Technology Development Programme

Technology Mapping

2026 Series

Plasma Facing Components

Technology and Manufacturing

FUSION
FOR
ENERGY

Contents

Version history

VERSION	DATE	CHANGES
0.0	31/01/2026	First issue: input data for online workshop. Covers: 1. Introduction 2. The mapping process 3. Plasma Facing Components technology breakdown (draft) Other sections will be completed after the workshop.
1.1	18/03/2026	After the online workshop, incorporating the changes agreed to the technology map
2.0	09/06/2026	After the in-person workshop - Draft final report for comments by participants
2.1	30/06/2026	Final report for publication

Foreword

We are entering a new era for the fusion sector, marked by a significant acceleration in technology development. Academia, public research organisations and private actors now need to rise to the challenge and coordinate efforts to ensure that the community follows a common technology roadmap that clearly shows how to advance critical technologies for fusion from fundamental research to industrial application.

Fusion for Energy, a European hub for fusion technology, in close collaboration with EuroFusion, plays a significant role at the heart of the fusion ecosystem, identifying research and development opportunities for future fusion power plants, facilitating exchange of knowledge and fostering partnerships across the fusion community.

We are now proud to present the report on the Plasma Facing Components workshop, the result of a collaborative process involving nearly 200 experts from over 60 public and private companies. It will serve as a valuable resource for all interested economic operators seeking national, international, and private funding.

The insights gathered during the workshop have enabled the development of a solid basis for strategic planning, and we intend to build on the information in this report to sustain progress on the development of plasma facing components.

However, these efforts cannot rely on internal activities alone. Active engagement from all stakeholders will be essential. We therefore invite the community to contribute to this process and work together to accelerate the development of plasma facing components and fusion technologies in general.

Dr. Enrique García-Vidorreta

Fusion for Energy

Executive summary

The Plasma Facing Components (PFC) Technology Mapping Report 2026 is an initiative by Fusion for Energy (F4E) to accelerate the development of critical technologies for fusion power plants. Involving nearly 200 experts from 60+ public and private organizations, this report provides a comprehensive assessment of PFC technologies in Europe. It outlines current capabilities, identifies gaps and opportunities, and establishes a strategic roadmap to guide investments and R&D efforts across the fusion ecosystem.

Key Findings:

- 50+ technologies were identified and characterized across 5 primary domains:
    - **Armour and Advanced Materials** (e.g., high-purity tungsten, nanostructured tungsten, silicon carbide, ductile ceramics).
    - **Heat Sink Technologies** (e.g., swirl tubes, additive manufacturing, microchannel heat exchangers, alternative coolants).
    - **Bonding Technologies** (e.g., Hot Isostatic Pressing, FAST diffusion bonding, transient liquid phase bonding).
    - **Maintainability** (e.g., remote handling, reversible pipe joints, armour repair techniques, embedded erosion monitoring).
    - **PFC Design & Modelling** (e.g., monolithic HIPed panels, liquid metal walls, lifecycle prediction models).
- Each technology was evaluated for Technology Readiness Level (TRL), criticality, development needs, and European capabilities, with results presented in visual dashboards for easy reference.

Europe’s strength as a global leader in fusion research and manufacturing

1. Robust Research & Testing Infrastructure

- Cutting-edge fusion laboratories test facilities (e.g., CEA’s WEST, Max Planck Institute’s Wendelstein 7-X, JET, ITER, JUDITH, GLADIS, HADES, HELCZA, HELOKA) providing data and reactor-relevant testing environments for PFC validation.
- Irradiation and lifecycle testing centers (e.g., BR2, MIAMI, NRG Pallas) supporting neutron damage studies, corrosion testing, and material validation under fusion-relevant conditions.

2. Excellence in Core Materials & Manufacturing embedded in strong industrial base

- World-class expertise in plasma facing and heat sink materials
- Leadership in bonding technologies and heat sink manufacturing capabilities, enabling high-integrity, thermally efficient joints critical for plasma-facing components optimized for high-heat-flux (HHF) applications in fusion reactors.

Opportunities to grow Europe's fusion ecosystem

Strengthening materials supply chain and Advanced Manufacturing

- **Supply Chain Strengthening**: Build European capacity for high-purity tungsten powders, copper alloys, and advanced ceramics to reduce reliance on external suppliers.
- **Additive Manufacturing (AM) Scaling**: Expand 3D printing of tungsten and complex heat sink geometries to reduce costs, improve precision, and enable on-demand production of PFCs.
- **Functionally Graded Materials**: Develop industrial-scale production of functionally graded tungsten (FGMs) to enhance thermal stress resistance and bonding integrity.

Next-Generation Cooling Solutions

- **Alternative Coolants**: Advance helium (He), FLiBe, and molten salt cooling systems for higher efficiency and compatibility with tritium systems.
- **Microchannel & Jet Impingement**: Optimize microchannel heat exchangers and jet impingement cooling for high-heat-flux (HHF) applications (10–20 MW/m^2).
- **Non-Copper Heat Sinks**: Develop steel-based heat sinks with AM cooling channels to eliminate copper in low-heat-flux regions, reducing costs and complexity.

Modular & Maintainable PFC Architectures

- **Repairable Designs**: Create modular, remotely maintainable PFCs with standardized joints and reversible pipe connections to minimize downtime.
- **Armour Repair Techniques**: Develop in-situ and ex-vessel repair methods for detached or damaged tiles, extending component lifetimes.

Emerging & Disruptive Technologies

- **Liquid Metal Walls**: Explore self-healing liquid metal surfaces (e.g., lithium, tin) for high heat flux capability and reduced erosion.
- **Self-Healing Armour**: Research self-repairing tungsten composites to mitigate damage from plasma interactions.

1 Introduction

1.1 Context

In 2024, Fusion for Energy launched a Technology Development Programme (TDP) as part of the implementation actions of its Industrial Policy. This TDP is dedicated to building and reinforcing European Fusion Supply chain capabilities for those technologies that are deemed to be critical for the future of commercial fusion. The Programme requires the identification of key technologies to direct R&D contracts to European contractors.

Prioritizing and allocating funding opportunities across both organizations requires a comprehensive review of the technologies involved in each major fusion technical domain. Doing this exercise in a collaborative way will enable stakeholders to identify which technologies are fundamentally needed (technology mapping) and when they are needed (technology road mapping). A roadmap built through consensus of key stakeholders in the field can also serve as a powerful argument when seeking additional funding from national and international public and private investors.

There are strong synergies in research and development activities linked to Plasma Facing Components for fusion and high energy physics applications, it was therefore natural for F4E launch a technology mapping initiative uniting academia, research laboratories, industry, start-ups and the ITER Organization to develop a comprehensive technology development roadmap for superconducting magnets technologies.

The outcome of this exercise will serve all stakeholders to guide their action in their respective domains, allowing an effective investment of resources. Given the fast evolution of technology, a periodical follow-up of the workshop outcome shall be assured in subsequent technology mapping exercises.

1.2 Plasma Facing Component technology and manufacturing mapping

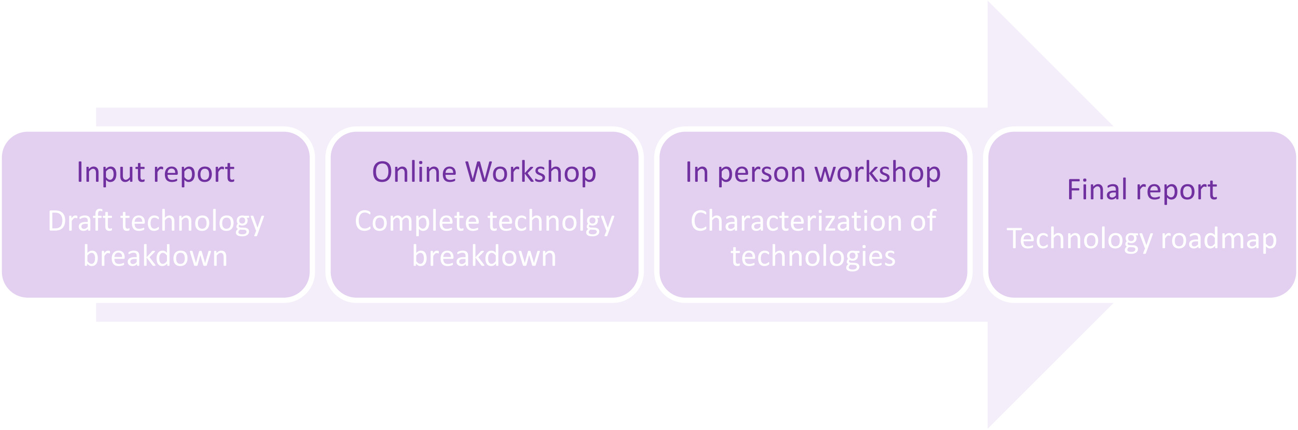
The scope of the Plasma Facing Components Mapping Workshop covers plasma facing armour such as emerging tungsten solutions, heat sink manufacturing optimisation including tile bonding and remote handling.

Two workshops bringing together laboratories, technical experts and industry with the objective of mapping out technology needs and development proposals are organised, composed of an online kick-off in February and an in-person session on 25th and 26th of March in Plzeň (Czech Republic), organised in collaboration with CVR (Centrum Výzkumu Řež) also facilitating knowledge exchange and networking.

This document provides a complete overview of the exercise, detailing the process and scope through a comprehensive technology breakdown, summarizing the meetings held and providing the resulting proposed technology development roadmap.

2 Technology mapping process

The technology mapping process consists of 4 stages.



2.1 Input report

In preparation of the exercise, staff from Fusion for Energy prepare a draft technology breakdown, listing technologies of interest and grouping them functionally.
This breakdown, together with a brief description of each selected technology, is included in a draft input report (see section 3) for consultation by participants ahead of the first meeting (an online workshop on February 11th 2026).

2.2 Online workshop

The purpose of the online workshop is to build a comprehensive list of relevant technologies with development potential giving participants the opportunity to put their ideas on the table. The agenda is structured with short talks introducing essential themes designed to trigger group discussions:

- Session #1: Armour materials, emerging tungsten solutions,
- Session #2: Heat sink manufacturability & armour bonding
- Session #3: Remote Handling

The technologies identified forms the basis for further ranking and proposal building to take place during the in-person workshop. An updated version of the input report with an updated technology breakdown is made available to participants before the in-person workshop.

2.3 In-person workshop

The in-person workshop aims at providing a detailed characterization of the technologies gathered during the online workshop including their prioritization (timeline).
The characterization of technologies takes place in three steps applicable to each technology:

- Agreement on current Technology Readiness Level (see Appendix 1 for definitions)
- Definition of the next step (eg analysis, prototype, testing, industrialization plan etc) and time permitting of the one after that.
- Quantification of the characteristics of the technology (see appendix 2 for a typical list of characteristics to be evaluated).
- A timeline with a classification of what is needed when, for the technologies considered in the technology mapping. Typical timelines can cover short, medium and long term activities.

The workshop is highly collaborative, with sessions designed for participants to exchange, build consensus and provide feedback on specific interests and the mapping process itself.
The workshop also provides ample opportunities for participants to share knowledge and form partnerships over a typical duration of one and a half day which includes specific times for formal and informal networking.

2.4 Final report

After the in-person workshop, staff from Fusion for Energy compile the outcome in a final report (an evolution of the input report). The report shall include an overview of European capabilities in the field as well as the proposed technology roadmap detailing and prioritizing possible actions for the period until the next review (typically 2 to 3 years).
Participants are given an opportunity to comment before the final version of the report is published.

3 Technology Breakdown

3.1 Technology overview

Among the key scientific challenges still to be solved on the road towards sustainable fusion power is a plasma facing technology capable of shielding the structure and external components of fusion machines from nuclear loads at the same time as efficiently exhausting the desired thermal power. Plasma Facing Components are a lifetime limiting factor for fusion reactors and so their performance is directly linked to the viability of fusion and its potential industrialisation.

Plasma Facing Armour

Armour materials must accommodate a range of essential requirements:

- Withstanding steady state head loads (0.5 – 20 MW/m^2) and transient events of much higher localised loads
- High melting temperature to avoid damage to components and the introduction of impurities into the plasma, resistance to erosion
- Low plasma contamination, minimising high-Z impurities that result in plasma cooling
- Materials tolerant of neutron bombardment, maintaining structural properties, avoiding excessive secondary nuclear activation (for waste handling), low embrittlement
- Low fuel retention, essential for good fuel economy and ensuring safe operation
- Ultra-high vacuum compatibility
- Requirements compatible with industrial scalability, ensuring reproducible performance, manufacturability at large volumes, and secure supply chains for reactor-scale deployment

Bonding, Armour to Heat Sink

Armour to heat sink bonding must cover the above requirements with additional emphasis on:

- Thermal fatigue resistance, accommodating differential expansion between armour and heat sink
- Facilitate efficient heat transfer
- Progressive failure preferred over catastrophic

Heat Sink

The heat sink and bulk structure of plasma facing components accommodate the active cooling necessary to exhaust the desired heat flux. These structures must be carefully formulated to:

- Above all perform the aforementioned efficient exhaust of heat
- Withstand large electromagnetic forces during plasma disruptions

- Resist leakage compatible with ultra-high vacuum environments
- Maintain geometric form within tight tolerances during operations

Complex cooling circuitry among other essential features such as divisions to isolate eddy currents can imply very intensive and costly precision machining.

- Emergent manufacturing techniques need to be explored to reduce production costs
- Tiles typically number into the tens of thousands and the plasma facing components into the hundreds, the ability to reliably and efficiently manufacture at scale with low scrappage rates is essential to establish the industrial potential of fusion.

Remote Handling – Replacement of Plasma Facing Components

Accumulated damage over the life of a fusion reactor will require scheduled and potentially non-scheduled shutdowns where Remote Handling maintenance will be necessary due to the high secondary nuclear activation of components and the plant structure after the plasma is extinguished preventing manned access.

The use of telerobotic equipment despite ever evolving sophistication implies a strong limitation compared to the ability to employ highly skilled human technicians. Restricted accessibility, limited viewing and illumination all compound to complicate maintenance operations. The inability to effectively maintain plant remotely can result in reduced reactor performance, extended shutdown periods or even in the worst scenario terminal inoperability of the tokamak.

For these reasons the design of in vessel components and the reactor as a whole must be carefully considered to accommodate a coherent Remote Handling operations strategy.

3.2 Plasma Facing Components technology map

Relevant technologies to Plasma facing components have been listed and broken down into 5 areas:

Armour, advanced materials

High purity forged tungsten
3D printed and functionally graded tungsten
Irregular tungsten powder
Ductile tungsten composites
Tungsten alloys
Nanostructured tungsten
Ductile ceramics
Silicon carbide
High performance copper alloys

Bonding technologies

Hot Isostatic Pressing
FAST diffusion bonding
Electric resistance welding
Brazing
3D printing of armour onto heat sink
Transient liquid phase bonding

Heat sink

Swirl tubes and turbulence promoters
Additive manufacturing of complex flow patterns
Micro-channel heat exchangers
Cooling channel extrusion in bulk material
Activated corrosion products control
Alternative coolants (He, FLiBe, molten salts)
Jet impingement

PFC design

Monolithic HIPed panels
Segmented finger panels
Non-copper heat sinks
Liquid metal walls
Advanced tile geometries (hexagonal, isotropic)
Lifecycle prediction models

Maintainability

Piping for remote handling
Reversible pipe joints
Armour repair techniques
Embedded erosion monitoring

3.3 Individual technologies at a glance

3.3.1 Armour, advanced materials

High-Purity Forged Tungsten

High-purity tungsten manufactured via powder metallurgy followed by forging and rolling remains the baseline solution for ITER armour due to its high melting point, thermal conductivity, and sputtering resistance.

Advantages:

- Proven industrial maturity
- High thermal conductivity
- Excellent erosion resistance

Challenges:

- Intrinsic brittleness, particularly at low temperatures
- Thermal fatigue cracking under cyclic heat loads
- Recrystallization and grain growth at high temperatures (>1200°C)
- Radiation-induced embrittlement and swelling under neutron irradiation

Functionally Graded Tungsten (FGMs) & Additive Manufacturing

Functionally graded materials (FGMs) incorporate compositional gradients between tungsten armour and heat sink materials, fabricated via spark plasma sintering (SPS), powder metallurgy, or additive manufacturing.

Advantages:

- Reduced thermal stress at material interfaces
- Improved bonding integrity
- Enhanced resistance to crack initiation and propagation

Challenges:

- Complex fabrication routes and qualification
- Residual stress accumulation during processing
- Limited irradiation performance data
- Scalability and reproducibility

Irregular Tungsten Powders

Use of irregular (non-spherical) tungsten powders offers a lower-cost alternative to conventional spherical powders.

Advantages:

- Reduced feedstock production cost
- Potentially improved packing density in some processes

Challenges:

- Poor flowability in additive manufacturing systems
- Non-uniform densification and porosity
- Increased surface roughness in final components

Ductile Tungsten Composites

Alloying tungsten with elements such as potassium (K-doped tungsten) enhances ductility and crack resistance.

Advantages:

- Improved thermal fatigue resistance
- Increased crack tolerance
- Enhanced ductility at intermediate temperatures

Challenges:

- Reduced thermal conductivity
- Lower effective melting point (depending on alloying additions)
- Microstructural stability under irradiation
- Cost and industrial scalability

Tungsten Alloys

Tungsten alloys incorporating elements such as Re, Ta, Mo, V, Ti, and La are developed to improve mechanical performance.

Advantages:

- Increased fracture toughness
- Improved grain boundary stability
- Enhanced oxidation resistance
- Potentially improved irradiation tolerance

Challenges:

- Activation concerns for high-Z alloying elements
- Degradation at extreme temperatures
- Bonding compatibility with heat sink materials

Tungsten Fiber-Reinforced Tungsten (Wf/W)

Composite material consisting of a tungsten matrix reinforced with tungsten fibers.

Advantages:

- Significant improvement in toughness and ductility
- Crack bridging and arrest mechanisms
- Enhanced thermal shock resistance
- Low activation potential

Challenges:

- Manufacturing complexity
- Anisotropic mechanical properties
- Fibre-matrix interface stability under irradiation
- Scale-up limitations

Nanostructured Tungsten

Includes nano-grained tungsten, oxide dispersion strengthened (ODS) tungsten, and nanolaminates (e.g., W/Cr, W/Cu).

Advantages:

- Improved strength and hardness
- Enhanced resistance to recrystallization
- Superior creep resistance
- Radiation defect pinning (ODS systems)

Challenges:

- Grain coarsening at high temperature
- Fabrication and consolidation complexity
- Industrial scalability
- Stability under neutron irradiation

Ductile Ceramics (UHTCs)

Ultra-high temperature ceramics (e.g., ZrC, HfC) offer extreme thermal resistance.

Advantages:

- Very high melting temperatures (>3000°C)
- Tailorable thermal properties
- Good oxidation resistance (with coatings)

Challenges:

- Intrinsic brittleness
- Thermal shock sensitivity
- Limited irradiation data
- Erosion and plasma compatibility concerns

Silicon Carbide (SiC/SiC - Silicon Carbide fiber-reinforced Silicon Carbide)

A promising low-activation ceramic material.

Advantages:

- Low thermal expansion
- High temperature capability
- Low neutron activation
- Good corrosion and erosion resistance

Challenges:

- Brittle failure modes
- Difficult joining and sealing technologies
- Machining challenges

- Limited thermal conductivity compared to metals

High-Performance Copper Alloys (e.g., CuCrZr)
Optimized copper alloys remain the reference heat sink materials.
Enhancements:

- Alloying with Hf, Nb for improved thermal stability
- Oxide dispersion strengthening (Al_2O_3, Y_2O_3) for radiation resistance

Challenges:

- Softening at high temperatures (>350°C)
- Radiation-induced embrittlement
- Compatibility with armour materials
- ODS Cu scalability assessment

3.3.2 Armour to heat sink bonding

Hot Isostatic Pressing (HIP)
Diffusion bonding under high temperature and pressure, used for plasma facing component materials manufacturing, consolidate assemblies bonding for optimal thermal conduction.
Advantages:

- Complex geometries fully consolidated with diffusion bonding for optimal thermal properties
- High structural integrity

Challenges:

- Process control for large components
- Risk of defects (voids, incomplete bonding)
- Long processing times

Field-Assisted (FAST) Diffusion Bonding
Uses electric current to enhance diffusion joining while under uniaxial pressing in vacuum.
Advantages:

- Reduced processing time
- Localized heating minimizes material degradation

Challenges:

- Scale-up to reactor components
- Long-term performance validation

Electrical Resistance Welding
Localized bonding via resistive heating.
Advantages:

- Minimal bulk heating
- Fast processing

Challenges:

- Formation of brittle intermetallics
- Limited joint geometry flexibility

Brazing
Widely used industrial bonding technique with history of use in plasma facing components.
Challenges:

- Residual stresses from CTE mismatch
- Crack initiation during cooling
- Radiation-induced embrittlement

Alternative HIP Spacers
Replacing graphite spacers with low-retention materials (e.g., boron nitride). Graphite is conventionally used to pack thermal expansion gaps between armour tiles to maintain geometry during Hot Isostatic

Pressing and then removed prior to assembly into the tokamak. Residual graphite is a problem during plasma operations as it can retain fusion fuels and pollute the plasma reducing performance.

Advantages:

- Reduced tritium retention
- Easier removal post-processing
- Reduced plasma pollutants

Transient liquid phase bonding

Diffusion-controlled joining process where a temporary liquid phase replaces applied pressure, resulting in a joint with diffusion-bond-like properties and no residual filler.

It enables pressure-free bonding of materials such as W/CuCrZr using a compatible thermal cycle, forming a high-integrity joint without visible interlayers. Also known as "diffusion brazing," as defined in ISO 17779:2021, and widely used in the aerospace industry.

Advantages

- Pressure-free diffusion-quality joints
- No residual filler / degradation
- CuCrZr-compatible thermal cycle
- High strength + clean interface
- Scalable via thin interlayers

Challenges

- Diffusion-controlled (tight process window)
- Interlayer design critical (Zr, thickness)
- Requires coating step (PVD)
- Early-stage validation

Applications

- W/CuCrZr bonding (ITER first wall)
- Plasma-facing components
- Modular tile / microbrush structures
- High heat flux systems

3.3.3 Heat sink

Swirl Tubes and Turbulence Promoters

Enhance convective heat transfer by promoting mixing between hot boundary layer and cooler core fluid in cooling channels.

Challenges:

- Increased pressure drop
- Erosion and cavitation
- Manufacturing precision requirements

Additive Manufacturing for Heat Sinks

Enables complex, optimized coolant channel geometries. Feedback from the ITER experience shows around half of all time to build plasma facing components goes into machining the complex geometries of the heat sink with its various coolant channels. Additive manufacturing may offer advantages in reducing multi-step HIP geometries, eliminating welding thereby potentially reducing/simplifying overall manufacturing time. Tailored flow patters can also be considered for improved heat removal performance.

Advantages:

- Reduced machining time
- Integrated structures (fewer joints)
- Tailored flow paths

Challenges:

- Porosity and defects
- Surface roughness

- Post-processing requirements
- Qualification and scalability

Microchannel Heat Exchangers

Provide very high heat transfer coefficients.

Challenges:

- High pressure drop
- Fouling and corrosion
- Limited irradiation data

Channel Extrusion in Bulk Materials

Similar to friction stir welding, direct formation of coolant channels in bulk materials.

Challenges:

- Maintaining uniform geometry
- Avoiding defects and porosity

Coolant Chemistry Control

Critical for managing corrosion and activation products that complicate waste management for fusion plant.

Approaches:

- Corrosion-resistant coatings
- Filtration systems
- Low-activation materials

Helium Cooling

A leading candidate for fusion reactors.

Advantages:

- Chemically inert
- High operating temperature capability
- Compatible with tritium systems

Challenges:

- Low heat capacity → high flow rates required
- High-pressure system design
- Compressor efficiency

Jet Impingement

Cooling technique where high-velocity coolant jets are directed normal (or nearly normal) to a hot surface to locally enhance heat transfer.

Advantages:

- Very high local heat transfer → enables removal of MW/m^2 heat fluxes in PFCs
- Effective hotspot cooling (strike points, edges) reducing W/CuCrZr degradation
- Strong turbulence → thin boundary layer → high cooling efficiency
- Flexible design (nozzle size, spacing, jet velocity) and compact heat sink integration

Challenges:

- High pressure drop → increased pumping power
- Non-uniform cooling → thermal gradients and stress concentration
- Thermo-mechanical fatigue at armour–heat sink interface
- Manufacturing complexity + risks (clogging, erosion, inspection difficulty)

Applications:

- Divertor target cooling in high heat flux regions
- Advanced heat sink designs (monoblocks, panels with jet arrays)
- High heat flux (HHF) testing and mock-ups
- AM-enabled cooling layouts and hybrid cooling concepts (jets + channels)

3.3.4 Plasma Facing Components concepts, design & modelling

Monolithic Hot Isostatic Pressed Panels (EU ITER Design)

Fully consolidated diffusion bonded structures.

Challenges:

- Manufacturing complexity
- Defect control in large components

Segmented Finger Panels (China ITER Design)

Modular “finger” elements attached to manifolds.

Advantages:

- Repairability

Challenges:

- Multiple welds, leak risk
- Assembly complexity

Non-Copper Heat Sinks (Steel + AM Channels)

Additive manufactured flow patterns generated in a stainless steel heat sink could provide the increased thermal exhaust efficiency to eliminate copper. potentially viable in low heat flux regions Potential alternative for lower heat flux regions.

Advantages:

- Significant simplification/cost reduction of panel design by eliminating copper
- Higher heat extraction temperature

Challenges:

- Limited thermal efficiency, likely suitable for low heat flux regions of tokamak first wall

Liquid Metal Plasma-Facing Surfaces

Thin flowing layers (e.g., Li, Sn).

Advantages:

- Self-healing surface
- High heat flux capability
- Reduced erosion

Challenges:

- Tritium management
- MHD effects (electromagnetic forces)
- Flow stability
- Compatibility with diagnostics
- Material corrosion

Advanced Tile Geometries (Hexagonal/Isotropic)

Improved stress distribution and fatigue resistance. Additive manufacturing 3D print direct to heat sink could mitigate some challenges.

Challenges:

- Higher manufacturing cost, plasma facing component design complexity, alignment and installation.

Lifecycle Prediction Models

Predict erosion, fatigue, and failure mechanisms.

Advancements:

- Coupled thermo-mechanical-radiation models
- Integration of recrystallization physics
- Digital twins using real-time sensor data

Challenges:

- Accurate modelling of neutron damage
- Hydrogen isotope, tritium interactions

3.3.5 Maintainability

Pipe Cutting, Alignment, and Rewelding

Standard method to facilitate replacement of plasma facing components but complex for remote handling without hands on access for skilled human technicians.

Challenges:

- Sufficient compliance in coolant piping to facilitate accurate joint fit-up, visual tactile fit-up verification
- Weld process qualification

Reversible Pipe Joints

Bolted flanges with seals or swaged fittings are an attractive alternative to permanent welding which is the preferred approach in fusion machines.

Challenges:

- Reliability under disruption loads
- Flange alignment, pipe compliance
- Leak-tight performance over lifecycle

Armour Repair Techniques

In-situ or manufacturing-stage repair methods for detached tiles.

Challenges:

- Localized heating and atmospheric control
- Avoiding degradation of surrounding material

Embedded Erosion Monitoring Sensors

Ultrasonic embedded in the heat sink can be used to measure time of flight to the armour surface to determine erosion.

Challenges:

- UT couplant stability
- Radiation effects (e.g., depoling)
- Long-term reliability

4 Summary of meetings

In total, 189 people registered for participation in the 2026 Plasma Facing Components Technology Mapping workshop. The online workshop registered a peak of 105 participants whilst 55 people attended the in-person workshop co-organised with CV Řež in Plzeň (Czech Republic). 60 public and private entities were represented. Fusion for Energy thanks all participants for their input during and after the workshop.

Logos of participating entities

Details of the meetings can be found on the event web page[1]. The agenda and outputs including presentations, documents and recordings are also available there.

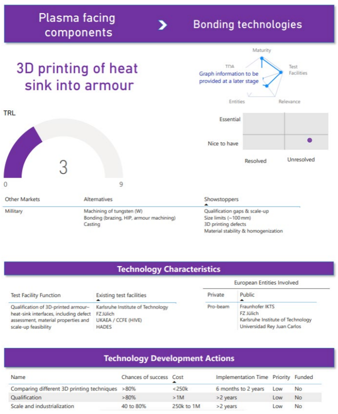
5 Outcome: technology road-mapping

5.1 Technology dashboards

During the in-person workshop and in the process of preparing this report, a lot of valuable data was collected into a database. For each technology, the following data is now available:

- TRL
- Criticality
- Other fields of application
- Alternative technologies
- Potential showstoppers
- Existing and needed test facilities
- European entities involved
- Technology development actions

This data has been arranged into a dashboard for each of the technologies:



Plasma facing components > Bonding technologies

3D printing of heat sink into armour

Other Markets	Alternatives	Showstoppers
Millitary	Machining of tungsten (W) Bonding (brazing, HIP, armour machining) Casting	Qualification gaps & scale-up Size limits (~100 mm) 3D printing defects Material stability & homogenization

Technology Characteristics

Test Facility Function	Existing test facilities
Qualification of 3D-printed armour–heat-sink interfaces, including defect assessment, material properties and scale-up feasibility	Karlsruhe Institute of Technology FZ Jülich UKAEA / CCFE (HIVE) HADES

European Entities Involved

Private	Public
Pro-beam	Fraunhofer IKTS FZ Jülich Karlsruhe Institute of Technology Universidad Rey Juan Carlos

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Comparing different 3D printing techniques	>80%	<250k	6 months to 2 years	Low	No
Qualification	>80%	>1M	>2 years	Low	No
Scale and industrialization	40 to 80%	250k to 1M	>2 years	Low	No

Typical technology dashboard

Note that the spider diagram (scores out of 9) has been arranged in such a way that the more the colored area, the more development is needed.

All technology dashboards are available in Appendix 3: Technology dashboards.

The dashboards are a view of the database at the time of publishing this document. The database will be updated regularly, and Appendix 3 may be re-published as necessary. We encourage the community

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[1] https://app.swapcard.com/event/in-vessel-technology-mapping-workshop

to communicate updates to their Fusion for Energy contact. In the future, we may publish this data for interactive consultation on the Fusion for Energy website.

5.2 Overview of the EU landscape for plasma facing components

5.2.1 SWOT analysis

Strengths	Weaknesses
• Strong European expertise across tungsten materials, bonding technologies, heat sinks and advanced PFC design concepts • Established network of specialised HHFT, irradiation and qualification facilities • Broad ecosystem of public laboratories, SMEs and industrial actors across fusion, aerospace and advanced manufacturing • Maturity in reference technologies such as forged tungsten, powder-HIP and HIP diffusion bonding	• Scalability challenges for additive manufacturing • Risks linked to brittleness, cracking, porosity, corrosion and bonding reliability • TRL level of joining dissimilar materials • Bottlenecks in qualification, neutron irradiation and large-scale lifecycle validation capabilities. In particular no 14 MeV test facilities to qualify components solutions under operational conditions.
Opportunities	**Threats**
• Accelerate industrialisation of additive manufacturing and functionally graded tungsten solutions • Develop repairable, modular, remotely maintainable industrialised PFC architectures • Develop next-generation cooling solutions including alternative coolants and non-copper heat sinks • Strengthen European supply chains for tungsten powders, copper alloys and advanced ceramics	• Dependence on external supply chains for strategic tungsten materials and powders Limited availability and high cost of high-purity tungsten and specialised powders • Risk of fragmented funding and discontinuity between R&D, prototyping and industrial deployment • Rising material and energy costs impacting advanced manufacturing routes

Strengths

Europe possesses a strong technological and industrial foundation in plasma facing components (PFCs), supported by extensive expertise in tungsten materials, alternative armour materials, bonding technologies, heat sinks and advanced thermo-mechanical design. This is largely down to an extensive ecosystem of large-scale fusion facilities that have played a central role in advancing plasma facing component (PFC) technologies from laboratory concepts to reactor-relevant operating conditions. Experimental devices such as CEA's WEST tokamak, Max Planck Institute for Plasma Physics's Wendelstein 7-X (W7-X), JET, ITER and multiple EUROfusion facilities. This together with key laboratories such as Forschungszentrum Jülich, UK Atomic Energy Authority, ENEA, CIEMAT, DIFFER and SCK-CEN provide Europe with world-leading capabilities in high-heat-flux operation, tungsten qualification, divertor technology and long-pulse plasma operation.

The technology mapping highlights a broad portfolio of mature and emerging technologies, ranging from hot isostatic pressing (HIP) and diffusion bonding to advanced tungsten manufacturing and innovative cooling concepts. Established competencies making use of high-purity forged tungsten, HIP bonding and alternative coolant systems provide a robust baseline for future fusion reactor development.
Another key strength is the existence of a geographically distributed, but highly capable network of qualification and testing facilities. Infrastructure such as HELCZA, OLMAT, GLADIS, HADES, JUDITH, Magnum-PSI with IFMIF-DONES plan for the future to support high-heat-flux testing, thermo-

mechanical qualification, irradiation studies and lifecycle assessment. These facilities are complemented by a diverse network of industrial and public actors, including research institutes, universities, SMEs and established industrial suppliers across the EU and UK.

Weaknesses

Despite these strengths, several critical technologies are still at relatively low technology readiness levels. Concepts covered during the workshops including liquid metal walls, silicon carbide components, and non-copper heat sinks, remain at TRL 2–4 and require substantial validation before industrial deployment. Significant technical challenges persist in material qualification, thermo-mechanical integrity, neutron irradiation resistance, tritium inventory and lifecycle prediction.

Additive manufacturing of tungsten and complex heat sink geometries face challenges linked to scalability, qualification and cost. In addition, neutron irradiation testing and long-term lifecycle validation infrastructure are costly bottlenecks for technology qualification. Dependence on specialised tungsten powders and advanced materials further increases vulnerability to supply chain disruptions and cost volatility.

Opportunities

The primary opportunity remains in the fusion community for a definitive solution for plasma facing armour operating at powerplant-relevant conditions capable of meeting demands in brittleness, porosity, corrosion, thermal creep, fatigue and reproducible bonding.

Another opportunity is the development of additive manufacturing and functionally graded tungsten technologies, which could simplify manufacturing routes and enable more complex cooling and structural geometries. Expanding European qualification and irradiation infrastructure will also strengthen Europe’s capacity to validate fusion-relevant materials and components domestically, reducing reliance on external facilities and improving technology readiness.

Additive manufacturing development of plasma facing component structural material as 316L(N)-IG already proved that properties can be achieved above conventional forged equivalent material. Demonstrating the potential if the technology can be upscaled and utilized for a wide range of materials.

The development of modular, repairable and remotely maintainable PFC architectures represents another major opportunity, particularly for future commercial fusion reactors where availability and maintenance costs will be critical economic drivers. The mapping also highlights opportunities to strengthen European supply chains for tungsten powders, advanced copper alloys, ceramics and specialised joining technologies. Emerging technologies such as alternative coolants, liquid metal walls and advanced lifecycle prediction models could also provide pathways toward improved reactor efficiency, durability and operational flexibility. In addition, leveraging synergies with other high-technology sectors facing similar challenges—such as hypersonics (thermal protection), electronics (advanced cooling, e.g. jet impingement), and X-ray technologies (tungsten joining)—offers potential to increase impact and accelerate technology development.

Threats

Several threats could undermine Europe’s long-term competitiveness in plasma facing components. One of the most significant risks is increasing dependence on external suppliers for strategic tungsten materials, powders and advanced manufacturing inputs. Global competition for critical raw materials and advanced manufacturing capacity may expose Europe to supply chain vulnerabilities, rising costs and procurement delays. At the same time, competing international fusion Programmes with more centralised and heavily funded strategies could accelerate technology deployment outside Europe, reducing European industrial influence in future fusion supply chains.

Another major threat relates to the complexity and duration of qualification processes for advanced PFC technologies. Neutron irradiation, lifecycle validation and licensing frameworks could significantly slow technology maturation and industrial deployment. Novel concepts such as liquid metal walls, silicon carbide composites and advanced segmented structures also carry substantial technical and operational risks, including integration complexity, maintainability challenges and uncertain long-term performance. Finally, fragmented funding mechanisms and discontinuity between R&D, prototyping and industrial deployment may hinder Europe's ability to transition promising laboratory-scale technologies into commercially viable fusion reactor solutions.

5.2.2 Main test facilities

High heat flux testing

Name	Operator	Functionality and main characteristics
JUDITH	FZ Julich	High heat flux testing Max power: 200kW Heat flux: 10 to 50 MW/m2 Hot cell available for testing of irradiated samples
GLADIS	IPP Garching	High heat flux testing Power: 2 x max. 1.1 MW Heat flux: 1 - 45 MW/m² Pulse length: 1 ms - 45 s Repetition rate: ~ 100 /h
CHIMERA (under construction)	UKAEA	Magnetic and heat flux combined testing Magnet: up to 5T static plus up to 12.5T/s pulsed field Heat flux: up to 20 MW/m^2 over 1500 mm^2 or 200 MW/m^2 over 100 mm^2 Water cooling: 30 – 328°C, up to 155 bar, up to 1000 litre/min
HADES	CEA	High heat flux testing Max. Power: 150 kW Heat flux: 10-1000 MW/m2 depending on surface area and pulse length Vacuum chamber: 8m3, opening 1.3m in diameter
HELCZA	Cv Řež	High heat flux testing Max. Power: 800 kW Heat flux: 10-4000 MW/m2 depending on surface area and pulse length Vacuum chamber: 245 cm in diameter Max available testing area: 4m2
HELOKA	KIT	High heat flux testing Max power: 800kW He cooling loop up to 700ºC Water cooling loop available Vacuum chamber diameter: 3m
SIRHEX	KIT	Medium heat flux test facility Max heat flux: 500 kW/m2 (peak), 300 KW/m2 (steady state)

		Vacuum chamber diameter: 1.8m
HIVE	UKAEA	High heat flux test facility Max power: 45kW Max heat flux: 15 MW/m2 Vacuum vessel diameter: 500mm
Laser thermal testing	University of West Bohemia	High heat flux test facility for small scale samples Max power: 4kW
Magnum-PSI	DIFFER	Plasma wall interactions Electron density ne ~ 1019 – 1021 m-3 Electron temperature Te ~ 0.1 – 10 eV Particle flux ~ 1023 - 1025 m-2 s-1 Heat fluxes > 10 MW m-2 Magnetic field up to 2.5 T Transient plasma loading: 2 GW/m2 Variable repetition rate: up to 70 Hz
OLMAT	CIEMAT	High heat flux testing NBI: 705 kW (with 33% ions), H+ energy: 30-40 keV; H+ flux: 1.45·1022 1/m2s. Heat flux: 8 to 40 MW/m2 CW laser Heat flux: 10 to 1000MW/m2 Active cooling
	University of West Bohemia	High heat flux testing Laser up to 5kW, vacuum or inert gas chamber with 200x120mm sample table Possibility of sample preheating Range of IR cameras and pyrometers
	Brno University of Technology	High heat flux testing Electron beam up to 15kW Large vacuum chamber, pyrometric measurement only
	PVA TePla	High heat flux testing Ultrasonic Microscopy

Others (irradiation, corrosion testing and remote handling facilities)

Name	Operator	Functionality and main characteristics
LIFUS II	ENEA	Corrosion testing loop for liquid metals Main parameters (for PbLi): 1m/s, 550ºC
LiMeS-Lab	DIFFER	Liquid metal / Plasma interactions
MIAMI	University of Huddersfield	Radiation damage 350 keV ions 20 keV H or He ions Temp. range: –173 to 1300°C
NRG Pallas	NRG Pallas	Neutron irradiation facility
BR2	SCK CEN	Neutron irradiation reactor Thermal neutron flux: 10^{15}n.cm-2s-1
DTP2	VTT	Divertor remote handling test facility
RACE	UKAEA	Remote Handling test facility

Ultra-Laser	AMAZEMET (Poland)	Laser up to 6 kW vacuum or inert gas. Rapid laser scanning capability and Programmable power density. DC plasma up to 20 kW in inert gas. 190 mm diameter sample stage. In-situ NDT for samples up to 30 mm. IR cameras.

5.2.3 Gaps in the ecosystem

This section describes the areas where new actors (R&D or Suppliers) would need to be mobilized to successfully develop the associated technology. This covers all actors based in the EU, UK and Switzerland.

More critical items are highlighted in **bold.**

Research and development		
Handful of actors	One actor	No identified actor
• Additive manufacturing of complex flow patterns • Cooling channel extrusion in bulk material • Swirl tubes and turbulences promoters • Armour repair techniques	• Jet impingement • Embedded erosion monitoring • Reversible pipe joints	

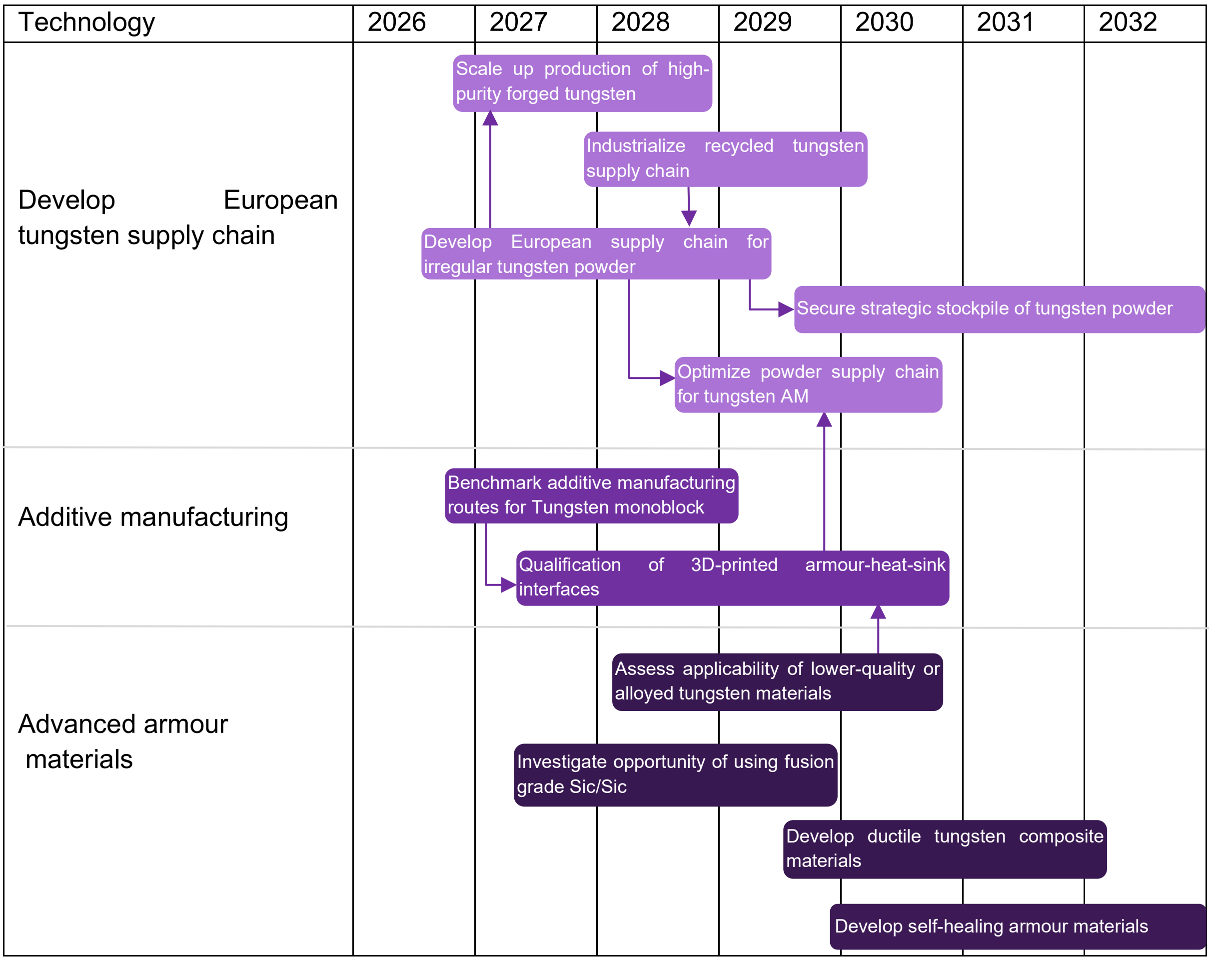
Supply chain		
Handful of actors	One actor	No active supplier
• Activated corrosion products control • Armour repair techniques • Reversible pipe joints • High performance copper alloys • Advanced tile geometries (hexagonal, isotropic) • Embedded erosion monitoring • Piping for remote handling • 3D printing of heat pipe arrays	• Electrical resistance welding • Transient liquid phase bonding • Cooling channel extrusion in bulk material • Liquid metal walls • 3D printing of heat sink into armour	• Jet impingement • Ductile tungsten composites

5.3 Roadmaps

This section presents some of the Technology Development Actions (TDAs) in the form of roadmaps for relevant technologies. The timings are indicative and may evolve significantly depending on funding available from various sources and associated priorities.
TDAs which are not fundamentally linked to other activities and can be executed independently are not included on roadmaps. This is true, for example, for the pumping area.

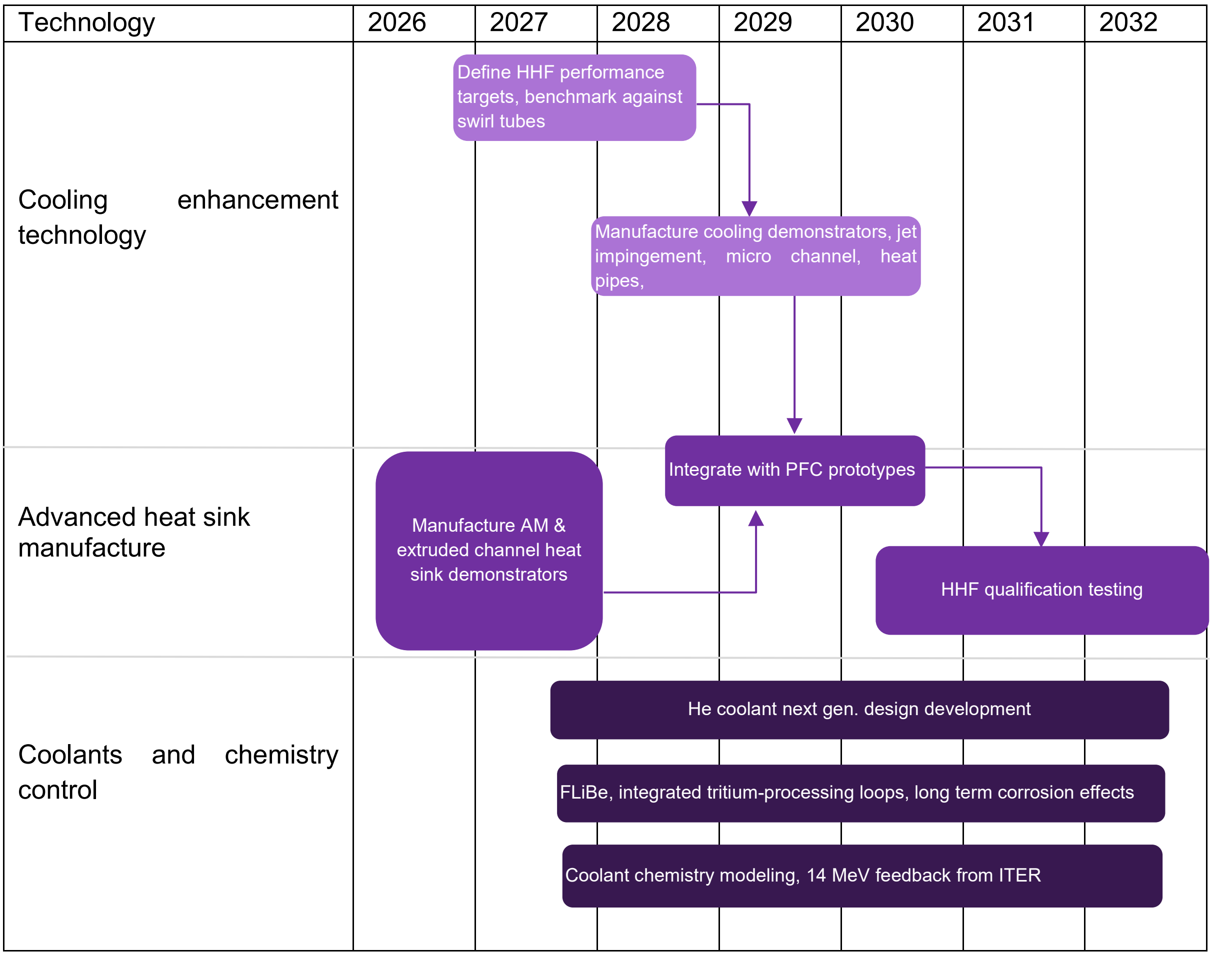
5.3.1 Armour and additive manufacturing

Objective: Develop and qualify advanced tungsten materials for PFCs, addressing performance, scalability, and cost, benchmarking additive manufacturing routes for monoblock components.



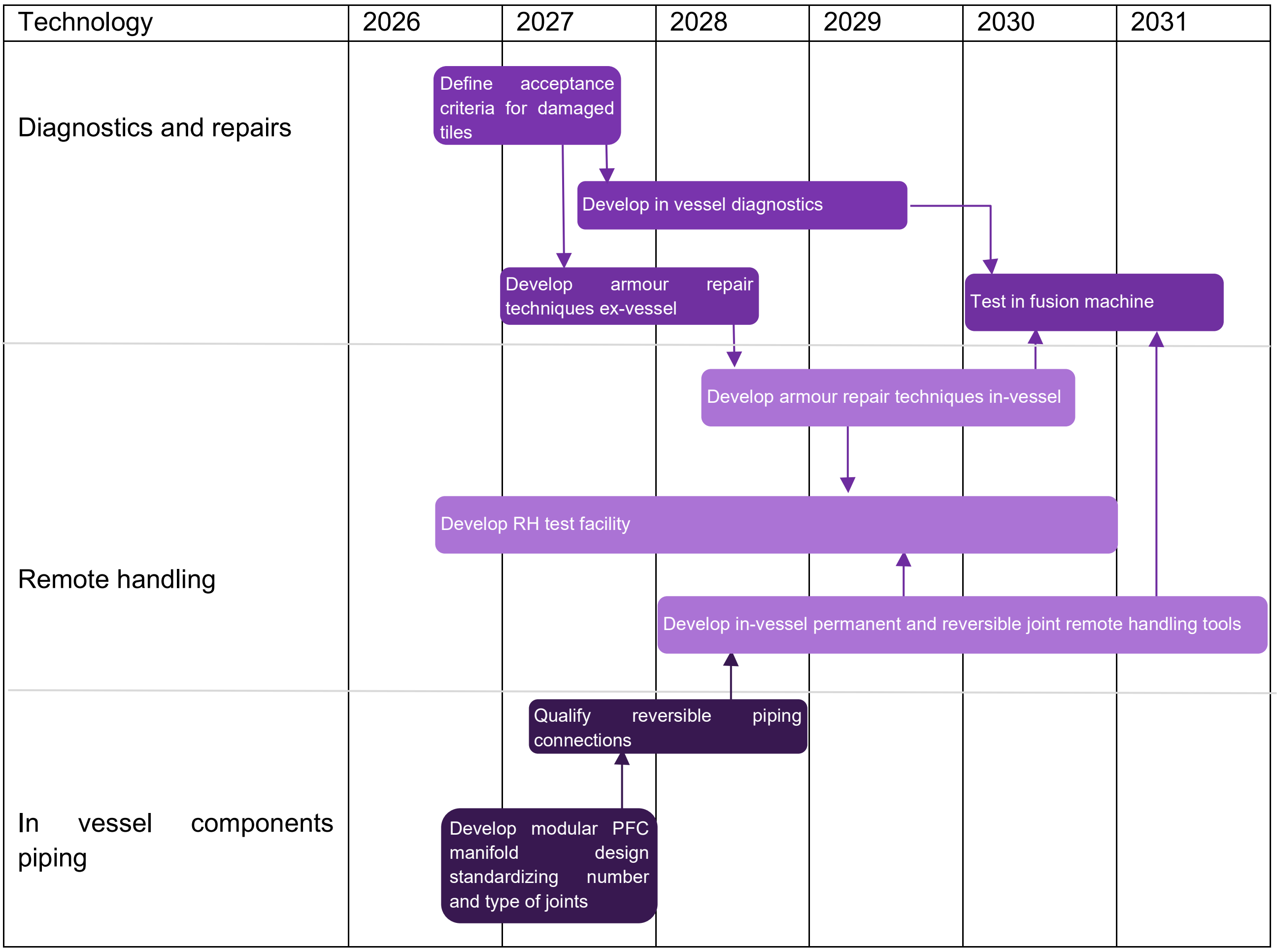
5.3.2 Heat sinks and cooling

Objective: Develop manufacturable, reliable, high-heat-flux cooling solutions capable of supporting fusion power plant conditions (>10–20 MW/m² steady-state, extreme transient loads) while reducing manufacturing cost and improving maintainability.



5.3.3 Maintainability

Objective: Develop maintenance optimized PFC design, for replacement, repair & erosion monitoring.



Technology	2026	2027	2028	2029	2030	2031
Diagnostics and repairs	Define acceptance criteria for damaged tiles	Develop in vessel diagnostics Develop armour repair techniques ex-vessel			Test in fusion machine	
Remote handling	Develop RH test facility		Develop armour repair techniques in-vessel Develop in-vessel permanent and reversible joint remote handling tools			
In vessel components piping	Develop modular PFC manifold design standardizing number and type of joints	Qualify reversible piping connections				

6 Conclusion

The first European Plasma Facing Components Technology Mapping exercise represents a major milestone in the coordinated development of one of the more critical technology areas for future power plants. Bringing together almost 190 experts from more than 60 public and private organisations, the workshops established a comprehensive overview of Europe's capabilities in plasma facing materials, manufacturing technologies, cooling systems, bonding methods and maintainability, while defining a common technology roadmap to guide future research, industrialisation and investment.

The workshop confirmed that Europe can look ahead from a position of considerable strength. A world-leading research infrastructure, extensive testing capabilities, and a highly specialised industrial ecosystem provide a strong foundation for future development. Europe also benefits from recognised expertise in tungsten materials, advanced bonding technologies, heat sink manufacturing and thermo-mechanical design, built through decades of experience delivering components for ITER and other major fusion facilities.

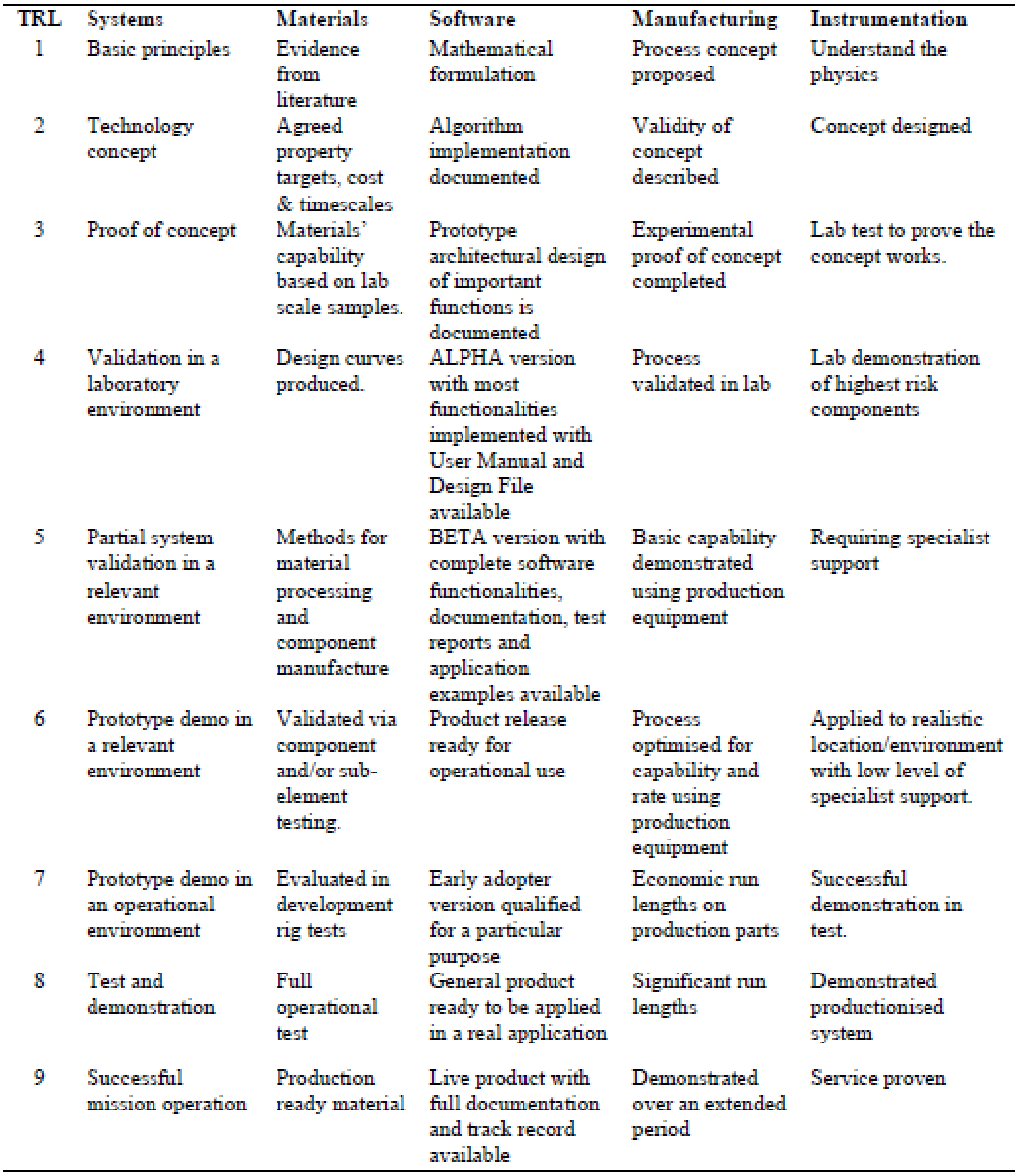
At the same time, the mapping exercise identified several strategic challenges that require coordinated action. Many promising technologies—including additive manufacturing of tungsten components, functionally graded materials, liquid metal plasma-facing surfaces, silicon carbide solutions and advanced maintainability concepts—remain at relatively low technology readiness levels and require substantial validation before industrial deployment. Qualification under representative neutron irradiation conditions, lifecycle testing and large-scale manufacturing remain significant bottlenecks, while dependence on external suppliers for high-purity tungsten powders and other strategic materials exposes Europe to supply chain vulnerabilities. Expanding European testing capabilities, strengthening domestic supply chains and accelerating technology qualification therefore emerge as priorities for the coming years.

The technology roadmaps developed during the workshop provide clear priorities for coordinated investment. These include scaling up European production of advanced tungsten materials, accelerating additive manufacturing for both armour and heat sink components, developing next-generation cooling concepts, qualifying innovative joining technologies, and designing modular, repairable plasma facing components compatible with remote maintenance. Together, these actions will improve manufacturability, reliability and maintainability while reducing lifecycle costs, bringing plasma facing components closer to the performance and availability required for commercial fusion power plants.

This report provides a strategic framework for researchers, industry, funding agencies and policymakers seeking to align future investments with the priorities identified by the European plasma facing components community. Fusion for Energy and EUROfusion remain committed to supporting this coordinated approach through the Technology Development Programme and future technology mapping exercises. By maintaining strong collaboration across research organisations, industry and emerging innovators, Europe can reinforce its technological leadership and build the plasma facing component technologies that will be essential for the successful deployment of fusion power.

Appendix 1: Technology Readiness Levels

For this workshop, a TRL scale from 1 to 9 will be used, in line with the IAEA definitions[2].
It considers the different criteria for different streams as illustrated in the table below extracted from the document in reference. By default, the "System" stream will be used. For more details, please refer to the TECDOC 2047 itself[1].



TRL	Systems	Materials	Software	Manufacturing	Instrumentation
1	Basic principles	Evidence from literature	Mathematical formulation	Process concept proposed	Understand the physics
2	Technology concept	Agreed property targets, cost & timescales	Algorithm implementation documented	Validity of concept described	Concept designed
3	Proof of concept	Materials' capability based on lab scale samples.	Prototype architectural design of important functions is documented	Experimental proof of concept completed	Lab test to prove the concept works.
4	Validation in a laboratory environment	Design curves produced.	ALPHA version with most functionalities implemented with User Manual and Design File available	Process validated in lab	Lab demonstration of highest risk components
5	Partial system validation in a relevant environment	Methods for material processing and component manufacture	BETA version with complete software functionalities, documentation, test reports and application examples available	Basic capability demonstrated using production equipment	Requiring specialist support
6	Prototype demo in a relevant environment	Validated via component and/or sub-element testing.	Product release ready for operational use	Process optimised for capability and rate using production equipment	Applied to realistic location/environment with low level of specialist support.
7	Prototype demo in an operational environment	Evaluated in development rig tests	Early adopter version qualified for a particular purpose	Economic run lengths on production parts	Successful demonstration in test.
8	Test and demonstration	Full operational test	General product ready to be applied in a real application	Significant run lengths	Demonstrated productionised system
9	Successful mission operation	Production ready material	Live product with full documentation and track record available	Demonstrated over an extended period	Service proven

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[2] IAEA TECDOC 2047 Considerations of TRL for Fusion Technology Components available from: https://www-pub.iaea.org/MTCD/Publications/PDF/TE-2047web.pdf

Appendix 2: Technology assessment

1. Added-Value Towards Nuclear Fusion		
Criterion	*Scale*	*Explanation*
Need for and potential benefit	Major / Medium / Minor	*Does this technology address a critical and unresolved challenge in nuclear fusion?*
Availability of alternative solutions	Yes/No (EU) Yes/No (Outside EU)	*Are there competing solutions in Europe or globally?*
Differentiation / Competitive Advantage	Yes / No	*Does this technology offer a unique advantage over existing solutions?*
2. Maturity & Feasibility		
Criterion	*Scale*	*Explanation*
Technology Readiness Level (TRL)	1 to 9	*Standard TRL scale (see Appendix).*
Expected time to TRL 9 (full maturity)	<5 years / 5–15 years / >15 years	*How long until the technology is commercially viable?*
Availability of test facilities	Yes / No	*Are there existing facilities in Europe to validate the technology?*
3. Interest from the Innovation Ecosystem		
Criterion	*Scale*	*Explanation*
Interest from start-ups	None / 1–3 interested parties / >3 interested parties	*Level of engagement from early-stage companies.*
Interest from industry	None / 1–3 interested parties / >3 interested parties	*Level of interest from established industry players.*
Interest from research institutions	None / 1–3 interested parties / >3 interested parties	*Interest from universities, national labs, and research centers.*
4. Other Investment Decision-Making Factors		
Criterion	*Scale*	*Explanation*
Market potential	Nuclear fusion-specific / Wider market potential	*Is the technology limited to fusion, or does it have broader applications?*
Competences & skills development	Yes / No	*Will this technology enhance European expertise in fusion?*
Regulatory impact	Yes / No	*Does the technology pose significant regulatory challenges?*
5. Risk, Cost, and Implementation Timeline of Next Step on Roadmap		
Criterion	*Scale*	*Explanation*
Outcome predictability & risks	Low risk / Medium risk / High risk	*How uncertain are the results of the next development?*
Estimated development cost	0–500k EUR / 501k–2M EUR / >2M EUR	*Rough cost estimate for next development step.*
Time to first output (once funded)	<1 year / 1–2 years / >2 years	*Timeframe for delivering tangible results.*

Appendix 3: Technology Dashboards

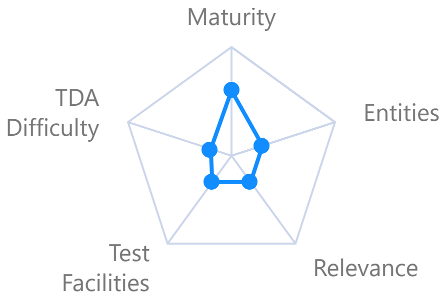
Fusion for Energy

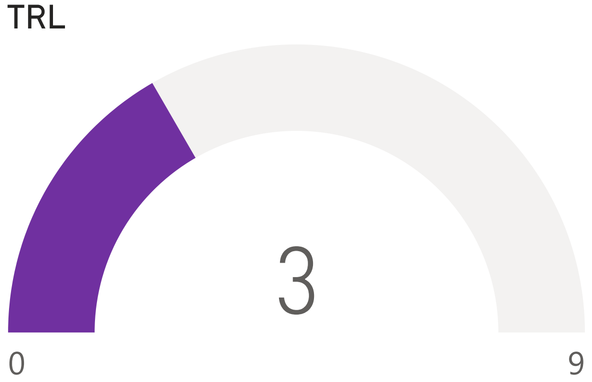
The European Joint Undertaking for ITER
and the Development of Fusion Energy
C/ Josep Pla 2,
Torres Diagonal Litoral
Edificio B3
08019 Barcelona
Spain

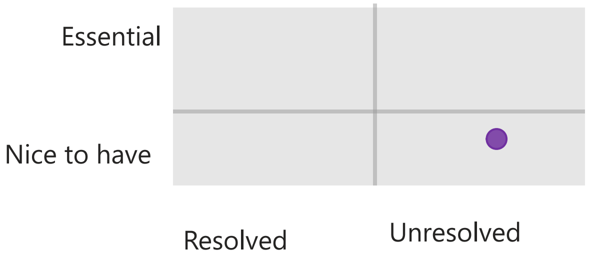
Tel: +34 933 201 800
E-mail: info@f4e.europa.eu

fusionforenergy.europa.eu

3D printing of heat sink into armour







Other Markets	Alternatives	Showstoppers
Millitary	Machining of tungsten (W) Bonding (brazing, HIP, armour machining) Casting Laser-based AM (Size limits 5mx5m with suitable machine)	Qualification gaps & scale-up Size limits (~100 mm) 3D printing defects Material stability & homogenization

Technology Characteristics

Test Facility Function	Existing test facilities
Qualification of 3D-printed armour–heat-sink interfaces, including defect assessment, material properties and scale-up feasibility	Karlsruhe Institute of Technology FZ Jülich UKAEA / CCFE (HIVE) HADES

European Entities Involved

Private	Public
Pro-beam	Fraunhofer (IKTS, IWS) FZ Jülich Karlsruhe Institute of Technology Universidad Rey Juan Carlos

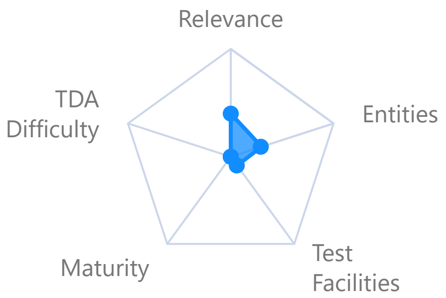
Technology Development Actions

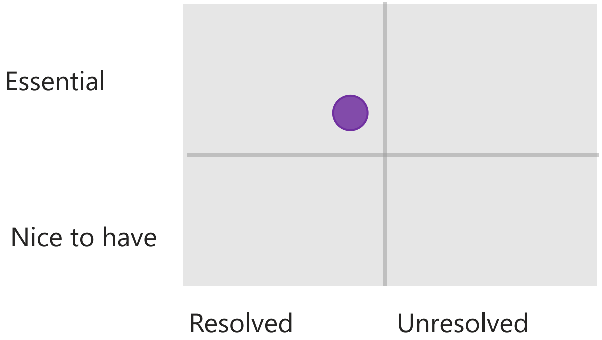
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Comparing different 3D printing techniques	>80%	<250k	6 months to 2 years	Low	No
Qualification	>80%	>1M	>2 years	Low	No
Scale and industrialization	40 to 80%	250k to 1M	>2 years	Low	No

Plasma facing components › Bonding technologies

Brazing

TRL





Other Markets	Alternatives	Showstoppers
Manufacturing	FAST HIP TLPB	Availability of large vacuum furnaces Bond strength lower Activation No stress reducing mechanism (pressure missing)

Technology Characteristics

Test Facility Function	Existing test facilities
High heat flux testing Mechanical testing	HADES HELZCA GLADYS JUDITH

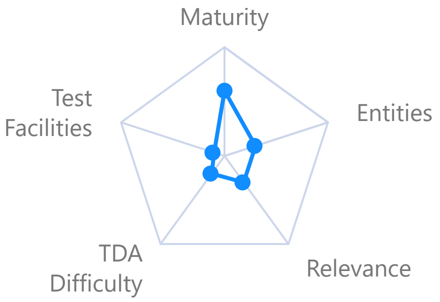
European Entities Involved

Private	Public
Research Instruments ALSYMEX SIMIC Ansaldo Nucleare Plansee Group PVA TePla	Many

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded

Electrical resistance welding



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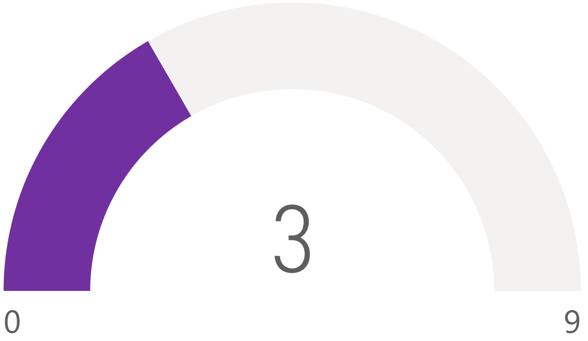
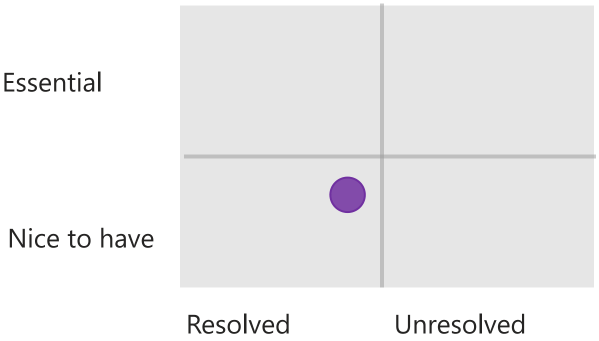




Other Markets	Alternatives	Showstoppers
Many manufacturing processes	Laser welding E-Beam welding HIP FAST Brazing TLPB	Large surface need high pressure. and high current ==> FAST / SPS machines Large surface Part size

Technology Characteristics

Test Facility Function	Existing test facilities
Mechanical testing High Heat Flux Testing	HADES HELCZA GLADYS

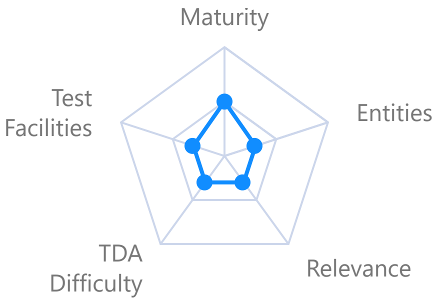
European Entities Involved

Private	Public
Oxford Sigma	

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Testing of large scale mock-ups	>80%	<250k	6 months to 2 years	Low	Partially

FAST diffusion bonding



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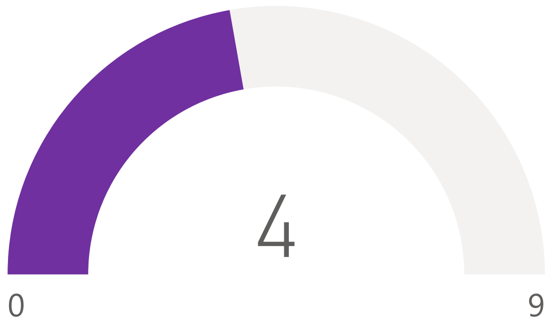
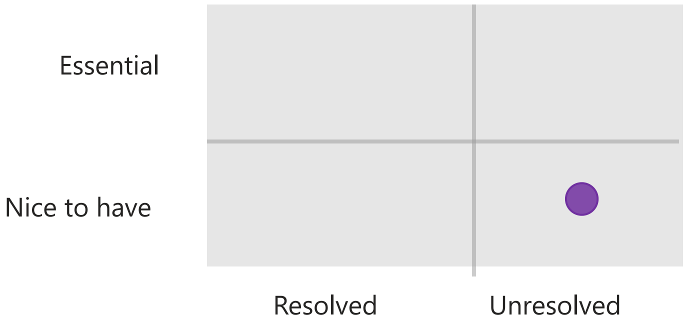




Other Markets	Alternatives	Showstoppers
Mobility	Hot Isostatic Pressing	Size limits (currently 450x450mm; next generation 600x600mm)
Fission	Casting	Mould degradation (high pressure)
Diamond tools	Additive Manufacturing	Low-vacuum atmosphere (~10 mbar)
Aviation	Spray coatings	High cost (compared to Brazing or Casting but cheaper than HIP)
Brake pads manufacturing	Diffusion bonding	Curved-geometry limits

Technology Characteristics

Test Facility Function	Existing test facilities
High-T bonding	Dr. Fritsch
Vacuum control	FZ Jülich
Uniaxial pressing	KIT
Scale-up bonding	RHP Technology
Defect assessment	GLADIS
Post-bond testing	HELCZA
	HADES
	UWB Pilsen

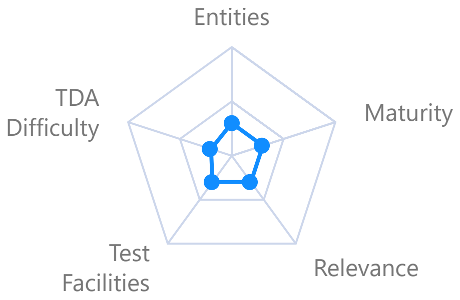
European Entities Involved

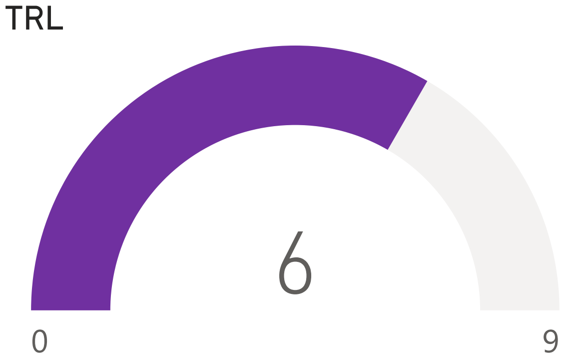
Private	Public
Dr. Fritsch	KIT
RTC Engineering	FZ Jülich
RHP Technology	MAGNUM-PSI
Tecnalia	

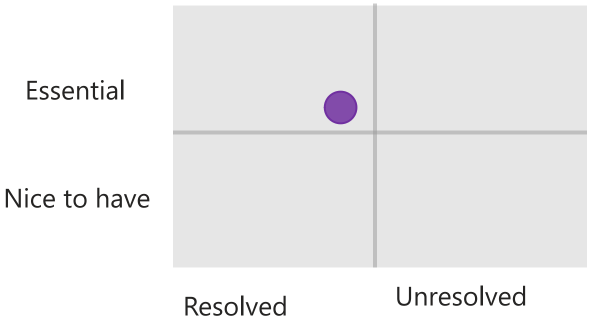
Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Combination with other bonding techniques	40 to 80%	<250k	<6 months	High	No
Upscaling and industrializing	>80%	>1M	6 months to 2 years	High	No
Testing of bonding of W to Steel and W to Cu	>80%	250k to 1M	6 months to 2 years	High	Yes

Hot Isostatic Pressing







Other Markets	Alternatives	Showstoppers
Military Medical Aviation	Casting 3D-printed Explosion bonding FAST/SPS diffusion bonding Diffusion bonding	Bonding failure (~10%) Undesired isostatic pressure (flat tiles) Residual/internal stresses

Technology Characteristics

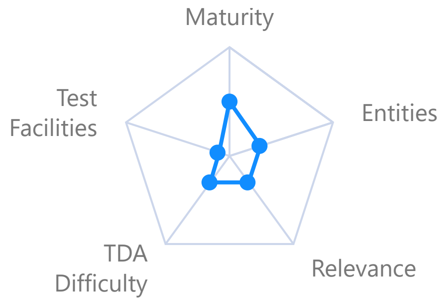
Test Facility Function	Existing test facilities
HIP process optimization Bonding & diffusion validation Residual stress assessment Scale-up trials Qualification & NDT	CEA KIT RHP Technology HELCZA HADES UWB Pilsen

European Entities Involved	
Private	Public
Bodycote Dr Fritsch Research Center for Tools and Materials	CERN KIT FZ Jülich

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Combining with other bonding techniques	40 to 80%	>1M	6 months to 2 years	High	Partially
Process cost reduction	<40%	250k to 1M	6 months to 2 years	Low	No

Transient liquid phase bonding



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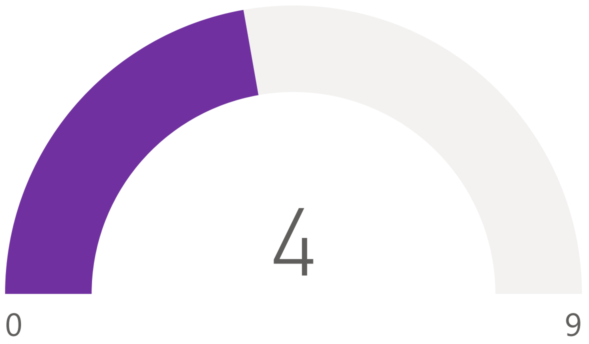
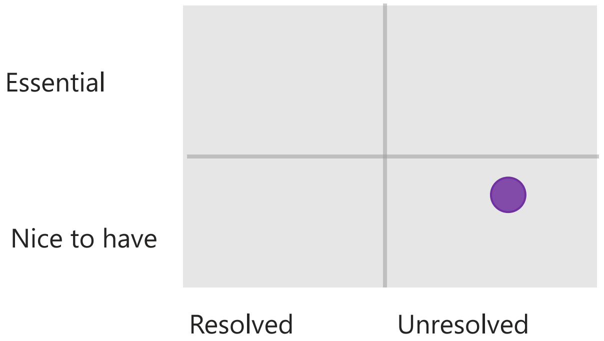




Other Markets ▲	Alternatives	Showstoppers
Electronics Oil and gas Automotive Aerospace	HIP Brazing FAST	Reliability for larger surfaces

Technology Characteristics

Test Facility Function	Existing test facilities ▲
High heat flux and mechanical testing Irradiation testing	HELZCA GLADYS HADES

European Entities Involved

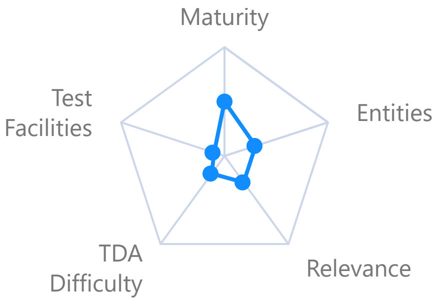
Private ▼	Public
AMAZEMET PVA TePla	

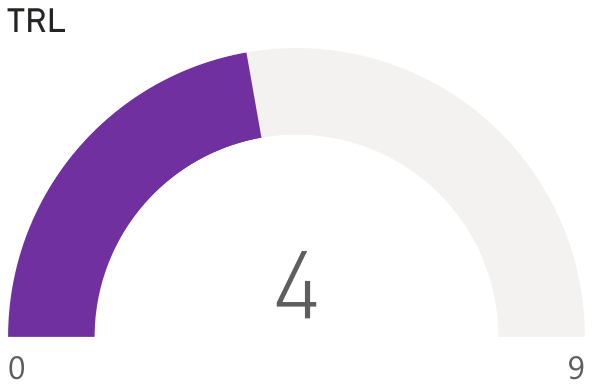
Technology Development Actions

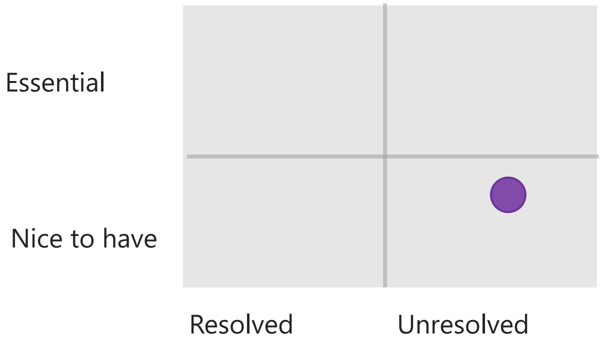
Name	Chances of success ▼	Cost	Implementation Time	Priority	Funded
Qualification of TLPB for CuCrZr to W joint	>80%	<250k	<6 months	Medium	Partially

Plasma facing components › Heat sink

Heat pipes







Other Markets	Alternatives	Showstoppers
Fission Semiconductor	Tungsten monoblocks	Reproducibility

Technology Characteristics

Test Facility Function	Existing test facilities
High heat flux PSI for simulated fusion conditions Real fusion conditions	HADES Magnum WEST

European Entities Involved

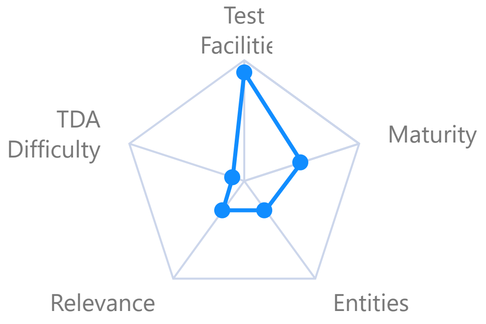
Private	Public
StarWarden Freemelt	Forschungszentrum Jülich DIFFER CEA Fraunhofer IWS

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
3D-printed Heat Pipe Array	40 to 80%	250k to 1M	6 months to 2 years	High	No

Plasma facing components › Heat sink

Activated corrosion products control



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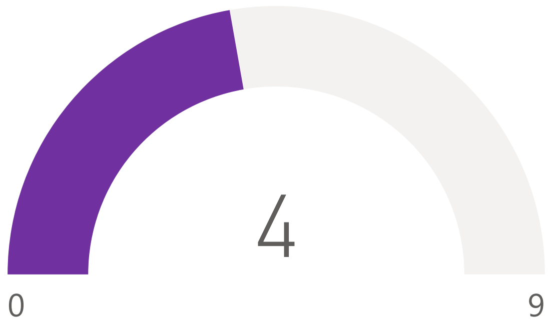
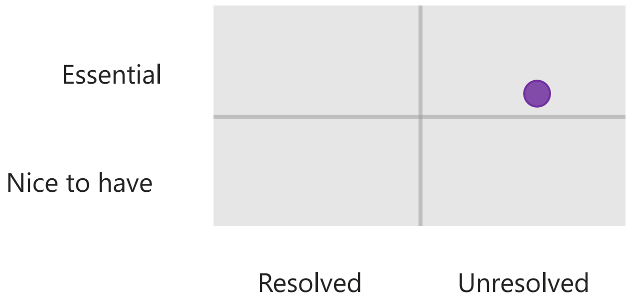




Other Markets	Alternatives	Showstoppers
Fission	Radiation management	Cost
Military	Corrosion-resistant materials	Maintainability

Technology Characteristics

Test Facility Function	Existing test facilities
Qualifications	HELCZA CERN ITER IFMIF-DONES HADES

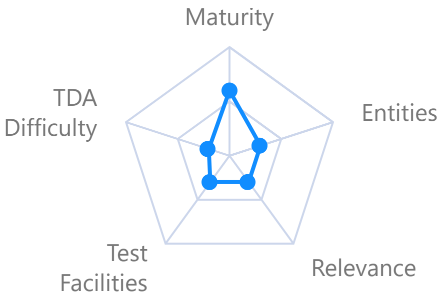
European Entities Involved

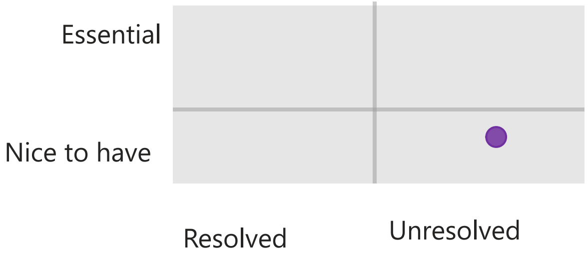
Private	Public
Bodycote	KIT
Tecnatom	CEA
Pro-beam	ENEA
	CIEMAT
	UKAEA

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Development of corrosion-resistant materials and coolants for cooling channels	40 to 80%	250k to 1M	>2 years	High	Partially

Additive manufacturing of complex flow patterns





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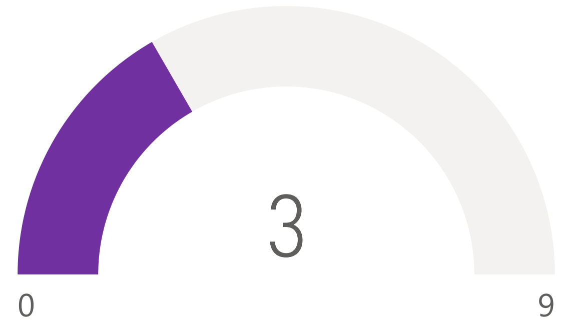


Other Markets	Alternatives	Showstoppers
Semi conductors	Conventional heat pipes	Material properties
Gyrotron cooling	Deep drilling techniques	Scalability
Heat exchange in fission	Diffusion bonding	Cost

Technology Characteristics

Test Facility Function	Existing test facilities
Qualification	HELCZA
Heat testing capacity	CHIMERA
First Panel simulation	AENIUM
	Pro-beam
	OLMAT

European Entities Involved

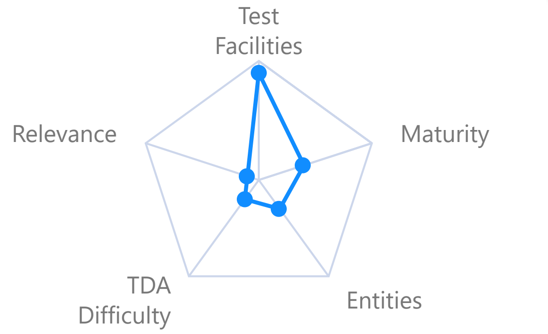
Private	Public
Freemelt	Fraunhofer IWS
AENIUM	CEA
Pro-beam	TUM (LBAM)
StarWarden	
TWI (UK)	
RHP-Technology	
PVA TePla	

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Additive Manufacturing Leak-Tight Tungsten Development	40 to 80%	250k to 1M	6 months to 2 years	Medium	No
Heat transfer and flow characterization	40 to 80%	250k to 1M	>2 years	Medium	No

Plasma facing components › Heat sink

Alternative coolants (He, FLiBe, molten salts)



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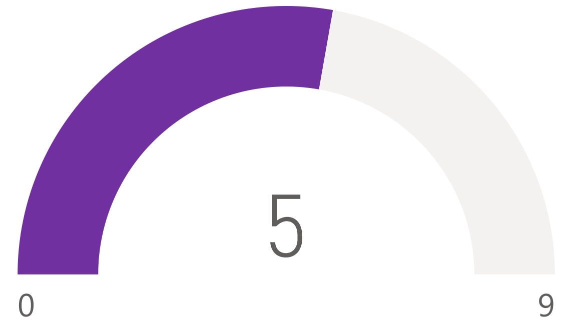
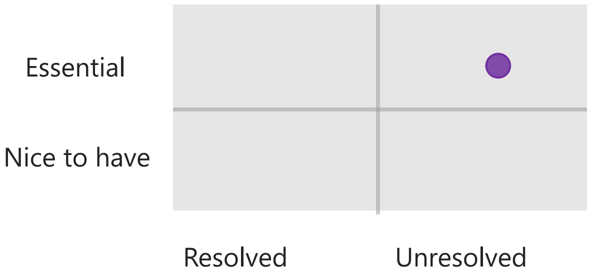




Other Markets	Alternatives	Showstoppers
Fission	Water cooling	Heat transfer & hydraulics Materials compatibility & wear Corrosion control (molten salts, not He) Coolant circulation & pumps System efficiency

Technology Characteristics

Test Facility Function	Existing test facilities
Qualification Performance Corrosion Equipment	HELOKA / KATHELO LIFUS II CiCLo-C (CIEMAT Corrosion Loop)

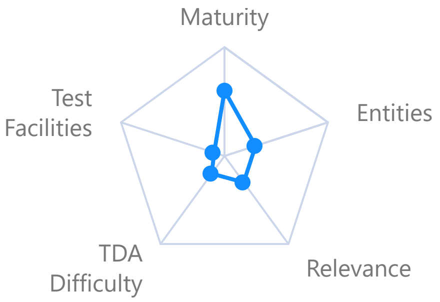
European Entities Involved

Private	Public
Proxima Fusion Thorizon Stellaria Copenhagen Atomics Marvel Fusion Gauss Fusion PVA TePla	KIT CEA ENEA CIEMAT UKAEA (UK)

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Characterization and qualification of alternative coolants for heat removal	40 to 80%	250k to 1M	6 months to 2 years	Medium	Partially

Cooling channel extrusion in bulk material



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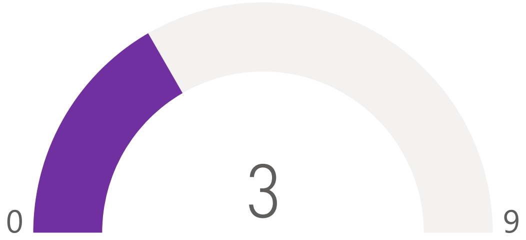


Other Markets

- Electronics cooling
- Big science projects
- Particle accelerators
- Aluminum cooling
- Electronics cooling,
- Semi-conductor fabrication
- Fission
- Automotive
- Aerospace

Alternatives

- Deep drilling
- 3D printing
- Traditional machining

Showstoppers

- Surface roughness & quality
- Qualification requirements
- Post-processing need

Technology Characteristics

Test Facility Function	Existing test facilities
Qualification Performance testing	HELCZA CHIMERA PSI HADES UKAEA ISQ

European Entities Involved

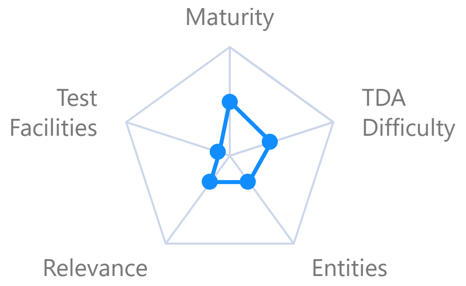
Private	Public
TWI (UK)	UKAEA ESA

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
HHFT-based validation of scale mock-ups to support qualification and technology transfer to industry	40 to 80%	250k to 1M	6 months to 2 years	Medium	No

Plasma facing components › Heat sink

Jet impingement



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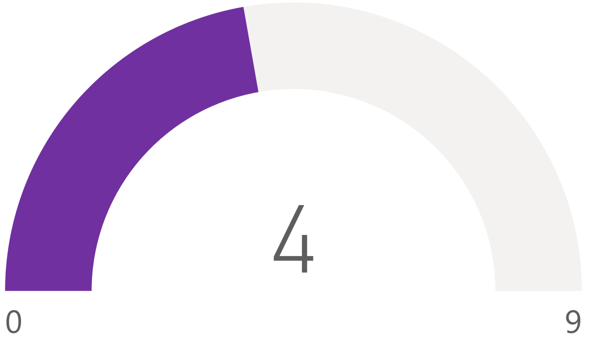

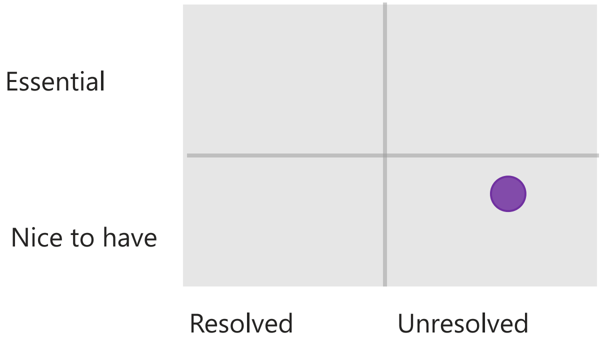

Other Markets	Alternatives	Showstoppers ▲
Electronics Defense Aerospace Automotive	Cooling pipes Pipe arrays	Scalability Energy consumption Space constraints Erosion

Technology Characteristics

Test Facility Function	Existing test facilities ▲
High Heat Flux testing	HELCZA GLADYS HADES JUDITH

European Entities Involved

Private ▼	Public
	IPP Prague

Technology Development Actions

Name	Chances of success ▼	Cost	Implementation Time	Priority	Funded
Design and engineering of full scale industrial prototype	>80%	<250k	<6 months	Low	No
High heat flux testing and qualification of the jet impigment technology	>80%	<250k	6 months to 2 years	Low	Partially

Plasma facing components › Heat sink

Micro-channel heat exchangers

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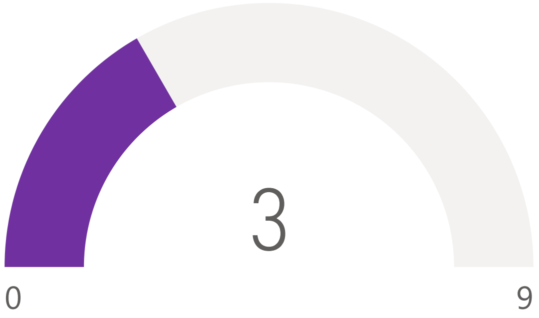
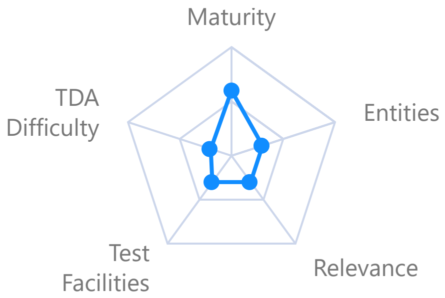




Other Markets	Alternatives	Showstoppers
Semiconductors Gyrotrons	Conventional heat exchangers Diffusion bonding	Flow-rate control Pressure drop Cleanliness Tolerances Corrosion risk Manufacturing complexity

Technology Characteristics

Test Facility Function	Existing test facilities
Qualification Requirements verification Feasibility	HELCZA JUDITH NRG PALLAS HADES

European Entities Involved

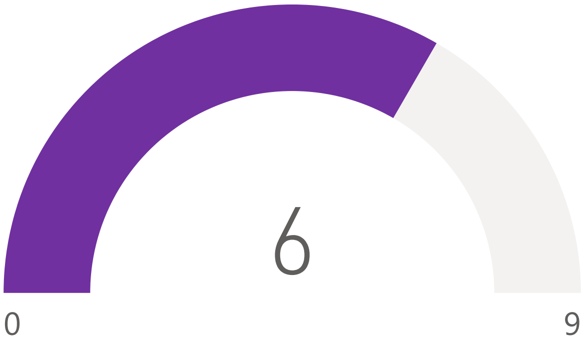
Private	Public
MAHLE Bosch Norsk Hydro TWI Ltd. Kaltra PVA TePla	Fraunhofer ISE / IMM FZ Jülich CTTC-UPC University of Stuttgart

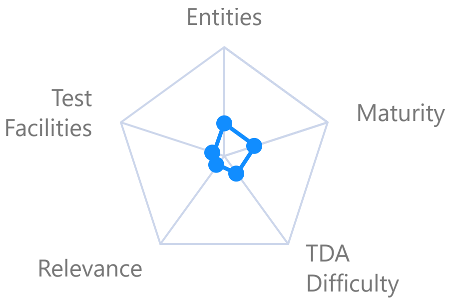
Technology Development Actions

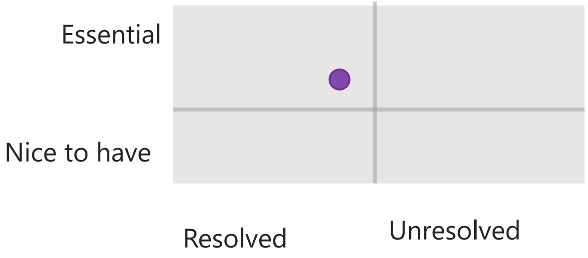
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Exploring fusion application	<40%	250k to 1M	6 months to 2 years	Low	No

Swirl tubes and turbulences promoters

TRL







Other Markets	Alternatives	Showstoppers
Gyrotron cooling	Increased channel density (smaller channels)	Fretting/erosion, heat-flux & DBTT limits
Heat exchangers	High heat-exchange efficiency drivers	Corrosion
Fission	Alternative concepts (e.g. heat pipes)	Modeling
		Vibration

Technology Characteristics

Test Facility Function	Existing test facilities
Corrosion	CEA
Vibration	HADES
Durability	

European Entities Involved

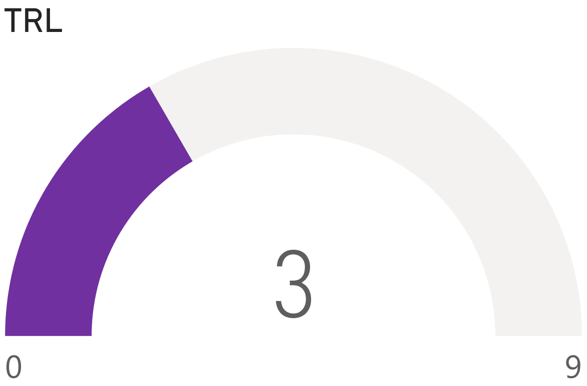
Private	Public
Technip Energies	CEA
JD Turbulators BV	F4E
Be. Tube Srl	ITER
IDOM	
Durafin Tube	
RTC Engineering	

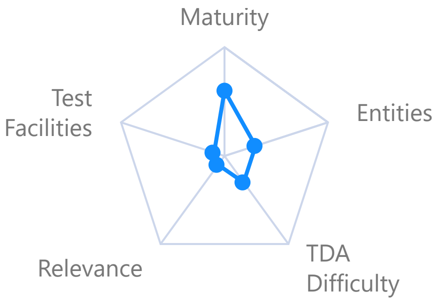
Technology Development Actions

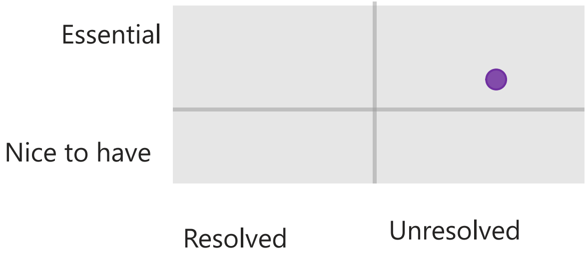
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Characterization and parametrization of swirl tubes	40 to 80%	250k to 1M	6 months to 2 years	High	No

Plasma facing components › Maintainability

Armour repair techniques







Other Markets	Alternatives	Showstoppers
Rotating machinery	Accept reduction in performance	Qualification costs
Coatings	Scrap components	Vacuum, neutron and tritium compatibility
Semiconductor		Oxygen pick-up

Technology Characteristics

Test Facility Function	Existing test facilities
High heat flux	HELCZA
Thermo-mechanical tests	HADES
Life cycling test	

European Entities Involved

Private	Public
Tokamak Energy	RACE (UKAEA)
Dr Frisch	AMRC (UK)
Gauss Fusion	

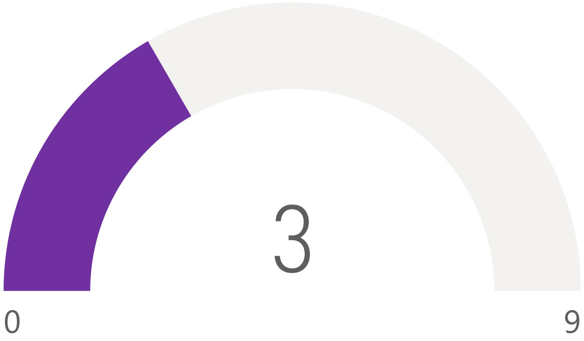
Technology Development Actions

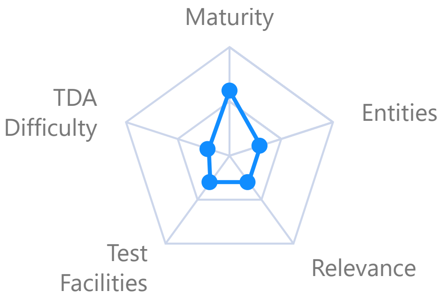
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Define acceptance criteria for damaged tiles	>80%	<250k	<6 months	High	No
Evaluate and qualify possible solutions for factory repairs	>80%	>1M	6 months to 2 years	Medium	Partially
Evaluate and qualify possible solutions for in situ repairs	40 to 80%	>1M	6 months to 2 years	Medium	Partially

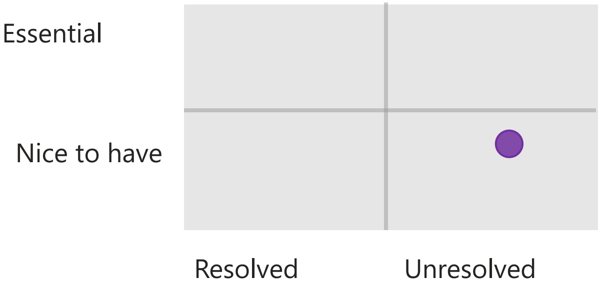
Plasma facing components › Maintainability

Embedded erosion monitoring

TRL







Other Markets	Alternatives	Showstoppers
Space	Diagnostics and viewing systems	Reliability
Offshore	Remote inspections	Added complexity
Fission		
Mining		

Technology Characteristics

Test Facility Function	Existing test facilities
Gamma irradiation facility	Magnum PSI DIPHER
Research tokamak	GLADIS - IPP Garching
"Erosion generator" - sputtering	Miami (UK)

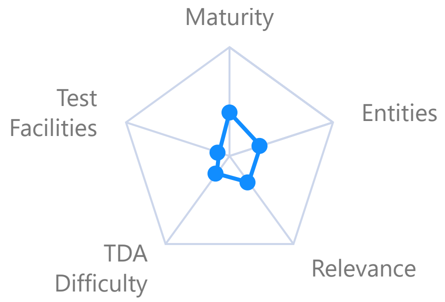
European Entities Involved	
Private	Public
Oxford Sigma	CEA
Gauss Fusion	

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Assess possibility to use the embedded UT sensor solution in fusion application	40 to 80%	250k to 1M	6 months to 2 years	Medium	No
Assess feasibility of graded tungsten armour monitoring via released chemical compounds	>80%	<250k	6 months to 2 years	Medium	No

Plasma facing components > Maintainability

Piping for remote handling



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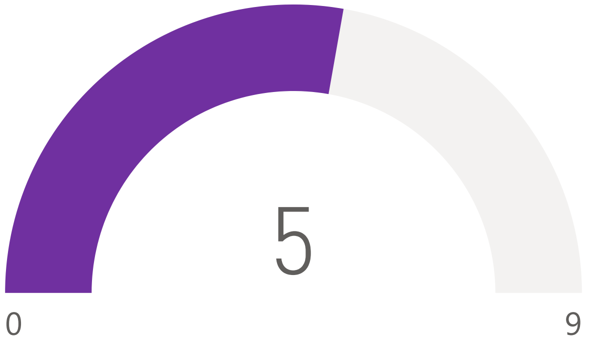
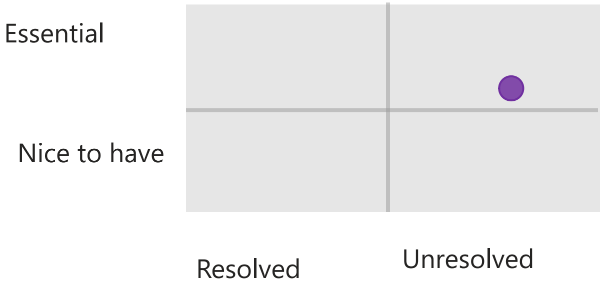




Other Markets	Alternatives	Showstoppers
Sub-sea	Demountable joints	Limited access
Space		Limited piping flexibility
Fission		Impact on machine downtime
		Harsh environment

Technology Characteristics

Test Facility Function	Existing test facilities
Remote handling test facility Mock-up	RACE (UKAEA) ITER test facility

European Entities Involved

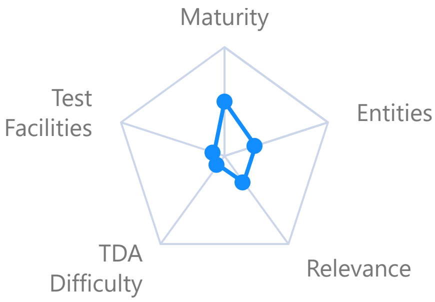
Private	Public
Jacobs	RACE
Gauss Fusion	ITER
	VTT
	ENEA
	CEA

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop prototype machine to align, weld and inspect joints remotely	40 to 80%	>1M	>2 years	High	Partially
Qualify prototype for fusion reactor conditions	40 to 80%	>1M	>2 years	Medium	Partially
Develop Modular PFC manifold design limiting number and type of joints	>80%	<250k	<6 months	Medium	No
Develop Remote Handling Test Facility	>80%	>1M	>2 years	High	Partially
Develop Remote-Handled Piping Standards					

Plasma facing components › Maintainability

Reversible pipe joints



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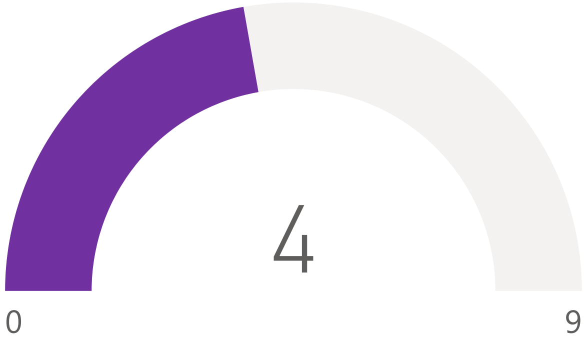
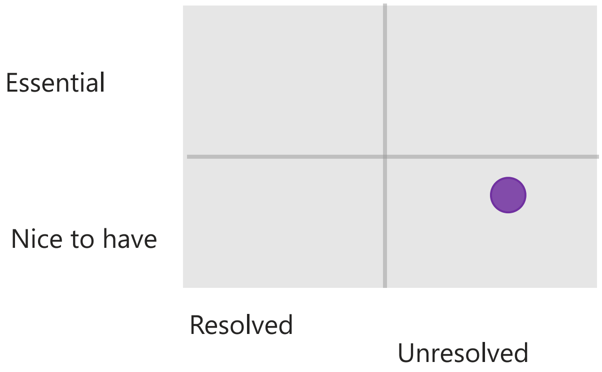




Other Markets	Alternatives	Showstoppers
Space	Cut and reweld	Limited space
Oil and Gas		Qualification requirements
Chemical		High mechanical loads
Subsea		Robustness
Fission		

Technology Characteristics

Test Facility Function	Existing test facilities
Remote handling test facility Pressure and leak test Research tokamak for operational test	

European Entities Involved

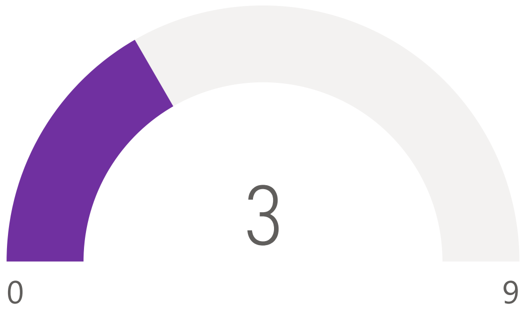
Private	Public
Garlock Technetics Eiffage-SPG Gauss Fusion	UKAEA

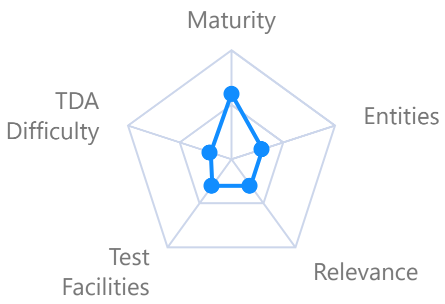
Technology Development Actions

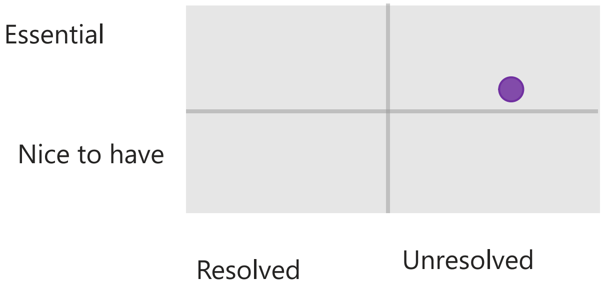
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Evaluate solutions for a 50 to 80 mm pipe (proof of principle) - swaged connection vs seals	>80%	250k to 1M	6 months to 2 years	High	Partially
Develop requirements for standard reversible joint (load, leak tightness, operating range, diameter etc).					

High performance copper alloys

TRL







Other Markets	Alternatives	Showstoppers
Aerospace	Multiple heat-sink material options available	High-temperature softening
Defense	Diffusion bonding	Creep limitations
Particle accelerators		Grain growth
Industrial applications		Oxidation / corrosion
		Conductivity–strength trade-off
		Manufacturing complexity
		Scalability constraints

Technology Characteristics

Test Facility Function	Existing test facilities
Heat flux test facility	HELCZA
Corrosion-erosion test facility	IFMIF-DONES
Neutron irradiation test facility	CERN
Vacuum and outgassing	ITER
	HADES
	OLMAT
	UWB Pilsen

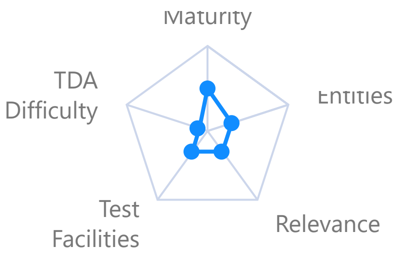
European Entities Involved

Private	Public
Luvata	CEA
Studsvik	ENEA
Outokumpu Ltd	FZ Jülich
RHP-Technology	KIT
	CIEMAT
	Fraunhofer IWS

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Development and qualification of ODS copper	>80%	250k to 1M	6 months to 2 years	High	

Silicon carbide



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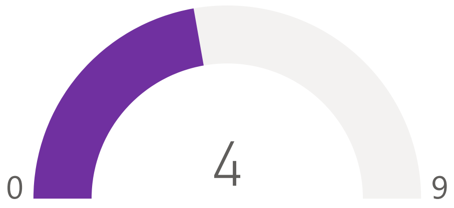
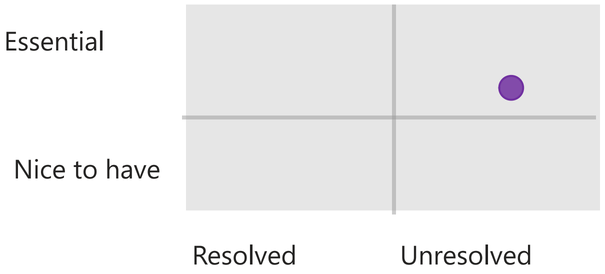




Other Markets

- Aero Engines
- Space
- Defense
- Fission
- Industrial Gas Turbines
- Pumps

Alternatives

- Emerging ductile composites (unexplored).

Showstoppers

- Fusion data gap
- Irradiation performance
- Structural reliability
- Cooling integration
- Manufacturing scalability
- Qualification & licensing
- Challenges (not showstoppers)
- Porosity
- Vacuum compatibility
- Complex geometries
- Bonding/joining technologies

Technology Characteristics

Test Facility Function

- Heat flux test facility
- Corrosion-erosion test facility
- Neutron irradiation test facility
- Vacuum and outgassing

Existing test facilities

- HELCZA
- IFMIF-DONES
- CERN
- ITER
- HADES
- OLMAT
- UWB Pilsen

European Entities Involved

Private

- BJS Composites
- Safran Ceramics
- Schunk
- DLR
- Petroceramics
- PVA TePla

Public

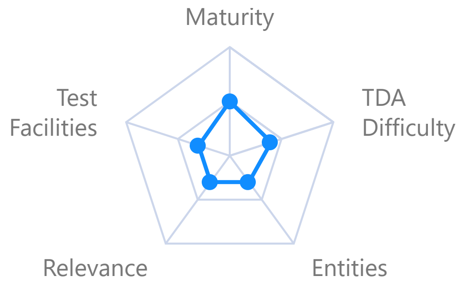
- HELZCA
- IFMIF-DONES
- CERN
- ITER
- CIEMAT

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Development of commercial fusion-grade SiC/SiC	>80%	>1M	>2 years	High	

Plasma facing components > **PFC design**

Advanced tile geometries (hexagonal, isotropic)



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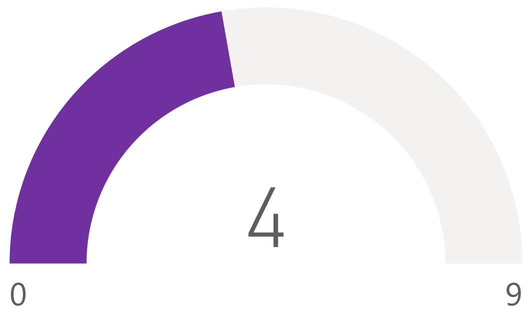
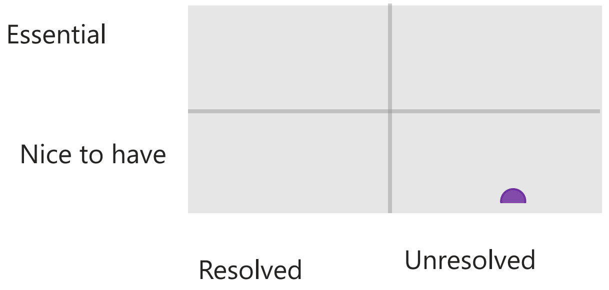




Other Markets	Alternatives	Showstoppers
Aerospace	Mesh / sponge structures	Thermo-mechanical integrity
Semiconductor	Conventional tiles	Manufacturability & reproducibility
		Bonding & interface reliability
		Qualification & validation
		Maintainability & lifecycle

Technology Characteristics

Test Facility Function	Existing test facilities
Thermal & structural performance testing Manufacturing & geometric validation Interfaces, surfaces & material integrity Qualification, inspection & lifecycle validation	HADES GLADIS MAST Upgrade TWI Laboratories (Granta Park) TÜV NORD Testing & Inspection Laboratories OLMAT

European Entities Involved

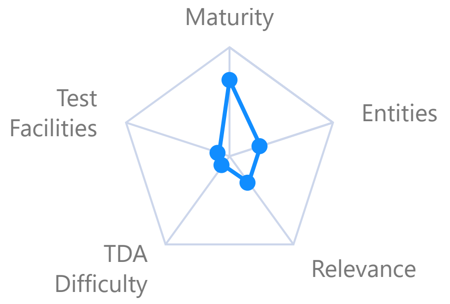
Private	Public
TWI – The Welding Institute	CEA
TÜV NORD	IPP
RHP-Technology	UKAEA / CCFE Culham
	CIEMAT

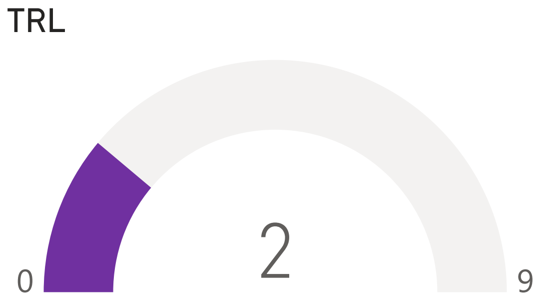
Technology Development Actions

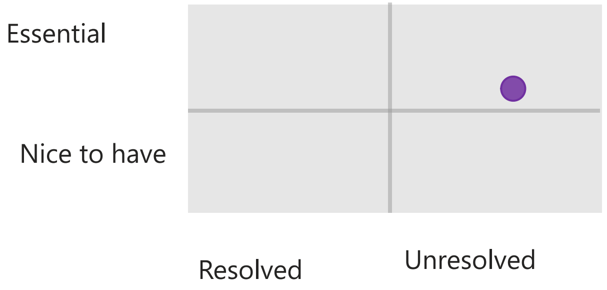
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop software to define and optimize tile geometry also across thickness	>80%	<250k	6 months to 2 years	Medium	Partially

Plasma facing components › PFC design

Lifecycle prediction models







Other Markets	Alternatives	Showstoppers
Aerospace Semiconductors Fission Automotive	Testing	Lack of relevant neutron source for validation Insufficient benchmarking data available Neutron damage on the bulk Hardly predictable fatigue of the armour to heat sink joint Immaturity of theoretical models for thermo-structural integrity evaluation

Technology Characteristics

Test Facility Function	Existing test facilities
Lifecycle testing	IFMIF-DONES GLADIS JUDITH-2 Magnum-PSI JET HADES

European Entities Involved

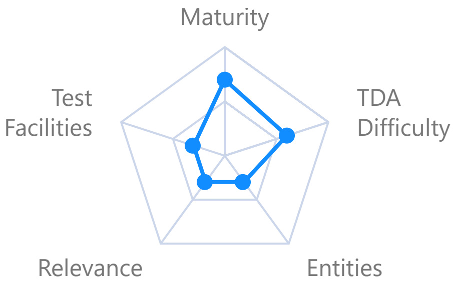
Private	Public
Framatome Assystem Tractebel STEP (UK) Oxford-Sigma Gauss Fusion	EUROfusion F4E CEA FZ Jülich IPP UKAEA

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Integrated modelling and funding for testing	>80%	>1M	>2 years	Medium	Partially

Plasma facing components > PFC design

Liquid metal walls



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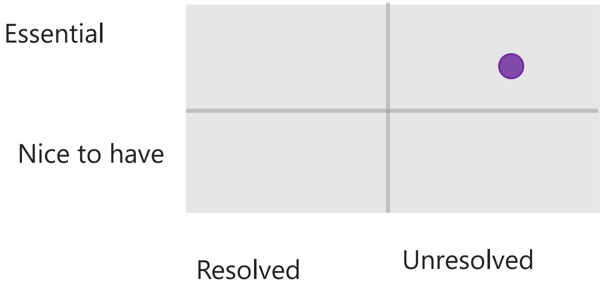


Other Markets	Alternatives	Showstoppers
Fission	Solid walls	Low maturity & practicality Operational constraints Plasma compatibility risks Integration challenges Safety

Technology Characteristics

Test Facility Function	Existing test facilities
Plasma–liquid metal interaction & compatibility High heat-flux and transient load testing Liquid metal flow, stability & CPS validation Component integration & lifetime assessment	Magnum-PSI LiMeS-Lab DTT HADES OLMAT UWB Pilsen

European Entities Involved

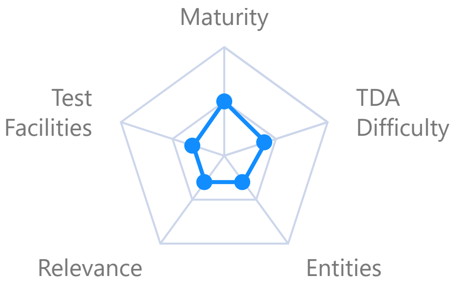
Private	Public
Renaissance Fusion	DIFFER CEA ENEA Frascati CIEMAT IPP Prague

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Economic and maintenance assessment in powerplant context	>80%	<250k	<6 months	Low	Partially

Plasma facing components › PFC design

Monolithic HIPed panels



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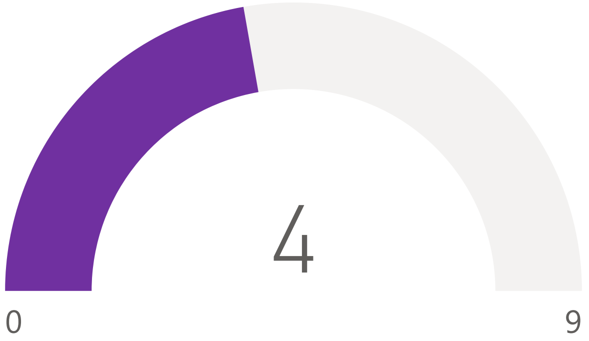

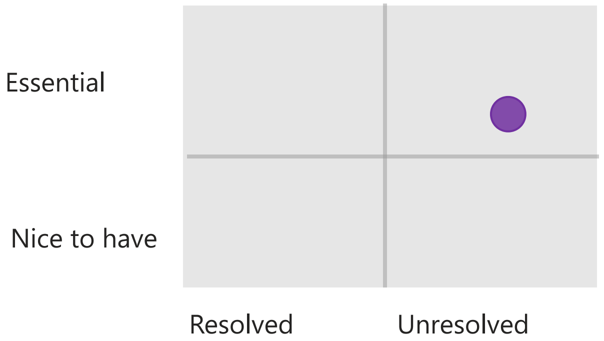

Other Markets	Alternatives	Showstoppers
Space aplications	Hypervapotron Additive / bonded / bolted Diffusion bonding	Manufacturing cost Part lifetime uncertainty / sputtering risk Scale-up to large dimensions Large-scale defect screening

Technology Characteristics

Test Facility Function	Existing test facilities
HHFT (incl. impurity contamination / outgassing) Neutron irradiation Hot-cell maintainability	HELCZA (CVR) GLADIS HADES JUDITH OLMAT

European Entities Involved

Private	Public
Plansee Group H.C. Starck Solutions ALSYMEX OC Oerlikon Gauss Fusion PVA TePla	CVR FZ Jülich IPP CEA CIEMAT

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Simplified Repairable Manufacturing	>80%	<250k	6 months to 2 years	Low	No

Non-copper heat sinks

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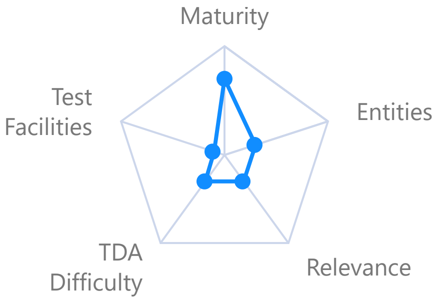
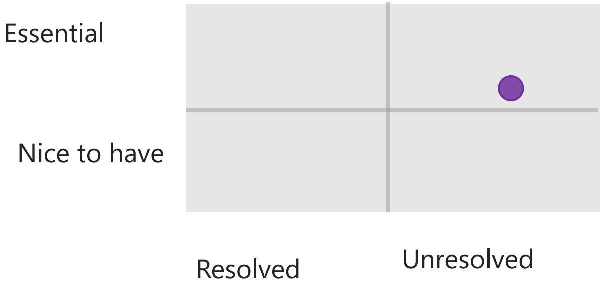




Other Markets	Alternatives	Showstoppers
Aerospace propulsion Heat exchangers Semiconductors	Heat pipes Custom cold plates Copper alloys Multi-material additive manufacturing Steel Diffusion bonding	Material & thermal limitations: Poor conductivity Low thermal diffusivity

Technology Characteristics

Test Facility Function	Existing test facilities
High-heat-flux thermal loading Active cooling performance validation Thermo-mechanical integrity assessment Thermal fatigue & cyclic loading tests Failure mode identification (cracks, leaks, joints)	HELCZA GLADIS HADES UWB Pilsen

European Entities Involved

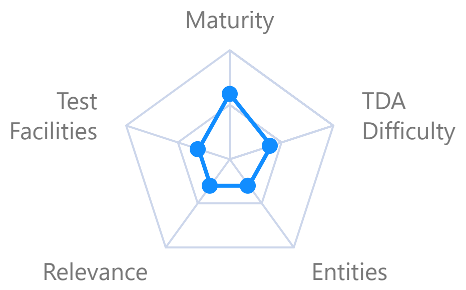
Private	Public
Plansee Rosswag Pro-beam AMCM AENIUM Gauss Fusion RHP-Technology PVA TePla	IPP CEA CVŘ KIT FZJ TUM (LBAM) Fraunhofer IWS

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Development of Copper-free high-temperature cooling components	40 to 80%	250k to 1M	6 months to 2 years	High	Partially

Plasma facing components › PFC design

Segmented finger panels



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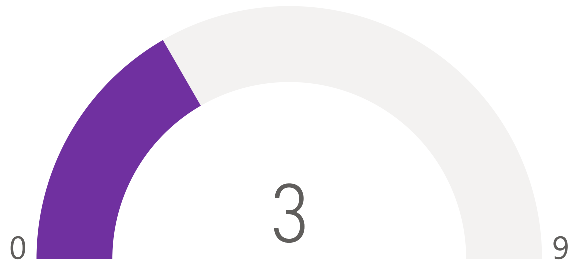
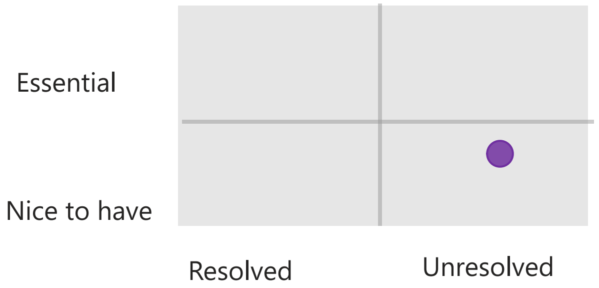




Other Markets	Alternatives	Showstoppers
	Liquid-metal PFC option Smaller blocks / panels Associated integration challenges	Maintenance & finger alignment Manufacturing complexity Manufacturing cost Extensive welds / coolant joints Weld qualification (in-reactor)

Technology Characteristics

Test Facility Function	Existing test facilities
HHFT (incl. impurity contamination & outgassing) Neutron irradiation effects Hot-cell maintainability	HELCZA GLADIS HADES JUDITH OLMAT

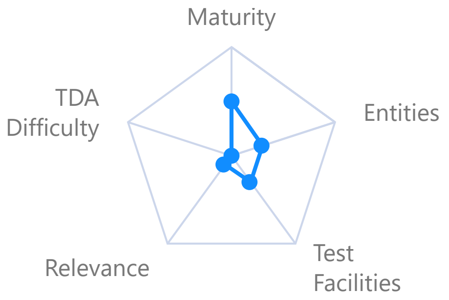
European Entities Involved

Private	Public
Plansee Group Ansaldo Energia / Leonardo supply chain TWI Ltd (UK) Gauss Fusion Kyoto Fusioneering (Europe) ALSYMEX Leading Freemelt	UKAEA Max Planck Institute for Plasma Physics (IPP) IPP Prague CIEMAT Fraunhofer IWS

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Prototyping of modular panels	>80%	<250k	6 months to 2 years	Medium	No

3D printed and functionally graded tungsten



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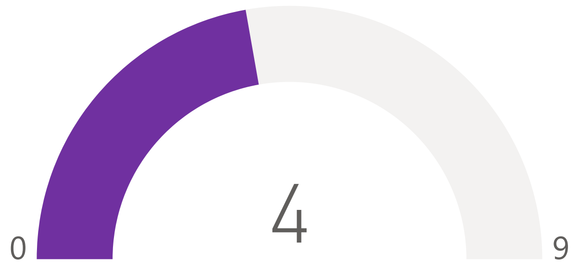
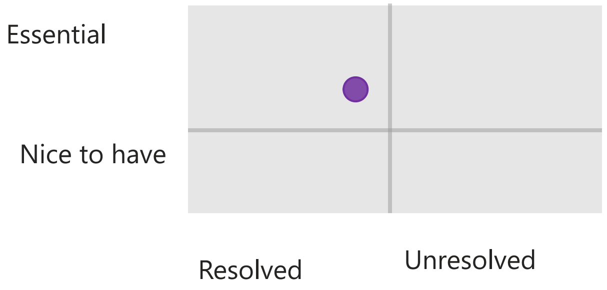




Other Markets	Alternatives	Showstoppers
Wear-resistant coatings	Rolled & forged W (subtractive machining)	HHFT & neutron performance
Aerospace	Coatings	High-stress multi-material joints
Defense	W-based composites	Brittleness, cracking & porosity
	Pressure-assisted / pressure-less sintering	Powder supply & cost

Technology Characteristics

Test Facility Function	Existing test facilities
Vacuum & outgassing	LAB
HHFT (fast / simulated)	HIVE
Production concepts	HELCZA
Thermal stability	JUDITH
NDT (UT & alternatives)	HADES
Powder quality & batch repeatability	OLMAT
	UWB Pilsen

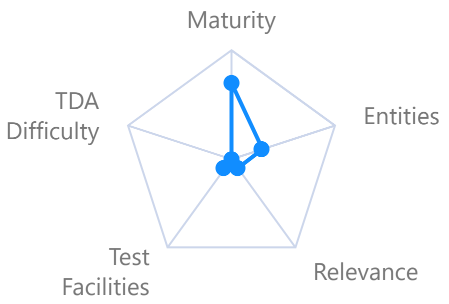
European Entities Involved

Private	Public
Freemelt	Fraunhofer (IGCV, IWS, IFAM)
Plansee	UKAEA
CERATIZIT	Max Planck Institute for Plasma Physics (IPP)
Sandvik	IPP Prague
Incus	TUM (LBAM)
Gauss Fusion	
Pro-beam	
RHP-Technology	

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Benchmark additive manufacturing routes for monoblock PFCs	>80%	>1M	>2 years	High	Yes

Ductile tungsten composites



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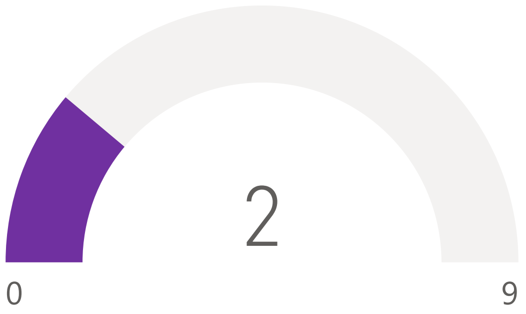
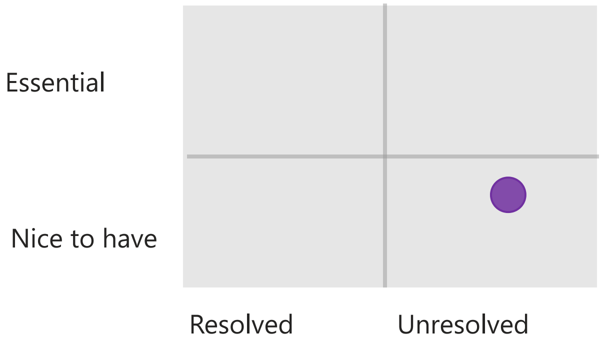




Other Markets	Alternatives	Showstoppers
Defense	Conventional rolled and forged W (machining of material by subtractive manufacturing) 3D printed W Coatings W-based composites Pressure-less or Pressure assisted sintering	Interface stability at high temperatures Degradation or reduction of required material properties In-situ repair capabilities and joint performance, including cost, industrial fabrication issues, gas entrapment, and irradiation damage Low melting point of certain phases Low technology maturity

Technology Characteristics

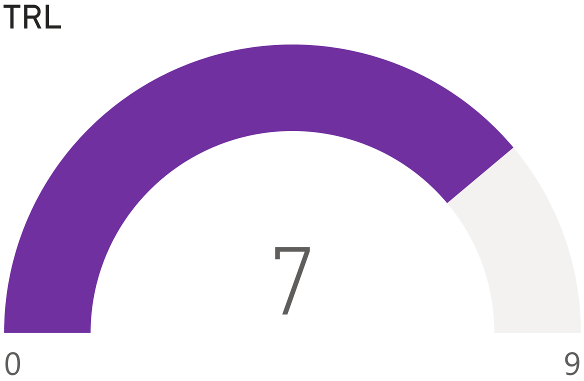
		European Entities Involved	
Test Facility Function	Existing test facilities	Private	Public
	HADES		

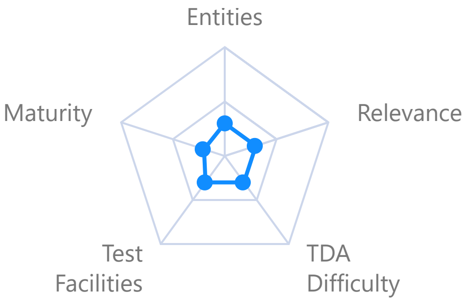
Technology Development Actions

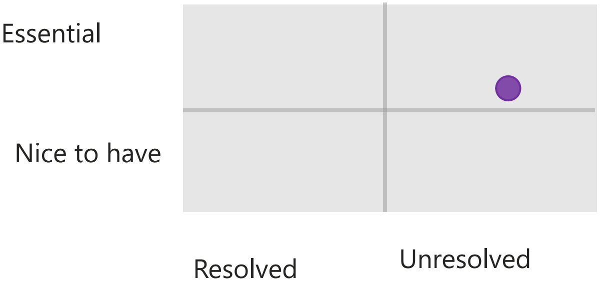
Name	Chances of success	Cost	Implementation Time	Priority	Funded

Plasma facing components › Tungsten materials

High purity forged tungsten







Other Markets	Alternatives	Showstoppers
Welding Defense	AM tungsten components	Availability constraints Cost drivers Long lead times Manufacturing complexity

Technology Characteristics

Test Facility Function	Existing test facilities
HHFT test facilities High-temperature mechanical properties Chemical composition testing Irradiation testing	HELCZA GLADIS HADES SCK CEN FZ Jülich OLMAT UWB Pilsen

European Entities Involved

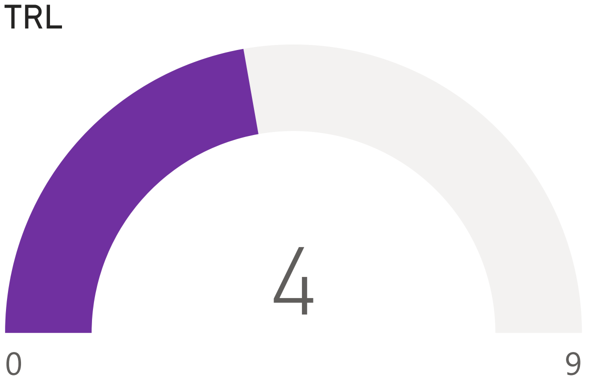
Private	Public
Plansee Group	FZ Jülich
H.C. Starck Solutions	CEA-IRFM
ALMT Europe	EUROfusion
Wolfram Bergbau	SCK CEN
Kyoto Fusioneering Europe	NRG
Gauss Fusion	CIEMAT

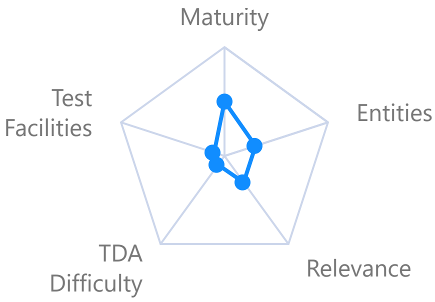
Technology Development Actions

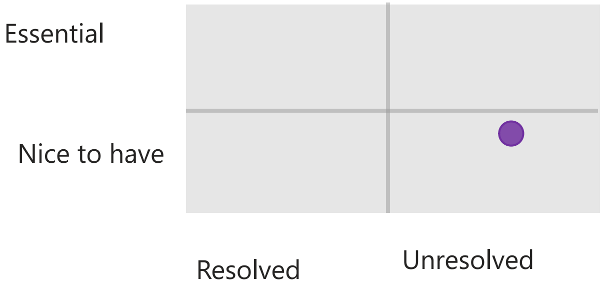
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop W armour Repair techniques	40 to 80%	250k to 1M	6 months to 2 years	Medium	Yes
Develop a Low-HF for PFCs	40 to 80%	250k to 1M	<6 months	Medium	Yes
Assess the applicability of lower-quality, damaged or alloyed tungsten materials	40 to 80%	250k to 1M	6 months to 2 years	High	Yes

Plasma facing components › Tungsten materials

Irregular tungsten powder







Other Markets	Alternatives	Showstoppers
Wear-Resistant Tooling	Rolled & forged W (subtractive machining)	Density
Defense	Coatings	Surface quality
Aerospace	W-based composites	Geometry
Nuclear	Pressure-assisted / pressure-less sintering	Mechanical properties
		Material purity

Technology Characteristics

Test Facility Function	Existing test facilities
Particle size distribution	Fraunhofer (IFAM, IWS)
Particle morphology	UKAEA (Culham)
Powder flowability	University of Birmingham
Packing / apparent density	CEA
Chemical purity	BAM
	HADES

European Entities Involved

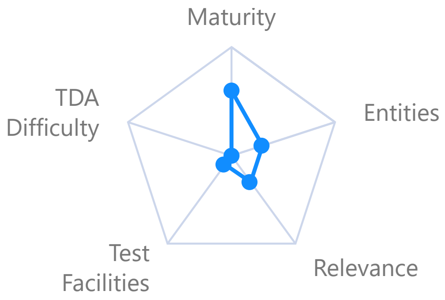
Private	Public
H.C. Starck Tungsten Powders	Fraunhofer IFAM
Global Tungsten & Powders	BAM
Plansee Group	CEA
Kennametal Europe	UKAEA
Sandvik Hard Materials	IPP

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
European Supply Chain Development	40 to 80%	>1M	>2 years	High	Yes

Plasma facing components › Tungsten materials

Tungsten alloys



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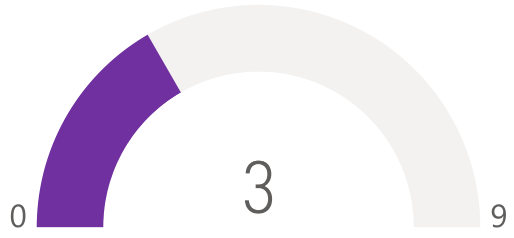

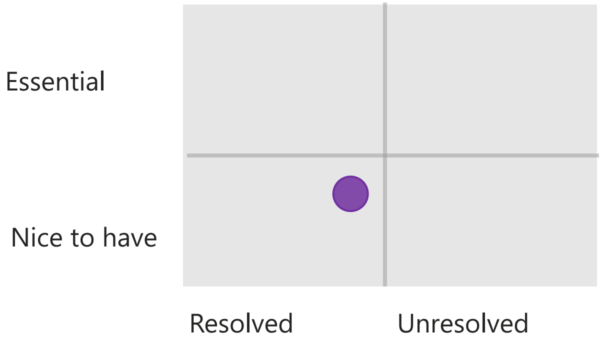

Other Markets	Alternatives	Showstoppers
Mechanical engineering and manufacturing applications Tool coatings and components for wear-resistant applications Defense and military applications, including wear-resistant parts and sintered carbide cutting tools Aerospace and defense sectors Radiation shielding applications	3D printed W Conventional rolled and forged W Coatings W-based composites Pressure-less or Pressure assisted sintering	Intrinsic brittleness and low ductility Degradation of mechanical properties under neutron irradiation Material erosion and plasma contamination Instability of interfaces and joints with other materials Low technological maturity of advanced tungsten alloys Manufacturing difficulties Limited industrial availability and high costs

Technology Characteristics

Test Facility Function	Existing test facilities	European Entities Involved	
		Private	Public
	HADES		

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded