UK Atomic Energy Authority

Fusion Technology
Year in Review 2024-25

The UK Atomic Energy Authority's mission is to deliver sustainable fusion energy and maximise scientific and economic benefit.

The Fusion Technology Division's vision is to develop a qualified suite of all technologies needed to realise deployable commercial fusion power plants.

Contents

List of Abbreviations/Acronyms

Abbreviation/Acronym	Name
ACP	Activated Corrosion Products
AM	Additive Manufacturing
AMT	Applied Materials Technology
ART	Applied Radiation Technology
BB	Breeding Blankets
BZ	Breeding Zone
CAD	Computer-Aided Design
CAV	Computer Aided Validation
CDT	Centre for Doctoral Training
CFD	Computational Fluid Dynamics
CHF	Critical Heat Flux
CHIMERA	Combined Heating and Magnetic Research Apparatus
CuCrZr	Copper-Chrome-Zirconium material
DAGMC	Direct Accelerated Geometry Monte Carlo
DIC	Digital Image Correlation
DNB	Departure from Nucleate Boiling
DWT	Double Wall Tube
EMAT	Electromagnetic Acoustic Transducer
ENEA	Italian National Agency for New Technologies Energy and Sustainable Economic Development
EPSRC	Engineering and Physical Sciences Research Council
EU-DEMO	EUROfusion Demonstration
EUROFER97	European Reduced Activation Ferritic Martensitic steel
F4E	Fusion for Energy
FEM	Finite Element Method
FOSTER	Fusion Opportunities in Skills, Training, Education and Research
FT	Fusion Technology
HIP	Hot Isostatic Pressing
HIVE	Heating by Induction to Verify Extremes
HPGe	High Purity Germanium
HTS	High-Temperature Superconductor
ITER	International Thermonuclear Experimental Reactor Organisation
LIBRTI	Lithium Breeding Tritium Innovation
LMD	Laser Metal Deposition
L-PBF	Laser Powder-Bed-Fusion Process
MBSE	Model-Based Systems Engineering
MDA	Minimum Detectable Activity
MHD	Magnetohydrodynamic
MLCSA	Machine Learning Compton Suppression Algorithm
MOAB	Mesh-Oriented Database
MTEQ	Manufacturing Technology Equipment Qualification
NBI	Neutral Beam Injector
PbLi	Lead-lithium
PM	Powder Metallurgy
PMU	Prototype Mock-up Unit
PPMI	Power Plant Modelling and Integration
RAMI	Reliability, Availability, Maintainability, Inspectability
RNN	Recurrent Neural Network
RPI	Rensselaer Polytechnic Institute
SmalLab	Surrogate MAgnetohydrodynamic Liquid-metal Laboratory
STEP	Spherical Tokamak for Energy Production
TBM	Test Blanket Module
UAM	Ultrasonic Additive Manufacturing
UKAEA	UK Atomic Energy Authority
UKIFS	United Kingdom Industrial Fusion Solutions
UKRI	United Kingdom Research and Innovation
VNS	Volumetric Neutron Source
W	Tungsten element
WCLL	Water-Cooled Lead-Lithium
XCT	X-ray Computed Tomography

Introduction

The Fusion Technology (FT) Division, one of seven technical divisions in the United Kingdom Atomic Energy Authority (UKAEA), has presence at Culham Campus (Abingdon, Oxfordshire), and the Fusion Technology Facility (Rotherham, South Yorkshire).

FT manages diverse technical specialisations, which are critical to the realisation of commercial fusion, and supports UKAEA's aim to lead the delivery of fusion power and maximise economic impact. As of FY25, Fusion Technology is split into six groups, with a seventh group on magnet technologies due to be created early in the next financial year. Each group and activities therein are making a meaningful contribution to UK research programmes, international collaborations, and to third-party private fusion companies .

FT has been a key contributor to the progress on the UK's proposed Spherical Tokamak for Energy Production (STEP) project, specifically in the development of integrated power plant models, neutronics, materials and manufacturing. Commercially, FT has observed an increasing level of engagement with third-party, start-up fusion organisations, and strong interest in prototype-scale, joint grant bids within the Yorkshire region. FT's engagement with the EUROfusion Demonstration (EU-DEMO) reactor programme community has continued, creating strategic relationships into the International Thermonuclear Experimental Reactor (ITER) programme via the ITER Organisation and Fusion for Energy (F4E). FT is contributing to the future of fusion research through funding PhD projects in the FT Engineering and Physical Sciences Research Council (EPSRC) Research Programme. Technical groups are increasingly focusing to attract high calibre staff , in conjunction with developing subject matter training to make sure that a skills pipeline is developed for each discipline.

FT continues to deliver world leading, essential assessments and research for the UKAEA, ITER Organisation, EU-DEMO and STEP programmes in:

- State-of-the-art small-scale tensile testing
- High heat flux testing
- Nuclear response modelling to determine radiological fields
- Utilising liquid metals to inform component design
- Whole plant design, integration and analysis through code development
- Improving the supply chain and updating manufacturing processes.

To support FT's work, significant time has been invested up-skilling existing staff, and understanding the Division's current resources. A skills, competency and behavioural framework has been implemented for each group within the Division. The new framework realises the individual skills and competencies needed to perform and succeed. Furthermore, it has enhanced and improved the training development budget by prioritising development, creating skills pipelines, and knowledge transfer to enable multiple subject matter experts. FT has introduced regular meetings to update information on staff resource, skill types and time management.

This document presents a selection of research highlights completed by the Fusion Technology Division for the year 2024/2025.

Accelerating the Materials Knowledgebase

- Fusion power promises ambitious timeframes with materials that are actively being developed.
- Materials qualification, by standard means, is traditionally slow and expensive.
- The Fusion Technology Division is pioneering a new approach to materials qualification that will permit acceleration of regulatory acceptance within these ambitious timeframes. This includes simulation-led qualification, developing new methods to extract more information from fewer physical specimens, and establishing new materials testing capabilities.
- The Division plays a leading role in developing materials testing technologies within the EU-DEMO materials and engineering design integration programmes. The Division works closely with several universities (University of Bristol, University of Manchester, University of Southampton, and The Open University) through dedicated research and development funding. Extreme environment materials are common across non-fusion partners; FT works with key collaborators in nuclear fission and defence on high temperature assessments and with the aerospace industry on low temperature assessments.

Surrogate Modelling of Microstructurally Informed Material Deformation

Establishing computationally efficient structure-property relationships in fusion engineering materials to simulate their response in untestable fusion environments.

Microstructurally informed (physical) material models are key to understanding the performance of materials in untestable fusion environments. Although some models exist with good predictive capability, these are "compute-intensive", and practical application is limited. Surrogate models act as fast-executing estimations of physical models, trained with simulation data and run by varying parameters of interest.

Members of the Fusion Technology Division and Computing Division have developed a microstructurally informed surrogate model to predict the deformation behaviour of fusion materials, as show in Figure 1. The model is trained using data from a complex full-field crystal plasticity model, and a Recurrent Neural Network (RNN) to approximate the average stress response history from a given loading history and microstructure (see Figure 2). Once trained the surrogate executes within a fraction of a second, compared to an hour for the underlying physical model, as illustrated in Figure 3.

Applications are being developed, including integration into uncertainty quantification algorithms and material models at component length-scale, thereby enabling practical application.

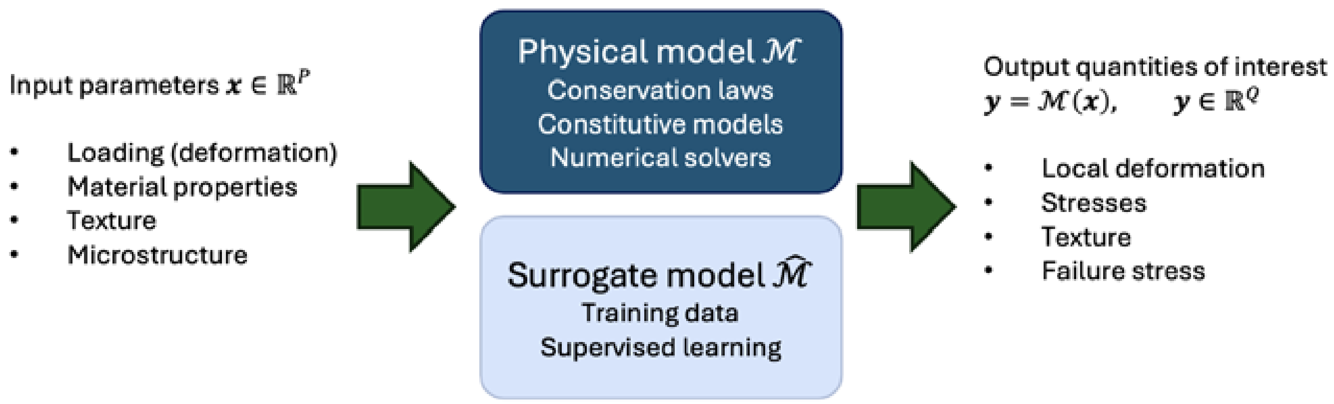


Figure 1: Examples of abstracted numerical inputs and outputs of interest to both physical and surrogate models. The surrogate model operates directly on these numeric vectors, whereas the physical model may have more complex representations.

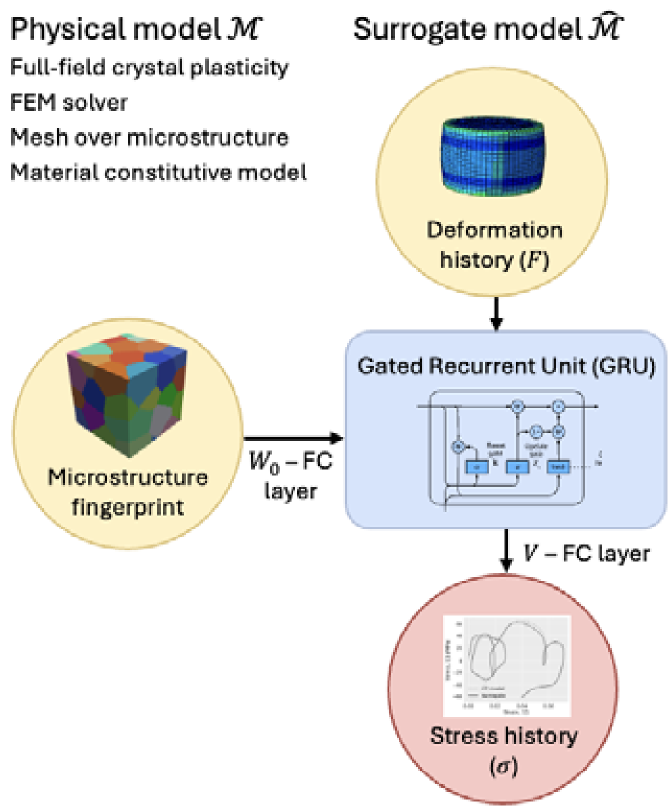


Figure 2: Overview of the surrogate model produced where microstructure is used to create an initial state, and the time-resolved output of stress response is predicted for an input loading history.

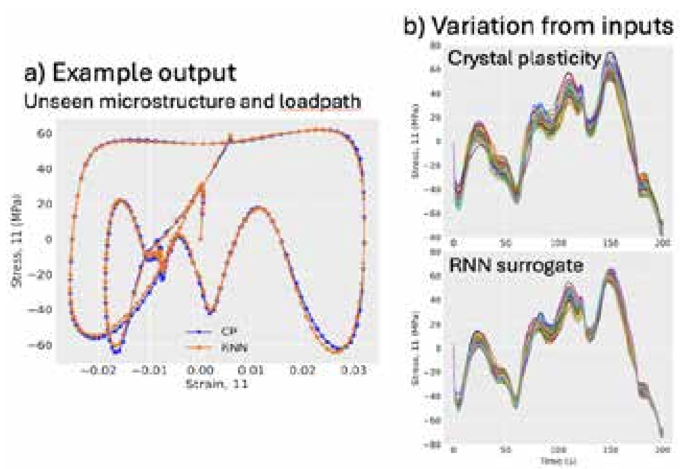


Figure 3: Plots showing a) comparison of physical and trained surrogate models for a complex load path and microstructure; and b) comparison of physical and trained surrogate models where 100 different microstructures have been modelled. While responses between the two models are in good agreement, each crystal plasticity simulation would take up to an hour to run, while each run of the RNN surrogate would take less than 10 minutes.

Materials Testing 2.0 (MT2) for Creep

Complex geometry creep specimens have been designed and tested at high temperature with advanced measurement techniques, demonstrating more data from a single test.

Shape optimisation routines were developed to optimise a specimen geometry with multiple stress states. Digital Image Correlation (DIC) was used to measure creep deformation at high temperature, seen below in Figure 4.

An increase in data from a single test (see Figures 5 and 6) was demonstrated, offering the potential to reduce material volume required for characterisation of creep behaviour.

Inverse modelling was used to determine material constitutive behaviour suitable for use in basic design.

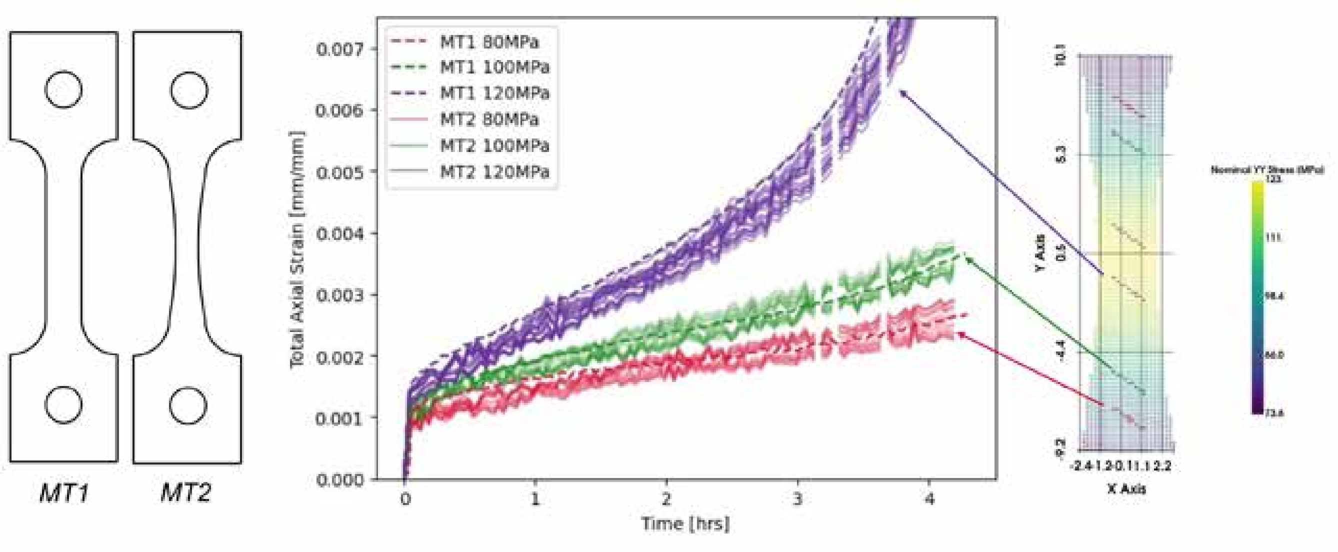


Figure 4: Creep of oxygen-free copper at 300°C. DIC has been used to monitor creep deformation on the surface of a single waisted specimen (MT2). Creep curves extracted from the specimen at regions with a stress of 80, 100 and 120 MPa compare favourably to conventional (MT1) tests performed at the same stresses. This demonstrates the potential to reduce the number of tests necessary to characterise creep behaviour.

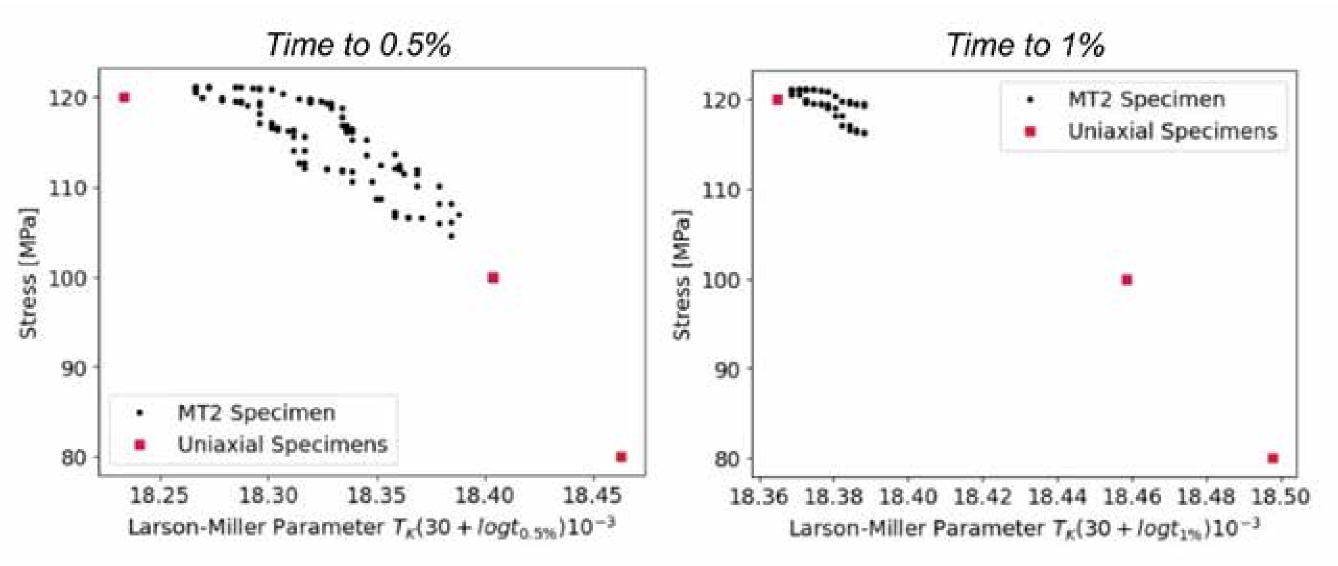


Figure 5: Larson-Miller plots to 0.5% and 1% total strain. These demonstrate the spread of data obtainable from a single test. There are fewer points on the 1% plot as less area of the specimen reaches 1% strain.

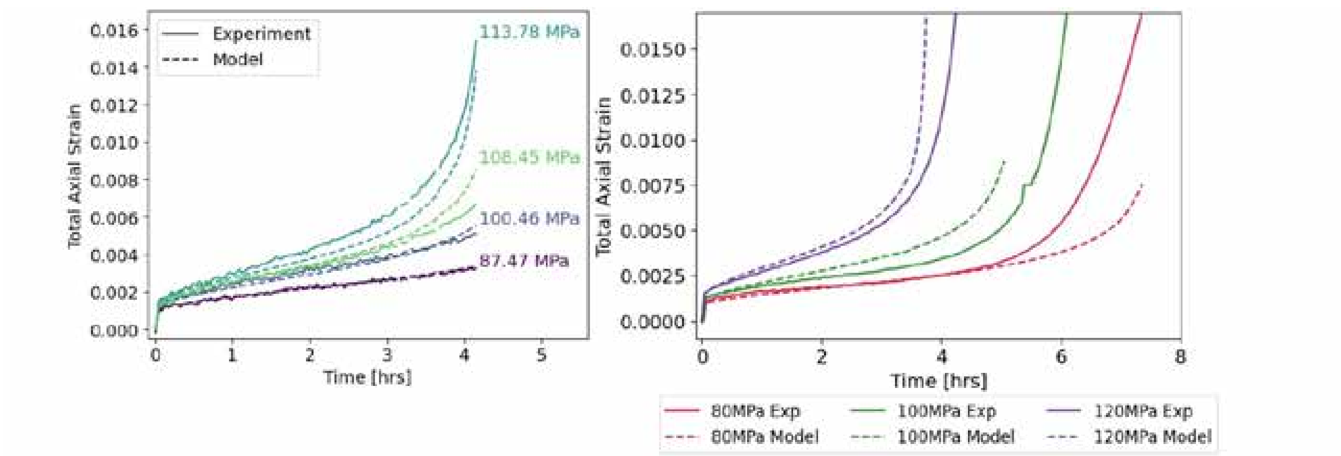


Figure 6: Calibration of an isotropic unified viscoplastic material model with damage. Full-field strain data from the single MT2 test has been used in a Finite Element Model Updating routine to determine the parameters of the model. The model has then been used to simulate the conventional tests. Reasonable agreement can be seen between the model and experimental behaviour in the primary and secondary regimes; however, the failure times are underestimated for the conventional tests.

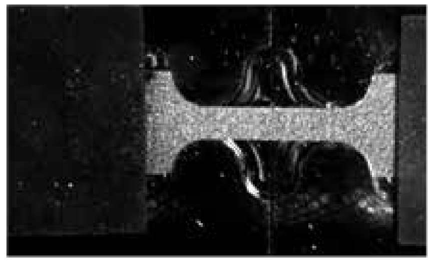
Small-scale Testing Techniques using Full-field Measurement Methods

Advancing full-field measurement techniques for small-scale, high-temperature testing of fusion materials.

The Applied Materials Technology (AMT) Group is leading the development and application of full-field measurement techniques, including Digital Image Correlation (DIC) and Thermoelastic Stress Analysis, tailored for small-scale mechanical testing under demanding conditions. Figure 7 shows details of the DIC setup.

This effort is part of a broader vision to build a robust full-field measurement capability that enables data-driven analysis across the entire lifecycle of a fusion-relevant component, from accelerated material qualification and component design validation to in-service performance assessment.

As part of AMT's work, DIC was successfully developed to extract tensile properties of Eurofer97[1] using miniature testing geometries (Figure 8) at elevated temperatures (up to 550°C), marking a key milestone in small-scale high-temperature testing.



DIC parameters based on iDICS guidelines

Stereo-DIC setup details	
Cameras	12 bit, 2056×2464 pixels^2
Lens focal length	200 mm
Stereo angle	12°
Scale	125 pixel/mm
Image correlation details	
Software	DaVis 10.2.1 (LaVision GmbH)
Subset size	35 px
Subset spacing	5 px
Shape function	Affine
Image interpolant	Bicubic polynomial
Correlation criterion	Zero-normalised sum of square differences

iDICS best practice guide: https://www.idics.org/guide/

Figure 7: Stereo-DIC setup for high-temperature tensile testing of small-scale geometries in a non-vacuum, sealed chamber.

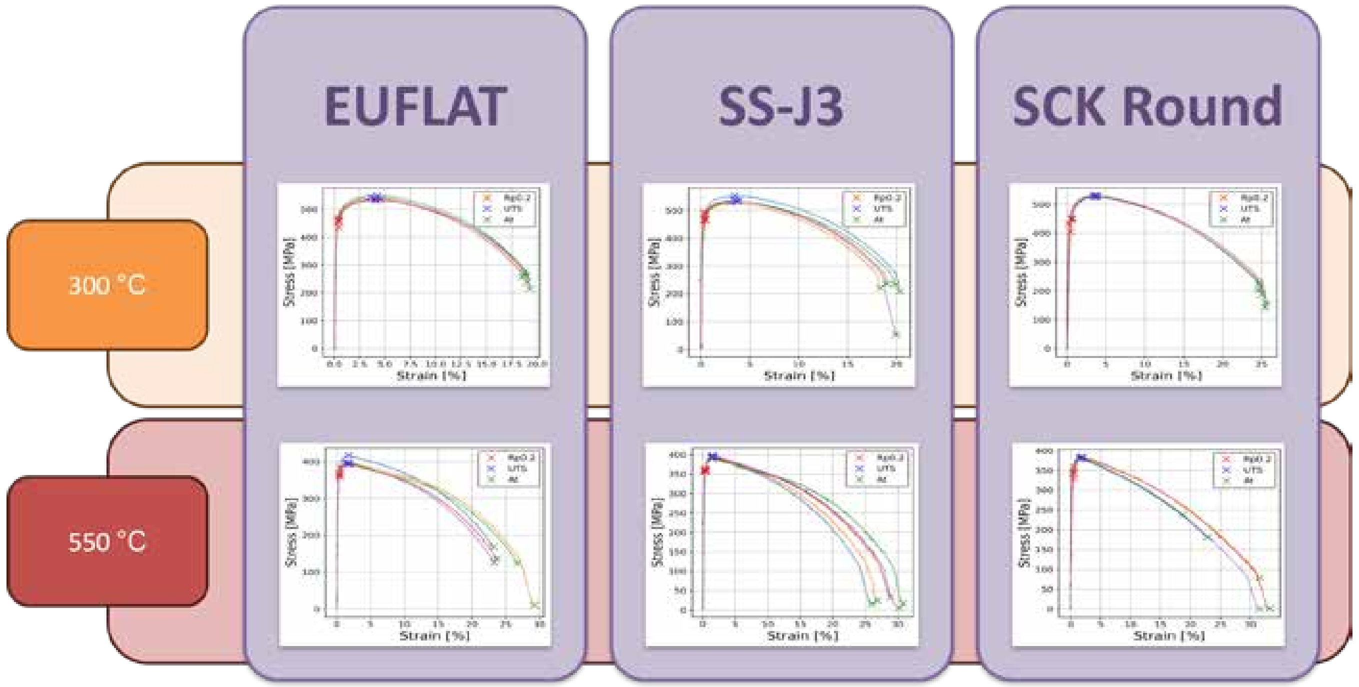


Figure 8: Tensile test curves acquired from a stereo-DIC setup for Eurofer97 material at 300°C and 550°C, using three small-scale geometries: SCK (round), EUFLAT, and SS-J3, with gauge lengths of 10mm, 9.2mm, and 5mm, respectively.

1 European Reduced Activation Ferritic-Martensitic (RAFM), ultra fine grained steel used as a structural material in fusion machines.

Advanced Manufacturing

- Material performance is strongly affected by its manufacturing history.
- Novel material development cannot take place in isolation; parallel manufacturing development, standardisation and qualification for the specific application ensures that the material can be used as intended while retaining its essential structural or functional properties.
- Complex component geometries and multi-material systems often require advanced manufacturing techniques to translate a functional design into a precise reality.
- The Fusion Technology Division has impacted the manufacturing for ITER, developing and qualifying manufacturing for EU-DEMO, and has linked with non-fusion partners in aerospace and quantum science to solve common challenges.
- FT links with many external organisations, particularly the University of Birmingham, the University of Sheffield, the University of Huddersfield, the Royce Institute, the Advanced Manufacturing Research Centre and The Welding Institute . The organisations engage on a wide range of subjects, from the manufacturing of geometrically complex plasma facing components with refractory materials and the joining of dissimilar materials, to novel manufacturing qualification approaches that are specific to the fusion environment.

Production and Testing of Prototype Complex Internal Channelled Hot Isostatic Pressing (HIP) Components

To develop Powder Metallurgy (PM) HIP method of manufacturing to produce fusion relevant structures with complex conformal cooling channels.

By the end of the 2023/24 Financial Year, the PM-HIP process was successfully demonstrated simultaneously as a near-net shape manufacturing and dissimilar-material joining method, with the potential to produce conformal cooling channels in multi-material and graded components.

Dissimilar material joining by PM-HIP with a graded powder filling method was demonstrated to produce W/EUROFER97[2] joints.

Complex cooling channels are a key part of novel component designs but are difficult to manufacture through traditional routes. This year, we successfully produced these complex structures through a hybrid Additively Manufactured (AM) / PM HIP process, as shown in Figure 9. However, the AM material / design needs further development to avoid "hotspots" that can collapse under high temperature during the HIP run (see Figures 10 and 11). Alternatively, a conventional tube-bending method was successfully tested to introduce channels with more limited geometric complexity.

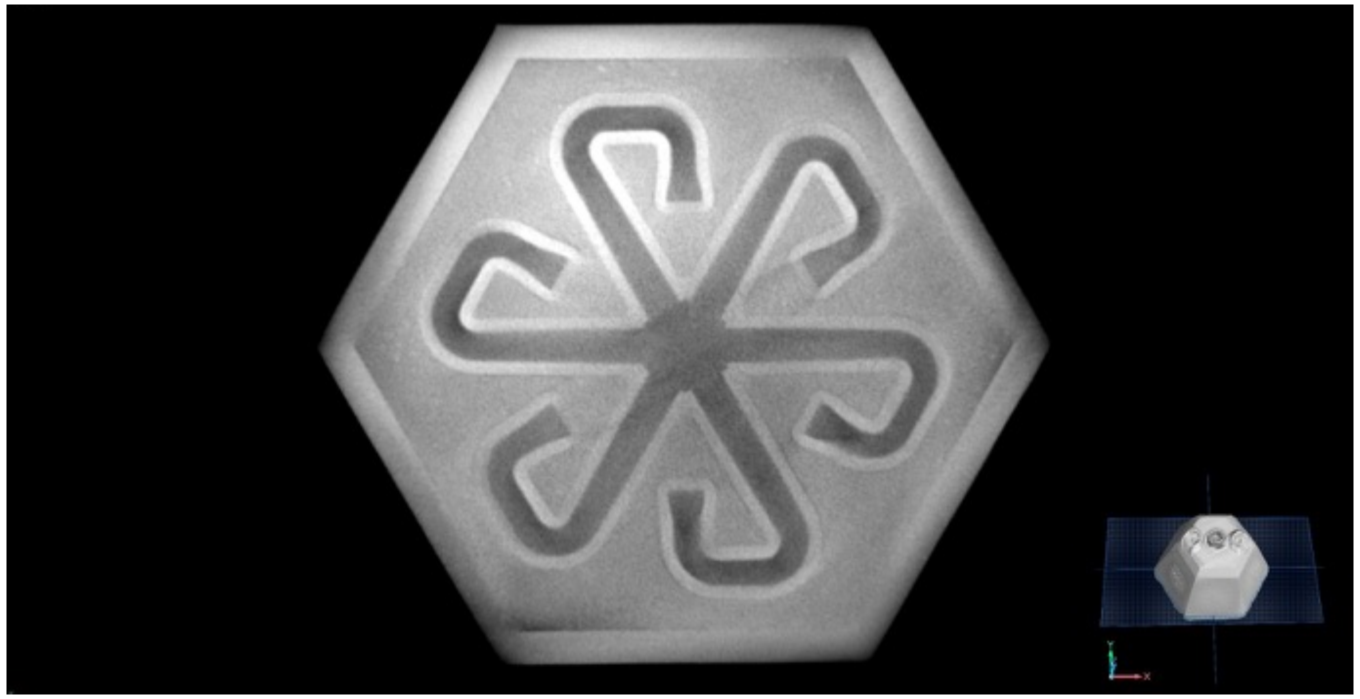


Figure 9: X-ray Computed Tomography (XCT) top view cross section image of ODS steel component showing conformal cooling channels within consolidated material. The part was successfully produced by Powder Metallurgy Hot Isostatic Pressing (PM-HIP) process. The mandrel used for the fabrication of the channels was additively manufactured in 316L steel material by laser powder bed fusion process.

2 W/EUROFER97 refers to a diffusion bonded joint between tungsten (W) and the European Reduced Activation Ferritic-Martensitic (RAFM) steel, EUROFER97. This combination is being investigated for use in fusion machines, specifically as plasma-facing components. The tungsten is often coated onto EUROFER97, and the joint is created through diffusion bonding, sometimes with an interlayer like vanadium (V).

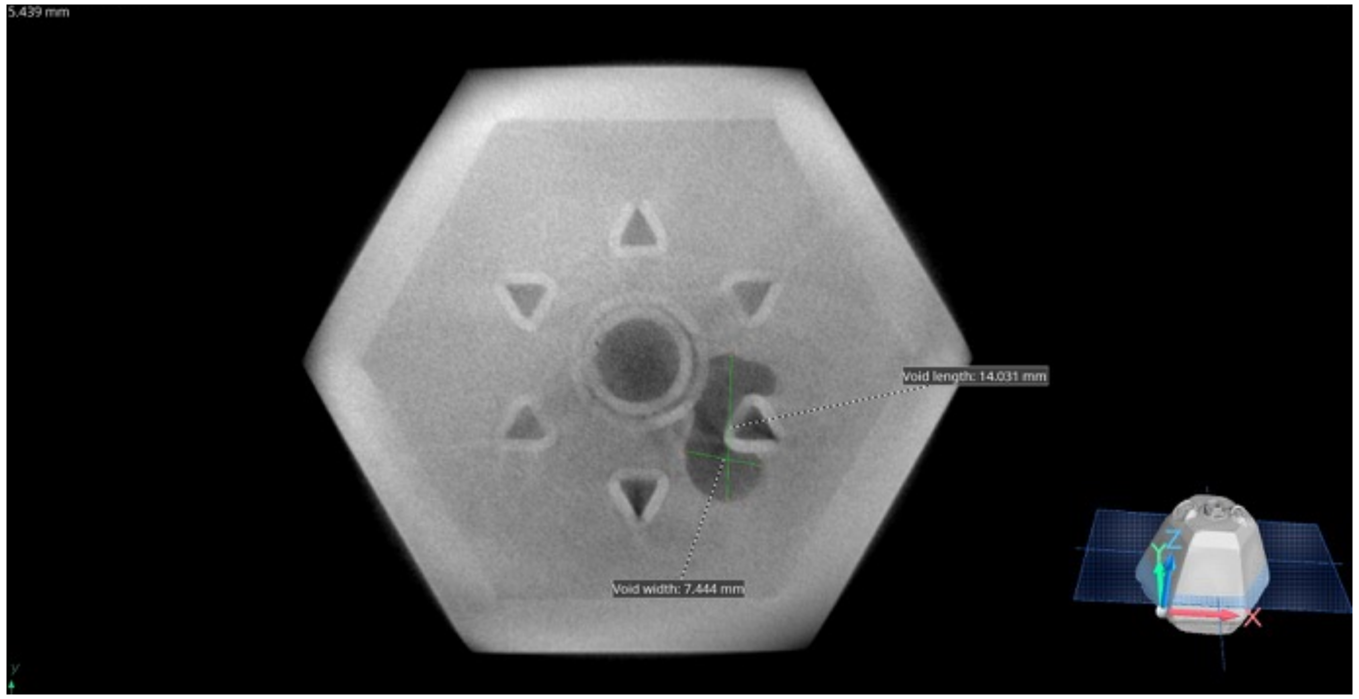


Figure 10: XCT top view cross section of void around a channel that collapsed during the HIP run.

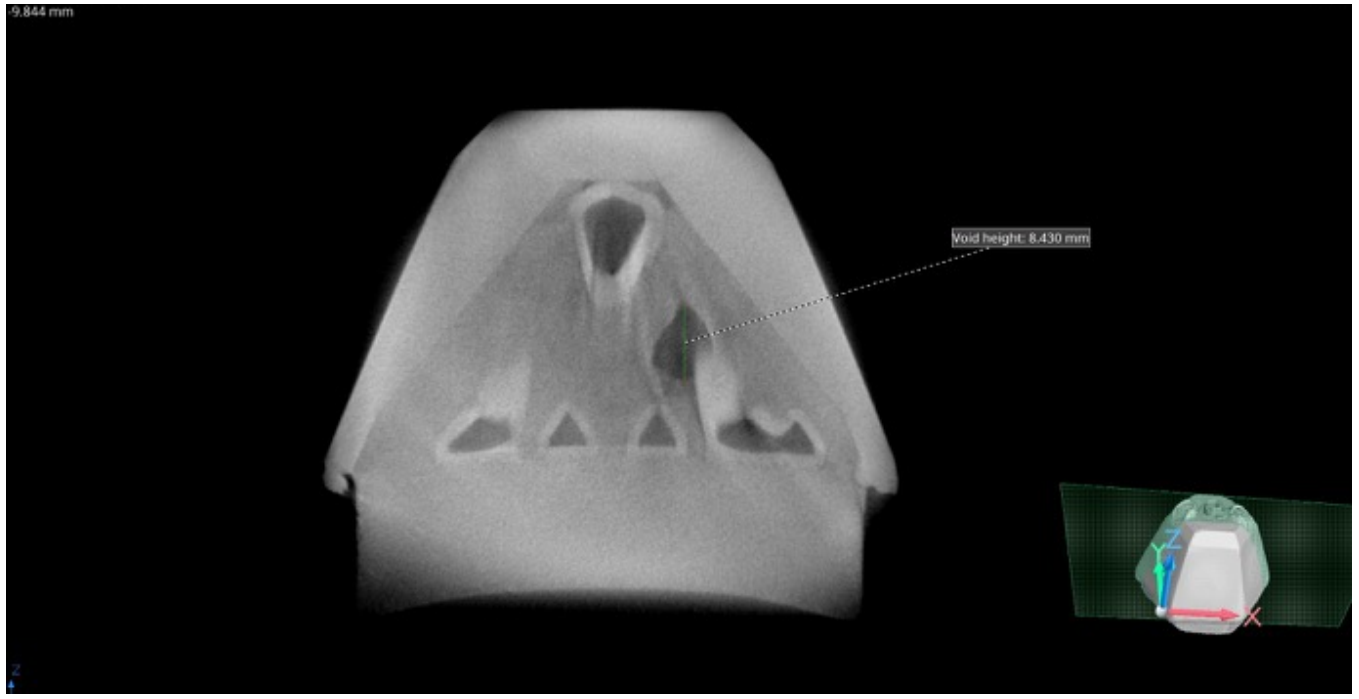


Figure 11: XCT front view cross section of void around a channel that collapsed during the HIP run.

SmartPipe - Radiation Hard Sensors Embedded within Steel Pipes

Manufacturing trials for the embedding of radiation-hard fibre sensors within fusion relevant components.

The SmartPipe project has successfully demonstrated several potential techniques for embedding advanced fibre optic sensors (see Figure 12) directly into structural components within the fusion sector. These sensors offer a compact and reliable way to monitor internal conditions such as temperature, pressure and strain.

These hollow core fibre sensors are highly accurate and radiation tolerant, making them well-suited for demanding environments. While similar technologies exist in construction, embedding radiation resistant sensors at a scale suitable for fusion has not previously been developed.

The project explored several manufacturing methods to embed the sensors within pipe walls, including electroplating, cold spray laser deposition, diffusion bonding and electrical discharge machining. A benchtop heating experiment, which can be seen in Figure 13, was then undertaken to determine if the sensors had been damaged during installation and to make sure that they remained effective at elevated temperatures after manufacturing.

Unlike traditional sensors that are added as external modules, these embedded sensors (as seen in Figure 14) sit directly within the structural components. This allows for more direct and accurate readings, while also enabling the monitoring of material health over time. The ability to track internal stresses and conditions from within the structure may offer earlier insights into component performance and longevity—supporting more efficient maintenance and improved system reliability.

Figure 12: Experimental setup for the pipe heating experiment, including an interrogator to process the readings from the fibre sensors.

Figure 13: Copper electroplated pipe with embedded sensor ready for heating.

Figure 14: Successfully embedded steel rod by cold spray deposition in the initial manufacturing trials.

SuperEMAT Technology Evaluation - Comparison with Conventional Electro Magnetic Acoustic Transducer (EMAT) for Defect Detection

Integrating a superconducting magnet with an EMAT coil has shown a significant improvement in signal amplitude and signal-to-noise ratio in comparison to the standard commercial magnets available.

The superconducting magnet enabled smaller defects to be detected in materials, and in thinner materials, shown in Figure 15. The superconducting magnet set up has been optimised with a sapphire insulating layer, which increased the magnetic field available and hence reduced the noise signals, as illustrated in the table in Figure 16.

The magnet used in the super Electro Magnetic Acoustic Transducer (EMAT) system was a bulk High-Temperature Superconductor (HTS) developed by the University of Cambridge.

	Standard EMAT (~0.9T)	Super EMAT (~0.4T)
Titanium	2mm	1mm
Copper	>2mm	0.5mm
Brass	2mm	0.5mm
Aluminium	3mm	3mm
Stainless Steel	>2mm	>2mm

Figure 15: Comparison of smallest measurable defect on the materials.

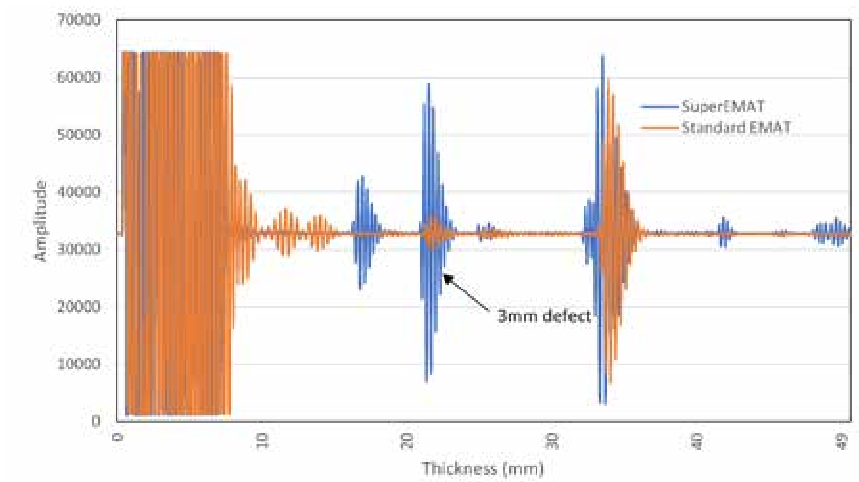


Figure 16: Comparison of signal amplitude for aluminium 40mm block at 72dB, 4MHz, where the superconducting magnet has increased the defect signal amplitude by 18.6 dB.

Dissimilar Material Joining of Tungsten

Example of hybrid manufacturing methods using AM and PM-HIP processes for dissimilar material joining of tungsten and tungsten alloy with copper (Cu), chromium (Cr), and zirconium (Zr) (CuCrZr), V-4Ti-4Cr[3], and EUROFER97.

Tungsten is identified as one of the leading shielding materials for Plasma Facing Component applications. It is typically joined with heat sink and structural materials to improve the thermal performance of fusion devices. However, unique material properties of tungsten respond more to extremely high melting points, high ductile-to-brittle transition temperature, and low thermal expansion coefficient, making dissimilar material joining of tungsten extremely complicated.

Near net shape manufacturing methods like AM and PM-HIP offer the advantage of introducing complex geometries in this difficult-to-process material. This can be used to improve the strength of tungsten joints by mechanical locking mechanisms. The present project demonstrates hybrid AM/PM-HIP manufacturing methods for mechanical locking of tungsten with CuCrZr (Figure 17), V-4Ti-4Cr (Figure 18), and EUROFER97 (Figure 19) materials, respectively.

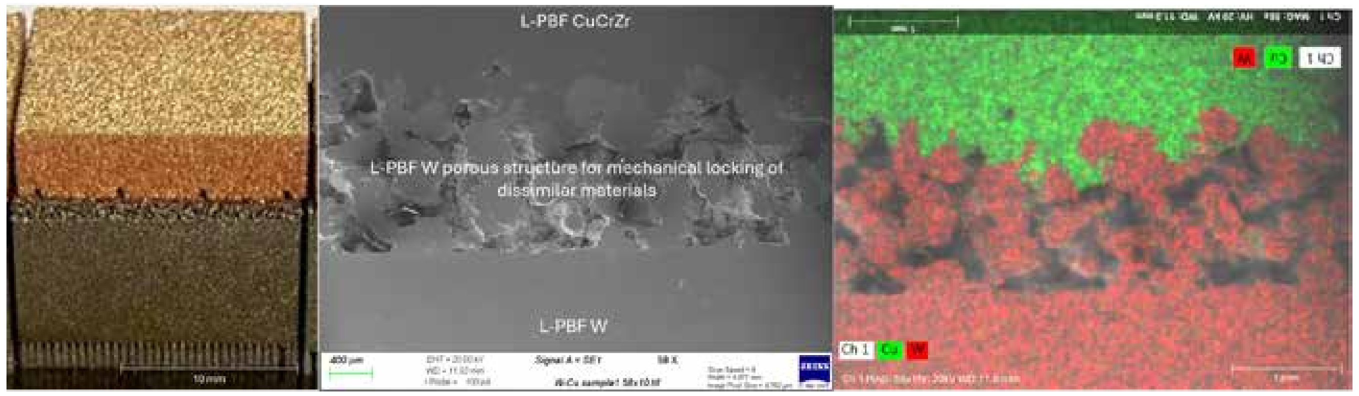


Figure 17: Dissimilar material joining of tungsten and CuCrZr by Laser Powder-Bed-Fusion Process (L-PBF). Mechanical locking of dissimilar materials enhanced by controlled porous structure additively manufactured by L-PBF.

3 A vanadium-based alloy which has 4% weight titanium and 4% weight chromium

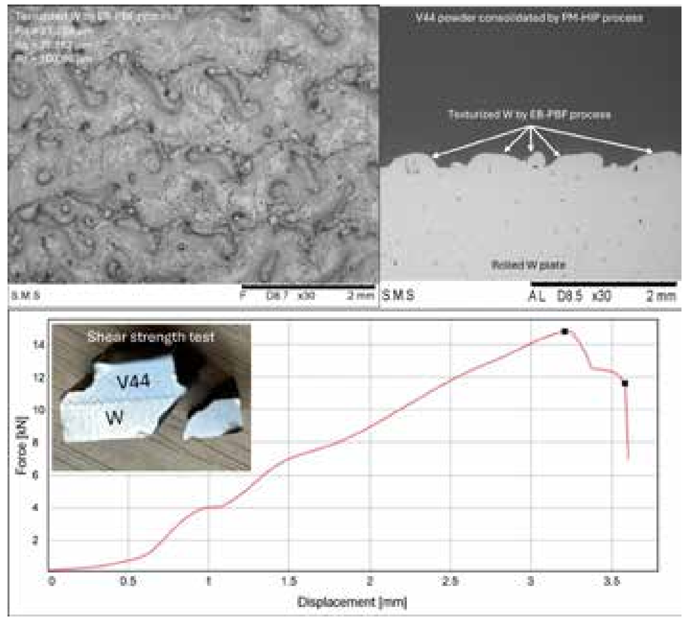


Figure 18: PM-HIP joining of V-4Ti-4Cr powder with tungsten plate. Tungsten surface texturisation applied by Electron Beam Powder-Bed-Fusion process.

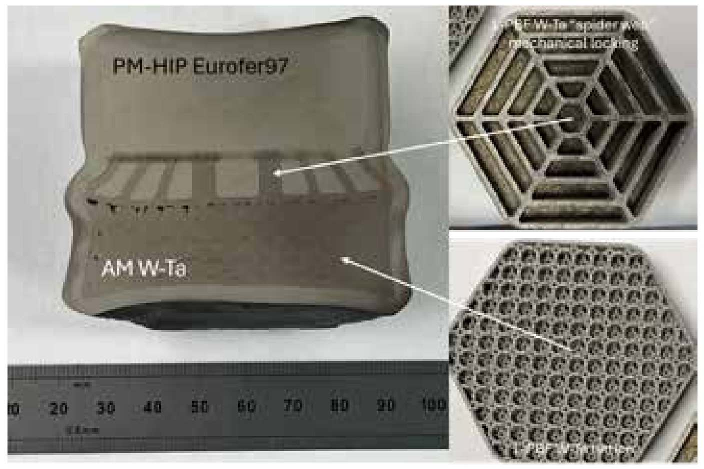


Figure 19: PM-HIP joining of EUROFER-97 powder with W-Ta lattice structure additively manufactured by L-PBF.

Heating by Induction to Verify Extremes (HIVE) Cyclic Testing of EUROfusion Demonstration (EU-DEMO) Sacrificial Limiter

A sacrificial lattice limiter mock-up for EU-DEMO's Work Package Divertor (WP-DIV) was tested under cyclic heat flux for 3,400 cycles and no loss of performance was observed, demonstrating the integrity of the additively manufactured lattice and the brazed tungsten (W), copper (Cu), chromium (Cr), and zirconium (Zr) (W-CuCrZr) joint.

A sacrificial limiter mock-up (see Figure 20) consisting of an additively manufactured tungsten lattice with a solid tungsten bottom brazed to a copper alloy heatsink was tested under medium heat flux cyclic conditions, selected to be representative of plasma ramp down in EU-DEMO. Cooling water at 150°C was pumped through the heatsink while a 5MW/m2 average heat flux was applied using an induction coil to the front face of the lattice. Testing was performed in the HIVE Facility at UKAEA.

The mock-up underwent 1,700 cycles of heating in previous years. A further 1,700 cycles were performed in 2024 bringing the total to 3,400 (approximately 50% of the expected number of plasma ramp-downs in the lifetime of EU-DEMO).

Throughout the thermal cycling, no loss of thermal performance was observed, nor were there any mechanical failures. The only damage recorded were some long cracks parallel to the heat flux direction, shown in Figure 21. These result from the expansion and connection of multiple microcracks present from the manufacturing process. The cracks appear to grow quickly when the lattice is exposed to a local hotspot from uneven induction heating profile but then stabilise at a length of 4-9 unit cells, approximately one third towards the heatsink.

The tests reveal that the B278 lattice[4] brazed to a copper-chromium-zirconium alloy performs well under ramp-down type repetitive heat loads and is not likely to thermally or structurally fail due to thermal fatigue within the lifetime of EU-DEMO. This conclusion does not consider material degradation, due to neutrons or hydrogen, which requires further testing and analysis.

4 A specific tungsten (W) lattice structure, primarily used in the context of fusion reactor components, particularly as a sacrificial limiter.

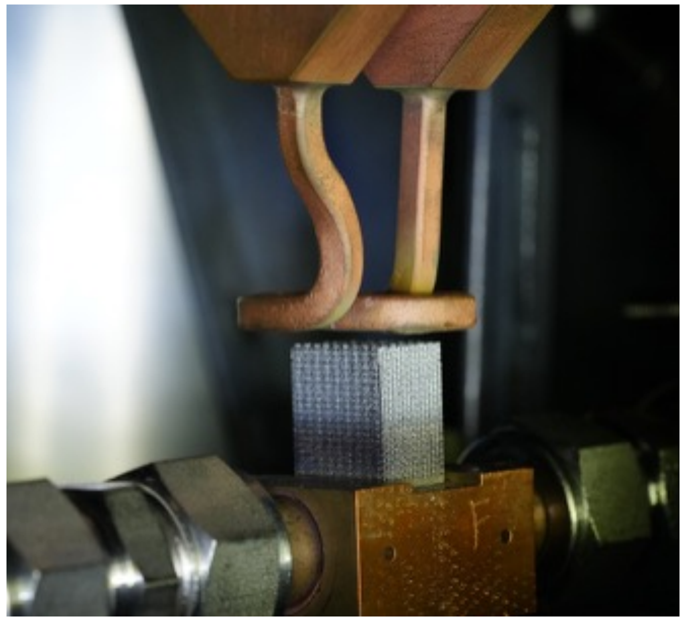


Figure 20: Mock-up inside the HIVE vacuum vessel with induction coil positioned above the lattice, ready to heat.

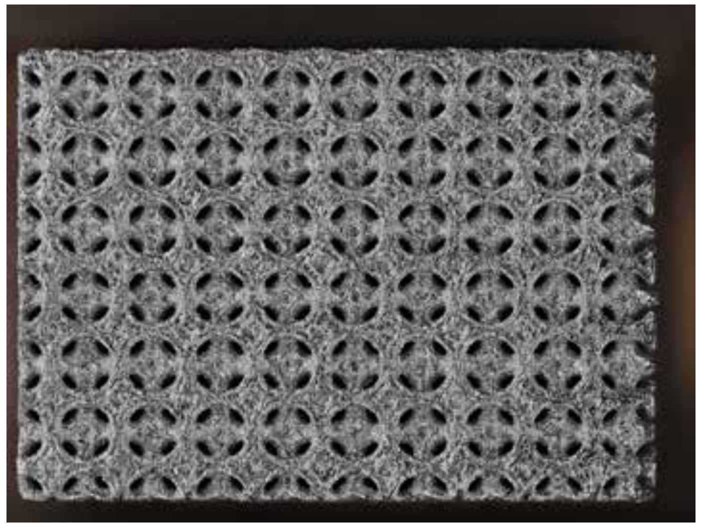


Figure 21: Macro photography view of 12x17mm heated face of lattice after 3,400 heating cycles. Upon close inspection the image shows the largest crack at the bottom of the image (just to the right of centre).

Ultrasonic Additive Manufacturing (UAM) of HTS

Innovation-funded project to develop a novel manufacturing technique for HTS applications, in partnership with an industrial supplier.

Current solder-based methods for joining or embedding HTS tapes are highly manual, variable, and slow. As demand for complex superconducting systems increases, there is a need to quickly and reliably join HTS tapes both to themselves and to other materials. UKAEA is developing a novel manufacturing technique for superconducting applications, in partnership with industry (see Figure 22), based on ultrasonic additive manufacturing.

The technique applies a commercially mature foil-based ultrasonic process to new materials to provide a low-temperature, automated, repeatable, scalable, and high-speed manufacturing method for embedding HTS tapes in metal support material, including the possibility of combining multiple materials and creating complex internal structures and joints.

The research progressed through a series of experimental phases:

- **Phase 1** involved broad parameter exploration. While some samples showed degradation in superconducting performance, others maintained mechanical integrity, highlighting the complexity of the process and the need for refined control.
- **Phase 2a** focused on isolating key variables through ultrasonic spot welding of REBCO[5] to copper. Peel tests helped define bonding thresholds, and subsequent cryogenic testing identified force ranges that preserved superconductivity.
- **Phase 2b** introduced a statistically designed experiment (see Figure 23) to optimise parameters such as sonotrode speed, amplitude, and downforce. New sample geometries were used to isolate UAM-specific effects and eliminate external damage sources.

Figure 22: Experimental team in Columbus, Ohio, USA. UKAEA's Davidson Sabu, Yannik Dieudonne and Fabrisonic representatives stood beside 'Big Blue' machine which conducted the Phase 2 exploratory welds.

Figure 23: Samples of Phase 2b, with REBCO tape embedded into the copper substrate before electrical testing.

5 *Rare-earth Barium Copper Oxide, a chemical compound known for exhibiting HTS.*

Developing New Test Facilities

- The fusion environment is unique and complex: strong local magnetic forces in the meganewton range, extreme high and low temperatures, intense neutron irradiation and exotic materials and liquids.
- Before a fusion power plant is built, dedicated test facilities need constructing to re-create these unique conditions, informing and validating the design of materials, components and systems; this improves confidence in their function and safety.
- The facilities that the FT Division build have historically proven to appeal to external organisations, resulting in collaboration agreements and commercial contracts for access with many universities and with non-fusion organisations for example, in rocketry and space exploration.

Work Package Design Volumetric Neutron Source (VNS) Neutronics Analysis

Nuclear analysis of EUROfusion VNS device Neutral Beam Injectors (NBIs).

In the European roadmap to commercial fusion energy, a major new device is currently being designed to address key issues surrounding the technology readiness of breeding blankets. This device, a Volumetric Neutron Source (VNS), will operate at modest fusion power with sufficient neutron wall load to test different blanket technologies.

VNS is beam-driven and foresees at least three NBIs. These present a large opening into the plasma chamber and therefore a significant challenge for the nuclear environment. Based on the latest design, nuclear analysis was performed for outboard ports occupied by NBIs, determining responses such as the nuclear heating and particle flux in neighbouring coil systems (as illustrated in Figure 24). These studies inform on the shielding needs and geometry of the NBIs to ensure the integrity of components and safe operation of VNS over its lifetime.

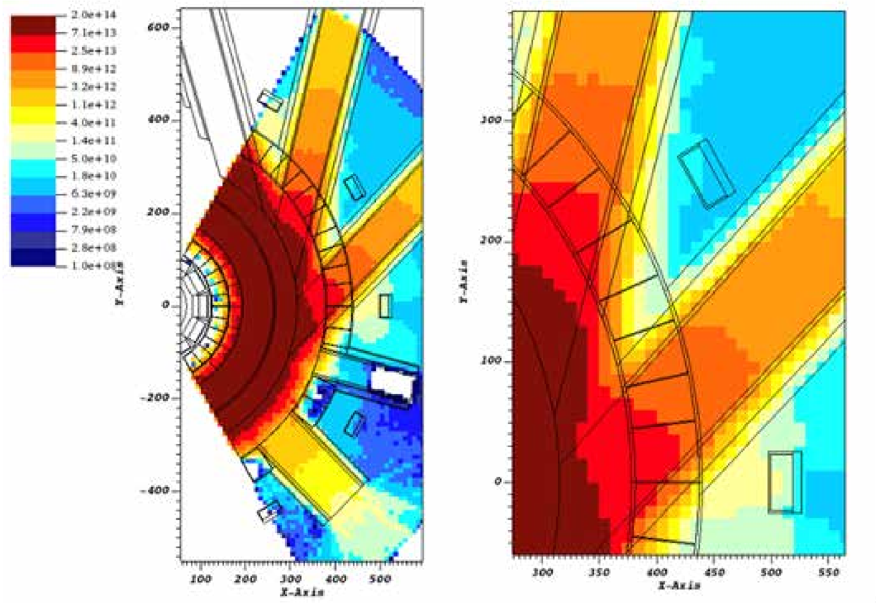


Figure 24: VNS neutron flux (n cm^-2 s-1) for a horizontal slice at Z=0.

Lithium Breeding Tritium Innovation (LIBRTI) Experiment Integration Model-Based Systems Engineering (MBSE) and Interface Process Developed

One of the key integration challenges on the LIBRTI programme is to understand experiment user needs and translate these into Facility requirements.

To achieve this, as shown in Figure 25, a MBSE approach was developed to produce functional architecture of the molten salt (FLiBe6), solid and liquid metal breeding experiments, and identify facility experiment interfaces (Figure 26) based on these.

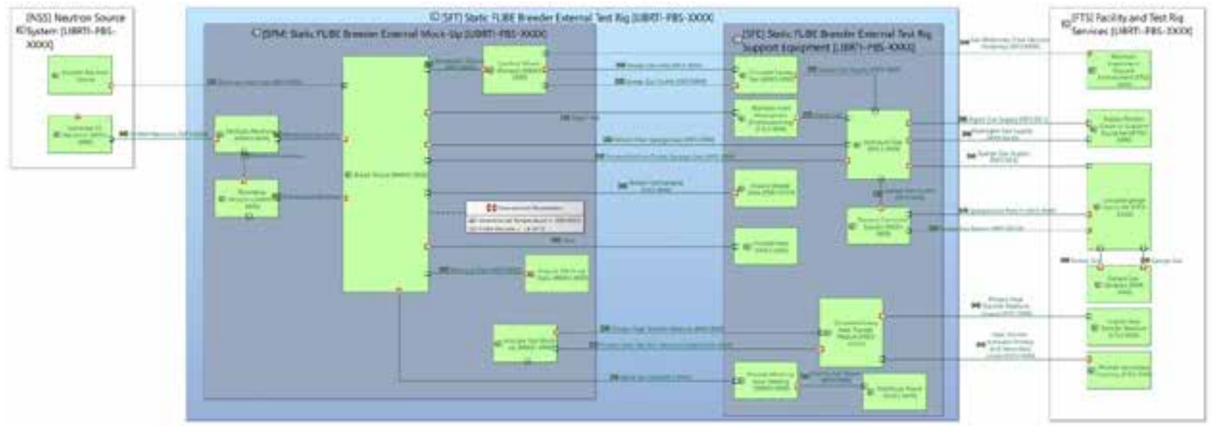


Figure 25: Functional architecture of the molten salt static FLiBe experiment, with interfacing systems (neutron source system, facility and test rig services) using Capella MBSE method.

Object Type - Heading - Component Exchange - Functional Exchange - Physical Links - Property Values	Interface Type Functional: - Energy - Material - Information Physical: - Geometry - Clearance	Object Heading : Text Interface Detail	Nominal Value	Unit	Source System	Target System
Functional_Interface	Material	Sparge Gas Supply			Facility and Test Rig Services	Static FLiBe Test Rig Support Equipment
Property_Value	Material	Flow Rate Range	<50	L/min		
Property_Value	Material	Maximum Composition of O2	1	ppm		
Property_Value	Material	Maximum Composition of H2O	1	ppm		
Property_Value	Material	Helium Content	95-100	w%		
Property_Value	Material	Hydrogen Content	1 to 5	w%		
Property_Value	Material	Temperature Range	600-700	°C		
Property_Value	Material	Pressure Range	0.5-1	bar		
Property_Value	Material	Sparge Gas Supply Pipe Quantity	1			
Functional_Interface	Energy	14MeV Neutrons			Neutron Source System	Static FLiBe Breeder Mock-up
Property_Value	Energy	Minimum Neutron Fluence		n cm²		
Property_Value	Energy	Neutron Source Strength	10^13	n/s		
Functional_Interface	Energy	Mock-up Heat Loss to Neutron Source Target Section			Static FLiBe Breeder Mock-up	Neutron Source System
Property_Value	Energy	Maximum Power during Normal Operation	7.00	kW		
Property_Value	Energy	Maximum Power in Off-normal Scenario		kW		

Figure 26: Interface control document defining material and energy interfaces between static FLiBe experiment and neutron source, facility and test rig services systems.

6 Molten salt mixture primarily composed of lithium fluoride (LiF) and beryllium fluoride (BeF2). Known for its excellent thermal properties and chemical stability at high temperatures, making it a candidate for use as a coolant and fuel solvent in advanced nuclear reactors, particularly molten salt reactors.

Laser Metal Deposition (LMD) Target Design for Experiments in COMPASS-U

Liquid metal divertor activities for 2024 included work on advancing the tile design to make compatible with COMPASS-U[7] plasma.

COMPASS-U is a key test facility for the LMD technology. UKAEA provided design expertise to develop the COMPASS-U divertor module tile with the Institute of Plasma Physics (IPP, Czech Republic) using Computer-Aided Design (CAD) and Finite Element Method (FEM) tools. This includes developing the concept design developed in 2023 by refining the conceptual design of the Liquid Metal Capillary Porous Structure (LM-CPS) module, including mounting and heating, for COMPASS-U divertor. Two different "variants" of CPS were elaborated.

The main aims of the project were to:

- Create operational states specification compatible with COMPASS-U
- Finalise concept design including required heaters, liquid metal reservoir and mounting arrangement
- Perform thermal and structural analysis and ensure compatibility with operational cycles.

In February 2024 we presented the single tile design at a workshop. A further workshop between the UKAEA and the IPP was held in May 2024. From these two meetings, several shortcomings and issues in the design were noted. These were addressed in the second half of the year.

The design was changed to one that takes the place of two tiles and two different variants (CPS 3-Dimensional printed and CPS mesh) were modelled. A structural analysis was also performed with positive outcomes for both variants. All of the work undertaken during 2024 was presented at the EUROfusion end of year meeting in Differ (November 2024), and further developmental ideas discussed for implementation during 2025.

In 2025, focus turned to thermocouples, engaging with suppliers, and implementing a seal between the inner body and the lid of the divertor, to mitigate the leaking of liquid metals.

7 Tokamak upgrade with high magnetic field, enlarged operational space and broader flexibility. Designed and constructed with the participation of European and international partners, COMPASS-U will support ITER operation and address some of the key challenges for the design and construction of a next-phase reactor, DEMO.

Commissioning of Surrogate MAgnetohydrodynamic Liquid-metal LABoratory (SmalLab)

SmalLab, UKAEA's first in-house designed liquid metal test facility, was commissioned to study Magnetohydrodynamic (MHD) phenomena and test Liquid Metal (LM) diagnostics in a controlled environment.

As UKAEA's first LM test facility, SmalLab marks a critical advancement in addressing challenges in fusion reactor LM-based blanket technologies. The objectives of the project are:

- A controlled and safe environment for the study of MHD phenomena, the response of LMs to magnetic fields
- Testing of instruments for data diversification and future application in large scale LM loops e.g., lead-lithium (PbLi) loop
- Generation of internal data under well-defined conditions for flexible investigations
- Building engineering and scientific expertise in LM experiments at UKAEA.

The SmalLab project successfully passed all demanding design processes, demonstrating the robustness of its engineering and planning.

A pressure test (0.5 bar) and vacuum test (-0.5bar) was carried out prior to the Galinstan[8] filling process (Figure 27). Galinstan was siphoned from the glovebox into the loop, by introducing a vacuum condition in the loop. The entire process was carried out in an inert atmosphere using argon to prevent oxidation. The pump was started, and smooth flow within the loop was achieved.

The commissioning of UKAEA's first liquid metal flow loop was completed, validating the design and ensuring operational functionality – Figure 28 shows SmalLab in use. Notably, the setup was entirely designed and built in-house at the Fusion Technology Facility, making it a unique and pioneering LM flow loop within the organisation. These achievements provide a strong foundation for future LM and MHD studies.

8 Brand name for a liquid metal alloy composed of gallium, indium, and tin. It is liquid at room temperature, with a melting point of -19°C. This makes it a useful alternative to mercury in various applications, especially where a non-toxic liquid metal is needed.

Figure 27: Image of SmalLab facility filled with Galinstan.

Figure 28: SmalLab commissioning activities.

Qualification at the Physical Digital Interface

- In the unique and complex fusion environment, it is essential to determine which models are useful. This can be achieved by comparing the output of simulations to their experimental counterparts. When these agree within the assumptions and uncertainties, the model is validated and hence useful.
- The Fusion Technology Division are leaders in developing the process for selecting the right tests to validate the right models and to make the right decisions in design. FT are also world leaders in the development of digital tools with which these comparisons can be made, demonstrated by the success of Lloyd Fletcher's Future Leaders Fellowship grant.
- FT have made clear progress this year in experimental validation of high heat flux of fusion components and in flow-induced vibration for key breeding blanket designs. Further, the Division leads a working group to develop a unified strategy for qualification at UKAEA.

A Computer Aided Validation (CAV) Framework for Digital Design Qualification: United Kingdom Research and Innovation (UKRI) Future Leaders Fellowship of Dr Lloyd Fletcher

Dr Lloyd Fletcher was awarded a UKRI Future Leaders Fellowship (£1.6M) to develop the next generation of engineering software tools for designing smart simulation validation experiments with image-based sensors.

In the first few months of Dr Fletcher's fellowship, he has:

1. Delivered the first alpha version of the open-source python package 'Pyvale' (python validation engine), which is the main output of the project. 'Pyvale' is an all-in-one package for sensor simulation, sensor uncertainty quantification, sensor placement optimisation and simulation calibration/validation
2. Hired and onboarded two new research software engineers as core developers and maintainers for 'Pyvale'
3. Established a network with external mentors and accepted a visiting position at the University of Sheffield to support the fellowship.

The CAV framework which Dr Fletcher develops will be a new method for determining which engineering simulations are useful, while maximising experimental "information" from limited test campaigns.

The Future Leaders Fellowship will be used to deploy the CAV framework to solve international fusion engineering challenges where it is expensive, time consuming and difficult to obtain data.

Image-Based Data Pipeline for Fusion Engineering Qualification And Model Validation

Qualification in fusion engineering is reliant on the simulation of component performance under the extreme multi-physics fusion environment.

It is therefore crucial to validate simulations under combined testable environments and extrapolate model predictions only for the untestable fusion neutron damage. This includes validation under high temperature, strong magnetic fields and vacuum conditions.

This can be achieved by designing data-rich experiments under combined thermo-mechanical loads coupled with the use of image-based diagnostics. DIC and Infrared Thermography are imaging techniques that are used extensively in experimental mechanics for material characterisation. In recent years, the use of these techniques was extended to the framework of model validation in solid mechanics.

In this research case, the AMT Group conducted a full kinematic and thermal field characterisation of a water-cooled, heat sink mock-up under high heat flux and vacuum conditions. The experimental setup and full-field strain data is presented in Figure 29. AMT performed a thorough uncertainty quantification for both the kinematic and thermal fields and used the uncertainty analysis to perform a quantitative comparison to the dedicated model.

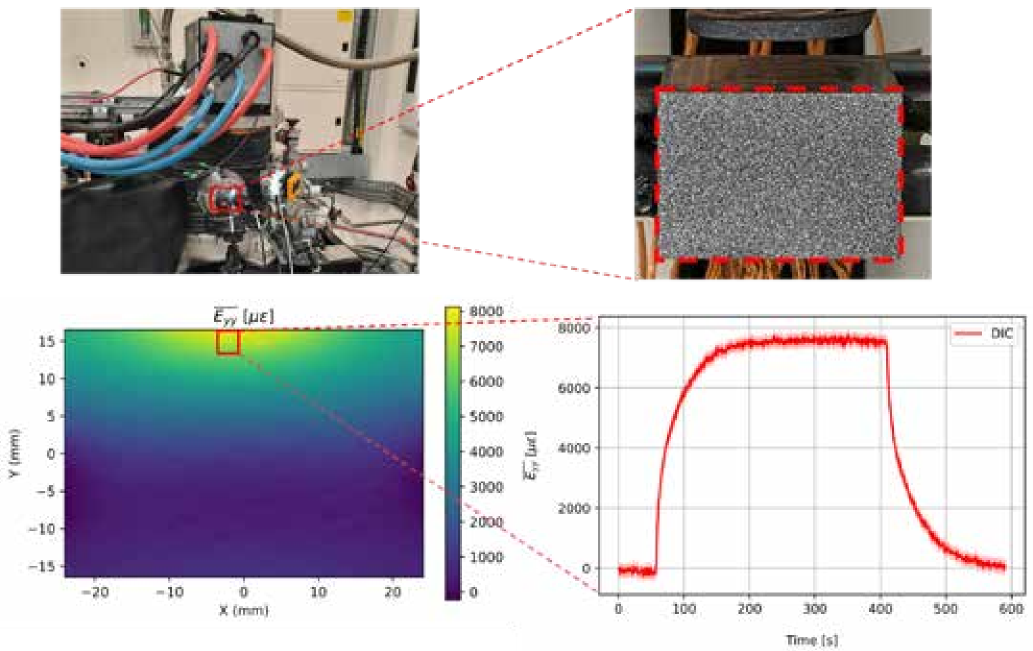


Figure 29: Region of interest and example of full-field strain data.

Experimental Validation of Computational Fluid Dynamics (CFD) and Finite Element Method FEM Coupled Flow Induced Vibration Simulation

Advancing the validation of coupled CFD and FEM simulations for flow-induced vibration in double-wall tubes through experimental correlation and spectral analysis.

Previous computational simulations of flow-induced vibration in Test Blanket Modules (TBM) have shown that the risk of fatigue failure due to Flow-Induced Vibration stresses is minimal. However, questions remained about the accuracy of the models used.

An in-house DIC experiment was conducted to capture the vibratory response of a copper u-tube, like Double Wall Tube (DWT), with a 900 bend, under turbulent flow. A CFD model of the u-bend was developed with the boundary condition like the experiment. Large Eddy Simulation[9] of flow through the u-bend was carried out until a statistical steady state was achieved. Wall pressure data across the tube wall at intervals of 0.004 seconds were extracted, building a highly resolved picture of flow behaviour over a 4-second window, as illustrated in Figure 30.

Spectral analysis of the pressure time series at selected points on the bend was carried out to determine whether a dominant frequency exists in the turbulence spectrum.

The turbulent spectrum was compared with the mode obtained from the experiment and there were no significant frequency excursions in the power spectral distribution in the range of the first two nodes of the DWT (0-100Hz). The pressure pulse was divided into 2-second segments, and spectral analysis was performed on each to assess sampling adequacy (Figure 31).

The validation of coupled CFD-FEM methodology was attempted using the DIC experiment results. Although exact matching between the CFD-FEM simulation and experimental results has not been achieved (see Figure 32), the correlation is promising. Particularly as the predicted vibration amplitudes align with experimental observations. This outcome is paving the way for a new research direction focused on refining coupled simulation techniques and deepening the understanding of fluid-structure interactions in complex geometries.

9 *Mathematical model for turbulence used in CFD.*

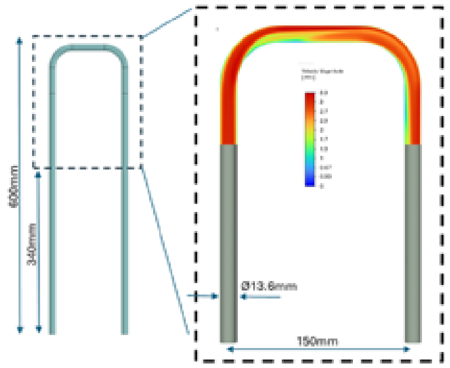


Figure 30: Computational domain and time averaged mean velocity contour (superposed on geometry).

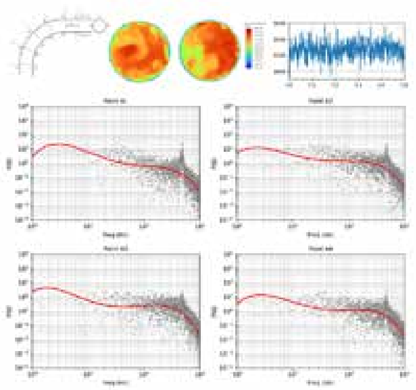


Figure 31: Pressure monitoring points, cross section velocity contour, representative pressure pulse and pressure spectral density at bend.

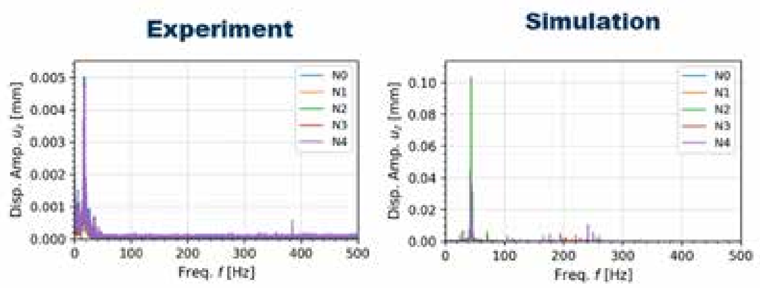


Figure 32: Comparison of frequency spectrum of vibration from simulation and experiment.

Qualification Process Blueprint and Strategy

Manufacturing Technology Equipment Qualification (MTEQ) leads the development of a qualification blueprint and establishment of a cross-organisational Working Group, whilst creating a proposed qualification strategy at the component level, centred on manufacturing needs.

As fusion technology moves into the engineering and manufacturing phase, UKAEA is taking important steps to ensure that components can be qualified in a consistent, scalable and confident way. This year the MTEQ Group has played a role in shaping how component level qualification can be supported.

A major step forward was the launch of the Qualification Working Group, which brings together colleagues from across the organisation to align terminology, goals, and emerging needs in qualification, whilst sharing best practice. The Working Group has developed a shared language, terms of reference, and provided a collaborative space.

MTEQ also supported the delivery of a proposed qualification process blueprint. This top-level framework demonstrates how qualification needs could be identified, matched with tools and transformed into evidence-based validation. Once adopted, the blueprint aims to support smoother Technology Readiness Level progression and give teams a clear and consistent process for qualification planning.

In parallel, MTEQ also produced a group-level qualification strategy, focused on component manufacturing. This strategy identifies key research gaps and outlines areas where MTEQ can help bridge the transition from validated materials to qualified components and ultimately, system level integration. It strengthens MTEQ's internal direction while aligning with the broader qualification landscape.

Together, these initiatives form a solid foundation for more collaborative, strategic qualification as fusion progresses toward real-world deployment.

Technology for Power Plant Design

- Whole design of a future fusion power plant requires the optimisation of many interacting parameters. For example, the:
  - Plasma shape and its performance
  - Configuration of the magnets and their strength
  - Configuration of other components essential for heat exhaust and the fuel cycle
  - Materials used to make all the structures and the coolants
  - Temperatures involved
  - Efficiency of the power cycle
  - Power that is extracted to provide electricity to the grid
- Integration of these complex and interacting systems is an essential part of fusion power plant design. Otherwise, the individual systems would end up with competing requirements, making the design unworkable.
- The Fusion Technology Division adopts leading roles in EU-DEMO and STEP fusion power plant design. The Fusion Technology Division owns, and actively develops, world leading codes PROCESS and bluemira to enhance speed, flexibility and confidence in the design space. This expertise is recognised in the fusion community, whilst collaborating on application and development of these codes, particularly across the EU-DEMO partners.

Stellarator Pipeline for Bluemira

FT developed the basis of stellarator capability for bluemira[10] and hosted it on an open-source GitHub[11] repository.

Optimisation tools such as SIMSOPT[12] are driving the design of high-performance magnetic configurations. Proving the engineering feasibility of stellarators remains a crucial step toward realising practical fusion machines. With expertise in engineering, neutronics, and power plant modelling, UKAEA is uniquely positioned to tackle these challenges and progress stellarator viability.

The Power Plant Modelling and Integration (PPMI) Group has developed a pipeline to generate bluemira CAD from SIMSOPT-optimised plasma surfaces and coils (see Figure 33). This is the basis for using PPMI's plant optimisation tools to integrate engineering and neutronics constraints into stellarator optimisation.

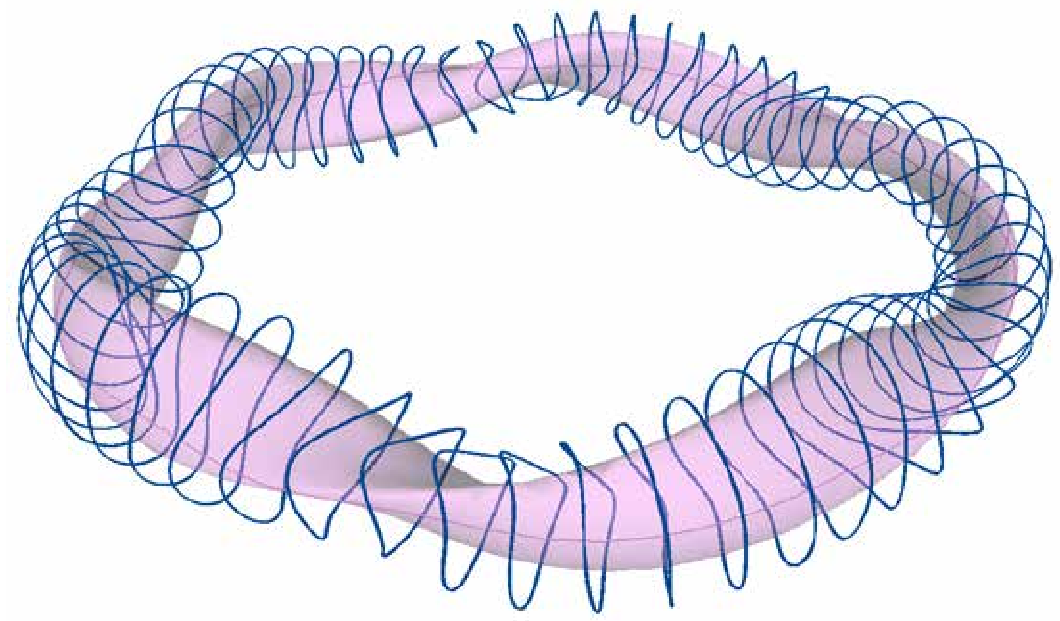


Figure 33: Helias 5B stellarator coils and plasma rendered in bluemira.

10 Bluemira is an integrated inter-disciplinary design tool for future fusion machines.

11 GitHub provides a shared repository to create, store, change, merge, and collaborate on files or code. Any team member can access the GitHub repository and see the most recent version in real time. Edits or changes can be applied that other collaborators also see.

12 A flexible framework and collection of software components for carrying out stellarator optimisation.

PPMI Paper Cuts

The Paper Cuts initiative via the PPMI code maintenance project improved coding practice and competence across the PPMI group.

The Paper Cuts[13] initiative is an internal exercise led by J Cook and J Maddock which began in January 2024. Every fortnight the Group is given small issues from PROCESS[14] and bluemira to resolve. These are typically small bugs, improvements, suggestions, documentation, etc. that can accumulate into issues.

The project successfully reduced the backlog of issues on both codes, reduced technical debt, and improved Group cohesion on coding workflows and outcomes. This is quantitatively evidenced in Figure 34.

Figure 34: Issue burndown chart of PROCESS showing total outstanding issues over time and the clear impact of the Paper Cuts initiative.

13 *Paper Cuts is dedicated to working directly with the community to fix small to medium-sized workflow problems, iterate on UI/UX, and find other ways to make the quick improvements that matter most.*

14 *A systems code used for conceptual design, optimisation, and assessment of fusion power plants. It models plasma physics, engineering systems (magnets, heat conversion, structures), plant operation, and economics – all in one simulation.*

Bluemira Development: Magnet Design Module with Automated Toroidal Field (TF) Winding Pack (WP) Design

Optimisation of the toroidal field (TF) winding pack (WP) layout and case dimension improving the automated magnet design capabilities within bluemira.

The bluemira magnets module aims to provide an "initial" optimisation of the winding pack and case dimension for all magnets (example shown in Figure 35), following the work of L Giannini (EUROfusion Programme Management Unit, Garching, Germany)[15].

Optimisation is based on the:

1. Amount of superconducting material
2. Amount of stabilising material (consideration on hot spot temperature criteria)
3. Steel thickness (consideration on the allowable stress using an equivalent spring system approach – pictured in Figure 36).

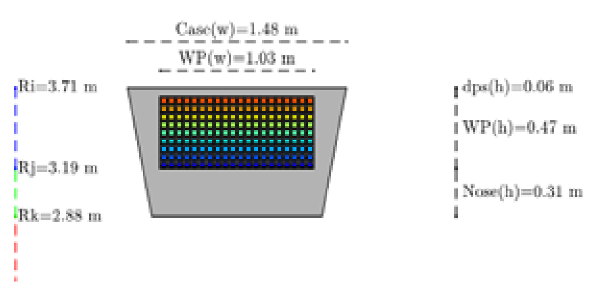


Figure 35: Example of TF coil winding pack design after optimisation.

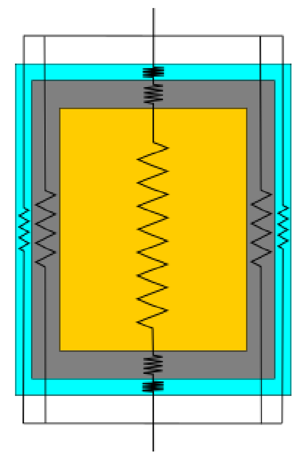


Figure 36: Equivalent spring system for a conductor.

15 *The MAgnet Design Explorer algorithm (MADE) for LTS, Hybrid or HTS toroidal and poloidal systems of a tokamak with a view to DEMO* https://doi.org/10.1016/j.fusengdes.2023.113659

Bluemira Development - Neutronics Model Automatic Generation

Automatically generate a CAD Direct Accelerated Geometry Monte Carlo (DAGMC) model for neutronics simulation and analysis without any intermediate user interaction.

Using the bluemira software package, a detailed neutronics model is generated from the bluemira CAD, creating a DAGMC model16 for use in OpenMC17. This "meshed" approach provides a more detailed model, reproducing the CAD in a form that OpenMC can utilise. Integration provides a complete workflow (from an initial PROCESS) via the bluemira optimisation and generation design flow for EU-DEMO, to a neutronics model for OpenMC.

The processing pipeline links existing open-source tools to perform overlap checking, imprinting, merging, and finally meshing, using the Mesh-Oriented Database (MOAB18) library.

An integrated pipeline such as bluemira, significantly increases the speed at which neutronics studies can be performed, providing substantial value for modellers and engineers working in the concept design space – Figure 37 shows an example of neutron flux tally generated by bluemira. It allows more rapid exploration of the design parameter space, ultimately enhancing the result of design studies.

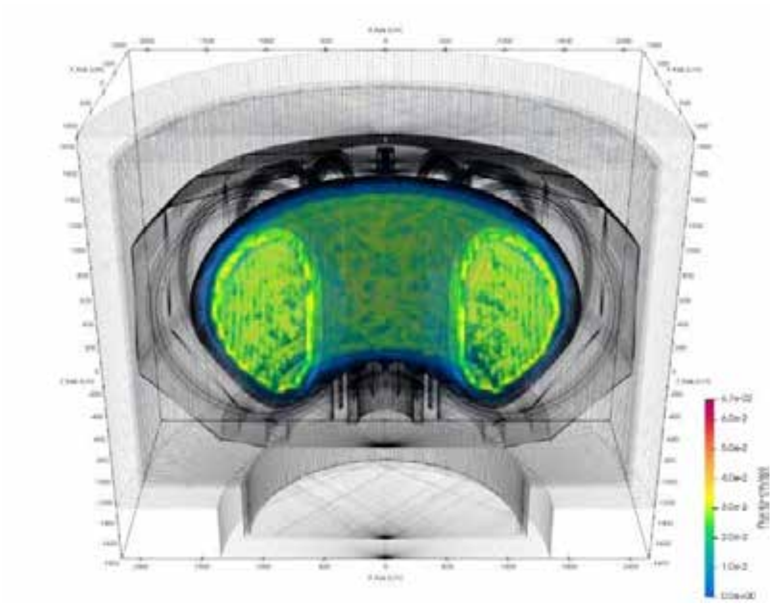


Figure 37: A neutron flux tally resulting from an OpenMC run of a DAGMC Model of EU-DEMO, as generated by bluemira.

16 A software package that allows users to perform Monte Carlo radiation transport directly on CAD models.

17 An open-source Monte Carlo particle transport code, capable of scaling up to hundreds of thousands of processors.

18 MOAB is a component for representing and evaluating mesh data. MOAB can store and represent structured and unstructured meshes consisting of elements in the finite element "zoo", including polygons and polyhedra.

Water-Cooled Lead-Lithium (WCLL) Breeding Zone (BZ) Mock-ups and Modelling Activities

Advanced MHD analytical modelling capability at UKAEA and further development of experimental series for increasing readiness experiments for liquid breeding blankets (BB).

This year's work was concluded with an updated WCLL EUROfusion Prototype Mock-up Unit (PMU) series of experiments, and an increased MHD capability. The mini-PMU was updated to reflect significant changes in the baseline WCLL design.

At the outset, there was uncertainty of continuing with the WCLL in its current form, as there was a shift to the "double bundle" concept[19]. The design teams at the Italian National Agency for New Technologies Energy and Sustainable Economic Development (ENEA) addressed the issues presented in the Reliability, Availability, Maintainability, Inspectability (RAMI) analyses20, and it was agreed at EUROfusion WPBB project level that the revised design will progress. Close collaboration with ENEA was therefore required to update the mini-PMU relevant to the new design (which primarily increased reliability through reduction of weld). These changes were captured in the PMU design and are in addition to the modifications made to make experiments more generalised (i.e., they will no longer be EU-DEMO specific and will provide scientific value for any liquid breeding design).

Another deliverable of the project was to perform MHD modelling activities using PbLi as the use case to increase MHD capability as an organisation. This considers analytical solutions to electrically coupled duct problems that will be numerically verified and validated by future experiments. The MHD Team have been involved in EUROfusion MHD benchmarking activities as part of this deliverable.

Finally, an investigation has been conducted into the applicability of helium being used as a coolant and the impact on experiments. This is to mitigate the risk following the decision not to proceed with the build of the pressurised water reactor loop on the Combined Heating and Magnetic Research Apparatus (CHIMERA21), resulting in a lack of heat rejection capability. This investigation is critical for verifying MHD regimes experiencing heat transfer in the breeding zone.

19 This concept adopts an array of double bundle tubes poloidally distributed inside the breeding zone, mimicking the arrangement inside heat exchangers. These are coaxial pipes, the gap between which is filled with PbBi (or alternatively with gas and fins), which avoids direct contact between PbLi and water in case of in-box LOCA events.

20 RAMI is one of the main stages of technical risk control and it focuses on the operational functions required by the nuclear fusion device operation, but not on physical components.

21 CHIMERA will be the only machine in the world able to test components in the combination of high temperatures, magnetic fields and vacuum expected in a fusion power plant.

Understanding and Measuring the Fusion Environment

It is important to ensure that a fusion power plant is both functional and safe from the initial design through to build, operations and decommissioning. This assurance is gained through simulation validation, inspection and monitoring of the fusion environment and its effect on materials and components.

The Fusion Technology Division engages and leads on several critical areas across nuclear safety, complex fluid-structure interactions, and inspection for maintenance scenarios. Our unique skills and capabilities lead to strong working relationships with industry (external to UKAEA), such as thermal hydraulics (for fission), high heat flux testing (for rocketry and space exploration), and the simulation and measurement of radiation fields (for private fusion companies).

Publication of the Machine Learning Compton Suppression Algorithm (MLCSA)

The MLCSA development was published in the Journal of Fusion Energy.

Diagnostics are critical to commercial fusion machines, since measurements and characterisation of the plasma are important for sustaining fusion. Gamma spectroscopy is commonly used to provide information about the neutron energy spectrum from activation analysis, which can be used to calculate the neutron flux and fusion power.

The detection limits for measuring nuclear dosimetry reactions, used in such diagnostics, are fundamentally related to Compton scattering events (or the Compton Effect)[22] making up a background continuum in measured spectra. The background lies in the same energy region as peaks from low-energy gamma rays, leading to detection and characterisation limitations.

The publication[23] by Lennon et al. was a collaboration between the Applied Radiation Technology (ART) Group and the University of Sheffield's Materials and Engineering Research Institute. The paper presents a digital MLCSA that uses state-of-the-art machine learning techniques to perform pulse shape discrimination for High Purity Germanium (HPGe) detectors.

The MLCSA identifies key features of individual pulses to differentiate between those that are generated from photopeaks[24] and Compton scatter events. Compton events are rejected, reducing the low energy background. This novel suppression algorithm improves gamma spectroscopy results by lowering Minimum Detectable Activity (MDA) limits, and thus reduces the measurement time required to reach the desired detection limit.

In the published paper, performance of the MLCSA is demonstrated using an HPGe detector, with a gamma spectrum containing americium-241 (Am-241) and cobalt-60 (Co-60). The MDA of Am-241 improved by 51% and the signal to background ratio improved by 49%, whereas the Co-60 peaks were partially preserved (reduced by 78%). Figure 38 shows a graph of the results.

The MLCSA requires no modelling of the specific detector and therefore has the potential to be detector agnostic, meaning that the technique could be applied to a variety of detector types and applications. The detector used in this study is shown in Figure 39.

22 Compton scattering events or the Compton Effect: a phenomenon where high-energy photons (like X-rays or gamma rays) collide with charged particles, typically electrons, causing the photon to scatter at a different angle and with a longer wavelength (lower energy). The electron also recoils, gaining some of the photon's energy. This process is a crucial form of photon interaction with matter and provides evidence for the particle-like nature of light.

23 Machine Learning Based Compton Suppression for Nuclear Fusion Plasma Diagnostics https://link.springer.com/article/10.1007/s10894-024-00408-9

24 A photopeak refers to a distinct peak in the spectrum that represents the full energy of a gamma ray being deposited in the detector through the photoelectric effect. Essentially, it's the signal produced when a gamma ray is completely absorbed by the detector's sensitive material, and all its energy is transferred to the detector's material.

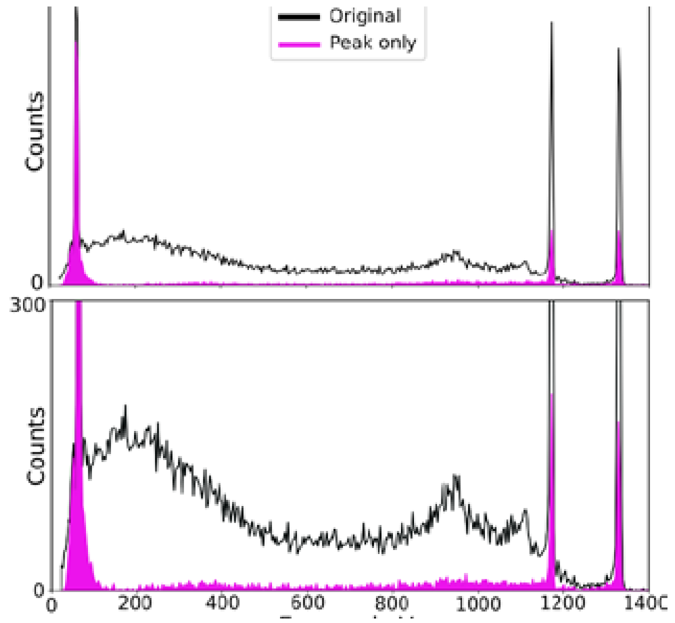


Figure 38: Mixed Am-241 and Co-60 spectrum before (line) and after (filled) the MLCSA. Top shows the full spectrum. Middle is zoomed along the vertical axis. Bottom is zoomed along the horizontal axis. Left shows around the Am-241 photopeak and right around the Co-60 photopeaks).

Figure 39: The Mirion Broad Energy Germanium (BEGe) detector used in this work, with the physical Compton suppression system surrounding the main HPGe crystal. The MLCSA produced the same suppression effects as this bespoke (expensive) system, but with no cost.

Roadmap for Applied Radiation Technology Fluid Activation Modelling

The fluid activation modelling roadmap will guide future work on fluid activation and Activated Corrosion Products (ACPs) in the ART, making sure that validated modelling tools will be available when needed, and to the required level of accuracy.

Neutron activation of fluids and corrosion products in coolant and breeding circuits is a critical driver of dose rates in future fusion machines due to the extreme conditions. This criticality has been recognised through dedicated activity on ITER to calculate and address high dose rates resulting from ACPs.

ART has developed codes to account for fluid activation, and more recently has recognised the impact of ACPs. During the Fluid Activation Strategy[25] Project in 2024, existing modelling solutions were reviewed, opportunities for developments and code validation explored, and meetings held with a range of expert stakeholders.

From the strategy, a fluid activation roadmap was written to guide the Group's work on the specific goals, identified for either fluid activation or corrosion codes. The items cover benchmarking activities, code developments, strategies for addressing knowledge gaps, code releases, engagement with the community, and validation activities (including uncertainty quantification).

Outcomes include better-informed development of fluid activation codes, a new EPSRC task for 2025 to:

- Develop a UKAEA corrosion modelling solution
- Motivation for publicising and sharing this code with the fusion community
- Validation activities, informed by safety case timelines.

The roadmap, as seen in Figure 40 will be reviewed annually, informed by engagement with a wider range of external groups, and progress on the existing goals (Figure 41).

25 *A report summary of the status of UKAEA's capabilities in fluid activation and corrosion product modelling and exploring possibilities for future developments.*

2025	2026	2027	2028	2029+
➢ GammaFlow-FARBASE demonstration for variety of parametrised components under WPSAE (**F1**) ➢ Application of GammaFlow-FARBASE to 2019 FNG benchmark (**F2**) ➢ Benchmark of fluid activation codes against KATANA experiment (**F2**, **F7**) ➢ Benchmark of GammaFlow against JET water activation experiment (**F2**, **F6**) ➢ GammaFlow code development to simulate transient flows (**F4**) ➢ Design of corrosion code (**C1**) ➢ Prepare corrosion code software development strategy including plans for open-sourcing and resource requirements (**C7**) ➢ Strategy for experimental data on transport of Co-60 ions (**C6**) ➢ Engagement with external neutronics groups on topic of ACP modelling (**C8**)	➢ Analysis of fluid experiments (SmallLab, MULTIForm, PEPT) for FARBASE non-water benchmarking (**F3**) ➢ Investigation of FLUNED and scope of integration into existing capabilities (**F5**) ➢ Demonstration of fluid activation code for theoretical complex circuit (**F8**) ➢ Initial internal code release (**C7**) ➢ Code-to-code corrosion modelling comparison on ITER limiter-outboard loop (**C2**) ➢ Benchmark of corrosion code against Belous data (**C3**) ➢ Benchmark of corrosion code against results from FNG deposition experiment (**C5**) ➢ Gate review of code progress and status of alternatives (**C15**) ➢ Open source code release (**C7**) ➢ Present code and benchmark status at conference (**C7**) ➢ Extension of corrosion code to output ACP source terms (**C8**) ➢ Review of inclusion of radiolysis and magnetic fields in UKAEA corrosion loops (**C13, C14**) ➢ Evaluation of LIBRTI circuits and requirements for benchmark data collection (**F2, C12**)	➢ First uncertainty quantification for STEP-relevant coolant activation source term (**F9**) ➢ Benchmark of corrosion code against results from UKAEA high-speed corrosion loop (**C4**) ➢ First uncertainty quantification for STEP-relevant ACP source term (**C9**) ➢ First uncertainty quantification for LIBRTI-relevant ACP source term (**C9, C12**) ➢ Comprehensive benchmark against full range of fusion-relevant corrosion experiments (**C3, C4**) ➢ Dedicated projects on increases to simulated media and detailed interaction laws (**C10, C11**)	➢ Continued development of media and interaction laws (**C10, C11**) ➢ Benchmark against radiolysis and magnetic field data (**C13, C14**) ➢ Input from fluid activation and corrosion codes to STEP safety case report (**F9, C15**)	➢ Possible validation data from LIBRTI fluid circuits (**F9, C12, C15**) ➢ Validation data from other large-scale fusion devices (**F9, C15**)

Figure 40: Fluid activation modelling roadmap defined In EPSRC fluid activation strategy report. Each roadmap item is linked to one or more identified goals for fluid activation and corrosion modelling (Figure 41).

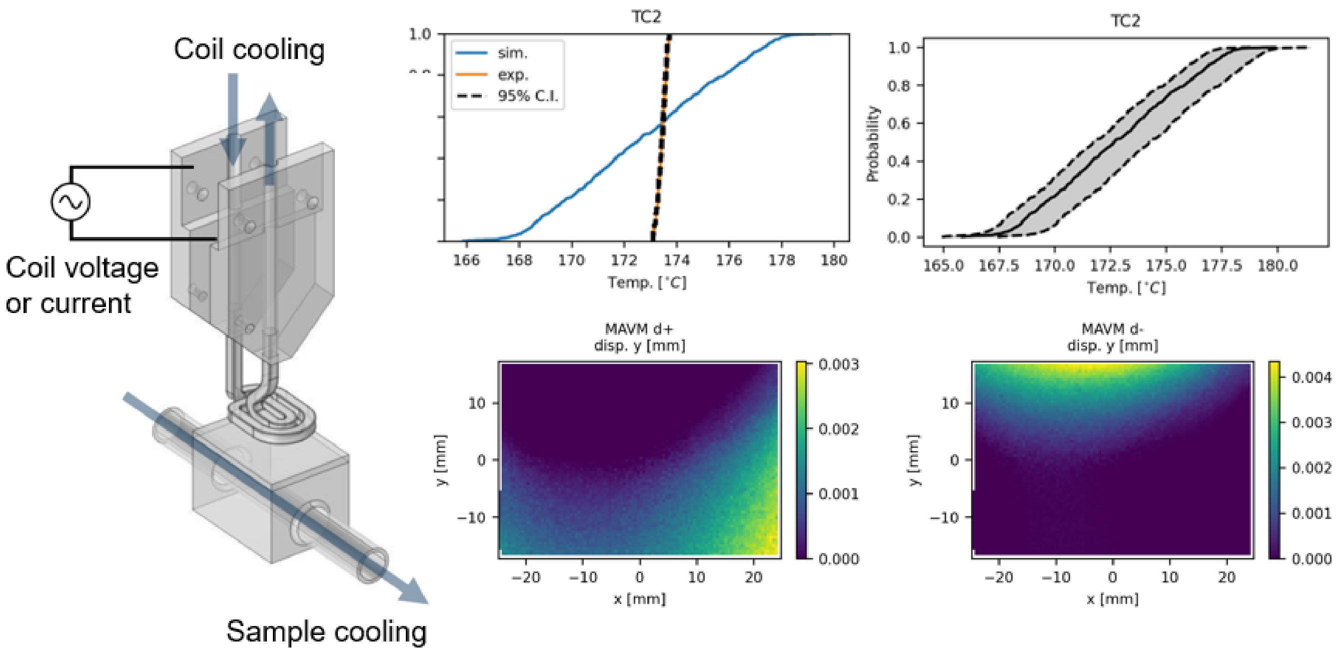


Figure 41: Goals for fluid activation and corrosion modelling, defined in EPSRC fluid activation strategy report.

Computational Prediction of Flow Boiling and Departure from Nucleate Boiling in ITER TBM

CFD analysis to predict departure from nucleate boiling in WCLL TBM double wall tubes under normal operation condition, following optimisation of multiphase flow boiling and momentum transfer models for high-pressure conditions.

The potential of the CFD to predict Critical Heat Flux (CHF) results and validate against experimental data and empirical correlations, enhancing confidence in the thermal-hydraulic design and safety margins of fusion components.

The current research focuses on predicting Departure from Nucleate Boiling (DNB) using CFD in the Double Wall Tube of the WCLL-TBM for ITER. At the DNB or CHF, the wall temperature rises sharply beyond material limits, posing a significant risk of component failure. Therefore, accurate prediction of CHF is essential for the safe operation of the test blanket module.

Traditionally, CHF prediction relies on empirical correlations, or look-up tables, derived from historical data for straight pipes. However, these methods have limited accuracy and applicability, especially under the complex geometries and operating conditions relevant to fusion environments.

In contrast, advanced multiphase CFD offers a more detailed and versatile approach for analysing flow boiling across a broader range of geometries and conditions. An inhomogeneous Eulerian multiphase model26, incorporating the Rensselaer Polytechnic Institute's (RPI), New York, boiling model, was employed to simulate flow boiling and estimate CHF. The associated boiling and momentum closure models were optimised and validated under high-pressure conditions, typical of TBM operating conditions, as shown in Figure 42.

Two-phase boiling simulations were conducted on various DWT geometries27 immersed in PbLi to study the influence of geometry on vapour distribution within the flow domain. The results, illustrated in Figure 43, indicate that vapour generation is strongly geometry-dependent, with the highest vapour fractions occurring at the tube bends. Under normal operating conditions, the vapour fraction remained well below the DNB criterion threshold (set at vapour fraction > 0.9), indicating a significant safety margin to CHF. These findings provide confidence in the thermal-hydraulic design of WCLL-TBM.

Further analysis was carried out by incrementally increasing the surface heat flux on different discrete wavelet transform geometries to identify the onset of DNB. Wall temperature behaviour qualitatively followed anticipated CHF trends, displayed in Figure 44. These outcomes offer valuable insight into thermal limits and highlight the importance of further experimental validation under fusion-relevant conditions.

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26 The Eulerian multiphase model is a CFD approach used to simulate the behaviour of systems with multiple interacting phases (like gas, liquid, or solid particles). It treats each phase as a continuous interpenetrating fluid, allowing for the calculation of individual phase properties like velocity and volume fraction. This model is particularly useful for analysing flows where phases are intimately mixed and where interactions between phases are significant.

27 The geometric characteristics of a DWT and how it is used to analyse or represent images, signals, or other data. DWT decomposes data into different frequency components at various scales, providing both spatial and frequency information. This decomposition is influenced by the geometry of the filters used and the way the data is sampled.

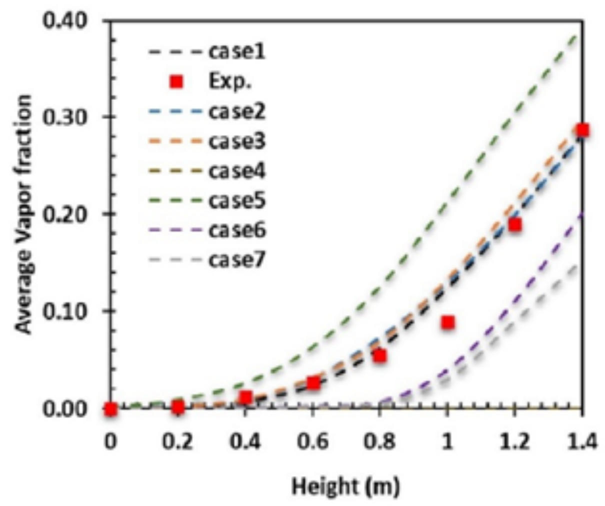

Figure 42: Model optimisation and validation with experimental void fraction data under high pressure condition.

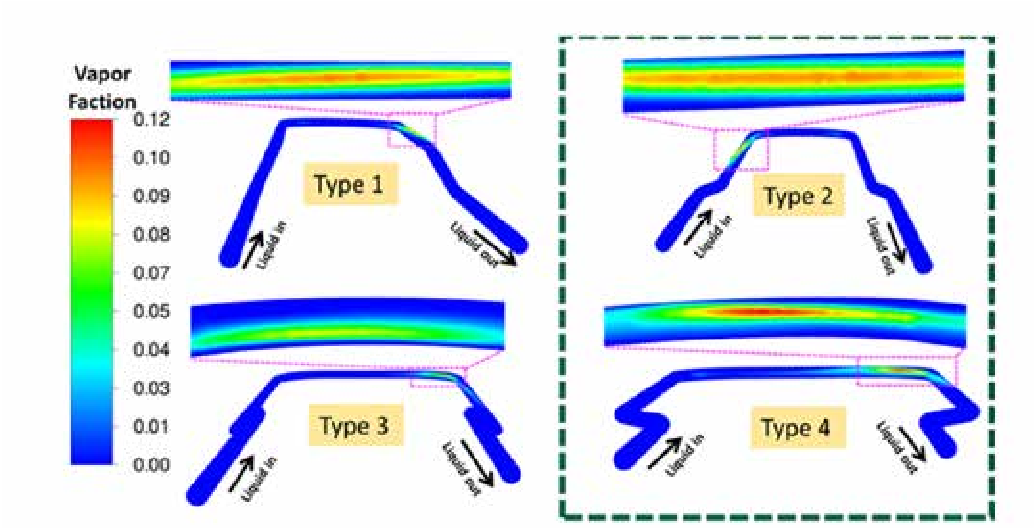

Figure 43: Contours of vapour fraction at the bend of different types of discrete wavelet transforms.

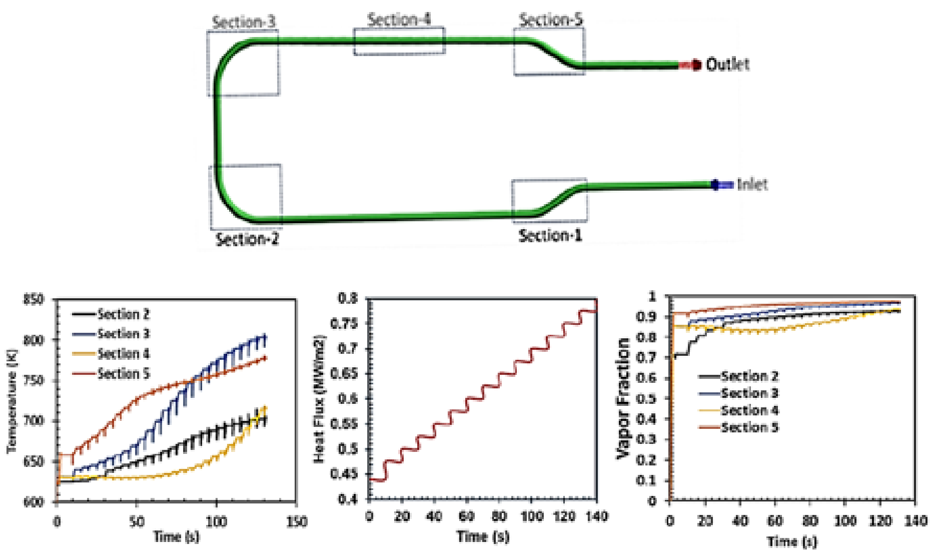

Figure 44: (a) Temperature with respect to time (b) Stepwise effective heat flux as input to pipe wall (c) Vapour fraction with respect to time.

Developing the Skills Base

Whilst fusion power is an unprecedented scientific challenge in scope and difficulty, it is very much a niche scientific discipline. Large scientific endeavours have something in common, given that they have a team of dedicated, creative, and talented individuals who are essential to the success of fusion power.

To achieve a workforce to deliver the mission of achieving fusion power, it is necessary to actively engage with training, and develop the skills of people across the organisation, academia, and industry. As a Division, there are several initiatives which contribute towards establishing a fusion skills base.

- Since 2021, the Division undertakes a "Fusion Training Programme" for new starters across UKAEA. The programme provides an overview of fusion power plants across approximately 20 talks, where attendees have an opportunity to discuss and ask questions with speakers. It provides a common baseline of knowledge to staff who are new to the organisation, many of which have had no previous or formal fusion training.
- The Fusion Training Programme provides a foundation on which to build new training provisions. The Team are exploring short-form content, online availability, potential collaborations with United Kingdom Industrial Fusion Solutions (UKIFS) for training the engineering partner, and interaction with Fusion Opportunities in Skills, Training, Education and Research (FOSTER).
- Fusion Technology has expanded its ongoing collaboration with the academic sector. In 2024, 8 PhD projects were established, with 12 new PhD starters planned for 2025, creating a total of 40 active PhDs supported by the Division. The physical-digital interface is a focus area, underlining the key nature of digital tools in delivering a feasible fusion power plant.
- The Division will be supporting PhDs under the Fusion Engineering Centre for Doctoral Training (CDT) for the first time in 2025, acknowledging the significant technology and engineering challenges that must be overcome. The growth of the Fusion Engineering CDT will complement the FOSTER programmes (Level 7 qualification, equivalent to a Master's Degree), thereby establishing a larger academic forum for fusion engineering.

Fusion Training Programme

The PPMI Group provided their annual training programme, designed to highlight key aspects of the broad range of fusion fields. The aim was to provide staff with a foundation that enables whole plant awareness and cross-disciplinary collaboration.

Designing and building a fusion power plant is a complex, multidisciplinary enigma which requires understanding the interactions between different plant systems. It requires scientists and engineers with different specialties, who:

- may not have completed any fusion focused training/education or have any previous experience working in the field
- must understand the impact their work will have on the overall challenges and goals of plant design.

PPMI's Annual Fusion Training Programme began in 2021 and is aimed at new starters and those on the Graduate Programme. Lectures are given by members of PPMI and experts from departments within UKAEA. Figure 45 shows the power plant system breakdown and key functions.

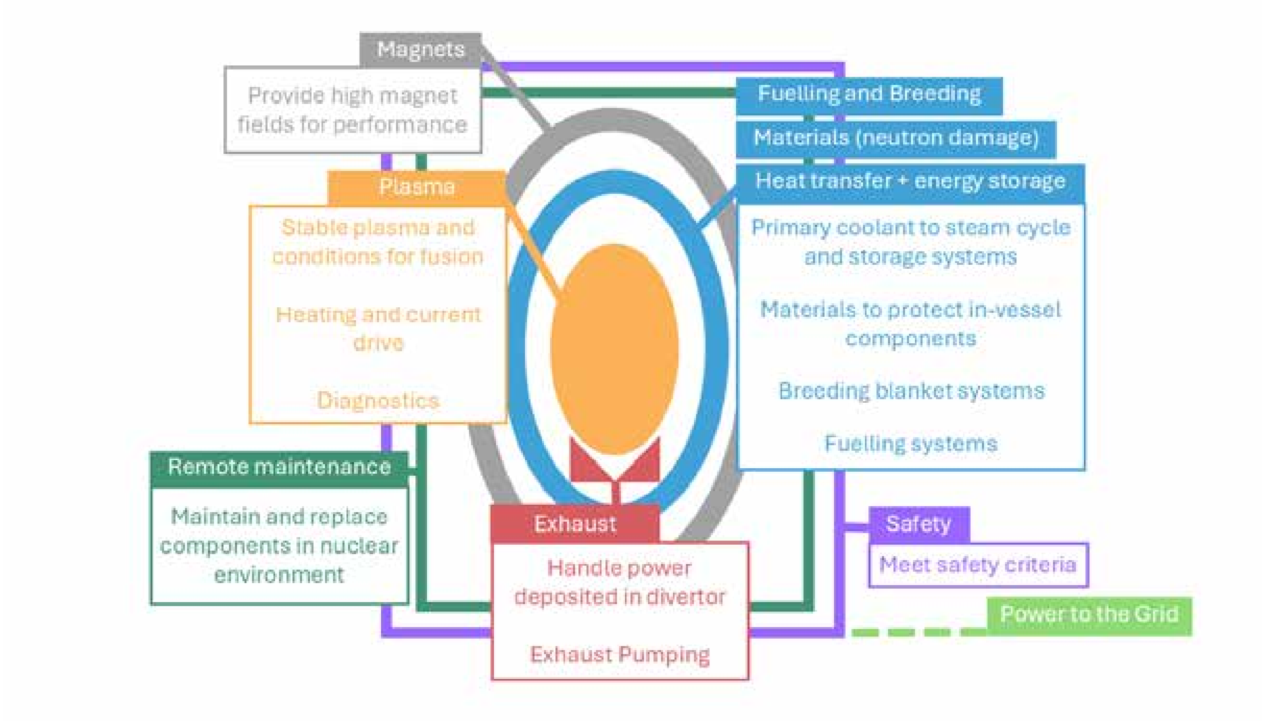

Figure 45: Fusion power plant systems.

Fusion Technology Grows University Collaboration and PhD Programme in 2024

Eight new PhD projects started in 2024 and Fusion Technology (in partnership with UKAEA programmes and universities) will be supporting 12 new PhD projects in 2025. Covering a strategic range of topics, these vital collaborations with universities will seek to build the fusion skills pipeline and undertake critical fusion-related research.

The 2024 cohort of Fusion Technology-supported PhDs continued the Division's strong track record of projects in advanced manufacturing, materials qualification and radiometrics, with a notable shift towards uncertainty quantification and digital methodologies, in keeping with the Division's strategic priorities. Figure 46 shows a word cloud corresponding to the popular themes covered by current PhD projects.

As these projects commenced, the Fusion Technology Research Programme agreed to support a total of 12 new PhD projects (to start in 2025), across 13 universities. Of these, 5 projects are directly funded by the FT EPSRC Programme, with the remainder funded by programmes including FOSTER, LIBRTI, and Dr Lloyd Fletcher's Future Leaders Fellowship. Next year's cohort marks an increase in the number of cross-divisional projects, an increasing trend across UKAEA, in recognition of the integrated nature of many of the most pressing research challenges facing fusion.

The 2025 projects also reflect the Division's emphasis on the digital-physical interface and the need for new approaches to material and component qualification supported by simulation and sensor technology development. These new projects will bring the total number of active Fusion Technology PhDs to 40, across 17 universities. Figure 47 shows the trend in increasing number of projects FT Division are contributing to, either supporting or directly funding.

Fundamentally, the FT Division will be supporting projects from the new Fusion Engineering CDT, as part of our intention to fund at least two new projects per annum, over the next four years. This CDT will provide an exciting opportunity to engage with "core" universities, "associate" universities, and industry partners. Kick-off meetings at the University of Manchester and University of Birmingham have already generated significant interest, with several proposals expected to be submitted in the coming year.

Beyond PhDs, a few people in the Division hold visiting posts at universities, and the Fusion Technology Division continues to strengthen relationships by supporting thermofluids research at the University of Sheffield, whilst retaining an ambition to establish a Research Chair in the Mechanical Engineering Department.

Figure 46: Word cloud of active PhD project topics.

UK Atomic Energy Authority

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