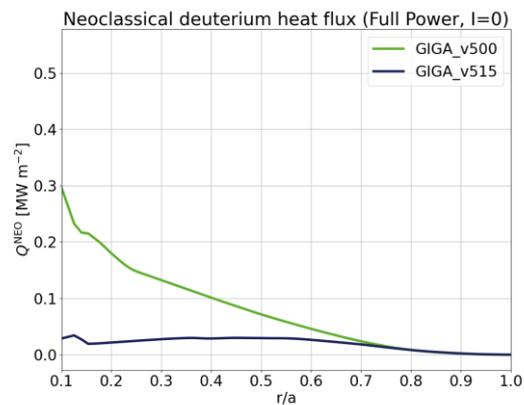

Figure 2.5: Comparison of deuterium neoclassical heat flux comparing initial (v500) and optimized configuration (v515).

experiment. It was found that given the current performance of GIGA a 3 GW fully ignited state could be reached.

Qualification Plan

Moving forward from this conceptual design, work will be performed to further improve the stellarator configuration. The need to reduce bootstrap current was clearly identified to improve kink stability and overall improve control of the rotational transform profile. While acceptable for core heating, improvement of alpha confinement is needed to reduce fast ion wall loads, and further improve access to the ignited state. More recently, it has been shown that core electron root confinement can be achieved at reactor relevant plasma parameters. Such a feature would improve core fuelling and assist with impurity expulsion. Finally, although not formally part of the plasma design, consideration of features affecting coil design is desirable.

A key outcome from this work was the demonstration that further improvements in confinement (fast ion and impurity) can reduce the required auxiliary power needed to achieve ignition. This has a direct economic impact on the project. This may also simplify packaging of the heating system interfaces and allow for a more detailed set of diagnostics in the stellarator device. What is encouraging is that further improvements to the equilibrium do not, at this time, change feasibility of access to full power operation.

2.2. Tritium Breeding Blanket

System description

Within the architecture of fusion power plants regardless of whether driven by laser or enabled by magnets, the tritium breeding blankets (TBB) play a key role. By capturing the emerging neutrons from the fusion plasma, they generate tritium whilst also capturing heat that is used to produce electricity through the power conversion system. However, the neutron bombardment from the fusion process damages materials, causing them to degrade over time. As a result, the blankets must be periodically replaced; the more compact the device and the higher the power density, the more rapidly the materials reach end-of-life. Removing end-of-life blankets and installing their replacements require a temporary shutdown of the plant, resulting in reduced plant availability. Hence, an enhanced intrinsic modularity in the plant design will enable faster component replacement and is expected to have a large impact on the overall cost of electricity from fusion, influencing the economic viability of commercial fusion. A third function of the breeding blanket is to shield device elements allowing them to be lifetime components, namely the vacuum vessel and the superconducting coils. Additionally, besides enabling efficient remote maintenance, the TBB must survive and maintain an operational integrity in reactor environment, and provide condition monitoring to support asset life management.

Gauss Fusion's solution consists of an innovative helium-cooled pebble bed (HCPB) blanket, drawing on the development work of EU-DEMO with three key differentiators. This design improves on scalability, manufacturability, longevity, and sustainability issues.
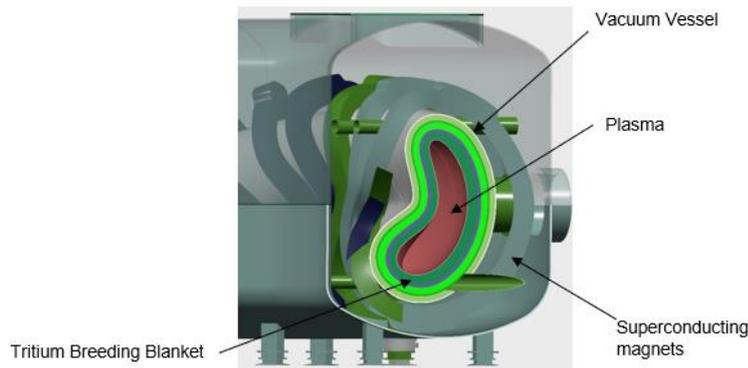
Figure 2.7. Layout of the tritium breeding blanket in GIGA

This solution was selected following an optioneering assessment of different alternatives (water-cooled ceramic breeder, water-cooled lithium lead, helium-cooled lithium lead, dual-coolant lithium lead and FLiBe). Selection criteria included efficiency, licensing, maintenance, TRL and supply chain.

Before reaching operational deployment, the TBB must undergo a progressive development and validation process aimed at increasing its TRL from its current ~TRL3.
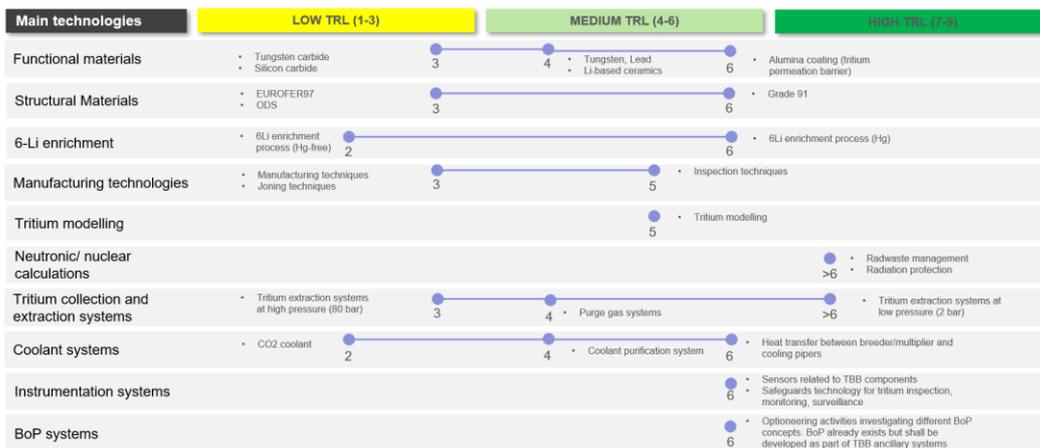

Main technologies	LOW TRL (1-3)		MEDIUM TRL (4-6)		HIGH TRL (7-9)	
Functional materials	• Tungsten carbide • Silicon carbide	3	4 • Tungsten, Lead • Li-based ceramics	6	• Alumina coating (tritium permeation barrier)	
Structural Materials	• EUROFER97 • ODS	3		6	• Grade 91	
6-Li enrichment	• 6Li enrichment process (Hg-free)	2		6	• 6Li enrichment process (Hg)	
Manufacturing technologies	• Manufacturing techniques • Joining techniques	3		5	• Inspection techniques	
Tritium modelling				5	• Tritium modelling	
Neutronic/ nuclear calculations					>6	• Radwaste management • Radiation protection
Tritium collection and extraction systems	• Tritium extraction systems at high pressure (80 bar)	3	4 • Purge gas systems	>6	• Tritium extraction systems at low pressure (2 bar)	
Coolant systems	• CO2 coolant	2	4 • Coolant purification system	6	• Heat transfer between breeder/multiplier and cooling pipers	
Instrumentation systems				6	• Sensors related to TBB components • Safeguards technology for tritium inspection, monitoring, surveillance	
BoP systems				6	• Optioneering activities investigating different BoP concepts. BoP already exists but shall be developed as part of TBB ancillary systems	

Figure 2.8. Technology Readiness Level of main Tritium Breeding Blanket technologies

The backbone of the TBB concept architecture is a pin element or finger, for which Gauss Fusion has already filed a patent application. The pins will be engineered to cover most of the internal surface of the vacuum vessel, as depicted in Figure 1.8.

Internal coaxial channels enable a multifunctional architecture. Purge gas flows through the Li-based ceramics in the breeding zone at very low speed and collects tritium, before being redirected towards an adjacent volume of the pin through filters, which allow the purge gas to pass through while retaining the pebbles within the assembly. Coolant gas flows through dedicated channels to extract the generated heat and to maintain the thermal integrity of TBB.

The TBB pins are attached to a backplate to form TBB modules. The backplates, besides their supporting function, direct the processing flows (e.g. coolant and purge gas) through the TBB pins.
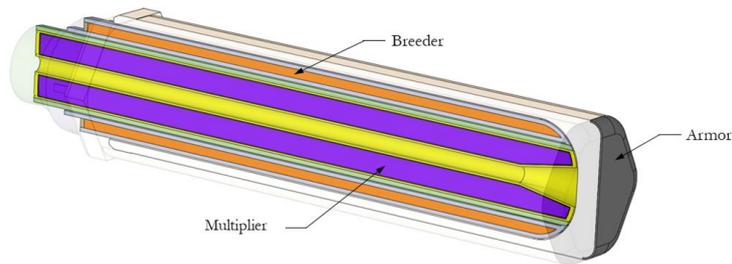
Figure 2.9: TBB pin concept architecture

TBB modules are further grouped into TBB segments to enable engineering, manufacturing and maintenance following best industrial practices. TBB segments, which are the core unit for remote handling operations, comprise modules (with pins), shield and neutron reflector layers.
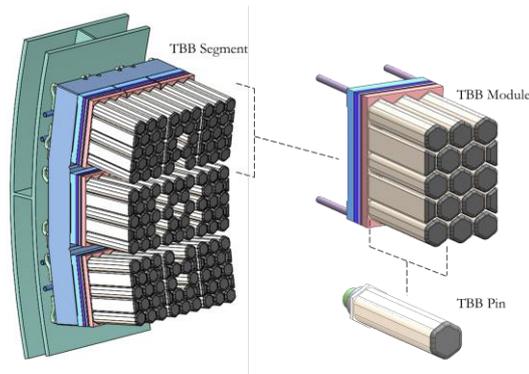

Figure 2.10: Illustrative concept: TBB segment, module and pin overview

The TBB lifetime and maintenance (exchange) timescales will drive the FPP operating cycles. The target for GIGA is to operate for not less than 54 months, equivalent to 4.5 full power years, and for the removal and insertion of a full set of segments to be completed within 4 months, so that the target overall outage time is limited to 6 months. Therefore, it is essential that the TBB segments are designed for straightforward maintenance operations to enable their prompt removal and exchange, either at the end of their lifecycle or in case of failure.

Due to high-radiation and the harsh environment in the stellarator, direct access for TBB maintenance is not possible, making remote handling mandatory. To expedite the maintenance, the TBB components shall be grouped in larger and fewer segments for an optimal remote maintenance approach. This will require trade-offs with the available space and the loading constraints of remote handling and lifting tools. Maintenance within the device will involve two key operations: remote/connection and disconnection of helium pipes and remote attachment/removal of the segment. After removal from the reactor, the TBB segments must be transferred to an enclosed (tritium-tight) area, where they can be decontaminated and prepared for storage as radioactive waste.

During the conceptual design phase, several iterations of pin and module design have been developed to explore and improve component functionality. As an order of magnitude, based on the pin v3.5 concept, the GIGA vacuum vessel will contain more than 80,000 pin elements.

This design shall be further optimized to support remote maintenance and scheduled replacement.

After effective TRL development and prototype development, the TBB components will follow distinct lifecycle phases, each requiring careful planning and tailored approaches to ensure reliable performance, safety and compatibility with the stellarator environment. These phases will include manufacturing, factory acceptance testing, storage (pre-installation), transport, installation, commissioning, operation and decommissioning.

Design basis

GIGA is designed as a power plant for electricity production for at least 40 years, and not just to briefly demonstrate net electrical power. According to the current Gauss Fusion Business Plan, GIGA should be ready to operate by the 2040's and, therefore, the TBB technology selection has prioritised reasonably mature technologies, using available materials and requiring the minimal timeline for further development and qualification. Gauss Fusion's strategy is to focus efforts and resources on single, well-defined blanket architecture, the Helium Cooled Pebble Bed, rather than spreading resources across multiple early-stage options. However, challenges may appear during the design phases (Phase 2) leading to a reassessment of the technology path and proposal of alternative blanket concepts.

With the baseline architecture identified, the conceptual design phase covers a primary system breakdown consisting of first wall, breeding zone, multiplier, piping, structural materials, shield and reflector. A functionality analysis has been carried out up to this breakdown level, in which the main and supporting functions (in terms of inputs, outputs and assumptions) were identified, enabling the development and definition of a baseline architecture. In parallel, a technology assessment was conducted to identify applicable TBB technologies, and the needed qualification activities required to bring their TRL from current low levels ~TRL3 to higher levels required for the GIGA delivery and commercialization schedule targeting the 2040s.

A systematic methodology is proposed to verify that selected TBB concept is feasible, and to support further improvement of the baseline design. This approach is based on multi-physics, design for manufacturing (DxM), and remote maintenance analysis. Other analyses including safety analysis, tritium transport, and mock-up /prototyping will be incorporated into the later stages of the design phase.

The scope of TBB program includes:

- The TBB installed in the vacuum vessel, consisting of modules mounted on dismountable supporting structures attached onto the vacuum vessel
- The attachment system, including all connection pipework back to mount/dismount points to enable the pipework to be broken for remote maintenance

The TBB is a multifunctional component and has several interfaces with other plant systems. The most relevant identified interfaces are Plasma, Fuel Cycle, Primary Heat Transfer System, Vacuum Vessel, Divertor and Remote Maintenance.

The TBB is a plasma-facing component subjected to some of the harshest neutron and thermal loads of the fusion power plant, and its performance under different modes

determines both its feasibility and lifetime. After the commissioning phase, GIGA will operate following various operating modes and transitions as defined Concept of Operations (ConOps). The main loads on the blankets during power generation conditions have been described and assessed as part of the conceptual design phase. During the engineering design phase, the overall performance of the blankets in each mode and transition will be defined and assessed considering the specific mechanical, thermal and nuclear loads imposed on the component.

The TBB will maintain pressure and leak-tight boundaries between the coolant and the vacuum vessel, ensuring that penetrations and interfaces remain leak-tight during both normal and abnormal conditions. For the current status of design, the TBB can be classified as safety-related. However, this preliminary safety classification shall be justified and endorsed with the corresponding accident analysis, which is planned to be conducted during the engineering phase, to indicate compliance with the identified safety requirements on dose limits for public and no impact on lines of defence, 'detection' and 'mitigation'.

Minimization of radioactive waste hazards and volumes is a priority for TBB components. A radwaste plan for classification, conditioning, recycling and disposal routes will be developed in detail after conceptual design. Activation studies have begun and a first estimation of the quantities of radioactive material for several components, including blankets, have been obtained on a homogeneous model that approximates the current design. These studies are useful to obtain a first very rough estimate of the waste implications for operational durations of 40, 60 and 80 full power years. However, iterations shall be carried out in the future to rerun the predictive models for a more detailed TBB design.

The design will consider the use of surveillance samples within the operating stellarator to provide representative material degradation data for GIGA; these will give direct feedback on the state of TBB materials. Surveillance programs of materials are part of the proposed substantiation framework to balance evaluation across four key areas: failure tolerability, available margins to failure, prior knowledge of material behaviour, and the feasibility of monitoring degradation in service.

The TBB must perform consistently under demanding conditions, with minimum downtime or failure, and is required to operate predictably under all planned operational conditions, while maintaining performance over its lifetime. The TBB availability constrains the duration of GIGA operation cycles, and must keep its functionality for at least 54 months of operations without degradation. The TBB system must adhere to this high-level requirement of the fusion power plant (post-commissioning unplanned availability limit of 2%) because any TBB failure triggering plant shutdowns risks making the plant less competitive (in terms of LCOE) against other power generation alternatives.

While the target reliability of TBB is 100%, an acceptable lower threshold may be proposed following RAMI analysis and endorsement by the GIGA safety case. This situation may lead to the TBB operating in a degraded condition but still compatible with safe operation of the fusion plant in accordance with the Safety Case. Hence, limited TBB failure is assumed tolerable if safety margins are preserved and a minimum level of performance is achieved. The degree of tolerability must be clearly defined and justified through safety analysis, operational experience, and regulatory acceptance.

Development of TBB technologies for commercial fusion power plants requires a proactive and extensive risk management approach. The risk management process implemented at Department level, which is embedded in the project management process following PMI standards, complies with ISO 31000 and uses as a main tool a risk register, which ensures transparency and traceability. As per the last risk register review, dated November 2025, 64 risks and opportunities have been identified covering safety, design, interfaces, supply chain, materials, manufacturing, testing and operation areas.

Besides the risk register, Failure Modes and Effects Analysis (FMEA) is an important tool embedded in the design process that provides a bottom-up technical view of potential failures, supporting development of design modifications and/or effective mitigation and recovery actions. FMEA spans all lifecycle phases and cover all primary blanket functions. As per last iteration of FMEA analysis, dated September-2025, 43 failures have been identified and assessed. This identification of potential failure modes, risks and criticalities, together with actions to keep traceability of design decisions, and definition of control points and validation criteria, among others, are compliant with ISO 9001 principles and typical quality assurance specifications for nuclear and safety-related projects. This has established the foundational framework for deployment of more systematic quality assurance provisions in the future.

Concept definition

The blanket design process at concept phase has progressed along several interdependent lines of development that have been treated semi-independently to allow for parallel progress within respective maturity levels. However, in later design phases, all domains will be progressively integrated to ensure all areas remain within compatible operational envelope.

The following table presents a summary of main tritium breeding blanket components. Although the current pin baseline design corresponds to the prototypical v3.5 model installed uniformly throughout the stellarator, variations in the baseline pin design (dimension changes) as a function of the pin position in the stellarator geometry will be considered in next design phases.

Main Component	Baseline material	Alternative material
First Wall	Tungsten	n/a
Breeding Zone	ACB (Li_4SiO_4–Li_2TiO_3)	Other advanced ceramics
Multiplier	Lead	LaPb3
Piping	Grade 91	Other steels
Structural components	Grade 91	EUROFER, ODS
Reflector	W, WC	n/a
Shielding	Water and Grade 91 steel	Tungsten borides

Table 2.1: TBB main components

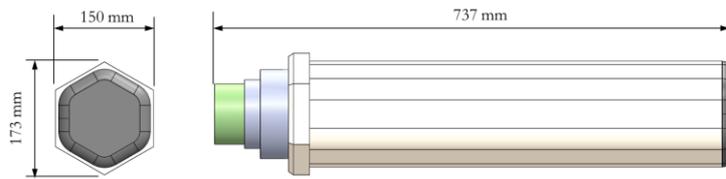An optimization in the number of variants shall be assessed as well.

Figure 2.11: Prototypical pin depiction

The TBB is a cross-functional component coupled with several interfaces that operates within an extremely harsh environment and must comply (primarily) with thermal, structural, shielding, tritium generation, remote maintenance, and manufacturability criteria. Design iterations are, therefore, unavoidable to optimize and enhance robustness of the design. However, design modifications lead to a trade-off analysis that is not easy to implement quickly, particularly, when the analysis of different areas is to be coupled. During the conceptual design, several design modifications to v3.5 have been investigated, and a new design iteration is already under development with an improved combination of optimized features.

Having a pin as a common modular component allows for the targeted modularization and segmentation of the breeding blanket to enable efficient assembly, disassembly and remote maintenance approaches. The vacuum vessel ports configuration for the device segmentation, following the identified remote management strategy for TBB development, is based on four vertical ports per stellarator quadrant, although with only 3 of them being practicable for TBB remote maintenance purposes. If larger ports become available during the stellarator design process, larger TBB segments will be designed and assembled up to the limiting constraints of remote handling tools. The breeding blanket volume is divided into slices parallel to the direction of the ports, and 3 slices per port width has been preliminary identified to create a reasonable module pattern and accommodate curvature of the vessel. However, there are transition areas that need a dedicated solution in the following design phase. Considering further segmentation, a spine is defined as a decoupling of the inner and outer segmentation of the reactor.

The proposed segmentation leads to slices based on module widths of ~460 mm, for an array of nx3 configuration module. Two module variants are considered, 3x3 and 5x3, which permit a proper adaptation to curvature in both axes. Pins, modules and segments will have variants to adapt to the optimal solution complying with the identified criteria (e.g. breeding, cooling, remote maintenance, etc.) keeping always as top objectives industrialization, standardization and operations compatibility.

Qualification overview

Although TBB technologies are key for the commercialization of fusion power plants to enable plant scalability, their TRL is still very low. This is because developed qualification activities in international programs have been only able to include a very limited number of partially integrated experiments and a limited number of basic, single-effect and multiple-effect experiments for a limited number of concepts and constrained to non-fusion testing facilities.
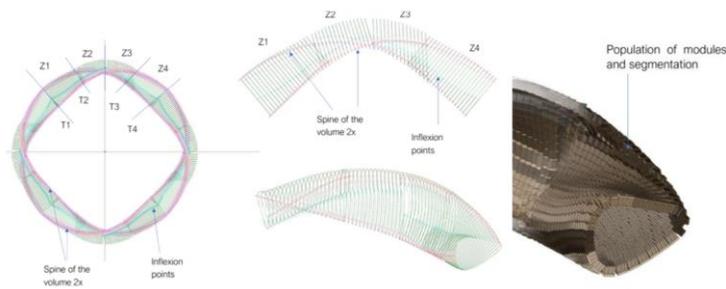
Figure 2.12: Segmentation and section population process

The EU Fusion Roadmap relies on the results of the ITER TBM program to further increase the readiness level of the HCPB concept up to ~TRL 5-6 and to use DEMO as a qualifying device to operate with an integrated self-sufficient breeding blanket and therefore achieve ~TRL 9. Lately, EUROfusion is considering reintroducing a nuclear plasma device that may serve as a 14 MeV neutron source (VNS) for testing and qualification of the breeding blanket to be run in parallel to both ITER operation and DEMO design process. However, timeframes of all these initiatives are very unlikely to be compatible with GIGA target dates to start commercial operations by 2040s.

For the proposed tritium breeding blanket technology at Gauss Fusion to achieve ~TRL8, a full-scale TBB segment must be delivered (identical systems) and tested within a large testing volume under a stellarator relevant operational environment to fully qualify the component. This can only be achieved using a VNS compatible with stellarator operation (scenario 1) or using GIGA as the qualifying device (scenario 2). A risk management model for decision-making is proposed at this stage to decide whether to wait until a VNS compatible with TRL8 is available or to use GIGA as a qualification device from lower TRL levels, ~TRL 5-6. Both proposed scenarios rely on international programs to increase the maturity of tritium breeding blanket technologies up to ~TRL 5-6. Thus, a dedicated qualification strategy is proposed under two scenarios following a staged approach, aimed at increasing both Technical Readiness Level (TRL) and Manufacturing Readiness Level (MRL) for the development of TBB technologies.

- Phase 1   Conceptual design   2024-2025
- Phase 2   Engineering phase   2026-2032
- Phase 3.1   Implementation of industrial organization   2032-2035
- Phase 3.2   Qualification of industrial organization   2035-2038
- Phase 3.3   Series production   2037-
- Phase 3b   Commissioning   2039-2044

At conceptual design level, the areas of safety, primary functions, and manufacturing and maintenance are assessed to demonstrate feasibility of the proposed solution.

Gauss Fusion's conceptual design approach has involved performing rigorous assessments around broad parameter margins that will allow ensuring feasibility of the proposed concept. No codes and standards have been imposed at this stage, but some of the identified ones have been useful to propose acceptance criteria aiming at feasibility demonstration.
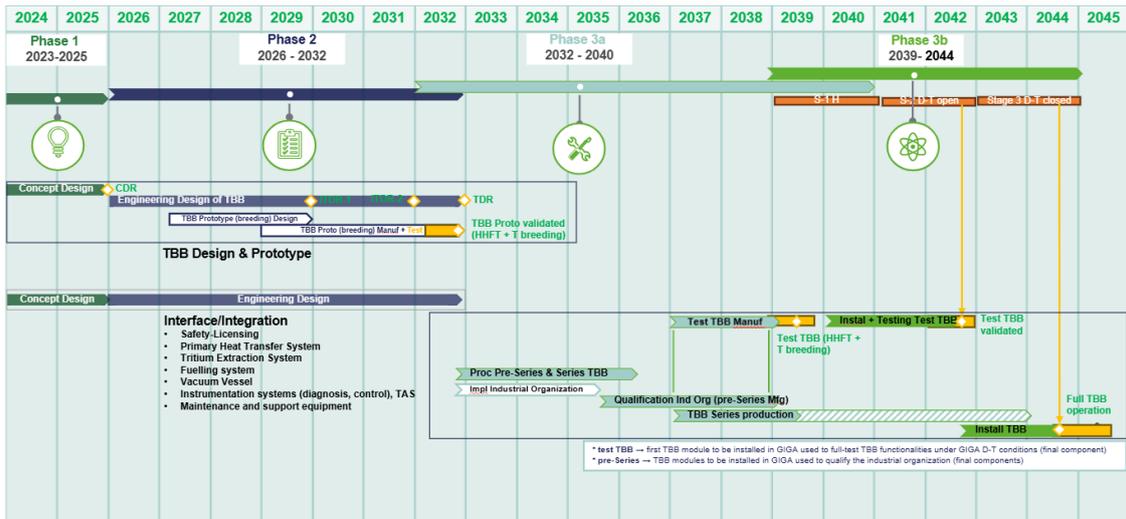
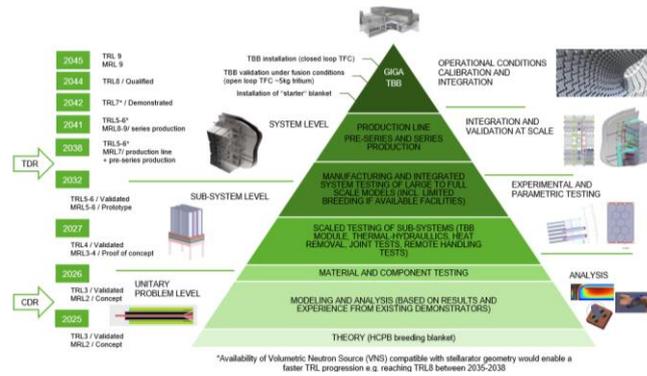*Figure 2.13: TBB development phases within GIGA staged approach*

Figure 2.14: TBB building block approach – qualification strategy

As a summary, the main conclusions of the conceptual design phase (Phase 1) are:

- Shielding to lifetime stellarator components and TBR>1.05 has been demonstrated developing a radial build compliant with the requirements identified through neutronic calculations on homogeneous model.

- Proposed evolutions of pin design indicates promising levels of structural and mechanical integrity under anticipated mechanical and thermal loading conditions.

- Proposed module design demonstrates robust thermo-structural performance and integrity under anticipated mechanical and thermal loading conditions. Joints between backplates shows compliance with resistance requirements.

- Parametric thermal fluid dynamics analysis shows promising design drivers to indicate compliance of G91 internal structural components with thermal criteria.

- Selection of Grade 91 over EUROFER as structural material for the first blanket generation has been justified based on ALARP/ALARA principles. Regulatory framework and purity control of steel compositions are key drivers for waste classification.

- Coolant temperatures (inlet and outlet) needed for PHTS has been demonstrated achievable with a pin configuration through thermal analysis.

- Segmentation of the TBB is compatible with the initial remote handling strategy and provides flexibility to adapt to new remote handling strategies if larger ports become available. These segmentation and modularization are compatible with the vacuum vessel shape and presents no showstoppers for divertor integration.
- Coolant and purge gas manifolds in the segment have been conceptualized to minimise the number of connections with the coolant and purge gas pipes coming from the vacuum vessel.
- Maintainability of the TBB design shows promising feasibility. However, dedicated RH tool shall be designed to comply with safety and operational requirements. The prototypic segment facilitates integration with vacuum vessel but presents some challenges to be solved during Phase 2. Provisions for remote connection/disconnection of helium pipes and remote attachment/removal of the segment are included.
- Manufacturability of the tritium breeding blanket design presents no showstoppers and may be compatible with a realistic development plan.

After the CDR, Phase 2 – Engineering Phase (2026-2032) is planned to start aimed at progressing the design to the point that the TBB maturity is appropriate to support proceeding with full-scale fabrication, assembly, integration and testing. This phase covers intermediate and detailed design and ensures that the technical effort is on track to complete the project development and operation, meeting project performance requirements within the identified cost and schedule constraints. Phase 2 includes fabrication and testing of a TBB full-scale prototype (thermal, breeding, structural, etc.) as a condition to move to the next project phase.

The main engineering gates included in Phase 2 are:

- System Integration Review (SIR)   Q4 2026
- Intermediate Technical Design Review 1 (ITDR-1)   2029
- Intermediate Technical Design Review 2 (ITDR-2)   2031-2032
- Technical Design Review (TDR)   Q4 2032

Supply chain and FOAK system validation

The progress made during the conceptual design phase on the development of TBB technologies for GIGA is supported by a joint public-private project 'SyrVBreTT- Synergy Consortium Fuel Cycle and Tritium Technologies' primarily sponsored by the German Federal Ministry BMFTR. This effort is helping to secure strategic partnerships that will be the basis of a solid supply chain for breeding blanket technologies.

Europe has the intellectual and test infrastructure to support design and series production of TBB based on Gauss Fusion concept. However, the industrial supply chain must be scaled up and qualified urgently, between the time frame 2029-2031.

FOAK manufacturing development is embedded in GIGA Phase 3a, construction and assembly phase (2032-2038), which is divided in the following steps for TBB:

- Phase 3.1   Implementation of industrial organization   2032-2035
- Phase 3.2   Qualification of industrial organization   2035-2038
- Phase 3.3   Series production   2037+

As part of the conceptual design activities, a manufacturability assessment has been developed aimed at assessing relevant manufacturing aspects of the proposed design including its potential for series production. A preliminary manufacturing route has been proposed focused on the assembly of several subcomponents including the attachment to the back-plates for prototype manufacturing. Each manufacturing step is described with the associated assumptions and assessed under manufacturability criteria leading to identification of manufacturing risks and design implications. The manufacturing sequence for a prototype may differ from the sequence used for pre-series (including FOAK) and series production.

GIGA is planned to be used, under the oversight of the competent regulatory authority, as a qualifying device to reach ~TRL9 and therefore achieve full FOAK system validation through a staged commissioning approach, which consists of:

- Installation of starter 'ferritic' blanket   2039-2041
- TBB validation under fusion conditions   2041-2042
- TBB installation   2043-2044

2.3. Divertor

In magnetic-confinement fusion, the divertor is the engineered interface between the hot plasma and the reactor wall, removing heat, helium ash, and impurities while maintaining plasma performance. It is therefore central to GIGA stellarator's mission, as it experiences the highest thermal and gas loads of all in-vessel components.

In stellarators, this function is performed continuously: detached regime is used to suppress sputtering and heat fluxes, while aiding pumping. Crucially, off-normal attached operation at full power is possible for a few seconds, especially because ELMs—large impulsive loads—are intrinsically absent in a stellarator. Neutral exhaust, however, operates under tighter constraints that needs dedicated assessment.
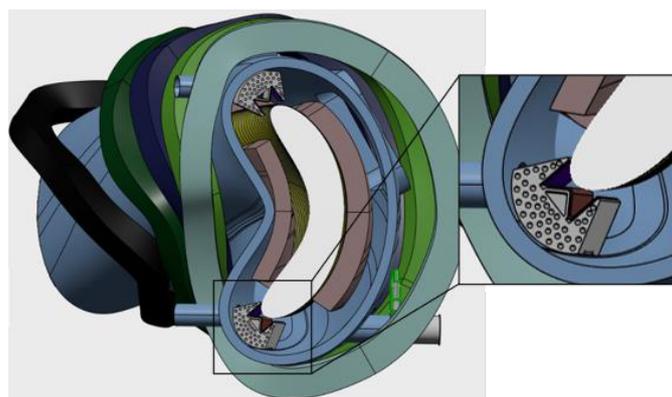
Figure 2.15: Divertor location in the vacuum vessel. Plasma in white, divertor in grey (symmetric top and bottom).

Within this context, the divertor combines exhaust, mechanical, and neutronic functions in a compact integrated architecture (Figure 2.15) and fulfils three linked roles:

1. Power and particle exhaust: In steady state, the divertor must remove up to 600 MW of heat through plasma, radiative, and neutral processes, with peak surface fluxes nearing 10

MW m^{-2} on the plasma-facing units (PFUs). The cassette body (CB) also receives more than 100 MW of volumetric nuclear heating, with local densities up to 10 MW m^{-3}. Pumping must provide approximately 10^{24} DT s^{-1} (fuel), 10^{21} He s^{-1} (helium ash), and 10^{21} Z s^{-1} (seeded impurities) of particle exhaust.

2. Plasma detachment and purity control: Detachment is the main method for reliable steady-state operation. Its onset and stability are regulated through coordinated fuelling and seeding, supported by geometry that enhances volumetric radiation and neutral trapping. This also suppresses recycling-driven impurities before they re-enter the confined plasma.

3. Structural protection and support: The divertor shields the vessel and blanket from direct plasma contact and high-energy neutrons. Erosion must be kept below 1 mm per full-power year to maintain geometry over a full maintenance cycle.

For GIGA, the divertor design draws on ITER and EU-DEMO highest-TRL technology, adapted to the W7-X–type island-divertor geometry of stellarators. It may also incorporate targeted innovation in the GFG-patented toroidal flow pump, aimed at improving neutral capture and exhaust efficiency—an important challenge for steady-state operation.

Concept Overview

Physics Concept – Island Divertor

In magnetically confined plasmas, heat and particles follow magnetic field lines, so the divertor is placed where these lines intersect solid surfaces, forming controlled strike zones for exhaust. In tokamaks, the magnetic equilibrium is toroidally symmetric, so features repeat around the torus, and the familiar 2D divertor view—scrape-off layer, separatrix, and strike points—captures the exhaust geometry well.

In stellarators, the edge magnetic field is fully three-dimensional. Instead of a single continuous contour, the equilibrium produces magnetic islands: helical field-line structures at the plasma boundary that form discrete exhaust channels. Field lines wind through the island region and intercept the plates at toroidally separated strike zones. The island-divertor configuration preserves the successful 2D divertor behaviour at each poloidal cross-section—field-line following, well-defined connection lengths, and controlled strike-point placement—while embedding it in a 3D magnetic structure suited to steady-state stellarator operation and continuous exhaust.

Engineering Concept – ITER / EU-DEMO Heritage

From an engineering standpoint, the GIGA divertor builds on ITER and EU-DEMO heritage, adapting their industrially qualified technology to a stellarator geometry. The PFUs and baffles use tungsten monoblocks bonded to CuCrZr heat sinks, cooled by pressurised-water circuits capable of handling surface heat fluxes up to 10 MW/m^2 using swirl-tube inserts. The CB, made of structural steel, contains dedicated cooling and shielding channels sized for its thermal and neutronic loads. This modular approach supports maintainability, clean

integration with the vessel and remote-handling systems, and limits the degree of extrapolation beyond Europe's highest-TRL divertor technologies.

Distinctive design features define GIGA's divertor as a system that combines mature European engineering with advanced three-dimensional exhaust physics:

- **Toroidally integrated cassette cooling** (Figure 1.10): a continuous, machined network of coolant manifolds embedded in CB, designed for hydraulic efficiency, mechanical stiffness, and resistance to irradiation-induced embrittlement over the 5-year maintenance cycle (operating at 15.5 MPa and 285 °C).
- **Baffled, toroidally modulated wedge PFU geometry** (Figure 1.10 and Figure 2.17, left): inclined and toroidally varying PFUs that promote neutral channelling toward the pump inlets while increasing divertor closure.
- **Toroidal Flow Pump (TFP) concept** (GFG patent; Figure 2.18, right): a redesigned neutral-exhaust interface aimed at higher neutral collection efficiency than conventional pressure-driven systems. Its feasibility will be assessed through numerical and experimental testing in Phase 2, with a W7-X–like pumping system retained as a fallback.

Design Development at Concept Phase

The CDR divertor design follows two coordinated but decoupled tracks—engineering and physics—reflecting their different maturity levels. This approach lets structural and cooling feasibility progress under conservative assumptions while physics predictions mature. This ensures consistency within shared envelopes and retains flexibility to refine loads and geometry as the design evolves. Convergence into a physics-informed engineering loop is planned for Phase 2.

- **Engineering design** focuses on structural and thermal–hydraulic feasibility, with manufacturability and remote-handling considerations carried forward for later refinement.
- **Physics design** employs field-line tracing and diffusion to set the geometric requirements and prepare inputs for high-fidelity edge-transport modelling. Coil-optimisation studies are also examining the impact of edge-island shape and width.

The engineering stream established a thermal–hydraulic and mechanical feasibility baseline through CAD modelling and CFD analysis. Key outcomes include:

- **Thermal–hydraulic performance** (Figure 2.16, right): CFD results show that cooling circuits handle reactor-level loads within limits. Sensitivity scans on heat-transfer coefficients and conduit geometry indicate robustness and provide estimates of pumping-power requirements.

- **Geometric and mechanical feasibility:** The cassette and PFU assemblies meet manufacturability and integration constraints, including penetrations for remote handling.
- **Pumping and exhaust system:** A preliminary 0D pumping model, informed by a GFG submission to *Nuclear Fusion*, confirms that a realistic vacuum system is achievable. These results supply first-order inputs for upcoming 3D modelling and help define requirements for evaluating the TFP in Phase 2.

Overall, the Concept Phase engineering baseline shows thermal, hydraulic, and integration feasibility with adequate design headroom under reactor-relevant conditions.
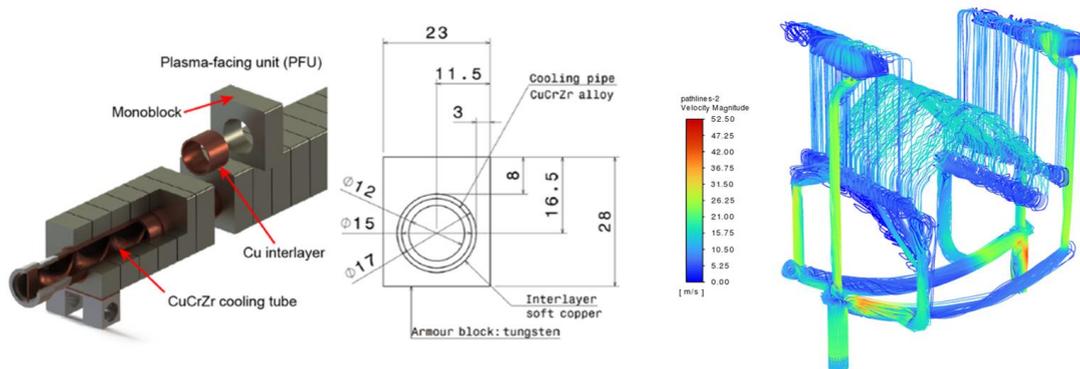

Figure 2.16: Left: ITER's PFU monoblock technology. Centre: revisited specs for EU-DEMO (also adopted by GIGA). Right: streamlines of the hydraulic assessment of the PFU-baffle serial cooling circuit.

Physics Design Stream

The physics stream ensures that the divertor geometry remains consistent with the stellarator equilibrium and correctly intercepts the exhaust. Key activities include:

- **Field-line tracing and diffusion:** 3D simulations identify strike points and power footprints, confirming that over 95% of field lines reach the PFUs (Figure 2.17, right).
- **Toroidal modulation and wedge shaping:** The PFUs use a toroidally varying wedge geometry that follows local magnetic-field structure (Figure 2.17, left), maintaining closure via baffles and passively guiding neutrals toward the pump inlets to improve pumping beyond W7-X's. Experience from the Large Helical Device indeed proved divertor baffling as crucial to achieving enhanced neutral exhaust.
- **Preparation for full edge-transport modelling:** The validated field-line configuration will serve as input for EMC3–EIRENE and Hermes-3, which will be cross-compared in Phase 2 to quantify heat loads, neutral dynamics, and detachment behaviour.

Together, these results show that the divertor geometry is magnetically coherent and ready for physics–engineering coupling in the next design stage.
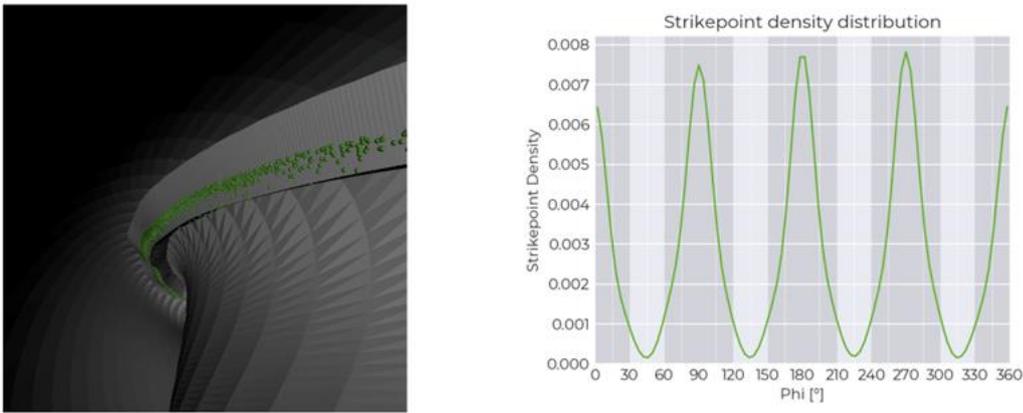
Figure 2.17: Left: strike point location on a divertor island produced via field line tracing. Right: corresponding strike point density distribution along the torus (95% capture efficiency on divertor PFUs).

Tackling the Particle Exhaust Challenge: The TFP

Particle exhaust is a key challenge for reactor-scale stellarators. In island-divertor configurations, divertor neutral pressure is typically much lower than in tokamaks—partly because discrete strike zones create segmented recycling volumes, and partly because the small poloidal extent of the island legs limits divertor closure. These factors weaken neutral compression and constrain exhaust performance. Improving pumping efficiency is therefore an attractive route to enhance operating space, and GFG has made it a central area for targeted innovation.

The Toroidal Flow Pump (TFP) is being advanced under a dedicated programme with a TRL-raising pathway (currently TRL 2) to assess its suitability for GIGA integration. The concept aims to leverage ordered toroidal neutral flows that arise in toroidal devices in detached conditions. The TFP seeks to harness this motion to collect neutrals more efficiently than conventional pressure-driven poloidal exhaust. Experimental observations already confirm the presence of toroidal neutral flows, and simulations indicate they may become dominant (Figure 2.18, left). Ongoing work will quantify how effectively they can be channelled into a TFP inlet. The GIGA divertor already improves particle exhaust through enhanced closure and PFU geometry. The TFP offers an additional potential boost, and is being considered because its integration would require only local modifications to the divertor cassette, without major redesigns. These aspects will be examined in Phase 2 once numerical and experimental feedback from the TFP campaign becomes available.

Divertor Qualification and Roadmap

The divertor system follows a structured TRL-raising pathway (TRL 3 → TRL 6, 2026–2032) aligned with the ITDR-1 / ITDR-2 milestones—where TRL 6 corresponds to full-scale qualification under representative thermal and vacuum conditions, ready for GIGA integration. The programme couples technology maturation, industrial qualification, and physics validation ensuring coherent progress across engineering and scientific fronts. The budget for the programme is estimated at €475–725 M, covering physics, design, manufacturing, and system-level testing.
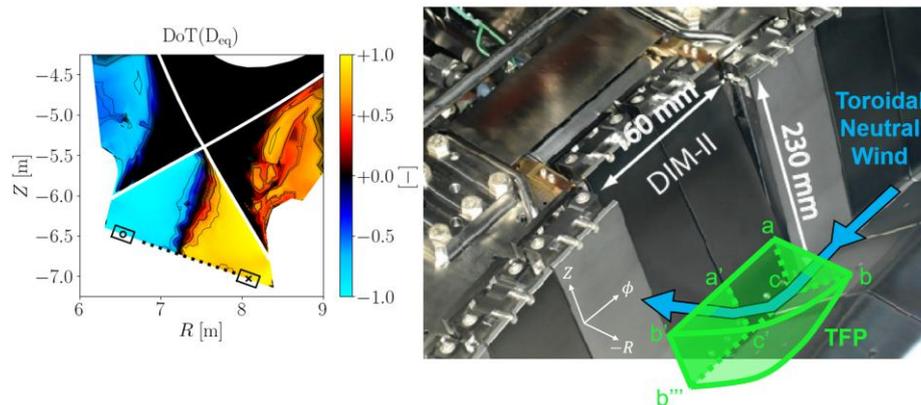
Figure 2.18: Left (degree of toroidality, DoT): SOLPS-ITER simulation of EU-DEMO, showing that >80% of the motion of neutral deuterium is toroidal (into the page). Right: TFP in AUG via divertor manipulator (DIM-II): inlet abc captures the neutral "wind" (blue) and redirects it outside the system.

A key outcome of concept consolidation is the elevation of the Toroidal Flow Pump (TFP) from a parallel study to one of the main development lines of the divertor programme, pursued in parallel with the baseline exhaust architecture.

TRL 3–4 (2026–2027): Physics Design and Early Engineering Validation

- Establish a geometrically and physically coherent divertor baseline consistent with the stellarator magnetic configuration.

- Conduct 3D edge-plasma and particle-transport modelling (EMC3-EIRENE/Hermes-3) to define heat flux magnitude, neutral pressures and detachment behaviour.

- Initiate neutronic shielding, erosion, and photon-transport analyses to verify dose attenuation and first-wall limits.

- Progressively refine CAD geometry, followed by CFD/FEA verification of PFU cooling, cassette stresses, and neutral exhaust conductance.

- Advance R&D on the patented TFP through initial SOLPS-ITER/DIVGAS studies and partner identification for prototype testing.

- Deliver TRL 3 Verification Report, updated CAD / ICDs, and a first TFP prototype plan.

- A System Integration Review in Q4 2026 will confirm alignment with adjacent systems (blanket, vessel, vacuum).

- Early engagement with experimental partners and host facilities will be crucial for both the divertor and TFP, establishing credibility through a staged, data-driven validation approach.

TRL 5 (2028–2029): Integrated Sub-System Demonstration

• Fabricate and test plasma-facing units and cassette body mock-ups under reactor-relevant loads (10 MW/m^2).

• Execute digital-twin RH simulations for cassette handling and maintenance cycles.

• Prototype and experimentally test the TFP inlet; if performance confirmed, re-baseline divertor exhaust geometry and routing.

• Produce ITDR-1 documentation, preliminary Bill of Materials, and Quality Plan. → Outcome: validated manufacturability and sub-system performance; TRL 5 readiness for detailed design.

TRL 6 (2030–2032): Full-System Qualification

• Assemble and test a complete divertor cassette in vessel mock-up.

• Perform leak, pressure, LOCA/LOFA, and neutronic verification (MCNP/FISPACT).

• Complete supplier qualification and pre-production qualification report. → Outcome: divertor system fully validated for FOAK deployment (TRL 6) and transition to Phase 3.

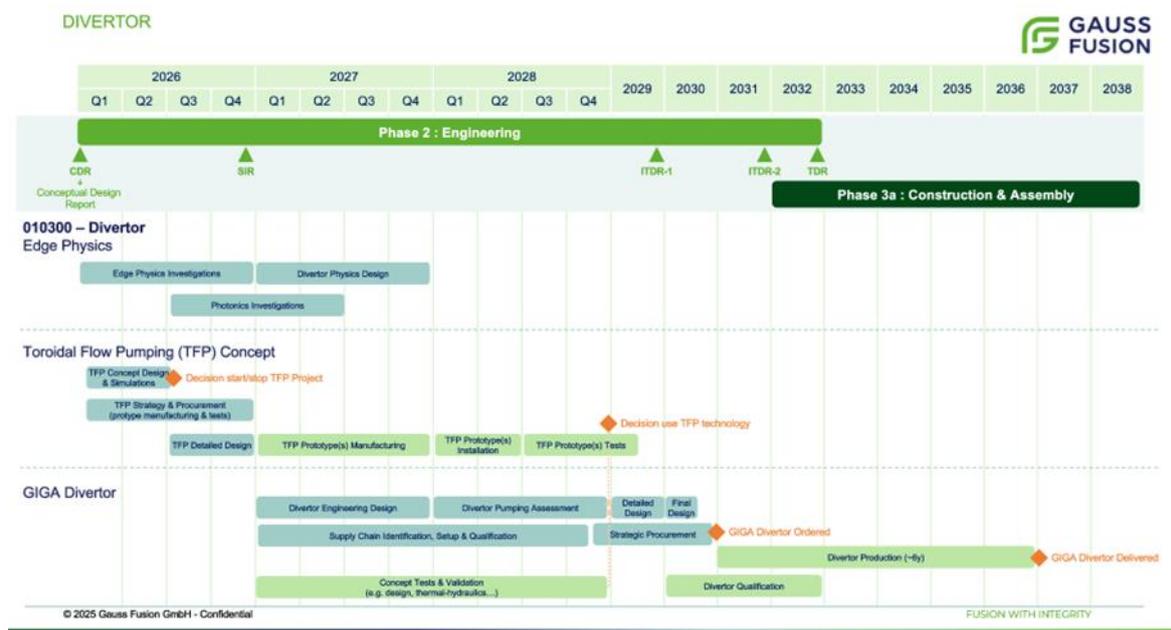*Figure 2.19: High-level Divertor Qualification Roadmap through Phase 2 and towards Phase 3.*

Supply Chain and FOAK Manufacturing

Consistent with adopting the highest-TRL available engineering, the GIGA divertor supply chain builds on the ITER and WEST industrial ecosystem, which has already demonstrated serial production of actively cooled tungsten monoblock PFUs. This provides a solid industrial

baseline for GIGA to improve upon, while new features such as the TFP create an additional forward-looking manufacturing path.

Industrial Readiness

- Tungsten Components: Qualified vendors — ALMT (Japan), PLANSEE (Austria), AT&M (China), and RTC Engineering (Slovakia) — have demonstrated HIP-bonded W–CuCrZr monoblock fabrication at ITER quality levels.

- Cassette Bodies and Cooling Circuits: Experienced European manufacturers such as IDOM, ENSA, and RI Research Instruments can adapt ITER tooling for GIGA's toroidally integrated cassettes, leveraging high-precision machining and coolant drilling expertise.

- TFP Pump Inlet (Patented): A dedicated industrial partnership will be established, exploring both precision-machined and additive-manufacturing (AM) routes. Early prototyping (TRL 4) will validate manufacturability and performance; conventional ducts from Pfeiffer Vacuum, Leybold, Edwards, and VAT Group remain the qualified option for attached conduits.

Manufacturing Approach

Production will follow a serial model emphasising quality control and modular assembly:

1. Material pre-qualification using QA protocols.

2. PFU fabrication via HIP bonding, ultrasonic and IR testing, and HHF validation.

3. Cassette machining with integrated manifold routing and digital-twin metrology.

4. Assembly and welding of manifolds and ducts with leak-testing certification.

5. Qualification testing at for high-heat-flux performance and potentially KIT facilities for thermal-hydraulic and neutral-flow validation.

GIGA Manufacturing and Outlook

A staged supplier-development programme (2027–2032) will strengthen industrial capability through targeted mock-up fabrication, process refinement, and tooling qualification, leading to GIGA manufacturing preparation and readiness for full module production. During construction (2032–2040), the divertor will be among the first in-vessel systems to be assembled, with commissioning (2039–2044) bringing the system to TRL 7–8 under reactor conditions.

This staged approach builds on the industrial experience developed for ITER and WEST—especially in tungsten component fabrication, CuCrZr heat-sink processing, and high-heat-flux qualification. GIGA's programme must now extend this heritage further to meet the higher performance, and reliability demands of a reactor-scale stellarator. GIGA's approach will introduce refined manufacturing routes and new advanced features—most notably the TFP pump inlet, whose feasibility may become a distinguishing capability for next-generation stellarator reactors.

Risk and Safety Summary

The divertor faces intertwined physics, engineering, and operational risks inherent to a first-of-a-kind fusion power plant. These risks are captured through a comprehensive FMEA and tracked through design, qualification, and operations. The risk posture is acceptable for a CDR given mitigations and fallback paths.

Top Technical and Scientific Risks: Examples

- Physics uncertainty in heat-exhaust performance: The edge-plasma and detachment regimes expected in GIGA have never been experimentally validated at reactor scale. Cross-field transport, impurity radiation, and neutral trapping (at least) remain uncertain, creating risk of thermal overload or unstable detachment. *Mitigations:* cross-code numerical scans (Hermes-3 / EMC3-EIRENE), conservative margins in geometry and closure, staged power ramp-ups, and GIGA validation under controlled conditions.

- Particle-exhaust and pumping performance: Particle exhaust in stellarators operates under tighter constraints, which places greater demands on exhaust efficiency and divertor pumping performance. *Mitigations:* optimization of divertor shape and baffling for pumping, parallel development of the TFP, extensive modelling, and progressive validation of neutral throughput during GIGA commissioning.

- LOCA / LOFA and coolant-loop reliability: As with all water-cooled components, loss-of-coolant or loss-of-flow accidents remain critical design-basis events. *Mitigations:* redundancy, double-wall manifolds, passive drain routing, and validated critical heat flux (CHF) margins. Accident analyses will be qualified through ITDR-2 safety reviews.

- Manufacturing and alignment tolerances: Local PFU misalignment increases incidence angles, and thus heat loads and erosion, especially during plasma re-attachment. *Mitigations:* shaped PFUs, laser-tracker verification, and dedicated analysis of module misalignment to build robustness into divertor positioning.

- Schedule and integration risk: The GIGA sequencing—in which divertor components must be developed, tested, and installed early in the machine build—requires early supply-chain readiness to secure manufacturing slots, priority in vendor queues, and timely access to key test facilities (e.g. GLADIS, KIT). *Mitigations:* parallel qualification lines for baseline and TFP hardware, early supplier engagement, and clear decision points at ITDR-1/2.

Stellarator and Control Infrastructure

The divertor protection concept relies on real-time detection and shutdown via the Stellarator Control Infrastructure (SCI). Key parameters— coolant flow, coolant pressure, particle exhaust pressure, and detachment state—are continuously monitored. In the event of deviation, the SCI initiates staged mitigations (impurity seeding, power reduction) or an immediate safe-shutdown sequence. All safety analyses (thermal-hydraulic, LOCA/LOFA, neutronic) are being integrated with the broader GIGA safety framework, ensuring traceable linkage between design limits, monitoring thresholds, and interlock logic.

Path Forward and Strategic Impact

GFG's divertor programme combines proven industrial heritage with targeted innovation to address the last major open issues for reactor-scale stellarators and magnetic-confinement-based nuclear fusion as a whole. Building on the ITER / WEST supply chain and qualification experience ensures a solid baseline of manufacturability to improve upon, while focussed innovations — notably the patented Toroidal Flow Pump (TFP) — pursue performance gains that could redefine exhaust capability.

At GFG scientific developments are being exploited for the scoping and de-risking of the GIGA power plant divertor, most notably through the development of scaling laws for separatrix quantities —the analytical bridge between edge-plasma physics and tritium fuel-cycle (TFC) design, mediated by divertor engineering. These laws are used to inform TFC requirements and to constrain high-fidelity parametric scans, ensuring that computational resources focus on the most relevant operating regimes instead of exploring the full parameter space blindly.

Future refinements of these scaling laws will validate TFC figures, support experimental campaign planning and later in-operation analysis. Any new scientific insight generated directly contributes to understanding, de-risking, and progressive consolidation of the divertor design and operating strategy.

2.4. Vacuum Vessel

Purpose and Function of the Vacuum Vessel

The Vacuum Vessel (VV) serves as the vacuum chamber where the plasma is generated and confined, and as a result is a barrier for containing tritium losses or any radioactive material dispersion. Consequently, it must fully comply with applicable environmental and nuclear safety regulations. It supports all in-vessel components, including the breeding blanket modules and divertor assemblies, while maintaining an internal vacuum level of 1×10^{-6} Pa, required for stable thermonuclear operation. The VV incorporates multiple penetrations for heating, fuelling, diagnostics, pumping ducts, and remote maintenance access.

It adopts a double-walled stainless-steel configuration, comprising inner and outer shells separated by a water-cooled interlayer that provides thermal shielding, neutron attenuation, and structural reinforcement. Designed for a service life exceeding 40 full-power years under high neutron fluence, the VV must meet stringent nuclear regulatory and structural integrity standards.

Figure 2.20: VV concept design

The outer wall also supports a thermal shield, which limits heat transfer toward the superconducting coils. This shield operates at approximately 80 K, with low-emissivity surfaces to minimize radiative heat load. Due to its position between the plasma and the magnetic coils, it must adapt to the helical shape of the magnetic field around the torus. The vessel geometry is therefore helically twisted, with two
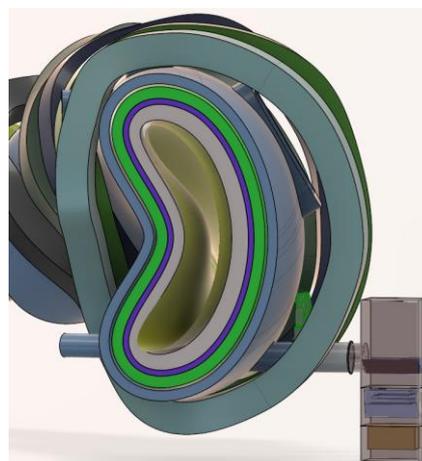
symmetry planes that define its overall configuration. This arrangement produces a fourfold toroidal periodicity, consisting of four identical 90° sectors.

Design Development at Concept Phase

The design evolution of the VV draws extensively on experience from major fusion programs such as ITER, DEMO, and W7-X. ITER validated the feasibility of a double-walled stainless-steel structure with integrated water-cooling channels, although its implementation encountered challenges related to weld integrity, dimensional distortion, and sector alignment. DEMO, currently in the preliminary design phase, anticipates even higher neutron loads and thermal stresses, necessitating different shielding strategies. W7-X demonstrated that highly non-axisymmetric geometries can be manufactured and assembled with acceptable tolerances, providing a benchmark for complex stellarator configurations. Building on these precedents, the GIGA VV concept scales these technologies to unprecedented dimensions and complexity. The proposed architecture consists of a helically twisted toroidal chamber with an average major diameter of about 41.5 meters and an estimated mass exceeding 11,000 tons. To address manufacturability and future maintainability, the design adopts a modular segmentation strategy, enabling parallel fabrication and controlled assembly within the reactor pit.

The VV has been designed employing parametric CAD modelling not only to enable rapid adaptation to iterative changes in plasma configuration and coil geometry during the concept development phase but also to begin a structured optimization of the VV geometry considering interface integration. In parallel, remote handling compatibility is embedded as a primary design driver, influencing port geometry, flange configuration, and spatial clearances to ensure seamless integration with robotic manipulators and maintenance casks throughout the vessel's operational lifecycle.

The VV is supported by gravity supports mechanically decoupled from the cryostat through flexible bellows, minimizing stress transmission due to differential deformations. Spherical joints integrated into the support pillars allow controlled rotation and sliding to accommodate thermal expansion and attenuate seismic loads, thereby reducing localized stress concentrations. The adoption of commercially available spherical joints is being evaluated as a strategy to streamline procurement processes and reduce maintenance complexity, while ensuring compliance with load-bearing and seismic qualification requirements. Evaluation tests will begin during the engineering phase.
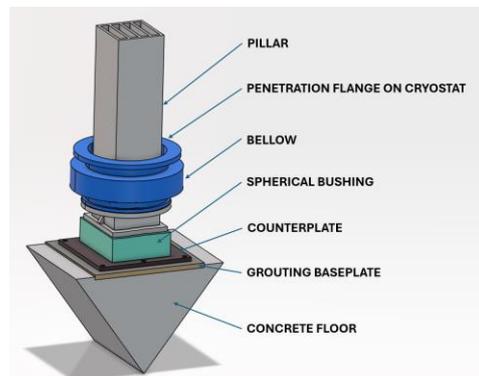
Figure 2.21: Gravity support concept.

Due to its broad industrial availability, structural stability, excellent weldability, demonstrated performance in vacuum and proven operational record in previous fusion applications, 316LN has been selected as the optimal material for the GIGA VV. This choice ensures compliance with current design codes without requiring additional qualification for neutron irradiation levels up to 2.5 dpa, which corresponds to the estimated lifetime dose.

Dedicated welding samples and representative mock-ups will be fabricated during the engineering phase to validate joining technologies, assess distortion control strategies, and confirm compliance with vacuum integrity and structural performance requirements under simulated operational conditions.

Preliminary finite element analyses (FEA) were conducted to assess the thermal and mechanical behavior of the VV during concept development. Thermal simulations were performed using load cases derived from a homogenized neutron heating analysis. The results demonstrate full compliance with thermal design criteria, maintaining the operational vessel temperature below 250 °C and limiting local hotspots to less than 400 °C.

Structural analysis considered gravity, external pressure, and thermal expansion from 20 °C to operational temperature, assuming a conservative uniform wall thickness of 350 mm. FEA indicate that the VV satisfies structural design requirements, with calculated stress levels and deformation values remaining within permissible limits. Localized stress concentrations occur at the interfaces between the vessel and its supports; however, these are primarily numerical singularities and are expected to be mitigated through a refined design of the connection geometry and load transfer features.

Future work includes detailed thermo-hydraulic modeling, structural analysis integrating in-vessel components, and buckling simulations. A parametric design framework is currently being implemented and will be further improved during the initial stage of the engineering phase for the key dimensions of the double-walled structure, enabling systematic thermal-structural optimization and enhancing global stiffness and mechanical performance.
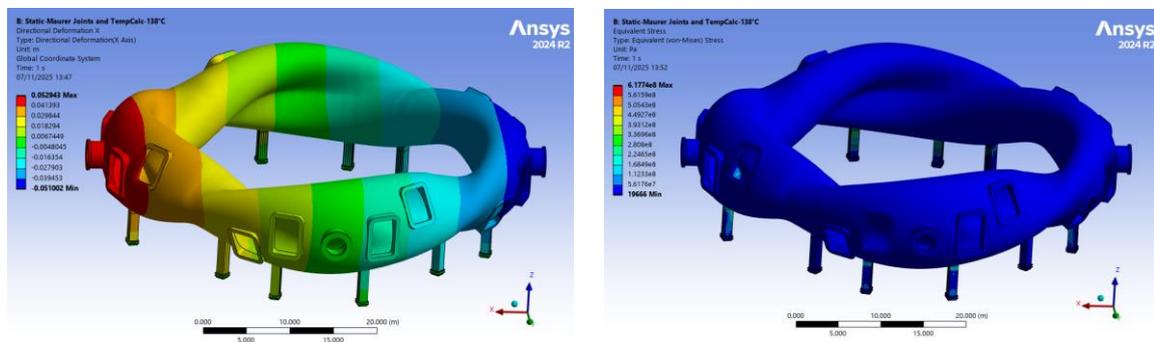
Figure 2.22: VV structural simulation, contours of Total Deformation [m] and von Mises stresses [MPa].

In the engineering phase, the thermal shield and its support structures will be designed in detail, building upon the currently defined functional requirements. The design will evolve from the EU-DEMO thermal shield concept, incorporating lessons learned from ITER's design, manufacturing, and installation.

Qualification and Roadmap

Despite its relative maturity compared with other major systems in a fusion power plant, the VV remains a component of high technical risk and engineering complexity. Its dual role, serving as both the primary confinement barrier and a structural backbone for numerous

interfacing systems, exposes it to a unique combination of challenges that must be carefully managed throughout design, fabrication, and operation.

The VV concept has undergone preliminary qualification activities during the Concept Phase, confirming its technical feasibility and readiness for progression to the Engineering Phase. The qualification strategy is structured around a systematic approach to verify structural integrity, thermal performance, and functional integration within the GIGA Power Plant.

At this stage, no critical structural or functional weaknesses have been identified; however, several areas require further development. Upcoming activities will include comprehensive neutronics modelling and thermohydraulic simulations to validate cooling strategies, full thermo-mechanical analyses covering all load cases in accordance with nuclear design codes, non-destructive testing and leak tests on welds using representative samples of ports and double-walled structures, detailed definition of all interfaces, particularly in the port regions, and empirical validation through dedicated mock-up testing.

In 2026, the primary focus will be on VV concept consolidation and system-level integration. The objectives are to update the VV geometry to reflect the latest plasma shape and coil configuration and to validate all critical interfaces with major systems, including in-vessel components, coils, and the cryostat.

Between 2027 and 2029, the primary objectives are to complete the detailed mechanical and thermal design of the VV, incorporating the double-walled cooling concept, full segmentation strategy, and port integration, while initiating design validation through representative mock-ups.

These activities will support the update of the Qualification Plan, refinement of CAD models, and development of a comprehensive risk mitigation strategy consolidating the design baseline culminating with the Intermediate Technical Design Review 1 (ITDR1),

Between 2030 and 2031, the focus will shift to the qualification of integral prototypes, aimed at validating manufacturability and structural integrity. The finalization of the engineering design supported by comprehensive FEA analyses, together with FMEA/FMECA analysis, updated risk assessments, and comprehensive Quality Assurance plans will culminate with the Intermediate Technical Design Review 2 (ITDR2).

In 2032, the Final Qualification phase will ensure construction readiness for manufacturing by completing all design activities, regulatory compliance checks, and safety case approval. The Technical Design Review (TDR) will be supported by a comprehensive qualification dossier.

The scale, precision, and nuclear-grade requirements of the VV demand capabilities that only a limited number of suppliers worldwide can currently deliver. The FOAK nature of the project compounds this challenge: industrial capacity for thick-section austenitic stainless-steel components of complex, non-axisymmetric geometry is scarce, and few firms possess both the equipment and the strategic orientation to quality assurance to operate under nuclear-class standards.

The supply chain will necessarily be international and structured, involving specialized manufacturers for heavy forging, large-scale welding, precision machining, vacuum compatibility, testing, and metrology. Core fabrication is expected to rely on a small number of lead suppliers capable of handling large component envelopes and implementing qualified welding processes for 316LN. Surrounding these primary fabricators will be a network of suppliers providing subcomponents. Each tier will need to operate within a unified quality assurance framework and maintain full material traceability from melt to final assembly.

Quality assurance will be governed by ISO 19443 and aligned with ASME principles for nuclear pressure-retaining components. Each manufacturing stage will be subject to digital traceability, welding, and test reports into a centralized configuration database. NDT, and helium leak detection shall ensure verifying both structural integrity and vacuum tightness. Independent inspection authorities will verify conformance before release to integration.

Given the size and weight of the sectors, logistics planning defines a major challenge in the supply chain strategy. Transportation constraints will influence both modular segmentation and weld joint design. The final assembly will take place at the plant site to minimize handling risk. A dedicated assembly hall with controlled environment and precision handling systems will be required to maintain tolerances during sector joining and alignment.

The FOAK nature of the VV demands proactive risk management and supply chain resilience planning. Single-source dependencies will be reduced through dual qualification of key processes and the establishment of backup suppliers. Long-lead procurement should be considered. Schedule monitoring will track progress, certification status, and non-conformance reports in real time.

2.5. Magnets

Purpose and Function of the Magnets

The function of the magnets is to generate the magnetic fields that confine the plasma at a sufficient pressure for the required rate of nuclear reactions to occur, and to introduce field line configurations to form magnetic island divertors. There are other refinements in the field curvature and gradients within the plasma.

There are multiple configuration solutions available for the coil sets that can produce the required plasma. Other constraints can then be applied to produce coil sets that have improved engineering parameters, resulting in improved manufacturability and integration with the device.

Modern numerical techniques for stellarator plasma-coil optimization can substantially improve on the traditional view of stellarator coil complexity which prevailed at the time of the W7X construction. For the coils this means:

- Winding surface optimization with more efficient mathematics
- Engineering constraints as optimization criterion, e.g. coil current densities compatible with conductor designs and structural stiffness, coil to plasma separation allowing space for in-vessel components and nuclear shielding, and coil to coil gaps for ports

- Divertor configuration and field line local alignment
- Coil shape sensitivity analysis
- Robust optimization to build in tolerance to error fields.

In addition to the coil functionality, there are many requirements on the magnets driven by the need to integrate the coils into the device, such as:

- Repairability during manufacture and operation through remote handling
- Steady state magnet operation without the need for plasma control actions, with adaptable plasma power controlled through plasma fuelling and heating
- Accessibility for construction of magnets, Vacuum Vessel (VV), and Thermal Shield (TS), avoiding excessive on-site constraints and workspace conflicts
- Magnet design should not drive access or maintenance requirements for in-vessel components, which remain at lower Technology Readiness Level (TRL)
- Performance validation by qualification & testing before/ during assembly rather than after completion
- Reliable magnetic energy management, which is the main safety issue with magnets
- Use of components and processes which are 'industrialised' and for which basic supply chains exist, although at insufficient capacity or committed elsewhere
- Design margins consistent with manufacturability and operating experience and based on established structural and electrical design codes

Stellarators require very precise and local field control which results in an extensive coverage of the surface by coils. Optimisation can reduce the extent of the out of plane distortion, but individual coils still retain a significant 3D shaping. GFG has selected a 4-quadrant plasma which requires 8 identical sets of 5 different coils, mirrored and rotated as shown in Figure 2.23 (coil types are designated by colour).

The GFG magnet engineering approach has identified 2 key technologies which together allow a practical resolution for many of the integration requirements on the magnets:

First key is joinable magnets, made in sections using a plate concept as illustrated in Figure 1.6 and Figure 2.24.

- Each coil is built up of stacked and insulated 3D pancakes, held together by clamps. Each plate is (in conventional coil terms) a pancake, albeit a 3D one. A circular conductor is contained in a spiral groove in the plate, Figure 2.25. The clamps are removed in order to demount the coil.
- Each plate is then split into 2 circumferential sections, roughly 180 degrees each. At each end, each conductor turn contains an electrical joint, and there is a mechanical link between the plate structural material. The conductor and plate joints are demountable, opened and closed by bolts and wedges, capable of being adapted to remote handling.
- The joints in each plate are at slightly different circumferential locations so that removing the outer plate exposes the joint of the one below, enabling plates to be removed in succession. A full coil is then built up by stacking the plates of the innermost part and clamping them. The outer part is then built up by stacking the outer plates, Figure 1.6.

- During assembly, the VV is put together first and the magnets are then assembled and joined around it. This opens the door to much more practical (and cost and schedule effective) ways to build the VV than if it has to be built inside the magnets.
- Some magnets are designed re-mountable, which opens the possibility to allow large hatches to access the VV, Figure 1.6.
- Other magnets are intended as mount once (which allows joints to be soldered if needed – development is needed to see if there is any advantage) but can still be replaced in the event of a fault, removing and rebuilding the sections.

Second key is magnetic energy management

- Many of the operational issues associated with medium and high field magnets are associated with magnetic energy management: converting the electromagnetic energy stored in a magnet either back to the supply grid or to heat, in a resistor. Generally, return to the grid would be preferred but is relatively slow and relies on a grid connection. In the event of a fault condition, in the magnet or the auxiliaries, a faster system is needed, and the only option is conversion to heat through a resistance. This conversion requires a voltage and the voltage itself can produce a risk of arcing and a resultant loss of control of the conversion process.
- In GIGA, energy management is kept local to each coil, and the jointed plate concept is exploited to allow the coil structure to function as an energy dump.
- The magnets are still insulated but at low voltage, under the Paschen minimum which governs arc breakdown in low pressure environments like the cryostat. The use of varistors combined with internal energy dissipation allows robust but still active quench protection. For safety, where even extensive coil damage can be tolerated if there is no damage to the adjacent nuclear containments, it is possible that self-protection can be achieved without active intervention.
- As part of the internal energy dissipation, the plates are used as a low voltage discharge resistor for each coil. Each plate contains an insulated break (non-conducting joint integrated with one of the two segment joints), and the plates are then connected in series in a form of 'reverse spiral' to the conductor. The coil is built from Grooved Plates (containing the conductor) and Resistive Plates (no conductor) which allows flexibility in matching structural stiffness to the discharge resistance.

The GFG coil concepts are being developed to accommodate both HTS and LTS superconducting material with key enabling features accommodated by both options. Market developments and technical performance through qualification will inform a timely decision on which material will ultimately be employed in GIGA.
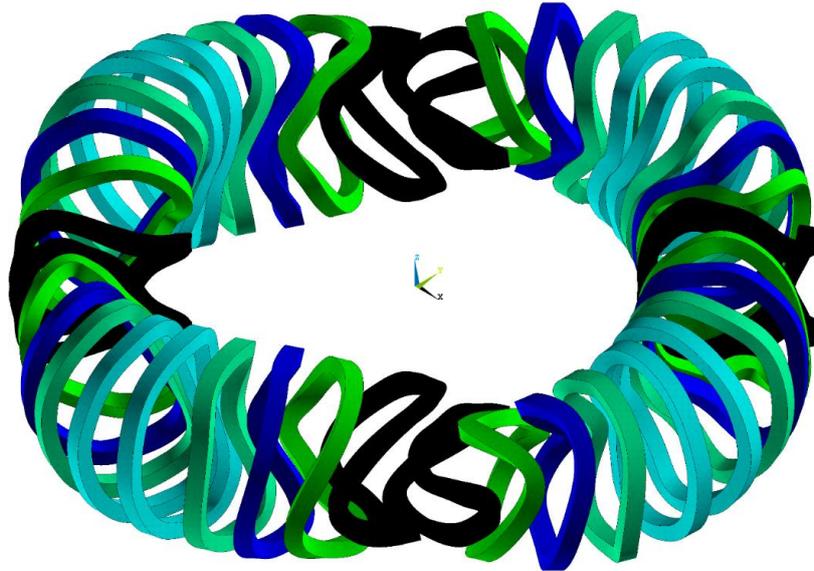
Figure 2.23: GFG-GIGA Coil Set (colours show identical coils)

Concept Overview

Concept – Demountable Coils and Winding Pack

The GFG coil concept avoids a conventional coil case, being very difficult to manufacture and fit to a large 3D stellarator coil, by distributing the structural support to the winding package while maintaining a conductor that is reasonably easy to bend with a thin steel jacket and circular cross-section. The concept is illustrated in Figure 2.25 (for the cross section). A circular conductor is contained by a series of grooves in a 3D curved plate (Figure 2.24). The conductor is insulated from the plate and after being placed in the grooves, is fixed in place by a welded cap. The plate provides the structural support and is multi-purpose, enabling a demountable joint and internal quench protection.

These plates are insulated and then stacked together to form the winding pack, as shown in Figure 2.25. The individual plates are not bonded but clamped. The frictional force from the clamping plus the 3D curvature is sufficient to lock the plates together.

A coil is opened by successive removal of sections of plates, as shown in Figure 2.24. To allow underlaying joints to be accessed from one side, the joints are stepped, and to reduce the overall length of the stepped region, plates can be removed from both sides, producing a V shaped section. If the coil is split into 2 more or less equal sections, then the weight of the 24 plate sections is about 15-20 t each, which allows much easier handling than a full coil of 350 t.
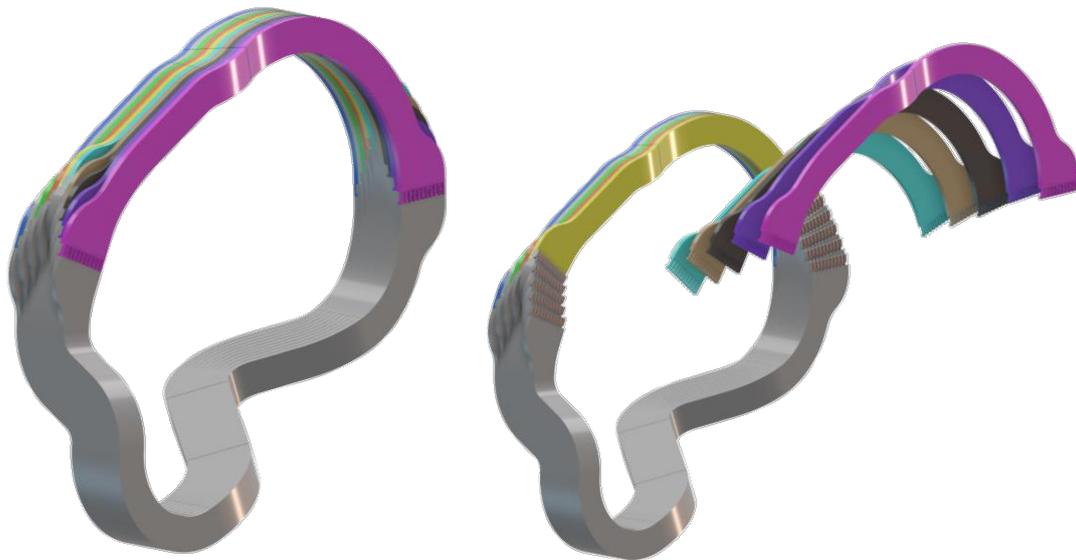
Figure 2.24: Illustration of a Mount-Once/Mount-Many Concept, coil split into separate plates once clamps are removed

Engineering Issue – Coil Joints

The configuration selected for the GIGA coil internal joints is an in-line type, where electrical, fluid and mechanical links are in parallel, aligned with the coil centreline and closed in parallel. This gives by far the minimum space requirement and is least disruptive to the integration of the coils into the device, but it is of course the most difficult to achieve.
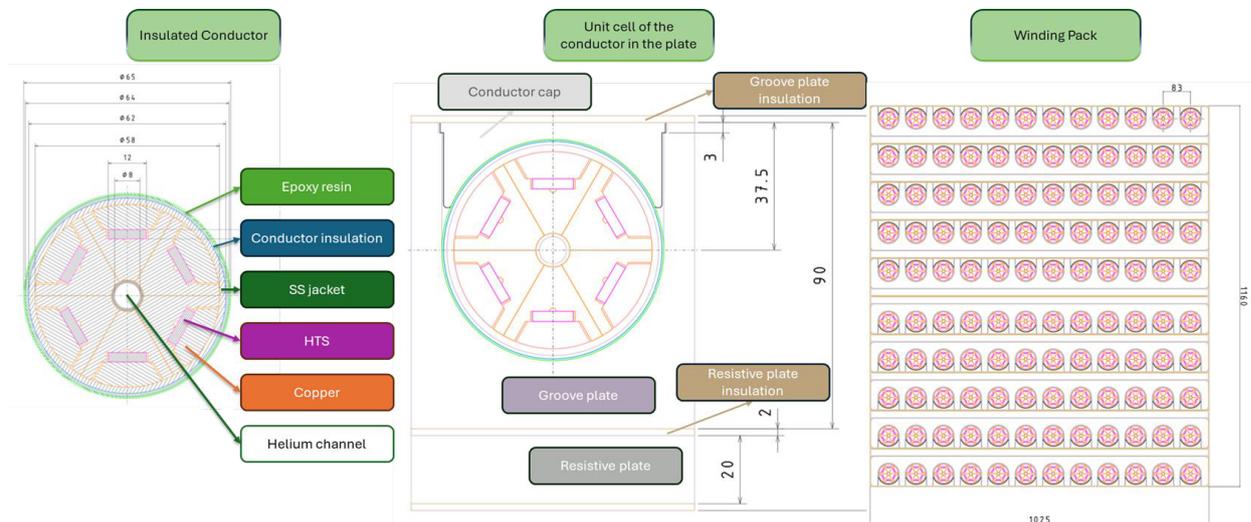
Figure 2.25: Diagram of the conductor, plate and winding pack arrangement.

The baseline demountable interface is a scarf joint applied to an LTS or HTS CICC conductor. The scarf geometry provides a large, overlapping contact surface that lowers contact resistance while allowing the conduit central channel to remain open, so helium coolant can pass through the joint without flow restriction. Electrical contact and primary helium sealing are provided by a soft metal foil (e.g., indium) placed between the mating scarf faces. A transverse compaction clamp for each joint provides the contact pressure and, together with

the scarf wedge geometry, resists longitudinal separation. In the same region a 'hook and wedge' system provides a strong mechanical link with an adaptation for tolerance compensation, Figure 2.26.

The joint resistance target is in the range 1-3nΩ with a total cryogenic heat load, including thermal and nuclear radiation, in the range 150-250 kW (at 4 K or 20 K), acceptable in a 3 GW (thermal) power plant
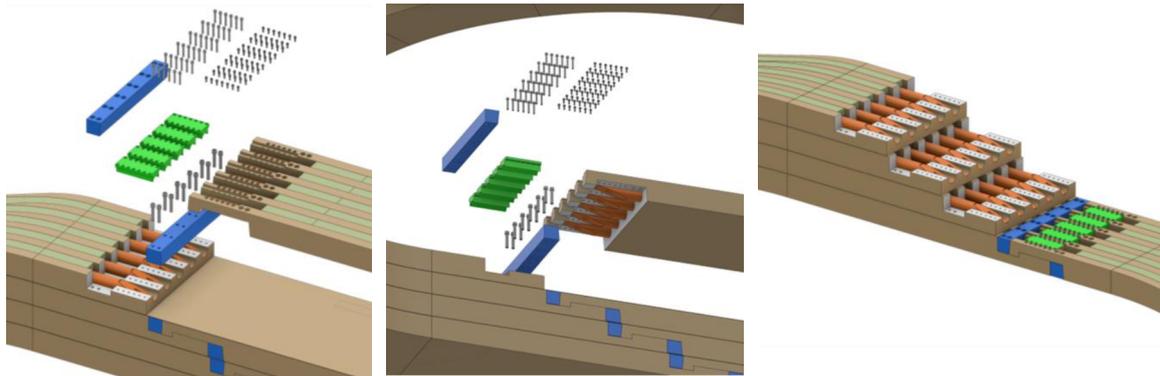
Figure 2.26: Components of a Demountable Joint (shown for the model coil). Blue is mechanical wedges, green is joint clamps, red is the conductor and joint surfaces and brown is the plates

Engineering Issue – Magnetic Energy Management

The GFG strategy for coil protection is 'active' in the sense that a quench must be detected to initiate a fast discharge. However, the energy is kept within the coils, transferring the magnetic energy into thermal heating. Global calculations show that using the GFG strategy of distributing structural material into the winding pack provides sufficient thermal capacity to keep temperature rises well below 150 K, standard for superconducting coil design, even allowing for some non-uniformity.

To avoid high voltages, a general principle of long (>30 s) discharge times is followed, with adequate copper being placed in the cable to achieve this. This relaxes quench detection times especially for fibre optic hot spot detection, and brings more flexibility into the discharge system.

To achieve a discharge, the coil current has to be redirected to flow in the structures, allowing them to function as resistors. The concept is shown in Figure 2.27 & Figure 2.28. A coil is built up from pancakes stacked together, typically 10 of them. Each pancake of the coil has 12 conductors embedded in a grooved plate (shaded green), Figure 2.28. Sandwiched to this (bonded and clamped) is an extra resistive plate (grey). The plates (grooved and resistive) have a circumferential break (and insulated mechanical link, Figure 2.27), whereas the conductors are a continuous spiral. The stacked plates are connected in series, forming a 'reverse spiral' coil. The ends of this reverse spiral coil are connected permanently to the conductor terminals of the coil, i.e. the discharge resistor is electrically parallel to the coil. The 40 stellarator coils are initially in series, and the discharge into the resistor is then initiated by opening the connections between each coil.
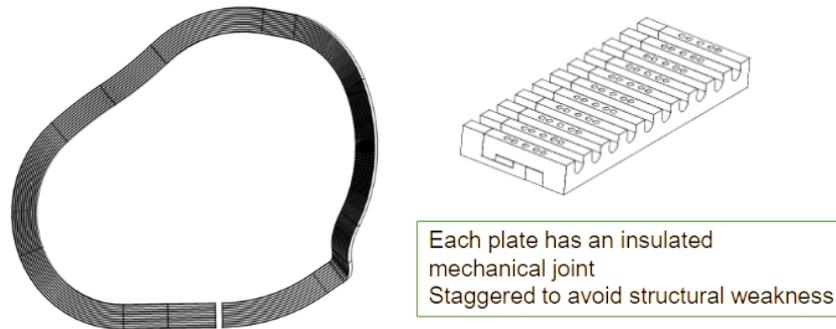
Figure 2.27: One plate pancake of a coil, where each coil consists of 10-12 of these plates stacked together. The insulated mechanical joint is shown on the right
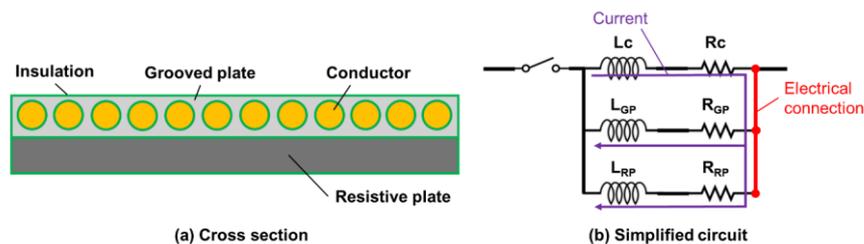
Figure 2.28: Electrical arrangement of the plates to achieve a fast discharge. Left, the grooved plate (shaded green) and sandwiched below this (bonded and clamped), an extra resistive plate (grey). Right, the GP (L_{GP}, R_{GP}) and RP (L_{RP}, R_{RP}) are permanently electrically connected across the conductor (L_c, R_c) and open the power supply switch

Engineering Issue – Superconductor

The conductors are designed to a Form/Fit/Function (3F) principle with a range of internal options possible inside the jacket envelope. The 2 baselines are HTS REBCO Soldered Stacked Tape and LTS CICC Nb3Sn concepts, with the following characteristics:

- Conductor outer form common to LTS and HTS conductors, operating temperature different (~7 K vs ~20 K)

- Most of the cable is copper for thermal protection, hot spot <150 K, discharge time constant >30 s, OD<60 mm, so insensitive (at 12-13 T) to strand or tape performance

- Both allow current redistribution, and are robust to local damage. It is easy to provide extra SC material (20-30 % in HTS as space is negligible) and accept conductor degradation locally. Short unit lengths <25 m reduce HTS cost, cable local damage tolerance allows tolerance of tape dropouts

An example of the HTS application of the concept is shown in Figure 2.29.

Design Integration

The main design step at the concept phase is the integration of the key coil technologies into a functioning design. As a part of the opening and closing of the coils, the structural support between the coils has also to be considered. The 3D nature of the coils puts conflicting requirements on this Intercoil Structure (ICS) and it can easily become a bigger obstacle to access to the VV than the coils themselves (as can be seen for example in the Helias studies).

The coils have a complex pattern of magnetic forces and although the internal plates provide a robust coil support, bracing between coils is also required.
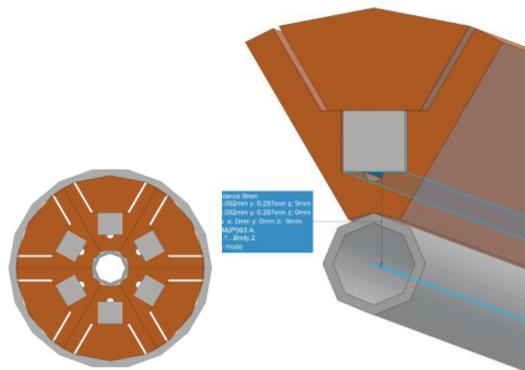
Figure 2.29: HTS Cable in Conduit

Filling up the coil interspaces with large thick pieces of ICS can produce acceptable finite element results but is highly unlikely to produce valid engineering solutions. The problem, as in tokamak intercoil structures, is that the ICS has to be joined to the coils and unless this joint is welded (which is seldom feasible and never compatible with demounting coils), practical solutions with keys and bolts that are also consistent with bolt loads and assembly tolerances are extremely difficult to realise.
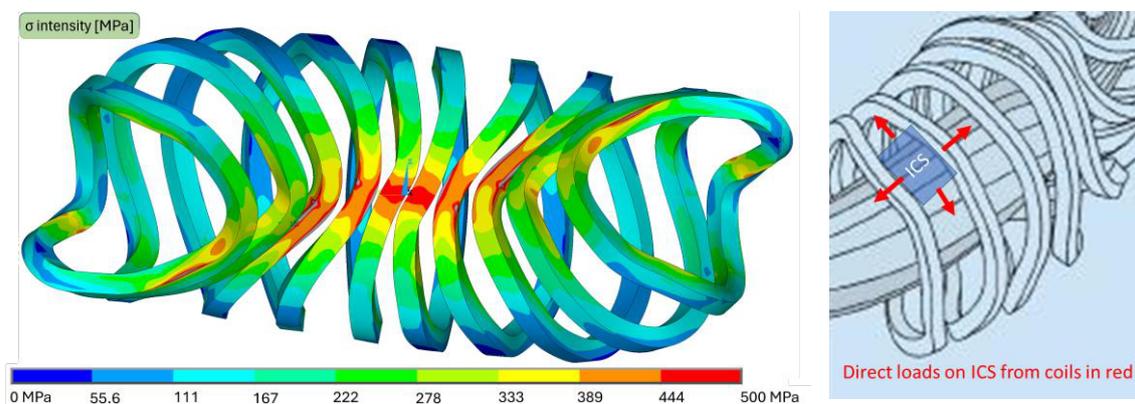
Figure 2.30: Right: Intercoil Structure Concept, Left: Resulting coil stresses (equivalent steel)

GFG has developed a novel highly modular concept for the intercoil structures between the coils, compatible with demounting in small (and variable) sections by remote handling and adaptable to the 3D curves and variability of the gap between the coils and multiple large and small penetrations. For regions of proximity (on the inner bore especially in the elbow region) the coils are locally locked together through removable cassettes and clamps, Figure 2.30.

Risk Mitigation

Risk mitigation is implemented at 2 levels

1. Within components, the 3F principle is applied where a range of technical solutions are possible within a subcomponent as long as it meets the same geometry and

mechanical conditions and provides the same functionality. Two examples of this are the conductor which allows many HTS and LTS cable configurations as long as they are circular, and the joints, where the space constraints, helium containment, resistance and one-side opening/closing procedures have to be met, but multiple variants are possible. There are also multiple options for the active quench detection that is required, simplified by the long discharge time constants.

2. At a global level the basic concepts are adaptable, and the coil arrangement could be adjusted if configuration or operational challenges develop. Achieving a remountable coil is critical to the overall concept, but if severe problems are found achieving low resistances, as few of 8 coils out of the 40 could be remountable and the remainder could be wound conventionally. Another possibility is that multiple in parallel joint resistances <3 nΩ require soldering to consistently achieve <1 nΩ. This risk is already mitigated in that 'mount once' coils have been differentiated from 'mount many'.

Regarding design qualification, the design is focused on conventional solutions whose performance can be predicted with confidence, even if the solutions are applied in a novel way. These means qualification is mainly about confirmation of the integration and establishing cost effective routes to manufacture.

Magnet Qualification and Roadmap

An assessment of the TRL levels of the main coil technologies is given in Table 2.2: TRL overview of magnet technologies. A development and qualification program, outlined below, will bring these technologies up to a TRL of 7 by 2030, ready for the start of manufacturing of a FOAK coil. CDR Section on Magnets describes in more detail the programme, with the cornerstone being the 1:1 Prototype supported by the Bundesministerium für Forschung, Technologie und Raumfahrt (BMFTR, formally BMBF).

	Present TRL Level	TRL after BMFTR 1:1 Prototype and conductor high field tests	TRL level after model coil test, high conductor test and prototype dummy plate
Demountable Single Joints	3	5	7
Demountable multiple joints (ie in a coil)	3	5	7
Conductor Cable	LTS 7 HTS 5	LTS 7 HTS 7	7
Quench protection using plates	5	5	7
Cold switches and varistors	4	5	7
Quench detection	LTS 7 HTS 4	LTS 7 HTS 5	7
Low voltage breaks in 3D plates	4	5	7
Plate insulation	5	5	7
3D plates with conductor in groove	6	6	7

Table 2.2: TRL overview of magnet technologies

Within the BMFTR funded demountable coil project several subprojects are running, all to be completed by early 2027

- • Demountable Coil 1:1 Prototype
- • High Field Conductor and Joint Samples

The project will include the design and procurement of both HTS and LTS based conductors for testing in prototype joint samples. It will continue with the fabrication and test (mechanical and superconducting) at room temperature and 77 K of a 1:1 prototype of a coil joint region, with 16 conductors and 32 joints. In parallel full size joint samples will be tested up to 11 T.

Model Coils

GFG intends to verify the manufacturing route of the GIGA coils with 3 parallel qualification items

1. A set of half size (on linear dimensions) model coils
2. Short conductor samples
3. A full-size grooved plate, with dummy conductor
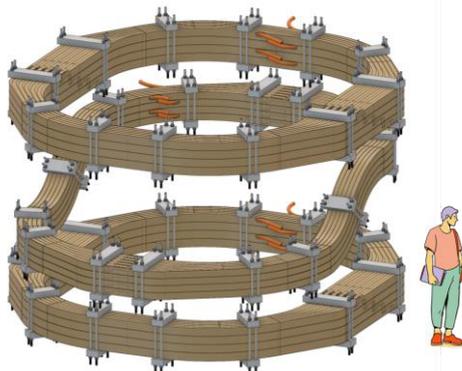
Figure 2.31: GFG Model Coil Concept

The core of the program is the model coils themselves, Figure 2.31, with high field tests of short conductor samples and a full-sized 3D plate intended to fill in gaps which would be costly to include in the model coils themselves and where separate validation is well known (from ITER experience) to be fully adequate.

The short conductor samples will be tested up to 11 - 12 T. One of the advantages of the GFG GIGA stellarator is that we can exploit existing test facilities for conductor verification, as did ITER. Tests will confirm resilience to bending of the cables during manufacture, resilience to degradation from operation loads and quench, and uniform current redistribution to copper during the early stages of quench.

The full-size grooved plate is an industrial manufacturing qualification and optimisation. One major cost driver of the GIGA magnets will be the cost of the structural steel, forming and machining to high tolerances, with associated welding steps. There are multiple options for the plate manufacture (as known from ITER experience) several of which could be qualified.

The object of the full-size plate (and associated trials) is to identify the options with the best possibility for cost reduction during a learning curve.

Supply Chains

The magnet design (in particular the manufacturing design) for the main components, the steel in the case and intercoil structures and the superconductor (HTS or LTS) has been chosen with the lessons from the ITER magnet construction in mind. These can be briefly summarised as:

- Apply Fit, Form and Function (3F) principle for the superconductor and for the steel. 3F refers to the set of essential characteristics that define a component or subassembly. These characteristics determine whether a part can be used interchangeably with another without affecting the overall design or functionality of the end-product.
- Ensure that fabrication routes exist that are capable of scale up and potentially not limited to one supplier (even if a close collaborator). This is critical for components in the TRL 3-5 range. A TRL refers to the maturity of the technology and not the manufacturability, still less the manufacturability at an acceptable price.

There can be two issues with supply chains, with the first occurring for the superconductor and the second for the structural steels.

- The first (and more commonly understood) issue is that a supply chain does not exist because there is no (or weak) demand. In this case the 3F principle is a good start, although insufficient on its own. The component must have a manufacturing route that is capable of scale up in terms of manufacturing personnel, team training and tooling in a reasonable time, and it must allow flexibility in the details while maintaining a common function (i.e. 3F) to allow multiple suppliers. If the only market for the component is fusion, scale up becomes expensive, whereas allowing some flexibility in the details allows potential suppliers to consider also other markets.
- The second is in a mature, large and competitive market. Here the supply chains are well established and focused on their known markets. To devote resources (and often expert engineering ones) to a new risky market can be difficult and getting access to the supply chain with any sort of priority even more difficult. It is even worse if the new product deviates slightly from the existing ones and is disruptive to the use of the supplier's resources.

The main supply chain concerns and assessments are:

Superconductor material: Both HTS and LTS are assessed as viable, both having an established industrialised production route and multiple companies involved in the supply. Trends, on cost and capacity, seem to favour HTS and will be assessed on an ongoing basis through the GFG qualification program.

Structural steels: Concern is the available spare capacity for forging and machining, and the availability of manual welders. Fusion will be competing with a large expansion in the fission industry which increasingly uses the specialised steels and sophisticated forming that was applied for ITER. The mitigation is to use simpler product forms (for example rolled plate) and adapt to the lower performance. The GIGA coil plates and ICS are well adapted to this.

Schedule

Figure 2.32 shows a top-level schedule of the magnet qualification leading to manufacturing and GIGA assembly.
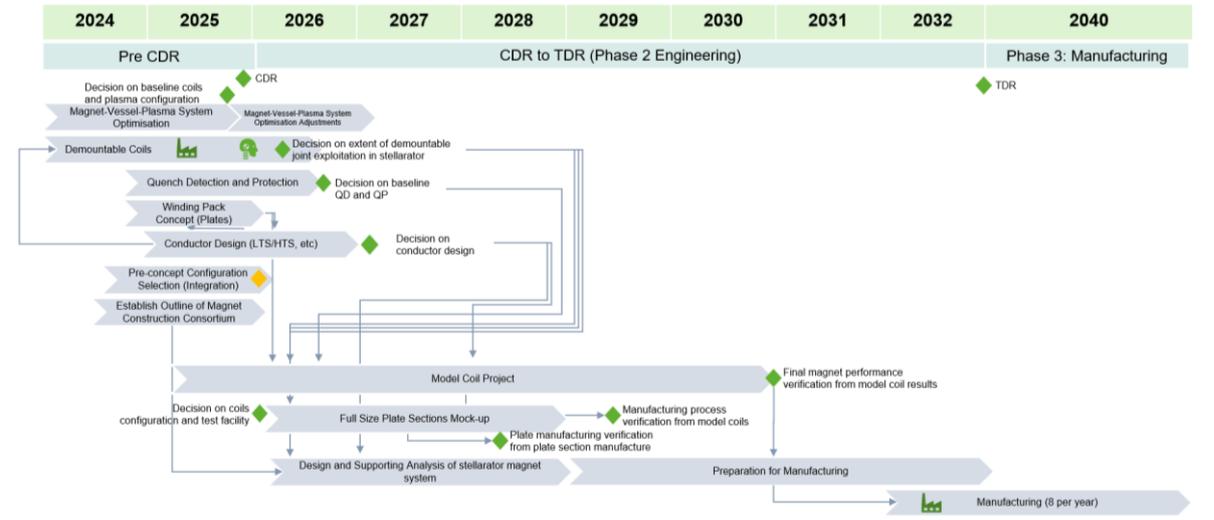
Figure 2.32: Top-level magnet qualification plan leading to construction

2.6. Cryostat

Purpose and Function of the Cryostat

The cryostat is a large and vacuum-tight vessel that houses and provides thermal insulation for key internal components such as superconducting magnets, the vacuum vessel, and thermal shields. It establishes mechanical interfaces and integration with the supporting structure and essential services of the internal components, including diagnostics, vacuum, piping, cabling, and cryogenic feedthroughs.

Vacuum stable conditions, on the order of 1×10^{-4} Pa, effectively minimize convective and conductive heat transfer to the cryogenic systems, ensuring the requested thermal isolation. The cryostat supports a cryogenic thermal shield designed to reduce radiative heat flux from the external environment, thereby protecting the superconducting magnets and maintaining their operational stability.

The cryostat ensures operational reliability by enclosing activated components and limiting the potential release of hazardous materials. Although the cryostat is not formally a containment barrier due to the access requirements for maintenance, the possibility of tritium release into the cryostat must be considered and monitoring will be installed, and a recovery plan for in-vessel tritium release developed. Due to this risk, the vacuum pumping system for the cryostat is also monitored and can be routed through a tritium recovery system under the control of the TFC system. The cryostat ensures dedicated port access for critical systems such as heating and remote handling, enabling efficient integration and maintainability of in-vessel components throughout the reactor's lifecycle. The cryostat is designed for a 40-year operational lifespan, with minimal direct intervention, relying instead on predictive maintenance strategies and modular access for inspection and repair.

Figure 2.33: Cryostat section including the Vacuum Vessel and cryostat interfaces with RHR systems

Design Development at Concept Phase

The cryostat of a stellarator is founded on mature cryogenic and high-vacuum technologies that have been extensively validated in prior large-scale fusion facilities. Although the fundamental design principles are well established, a cryostat of the scale, geometry, and integration complexity envisioned for GIGA has not yet been realized in an operational environment.

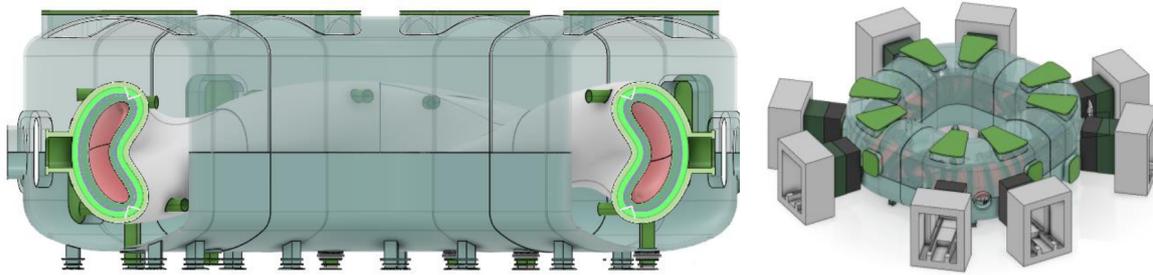The GIGA cryostat design leverages proven methodologies from state-of-the-art systems such as ITER and W7-X. Both projects have demonstrated the feasibility of constructing and operating large, cryogenic vacuum enclosures within highly constrained magnetic and thermal environments. The cryostat preliminary concept was developed through a structured and iterative design process, beginning with functional requirements derived from the stellarator and plant-level systems. The selected concept, a toroidal, single-walled structure reinforced with ribs, was chosen for its structural robustness and ease of integration. The relative deformations of the cryostat with respect to the magnets, vacuum vessel, and thermal shield are expected to be significant due to differential thermal expansions or contractions and structural loads combined with very large radius of GIGA. Thermo-elastic analyses are currently underway to quantify these differential displacements and assess their impact on alignment and interfaces. In the preliminary design, the cryostat integrates spherical joints and a sliding system, that will be tested in the engineering phase, to accommodate relative deformations during cooldown and operation. Intermediate bellows are incorporated to decouple movements between the cryostat and internal component supports, as well as between the VV and cryostat ports, ensuring structural integrity and preserving alignment under differential thermal and mechanical loads.

Finite Element Analysis (FEA) was employed to simulate thermal and structural behaviour under operational loads. In the model the cryostat was designed with a constant thickness. Simulations confirmed that the cryostat maintains structural integrity under vacuum pressure, gravitational forces, and thermal contraction, and the maximum deflections remain within acceptable limits in the ports. While no overstress was detected in the walls, elevated stress concentrations were observed in the support regions, primarily due to geometric singularities and the absence of a finalized design for the leg-to-vacuum vessel interface. Further FEA were performed to assess the structural performance of the ports used for RHR operations. An assessment of port integrity considered a distributed load of up to 1,000 tons from cask-supporting plugs. Under these conditions, local deformations remain below 2 mm,

ensuring compatibility with remote handling systems. Stress levels are also within allowable design limits, confirming structural integrity for the intended operational scenarios. During the engineering phase, structural optimization will be carried out by implementing variable wall thickness, refining the placement of stiffeners, and advancing the detailed design of the support structure to enhance overall stiffness and mechanical performance.
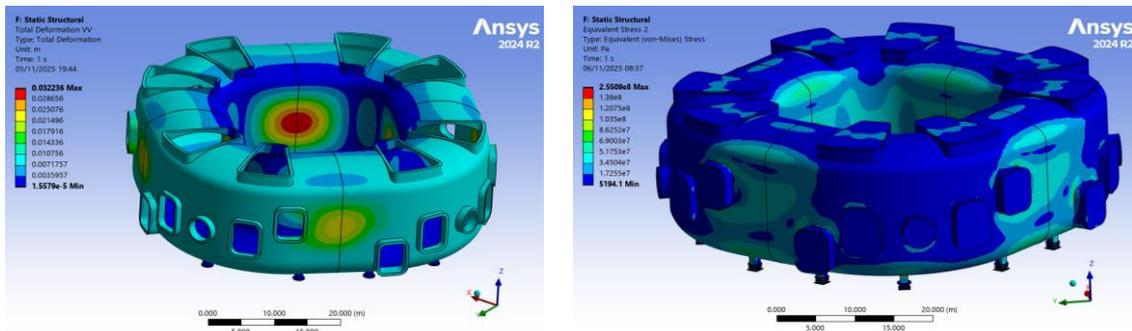
Figure 2.34 Preliminary cryostat FEA simulation, contours of Total Deformation [m] and von Mises stresses [MPa].

In the engineering phase, the thermal shield and its support arrangement will be developed in detail to ensure proper integration with the cryostat and internal components. This component provides a thermal barrier for the magnets, which operate at 20K, to limit heat transfer into the cryogenic system, and requires a space reservation and thermal expansion/contraction considerations from the earliest design stages. At this stage for GIGA, only functional specifications have been defined. Detailed design will develop based on optimised design for the EU-DEMO thermal shield and lessons learned from ITER design, manufacturing, and installation, and will address critical aspects such as differential thermal contraction between the shield and cryostat. The thermal shield is designed to operate in the range of 80 K to 100 K, the temperature is chosen to minimize radiative heat transfer from the cryostat at room temperature and the superconducting magnets. Considerations for thermal shielding of in-cryostat components such as hot pipework will also be assessed.

A Failure Modes and Effects Analysis (FMEA) was conducted on the cryostat to identify potential failure modes, assess their impact on system performance, and specify mitigation strategies. The analysis focused on structural integrity, thermal insulation, vacuum performance, and interface components.

Qualification and Roadmap

The cryostat is currently in the Preliminary Concept Design Phase, with several qualification activities already underway. CAD models, FEA simulations, and concept-level validation studies have demonstrated the feasibility of the design and its alignment with functional requirements. However, full system-level integration is still in progress, pending finalization of interfacing systems such as remote handling, diagnostics, and magnet supports.

The qualification roadmap is structured around key milestones:

- System Integration Review (SIR) in 2026 establishing interface consistency and system-level maturity.
- Intermediate Technical Design Reviews (ITDR-1 and ITDR-2), scheduled in 2029 and 2031, will form a comprehensive qualification process aimed at validating system integrity in full compliance with applicable codes and standards. These reviews will also confirm the maturity of subsystem designs through mock-up testing.
- Technical Design Review (TDR) in 2032 will prepare the system for tendering and construction.

By the conclusion of the Engineering Phase, the cryostat is expected to achieve TRL 6, corresponding to a fully validated prototype in a relevant environment. Subsequent verification and performance testing during FOAK commissioning will demonstrate functionality and reliability under operational fusion conditions.

Supply Chain and FOAK Manufacturing

The supplier landscape for large cryogenic vacuum vessels is limited, with only a few European manufacturers possessing the necessary capabilities.

Manufacturing will follow a modular approach, with sub-sections fabricated off-site and assembled on-site using precision welding and metrology systems. Each module will undergo dimensional verification and helium leak testing prior to integration. Risks specific to FOAK manufacturing include supplier availability, logistical complexity, post-weld precision, and long-lead procurement of high-grade materials. These will be mitigated through early supplier engagement, phased qualification programs, and framework agreements with multiple vendors. The procurement and qualification phase is expected to span 2–3 years, followed by 5–7 years of manufacturing and integration. By the conclusion of Phase 3b in 2044, the cryostat will have demonstrated full operational readiness, providing a validated foundation for future fusion power plants.

2.7. Heating System

Purpose and Function of the heating system

The heating system provides a means to create the initial plasma and provide heating of the plasma to the point where the nuclear reactions can take over (alpha heating). In experimental settings four concepts are utilized ohmic heating, neutral beam injection (NBI), ion cyclotron resonance heating (ICRH), and electron cyclotron resonance heating (ECRH). In ohmic heating a voltage is ramped in a central solenoid treating the plasma like the secondary winding of a transformer. This form of heating is heavily utilized in tokamaks as it drives a large toroidal current as well. For this reason, it is not generally applicable to the low toroidal current nature of the GIGA stellarator. NBI injects high energy neutrals into the plasma which ionize and then heat the plasma through collisions. This requires a direct line of sight between plasma and neutral beam hardware, a configuration which is not compatible with the nuclear environment of the GIGA stellarator. ICRH systems inject electromagnetic waves in the tens of MHz range into the device, coupling them to the plasma through a complex wave-particle
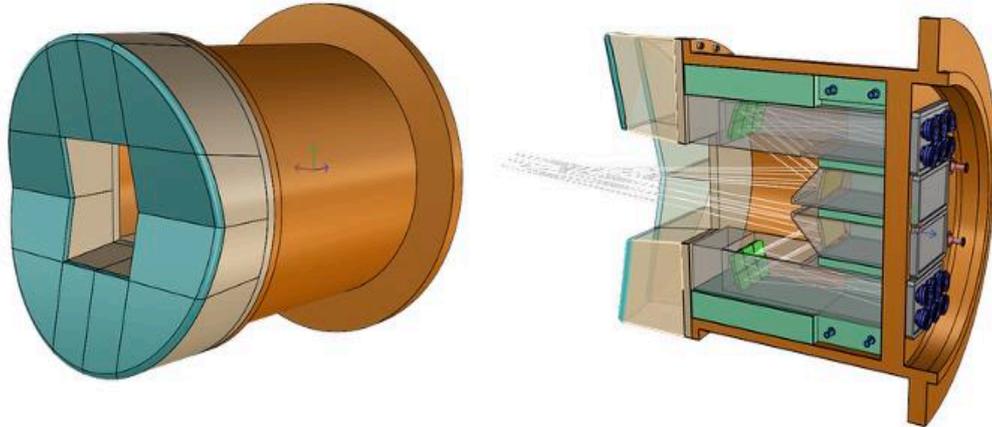
Figure 2.35 Conceptual layout of the ECRH launcher showing mirror position concept.

interaction. They generally require front-end antennas systems which must be placed close to the plasma. ICRH is generally not compatible with the high temperature nuclear environment of the power plant. ECRH systems inject electromagnetic waves in the hundreds of GHz into the device coupling directly to the cross-field motion of the electrons. Transmission of the waves can be done quasi-optically requiring only mirrors to route and aim the waves at the plasma. Systems for generation of the waves are relatively compact and modular. For this reason, electron cyclotron resonance heating has been selected as the heating system for the GIGA stellarator plasma.

The physics of ECRH is generally focused on how the waves propagate through the plasma as the mechanism by which ECRH heats it quite simple. Charged particles in a magnetic field move under the influence of the Lorentz force. This results in an orbit-like motion perpendicular to the magnetic field and a free-streaming motion along the magnetic field lines. The net result is a helical motion. The frequency of the orbit-like motion is determined by the particle charge to mass ratio and the local magnetic field. As the electron has a fixed charge to mass ratio ($1.75882000838 \times 10^{11}\ C/kg$) this cyclotron frequency (also known as the gyrofrequency) is simply a function of the magnetic field strength. We find that for a 6T magnetic field a frequency of 170 GHz is in resonance. The angle of incidence of the wave with the magnetic field can result in toroidal currents, a phenomenon known as electron cyclotron current drive (ECCD).

Design Basis

The total ECRH system is broken down into three fundamental components: the gyrotrons, the waveguides, and the launchers. Gyrotrons are a class of high-power linear-beam vacuum tubes which generate millimetre wavelength (20-527 GHz) electromagnetic waves by the gyromotion of electrons in a strong magnetic field. They are essentially a free-electron maser, in that electrons produced by a cathode are accelerated via a DC voltage into a region of high axial magnetic field where the wave is emitted.

The produced waves must be guided from the gyrotron, usually installed in a separate building, to the plasma by waveguides. As the wave are millimetre in nature, polished copper

Figure 2.36 Simulations of ECRH deposition using the conceptual placement of the ECRH launcher steering mirrors. Equilibrium is depicted in green, with the color of ECRH rays indicating minor radius. Layout shown on left with simulations on right.

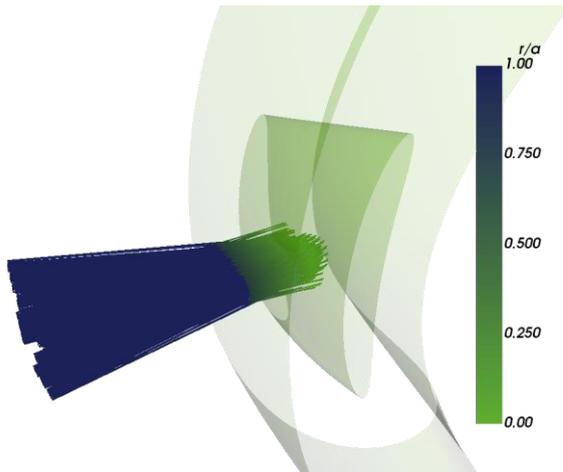with stainless steel water cooled backplates works well as a reflecting medium allowing a labyrinth of focusing and defocusing optics to be used to bring the waves to the device. In the W7-X project such transmission was carried out in open air indicating less than 1% transmission loss. However, arcing and the formation of ozone have been a recuring problem during operation

The ECRH system for the GIGA power plant utilizes the 170 GHz 1 MW gyrotrons developed for ITER. Modelling with the TRAVIS code of the Cordey path scenario (maximum require ECRH power) suggests that the vacuum magnetic field on axis in the bean shaped cross section be 6.26 T. Doing so accounts for both the plasma effects on deposition and the lowering of the toroidal magnetic field by the plasma diamagnetic effect. Additionally, simulations of ECCD suggest a maximum steering angle of 25°. Scoping of the total required power for GIGA are still ongoing but under ideal conditions the Cordey pass require 27 MW of ECRH, accounting for uncertainty in transport phenomena can increase this value to just under 50 MW. Thus, the assumed total required ECRH power is between 50 and 100 MW.

The technology of waveguides is well established with most systems being custom designed pieces. Quasi-optical transmission in open air has been demonstrated on the W7-X experiment. While successful, arcing at mirrors can occur in open air. This produces ozone which can get trapped in regions of the waveguide tunnel and exacerbate arcing. To this end DTT and ITER employ quasi-optical transmission under vacuum (~1E-5 mbar). Cooling of mirrors is necessary in steady state with a copper mirror surface bonded to a stainless-steel water-cooled structure. Of critical concern is that deformation of the mirror due to temperature variations do not over perturb the beam paths.

Plug-in modules for the front end have been custom pieces with varying levels of sophistication. The W7-X plugins must provide a plasma-vacuum interface as the waveguide is in open air. No neutron labyrinth is present and mirror pairs in the front of the launcher provide focusing and steering of the beam. The ITER and DEMO designs include a neutron labyrinth, but neither are intended for steady-state scenarios. Additionally, considerations must be made for the degradation of the steering mirrors due to long term plasma exposure and neutron bombardment. The conceptual design for GIGA can be seen in Figure 2.35.

Concept Definition

Simulations of ECRH deposition examined two scenarios for ECRH launch. In the first, scenario waves were launched from the bean shaped cross section toward the 6T on axis resonance (Figure 2.36). This is similar in design to the system used on W7-X and behaved as predicted. A second scenario where the field was lowered to 5 T in the triangular cross section

was examined with 140 GHz fundamental mode waves. The saddle nature of the magnetic field in this region made deposition very broad and highly sensitive to field variation. It was decided based on these simulations to choose 170 GHz gyrotrons firing from the bean shaped cross section of the plasma. Four identical equatorial ports in this location are envisioned. Preliminary scoping studies suggest a 3m diameter port can be utilized here.

Figure 2.37 ECRH deposition profiles for launcher mirror layout showing good core deposition in the Cordey pass where maximum heating is needed.

The gyrotron plant produces, controls, and monitors the production of 170 GHz waves. The waves themselves are produced by gyrotrons. Current ITER technology rates the 170 GHz gyrotrons at 1 MW with 1.5 and 2 MW gyrotrons of this frequency in development. Simulations suggest a need for up to 50 MW of ECRH power. For the sake of redundancy, it is envisioned that the gyrotron plant should provide around 100 MW of installed power. We follow the DTT device philosophy of grouping gyrotrons into groups of 8 we refer to as islands. Thus, each launcher is connected to 3 islands for a total of 96 gyrotrons. For the purposes of upgrades to later 2 MW gyrotrons over the course of the project, all components will be rated with the assumption of 2 MW gyrotrons.

The ECRH launchers reside in four identical equatorial ports around the device. Each port is nominally a 3 m diameter port. The ports are physically connected to the vacuum vessel and seal to the cryostat via bellows. This allows differential motion between the vessel and cryostat. The ECRH launcher seals to a recessed flange in the port sealing the tritium barrier of the vessel. A large shutter on the cryostat serves an airlock like function for remote maintenance of the ECRH launcher into a cask. The launcher itself is a truss structure attached to the mounting flange. Rails inside the port help align and guide the structure in and out of the port. Integrated into the port is a water shield like that found behind the tritium breeder blanket. This feature however extends further back into the port to better shield port. Within this feature are labyrinthine to provide penetrations through the shield. Approximately half of the space inside the port is dedicated to the ECRH system with the rest being allocated to diagnostics, a material sample exposure system, and the water feedthroughs.

Qualification Record

The electron cyclotron resonance heating (ECRH) heating systems is designed to deliver up to 100 MW of ECRH heating to the plasma and drive up to ±100 kA of toroidal current. Preliminary assessment of these capabilities was performed suggesting that launch from the outboard midplane bean (170 GHz) was a better choice than that of outboard midplane triangular cross section (140 GHz). A gyrotron and waveguide layout making use of vacuum quasi-optical (vQO) transmission was developed. A launcher system to fit inside a DN3000 port was developed with integrated water shield and neutron labyrinth. Space was reserved in the
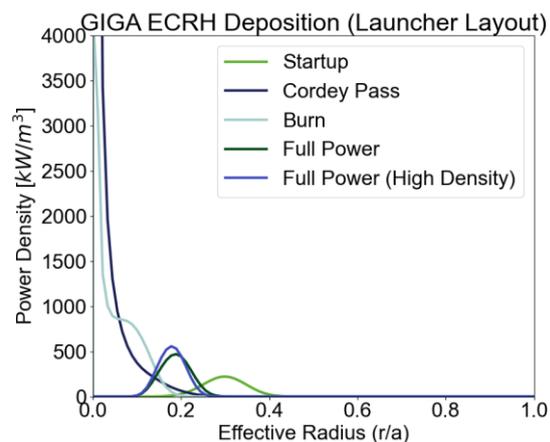
launcher for material sample exposure tests and additional diagnostic systems. This design serves as the conceptual basis for the ECRH system.

The conceptual mirror layout for the ECRH launcher utilizes two mirrors for each group of six gyrotron beamlines. As viewed from top down the mirrors aim across the center line of the port. As can be seen in the cross-section, the beams are also aimed vertically toward the center of the port. Simulations show good, localized core heating while traversing the Cordey pass for the 6.28 T vacuum field scenario (Figure 2.37).

Qualification Plan

The ECRH system is developed through Phase 2 in three separate thrusts associated with the identified L03 systems: the Gyrotron plant, the Waveguides, and the Launchers. The development and qualification of the Gyrotron plant begins with parallel engineering work for the Gyrotron hall and testing of prototype 2 MW gyrotrons. Waveguide development is focused on detailed engineering. Launcher development involves integration of engineering designs into the stellarator device along with integration of any necessary diagnostics as needed for the stellarator control interface.

It is worthwhile noting that the launcher system has a five full power year lifetime requiring replacement at that point. As this is a FOAK system in a completely new neutronics environment, the ability to 'refurbish' a launcher in a hot-cell is unknown. Given the size of the launchers, and their number, a dedicated hot-cell facility for the launchers will be needed whether refurbishment or simply decommissioning is sought. It is expected that in either case the first set of launchers will be replaced, and any refurbishment activities carried out over the next operational window in preparation for reuse in the next operational cycle.

2.8. Stellarator Control Infrastructure

Purpose and Function of the Stellarator Control Infrastructure

The stellarator control infrastructure (SCI) provides the mechanism by which the stellarator plasma parameters are controlled, specifically the fusion power. This is achieved through control of the actuators of the stellarator (heating and fuelling systems) using the observables (measurements) and models (predictive equations) for the stellarator. The observables and models are used to adjust the actuators to achieve desired parameters in the machine. The adjustments are made in real-time to provide feed-back control on the desired quantity. In the most basic case, the desired target quantity is also directly measured, an example being density control in tokamaks and stellarators. There the line-integrated density (or local density) is measured by a diagnostic, and a control algorithm is used to adjust the fuelling rate to achieve a desired plasma density. In more sophisticated systems, a variety of measurements are synthesized in real time via plasma models to allow control of a quantity which cannot be directly measured (or at least cannot be measured fast enough to control the plasma). A classic example of this in tokamaks is plasma position control via magnetic diagnostics. Finally, the SCI is responsible for monitoring the health of the plasma and controlling the shutdown of the plasma.

Our actuators for the stellarator plasma are the heating system and fuelling systems. The heating system provides a means to both initiate the plasma and sustain it to the point where

the fusion alphas can support the heating needs of the plasma (the so-called burn condition, or ignition). For the purposes of this system, the heating system will be assumed to be an electron cyclotron resonance heating system (ECRH). This system can also be used to drive toroidal current through the electron cyclotron current drive mechanism (ECCD), for compensation of plasma currents. Fuelling of the plasma comes in two forms, fuel and impurity. Fuel is injected into the plasma either by cryogenic pellets or via gas valves. These supply deuterium and tritium to the plasma. An impurity gas is injected as well to create a radiative feature in the divertor, known as detachment. Although this reduces heat flux to the divertor significantly, the main purpose of detachment in GIGA is to reduce divertor sputtering. It should be noted that attached operation at full power is possible without exceeding the heat-handling capabilities of the divertor. The ultimate duration of attached operation will be set by sputtering rates and divertor tungsten thickness. However, to achieve five full power years of divertor lifetime, sputtering and the associated erosion should be suppressed for most of the operation through divertor detachment.

The most fundamental parameter which we wish to control is the fusion power. The fusion of deuterium and tritium produces a 3.52 MeV alpha particle (^{4}He) and a 14.1 MeV neutron. A small fraction of the reaction produces an energetic alpha (^{5}He) and a 16 MeV photon (gamma-ray). The total fusion power can be measured via the 14.1 MeV neutrons or the ~16 MeV gamma rays, or it can be computed if the density and temperature profiles are known. Additionally, if the fuel ion density and temperature are known in the plasma, then the total fusion power can be computed.

Control over the total toroidal plasma current is also desired. This is needed because plasma-generated currents (e.g. the bootstrap current) can alter the edge magnetic structure of the plasma reducing divertor efficiency and possibly placing unwanted heat loads on components. Measurement of the net toroidal current is a standard practice in stellarator and tokamaks, making use of magnetic field measurements to provide this value. The total plasma current is a key state parameter.

The control of the divertor detachment requires that the detachment condition be known. The physics of detachment can become rather complex, but from an actuator standpoint are rather straightforward. Power is exhausted through the divertor, and through injection of a gas with higher ionization energies this thermal heat is converted into light via ionization and recombination physics. The degree of detachment is the measure of the percentage of heat which is radiated away before reaching the divertor. Additionally, currents flowing into the divertor can be measured as well providing a second (and more direct) means of measuring the level of detachment. However, these current measurements can't measure changes after full detachment making them less useful for controlling detachment. Thus the key parameter for control of the divertor detachment is knowing the profile of radiated power (from core to edge).

The plasma must also be brought into existence through application of the heating system and fuel injection, plasma startup. In its simplest form this requires control of the density with power being a feed-forward parameter. More sophisticated systems would control the ECRH power and fuelling system to achieve a given density and temperature. A multitude of systems exist for measuring density and temperature in experimental devices, ranging from

perturbative to non-perturbative systems. The plasma density becomes a key state parameter in this regime of operation.

Finally, in addition to providing control capabilities, the SCI should monitor the health of the plasma. One key parameter for the plasma health is the plasma stored energy. This is essentially a measure of the total thermal energy in the plasma at any given time. This is measured by magnetic diagnostics.

From a control standpoint, the state parameters of interest regarding the plasma are fusion power, stored energy, total toroidal current, radiated power profile, and plasma density. Additionally, if the electron temperature profile is measured then we can use the density and stored energy to infer the ion temperature. This would provide an additional check of the fusion power and plasma health. By comparing the measured fusion power and the estimated fusion power the level of plasma purity can be monitored. Measurement of the ion temperature would allow further confirmation of the plasma health and performance. Additionally, many of the techniques used to measure plasma ion temperature provide information about the plasma makeup and electron temperature as well, providing a robust cross-check of the plasma state. The challenge is to down-select robust and redundant diagnostic systems which are compatible with the nuclear, high temperature environment of the GIGA power plant.

The diagnostics components located inside the cryostat and those located inside the vessel must survive those environments for five full-power years. The in-vessel environment of GIGA is a nuclear environment seeing volumetric heat loads of around 1 MW/m^3 in steady state. Because of this neutron fluence, embrittlement of steels is of great concern. For this reason, steady state temperatures of 450°C are envisioned for most structural components, with plasma facing components receiving an additional 200 kW/m^2 photon flux. It should also be noted that tritium breeding blankets (which cover the majority of the wall) can have surface temperatures of 1000°C and are coated in tungsten. The majority of fast neutrons must be captured in blanket modules and steel/water shielding blocks. As a result, diagnostics cannot have a direct line of sight to the plasma from the vessel and must pass through a neutron labyrinth.

The computer software and hardware at the core of stellarator control infrastructure are commercially-available today and borrow much of the design philosophy already present in existing power plant control systems. Such systems will continue to evolve into the future given the rather rapid development and deployment timelines for computer hardware and software. It should be noted that algorithmically the proportional-integral-derivative (PID) controller algorithm provides a key feedback algorithm for process control, often being utilized in the feedback control of experimental parameters.

Design Basis

The design of the stellarator control infrastructure involves selection of key state parameters for the system, diagnostic down-selection for compatibility with the fusion environment, and scoping of control hardware and software. Table 2.3 provides a list of the diagnostic groups, their associated state parameters and possible diagnostics which can provide these state parameters.

Diagnostic Group Name	State Parameters [unit]	Possible Diagnostics
Fusion Power	Total Fusion Power [W]	Scintillating Fiber Detectors, Neutron Counters, Gamma Ray Spectrometers
Plasma Stored Energy	Total Plasma Energy [J]	Flux Loops, Hall sensors, Superconducting coil pickup, Rogowski coil
Plasma Current	Total Plasma Current [A]	Rogowski coil, Hall sensors
Plasma Radiated Power	Total Plasma Radiated Power [W]	Bolometers, divertor current shunts, spectrometers
Plasma Density	Core plasma density [m^{-3}]	Reflectometer, Electron cyclotron emission spectrometers
Electron Temperature	Core electron temperature [eV]	Electron cyclotron emission spectrometers, X-Ray spectrometers
Ion Temperature	Core ion temperature [eV]	X-Ray spectrometers

Table 2.3: Diagnostic Groups and associated state parameters are listed with possible diagnostics which can provide these measurements.

Concept Definition

The stellarator control infrastructure provides a means of controlling the state of the stellarator plasma via computer hardware, software, and diagnostic systems. The general concept of the system is that of a state-space controller where the control system maintains a given plasma state and controls the transitions between states. Inputs to the controllers are the plasma state parameters: Total Fusion Power, Total Plasma Energy, Total Plasma Current, Total Plasma Radiated Power, and Core Plasma Density. The Core Electron Temperature and Core Ion Temperature are also considered in the design but not considered essential to operation at this point. The value of these parameters determines the state of the plasma, with the actuators for control of the plasma being auxiliary heating power, current drive, fuelling rate, and impurity seeding rate. The state parameters themselves are derived from a synthesis of independent diagnostic measures, providing validation and redundancy of the system.

The total fusion power is a composite of multiple diagnostic systems meant for measurement of this property, providing redundancy and cross validation. The scintillating fibre detectors are designed to directly measure the 14.1 MeV neutrons coming from the fusion reactions themselves. Various detector systems are designed to measure the total neutron fluence and provide some level of neutron spectroscopy. The 16.63 MeV gamma rays produced by the D-T reactions are measured via a gamma ray spectrometer. These systems are all envisioned to be in the cryostat.

In our system three techniques are employed to provide a reliable redundant measure of the total plasma energy. The primary method makes use of the superconducting coils themselves to measure the diamagnetic flux. The currents in the plasma induce a back-reaction in the superconducting coils, which one can measure. In doing so we treat the superconducting coils as diamagnetic loops. In addition to providing 5 redundant measures (one per coil type) of the diamagnetic flux, by comparing measurements in similar coils around the machine we can gauge some level of symmetry-breaking fields as well. In order to compensate drifts

associated with this measurement a set of Hall effect B-field probes measure the magnetic field in the toroidal direction near each coil. This provides a reference measurement for periodic recalibration of the signal. Finally, radial flux loops located on the port structures and vessel provide a measure of the radial magnetic flux which is correlated with the total plasma energy (and current). This provides an additional redundant measure of the total plasma energy.

The bolometer sensors, divertor shunt tiles, and visible spectrometers provide a redundant means for measuring the radiated power and verifying the degree of detachment. The bolometers themselves are small solid state systems requiring line of sight to the plasma. This suggests the divertor cassette and ECRH launchers as possible locations for arrays of sensors to be installed. Divertor shunt tiles are integrated into the divertor high heat flux plasma facing components and provide a verification of the level of detachment.

The primary means proposed to measure the electron temperature is via the Michelson ECE system. This system can be integrated into the ECRH launcher and possibly make use of the existing ECRH transmission line infrastructure. Two systems are considered for the measurement of ion temperature, X-ray spectrometers and collective Thomson scattering (CTS). Imaging X-ray spectrometers use the X-ray spectrum emitted by plasma impurities to measure the ion temperature (along with impurity density and electron temperature). These systems have seen good success in many experimental devices around the world. CTS systems usually benefit from a nearly 90° angle of incidence between the probing beam and receiving line of sight. As such integration into the ECRH launcher may severely restrict the value of measured information. Still the system is considered here for completeness.

Qualification Plan

Following from the plasma re-optimization being undertaken towards the SIR milestone in 2026, the diagnostics systems will be sequentially re-assessed from a synthetic signal perspective. The team will be expanded with the necessary expertise to lead this development activity. Beginning in 2027 a diagnostic down-selection will be made, resulting in a list of diagnostic systems and their key features which need to be brought to TRL 5. Following this down-selection, engineering design work for these diagnostics will commence. This will include design of test articles as needed to achieve TRL 5. This engineering activity will include industrial partners where possible to aid in any certification activities needed for commercial use. Engineering activities of this nature will be ongoing throughout phase 2.

In the beginning of 2027, a commercial partner will be identified with which Gauss will contract for initial design work implementing our diagnostic systems into their production systems. As the target date of 2039 for operation is 12 years away at that point, this work will only serve to guide development moving forward with dedicated design activity to be carried out a few years before device completion.

In Q3 and Q4 of 2027, an assessment will be carried out to identify a partner for testing and demonstration of our diagnostic systems. The purpose will be to develop scale diagnostic systems which can be brought to TRL 5 through installation and testing at the partner's facility. This work will continue through the end of phase 2 in 2032.

On longer timescales the procurement and installation of diagnostic systems will depend on the systems into which they're integrated. Magnetic diagnostics will most likely be integrated

in the cryostat around the vacuum vessel in a similar manner to the superconducting coils themselves. Diagnostics integrated into the ECRH launchers will depend on the procurement and delivery schedule of the launchers. The same can be said for any diagnostic (bolometers for example) which may integrate into the divertor cassettes. Thus, diagnostic procurement and integration is expected to occur from 2032 to 2038. The design, procurement, and programming of the stellarator control infrastructure will take place from 2035 through 2039.

2.9. Remote Handling Robotics

Purpose and Function of the Remote Handling Robotics system

From the preliminary design phase, the Remote Handling Robotics (RHR) system has been tasked with ensuring safe, efficient, and fully remote maintenance of both in-vessel and ex-vessel components. This requirement is fundamental to sustaining plant performance while protecting personnel from radiation exposure.

The RHR system is designed to:

- Enable safe extraction and transport of activated materials, ensuring compliance with nuclear safety standards and minimizing radiation risks.
- Handle breeding blanket segments, divertor modules, and diagnostic tools without direct human intervention.
- Conduct sample inspections.
- Perform scheduled and unscheduled maintenance.

To achieve these objectives without direct human intervention, the system relies on an integrated suite of robotic manipulators for precision handling, advanced control infrastructure for remote operation and monitoring, transport and positioning systems for component movement. Its development is tightly coupled with the design of the VV, the cryostat, the coils and in-vacuum components. This early integration aims to ensure that all systems remain accessible and maintainable through dedicated ports and interfaces.

Design Development at Concept Phase

The RHR system for GIGA builds upon the technological advancements achieved in ITER and DEMO, which represent the current state-of-the-art in fusion remote maintenance. ITER's integrated architecture of in-vessel articulated manipulators, cask-based deployment systems, and ex-vessel transport lines has established the foundational framework for high-precision, teleoperated maintenance in extreme radiation and thermal environments. DEMO aims to further this progress by incorporating digital twin integration enabling predictive maintenance and autonomous path correction. The complex, non-axisymmetric geometry of a stellarator like GIGA limits line-of-sight access, creating challenges for remote handling. This demands robotic systems capable of operating in confined, cluttered spaces.

Subsystem	Function	Description
Out-of-cryostat transfer cranes	Moving components to storage /refurbishment.	Large overhead cranes or modular carts.
Vertical transporters	Deploy RHR tools and in-vessel modules through vertical ports	High payload lifting systems.
In-vessel transport platform	Moving components inside vessel.	Mobile base for tools and manipulators
Manipulator arms	Precision handling for attachment/ detachment	6-DOF with radiation-hardened actuators.
End-effectors	Specialized tools for fastening, cutting, gripping, and welding.	Modular, quick-change couplings
Casks	Safety shielding during component transfer	Shielded containers with thermal management
Docking and storage units	Secure storage for tools and components	Warehouse or temp storage
Remote control and sensors suite	Enabling teleoperation and monitoring	Vision, haptic feedback, position tracker.

Table 2.4: Subsystems breakdown

The preliminary RHR concept for GIGA follows these guidelines:

- Full remote operability for scheduled and unscheduled maintenance.
- Integration from the early design stage to avoid retrofitting issues.
- Modularity and flexibility to handle diverse tasks such as inspection, replacement, and refurbishment.
- Compliance with nuclear safety standards for activated material handling.

The RHR covers inspection and maintenance of in-vessel components, transport and storage of activated and other components, but also tooling and control infrastructure. So, it is composed of multiple subsystems, each fulfilling a specific role outlined in the following table.

In the following table the key design parameters are outlined.

Input	Unit	Value
Maximum in-vessel temperature during maintenance	°C	200
Minimum size of maintenance ports	mm	1400 x 4000
Maximum payload for RHR in-vessel tools (blanket mass)	tons	100
Coils weight	tons	350
Blanket/divertor expected lifespan	years	5
GIGA operational lifetime	years	40
Component alignment precision	mm	±2

Table 2.5: Key Design Criteria from L01 applicable to RHR

Despite the current low maturity of several systems interfacing with the RHR and the resulting preliminary definition of certain requirements, initial CAD models have been developed to evaluate spatial constraints, port accessibility, and robotic reachability.

These models have played a crucial role in shaping the layout of maintenance ports, assessing the feasibility of component removal paths, and verifying the integration of robotic arms and transport systems within the plant architecture.
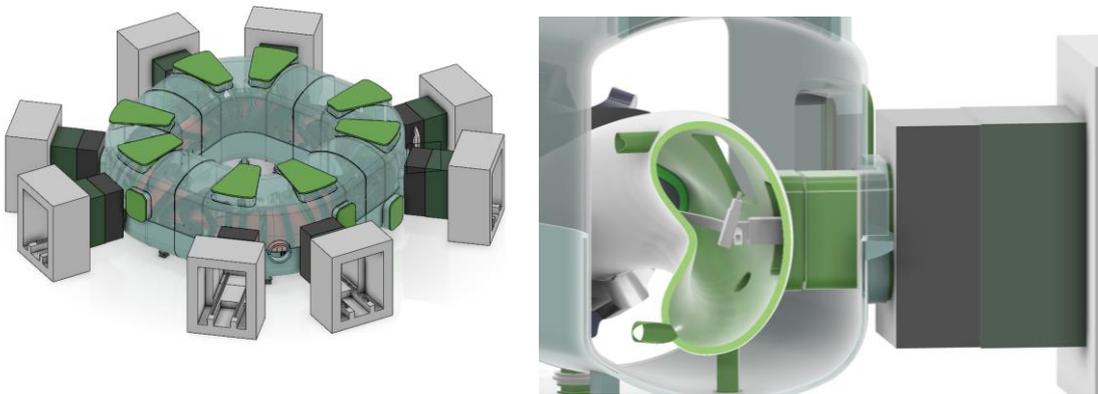
Figure 2.38 Cryostat with RHR plugs connected and in-vessel transport platform concept.

The design process adheres to a rigorous systems engineering methodology, ensuring that all functional requirements, interface conditions, and environmental constraints are systematically addressed from the earliest stages of development.

The RHR procedures during the maintenance are defined as follows:

1. **Coil Removal and Reassembly**
- Removal of cryostat top flange for internal access.
- Remove intercoil support structures.
- Engage coil plates using remote-handling tools.
- Unscrew coil joints with robotic manipulators equipped with motorized screwdrivers.
- Extract coil plates using cranes with controlled movements and transfer to storage.
- Reassembly follows the reverse sequence, ensuring alignment and secure fastening.
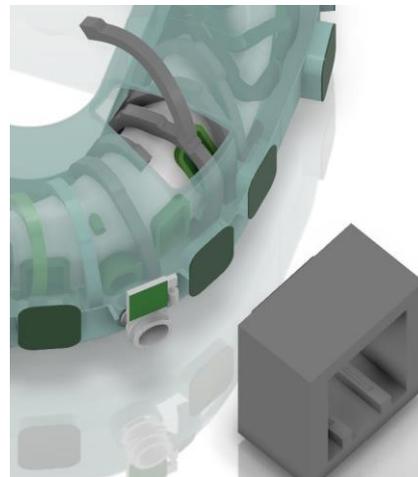
Figure 2.39: Coil removal path

2. **B and divertor removal and shielded transfer**

   Replacing breeding blanket and divertor modules involves disconnecting and isolating cooling pipes, loosening bolts, and removing the segment with robotic tools. The new module is then aligned, secured, and reconnected to ensure vacuum integrity.

   - A rail-mounted shielded plug and cask system, designed to provide biological protection, interfaces

Figure 2.40: TBB connections with VV and pipeline

with the cryostat port to enable the safe transfer of activated components.
   - Components removed from the vessel are placed inside the cask by robotic grippers.
   - Cask is transferred to hot cells for maintenance.

3. **Active Material Facility Operations**
   - Disassembly of modules and subparts occurs inside hot cells.
   - Maintenance can proceed while the stellarator remains operational.

Qualification and Roadmap

The development of RHR system for GIGA involves several technological and integration risks, primarily due to its First-of-a-Kind nature (FOAK).

These risks have been identified and characterized at an initial level to guide subsequent design and mitigation strategies.

The RHR system completed initial concept-phase prequalification, confirming compliance with boundary conditions and general requirements for transition to the Engineering Phase. However, several critical interface definitions are still evolving, such as final port dimensions, coil positions, and modules dimensions and weights. As a result, the system remains in a high-level conceptual phase, with detailed engineering deferred until sufficient data becomes available. The roadmap is designed to ensuring a structured evolution from conceptual design to full deployment while aligning with major engineering milestones.

During 2026, the concept will be consolidated through the finalization of all critical interfaces with the VV, in-vessel components, cryostat, and bio-shield. This phase also includes updating ICDs and FMEAs. In parallel, engagement with specialized suppliers for robotic systems and nuclear-grade materials will begin and continue throughout subsequent phases. CAD integration will be carried out to validate spatial constraints, port accessibility, and robotic reachability. These activities will culminate in the completion of the System Integration Review (SIR).

Between 2027 and 2029, the design effort will advance alongside the prototyping of critical subsystems such as manipulator arms, end-effectors, and shielded casks. Mock-up environments will be developed to enable preliminary operational trials, while simpler components and actuators will undergo testing under simulated radiation and thermal conditions to validate their performance in representative environments.

By 2030, detailed engineering design for all RHR subsystems will be completed. Full-scale mock-up testing will then be conducted to verify kinematics, tool exchange mechanisms, and component removal paths, ensuring seamless integration with the plant architecture and compliance with safety standards. Concurrently, advanced control systems for teleoperation and sensor feedback will be implemented.

The final qualification phase will confirm compliance with nuclear regulatory requirements through rigorous design validation and operational testing under representative operational conditions. This stage will also include the preparation of tender documentation and the definition of procurement strategies for industrial deployment. This phased approach guarantees that the RHR system evolves in parallel with the overall plant design, maintaining alignment with integration requirements and minimizing rework.

Supply Chain and FOAK Manufacturing

The FOAK nature of the GIGA plant necessitates the establishment of a qualified industrial supply chain capable of producing nuclear-grade robotic systems. Currently, the supplier landscape includes a mix of robotics manufacturers, precision engineering firms, and nuclear equipment providers. Only very few meet the comprehensive requirements for fusion applications, such as radiation tolerance, vacuum compatibility, and traceability. To bridge this gap, a structured supplier development program will be launched during the engineering phase.

This program will include capability assessments, process qualification, and the implementation of quality assurance protocols aligned with standards. Final integration and testing will occur at a centralized facility equipped with clean assembly zones and precision metrology tools.

3. Tritium Fuel Cycle

Opening Remarks on TFC Strategies and Design Maturity

In most new FPP concepts, the Tritium Fuel Cycle (TFC) is typically among the last core systems to enter FPP-scale development, despite its centrality to the plant operations, FPP viability and economics. This delay can be for several reasons:

1. **Insufficient information to begin TFC design**
   The development of a fuel cycle concept depends on the prior selection of key technologies central to the FPP concept, namely the fusion device type (e.g. stellarator), breeding blanket technology (e.g. HCPB), and an initial estimation of the FPP operating parameters. As this delay is unavoidable, the start of TFC design inevitably lags behind the development of the fusion device itself.

2. **FPP project focussed solely on the central device**
   In some cases, a decision is taken to defer the TFC to later in the FPP development. This is a high-risk strategy which underestimates the complexity, technology readiness levels, timelines associated with tritium, and the tight integration of the fuel cycle design with the wider FPP. This creates significant risk of delayed delivery of the TFC compared to the device, potentially delaying overall FPP progress. Compatibility and integration features may be overlooked, raising the risk of costly device redesigns or commissioning challenges.

3. **FPP project focus on developing a demonstrator device(s) and TFC**
   A common strategy of fusion endeavours involves developing a demonstrator-scale device and thus focussing on developing a minimal, simplified TFC for the demonstrator. While a small TFC is essential for any DT demonstrator, such designs cannot be simply scaled up to meet FPP requirements. There is a frequent misconception that building a demonstrator-appropriate TFC represents a major milestone towards FPP-scale readiness. In reality, batch-mode and small scale TFC have existed since the 1990s. This approach to "reinvent the wheel" represents a drain on resources without significantly advancing the FPP development.

Early in its conception, Gauss Fusion committed to the strategy to build a full-scale FPP device, without a demonstrator stage device, and to begin development of the TFC as soon as possible. This has enabled GFG to move directly to focusing on the design and delivery of an FPP scale TFC (and thus avoiding the pitfalls of scenarios 2 and 3 above).

The prerequisites (scenario 1) for pre-conceptual design were met in 2024, following the publication of the GFG White Paper, and a Tritium Fuel Cycle Lead was appointed in November 2024. At the time of this document, the tritium programme has reached an advanced pre-conceptual to early conceptual level of maturity. Further refinement of plasma requirements remains ongoing and is necessary before the TFC can be developed to full conceptual maturity, including technology selection, inventory assessment, process scaling and validation. Full conceptual development is anticipated by early 2027.

Accordingly, the information presented for the TFC in the CDR reflects a lower level of maturity than that presented for the stellarator (e.g. plasma physics, magnet design, etc). Additionally, some technical work is omitted due to export control limitations. ***Note:*** *Supporting references for this summary are contained in the main CDR document.*

Tritium Fuel Cycle Introduction

Introduction to DT

Hydrogen is the lightest element and has three naturally occurring isotopes: protium, deuterium and tritium, as shown in Figure 3.1. Most fusion concepts are built around the DT reaction (see Equation 3.1). The resultant high energy neutron carries the thermal energy that is ultimately used to heat water to steam and may also be captured in the tritium breeding blankets (TBB) to produce new tritium.
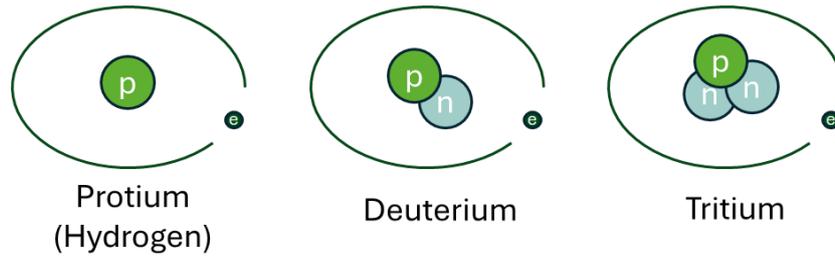
Figure 3.1: The three isotopes of hydrogen.

$$^2_1H + ^3_1H \rightarrow ^4_2He + ^1_0n$$
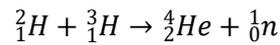
Equation 3.1: DT Fusion Reaction

Deuterium is a naturally occurring, stable isotope abundantly available from water (~150 ppm). Tritium, by contrast, occurs naturally only in trace amounts in the stratosphere. It must therefore be produced artificially via one of two mechanisms, high energy neutrons interacting with lithium or lower-energy neutrons interacting with deuterium.

Tritium Dual-Use & Export Control

While tritium may be used for peaceful energy production, it is also a key component in advanced nuclear weaponry (i.e. hydrogen bombs). Therefore, tritium inventories and any associated technology involved in its storage, processing, or production are subject to strict dual-use export controls and regulatory oversight. This includes design and technical data, not just the physical apparatus.

Additionally, this places obligations on an FPP to demonstrate that all tritium inventory is traced throughout the full plant lifecycle, and no inventory is removed without authorisation. To provide context: any FPP will have an operating inventory of the order of kg, whereas only a few grams are required for a weapon.

Introduction to Start-Up Inventory and Breeding

Global commercial stockpiles of tritium are comparatively small, with limited annual production. Academic estimates suggest a current commercial stockpile of the order of 30kg (anticipated to decrease in the coming years due to FPP R&D) with an annual global commercial production of a few kg.

Given a single FPP generating 3GW of fusion power will require over 150 kg/yr of tritium versus a global supply chain a fraction of that, FPP's cannot rely on a continuous external fuel source. Instead, an initial startup stock must be introduced to begin the DT reaction, with replacement tritium bred via tritium breeding blankets (TBB), using the neutrons generated by the fusion reaction.

The most recent publicly available tritium cost estimation is $30M (€26M) per kg, and is likely to increase significantly in the near-term. This makes it clear that the TFC should be designed to minimise the start-up tritium inventory required (which will be of the order of kilograms).

The supply of a start-up tritium stock for subsequent FPP devices, such as the rollout of a GIGA fleet, becomes increasingly less challenging as more FPP come online. Each FPP will breed a small excess which in time will accumulate to represent a start-up stock available for a new FPP startup (this is known as the "tritium doubling time").

Key Attributes and Challenges of Working with Tritium

Tritium shares many physical and chemical properties with the other hydrogen isotopes. However, a critical distinction is that tritium is radioactively unstable, with a half-life of approximately 12.4 years (see Equation 3.2).

$$^{3}_{1}H \rightarrow {}^{3}_{2}He + e^{-} + \overline{v}_e$$
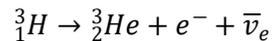
Equation 3.2: Tritium decay mechanism, producing helium-3, a beta electron and antineutrino.

The properties of tritium have several key consequences for an FPP:

- The radiological hazard presented by tritium will be a dominant consideration of any FPP safety case and regulatory approval process.
- A wide range of materials are incompatible for use with tritium, as they are susceptible to high rates of permeation and/or damage caused by tritium decay. This severely limits viable material selections and precludes the use of many commercially available instruments and components.
- Most end-of-life components will become low-to-medium-term (depending on the inventory) radiological waste. Decontamination (requiring dedicated facilities) can significantly reduce the contamination and recover tritium for reuse, but will not reduce contamination to levels to permit immediate general disposal.
- Any tritium inventory decays into helium at a rate of approximately 5% annually, as such the start-up inventory should be delivered on a "just-in-time" basis. Premature procurement of this inventory would incur an annual decay loss of around 5%, representing a significant financial penalty (estimated at €1.3M per kilogram).

Key Attributes of a Tritium Fuel Cycle Architecture

Fuelling and Pumping the Device, Reprocessing Tritium

The TFC must first provide the fuel to the fusion device, supplied directly into the core of the plasma. In addition to core fuelling, gas must also be supplied via edge puffing near the divertor to serve two key functions:

- Plasma density control (DT or noble gas)
- Divertor detachment, which protects surfaces from extreme thermal loads (noble gas).

The nature of a magnetic confinement device means they do not confine injected matter indefinitely. Instead, the DT fuel injected into the plasma core (where fusion occurs) is typically confined on the order of seconds, before it diffuses to the cooler plasma edge and must be pumped away. As a result, only ~1% of the injected DT gas undergoes fusion, with the remaining ~99% lost to the device's exhaust (not to be confused with the stack exhaust of the whole facility).   Given the radiological nature, scarcity, and high value of tritium, this unused

inventory cannot be discharged to the environment. Instead, it must be recovered and recycled for reinjection into the reactor, as illustrated by the red arrow in Figure 3.2.

However, other species are also present in the exhaust stream, including helium-4 (fusion product), helium-3 (from tritium decay) and protium (fusion product and from hydrogen exchange with surface materials in the device and pumping systems). These gases and impurities, if directly recycled and allowed to build up in sufficient quantities, would poison the fusion reaction and lower the FPP efficiency. As a result, the TFC cannot indiscriminately recycle all exhaust gases back into the fuel stream. Instead, a targeted separation process is necessary.
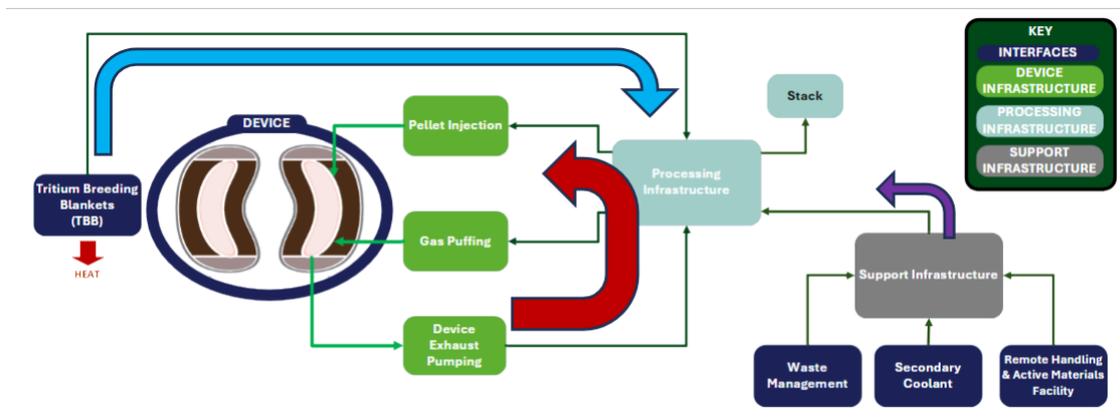
Figure 3.2: Highly simplified generic TFC infrastructure. Key functions highlighted as follows: (red arrow) the recycling / reprocessing of unused DT fuel exhausted from the device; (blue arrow) extraction from the tritium breeder blankets (TBB); (purple arrow) tritium recovery from the wider FPP site.

While early experimental fuel cycles separated exhaust gases into pure tritium and deuterium streams, it is now recognized that for FPPs this approach is too inefficient. Since the two isotopes would immediately be remixed into DT for reinjection, full separation is no longer justified.

Breeding Extraction Function

As highlighted earlier, the tritium consumed in the fusion reaction must be bred in the TBB to enable the FPP to be tritium self-sufficient. The TFC is responsible for the extraction of tritium from the TBB and transfer into the fuel cycle (blue arrow in Figure 3.2).

Supporting Functions

The TFC is also responsible for enabling safe tritium operations and handling across the GIGA site and supporting regulatory compliance. This includes detritiation of coolants and supporting the safe handling, storage, and detritiation of waste (purple arrow in Figure 3.2).

State of the Art

Considering the SOA for TFC architecture, Gauss Fusion has broadly divided TFCs into one of four categories: Batch-Mode Single-Loop (BSL), Semi-Continuous Mode Single-Loop (SCSL), Semi-Continuous Mode Multi-Loop (SCML) and Continuous Mode Multi-Loop (CML).

The SOA for a validated holistic closed-loop architecture with a fusion device is the BSL demonstrated in the 1990's by the Joint European Tokamak (JET) [UK] and Tokamak Fusion Test Reactor (TFTR) [USA]. The SCSL has been demonstrated at reduced scale without a fusion device by the Tritium Systems Test Assembly (TSTA) [USA], but has yet to be demonstrated by ITER. However, such single loops are not suitable for FPP scale.

A SCML was proposed for DEMO and since adopted for all tokamak concepts, but remains undemonstrated. GIGA is at the forefront of TFC architecture development of a CML architecture suitable for a stellarator.

Main Challenges in TFC Development

1. Minimise Reprocessing & Inventory

Even modest increases in gas separation and processing requirements can lead to significantly larger process infrastructure, driving up both capital and operational costs, and requiring greater total tritium inventory within the system which is undesirable from both safety and regulatory perspectives. As such, the core challenge in architecture and subsystem design is to maximize direct recycling of exhaust gases and minimize reprocessing demands.

2. Design Uncertainty

All fusion concepts face issues surrounding the uncertainty in the fusion device's fuelling requirements, outgassing behaviour, and divertor conditions and pumping performance. Uncertainty in these requirements makes it difficult to design the fuelling and pumping systems, and scale / optimise the wider process (in line with the first challenge). Ultimately, the TFCs for FOAK devices will need to be designed with a significant error margin for the fusion device, likely requiring higher inventories and sub-optimal costs (both CAPEX and OPEX). It can be anticipated that the second generation FPPs will have slightly smaller and cheaper TFC infrastructure.

3. TRL Barriers

The third challenge is that the architecture involves a great many different sub-systems and processes, all with differing TRL levels. Work is ongoing at numerous research institutions to address technology gaps and raise TRLs for the required sub-system technologies. However, the focus has been predominantly on small lab-scale fundamental work and use of deuterium as a substitute for tritium. This is largely due to the extremely high costs and lead-times involved in tritium work, a shortage of a manufacturing base for tritium-compatible components, and a lack of suitable testing facilities where at-scale testing is possible. Any FPP will need to operate a semi-continuous or continuous TFC, which will share most of the same key components. These components may differ in their sizing and integration, bespoke to each fuel-cycle, but the R&D, manufacturing base and basic demonstrator validation can, in principle, be shared.

Technology Assessment (TA)

The broad scope of the TFC, encompassing diverse functions and numerous sub-systems, makes it impractical to assign a single TRL level that accurately reflects the overall technology

status. As a high-level introduction, the novelty assessment is therefore presented for the key technologies grouped into infrastructure categories, as shown in Figure 3.3.

Main technologies	LOW TRL (1-3)	MEDIUM TRL (4-6)	HIGH TRL (7-8)
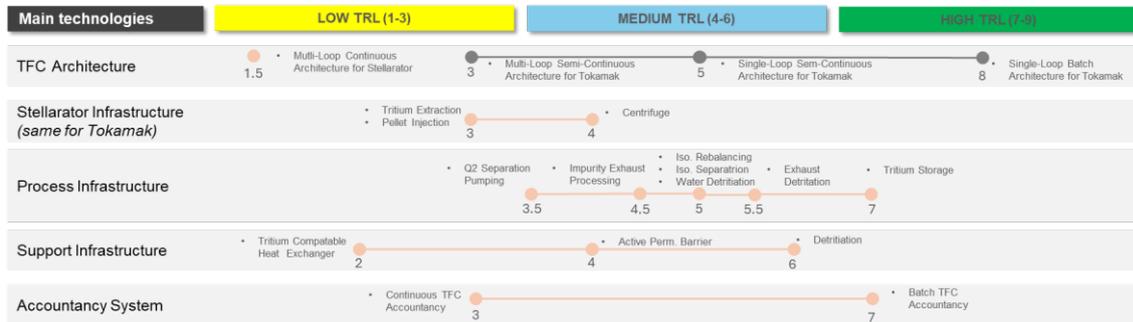
Figure 3.3: The TRL levels of key high-level architecture groupings

Breakdown Structure & Interfaces

The Product Breakdown Structure of GIGA defines the TFC as a Level 1 block, and is divided into eleven Level 2 blocks. The simplified physical relationship between these 11 blocks on the GIGA site is illustrated in Figure 3.4. A map depicting the interactions of the TFC blocks with other Level 2 blocks across GIGA is shown in Figure 3.5. This illustrates how widely integrated the TFC is with the other GIGA systems across the FPP site.
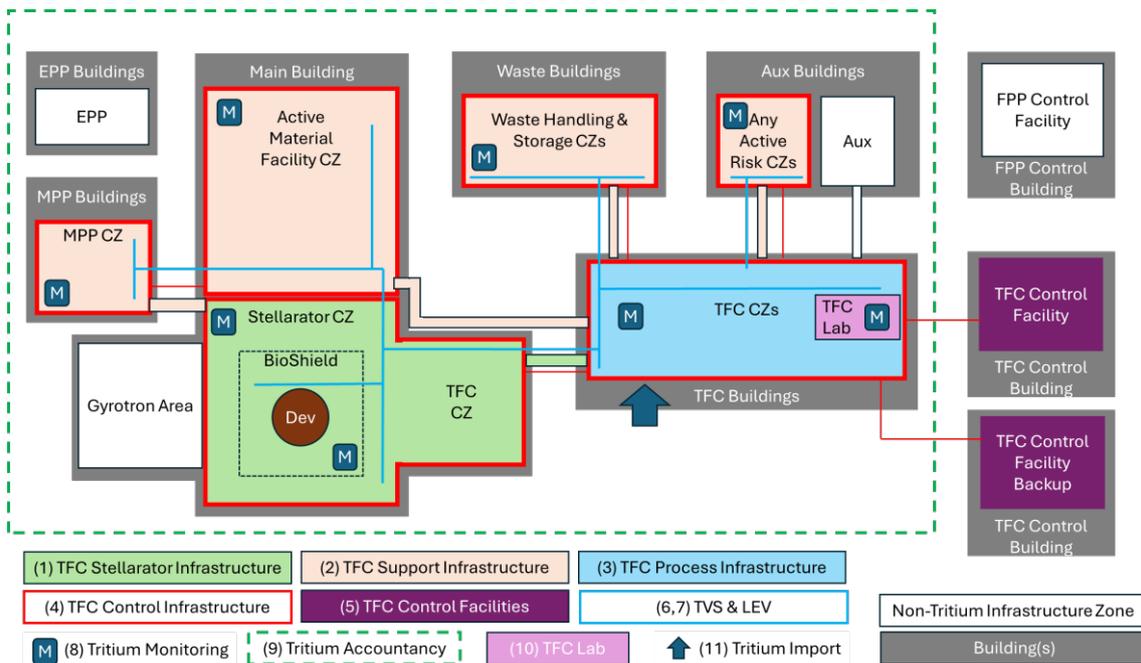
Figure 3.4: Physical relationship between the 11 Level-2 blocks on the GIGA site

Figure 3.5: Illustration of the interfaces between the 11 Level-2 blocks of the Tritium Fuel Cycle product breakdown structure and other Level-2 blocks at GIGA. Note the arrow colours are only to aid reading the diagram and carry no further meaning.

Architecture Concept

A single-loop structure is highly undesirable for a large FPP TFC, as this would create unacceptably large gas hold-ups and require an unacceptably large inventory. This led to the multi-loop architecture proposed by C. Day and T. Giegerich for the DEMO TFC, comprising a direct recycling loop, inner process loop and outer process loops.

The GIGA design is the first reimagined TFC for a stellarator, which builds upon the DEMO tokomak design, but makes a number of changes. A simplified schematic of these loops are illustrated in Figure 1.12. These loops represent over 35 discrete sub-system blocks.

In summary:
- Bypass Loop: The recycling of gas used for density control and detachment.
- Direct Loop: The recycling of gas used for pellet fuelling.
- Inner Loop: Processing of most of the remaining exhausted gas, and fuel storage.
- Outer Loops: Detritiation of exhaust gas and liquid streams.
- Breeding Loop: Extraction from the TBB.
- Support Loops: Support for waste handling, Active Materials Facility (AMF) and remote handling.
- Ancillary Loops: Supporting export of pure tritium and helium-3.

The infrastructure is divided into four physical groupings, highlighted in Figure 1.12 and are:

- The **Stellarator Infrastructure** collates all systems which are either physically connected to the stellarator, or must be in close proximity to it.
- The **Support Infrastructure** collates support functions localized at various positions around the GIGA site, such as the AMF or Waste Facility.
- The **Process Infrastructure** will be contained in a dedicated facility building, and house the inner and outer loops, as well as various ancillary functions.
- The **Site-wide systems** that are localised, but will ultimately feed back into the Outer Loops of the main Process Infrastructure.

TFC Phase 2: Definition Phase

Phase 2 represents the definition (design) of GIGA, which runs between 2026 and 2032, with several delivery review milestones during the timeline. For the TFC, Phase 2 has been divided into five distinct stages, which also largely align with the GIGA milestones. The timeline for Phase 2 is shown in Figure 3.6, including other relevant timescales.

The role of the modelling activities and the dependence on the device requirements are also identified on the figure. Included are the anticipated availability of tritium, and large-scale deuterium, testing facilities capable of providing up to TRL 6 validation. These facilities are still under construction, and access agreements are not yet put in place, but GFG envisions using these facilities once they become available.
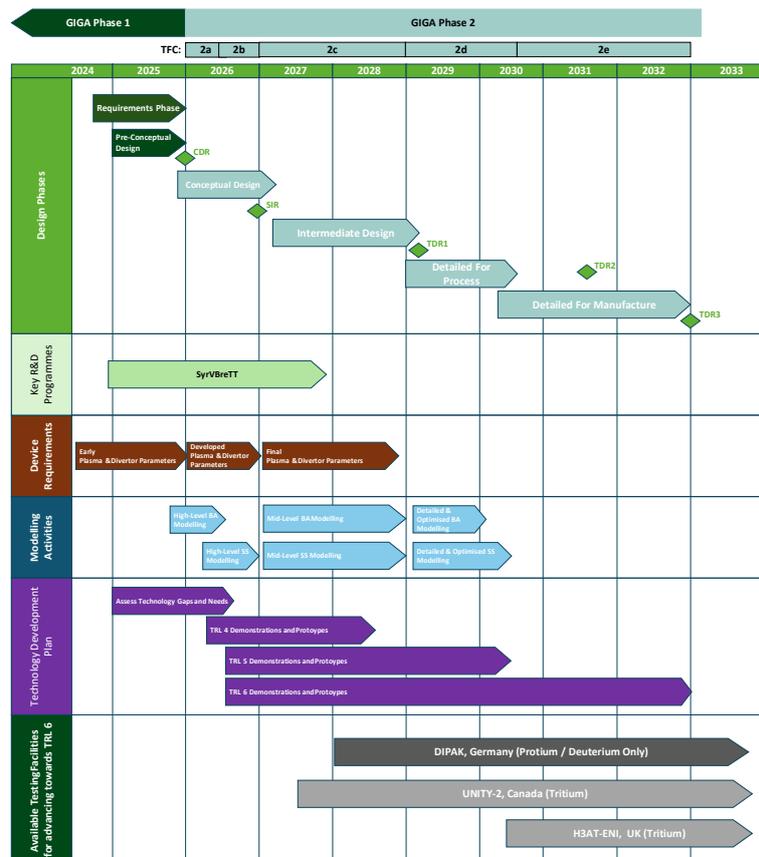

Figure 3.6: Timeline of Phase 2 development of the GIGA TFC, alongside other relevant timescales. BA = Block Architecture, SS = Sub-system.

Challenges of Raising Tritium TRL Levels & Component Testing

To conduct any tritium experiment (whether TRL 4 benchtop scale, TRL 6 reduced scale prototype, or TRL 7 full scale prototype), a supporting infrastructure of commensurate scale is required. In fact, the scale of the supporting infrastructure must be slightly larger, due to the limitations of the minimum process volumes, operational heels and tritium retention in materials. The infrastructure is required to provide several key functions, and in practice, will closely resemble a batch-mode or semi-continuous-mode fuel-cycle facility.

The scale of the experiment-supporting infrastructure, and the associated available tritium inventory, will depend on the scope of the work being conducted. TRL 4 benchtop work can be achieved with only a few grams of tritium, while TRL 6 may require tens of grams. At present, only a handful of facilities exist in Europe and North America, with appropriate inventories and infrastructure suitable for TRL 4-5.5 testing (see Figure 3.7). No facilities are currently available for TRL 6 testing, but two are under construction and are due to come available in 2028 (UNITY-2) and 2030 (HEAT-ENI). There are currently no planned facilities in the tritium community that will allow full scale testing required for TRL 7+.
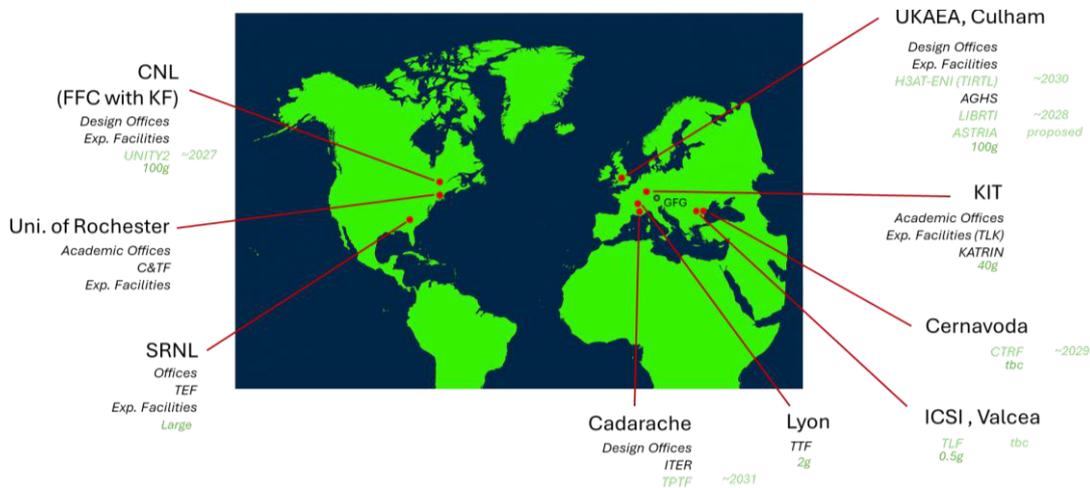
Figure 3.7: Current (black) and upcoming (green) tritium design and experimental facilities in Europe and N. America, with approximate dates of operational and publicly declared inventories.

Phase 2 TRL Development Strategy

For technologies identified as likely essential to the GIGA TFC, but currently below TRL 4, assessment work is already underway. Where active R&D efforts are progressing externally, GFG will avoid duplicating these initiatives, but may instead offer support or partnership where feasible.

In early 2027, the fully-quantified conceptual design phase for the TFC will conclude. This phase will define flow boundary conditions between core architectural blocks and enable definitive technology selections. These outputs will inform the process-scale requirements of systems and components, and thus the required TRL 5 and TRL 6 demonstrations that will be necessary in subsequent years. Again, where third-party R&D aligns with acceptable timelines for GIGA Phase 2, GFG may elect to not duplicate efforts, and collaborate or allow the market to develop as appropriate.

Phase 3: FOAK system validation

There is currently no existing or upcoming tritium testing/demonstrator infrastructure suitable to taking TFC technology systems or architecture beyond TRL 6. The timescales for the design and construction of such a facility are substantial, and comparable to the timescales for a FOAK FPP TFC. Awaiting additional facilities to be available to enable TFC validation to TRL7 prior to completing the design or build of the GIGA TFC is incompatible with Gauss Fusion's timeline to begin DT commissioning of the stellarator in 2041.

Therefore, the GIGA TFC will need to provide the validation to TRL7 itself. The risk presented by this strategy will be mitigated by prioritising the build of the TFC systems on the GIGA site and their substantial commissioning with tritium in advance of the stellarator commissioning (see Figure 3.8). This will provide more scope for any corrective actions without impacting the DT commissioning of the device. To support commissioning of the Process Infrastructure ahead of the stellarator readiness, a temporary dummy vessel can simulate the device. To prevent contamination of the stellarator during its Stage 1 of commissioning, temporary systems will be provided to supply and exhaust protium (see Figure 3.9).

Figure 3.8 Timescales for TFC commissioning, with TFC process facility disconnected from device & using temporary testing systems (TTS) during Stage 1 of device commissioning. IC = Inactive Commissioning, ATC = Active Trace Commissioning, AFC = Active Full Commissioning; SIC = Stellarator Infrastructure Connection.

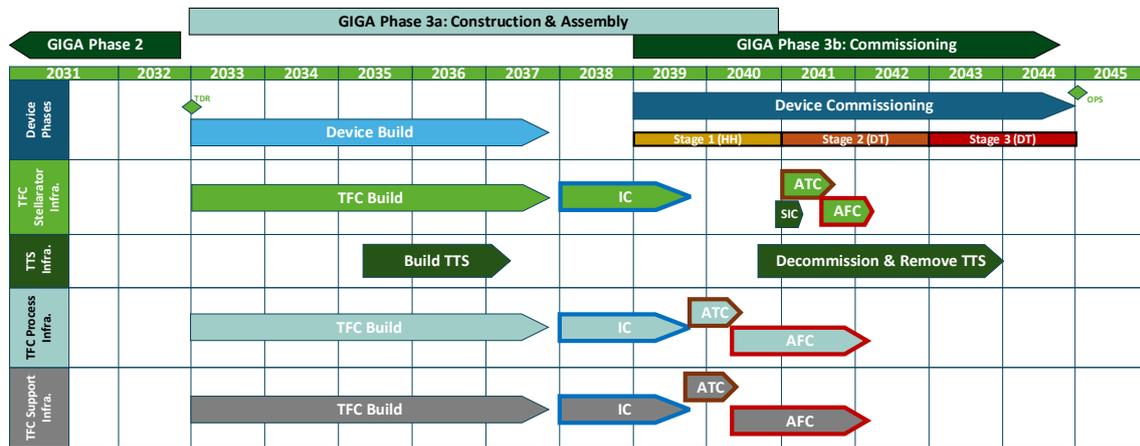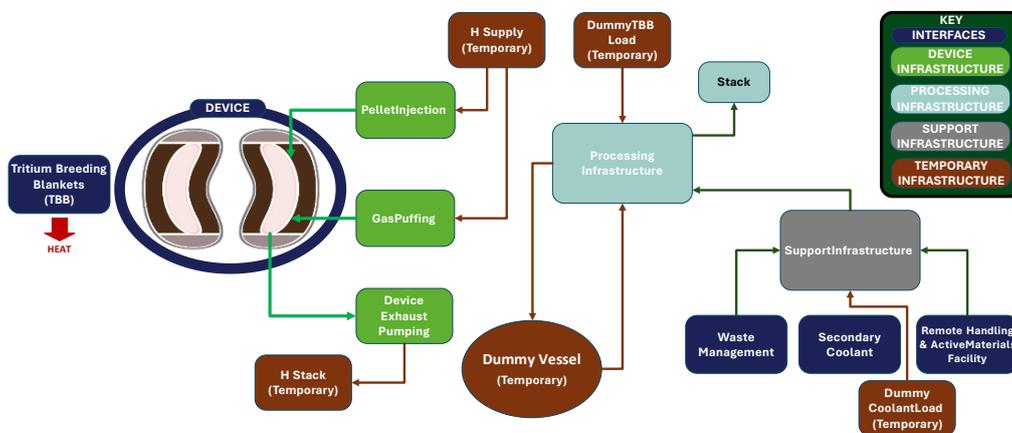*Figure 3.9 TFC connections during early Stage 1 commissioning, with TFC process facility disconnected from device, using temporary testing systems (TTS), during Stage 1 of device commissioning.*

4. Auxiliary Systems

Introduction

The GIGA Auxiliary systems support the safe management and operation of various systems across the FPP. They are critical to the operation of the fusion reactor, the fuel cycle, managing nuclear safety and operating the power systems that manage the conditioning and export of power to the grid. As presented in the EPP design, the Auxiliaries can draw over 300MW at peak total to support operation of GIGA. The EPP manages the electric supply to the Auxiliaries, which in turn provide essential supporting functions across GIGA. In Phase 2, the power consumption and sequencing will be optimised.

Auxiliaries Architecture

The Auxiliaries Architecture is presented in Figure 4.1 and has six Level 02 Systems, as shown.
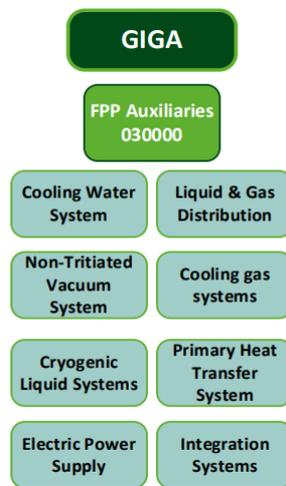
Figure 4.1: Level 02 Architectural breakdown of the Auxiliary System

The Auxiliary systems consist of a variety of technologies, most of which are mature technologies operational in other industrial applications and in nuclear fusion demonstrators previously. The PHTS will require development through Phase 2 to elevate its TRL to 6 prior to incorporation in GIGA FOAK. The Auxiliaries are heavily interfaces across the FPP and particularly with the reactor and fuel cycle as they provide critical support to their operation.

The significant equipment power consumption withing the Auxiliary Systems is outlined in Table 4.1.

Auxiliary System	Power [MW]	Operating voltage [V]
He pumps	120	400
Cryoplant	20	400
Maintenance and other systems	70	400
Tritium plant	15	400
Magnets	5	400
Plant building heating/air conditioning	70	400
Plant Control	TBC	TBC
Plasma heating	125	50000
Power island auxiliary consumption	TBC	TBC

Table 4.1: Equipment power consumption through the Auxiliary Systems

The following describes the auxiliary systems in further detail.

Cooling Water System

The Cooling Water System (CWS) is for supply to chillers, steam turbine, heat exchanger, generators, transformers and other systems across the FPP. One closed cooling water system per power block is installed in the plant. The complete circuit is maintained under pressure with an expansion tank installed at a high elevation and connected to the suction of the CWS pumps. After cooling the equipment, the CWS goes to the CWS plate heat exchangers, where it is cooled again by transferring the heat to a water flow coming from the cooling towers. Then, it is again pumped in the CWS pumps, and the cycle is repeated.

Non-tritiated Vacuum System

The primary aim of the non-T vacuum system is to eliminate the air and gases from the Cryostat vacuum chamber where the vacuum vessel and magnets systems are located. To obtain a high vacuum efficiently the system will consist mainly in two stages: a mechanical vacuum pump to achieve a medium vacuum and continuously a high vacuum pump, such as a turbo molecular pump. The non-tritiated Vacuum Systems also support operation of the gyrotron insulations systems and provide vacuum as service across the FPP.

Cryogenic Liquid System

The cryogenic liquid system will be used to provide cryogenic cooling to the following critical parts of the fusion reactor:

- Cryostat thermal shield: cooling with gaseous helium at 80 K.

- Magnet cooling: cooling with liquid helium at 4.5 K or 20 K, depending on the final technology selected (LTS or HTS, to be defined).

The cryogenic system will consist mainly in the production of helium at 80 K, the production of helium at 4.5 K, the production of nitrogen and the nitrogen recondensation.

The cryogenic liquid system provides LN2 for use in pumps, for dehydration of gas flows, baffles, as a pre-cooling stage for LHe systems.

Electric Power Supply

Electric Power Supply is primarily for powering the magnets, gyrotrons, He pumps for the cooling system, other stellarator supply and electric loads across the FPP.

Liquid & Gas Distribution

The Liquid & Gas distribution system provides non-fuel cycle systems, water, and other gas services around the plant.

Cooling Gas System

The cooling gas systems will supply gHe to cool the thermal shield. The helium will be sent from the gaseous storage to a compression system and then it will enter the helium 80 K cold box, where it will be cooled down to 80 K with liquid nitrogen through a heat exchanger. Finally, this helium will be sent to the thermal shield.

Primary Heat Transfer System (PHTS)

The PHTS provides the high pressure gHe to the TBB which extracts the thermal power of the fusion reaction. The PHTS then passes this power to the Mechanical Power System. In the PHTS circuit, hot helium comes from the TBB (from the terminal points) and is sent to PHTS heat exchangers, where heat will be transferred to the Secondary Heat Transfer System. After

being cooled, helium will be compressed in the helium circulators (compressors) and the cooled Helium will again be sent to the TBB to further collect thermal power from the fusion reaction. Molten-salt based systems are used in fission reactors for reasons including their operational efficiency. They have been proposed for use in fusion tokomak systems to also leverage their energy balancing capabilities. De-tritiation methods for their use in GIGA will be explored in Phase 2. Other reactor thermal sources like the Divertor, the Vacuum Vessell and Water Shielding are water cooled and feed the Steam Cycle through the Feedwater Tank. Consideration of de-tritiating these systems will be developed in Phase 2.

Integration Systems

Integration Systems oversee the infrastructure and equipment development, provision and operation that enables the construction, assembly, commissioning, operation, maintenance and decommissioning of GIGA. Much of the technology employed in this System will be state-of-the-art commercial equipment and systems used in heavy construction, power plant and nuclear facilities currently, e.g. excavators, bulldozers, cranes, rollers, mixers, trucks, etc. Bespoke design may be appropriate to GIGA to facilitate the scale of the FPP construction and assembly operations. New technology development may be required to manage assembly of the components to the required tolerances, such as in metrology, visualisation, guidance and dynamic support and precision positioning. Some new equipment technologies will be required for QC compliance, undertaking SATs and through the commissioning process integrated systems testing.

Phase 2 and Phase 3

The Auxiliaries delivery timeline will align with the corporate milestones ensuring that the equipment is available to support commissioning and operation of GIGA when required. The Auxiliary Systems need to be operational to support commissioning from 2039.

To facilitate this, in consideration of procurement and manufacturing timelines, the design cycle for the FPP will be aligned with the corporate roadmap outlined in CDR Section 20.

- Auxiliaries Intermediate Technical Design Review 1 (ITDR-1) – 2029
- Auxiliaries Intermediate Technical Design Review 2 (ITDR-2) – 2031
- Auxiliaries Technical Design Review (TDR) – Q4 2032

5. Waste Management System

Fusion does not, intrinsically, produce radioactive by-products, but the neutrons from the reaction, and the absorption of tritium into reactor materials, means that materials removed from the reactor, such as the blanket and divertor components must be handled as radioactive material, and at the end of life, components such as the vacuum vessel, and parts of the fuel cycle, among others, also need specialist handling. A wide range of studies have been conducted for EU-DEMO, and as GIGA relies on similar materials and components, these reports are very valuable in defining the waste management strategies for GIGA. A full blanket and divertor set may comprise of up to 10,000 tonnes of mixed materials that must be removed robotically from the reactor and securely transported to the Active Material Facility (AMF), where initial separation and detritiation will take place. Following this, the material will be moved into longer term storage or disposal routes. Thus, a fusion power plant will produce

10s of thousands of tonnes of activated materials during its lifetime, classified as intermediate-level waste (ILW) if moved for disposal. In the best cases, with effective low-activation materials, most of this material will be able to be recycled within 100 years and thus can be reintegrated into the supply chain. Some will require longer-term storage at a specialized facility.

A fusion power plant therefore needs a strategy to remove in-vessel components to a facility which can separate components according to material and activation, detritiate them, and move them to storage or recycling appropriately. This will continue through the plant lifecycle and culminate in the decommissioning and disposal of the device itself, also activated (although to a lower level than in-vessel components) and requiring detritiation.

The Waste Management system is responsible for storing and monitoring those activated materials until off-site recycling or disposal is possible. This system is required to remain operating after decommissioning of the power plant and will also have to deal with materials and waste from that decommissioning process. There are comprehensive guidance documents from the IAEA to help the development of the approach, but ultimately the solutions must be acceptable to local regulators.

The waste management system relies on infrastructures (i.e. Active Materials Facility/hot cell) and equipment (remote handling tools where required) allowing the maintenance of the plant in safe conditions. It has several principal functions that can be foreseen at the early design stage:

- Characterization of the waste to allow adequate treatment
- Radwaste sectorization of the plant in conjunction with the types of wastes that can be generated during maintenance
- Treatment of the waste including size reduction and as well as (pre-) packaging of the waste
- Extraction and recycling of breeder material if possible
- Safe intermediate storage before shipment

Most of the technologies involved in the waste management process relies on well-known design. However, some remote systems required qualification to unprecedent environmental conditions. In particular, the geometry and the radiation level are unique design conditions for the equipment and systems to be maintained.

For the specific systems involved in direct maintenance of the GIGA device, the TRL is very low (1-2). The maintenance strategy and concepts for the GIGA machine are totally novel, and indeed there is a very limited experience of the maintenance activities for a machine stellarator type. The remote tools need to be entirely designed for and tested to representative environmental conditions (geometry, weight, magnetic fields, thermal loads, dpa, …). The rest of infrastructure and equipment (such as hot cell, characterization and decontamination processes and (pre-) packaging, storage cans, control rooms, fire and radiological zonings, …) are well known and the TRL is around 6-7.

As well as equipment design, during the engineering phase calculations to assess the full expected inventories of waste of various materials and types will be conducted. The disassembly and separation of components such as TBB modules and divertor within the AMF

will be assessed. The AMF itself, and internal processes and robotics, will be defined and designed.

Methods for reducing the volume of ILW will be assessed and developed; this may involve ways of recycling; of carbon or other radionuclide removal from bulk smelted steel in specialist facilities in order to return the steel to the commercial market sooner; and further waste separation while in the storage facility to permit faster recycling of less activated elements. Waste minimization, on the scale of a human lifetime (up to 100 years), is important for the public acceptance of fusion.

Following the assessment of waste separation and inventories for the AMF, the capacity and lifetime requirements for the Active Material Storage facility will be defined. Assessments will be conducted to determine the storage lifetimes for different classes of materials coming from the AMF into storage. Systems will be designed for movement of waste from AMF to waste storage. Monitoring and tritium control systems will be defined.

Robotised systems for the handling of activated components and separated activated materials will be required in the AMF and activated material storage facilities. The latter has simpler requirements: the waste will need to be internally sorted and moved into storage locations, and its conditions monitored. Overall power plant availability, and hence commercial viability, is strongly affected by the efficiency of the overall maintenance procedure. If robotic failures cause delays in maintenance and hence delay operational restart, this is potentially very expensive, and so excess capacity and redundancy should be part of the design.

6. Mechanical Power Plant

The GIGA FPP plant will produce and export 1GW of net electric power to the grid. To enable this, the Fusion reaction will generate circa 3GW of thermal power, which will be managed, converted, exported or redeployed through the FPP in accordance with Figure 6.1, which indicatively outlines power conversion through GIGA. The Mechanical Power Plant (MPP) converts the thermal power to kinetic power which is in turn converted to electrical power by the Electrical Power Plant.

The Primary Heat Transfer System (PHTS), considered as part of the Auxiliary Systems in the FPP architecture, extracts heat from the TBB and integrates with the MPP via its Secondary Heat Transfer System (SHTS). The SHTS conveys power on to the Steam System.

The Turbine and Steam Cycle technologies are conventional, commercially available technology at TRL 9. Materials, designs, instrumentation and control will all be tailored designs of widely adopted systems.

The SHTS proposed is based around molten salt heat exchanger technology, which is commercially available for alternative applications and at TRL 6 for the GIGA application.
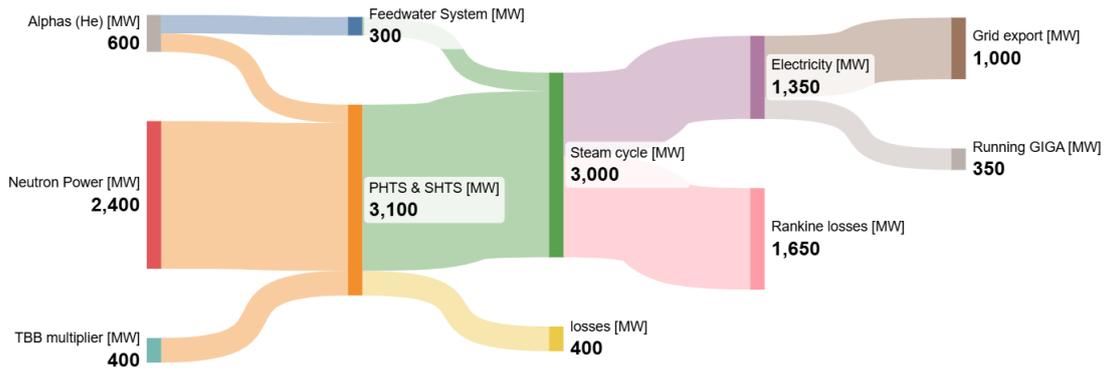
Figure 6.1: Indicative power breakdown across FPP generation and conversion systems

Mechanical Power Plant Architecture

The MPP Architecture is presented in Figure 6.2 and has three Level 02 Systems, the SHTS, the Steam System and the Turbine System, as shown.

Figure 6.2: Level 02 Architectural breakdown of the Mechanical Power Plant System

The Steam and Turbine Systems will be based on a regenerative Rankine (water-steam) cycle, with reheat and cooled by a seawater wet cooling tower. The Rankine cycle configuration was optimized for the Concept Phase study based on the specific requirements of the project and the general diagram and process data.

Due to the large thermal power evacuated from the fusion reactor, two steam turbines will be needed, and the Rankine cycles associated to these two steam turbines will be independent to each other, operated as separate 'power blocks'. Figure 6.3 shows the steam cycle for one power block.
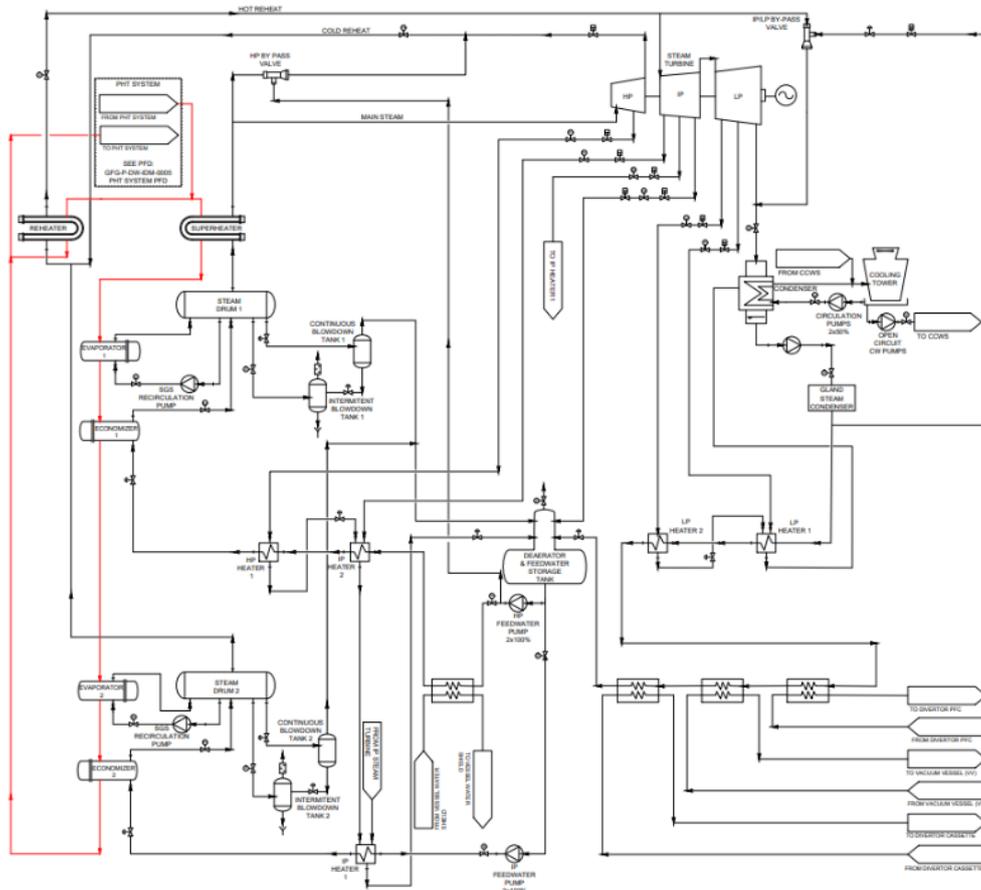
Figure 6.3: FPP Steam cycle concept Process Flow Diagram

Steam System

In Concept Phase, heat and mass balance calculations were undertaken for the power plant, tracking the flow of heat and mass through its components, using energy and mass conservation principles, to optimize efficiency, identify losses, and ensure proper operation of the system. Practical constraints on flowrates, temperatures, heat fluxes, pressures etc. were applied from systems like the boiler, turbine, condenser, cooling system and feedwater system. MPP load inputs are detailed in Table 6.1.

Main heat source (fusion power + energy multiplication in blanket)		
Heat transfer fluid type	Helium	-
Heat transfer fluid supply pressure	80	bar
Heat transfer fluid supply state	Gas	-
Temperature of fluid coming from reactor	500	°C
Temperature of fluid going to reactor	300	°C
Mass flow rate of HTF	TBD	kg/s
Heat input	3200	MW

Table 6.1: Main Reactor design inputs to the Mechanical System design for Concept Phase

Additionally, the heat sources coming from the auxiliary systems of the reactor (vessel water shield, divertor cassette, divertor Pfc and vacuum vessel) were optimally used for preheating the condensate and feedwater, as shown in Figure 6.3.

Secondary Heat Transfer System

The SHTS system proposed for GIGA consists of helium-molten salt heat exchanger. Such systems offer favourable thermal properties and have been proposed for EU-DEMO. In this heat exchanger, the molten salts will be heated absorbing the heat transferred from the hot helium, and then sent to the steam generator system as depicted in Figure 6.4.

The SHTS will manage thermal loads from the PHTS of circa 3-3.4GW, as outlined in Figure 6.1. The Heat exchangers themselves with be shell and tube type, optimised for efficiency using the molten salt fluid and the thermal ratings of the system. Tritium management for the system and detailed design will be developed in Phase 2.
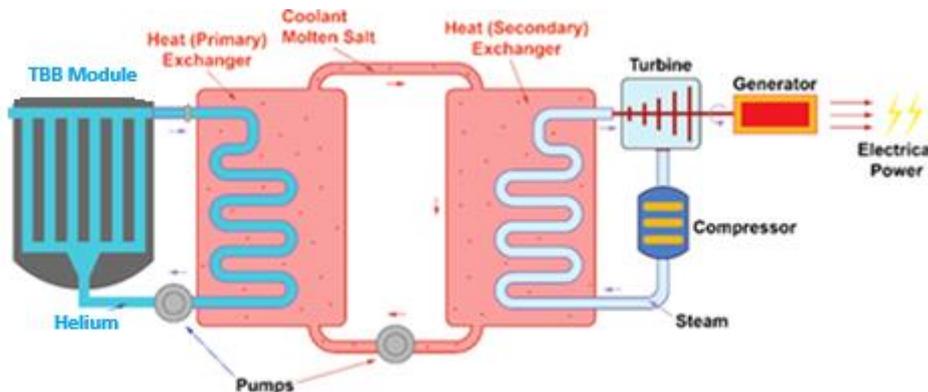
Figure 6.4: Simplified depiction of heat transfer systems from the TBB to the Steam System through the SHTS

Steam Turbine

The Steam Turbine will be of conventional commercially available technology systems such as the Siemens SST-6000 Utility Steam Turbine package. For the FPP application, it is proposed that two SST 6000s of 700MW rating employed in parallel. Turbine specification and characterisation in the steam system was undertaken in Concept Phase.

Phase 2 and Phase 3

The MPP delivery timeline will align with the corporate milestones ensuring that the equipment is available to support commissioning and operation of GIGA when required. The MPP Systems need to be operational to support commissioning from 2039. To facilitate this, in consideration of procurement and manufacturing timelines, the design cycle for the FPP will be aligned with the corporate roadmap outlined in Section 20.

- MPP Intermediate Technical Design Review 1 (ITDR-1) – 2029
- MPP Intermediate Technical Design Review 2 (ITDR-2) – 2031
- MPP Technical Design Review (TDR) – Q4 2032

The TDR is the final design review to close design, issue for construction (IFC) and call for tender (CFT) on the MPP system. The estimated lead time for the large mechanical systems is 5 years.

7. Electrical Power Plant

The GIGA FPP plant will produce and export 1GW of net electric power to the grid. To enable this, the Fusion reaction will generate circa 3GW of thermal power, which will be presented to the Electrical Power Plant System (EPP) through the Steam Turbine and Generator interface. Circa 1.5GW of electrical power will be managed, converted, exported or redeployed through the FPP in accordance with Figure 7.1.
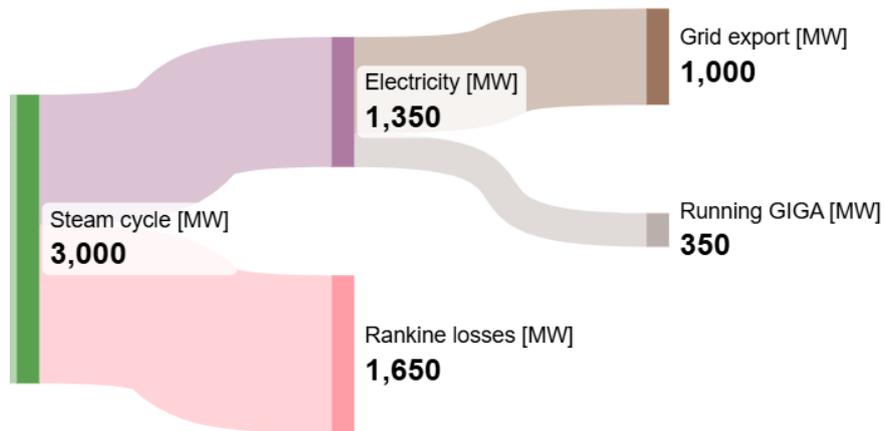
Figure 7.1. Estimated power breakdown across FPP power conversion and EPP

The ~350MW peak total load required to operate GIGA at various stages through its lifecycle will be managed from the substation through various 50kV and 33kV circuits around the FPP to the load centres requiring the power supply. The Power Conversion Control System will manage the safe conditioning and export of power to the grid at 400kV and the MV supply to the operational loads through the FPP.

Electrical Power Plant Architecture

The Electrical Power Plant Architecture is presented in Figure 7.2 and has three Level 02 Systems, the Generator, the Substation and the Power Conversion Control, as shown.

Figure 7.2: Level 02 Architectural breakdown of the Electrical Power Plant Systems

Due to the large thermal power evacuated from the fusion reactor, two Steam Turbines and Generator systems will be needed and operated in parallel.

A Single Line Diagram representing part of the EPP circuit is shown in Figure 7.3, a main output of the conceptual electrical design of the EPP. The SLD shows the connection of the generators to the 400kV busbar, the downstream connection of the 50kV and 33kV busbars with appropriate loads and the subsequent connection to the LV 400V system.
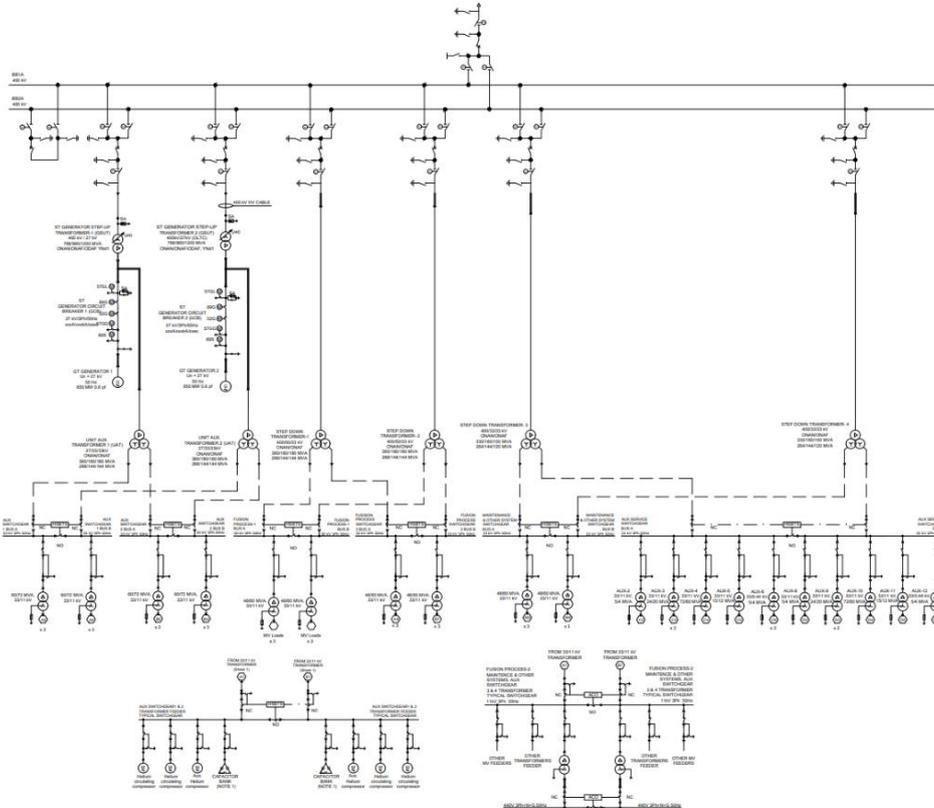
Figure 7.3: FPP Electrical system SLD

The Electrical Power Plant technology is conventional, commercially available technology at TRL 9. The system will be a bespoke design reflecting the variety and nature of the internal loads.

FPP internal electric loads

The FPP internal electrical equipment, preliminary load values of which employed for conceptual design are shown in Table 4.1, manage the systems that support operation of the Stellarator and Fuel Cycle Systems. Most of the equipment operates at conventional 400V supply. The Plasma heating Gyrotrons operate at 50kV.

Generator

The GIGA generator will be of conventional commercially available technology systems such as the Siemens SGen5-3000W Generator Series, depicted in Figure 7.4 and identified as suitable during conceptual design of the EPP.
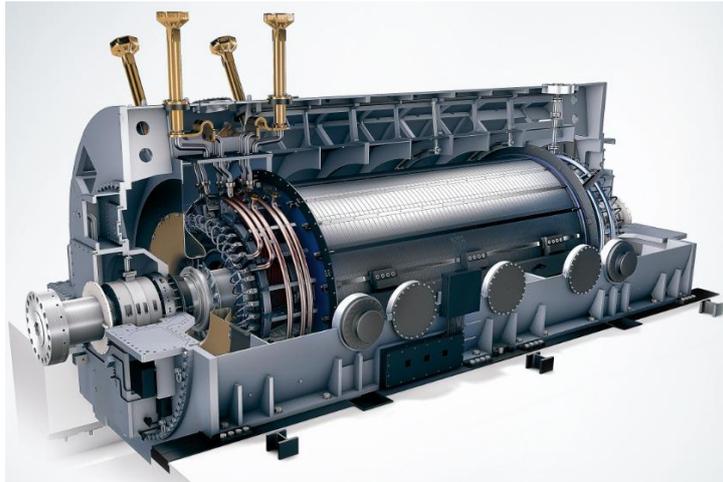
Figure 7.4: Siemens SGen5-3000W Generator Series

Substation

400kV System

The operation of the GIGA 400kV substation will be governed by the Power Conversion Control System, which manages switching, protection, and monitoring functions. The main components are the Generator Step Up Transformers, which export the generator power and the Generator Circuit Breakers which safely connect the output to the high-voltage grid.

Auxiliary Load system

The main components in the Auxiliary load supply circuit are the Auxiliary Transformers, the MV Switchgear, the LV Switchgear, the Motor Control Centres, the back-up generators and the DC & UPS systems.

Power Conversion Control

Power Conversion Control manages the safe operation of the EPP and its interfaces with other Level 01 & 02 Systems and the external environment. It is responsible for the interface with the transmission grid and managing power quality exported from the FPP.

Phase 2 and Phase 3

The EPP delivery timeline will align with the corporate milestones ensuring that the equipment is available to support commissioning and operation of GIGA when required.

The EPP Systems need to be operational to support commissioning from 2039. To facilitate this, in consideration of procurement and manufacturing timelines, the design cycle for the FPP will be aligned with the corporate roadmap outlined in CDR Section 20.

8. Fusion Power Plant Control

The digital architecture of the Fusion Power Plant (FPP) is founded on a clear and controlled separation between Information Technology (IT) and Operational Technology (OT), while still enabling the level of integration required for coordinated enterprise and operational performance. IT and OT represent two distinct domains within the enterprise architecture for manufacturing, each with its own purpose, technology stack and operational requirements. Although developments in modern industrial systems cause these domains to overlap more frequently, they must be treated as logically and technically separate. This separation is essential for cybersecurity, system reliability and operational safety.

The IT domain provides the foundational information systems and enterprise applications required to support business operations. These include systems like Enterprise Resource Planning, Document Management Systems, Access Control Systems, communication platforms and identity and security management. IT systems are responsible for planning, scheduling, analytics, collaboration, data storage and the overall business processes that support plant activities. They reside on an IT infrastructure consisting of servers, routers, switches and enterprise networking equipment and must enable secure data management, decision support and integration with operational systems.

The OT domain covers the systems responsible for controlling, monitoring and automating the physical processes of the FPP. This includes Supervisory Control and Data Acquisition systems (SCADA), Manufacturing Execution Systems (MES), Distributed Control Systems (DCS), Programmable Logic Controllers (PLC), sensors, actuators and industrial networks. OT systems interact directly with the physical world, enabling the safe and reliable operation of critical subsystems such as the Stellarator, Tritium Fuel Cycle, Power Grid Export systems, auxiliary systems and safety related systems. They must provide deterministic, real time performance and maintain process integrity under all operating conditions.

The MES layer, as described in the ISA95 standard, plays a key role in bridging IT and OT. MES is not a single product but a conceptual framework that defines functional domains, data exchanges and responsibilities connecting enterprise management with operational control. It ensures alignment between production activities, scheduling, quality, maintenance and inventory processes. In the architecture, the MES layer is positioned in the crossover area, often considered part of the OT domain because of its operational responsibilities and role in coordinating execution.

The design of the overall architecture must ensure that IT and OT can evolve at different speeds while maintaining stable interfaces and secure data exchange. The pace of innovation in IT is significantly higher than in OT, which requires an architectural approach that focuses on functional requirements, modularity and change resilience rather than specific technology choices. This avoids premature technology lock-in and supports the long operational lifecycle of a fusion power plant. The architecture must therefore support interoperability, strict segmentation, controlled interfaces and robust cybersecurity in line with IEC 62443 requirements.

Ultimately, the objective of the IT and OT architecture is to enable secure, reliable and scalable digital operations across all levels of the facility. It ensures that enterprise

information systems can operate independently from mission critical control systems while still providing the necessary data exchange to support analytics, reporting, diagnostics and decision making. At the same time, OT systems must maintain the deterministic behaviour required for plasma control, safety interlocks and plant operation, supported by a hardened infrastructure designed for high availability, redundancy and long term maintainability.

IT Systems and infrastructure

IT systems support planning, data management, analytics, collaboration and identity management. They provide secure communication, ensure data availability, support cloud connectivity and enable integration with OT through controlled interfaces.

The IT infrastructure provides network services, compute, storage and backup capabilities. It supports high availability and redundancy and enables internet connectivity with secure access. Key components include enterprise applications, communication tools, analytics platforms, cybersecurity tools, servers and virtualization platforms.

Design considerations include change resilience, scalability, security, reliability and compliance with ISO and GDPR requirements. The IT architecture interfaces with OT using firewalls, DMZ structures and controlled communication policies.

OT Systems and infrastructure

OT systems are responsible for the real time monitoring and control of the FPP. They support subsystems including the Stellarator, the Tritium Fuel Cycle, Power Grid Export, auxiliaries and safety related systems. OT includes SCADA, MES, PLCs, DCS, HMIs, industrial networks, sensors and actuators.

The OT infrastructure must ensure deterministic behaviour, real time performance, redundancy and high availability. It operates independently from IT while enabling controlled data exchange where required.

The architecture is based on PERA (Perdue Enterprise Reference Architecture) Level 0 to Level 3 segmentation and applies strict security measures using the IEC 62443 zone and conduit model. OT infrastructure may be fully on premises and remote vendor access restricted to secured jump servers.

Using MQTT (Message Queue Telemetry Transport) and UNS (Unified Namespac)based designs support high speed and high volume data exchange while contributing to a loosely coupled architecture as a basis for a change resilient ecosystem.

State of the art and Technology assessment

The current technological environment relevant to the FPP is defined by fast developments in IT and OT. Networking and infrastructure continue to advance toward higher availability, software defined capabilities and next generation wireless technologies. Cloud and edge computing are increasingly integrated into industrial environments, and cybersecurity practices incorporate Zero Trust principles, SASE and XDR. Data processing relies on high speed streaming technologies such as MQTT, Apache Kafka and Flink, while emerging technologies like Digital Twins and XR support future operational use cases.

The Technology Assessment shows that IT infrastructure, cloud platforms, virtualization, networking and most cybersecurity controls are highly mature. ICS technologies such as SCADA, PLCs and DCS are fully established and widely deployed. Other areas such as OT cybersecurity, Digital Twins and AI based predictive maintenance are less mature but progressing. Smart sensors and IIoT exhibit mixed maturity, especially when combined with radiation hardened components, where integration, communication resilience and cost remain significant challenges.

9. Site Selection

The selection of a suitable site for the GIGA Fusion Power Plant (FPP) is done by considering the site selection criteria applied for the international tokamak fusion experiment ITER, now under build in Cadarache/France. These criteria are following IAEA rules for the selection of nuclear installations.

These uniform site selection criteria can be categorized as:
- Global categories, where the data are stored in global databases, such as:
  - Energy and Electrical power
  - Heat sink - Water cooling and waste heat
  - Land - Geological, seismological, meteorological site conditions
- Special local features
  - Transport and Shipping
  - Infrastructure, Buildings
  - External Hazards and Accident scenarios.
- Licensing as well as Tritium handling and disposal facilities

1st step of site selection

In a first step the 3 global categories were investigated in the framework of a contract with the TU-Munich Chair of Renewable and Sustainable Energy Systems. As part of the contract, 7 countries in Europe (Germany, France, Italy, Spain, Netherland, Czech Republic, Denmark) were examined regarding possible sites for an FPP. The report considers 24 parameters with different acceptance levels that are applied to a 100 m x 100 m grid, resulting in 1 or 0, i.e. is candidate area or not. If all parameters are 1, the investigated area is taken as possible site. The lower limit for the size of a site was taken as 0.6 km^2 or 60 ha, a value that is typical for a fossil or nuclear power plant. One critical point is the lower value of 60 ha for the minimum area size that is too low for a fusion power plant due to additional infrastructure like tritium handling and the larger size of the Stellarator-building. Restricting the possible size to a higher value, e.g. 120ha reduces the number of possible sites moderately, as shown inTable 9.1.

Min. area size / ha	60	80	100	120	140
Number of sites / %	100	89	81	75	69
No. of FPPs (120 ha)	4507	4438	4372	4311	4241

Table 9.1: Reduction of available sites with increased minimum size of the FPP. For comparison the (theoretical) number of FPPs that could be built at the available sites is shown. This number falls by a lesser extent due to the fact that only small areas are ignored.

Next steps of site selection

In the following the focus is on special local features, the building site and transport conditions. The transport conditions might be a showstopper for certain regions due to the size and the weight of GIGA components.

Area requirement, building site

The required building site depends on the local situation, in particular on the amount of infra-structure that can be reused from existing and switched-off power plants. Also, the need for on-site manufacturing and assembly depends on the transport conditions. In the optimistic case, where an existing coal or fission reactor is replaced by GIGA an additional area of about 40 ha is sufficient. In reality at least 100 ha should be foreseen for the FPP.

Transport conditions

GIGA is a large device with a radius of the plasma centre of about 20 m and an outer cryostat diameter of 56 m. In addition, the weight of GIGA is in the order of 35 000 t. It is obvious that components like the cryostat and the vacuum vessel must be assembled on-site from pre-manufactured components.

The most critical components are the magnetic field coils because the manufacturing needs a lot of technological and manufacturing steps that should be done in external industrial units. The coils therefore determine the transport requirements. The weight of a single coil is 350 t. A major project of Gauss Fusion together with KIT-Karlsruhe in the framework of an BMFTR project is to qualify demountable superconducting coils for use in a FPP. Demountability relaxes the transport requirements because it allows to manufacture and test the demountable coils at industry premises and to transport the two parts of a single coil separately. Nevertheless, the size of the required transport box is (LxBxH) 11 m x 7 m x 6 m and requires a dedicated transport route. The "ITER Itinary" can be taken as reference due to comparable size and weight of transported components. Building the "ITER Itinerary" costs about 1 Mio Euro / km in total 110 Mio Euro paid by the local authority and the French government.

Summary

The site-selection study has equipped Gauss Fusion with a robust methodology and a comprehensive geospatial database for systematically assessing potential fusion plant locations across Europe. This framework enables the consistent, transparent, and evidence-based evaluation of any new site proposed by governments or partners.
This site survey is the basis for the dedicated site qualification process, considering local technical and social-economic parameters as well as regulatory rules.

The final site selection will be completed by the end of 2027 (see Figure 9.1).
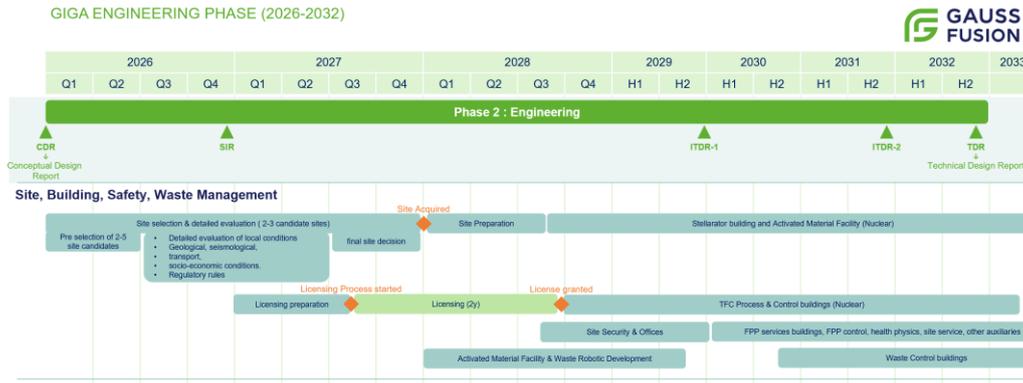
Figure 9.1: Timeline of site selection and the construction of the buildings

10.Buildings

Any power plant requires buildings for the housing and protection of personnel and equipment; for confinement of material in the event of an accident; and for security. The general power plant layout is shown in Figure 1.3. Many of these buildings will be of standard construction (conforming to relevant codes and standards) but considerations regarding earthquake stability and other risks must be applied; some require specialised construction based on the designs and operation of internal systems (e.g. fuel cycle building, AMF); some will be tritium confinement barriers and require related ventilation systems. The stellarator building, attached to the assembly hall and AMF, requires cranes for lifts of up to 100s of tonnes during assembly. A fusion power plant needs a strategy to remove in-vessel components to a facility which can separate components according to material and activation, detritiate them, and move them to storage or recycling appropriately. This will continue through the plant lifecycle and culminate in the decommissioning and disposal of the device itself, also activated (although to a lower level than in-vessel components) and requiring detritiation.

The buildings will conform to existing codes and standards. Two particular special cases are the fuel cycle building, which must be engineered as a confinement and accountancy barrier, and the stellarator building, which will be a large structure conforming to nuclear building standards as a radiation and confinement barrier, with additional tritium confinement requirements. A third case concerns waste storage for intermediate-level irradiated material, following detritiation and separation in the hot cell. Intermediate level waste (ILW) storage requirements are defined in standards; in this case there are tritium outgassing considerations which means the waste storage must also be connected to the tritium handling facilities.

Some specific considerations apply to:

Stellarator building: This building will require: a pit with bioshield lid for the stellarator, which provides vertical access to cranes for maintenance. Heavy-lift cranes for assembly and maintenance, and an assembly area where sections of the device can be built up before insertion into the pit. The building provides multi-level access to the stellarator from various

sides to allow provision of services, but services for cryogenics, water cooling, plasma fuelling and exhaust, diagnostics and control systems, etc. must also be provided and maintained.

The pit containing the stellarator is constructed of nuclear concrete and acts as a bioshield to allow human access to areas outside it. The building itself is airtight and operates at a slight negative pressure so that it can function as a tertiary tritium containment; it must also therefore be equipped with air monitoring systems and connected to the fuel cycle system for tritium removal if necessary. The building further conforms to nuclear regulatory requirements regarding e.g. earthquake and aircraft strike safety.

Access is provided through the building to the Active Material Facility (AMF): during maintenance the bioshield is opened and access to the vessel ports is gained. Casks are moved by crane from the hot cell to dock with the vacuum vessel to perform maintenance and component removal, preserving a tritium barrier at all times. The casks are then moved back through the building to the AMF. During these operations, interlocks exist to prevent human access for both radiation and crane/robotics operational safety.

TFC process facility building: Purpose-built facility for housing of the fuel cycle process elements. Requirements include controlled and filtered ventilation with monitoring to prevent tritium leakage to environment; detectors internally for personnel protection; fire prevention system and design to deal with possible hydrogen fires; operation at slight negative pressure to prevent T leakage; personnel shelters in case of fire or leak. This facility also provides tritium control services to the rest of site and requires integration with site layout. Most tritium on-site is stored here; this means e.g. earthquake and aircraft strike safety considerations.

Active Material Facility: This is the robotics and waste-handling facility, attached to the stellarator building, where material removed from the stellarator is brought for inspection, separation, detritiation, and movement to storage. It must also maintain and store the casks between maintenance intervals. For the most part, due to activated waste, tritium, and robotic activity, it will be a non-human accessible zone. Incoming components will be removed from the casks, deconstructed to separate waste into different streams for storage or reprocessing, and detritiated. If breeder pebble reprocessing is carried out on-site, this will be part of the AMF building. Once processed, waste is removed to the Waste Buildings for long-term storage, so that the AMF is ready for the next maintenance cycle – this means that there is a 4.5 yr period for processing of one set of in-vessel components. Due to the presence of active material, nuclear regulations and personnel monitoring apply to this building; tritium removal and monitoring applies to the air systems, and negative pressure will be required to prevent leakage to the environment. The AMF includes materials characterization facilities for assessing the condition of removed components and surveillance samples from inside the reactor.

Buildings start being constructed shortly after the site selection is complete and the site is secured, starting with site security and offices, but shortly starting on the fuel cycle buildings and stellarator buildings; large, specialist, and complex structures which will also need to be ready for delivery of components and start of assembly operations by the early- to mid-2030s. Given delivery lead times and assembly times, the stellarator building and gyrotron halls should be ready to start receiving components at least five years before planned operations for sequential testing, installation, assembly, etc.

Following end-of-life reactor shutdown, non-nuclear facilities can be decommissioned. The fuel cycle facility will continue to operate to provide detritiation services during decommissioning and decontamination of stellarator components. Final ILW will either continue to be stored on-site for an extended period, or can be removed to more specialized storage or recycling facilities if they are available at that point.

11.Safety Systems

Nuclear Safety & Regulatory Overview

The GIGA safety principles and the approach to developing and operating the Safety Systems relate to the safety and environment risks that are present for a Fusion based system at the relevant operational and waste ratings. Fusion is inherently safer than Fission, given the lower potential to develop mid and high-level nuclear waste and the fail-safe nature of the fusion reaction itself. For GIGA, one of the Level 01 architectural systems is the Safety Systems. The Safety Systems are technology systems that ensure safe operation of the FPP; protecting equipment, personnel, public & the environment through all stages of development and operational scenarios. This system has several Level 02 sub-systems, which are further detailed in Chapter 19 of this report.

Safety Systems and the safety philosophy are instrumental in enabling the licensed development and operation of GIGA with the relevant regulatory authorities. GFG are adopting a best-in-class approach to development of its Safety Case and implementation of risk management processes, informed by codes and standards in equivalent industries, which may assist in development of appropriate Nuclear Fusion Codes and in the regulatory process for authorities licensing GIGA. The following outlines considerations in developing the Safety Case and Safety Systems.

Safety objectives and principles

The top-level safety objectives for GIGA are:

- To protect workers, the public, and the environment from harm
- To ensure that safety functions are maintained in all situations (normal, incidental and accidental)
- To ensure that in normal operation exposure to hazards within the facility, and release of hazardous material from the facility, is controlled: minimized to be As Low As Reasonably Achievable (ALARA) and certainly kept below prescribed limits
- To ensure that the likelihood of incidents and accidents is minimized, that their consequences are bounded, and that resulting exposure of workers is bounded
- To apply a safety approach that limits the hazards from design basis accidents (DBA) and beyond design basis accidents (DEC) such that in any event there is no need for counter measures to civil populations outside the site boundaries
- And to minimize radioactive waste hazards and volumes.

To satisfy the above objectives, well-established safety principles shall be applied:

- Defence in Depth (DiD) with multiple independent lines of protection and barriers.

- ALARA for radiological risks (also applied to non-ionising hazards such as RF and magnetic fields where relevant).
- Passive safety wherever achievable, reducing reliance on active power or human intervention.

The defence-in-depth principle is applied to the safety design of GIGA, defined in 5 levels:

Level	Objective	Means
1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
2	Control of abnormal operation and detection of failures	Control, limiting- and protection systems and other surveillance features
3	Control of accidents within the design basis	Engineered safety features and accident procedures
4	Control of serious plant conditions, including prevention of accident progression and mitigation of the consequences of accidents	Complementary measures and accident management, including monitoring of plant conditions
5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

Table 11.1

Safety Functions

Safety functions are defined as specific actions that prevent or mitigate against radiological and other hazards. At the top level, three Fundamental Safety Functions are defined for GIGA:

- Confinement of radioactive and hazardous materials
- Limitation of exposure of workers to radiation and toxic materials
- Decay heat removal.

Confinement and tritium management

The confinement strategy implements two systems of barriers.

The first confinement, placed as close as practicable to the inventory, prevents mobilization and spread of hazardous material within plant areas (protecting personnel).

The second confinement prevents or strongly limits any release to the environment should the first be compromised (protecting the public).

Both include one or more static barriers and/or dynamic systems. During maintenance, temporary relaxation of barriers may be justified if the mobilizable inventory is reduced and risk remains acceptably low.

Safety Systems description

Concept Architecture

A systems architecture has been developed for the GIGA Safety Systems through which the safety objectives and functions can be managed and realised. The GIGA Safety Systems architecture is as follows:

Figure 11.1 Safety Services architecture

Nuclear Safety

GIGA requires radiation protection and tritium handling. Tritium must be carefully contained to prevent environmental release. Shielding and robust containment structures are designed to protect workers and the public from neutron and gamma radiation.

Overall, nuclear safety in GIGA relies on passive safety principles - designs that make serious accidents physically implausible. Through inherent stability, small fuel quantities in comparison with fission, and material choices, fusion promises a clean and fundamentally safe form of nuclear energy.

The system management of the GIGA project foresees to consider nuclear safety at the earlier stage (conceptual design review). The safety requirements have been defined and are detailed in the CDR.

Plant Safety

Safety in a fusion installation is based on the inherent characteristics of fusion reactions and on robust engineering design. Unlike fission reactors, fusion systems do not rely on a chain reaction; if the conditions for plasma confinement or temperature are disturbed, the reaction stops immediately. This self-limiting nature makes severe accidents physically implausible.

The fuel inventory is very small - typically only a few grams of deuterium and tritium - so there is no potential for large-scale energy release. The main radiological concerns come from neutron radiation during operation and from the handling of tritium, a radioactive hydrogen isotope. These are controlled through shielding, containment, and active monitoring systems designed to prevent any significant exposure or release to the environment.

The structural materials of the plant may become activated by neutron bombardment, but by using low-activation alloys, the resulting radioactivity decays to safe levels within a few decades, avoiding the long-term waste challenges of fission.

Health Services

Health and safety systems are designed to protect workers, the public, and the environment from potential hazards associated with radioactive materials and nuclear operations. These systems combine engineering controls, administrative procedures, and emergency preparedness measures to ensure safe and reliable operation under all conditions.

At the core are radiation protection systems, which monitor and limit exposure to ionizing radiation. Shielding, controlled access zones, personal dosimetry, and continuous monitoring of air and water ensure that exposure remains well below regulatory limits.

On the human side, occupational health and safety programs include rigorous training, protective equipment, controlled work practices, and strict adherence to procedures. Continuous safety culture promotion ensures that every individual is aware of their role in maintaining safe operations.

Finally, emergency preparedness - including alarms, evacuation routes, and coordination with local authorities - ensures readiness to respond effectively to any unlikely incident.

Environmental Safety

Environmental protection in a fusion installation is built on the principle of minimizing any impact on people and the environment during normal operation and in the event of an incident. Because fusion reactions are inherently clean - producing no greenhouse gases or long-lived radioactive waste - the environmental protection system mainly focuses on containment, monitoring, and waste management.

The primary containment systems ensure that all radioactive materials, especially tritium, remain confined within sealed process areas. Advanced ventilation, filtration, and detritiation units capture and recover any tritium that might escape from the fuel cycle systems, preventing its release to the environment.

Personnel Protection

Personnel protection focuses on ensuring the safety and health of all workers who operate, maintain, and support the facility. Since fusion does not produce a chain reaction or large-scale radioactive waste, the main safety concerns are radiation exposure, tritium handling, and general industrial hazards.

The first line of defense is radiation protection. Shielding structures - made of concrete, steel, and specialized materials - absorb neutron and gamma radiation generated during plasma operation. Access to areas near the reactor is restricted during operation, and personnel entry is allowed only after radiation levels have fallen to safe limits. Workers wear personal dosimeters to continuously monitor exposure, ensuring doses remain far below regulatory limits.

Tritium protection systems safeguard workers from potential contamination. The fuel cycle systems are fully enclosed, with leak detection, ventilation, and detritiation units maintaining clean air. Strict handling procedures, protective clothing, and continuous air monitoring prevent inhalation or contact with tritium.

Safety process and analysis methodology

Safety requirements are derived from safety objectives through a structured process: identification of radioactive source terms and stored energies; application of DiD and ALARA; definition of Systems-Structures-Components (SSCs) Safety Importance Class (SIC) and interfaces; and preparation of the licensing documentation. A graded approach reflects fusion-specific hazards (notably tritium and activation) that are generally lower than fission, while maintaining robust margins.

Event categorization and selection:

Design Basis Accidents (DBA) are conservatively analysed and assigned frequency categories (I–IV).

Design Extended Conditions (DEC) are built on DBA with aggravating failures and are analysed with realistic/best-estimate assumptions to demonstrate absence of cliff-edge effects and to establish ultimate margins.

Reference Events and rules:

For safety related components, main Postulated Initiating Events (PIE) are analysed (e.g. Lost of Vacuum Accident (LOVA), Lost of Coolant Accident (LOCA), Lost of Flow Accident (LOFA), Lost of Off-Site Power, Cryoline break, magnet event, plasma event, tritium leakage, etc.).

Only SIC-classified SSCs may be credited; limiting parameters (e.g., barrier leak rates) become design requirements. Loss of offsite power (non-SIC) must be assumed for a period of up to 32 hours, if this has an adverse effect on accident progression. Consequences are evaluated using conservative dispersion/dose modelling.

SADL and model quality:

A validated Safety Analysis Data List (SADL) underpins analyses.

Computer codes and data libraries are verified and qualified for their domains of application.

Lines of defence and practical elimination:

Risk management employs strong and moderate technical and administrative lines of defence. Accident sequences leading to early or large releases are "practically eliminated" by design provisions, probabilistic arguments where justified, and reinforced procedures; stress tests assess resilience to extreme external events.

System-level safety highlights

Vacuum Vessel (VV): First confinement barrier for in-vessel hazards; must control pressurization under in-vessel LOCA/LOVA. Neutrons shielding and hydrogen risks containment; penetrations maintain Ultra High Vacuum (UHV) and confinement.

Plasma: Major source of neutrons and electromagnetic radiations. Diagnostics and the plasma control system shall detect off-normal behaviour and trigger protective actions. Heating System windows/feedthroughs across barriers are leak-tight; failures include beam misalignment, window or cooling failure with potential VV ingress.

Magnet system: Safety-significant; quench protection to safely dissipate stored energy and prevent arcs/fire. Structural integrity under EM transients; robust insulation and QA; controlled energy discharge paths.

Tritium Breeding Blanket (TBB): Maintains pressure/leak-tight boundaries between coolant and VV, allowing for the monitoring of tritium inventory and permeation, and ensuring that penetrations and interfaces remain leak-tight during both normal operation and accidents.

Primary Heat Transfer Systems (PHTS): Provide heat removal and confinement; design for rapid leak detection, segmentation/isolation near the vessel, pressure relief to qualified volumes, and jet/pipe-whip protection.

Cryostat: Provides magnet vacuum and structural support; numerous openings require reliable seals to prevent air ingress or helium escape.

Fuel cycle: Enhances fuel efficiency and simplify tritium handling; prevention of leaks and radiological protection across all sub-systems.

Bio shield: Protects workers and environment; resists fire/explosion loads.

Remote Maintenance (RM): Enables maintenance without human entry in high-dose zones; cask strategy, shielding, and contamination control; recovery strategies for failed tools; manage potential fire/electrical hazards and radioactive releases during RH.

Interfaces, classification, codes & standards

Safety is a transversal function. Safety systems interface with all nuclear-building systems and site services (incident response, health physics). Safety Important Class (SIC) is assigned to SSCs credited in analyses, with relationships to other classifications (seismic, quality, vacuum). A Global Interface Matrix tracks inter-system dependencies.

The licensing set will be grounded in international frameworks , adapted by a graded approach for fusion. Project documents define general safety objectives, safety principles, high-level system safety requirements, accidental analysis approach, and applicable codes and standards; these will be refined during the Engineering Phase with regulator engagement.

Reliability and operational readiness

Safety-critical functionality targets continuous availability (with redundancy where required) and alignment to the planned operating/maintenance cycle. The programme provides for emergency coordination with external responders, health physics monitoring, regulatory inspections/audits, and end-of-life decommissioning for greenfield release. Material selection supports dose minimisation and waste objectives.

Forward work to Engineering Phase

GIGA's safety and regulatory approach is built on proven nuclear safety principles applied with a graded, fusion-appropriate philosophy. The two-tier confinement strategy, rigorous tritium management, robust safety analysis framework, and system-level provisions collectively aim to demonstrate that safety functions are maintained in all states, consequences are bounded without off-site protective actions, and occupational and

environmental exposures remain ALARA. The Engineering Phase will translate these principles into detailed requirements, analyses, and evidence for the licensing case.

12. Fusion Materials

The GIGA materials strategy is built on a pragmatic, near-term realisation philosophy: deliver a licensable, manufacturable, and industrially supported materials suite rather than pursue speculative innovation. GIGA adopts existing, codified alloys and ceramics—notably tungsten, Grade 91 steel, Li_4SiO_4–Li_2TiO_3 breeder pebbles, lead neutron multiplier, and 316LN stainless steel—each with established production chains and regulatory familiarity. This "evolutionary, not revolutionary" paradigm enables construction readiness and reduces risk while maintaining flexibility for later upgrades to low-activation variants. In-Vessel Materials Architecture: GIGA's in-vessel configuration follows a radially graded design optimised for thermal, neutronic, and safety performance:

- **Tungsten armour** protects against plasma heat and erosion.
- **Grade 91** ferritic–martensitic steel forms the primary structural backbone of the blanket and internal supports.
- **Li_4SiO_4–Li_2TiO_3 pebbles** (KALOS process) serve as solid breeders
- **Lead (Pb)** functions as the neutron multiplier and secondary heat sink.
- **316LN** stainless steel provides the vacuum vessel boundary.

Multiple coolant circuits (helium and water) manage heat transport, and the system is modular to permit staged replacement within ~5-year maintenance cycles.

Rational for Key materials Selection

- **Tungsten**: Proven ITER baseline with high thermal conductivity, low tritium retention, and industrial manufacturing maturity (VPS/HIP).
- **Grade 91 Steel**: Codified under ASME Div. 5 and RCC-MRx, immediately available at scale, and cost-efficient compared to EUROFER97. Waste-classification analyses show no meaningful disposal-cost difference for the GIGA environment, making Grade 91 the rational near-term choice. Similarity in manufacturing and joining techniques, and materials properties, allow seamless replacement with reduced-activation steels when available.
- **Li_4SiO_4–Li_2TiO_3 Breeder Pebbles**: Industrially reproducible via KALOS melt-jet process; mechanical integrity, controlled porosity, and optimised tritium release (500–800 °C).
- **Lead Multiplier**: Mature, re-meltable material providing effective neutron multiplication in the 350–550 °C range consistent with Grade 91 operating limits.
- **316LN Vacuum Vessel**: Fully licensed material ensuring compatibility with nuclear codes and long-term structural integrity.

This combination yields a high-TRL, manufacturing- and code-ready material selection roadmap.

Technology Readiness and Codification

All key materials are at TRL 4–9 and have corresponding codification pathways: tungsten (ITER-tested), breeder pebbles (EUROfusion design guidelines), lead (ASME materials basis), Grade 91 (fully codified), and 316LN (licensed nuclear-grade). This ensures immediate applicability under regulatory frameworks while maintaining room for future upgrades.

Material Substantiation Strategy

The GIGA Substantiation Plan integrates pre-operation and in-operation qualification:

- **Pre-operation:** Surrogate neutron-irradiation and high-heat-flux campaigns (DONES, HFIR) to characterise helium effects, embrittlement, corrosion, and joining integrity, as well as testing of breeder performance in facilities such as LIBRTI,
- **In-operation:** Surveillance and retrieval programmes embedded within blanket and divertor modules to monitor irradiation and microstructural evolution.
- **Regulatory Integration:** All data will be formatted for RCC-MRx and ASME Div. 5 inclusion, establishing design-allowable properties and enabling licensing.

A stepwise approach guarantees that materials reach TRL ≥ 7 in the first GIGA operational phase.

Lifecycle and Sustainability

All in-vessel components are designed for controlled replacement cycles—plasma-facing and blanket modules at ~5 FPY, vacuum vessel ≥ 40 years. Activation analyses has been performed assessing potential sustainability route through re-use and recycling. A closed-loop concept directly supports Gauss Fusion's sustainability and cost-reduction goals.

Outlook

GIGA's materials concept establishes an industrial, licensable, and evolutionary pathway toward fusion power. By prioritising codified materials with proven production and qualification routes, it secures near-term feasibility while still enabling the progressive introduction of advanced, low-activation solutions as they reach demonstrable maturity. A key example is the selection of Grade 91 for a first-of-a-kind implementation: an intentional compromise that accounts for all downstream implications, including waste management, while maintaining a clear strategy for long-term substitution or enhancement.

Central to this approach, the Gauss Materials programme evaluates supply-chain robustness, technology readiness, and manufacturability, supports engineering design with material performance data, and collaborates on neutronics assessments to ensure tritium breeding, shielding and activation behaviour remain aligned with regulatory and operational requirements. Together, these elements reinforce the broader fusion-to-industry transition: leveraging established technologies to form a reliable foundation for Europe's first power-producing stellarator-based fusion system.

13.Acronyms

Acronym	Meaning	Acronym	Meaning
0/1/2/3D	0/1/2/3 Dimensional	AC	Alternating Current
ACB	After Cooler Box	ACS	Access Control System
AFP	Automated Fiber Placement	AGHS	Active Gas Handling System
AI	Artificial Intelligence	AISI	American Iron And Steel Institute
ALARA	As Low As Reasonably Achievable	ALARP	As Low As Reasonably Practicable
AN	Active Neutral	APB	Active Permeation Barrier
ARC	Affordable, Robust, Compact Tokamak	ASME	American Society Of Mechanical Engineers
BDBA	Beyond Design Basis Accidents	BMBF	Bundesministerium Für Bildung Und Forschung
BOM	Bill Of Materials	BoP	Balance Of Plant
BPVC	Boiler And Pressure Vessel Code	BSI	British Standards Institution
CAD	Computer-Aided Design	CADD	Computer-Aided Design And Drafting
CANDU	Canada Deuterium Uranium	CAPEX	Capital Expenditure
CB	Circuit Breaker	CDR	Conceptual Design Review
CFD	Computational Fluid Dynamics	CFQS	Chinese First Quasi-Symmetric Stellarator
CFT	Call For Tender	CH	Cryogenic Helium
CHF	Critical Heat Flux	CICC	Cable-In-Conduit Conductor
CLIQ	Coupling-Loss Induced Quench	CN	Cryogenic Nitrogen
CONOPS	Concept Of Operations	CORC	Conductor On Round Core
CO2	Carbon Dioxide	CS	Central Solenoid
CSS	Central Safety System	CTAP	Thermal Cycling Absorption Process
CTH	Compact Toroidal Hybrid	CTS	Collective Thomson Scattering
CZ	Containment Zones	DBA	Design Basis Accidents
DC	Design Controls / Direct Current	DCLL	Dual-Coolant Lithium Lead
DCS	Distributed Control System	DD	Diamond Detector
DEC	Design Extended Condition	DIII-D	Doublet III-D
DIN	Deutsches Institut Für Normung	DIPAK	Deuterium Infrastructure Project At KIT
DIV	Divertor	DIVGAS	Divertor Gas
DMS	Document Management System	DOF	Degrees Of Freedom
DPA	Displacements Per Atom	DR/DDR	Decommissioning/Disposal Readiness Review
DTE1,2,3	Deuterium-Tritium Experiment 1,2,3	DTT	Divertor Tokamak Test
EB	Electron Beam	ECCD	Electron Cyclotron Current Drive
ECE	Electron Cyclotron Emission	ECRH	Electron Cyclotron Resonance Heating
EDG	Emergency Diesel Generator	EL	Electrical
ELM	Edge-Localized Mode	EMI	Electromagnetic Interference
EN	European Norm	ENI	Ente Nazionale Idrocarburi
EOL	End Of Life	EPC	Engineering, Procurement, And Construction
EPP	Electrical Power Plant	EPPS	Electrical Power Plant System
EPR	Enterprise Resource Planning	EPS	European Physical Society
ERP	Enterprise Resource Planning	EU	European Union
FAT	Factory Acceptance Test	FCTF	Fuel Cycle Testing Facility
FDU	Fast Discharge Unit	FEA/FEM	Finite Element Analysis / Method
FIPACT	Fusion-Fission Activation and Transmutation	FISPACT	Fusion-Fission Activation and Transmutation
FMEA	Failure Mode and Effects Analysis	FMECA	Failure Modes, Effects, and Criticality Analysis
FOAK	First Of A Kind	FPP	Fusion Power Plant
FPY	Full-Power Year	FSOM	Full Shutdown Operating Mode
FW	First Wall	FZJ	Forschungszentrum Jülich
GA	Gas Active	GC	Geometrical Constraint
GCB	Generator Circuit Breaker	GDPR	General Data Protection Regulation
GEM	Gas Electron Multiplier	GFG	Gauss Fusion
GI	Gas Inactive	GIGA	Gauss Fusion Fusion Power Plant
GP	Ground Plate	GS	Gravity Support
GSSR	Generic Site Safety Report	H&MB	Heat And Mass Balance
H3AT	Hydrogen-3 Advanced Technology	HAZID	Hazard Identification
HAZOP	Hazard And Operability Study	HCPB	Helium-Cooled Pebble Bed

HEAT	Hydrogen Energy Advanced Technology		**HELIAS**	Helical-Axis Advanced Stellarator
HEP	High-Energy Physics		**HHFT**	High Heat Flux Testing
HHLT	High Heat Load Testing		**HMI**	Human-Machine Interface
HOPG	Highly Oriented Pyrolytic Graphite		**HP**	High Pressure / Health Physics
HRSG	Heat Recovery Steam Generator		**HSX**	Helically Symmetric Experiment
HTO	Tritium Oxide		**HTS**	High-Temperature Superconductor
HV	High Voltage		**H2O**	Water
I&C	Instrumentation And Control		**IAEA**	International Atomic Energy Agency
ICD	Interface Control Document		**ICRH**	Ion Cyclotron Resonance Heating
IGCT	Integrated Gate-Commutated Thyristor		**ILW / LLW**	Intermediate-Level / Low-Level Waste
IM	Interface Matrix		**INR**	Institute for Neutron Physics and Reactor Technology
IO	Input/Output		**IP**	Intermediate Pressure / Intellectual Property
IST	Integrated Systems Testing		**IT**	Information Technology
ITDR-1	Intermediate Technical Design Review 1		**ITDR-2**	Intermediate Technical Design Review 2
ITEP	Institute For Technical Physics		**KFEU**	Korea Fusion Energy Unit
KIT	Karlsruhe Institute of Technology		**KPI**	Key Performance Indicator
LA	Liquid Active		**LAN**	Local Area Network
LCFS	Last Closed Flux Surface		**LF**	Lift Factor
LHD	Large Helical Device		**LHE**	Liquid Helium
LI	Liquid Inactive		**LIBRTI**	Lithium Breeding Blanket R&T Infrastructure
LOCA	Loss Of Coolant Accident		**LOFA**	Loss of Flow Accident
LOHS	Loss of Heat Sink Accident		**LTS**	Low-Temperature Superconductor
LV	Low Voltage		**MASCOT**	Manually Assisted Slave Controlled Tool
MCC	Motor Control Centres		**MCNP**	Monte Carlo N-Particle
MCR	Mission Concept Review		**MES**	Manufacturing Execution System
MHD	Magnetohydrodynamic		**MLI**	Multi-Layer Insulation
MOMS	Manufacturing Operations Management System		**MQTT**	Message Queuing Telemetry Transport
MTBF	Mean Time Between Failures		**MTTR**	Mean Time To Repair
NASA	National Aeronautics and Space Administration		**NBI**	Neutral Beam Injection
NDT / NDE	Non-Destructive Testing / Evaluation		**NF**	Neutron Flux
O&M	Operations And Maintenance		**OEM**	Original Equipment Manufacturer
OPEX	Operational Expenditure		**ORR**	Operational Readiness Review
P&ID	Piping And Instrumentation Diagram		**PCD**	Pre-Conceptual Design
PCS	Power Conversion System		**PERA**	Purdue Enterprise Reference Architecture
PFD	Product Flow Diagram		**PHTS**	Primary Heat Transfer System
PIE	Postulated Initiating Event		**PLC**	Programmable Logic Controller
PM	Preventive Maintenance		**PPP**	Public-Private Partnership
PSDR	Plant Safety Requirements Document		**PWR**	Pressurized Water Reactor
Q	Quarter		**QA/QC**	Quality Assurance / Quality Control
QD	Quench Detection		**QI**	Quasi-Isodynamic
QP	Quench Protection		**RAFM**	Reduced Activation Ferritic-Martensitic
RAMI	Reliability, Availability, Maintainability, Inspectability		**RCC-MRx**	Design Rules for High-T Nuclear Installations
REBCO	Rare-Earth Barium Copper Oxide		**RF**	Radiofrequency
RGA	Residual Gas Analyzer		**RH**	Remote Handling
RHR	Remote Handling Robotics		**ROM**	Rough Order of Magnitude
RP	Resistive Plate		**RPN**	Risk Priority Number
RT	Radiographic Testing		**RTD**	Resistance Temperature Detector
S&C	Standards And Codes		**S/FTP**	Shielded Foiled Twisted Pair
SASE	Secure Access Service Edge		**SAT**	Site Acceptance Test
SCADA	Supervisory Control And Data Acquisition		**SCI**	Stellarator Control Infrastructure
SDC	Structural Design Criteria		**SDR**	System Definition Review
SE	Systems Engineering		**SGS**	Steam Generation System
SHTS	Secondary Heat Transfer System		**SIC**	Safety Important Component
SIR	System Integration Review		**SLD**	Single-Line Diagram
SOA	State Of the Art		**SPARC**	Smallest Possible ARC
SQD	Slow Quench Detection		**SR**	Safety-Related
SRR	System Requirements Review		**SSAB**	Scientific And Strategic Advisory Board
SSC	Structure, System, Or Component		**SST**	Steam Turbine Series

ST	Steam Turbine / Structural	**STEP**	Spherical Tokamak for Energy Production
T&A	Time And Attendance	**TA**	Technology Assessment
TBB	Tritium Breeding Blanket	**TBM**	Test Blanket Module
TBR	Tritium Breeding Ratio	**TCAP**	Thermal Cycling Absorption Process
TCC	Toroidal Coil Circuit	**TCV**	Tokamak A' Configuration Variable
TDR	Technical Design Review	**TE**	Tokamak Energy
TES	Tritium Extraction System	**TF**	Toroidal Field
TFTR	Tokamak Fusion Test Reactor	**TIG**	Tungsten Inert Gas
TIRTL	Tritium Research and Integrated Test Laboratory	**TMC**	Thermal Management Circuit
TRAVIS	Transient Visualization	**TRL**	Technology Readiness Level
TSTA	Tritium Systems Test Assembly	**TTE**	Tritium Transfer Experiment
UAT	Unit Auxiliary Transformer	**UHV**	Ultra-High Vacuum
UNITY-2	Upgraded National Integrated Tritium Infrastructure	**UNS**	Unified Namespace
UPS	Uninterrupted Power Supply	**USD / EUR**	Dollar / Euro
VA / VI	Vacuum Active / Inactive	**VAC**	Vacuum Alternating Current
VNS	Voluntary Neutron Source	**VPI**	Vacuum Pressure Impregnation
VPN	Virtual Private Network	**VV**	Vacuum Vessel
VVPSS	Vacuum Vessel Pressure Suppression System	**W7-AS**	Wendelstein 7-AS
W7-X	Wendelstein 7-X	**WAN**	Wide Area Network
WCCB	Water-Cooled Ceramic Breeder	**WCLL**	Water-Cooled Lithium-Lead
WEEE	Waste Electrical And Electronic Equipment	**WP**	Work Package
XDR	Extended Detection And Response		

14. Appendix A: CDR Table of Content