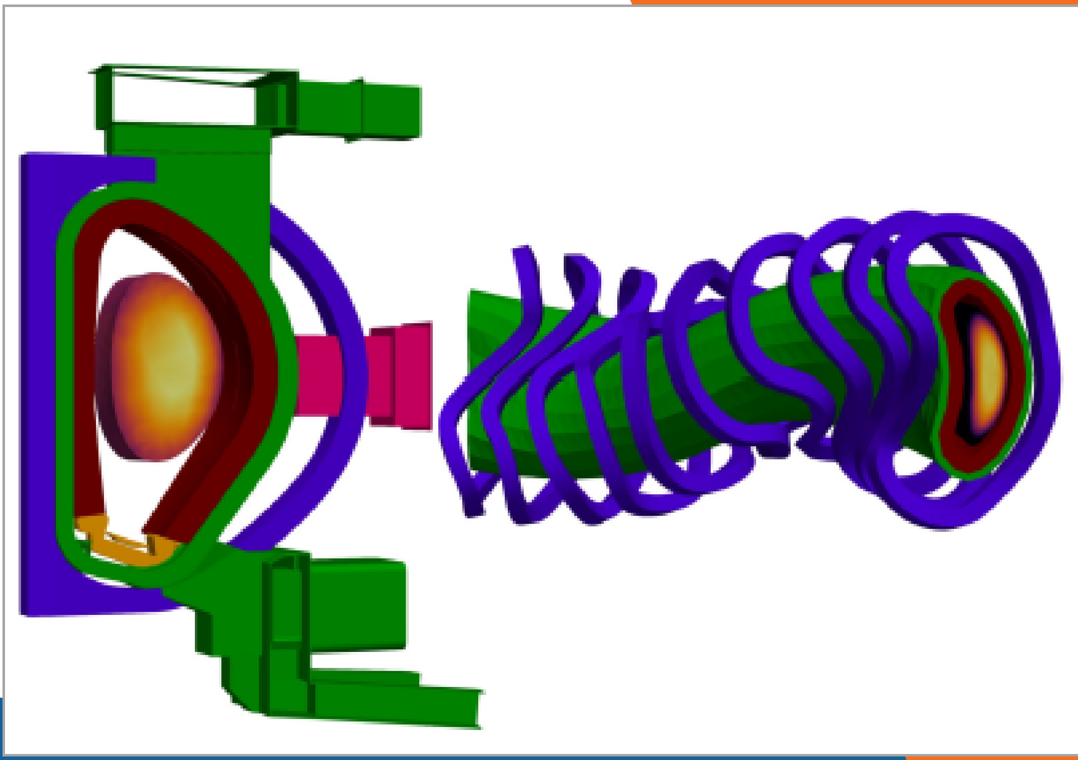

ECO-Fusion: Finnish Ecosystem for Industrial Fusion Technology

Final report

Antti Hakola | Tommi Lyytinen (Eds.)

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Preface

This report summarizes the work done under the VTT part of the ECO-Fusion co-innovation project (Finnish Ecosystem for Industrial Fusion Technology, 40962/31/2020), co-funded by Business Finland, VTT and the European Union (under EUROfusion Consortium). The co-innovation partners were VTT, University of Helsinki, Luvata Oy, Electro Optical Systems Finland Oy, Insinööritoimisto Comatec Oy, and Platom Oy. The main goals of the project were establishing a functional fusion ecosystem in Finland, facilitate growth and export of Finnish companies in fields related to fusion technology and take part in emerging tendering opportunities on the international arena, as well as increasing the competences of the participants in targeted research areas. For VTT, the latter included remote maintenance of components and sub-systems in fusion reactors, design and characterization of novel materials for the harsh environment inside fusion reactors, providing the scientific community with new information to guarantee successful operation of future fusion power plants, as well as ensuring safe operation of the plant, handling of the produced radioactive waste and final decommissioning of the fusion reactor. ECO-Fusion was part of the FinnFusion Consortium, a network for Finnish universities, research institutes, companies, and decision-makers, which ensured large visibility for the key achievements of the project and offered novel ways for collaboration. Thanks to the EU involvement, ECO-Fusion was a highly international programme and during its lifetime in 2021-2024 links and and new contracts were established with several foreign companies and organizations, including the US, the UK, and South Korea.

Contents

List of acronyms and names

ACH	Advanced Computing Hub
AI	Artificial Intelligence
APCS	Advanced Position Control System
AWG	Arrayed Waveguide Grating
BB	Breeding Blanket
BOP	Balance-Of-Plant
CA	Cellular Automation
CAD	Computer Aided Design
CFC	Carbon Fibre Composite
CFD	Computational Fluid Dynamics
COTS	Commercial Off-The-Shelf
CP	Crystal Plasticity
CPU	Central Processing Unit
EBM	Electron Beam Melting
EBSD	Electron BackScatter Diffraction
FBG	Fiber Bragg Grating
FCAI	Finnish Center for Artificial Intelligence
FDS	Fire Dynamics Simulator
FE	Finite Element
FILD	Fast Ion Loss Detector
GPU	Graphics Processing Unit
GSSR	Generic Site Safety Report
HCPB	Helium-Cooled Pebble Bed
HPC	High-Performance Computing
ICME	Integrated Computational Materials Engineering
IFMIF-DONES	International Fusion Materials Irradiation Facility – Demo-Oriented Neutron Source
IHTS	Intermediate Heat Transfer System
IHX	Intermediate Heat eXchanger

IMAS	Integrated Modelling and Analysis Suite
IROH	Integrated Remote Operations Handler
JET	Joint European Torus (tokamak facility)
LIBS	Laser-Induced Breakdown Spectroscopy
LIDAR	Light Detection and Ranging
MD	Molecular Dynamics
ML	Machine Learning
MZI	Mach-Zender Interferometer
OTSG	Once-Through Steam Generator
PBF	Powder Bed Fusion
PCS	Power Conversion System
PF	Phase Field
PHTS	Primary Heat Transfer System
PFC	Plasma-Facing Component
PRA	Probabilistic Risk Assessment
RAMI	Reliability, Availability, Maintainability, and Inspectability
RM	Remote Maintenance
SEM-EBSD	Scanning Electron Microscopy – Electron BackScatter Diffraction
SIMS	Secondary Ion Mass Spectrometry
SME	Small and Medium-sized Enterprises
SMR	Small Modular Reactor
TE/TM	Transverse Electric/Transverse Magnetic
TF	Taylor Field
TIR	Total Internal Reflection
TMT	Traceability Management Tool
VNS	Volumetric Neutron Source
VR	Virtual Reality
WCLL	Water-Cooled Lithium-Lead

1. Overview of ECO-Fusion

1.1 Introduction and research environment

The co-innovation project “Finnish Ecosystem for Industrial Fusion Technology” (ECO-Fusion) was established to promote the competitiveness of Finnish industry in fusion technology and beyond. The vision of the project was to facilitate the involvement of Finnish research organizations and companies in the international fusion-technology market and R&D activities. The focus was put on selected technology topics, creating an active fusion ecosystem in Finland, and supporting companies through business research. All this was facilitated by the existing strong links of VTT with Finnish and international partners, allowing active networking among all the partners.

The need for this co-innovation project stemmed from the ongoing, international gigascale fusion projects like the ITER and DEMO reactors. These represent a broad spectrum of opportunities for Finnish companies as big, reliable long-term customers of products and services. ITER is the largest of the Big Science projects and the largest joint research project in the world, both in terms of the budget and the number of countries behind the project. The ITER ecosystem creates an excellent scientific and commercial framework for international networking and knowledge building (budget approximately € 22 billion). Market potential is high in the fusion projects in Europe, but so is international competition. In Horizon Europe, ITER alone will procure at € 7-8 billion of tenders from European companies. Even for small Finland, the market potential alone around ITER is easily 200-300 M€. Even more importantly, deliveries to ITER and DEMO create significant non-monetary brand value, proving companies as competent suppliers approved by the most demanding high-profile customers. Especially for SMEs to capture value it is important to see the fusion industry as a channel to the larger market. This opens access to both inside and outside fusion projects to the high-value markets that require matching references. Furthermore, companies will have easier access to EU funding via the European projects as members of the consortia initiated under ECO-Fusion.

1.2 Project goals, deliverables, and milestones

The high-level goals of the project were formulated as follows:

<u>Goal 1: In accordance with VTT strategy 2025, develop new competence and research results in selected areas:</u>

- Enhance VTT’s capability in nuclear safety solutions for carbon neutral and flexible energy systems in the following areas: (i) Fusion power plant lifetime and maintenance; (ii) Development of novel materials for fusion applications; (iii); Establishing an advanced computing hub for fusion; (iv) Fusion power plant analysis; (v) Licensing and safety of fusion power plants, and (vi) Ecosystem and business development.
- In the selected research areas above, create research excellence measured with VTT’s KPIs, Quality in science and technology (publications, IPR, PhDs) and Innovation capabilities.
- Create an impact on VTT’s international research portfolio (EU funding) and commercial project basis.

Goal 2: Through well-targeted research, facilitate the entry to international fusion tenders and research projects for Finnish companies and academia.

- Build competence in Finnish research and business networks to reach the international level and opportunities to become a member of high-tech international consortia.
- Advance export in fusion research but extend also to other Big Science projects and markets outside fusion as well.
- Maximize EU (incl. DEMO) and ITER funding for both Finnish industry and research organizations.

Goal 3: Build a top ecosystem for Finnish companies to reach the development targets from the ordinary company to the international high-tech service provider.

- Support industry to build value networks (ecosystems) through business and collaboration model research in fusion / big science context both on company and ecosystem levels.
- Analyse communication between ITER and Finnish companies to boost business efficiency and development in big science projects and within the Finnish ecosystem.
- Maintain wide knowledge and information exchange with industry through collaboration with FinNuclear to learn from and co-innovate ILO and industry activation.

The following tables introduce the crucial metrics for characterizing the success of ECO-Fusion for the VTT Research project. Table 1 describes the Key Performance Indicators (KPIs), the milestones are given in Table 2, while the deliverables are listed in Table 3.

Table 1. KPIs of the co-innovation project for the VTT ECO-Fusion Research Project.

Partner	Expected impact of the project on partner	Metrics
VTT	1. Capabilities to better support Finnish companies to connect with international partners in fusion projects 2. Better hit rate in EU funding/tenders together with Finnish industry partners 3. Research excellence 4. Visibility, reputation, and trusted partner of VTT as a Finnish fusion co-ordinator in EU 5. Better commercial collaboration with Finnish companies	1. Number of Finnish companies involved/aware of ITER and DEMO tenders/projects. 2. Hit rate analysis 3. Publication record, number of citations 4. Independent evaluations from EC, EUROfusion, ITER and Finnish government 5. Turnover of VTT's commercial fusion project portfolio
EU fusion ecosystem	1. Better knowledge about Finnish companies and their products/services 2. Updated information about Finnish partners in EU fusion databases 3. Demonstration of Finnish excellence in selected focus areas (superconductors, novel materials, remote maintenance, artificial intelligence/high-performance computing, nuclear engineering)	1. Questionaire to EU stakeholders (F4E, ITER, European Commission) 2. Number and quality of Finnish companies information in EU fusion databases 3. Participation in business events (IBF and BSBF, SOFT exhibition)

Table 2. Milestones of the VTT ECO-Fusion research project.

No	Title	Description	Expected date
1	EUROfusion decisions for funding of Horizon Europe projects	EUROfusion decisions on all DEMO and ITER projects will be available. Refocussing and reresourcing on some resources may be performed.	3/2021
2	Decision on Advanved Computation Hub Helsinki	Start recruiting personnel or reduce significantly the scope, depends on the funding decision by EUROfusion.	4/2021
3	All co-innovation projects (VTT, UH and the 4 company projects started)	All the separate co-innovation projects have had their kick-off meetings and the first project steering group organized.	6/2021
4	Well-functioning collaboration with FinNuclear and its ILO activity established	One the FInNuclear collaboration is established with this co-innovation project, we will plan procedures on how to maximize the benefit from this co-innovation to ILO work and national fusion industry activation and vice versa from the national industry activation towards this co-innovation project.	1/2022
5	New research opening fields initiated	A critical mass of resources put in place for new research areas at VTT with the help of the companies involved, such as licensing, nuclear waste and decommissioning and novel fusion materials research.	6/2022
6	Data collection of ecosystem roles, processes, and cases	Data collection about different roles, processes and cases in related big science projects as well as about service/product-providing entities is completed. This is required to enable final analysis and network model creation.	11/2022
7	EUROfusion decision on the beneficiary to host EU test rigs	Start integrating the test rig with VTT’s existing environment on the virtual smart manufacturing test facility.	6/2023

Table 3. Deliverables of the VTT ECO-Fusion research project.

Year	Title	Description
2021	First Open Business Day seminar for Finnish companies	An annual open seminar for all interested parties to network and learn about the fusion industry and research opportunities.
2022	Well-operating Advanced Computing Hub	The Advanced Computing Hub is receiving EU funding and acting as the central point of Finnish HPC and AI expert centre both in fusion and spreading the know-how elsewhere.
2022	Generic business models and transition -report 1	Report on the current vision of generic industry business models and how they see their need for transition.
2022	Candidate materials for DEMO components and magnets	Report on the characteristics of advanced materials, developed within the scope of this project, fulfilling specifications required for DEMO components and magnets.
2023	New Finnish fusion activities born in this co-innovation project	List the number of new activities born from this co-innovation project (new companies, new projects, new tenders, new experts).
2023	Generic business models and transition -report 2	Report on the generic industry business models and transition, change of visions and practical actions taken.
2023	Digital thread models for fusion test rig	Simulated environments established for the fusion test rig and thread models available for testing virtual prototypes in DEMO-relevant conditions.
2023	Creation of the Finnish Fusion Ecosystem models	The ecosystem research supporting innovation actions creating export, international networks, internal collaboration, EU funding and added value to its participants.

1.3 Project structure

1.3.1 Co-innovation project

A schematic presentation of the structure and the operating environment of the ECO-Fusion project can be found in Figure 1. The research partners were VTT Technical Research Centre of Finland Ltd (VTT) and the University of Helsinki. Their research projects were originally proposed to cover the period 1.1.2021–31.12.2023 but were subsequently extended into 30.6.2024 in agreement with Business Finland. The company partners were Insinööritoimisto Comatec Oy (Development of Expertise and Service Portfolio for International Markets), Electro Optical Systems Finland Oy (Novel AM materials for Energy Segment), Luvata Oy (Fuusiokuparit) and Platom Oy (International Licensing Framework in Challenging Environments). All participating companies were attached to one or more scientific Work Packages of the VTT project (see section 1.4.1). Of the company projects, Luvata finished their activities on 31.12.2023 while the others extended the work until 31.12.2024.

The VTT part of the research project was co-funded by Business Finland, VTT, and the European Union via the EUROfusion Consortium. EUROfusion also gave large input for detailed contents of the different research tasks on an annual basis. Roughly 2/3 of the tasks under ECO-Fusion were fully aligned with the EU objectives (co-funded by Business Finland, VTT and EU), while the remaining 1/3 were new openings with no EU support (co-funding thus exclusively from Business Finland and VTT).

Several international and domestic stakeholders were identified, including (but not limited to) the funding bodies, the Research Council of Finland, the Ministry of Economic Affairs and Employment, the FinNuclear Association, the ITER Organization, and Fusion for Energy. All these were regularly informed on the project achievements or, in the case of international partners, on the Finnish capabilities for tendering opportunities.

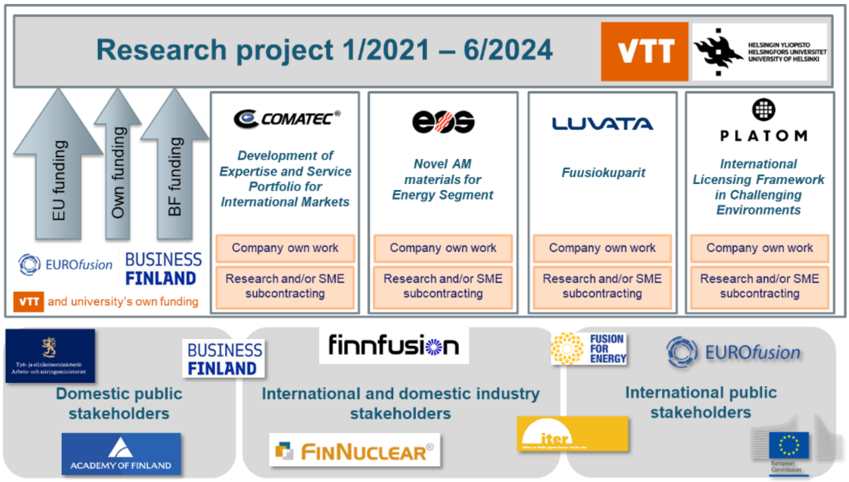

Figure 1. Schematic presentation of the structure, participants, funding sources, and key stakeholders of the ECO-Fusion project.

1.3.2 Project steering group and other support

The steering group for the co-innovation project consisted of the following people (deputies in parentheses):

- VTT: Tuomas Tala (Tapani Ryynänen)
- University of Helsinki: Kai Nordlund (Fredric Granberg)
- Luvata: Olli Naukkarinen (Tuomas Renfors and Sarita Hernesniemi)
- Comatec: Veikko Puumala (Petri Leino)
- EOS Finland: Pilvi Ylander (Paula Kainu)
- Platom: Toivo Kivirinta (Sami Kiviluoto)

In addition, Antti Hakola acted as the secretary for the steering group and the manager for the VTT Research Project. Business Finland representatives were invited to each Steering Group meeting.

1.4 VTT research project

1.4.1 Work breakdown into WPs and Tasks

The VTT research project was divided into five research-oriented work packages (labelled as WP VTT-1 etc.) and a work package (WP VTT-6) on project management and dissemination. The WPs were further broken down into Tasks which were treated as thematic focus areas of the research while the daily work was made within smaller Subtasks, later on referred to as "activities" in section 3. Coordinators were selected for each WP (1-3 people) and activity (a single person) to ensure fulfilling their main objectives.

The different WPs and Tasks are listed below and illustrated also in Figure 2. Task VTT-2.3 was handled jointly with University of Helsinki under their Advancing Computing Hub. This is the reason why is had been separated from the structure under WP VTT-2.

- **WP VTT-1**: Fusion power plant lifetime and maintenance

  Coordinator: William Brace
- **WP VTT-2**: Novel materials and material-treatment solutions for fusion reactors

  Coordinators: Anssi Laukkanen, Petteri Lappalainen, Tomi Suhonen
- **WP VTT-3**: Fusion power plant analysis

  Coordinators: Timo Aalto, Antti Salmi
- **WP VTT-4**: Licensing, safety, and nuclear waste management

  Coordinator: Markus Airila
- **WP VTT-5**: Fusion ecosystems and business models

  Coordinator: Tapani Ryynänen
- **WP VTT-6**: Project management and dissemination

  Coordinator: Antti Hakola (project manager)

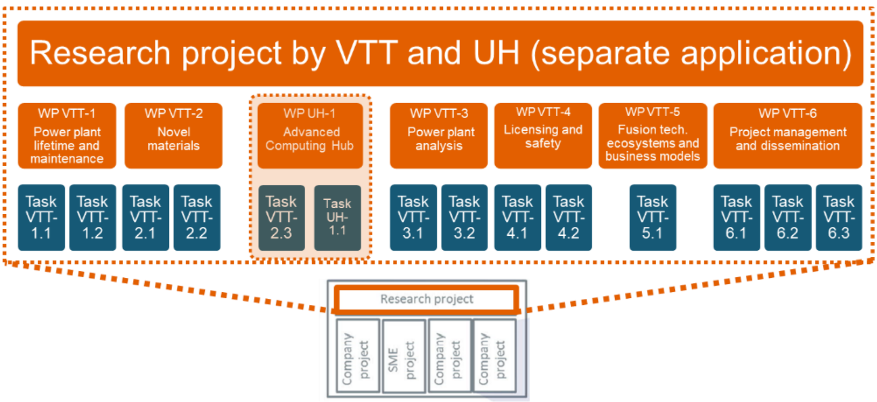

Figure 2. Structure and breakdown of the VTT research project.

1.4.2 Links to the different company projects

Planned links of the VTT research project to the different company projects can be seen in Figure 3. Original links of the VTT research project to the ongoing company projects.Figure 3. In WP VTT-1, collaboration with Comatec resulted in new design solutions for the European DEMO reactor, also within several subcontracting tasks for the EUROfusion Consortium. In WP VTT-2, the most active collaboration took place with EOS Finland and Luvata – by applying VTT's modelling expertise for understanding the details of their processes and the companies providing test components for various analyses and benchmarking modelling efforts at VTT. Within WP VTT-3 and WP VTT-4, for their part, collaboration with Platom was pursued. Similarly to the case of Comatec, this was facilitated by the EUROfusion subcontracting opportunities, to understand the production of radioactive waste and to cast light into the final decommissioning of the reactors. Finally, all the companies participated in interviews and workshops arranged under WP VTT-5.

	COMATEC	EOS	LUVATA	PLATOM
WP VTT-1 Power plant lifetime and maintenance	Remote handling			
WP VTT-2 Novel materials	Material for other industrial projects	Manu-facturing methods	Materials for magnets	
WP UH-1 Advanced Computing Hub		Materials modelling	Materials modelling	
WP VTT-3 Power plant analysis	Thermal & magnetic modelling			Process modelling
WP VTT-4 Licensing and safety	Safety critical software			Licensing framework
WP VTT-5 Ecosystems	Require-ments of Big Science	Information and capabilities	Information and capabilities	Information and capabilities

Figure 3. Original links of the VTT research project to the ongoing company projects.

1.4.3 Goals and deliverables of the WPs and Tasks

WP VTT-1: Fusion power plant lifetime and maintenance

VTT-1.1	Methods for remote maintenance in challenging environments
Task goals	1. Create an intelligent and agile remote maintenance system adaptable to a variety of changing conditions by enhancing human control via a cyber-system. 2. Develop condition monitoring of human controllers in remote maintenance using brain-machine interface (BMI) to get a neural command directly from the brain. 3. Develop intelligent algorithms for model-based condition monitoring for remote control.
Work description	This task develops novel methods for remote maintenance (RM) in challenging environments such as fusion power plant (FPP), which has extreme conditions and zero human access. However, policy demands human involvement due to safety issues, and for a commercially viable FPP, there should be higher plant availability and performance. Therefore, RM implements condition monitoring (CM) and human-in-the-loop (HITL) techniques to achieve higher equipment performance. However, in HITL, there is unpredicted scenarios, uncertainties, low efficiency, and low degree of automation. Increased use of multiple control gadgets in RM places a constraint on the human cognitive level. There are parallelism barriers in the form of reduced operator speed and precision, mental and physical limitation. Nevertheless, CM is applied only for equipment but not for human monitoring. The research work will involve: 1. Creating an intelligent and agile remote maintenance system (RMS) by building a Human-Analytics-Cyber-Physics (HACP) system to enhance HITL. The HACP will comprise human control via a cyber-system with an interconnected expert system combining principal components analysis, advanced data analytics, an ensemble machine-learning algorithm, and uncertainties handling system (UHS). 2. Emotion analysis of the human controller to provide an in-depth understanding of operator actions for developing human condition monitoring (HCM). An assistive technology for cognition (ATC) to augment cognitive processing during operator control will be developed, possibly including a brain-machine interface (BMI). Virtual reality technology, sensory feedback and visual mirror principle and other AI techniques as well as Internet of Humans (IoH) are applied in collaboration with Finnish Universities. 3. Developing AI-based intelligent algorithms for model-based condition monitoring (MBCM) for remote control. The task includes creating a model-based approach founded on analytical redundancy to compare systems available measurement with the priori information, represented with mathematical models.
Task deliverables	1. Human-Analytics-Cyber-Physics system for human-in-the-loop remote control of robots and maintenance systems in pre-determined challenging environments. 2. Report on applying assistive technology for cognition with a brain-machine interface for human condition monitoring in challenging environments. 3. Prototype design of a novel intelligent model-based condition monitoring for remote control.

VTT-1.2	Digital Thread for Fusion (DTh4F) – A digitized test-rig facility
Task goals	1. Design and develop an integrated digitized test-rig facility for a fusion power plant (FPP) in Finland and to serve as a test-rig facility for Industries in Challenging Environments (ICE). 2. Develop a digital framework for an easy plug-in digital twin of the future exploitable FPP (ITER, DEMO) to the test-rig. 3. Develop a test-rig hub allowing the participation of Finnish design, manufacturing, construction, and start-up companies in the development and construction of a FPP. 4. Develop a test-rig facility to allow studying high payload, robust, and cheap industrial robots for automated maintenance in ICE.
Work description	DTh4F proposes a holistic and hierarchically organized digital environment for a data-driven and interconnected fusion test-rig facility and to serve also as an Industries in Challenging Environment (ICE) test-rig facility. The work comprises the design and development for construction, a multi-functional test-rig facility for de-risking maintenance systems and digitally threading the test-rig to the various phases (design-build-operate-decommission) of fusion power plant (FPP) life cycle, creating a digital environment as an integral part of fusion lifetime. Lifecycle phases for FPP involve very long timescales, and a test-rig facility is the most feasible way to achieve a digital replica early enough. The work is to design and develop a test-rig as the Physical Twin (PT) replica of the future RM facility. This includes creating a twin2twin (T2T) ecosystem, which (i) captures the value-enhancing properties of the digital twin; (ii) leverages product-level and process-level twins in realizing a digital fusion ecosystem; and (iii) implements digital threading of the virtual environment, physical test-rig and real-world physical replica. We will exploit IoT and sensor technologies to enable the use of advanced analytics and design optimization. The intent is to utilize the PT for pairing the virtual world (engineering design and manufacturing phase) and the physical world (construction, operation, and decommissioning phases), while exploiting novel technologies such as AI and cognitive science. The fusion and ICE RM process is subject to many size-effects, and extreme conditions (radiation, high temperature, magnetic field, and ultra-high vacuum) that make it challenging to produce representative samples and component tests environment in the test-rig facility. Hence a digital thread model concept is implicated, modelling the many extreme conditions as part of the environment of the test-rig facility in the virtual prototypes.
Task deliverables	1. Documents on design, manufacturing, and construction of the test rig. 2. Twin2twin ecosystem for fusion power plants. 3. Ecosystem for testing fusion power plant equipment and for the needs of Industries in challenging environments. 4. Research Hub for systems and process in the field of fusion power plant development and Industries in Challenging Environments.

WP VTT-2: Novel materials and material-treatment solutions for fusion reactors

VTT-2.1	Developing novel materials for fusion reactors
Task goals	1. Develop novel materials for the wall structures of fusion reactors. 2. Investigate the characteristics of the produced material batches. 3. Design and produce materials for protecting sensitive electronics, optical components, and sensors from plasma and radiation exposure in fusion reactors. 4. Involve Finnish companies in developing new material solutions for fusion applications and in the tendering processes of ITER and DEMO.
Work description	The research will focus on developing and producing novel multicomponent materials that would have superior thermal and mechanical properties upon exposure to reactor-relevant heat loads and radiation doses. This will be done both with the help of numerical simulations and experimentally using additive manufacturing (3D printing). Following the first prototype tests, the studied material solutions and their production methods will be further optimized such that full-scale products or mock-ups for fusion reactors and fusion-relevant environments would result. The produced materials and components will be characterized both at VTT and at participating universities (e.g., University of Helsinki). Collaboration with Finnish SMEs in the fields of additive manufacturing and production of coatings has already been identified. In addition, new material solutions will be designed and produced to shield sensitive electronics, optical components, and sensors from damages that extreme heat, particle, and radiation loads may induce on them during the operation of fusion reactors. Here, intelligent materials in active or adaptive multifunctional systems with inherent capabilities for self-sensing, diagnostic and control capabilities are foreseen. An important part of the task will be providing a platform for Finnish companies to tailor their processes in producing different materials for meeting the deliverables of the task. In addition, the companies can be tightly integrated into the European network such that they will have opportunities to be involved in tendering processes for ITER and DEMO.
Task deliverables	1. Test batches of selected additively manufactured and intelligent materials. 2. Report on the applicability of tested additively manufactured materials for DEMO. 3. Report on the characteristics of tested intelligent materials for providing shielding against ITER- and DEMO-relevant plasma and radiation conditions. 4. Consortium of VTT and partner companies for at least one tendering process.

VTT-2.2	Characterising and treating materials originating from fusion reactors
Task goals	1. Identify changes in the microstructure of materials and the evolution of their properties upon exposure to fusion plasmas. 2. Develop novel techniques for restoring the original state of plasma-exposed components and/or for cleaning them. 3. Identify synergies of the proposed material-treatment methods in other complex environments than fusion reactors.
Work description	The materials exposed to plasma and radiation doses in fusion reactors will develop structural changes in their microstructure and manifest the formation of tritium-containing deposited layers on their surfaces. Detailed chemical and structural analyses are required, typically coupled to numerical modelling of the obtained experimental results. Controlled exposure to impurities and moisture is also proposed to be done within this project to assess the behaviour of the reactor materials during vacuum and water leaks as well as during off-normal events. Previous material characterization experiments have already revealed the need for regular cleaning of the most critical reactor components. Prototypes for cleaning devices, based on laser beams, plasma etching, and arc-discharge sputtering, have been developed in the past but only for testing the feasibility of the selected approaches. Recent results of tritium being persistently trapped on the deposited layers, however, indicate that a more thorough survey of potential cleaning techniques is needed. Laser ablation combined with laser spectroscopy is up to now the most promising solution but plasma etching in vent conditions of ITER will also be revisited. The work relies on close collaboration with Finnish SMEs from the fields of laser machining and the production of coatings. The new characterization and cleaning tools and techniques can also be applied to other areas where, e.g., strong radiation or excessive contamination of materials is apparent. Identification of Finnish companies most strongly benefiting from the advances made in this task will be carried out and solutions to promote their business lines will be proposed.
Task deliverables	1. Report on the structural changes, formation of deposited layers on, and accumulation of fusion fuel in materials extracted from fusion experiments. 2. Report on the feasibility of designed cleaning solutions based on laser ablation and plasma etching in reactor-relevant conditions. 3. Transfer of characterization and cleaning solutions in at least one new area where complex environment prevent the usage of conventional approaches.

VTT-2.3	Advanced Computing Hub
Task goals	1. Form and organize an advanced computing hub with 10-12 permanent and long-term personnel employed by UH and VTT. 2. Develop new AI solutions for fusion research and technology in collaboration with universities in the Finnish Center of Artificial Intelligence (FCAI), and industrial partners such as Nokia. At VTT, this concerns in particular development of new material solutions. 3. Set up an active training and Massive Open Online Course (MOOC) programme in collaboration with partners such as Reaktor. 4. Develop and carry out GPU programming in collaboration with Åbo Akademi University and the NVidia AI Technology Center in Finland (just agreed on by FCAI).
Work description	This task aims at setting up one of five E-TASC Advanced Computing Hubs within EUROfusion and start its operations for supporting advanced computing, especially AI and data handling techniques for the entire duration of Horizon Europe and with readiness to operate until 2035 as part of the EU Research FP10. The funding for the new hub scientific personnel is partly to come from EUROfusion, and premise funding from the University of Helsinki, while a Business Finland funding contribution will be mainly used to facilitate the industrial collaboration. The hub is to develop new AI and Big Data techniques as a collaboration among all the partners. Significant spin-off potential is foreseen in using the new methods developed for process control in other nuclear and materials systems. At VTT, the interest lies especially in designing and developing new materials and structures for fusion environments. The implications for Finnish industrial partners are twofold. First, ACH opens new opportunities for Finnish software industry to provide solutions for EUROfusion. This in itself is useful but is also a strong reference for the companies allowing them to extend their exports and increase their growth. Second although, physical applications are naturally the goal of the activity, from the software company point of view many of the needed techniques are general and can be applied to digital modelling and digital engineering tasks in other domains. This allows the companies to create new business in the increasingly important area of advanced simulation and computing.
Task deliverables	1. Advanced Computing Hub at UH and VTT together with including industrial partners. 2. New AI and Big Data algorithms and software suitable for use in EUROfusion and beyond, and for Finnish industrial partners. 3. Training programme and Massive Open Online Courses (MOOC) on advanced computational techniques for Finnish industry and EUROfusion. 4. GPU programming center for Finnish industrial and university partners.

WP VTT-3: Fusion power plant analysis

VTT-3.1	DEMO full-scale analyses
Task goals	1. Make Apros an established tool for fusion power plant analysis. 2. Further develop Apros Balance-of-Plant models for DEMO concepts, which have been down-selected for the Conceptual Design Phase. 3. Widen the range of modelled systems by using the knowledge from Finnish companies operating in the field of nuclear energy.
Work description	During the Pre-conceptual Design Phase of DEMO, several alternatives of Balance-of-Plant (BoP) configurations have been developed and investigated, where dynamic thermal hydraulic simulations with Apros have been one part of the development process. These analyses have been concentrated on normal operation of the main systems of the BoP, i.e. simulation of burn and dwell time operation and the transitions between these states. The number of alternatives will be down-selected for the Conceptual Design Phase, where the baseline concept(s) will be brought to a complete integrated system design, so that detailed assessments of technical feasibility, safety, licensing issues and lifecycle costs can be undertaken, and preparations can be made for major procurement and qualification activities foreseen during the Engineering Design Phase. In this process, dynamic thermal-hydraulic analyses of BoP systems will play an important role. The need for dynamic BoP analysis is expected to be widened considerably: besides normal operation also disturbances and mitigation of disturbances should be analysed alongside other operational states, all including optimizations of the system behaviour. This requires the availability of an extensive integrated plant model with interaction from different systems both on a physical level and through automation systems. By strongly involving the industry operating in the nuclear field (Fortum, Platom), their experience in plant design, operation and maintenance can be utilized and experience from the DEMO development work is transferred back to the industry partners. Cooperation with other engineering disciplines within the EUROfusion consortium is also important. By having a full-scope integrated model it is possible to provide versatile data to other DEMO development work packages, where dynamic simulation results are needed, e.g. for thermal stress analyses of key components.
Task deliverables	1. Inclusion of Apros in the international list of tools for fusion power plant analysis. 2. Refined Apros Balance-of-Plant models for DEMO concepts. 3. Involvement of Finnish companies in the field of nuclear energy in the design of the DEMO plant configurations.

VTT-3.2	Exploitation of fusion facilities
Task goals	1. Maximize the contribution of Finnish stakeholders in the European and worldwide fusion R&D agenda. 2. Enhance the Finnish state-of-the-art expertise on fusion technology and transfer it from the research community to stakeholders. 3. Initiate in-house diagnostics development for fusion power plants.
Work description	We participate in experimental activities in major European and international fusion devices, data and component analyses, making predictions for the plasma operations in ITER and DEMO. VTT will contribute to the research in the following frontiers: i. estimating the lifetime of wall components in plasma discharges relevant for the future fusion reactors ii. predicting the accumulation of radioactive tritium in wall structures of ITER and DEMO to meet their licensing and safety requirements iii. obtaining better understanding of the collective properties of plasma to maximize the fusion yield iv. assessing the functionality of different divertor solutions for the conceptual design of DEMO v. developing and validating diagnostics for fusion reactors including fast particles and in particular R&D of steady-state magnetic field measurements using optical fibre technology, a completely novel methodology In all these areas, collaboration with Finnish companies has been identified. Work will be done mainly on tokamaks (JET, AUG, TCV, MAST-U, WEST, DIII-D, KSTAR) but also on stellarators (W7-X, LHD), and linear plasma devices. Participation in and coordination of experiments is essential in fulfilling the goals of the task. The work plans are directly linked to the objectives of the relevant Work Packages of EUROfusion. The experimental data will be analysed and thoroughly modelled such that one could influence the operational scenarios selected for ITER and design solutions considered for DEMO. An important part will be analysis of wall components or small samples after the experiments. The results will help the Finnish industry to become more involved in ITER contracts and delivery of components for DEMO. The project team will apply for leading positions of the EUROfusion Consortium, ITER and F4E to influence its programmatic goals when activation of industry is concerned.
Task deliverables	1. Report on ITER and DEMO relevant technology results for the ILO and further to Finnish stakeholders. 2. Maintain Finland’s position in the core of the global fusion business by executing Finland’s role in the experimental work programme of EUROfusion facilities. a. Report on predictions for the lifetime of the wall structures of ITER and DEMO and accumulation of tritium on them. b. Report on fusion fuel optimization in reactor-relevant scenarios. c. Report on comparisons of different divertor solutions made for DEMO. 3. Prototype diagnostics for plasma and wall temperature and steady-state magnetic field measurements.

WP VTT-4: Licensing, safety and nuclear waste management

VTT-4.1	Licensing and safety
Task goals	1. Support the licensing and safety design of the DEMO reactor and supporting facilities, such as the International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Source (IFMIF-DONES). 2. Promote the Finnish safety and risk assessment competence, experience, and tools to the European fusion projects. 3. Promote the Finnish nuclear industry practices on licensing to the European fusion projects. Demonstrate how the fulfillment of safety requirements can be verified for the safety authorities by using state-of-the-art licensing tools and practices.
Work description	Nuclear technologies involve risks due to the harmful effects of radiation. For the benefits to outweigh the harm of the use of radiation, the use of radiation must always be justified. To minimize the probability of accidents leading to severe consequences in nuclear facilities, nuclear safety has a decisive role. Nuclear facilities include not only nuclear fission power reactors, but also fusion reactors and non-reactor nuclear facilities such as radioactive waste disposal facilities and neutron sources, which all need to be included under the nuclear safety regulation. The life cycle of a nuclear facility begins from siting and design and includes construction, commissioning, operation and finally decommissioning. All the steps in the lifetime must be regulated and included in the licensing process. In the licensing process, the licensee must prove to the regulatory authority, that all safety aspects have been acknowledged, and the safety requirements are fulfilled. This task concentrates on participating in the licensing support and safety design of the DEMO reactor and supporting facilities, such as IFMIF-DONES, which are developed in the EUROfusion programme. The aim is to provide best practices and guidance on how to implement balanced safety design for fusion reactors and supporting facilities by combining the deterministic and probabilistic safety assessments, human factors engineering and good safety culture practices.
Task deliverables	1. Guidance reports on the implementation of balanced safety design for fusion using the DEMO reactor and the fusion materials irradiation facility IFMIF-DONES as examples. 2. Inclusion of Finnish nuclear industry licensing practices for the preparation of the Preliminary Safety Report within fusion, using the DEMO reactor and the fusion materials irradiation facility IFMIF-DONES as examples. 3. Involvement of at least one new Finnish company in fusion power plant licensing.

VTT-4.2	Decommissioning and nuclear waste management
Task goals	1. Take a strong role for the Finnish industry in DEMO decommissioning and nuclear waste management planning tasks. Combine world-leading Finnish expertise on nuclear waste management with fusion technology knowledge to identify and solve essential waste management issues related to fusion power plants. 2. Near-term opportunities in ITER, e.g. hotcells. 3. Apply in DEMO Generic Site Safety Report preparation novel tools, which can be transferred to use also in fission power plant licensing processes.
Work description	Today's licensing requirements for a new nuclear facility include early preparation for decommissioning after the service life of the facility. The facilities are practically *designed to be decommissioned* in order to avoid facing again many of the present challenges in decommissioning old nuclear power plants, research and military facilities, and other legacy sites. Those challenges include e.g. incomplete data on structures, material compositions and radionuclide inventories. Therefore, in the design phase, it is very valuable to anticipate the far-reaching implications of material choices and construction techniques for the future safety, duration and cost of decommissioning as well as for the complexity and volume of waste management solutions needed for the operational and decommissioning waste. In practice, nuclear regulators require that license applicants present preliminary decommissioning plans for approval as part of construction licensing. Finland is currently designing, constructing, operating, and decommissioning nuclear facilities, including the construction of a nuclear waste repository for spent fuel as the first country in the world. This gives nuclear operators (utilities, waste management organizations and VTT as the licensee of the FiR 1 research reactor) an exceptional perspective to decommissioning and waste management planning over the lifecycle of a nuclear facility. Also, other Finnish partners in the recently launched dECOmm co-innovation project are developing novel methods for NPP decommissioning. VTT is in a position to facilitate close and fruitful interaction between these two innovation ecosystems. This Task will include gaining information on how DEMO decommissioning wastes generated can be safely disposed and accounted for in a repository safety case. In particular, fusion materials can impact the disposal by interacting with other waste streams. Efficient handling and treatment of the DEMO waste (reduction of waste, Waste Acceptance Criteria) are important and non-trivial issues to clarify. Concerning the timescale of decommissioning-related development in the EUROfusion DEMO programme, it is identified that industrial involvement in outlining the DEMO decommissioning plan and defining waste recycling processes will be topical in 2024–26. Prior to that, during 2021–23, the programme aims at completing several safety-related tests and analyses specific to fusion facilities. Taking an active role in the EUROfusion Safety and Environment (WP SAE) project is an opportunity for the Finnish industry and VTT to showcase the Finnish nuclear expertise in radwaste and decommissioning and to prepare for the upcoming significant industry tasks.
Task deliverables	1. Involvement of Finnish companies in the field of nuclear decommissioning and radwaste management in the analysis of DEMO decommissioning and waste management requirements. 2. Finnish mini-consortium for ITER hotcell opportunities 3. Completion of safety related tests, e.g.: a. Report on the quantification of tritium retention in tungsten and other plasma-facing and structural material candidates b. Report on material detritiation tests, having an impact on nuclear waste management.

WP VTT-5: Fusion ecosystems and business models

VTT-5.1	Fusion ecosystems and business models
Task goals	1. Supporting companies' international competitiveness through business research. 2. Raise companies' knowledge and understanding about ecosystemic business in big science context, its impact on their business models, and how connections between companies' business models change. 3. Understand and communicate the value creation mechanisms and real customer needs to advance fusion-related technologies and services. 4. Understand the value creation on the ecosystem level – how systemic and facilitated ecosystem collaboration adds value that cannot be achieved by individual organizations working as a loosely coupled network. 5. Bring together practice and research to innovate new successful business.
Work description	Customer cases, here ITER/DEMO, and their innovation and procurement processes will be analysed to gain better big science customer understanding. By analysing companies' business models, their linkages and value creation processes through the partnership network and customer channels, common challenges and required business model transitions are identified. Ecosystem-level processes need to be supported also by company-level processes and actions and this interaction will be studied. Especially attention is paid to the activities that cross intra/inter-organizational borders or one between a company and the ecosystem. Based on the individual business models and findings a number of generic reference models will be defined. Information becomes shared as well as owned within and by the group during the process through group work and researchers' actions. These actions structure, visualize, and document information during the process and support the transfer of information from the corporate level to the network level and vice versa. VTT is acting as the facilitator. This Task collaborates with FinNuclear in their ILO and Industry activation. Through interviews and round table sessions information is gathered for research. New knowledge and contacts that can be used for ILO and industry activation work for optimal impact is respectively provided to FinNuclear.
Task deliverables	1. Identified needs and wants of companies to better benefit from European fusion activities. Based on research of Business models of individual companies. 2. Publication or report on how the innovation ecosystem can support and be supported in innovation and business collaboration. 3. Publication or report on communication and decision-making related to the information exchange and how it can be turned into value also across organizational borders. 4. Formulated business models and case descriptions for use by the industry to improve customer understanding, value delivery processes and communication. 5. Generic case analysis of ITER and DEMO as examples of large innovation and business ecosystem structures and functions. If possible, include a review of approaches to Big Science industry activation approaches in selected European countries.

WP VTT-6: Project management

VTT-6.1	Overall project coordination
Task goals	1. Coordination and successful implementation of the project. 2. Interfacing with FinNuclear on the ILO and industry activation work. 3. Reporting to Business Finland (VTT and overall project), modifications to project plan if needed a. Monitoring project performance and making corrective actions when needed. b. Regular risk assessment of the technology, co-operation, funding, and operational model.
Work description	This task is responsible for executing and controlling the project plans, tracking and controlling the necessary changes, and managing the communication with the project stakeholders including project partners and Business Finland. Management activities include technical coordination by supervising the progress of the work, as measurable by the completion of milestones and deliverables, and guaranteeing the required reporting. VTT project management and quality guidelines are applied. VTT as the project manager will coordinate the communication together with partners. Regular project steering group meetings will be arranged as a dedicated session within the FinnFusion consortium advisory group meetings. While internal communication within VTT and between project partners is an important aspect of this task, any facilitation beyond daily project communication is in the scope of Task 6.2, and external dissemination is in the scope of Task 6.3. The consortium partners agree on IPR matters in the consortium agreement.
Task deliverables	1. All project documentation, including project reports as well as meeting materials and minutes. 2. Steering group meetings with suitable frequency as agreed with the partners and coordinated with the FinnFusion consortium. 3. Monthly operational meetings with the research partners. 4. Participation in miscellaneous project meetings that require the participation of the coordinator.

VTT-6.2	Collaboration facilitation
Task goals	1. Activate Finnish companies to join the ECO-Fusion ecosystem through regular and facilitated activities, e.g. round tables. 2. Knowledge management and distribution. 3. Organising experience-sharing activities (seminars, workshops, round table meetings)
Work description	It is vital for any ecosystem to keep up activities in order to evolve and grow. This requires a professional approach not only to get new members but also to keep up the interest of members and support their efforts in spreading the ideas inside their own organizations. All collaboration and group work activities in the project will be facilitated by VTT. The aim is to enhance project efficiency e.g. in supporting new business creation and planning new R&D activities. The project will arrange an annual open seminar, semiannual working seminars, and research topic-related round table meetings. Through research collaboration methods and approaches that add value to the communication channels in the ecosystem will be constantly developed. This will step up the cross-fertilization of ideas and transfer knowledge in order to accelerate ecosystem development and organizational learning also on company level. Round Tables bring together researchers and companies. This enables companies to commit subject specialists for each Round Table group. These groups are led by a company representative, and a researcher will act as the secretary and facilitator of the group. Groups' work will be coordinated by project management and disseminated through internal and external workshops and publications. The project will also actively facilitate connections to the European level and distribute information to its members. Visits and seminar/conference trips will be arranged together with FinNuclear, linking to Task 6.3 on public visibility e.g. through social media. The Task covers effective knowledge management by arranging the tools and defining the practices for making information available throughout the execution of the activity. The knowledge management infrastructure comprises of the public project website, social media channels, and internal project communication and document repository platform (MS Teams), supporting information distribution by the ILO/FinNuclear (Task 5.1). VTT will provide and maintain the project website and will host the services for a repository and collaboration platform. All partners will contribute to content related to its competencies and knowledge to support knowledge management and will use their channels and networks to disseminate information. VTT as the coordinator will establish an information-sharing platform that supports news updates, Q&A, and other exchange of information pertaining to decommissioning markets and the ecosystem. Where necessary VTT's department of Information Services will be used e.g. to acquire market data by utilizing data services like company information or patent databases, or by purchasing external reports, to support VTT's own analysis work.
Task deliverables	1. Annual open seminars jointly with dECOmm and EcoSMR ecosystem projects. Organized with FinNuclear. 2. Workshops and round table sessions on specific topics. 3. Related content production for Task 6.3. 4. Annual report about ecosystem activities and results.

VTT-6.3	Dissemination
Task goals	1. Enhance the involvement of Finnish companies to ITER deliveries by internal and external distribution of information about business opportunities. 2. Spread knowledge about the project and its results to other interest groups in addition to the project participants, including other firms than those participating in the project, academic communities, decision-makers, and the general public. 3. Visible multi-channel communication, including social media, enabling easy following of the project through Twitter and LinkedIn.
Work description	This task covers external dissemination activities. Internal daily communication and dissemination during the project is described in Tasks 6.1 (Overall project coordination) and 6.2 (Collaboration facilitation). In addition to articles published in academic journals and the general press, the project will utilize digital channels in its dissemination in order to distribute information about the project results to Finnish companies. The task takes benefits from the FuseCOM Network, maintained by EUROfusion and having about 60 members across Europe (fusion communication specialists from The Programme Management Unit, all EUROfusion Research Units, F4E and ITER). The network provides support, training, best practices, and material resources to all members. In dissemination activities, the European Commission rules and best practices, concerning e.g. the open access obligation making the results maximally widely available, will be respected.
Task deliverables	1. Continuous dissemination of information in collaboration with ILO/FinNuclear. 2. A project website will be established containing information about the project, its participants, partners, opportunities database, activities, blog posts, project results. 3. Posts of results and activities on Twitter and LinkedIn. Recent findings and project results reach companies interested in entering fusion technology markets. 4. Semiannual seminars and more frequent workshops / round tables which are also open for companies and organizations outside of the consortium. 5. A “Best practice's” publication on ecosystem collaboration topics for a broader business audience. 6. Articles published in the trade and business press and peer-reviewed fusion journals (like IAEA’s Nuclear Fusion). 7. Significant technical and scientific contribution published in academic journals and conference proceedings, covering all Work Packages and tasks. These dissemination activities will be covered in the respective tasks.

2. Status of the VTT research project

2.1 Overview of the budget and final expenditure profile

The VTT research project had a total budget of 11,786,000 € with the co-funding shares splitted as follows:

- EU (via EUROfusion): 3,948,000 €
- VTT: 3,928,000 €
- Business Finland: 3,910,000 €

A breakdown of the budget per WP can be seen in Table 4.

Table 4. Breakdown of the budget per WP.

WP VTT-1	WP VTT-2	WP VTT-3	WP VTT-4	WP VTT-5	WP VTT-6
4,574,000 €	1,729,000 €	3,853,000 €	887,000 €	529,000 €	214,000 €

The project reached its budget within less than 0.5% and the small excessive costs were due to the strong emphasis put on activities under WP VTT-3 in early 2024 – to ensure that a laser system designed for measurements at the JET tokamak (see section 3.3.5) would be ready before the end of the project. Most of the budget (>85%) was consumed for the actual work while materials and services corresponded to ~6%, traveling to ~3%, and usage of facilities to ~3% of the expenditure profile. A more detailed breakdown of the costs can be found in the Financial Statement.

2.2 Commitment of human resources

VTT committed overall 705 person months of its human resources for advancing the different WPs and activities under ECO-Fusion. This was ~13% smaller than the original estimate due to salaries and other costs increasing more than anticipated during the planning phase of the project. However, this deviation did not have an impact on reaching the main goals of the project – only the scope of a couple of activities was somewhat reduced. The versatility of the project is highlighted in Table 5, where the distribution of human resources across the different research areas at VTT is shown.

Table 5. Distribution of human resources (in person months) across the VTT research areas.

Research area and team	WP VTT-1	WP VTT-2	WP VTT-3	WP VTT-4	WP VTT-5	W VTT-6	SUM
Microelectronics and quantum technology	**0**	**0**	**70**	**0**	**0**	**0**	**70**
Silicon Photonics			70				70
Sensing solutions	**4**						
Flexible electronics integration	4						4
Safe and connected society	**4**						
Critical cyber physical systems	4						4
Foresight and data economy	**0**	**0**	**0**	**0**	**47**	**0**	**47**
Corporate Foresight and Strategy					47		47
Cognitive Production Industry	**136**	**0**	**0**	**22**	**0**	**2**	**160**
Intelligent robotics	6						6
Spatial computing	12			5			17
Human-robot mixed reality solutions	10						10
Agile intelligent production systems	82			6		2	90
Human factors and service engineering	8						8
Safety in complex sociotechnical systems	18			11			29
Knowledge-driven Design	**68**	**89**	**0**	**11**	**0**	**2**	**170**
ProperTune ICME		69				2	71
ProperTune ICME Integration		10		11			21
Sustainable material design		10					10
Operation and maintenance	28						28
Dynamic components and systems	40						40
Nuclear Energy	**14**	**31**	**165**	**20**	**12**	**8**	**250**
Reactor analysis		12		6			18
Nuclear power plant analysis			25				25
Nuclear reactor materials		19					19
Structural integrity	14						14
Fusion energy and decommissioning			140	8		6	154
Nuclear waste management				6			6
Nuclear energy solutions					12	2	14
Total	**226**	**120**	**235**	**53**	**59**	**12**	**705**

The key project members for a group of activities are listed below according to their competencies:

Activities: Remote maintenance (WP VTT-1 and WP VTT-4)
Members: Markku Alamäki, MSc. Jarmo Alanen, Dr. William Brace (WP VTT-1 coordinator), Jouko Heikkilä, Timo Hietavalkama, MSc. Tero Jokinen, MSc. Petri Kaarmila, MSc. Pekka Kilpeläinen, Petteri Kokkonen, Dr. Marja Liinasuo, MSc. Janne Lyytinen, MSc. Timo Malm, MSc. Hannu Martikainen, Riku Pennala, MSc. Kari Rainio, MSc. Hannu Saarinen, MSc. Qais Saifi, MSc. Tuisku-Tuuli Salonen, MSc. Janne Sarsama, Janne Saukkoriipi, MSc. Teemu Sipola, MSc. Mika Siren, Lic.Tech. Mikko Siuko, MSc. Esko Strömmer, MSc. Mikko Tahkola, Bastian Tammentie, MSc. Antti Tanskanen, Jussi Tenhunen, MSc. Petri Tikka, Msc. Van Dung Truong, Miika Uusi-Illikainen, Msc. Tapio Vaarala, MSc.Tero Välisalo, MSc. Arto Ylisaukko-oja, Akhtar Zeb

Activities: Materials modelling (WP VTT-2)
Members: Jukka Aho, MSc. Timo Avikainen, Aymara Baumann Duran, Dr. Andris Freimanis, Sneha Goel, Aloshious Lambai, Dr. Anssi Laukkanen (WP VTT-2 coordinator), MSc. Lassi Linnala, Dr. Sami Majaniemi, Olli Pakarinen, MSc. Rami Pohja, Sicong Ren, MSc. Tomi Suhonen (WP VTT-2 coordinator)

Activities: Experimental materials research (WP VTT-2)
Members: MSc. Jouni Alhainen, Pentti Arffman, MSc. Brahim Dif, Dr. Janne Heikinheimo, Mika Jokipii, MSc. Petteri Lappalainen (WP VTT-2 coordinator), Taru Lehtikuusi, Jussi Leporanta, Jukka Maunumäki, Pekka Moilanen, Asta Nurmela, Seppo Peltonen, Juhani Rantala, Kimmo Rämö, Jarmo Saarinen, Pekka Sinkkonen, Madelen Ulfves

Activities: Fusion energy and physics (WP VTT-3 and WP VTT-4)
Members: Dr. Leena Aho-Mantila, Dr. Markus Airila (WP VTT-4 coordinator), MSc. Amanda Bruncrona, Dr. Antti Hakola (Project Manager), MSc. Daniel Jordan, Dr. Aaro Järvinen, Dr. Juuso Karhunen, MSc. Anu Kirjasuo, Adam Kit, Dr. Jari Likonen, MSc. Tommi Lyytinen, MSc. Sixten Norrman, Samuli Saari, Dr. Antti Salmi (WP VTT-3 coordinator), Dr. Antti Snicker, Dr. Marton Szogradi, Dr. Konsta Särkimäki, Prof. Tuomas Tala

Activities: Silicon photonics (WP VTT-3)
Members: Dr. Timo Aalto (WP VTT-3 coordinator), MSc. Katherine Bryant, Mikko Harjanne, Dr. Ari Hokkanen, MSc. Markku Kapulainen, MSc. Dura Shahwar, Dr. Fei Sun, Mr. Ben Wälchli

Activities: Probabilistic risk assessment (WP VTT-4)
Members: MSc. Atte Helminen, MSc. Essi Immonen, Dr. Tero Tyrväinen, Kaupo Viitanen

Activities: Nuclear waste assessment (WP VTT-4)
Members: MSc. Daniel Kaartinen, MSc. Tiina Lavonen, Dr. Anumaija Leskinen

Activities: Fire safety (WP VTT-4)
Members: Dr. Tuula Hakkarainen, Dr. Timo Korhonen, MSc. Nikhil Verma

Activities: Ecosystem research (WP VTT-5)
Members: Dr. Tiina Apilo, MSc. Juuli Huuhanmäki, Dr. Jorge Martins, MSc. Tapani Ryynänen (WP VTT-5 coordinator), MSc. Jyri Rökman, MSc. Olli Soppela, Dr. Arto Wallin

Activities: Administration (WP VTT-6)
Members: Ulla Peltonen, Kirsi Selin

2.3 Progress made against the project goals

In the following, the main achievements are commented separately after each subgoal.

Goal 1: In accordance with VTT strategy 2025, develop new competence and research results in selected areas

- Enhance VTT's capability in nuclear safety solutions for carbon neutral and flexible energy systems in the following areas: (i) Fusion power plant lifetime and maintenance; (ii) Development of novel materials for fusion applications; (iii); Establishing an advanced computing hub for fusion; (iv) Fusion power plant analysis; (v) Licensing and safety of fusion power plants, and (vi) Ecosystem and business development.
  - ✓ *The scope and breadth of the VTT research has grown considerably in all the listed areas in 2021-2024: more than 100% increase in the volume of (i) and (iv) while (ii) and (iii) started from zero but are now representing 20-30% of all fusion research at VTT including contract work with private companies. Considering (v) and (vi), the work started slowly but by the end of the project new openings and initiatives were launched, thanks to the changing landscape of worldwide fusion research. A more thorough overview of the project achievement can be found in section 3.*
- In the selected research areas above, create research excellence measured with VTT's KPIs, Quality in science and technology (publications, IPR, PhDs) and Innovation capabilities.
  - ✓ *The excellence achieved with respect to the KPIs is reported in section 2.4. Overall more than 90 peer-reviewed publications were published during the project, accompanied with >75 conference contributions, thus manifesting the quality of the research. One patent application was filed related to novel sensor applications while 3 PhD and 4 MSc These were completed during the project, and more are expected to emerge from 2025 onwards.*
- Create an impact on VTT's international research portfolio (EU funding) and commercial project basis.
  - ✓ *The VTT involvement in EU projects, via EUROfusion, has grown by a factor of 2-3 during the ECO-Fusion project culminating in participation to a larger pool of activities than was the case in 2020. Several contracts have been made with public fusion organizations and private companies in Europe and worldwide thanks to the new expertise gained during ECO-Fusion and new people hired into the project team.*

Goal 2: Through well-targeted research, facilitate the entry to international fusion tenders and research projects for Finnish companies and academia.

- Build competence in Finnish research and business networks to reach the international level and opportunities to become a member in high-tech international consortia.
  - ✓ *The international collaboration, both with research organizations and private fusion companies, is much more extensive than it used to be before ECO-Fusion. VTT is a valued partner in varying consortia and has attracted Finnish companies into tenders and offerings towards ITER and international companies.*
- Advance export in fusion research but extending also to other Big Science projects and markets outside fusion as well.
  - ✓ *Export is expected to increase within the next 5 years thanks to the already agreed contracts or contacts with international fusion companies. The established network has given visibility to Finnish companies towards various Big Science projects, and they are continuously seeking opportunities in expanding their business in these fields.*
- Maximize EU (incl. DEMO) and ITER funding for both Finnish industry and research organizations.
  - ✓ *The EU funding has provided subcontracting work for >5 Finnish companies on a commercial basis. The revised strategy of ITER has recently been published and will continue providing opportunities for Finnish companies within the next 10 years. New companies have entered the Finnish fusion ecosystem, both as members of the FinnFusion Advisory Board and as partners for new co-innovation initiatives.*

Goal 3: Build a top ecosystem for Finnish companies to reach the development targets from the ordinary company to the international high-tech service provider.

- Support industry to build value networks (ecosystems) through business and collaboration model research in fusion / big science context both on company and ecosystem levels.
  - ✓ *Within ECO-Fusion, several interview rounds have been carried out and a list of actions have been formulated to promote expanding the value networks of companies. In addition, key factors have been identified that inspire Finnish companies to participate in fusion projects – or prevent them from doing that – and list of corrective measures has been compiled.*
- Analyse communication between ITER and Finnish companies to boost business efficiency and development in big science projects and within Finnish ecosystem.
  - ✓ *Communication from ITER to Finland was improved together with the Finnish ILO (FinNuclear), further facilitated by the nomination of VTT representative (O. Soppela) as the deputy ILO in 2023.*
- Maintain wide knowledge and information exchange with industry through collaboration with FinNuclear to learn from and co-innovate ILO and industry activation.
  - ✓ *In collaboration with ILO (FinNuclear), information has been more broadly disseminated to all FinnFusion members and other Finnish companies. Participation in Business Fora has been prominent and visible, on top of which new member companies have been attached to the FinnFusion Advisory Board and the Finnish fusion ecosystem. An Open Business Day with other VTT nuclear ecosystem projects was a success and a good opportunity for networking.*

2.4 Status of KPIs, milestones and deliverables

The commented version of the KPIs from Table 1 against the achievements made in the project can be found in Table 6. Similar analysis for the milestones and deliverables can be found in Table 7 and Table 8, respectively.

Table 6. Status of the KPIs of Table 1 in the end of the project

Partner	Expected impact of the project on partner	Metrics	Status in 30.06.2024
VTT	1. Capabilities to better support Finnish companies to connect with international partners in fusion projects 2. Better hit rate in EU funding/tenders together with Finnish industry partners 3. Research excellence 4. Visibility, reputation, and trusted partner of VTT as a Finnish fusion co-ordinator in EU 5. Better commercial collaboration with Finnish companies	1. Number of Finnish companies involved/aware of ITER and DEMO tenders/projects. 2. Hit rate analysis 3. Publication record, number of citations 4. Independent evaluations from EC, EUROfusion, ITER and the Finnish government 5. Turnover of VTT's commercial fusion project portfolio	1. >5 new companies involved in the FinnFusion network and participated in preparing the follow-up project 2. 5 companies involved in tendering opportunities during the project 3. More than 90 peer-reviewed journal articles and >75 conference contributions published 4. VTT is considered a trusted partner for new (>10) EUROfusion activities during the project 5. VTT has new commercial contracts with international fusion companies and involved also Finnish companies in the collaboration
EU fusion ecosystem	1. Better knowledge about Finnish companies and their products/services 2. Updated information about Finnish partners in EU fusion databases 3. Demonstration of Finnish excellence in selected focus areas (superconductors, novel materials, remote maintenance, artificial intelligence/high-performance computing, nuclear engineering)	1. Questionaire to EU stakeholders (F4E, ITER, European Commission) 2. Number and quality of Finnish companies information in EU fusion databases 3. Participation in business events (IBF and BSBF, SOFT exhibition)	1. A DELPHI questionnaire consisting of two rounds completed and analyzed 2. All companies included in ECO-Fusion and FinnFusion Consortium informed on the opportunities 3. VTT and >5 companies participated in each BSBF event and >2 companies joined the SOFT conferences

Table 7. Milestones of the VTT ECO-Fusion research project

No	Title	Description	Status 30.6.2024
1	EUROfusion decisions for funding of Horizon Europe projects	EUROfusion decisions on all DEMO and ITER projects will be available. Refocussing and reresourcing on some resources may be performed.	Fully reached – re-resourcing performed
2	Decision on Advanved Computation Hub Helsinki	Start recruiting personnel or reduce significantly the scope, depends on the funding decision by EUROfusion.	Fully reached – new people hired
3	All co-innovation projects (VTT, UH and the 4 company projects started)	All the separate co-innovation projects have had their kick-off meetings and the first project steering group organized.	Fully reached
4	Well-functioning collaboration with FinNuclear and its ILO activity established	Once the FinNuclear collaboration is established with this co-innovation project, we will plan procedures on how to maximize the benefit from this co-innovation to ILO work and national fusion industry activation and vice versa from the national industry activation towards this co-innovation project.	Partially reached - ILO works exclusively under FinNuclear while a deputy ILO selected from VTT in 2023
5	New research opening fields initiated	A critical mass of resources put in place for new research areas at VTT with the help of the companies involved, such as licensing, nuclear waste and decommissioning, and novel fusion materials research.	Fully reached – refer to activity reports in section 3
6	Data collection of ecosystem roles, processes, and cases	Data collection about different roles, processes, and cases in related big science projects as well as about service/product providing entities is completed. This is required to enable final analysis and network model creation.	Partially reached – some data collected and DELPHI questionnaire completed
7	EUROfusion decision on the beneficiary to host EU test rigs	Start integrating the test rig with VTT's existing environment on the virtual smart manufacturing test facility.	Delayed – EUROfusion decision late and no integration performed

Table 8. Deliverables of the VTT ECO-Fusion research project

Year	Title	Description	Status 30.6.2024
2021	First Open Business Day seminar for Finnish companies	An annual open seminar for all interested parties to network and learn about the fusion industry and research opportunities.	Completed – seminar held in early 2022
2022	Well-operating Advanced Computing Hub	The Advanced Computing Hub is receiving EU funding and acting as the central point of Finnish HPC and AI expert centre both in fusion and spreading the know-how elsewhere.	Completed – ACH established in late 2021 and is now fully operational
2022	Generic business models and transition - report 1	Report on the current vision of generic industry business models and how they see their need for transition.	Partially done – data collected but no analysis possible
2022	Candidate materials for DEMO components and magnets	Report on the characteristics of advanced materials, developed within the scope of this project, fulfilling specifications required for DEMO components and magnets.	Completed – reports available as documents in the EUROfusion database
2023	New Finnish fusion activities born in this co-innovation project	List the number of new activities born from this co-innovation project (new companies, new projects, new tenders, new experts).	Completed – >5 new companies attached to the ECO-Fusion ecosystem, >5 new commercial contracts established, >10 tenders placed, and >20 new experts attached to the project
2023	Generic business models and transition - report 2	Report on the generic industry business models and transition, change of visions and practical actions taken.	Cancelled – no report 1 performed
2023	Digital thread models for fusion test rig	Simulated environments established for the fusion test rig and thread models available for testing virtual prototypes in DEMO-relevant conditions.	Ongoing – test rig design and construction only started in 2023
2023	Creation of the Finnish Fusion Ecosystem models	The ecosystem research supporting innovation actions creating export, international networks, internal collaboration, EU funding and added value to its participants.	Completed – various models available for future analyses

3. Summary of achievements in different WPs

3.1 Main achievements in WP VTT-1

The work package WP VTT-1 concentrated on designing and developing solutions for remote maintenance of the European DEMO and other future fusion reactors (Task VTT-1.1), in addition to preparations for a Finnish testing facility (consisting of various test rigs) of different RM solutions were initiated (Task VTT-1.2). The advances will be reviewed in more detail below. Concerning the original goals and deliverables, tremendous progress was made in designing a remote maintenance system consisting of robots and human beings for varying conditions and environments (section 3.1.1) and the role of human factors was extensively investigated (section 3.1.3), though developing a brain-machine interface turned out to be a challenging task to even be initiated during ECO-Fusion. Algorithm development was intense, thanks to the new tools and methods that artificial intelligence and machine learning brought along, not only for routine operation but also to understand risks related to operating varying remote maintenance systems (sections 3.1.1 and 3.1.2). Condition monitoring was started, and novel sensor solutions were developed to track positions and velocities of various components in a fusion reactor (section 3.1.5); these also provided the necessary input for the design of test-rig facilities. Test-rig development was otherwise delayed due to EUROfusion taking a much longer time than anticipated in making decisions for its siting and scope. Therefore, many of the original project goals under Task VTT-1.2 could not be met. Instead, a large part of the project was devoted to finding the best solution for collecting requirements related to systems engineering in fusion reactors (section 3.1.4). This work will also benefit test-rig design from 2024 onwards. New companies were attached to the design of the test rigs which will hugely speed up the activity now that it is starting at full speed in early 2025.

3.1.1 Design work for the DEMO reactor

Activity coordinator: W. Brace
Related task: VTT-1.1

Developing and improving the design as well as assessing the architecture of a tokamak plant are key tasks in creating an intelligent and agile remote maintenance system adaptable to various changes that can be implemented in other industries apart from the fusion community. Within ECO-Fusion, the work has concentrated on the European DEMO reactor in tight collaboration with EUROfusion but the developed methodology applies to any other international fusion facility. The main achievements per theme area are listed below. A large part of the work was done in collaboration with the co-innovation partner Comatec as well as with Coresbond.

1. *Parametrized CAD Modelling:*
   a. R&D work was carried out to develop a novel, parametrized CATIA CAD tokamak model following the skeleton-based modelling hierarchy. The purpose of the model is to accelerate and harmonise the creation of variations of the tokamak geometry for plant architecture assessments. Tokamak design points can now be created by modifying parameter values in a reference skeleton. A case study including the envelopes of various in-vessel components and their remote maintenance (RM) trajectories was implemented on the DEMO configuration to demonstrate the responsiveness of the model to changes

in input parameters. A macro was developed to export design point parameters from the model to test data transfer.

   b. The developed model also includes the automation of geometry-based RM feasibility assessments to support the formulation of a structured design approach. This way, unstructured information on the feasibility of various options can be converted into explicit and traceable data for further calculations. The work included harmonisation and interdependency mapping of the key feasibility assessment criteria.

   c. The modelling further includes automating in-vessel trajectory generation by defining and executing a use case for path generation. Varying path-planning tools were considered. The best strategy turned out to be first using the Catia DMU Fitting tool to investigate the functionalities for the actual path planning, followed by applying machine learning (ML) based Unity ML-Agents Toolkit to establish a pipeline to generate paths for various demonstration cases. The parametrized CAD Modelling approach can also be applied to complex system modelling for equipment in other industries with extreme operational conditions.

2. *Multi-objective optimisation design of a tokamak architecture with an RM perspective.* Here the goal was to set up an optimisation model for the architecture of a fusion reactor from the RM viewpoint and constrain functions from the perspective of Bluemira, a Python-based framework for designing fusion reactors by considering both physics and engineering aspects. Following successful implementation of the individual building blocks, a preliminary case study was carried out. By changing the function of a breeding blanket (BB), the mass centre can be shifted close to the operation position, reducing the moment on a lifting manipulator.

3. *Design by cataloguing, an engineering concept development of RM equipment.* A novel approach to conceptual design was adopted to maximise the inclusion of existing designs by companies into the maintenance of a fusion reactor or power plant. The methodology is a product-driven approach using a design catalogue, the fundamentals of reverse engineering and design by retrofitting. The proposed method implicates the analysis and synthesis of the design of complex systems by systematically reviewing various available commercial off-the-shelf (COTS) solutions while performing functional analysis and evaluating the technological maturity of each solution.

3.1.2 Risk assessment for DEMO

Activity coordinator: W. Brace
Related task: VTT-1.1

Risk and RAMI (Reliability, Availability, Maintainability, and Inspectability) compounded with rescue and recoverability are essential concepts in defining reliable RM equipment design to improve the maintenance efficiency and maximise the operational duty cycle of a fusion power plant. Two research studies were carried out during ECO-Fusion.

1. *Automated tools for quantitative application in risk analysis:* Risk is the combination of severity and occurrence of the consequences as a failure. Severity for the operation of a fusion power plant can be assessed as the length for the unavailability of the plant following a failure while

occurrence is the expected frequency of failures. Risk analysis is a traditional research topic premised mainly on qualitative and semi-quantitative methods. The research implements a formal method using applied mathematics to rigorously model risks quantitatively. During ECO-Fusion, artificial intelligence (AI) together with ML tools were adopted to analyse quantified risk models and to apply the underlying methodology to the DEMO reactor. The assessment of the obtained results is ongoing, with possible implications for the DEMO design.

2. *RAMI, Rescue, and Recoverability:* The RAMI analysis process is an association of methods and integrative concepts based on the results obtained to control technical risks. Within ECO-fusion, the research focused on the technical aspects of RM. In the different design phases, different types of analyses are carried out to examine different levels of details. While reliability, maintainability, and inspectability are factors related to preventing failure and further the availability of function or component, recovery and rescue operations show the means to restore functionality and continue operations after failure. Analyses have identified several situations where recovery and rescue would be needed, what would be required for successful recovery or rescue operations, and how much unavailability the planned operations may cause during the lifecycle of DEMO.

3.1.3 Human factors in DEMO design

Activity coordinator: M. Liinasuo
Related task: VTT-1.1

Human factors are connected to the technology readiness level of the system to be developed, i.e., the fusion power plant. This project is mainly in the phase of research and development although also demonstrations of technical solutions are being made. Hence, human factors have, so far, focused on a conceptual level (see Figure 4); testing the potential technical solutions from the human factors perspective is planned for the next year. Thus, the development of the fusion power plant from the human factors' perspective is in accordance with the technical development.

	Level	Technology Readiness Level	Human Readiness Level
Production / Deployment	9	Operational use of deliverable	Post-deployment and sustainment of human performance capability
	8	Actual deliverable qualified through test and demonstration	HSI-related requirements qualified and verified through test and demonstration in a representative environment
	7	Final development version of the deliverable demonstrated in operational environment	Human performance using system equipment fully tested, validated, and approved in mission operations
Technology Demonstration	6	Representative of the deliverable demonstrated in relevant environments	System design fully matured as influenced by human performance analyses, metrics, and prototyping
	5	Key elements demonstrated in relevant environments	HSI demonstration and early user evaluation of initial and/or preliminary prototype to inform preliminary design
	4	Key elements demonstrated in laboratory environment	Modeling and analysis of human performance conducted and applied within system concept
Research & Development	3	Concepts demonstrated analytically or experimentally	Mapping of human interactions and application of standards to proof of concept
	2	Concept and application formulated	Human capabilities and limitations and system affordances and constraints applied to preliminary conceptual designs
	1	Basic principles observed and reported	Human-focused concept of operations (human use scenario) defined

Figure 4. Technology Readiness Levels and the corresponding Human Readiness Levels (copy from See & Hindley, 2019). Maturity is the lowest at the bottom and highest at the top of the figure.

First, the focus in human factors research has been in identifying the role of the human operator in a complex, highly automated/autonomous system that the fusion power plant RM system represents. One of the best descriptions of the human share of work in such a case has been provided by Sawyer et al. (2021). Work can be traded between human and the system in many ways (see Figure 5). The purpose of sharing work is to achieve better performance than when having the human or automation working or functioning alone. There are tasks that are inherently human in a safety-critical system (making plans and high-level decisions), just like there are the ones that need to be dedicated to the automated system (similarly repeating tasks that require strength, precision and endurance beyond human capabilities). Between these endpoints, there is a grey area that is here focused on.

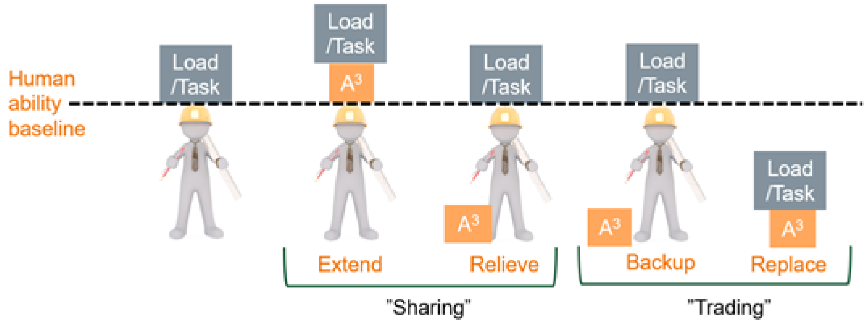

Figure 5. Options for work sharing between human and automation (redrawn from Sayer et al., 2021). Automation is marked as A^3.

Human working alone is as (in)efficient as when the system performs human tasks to give the human some rest or when the system trades the task with humans, e.g., by serving as a backup. The best outcome is reached by collaboration between human and /automation in most situations. In such a situation, the share of tasks dedicated to the system should be the kind in which the automated solution outperforms human. If the system replaces human, the performance is at a lower level than when human works alone. An expressive term to be used in this context is *human-system (automation) teaming*.

Secondly, such tools or boundary objects have been sought to support the integration of human factors into technical development. One of such objects is the presentation of technology and human readiness levels side by side (see Figure 4). One tool is to contemplate the principles for function allocation between the operator and the technological system of the fusion power plant maintenance. A recommended approach also used in the military and nuclear practice (see Figure 6), is to start the contemplation from the understanding of the entire system, i.e., developing the fusion power plant as an entity, instead of deciding function allocation sub-system or solution by sub-system or solution.

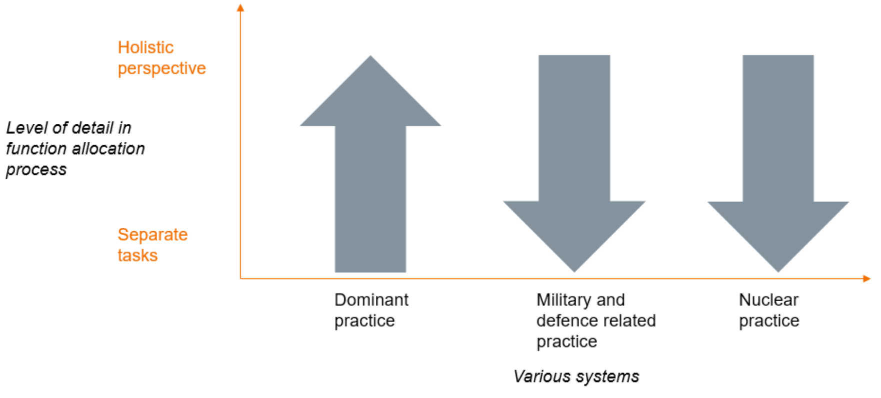

Figure 6. Examples of function allocation practices.

Within ECO-Fusion, the methodology described above has been adopted for the RM needs of the DEMO reactor. The purpose of the concept document or template is to provide an overview of the human share of the operations of DEMO remote maintenance systems. It is to be written and used by technical developers and human factors specialists to enhance the collaborative development of the maintenance systems. In the template, the remote maintenance system is scrutinised from various perspectives, describing, e.g., the system overview, operational policies and constraints, remote maintenance systems and the related human involvement, relationship with other systems, incident management, and human competence and staffing.

3.1.4 Supporting engineering management of the DEMO Remote Maintenance System

Activity coordinator: J. Alanen
Related task: VTT-1.2

Aras Innovator PLM platform was demonstrated by VTT during the period 2022-2023 to study its capabilities in storing engineering data for the DEMO reactor according to a pre-defined piece of systems engineering ontology created by VTT. The demonstration and proof-of-concept studies indicated that Aras PLM can provide the relevant functionality of an engineering hub to host the digital thread of DEMO including its maintenance system, see Figure 7. The overall goal was to foster the move from document-centric engineering to model-based engineering. During 2023-2024 we decided to extend the proof-of-concept study with the objectives as follows:

- to study the feasibility of the Aras Product Lifecycle Management Platform as the integration platform for the IROH (Integrated Remote Operations Handler) design tools. The IROH design tools are the following: Planning and Scheduling tool; Space Simulation tool; Clash and Collision Detection tool; Model-based engineering tool; Radiation Modeling tool.
- to demonstrate that the created engineering repository can be used for storing and management of:
  - alternative designs
  - digital thread of the plant elements under maintenance as well; limiter structures of DEMO were used as an example.
  - standard tools catalogue instead of using Excel.
- to create a Traceability Management Tool (TMT) onto Aras PLM.

With these proof-of-concept tasks we demonstrated that using Digital Thread instead of office software applications is the way to speed up and manage, in a traceable manner, DEMO fusion power plant design.

Fulvisol, a Finnish partner of Aras, was included in the implementation of the activity via a subcontracting project funded by EUROfusion.

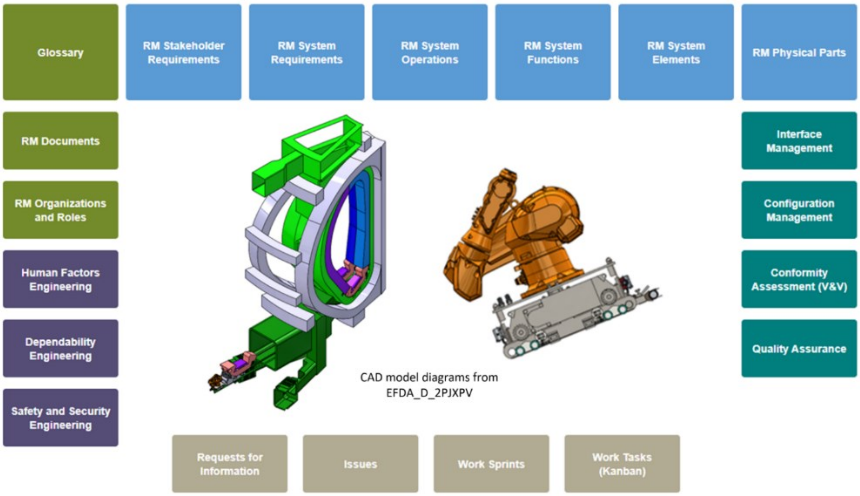

Figure 7. Remote Maintenance System graphical user interface on Aras

3.1.5 Sensors and communications

Activity coordinator: A. Ylisaukko-oja
Related task: VTT-1.2

Due to the nature of tokamak in-vessel maintenance operations, the associated risks must be carefully considered early in the conceptual design phase. The most typical task of remote maintenance is replacing an old breeding blanket with a new one. According to the current plans, the weight of a single vertical slice of BB is in the scale of ~80 tons and the height ~12.8 m. Because of very low mechanical margins (~20 mm), installing and removing Breeding Blankets will need applicable sensor solutions that must be tolerant to environmental conditions such as radiation. The target has been from the beginning to find or develop sensor solutions for Advanced Position Control System (APCS) that would enable the lifting and moving of the blanket segments within the tokamak vessel without risks of damage.

The main emphasis of this activity was to implement and test solutions to be applied in APCS for remote maintenance. So far, five different technologies have been considered, four of them being implemented at least on a preliminary level. At least preliminary measurement results in laboratory tests are available from all of them. The fifth technology (3D Node) has earlier been applied in ITER development projects with good results. Depending on the technology, sensor tests have been made either close to the final dimensions of the DEMO reactor, or with a miniature mock-up BB prototype that was implemented in the project. Tests have been mainly static – dynamic measurements are to be started soon along with further development of the sensor devices. A common Test Rig design for all these technologies was started. It will be located at VTT Tampere.

For tracking the position of the breeding blanket during remote maintenance, a new printed circuit board for capacitive proximity sensors was designed, implemented, and successfully tested with connection cable lengths between the sensing electrode and electronics up to 30 m. This enables separating electronics out from the vessel. Successful static measurements with promising accuracy were done both with a small scale and close to full-scale versions.

The miniature mock-up BB (Figure 8) was designed and implemented to serve tests with both capacitive sensor and 3D Fiber Bragg Grating (FBG) optical fiber sensor. The 3D FBG sensor can be used for measuring the shape and movement of the object, including the frequency of movement. This could be utilized to affect the behaviour of the manipulator to avoid mechanical resonance of the BB structure. The FBG interrogator device can reside outside of the vessel, measuring the spectrum reflected back from the FGB sensor – therefore, no semiconductors are needed within the tokamak. 3D FBG static tests were done with miniature BB – dynamic tests are to be done later (Figure 9). As expected, based on mechanical implementation and design issues, the static accuracy of this device was not good in these tests (especially when compared to other sensor options). However, means to improve performance have been recognized and will be realized later.

A camera-based position estimation (Figure 10) was implemented to find out its applicability to APCS under the environment conditions during RM. A radiation-hard solution was implemented, giving excellent accuracy for measuring the location of the bottom part of the blanket. The camera is to be located close to the bottom of the vessel.

The concept of a novel LIDAR (light detection and ranging) technology for monitoring the position of the breeding blanket in three-dimensional space was designed and refined. It was then constructed with VTT's laboratory instruments. The hardware used resulted in a standard deviation of distance to approximately 1 millimeter in 1 second integration time. These values can easily be improved by a factor of ten with more relevant hardware choices. This method requires retroreflectors to be installed to the BB. They are passive, non-scanning optical transceivers. Meanwhile, all active components, including semiconductor devices, remain at a safe distance from the tokamak and are connected via optical fibers to the optical transceivers. The benefits of the methods are high accuracy and precision, short integration time and simple computation, and thus a short lag time.

3D Node is a conservative approach that can provide an accurate and reliable measure of the six degrees of freedom of the marked targets. It takes images as inputs and is agnostic for the type of camera and interface being used. The approach could potentially be a key facilitator of remote handling operations at DEMO, including both the divertor and BB handling applications. The feasibility of this sensor was estimated, including analyzing the monitoring needs in the remote maintenance system for DEMO. It focused, particularly, on the 3D Node marker-based machine vision system developed earlier for ITER. The capabilities and limitations of 3D Node were briefly described. Practical work with 3D Node will be started in the next phase of the project.

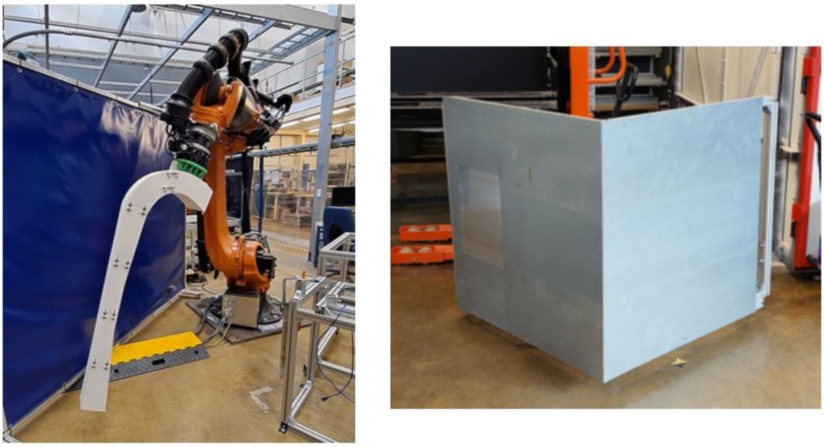

Figure 8. (Left) Miniature mock-up BB attached to a robot. (Right) BB mock-up used in the tests: two pieces of 1 m x 1 m sheet steel on an aluminium frame. The frame was mounted on a motorized linear stage.

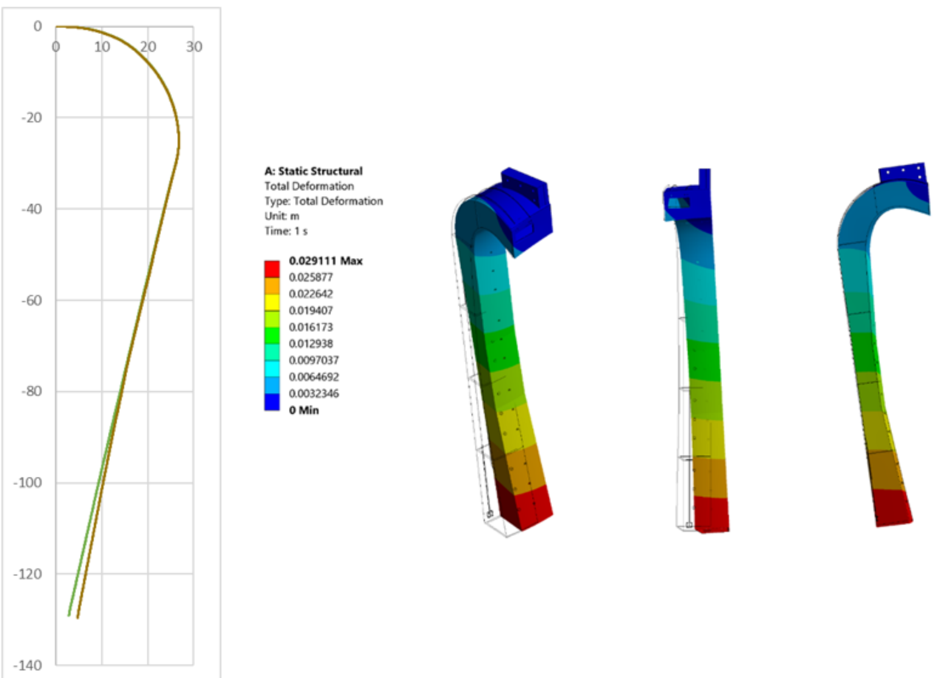

Figure 9. (Left) Measuring two states of miniature BB mock-up's form with a 3D FBG sensor. (Right) Finite element modelling of the miniature BB mock-up.

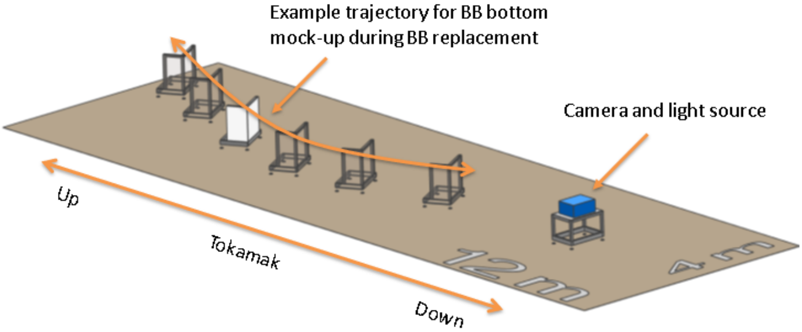

Figure 10. Breeding blanket position estimation using one camera.

3.2 Main achievements in WP VTT-2

The work package WP VTT-2 had a large scope, ranging from developing and modelling the properties of the novel materials for future fusion reactors, largely using the VTT ProperTune® simulation framework (Task VTT-2.1), to characterizing irradiated material samples in the VTT hot-cell facilities along with developing new measurement techniques at high temperatures in a hydrogen atmosphere (Task VTT-2.2). The utilization of the Advanced Computing Hub at the University of Helsinki and the application of machine learning and artificial intelligence tools also belonged to WP VTT-2 (Task VTT-2.3). Much progress was made in developing new modelling approaches (section 3.2.1) as well as applying the ProperTune® toolbox to selected candidate materials for fusion reactors (sections 3.2.2 and 3.2.3); also the production of test batches and their characterization is discussed and how modelling can support additive manufacturing approaches. Of the co-innovation partners, Luvata and EOS Finland were strongly involved in the work. Development of intelligent materials to provide radiation shielding for critical components in ITER and DEMO, for its part, proceeded more slowly and was re-directed to cover insulating solutions for magnets in fusion reactors – in collaboration with Luvata. This work will continue after ECO-Fusion under a separate project. For the microstructural characterization of irradiated fusion reactor materials (in nuclear test reactors), methods and tools were designed and commissioned and the first results have been recently obtained (sections 3.2.4 and 3.2.5). Development of cleaning methods, for its part, was transferred to be done under WP VTT-3 (section 3.3.5) and the scope was altered to focus exclusively on laser-based techniques. VTT contributed strongly to organizing and running the Advanced Computing Hub (section 5), in addition to which several algorithms and methods to speed up modelling activities were introduced and developed (section 3.2.6).

3.2.1 Modelling irradiation embrittled EUROFER 97 steel

Activity coordinator: A. Freimanis
Related task: VTT-2.1

This activity focused on the development, validation, and verification of computational tools for modelling of irradiated materials, specifically targeting EUROFER97, a reduced activation ferritic-martensitic steel. Materials in future fusion reactors will face complex and extreme environmental conditions. As a result, the modeling approach needed to be comprehensive, combining multiscale and multiphysics solutions to accurately capture material behavior under such conditions.

VTT leveraged open-source software to accelerate the development and benefit from the broader community's contributions. The primary framework used was the finite element (FE) platform MOOSE, developed by the Idaho National Laboratory. MOOSE provided excellent parallel scalability, high-quality code, and a permissive open-source license, which facilitated code dissemination and future development. On the computational side, the development work was split into two categories.

Material Models:
The focus was on crystal plasticity (CP) modeling. We implemented three new flow rules (which describe material deformation under applied loads) and eight different state variable models (which capture the current properties of the materials). These flow rules are essential to model the wide range of temperatures and strain rates encountered in fusion environments, while the state variable models address different material structures and conditions, such as FCC and BCC crystal types, irradiation hardening, and phenomena like the Hall-Petch effect. By offering multiple model options, users can perform a simplified and quick initial analysis or a more detailed, albeit slower, one afterwards. Additionally, eigenstrain calculations within the CP framework were developed to simulate irradiation-induced swelling and thermal expansion—critical factors in fusion reactors due to the high irradiation flux and thermal gradients expected.

We introduced a significant improvement by decoupling flow rules from state variable models. Previously, these components were combined within a single material model, requiring complete rewriting of the codes to implement new models. Our enhancement allows users to select flow rules and state variable models independently, significantly increasing flexibility and enabling reusing the codes. This modular approach also accelerates future developments.

Fracture Models:
Fracture modeling was enhanced using peridynamic theory, a non-local approach that better accommodates crack nucleation, propagation, and arrest. To improve accuracy near crack surfaces and model boundaries, we developed an enhanced strain calculation method. We also implemented a brittle fracture model based on cleavage stress and a ductile fracture model based on void coalescence.

Material-scale simulations are computationally intensive due to the large models required to capture fine details of the material microstructure. We tested the performance of our models on the Finnish Supercomputing Centre's (CSC) clusters, utilizing over 2000 CPUs, and continue to conduct larger-scale tests. Validation and verification of the models were conducted using existing data from the EUROFER97 material handbook, developed by the EUROfusion Consortium. The models have been validated across a broad range of irradiation doses, temperature conditions, and loading scenarios. Additionally, experimental fracture tests are ongoing. The work was carried out as part of a EUROfusion Engineering Grant and will extend beyond the timeline of ECO-Fusion, thus full validation of the fracture models is still underway. The first results on simulating material microstructure and initiation of damages can be found in Figure 11, while the modelling results for the total accumulated slip, maximal principal strain, and von Mises stress are shown in Figure 12.

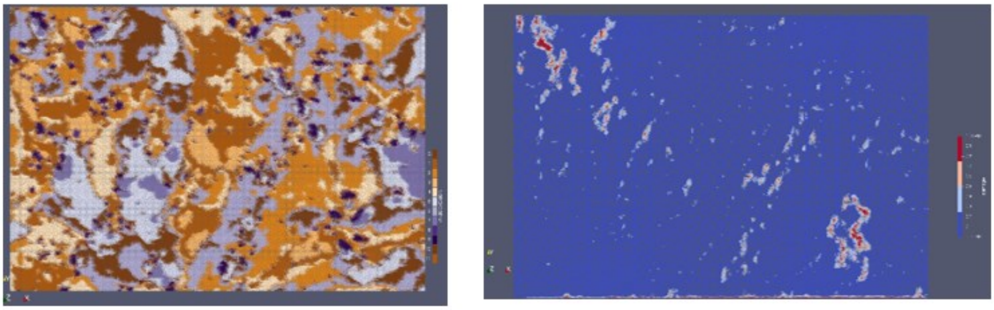

Figure 11. Material microstructure and simulated damage initiation.

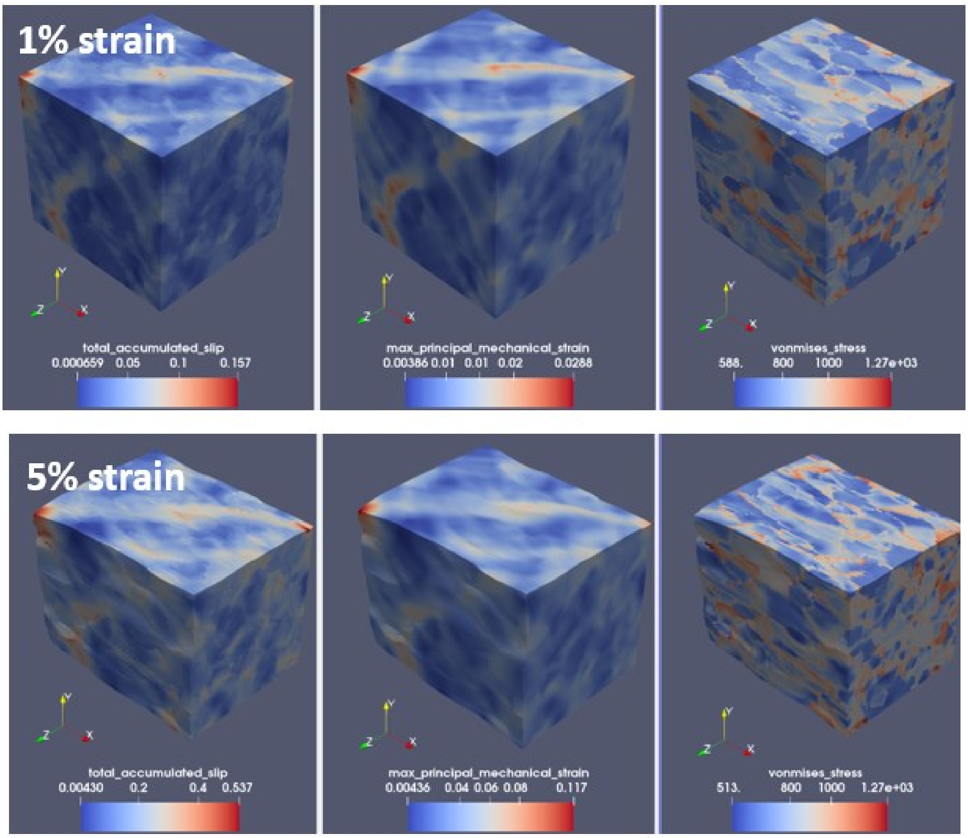

Figure 12. Total accumulated slip, maximal principal strain, von Mises stress at 1% and 5% strain.

3.2.2 Production and modelling of Cu- and CuCrZr-based alloys

Activity coordinator: A. Laukkanen, T. Suhonen
Related task: VTT-2.1

Special emphasis was directed on the manufacturing aspects of CuCrZr-alloys even though a framework was created to model the entire process-structure-properties-performance chain. Several samples from all manufacturing steps (casting, drawing, cold working, precipitation, annealing, and forging) were characterized and process-structure models were created. Also dedicated samples from other EUROfusion members, including extruded plates and pipes, were studied and the obtained data was included into the ICME (Integrated Computational Materials Engineering) framework running at VTT.

CuCrZr-alloys are manufactured in several process steps starting from casting a billet. The casting parameters like the composition (even within standard), thermal gradients (pulling speed, different cooling parameters) and perturbations will have a major role in determining the microstructure of the cast and possible defects like cracking of the central line. The microstructure of the cast will have an impact on the final microstructure of the end product, and this was the reason why an ICME workflow for casting (Cellular Automation (CA) and Phase Field (PF) simulations) was created along with the experimental approach. This framework was used to generate direct inputs for CP-based property and performance models.

The complete simulation framework for Cu- and CuCrZr-alloys is presented in Figure 13.

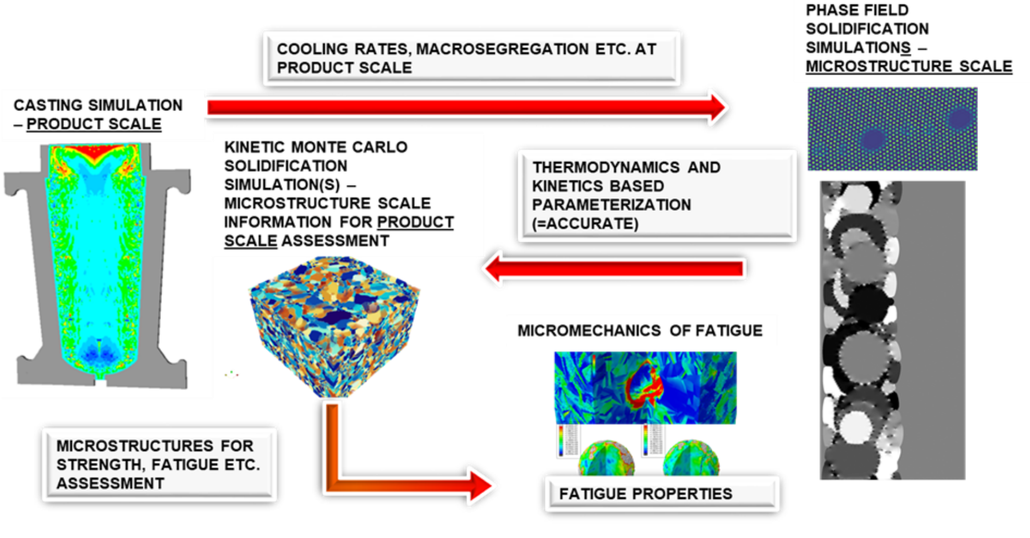

Figure 13. Complete ICME simulation framework for Cu- and CuCrZr-alloys.

CA and PF simulations were performed by systematically scanning through the design space of casting (composition, thermal gradients arising from multiple factors, perturbations etc.) and examples are presented in Figure 14, Figure 15, and Figure 16.

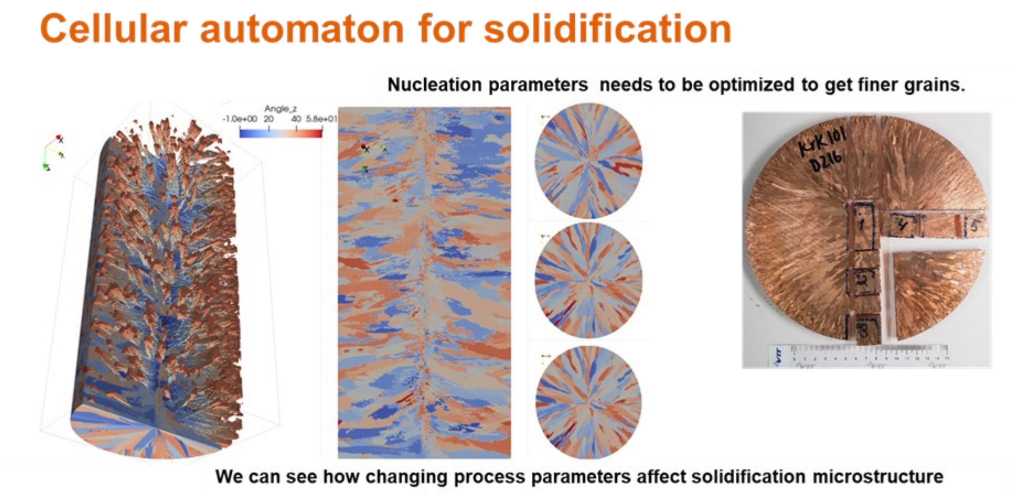

Figure 14. Example of a CA simulation and microstructural variation of the entire casting billet. A photograph of the cross sections of an actual billet is shown on the right.

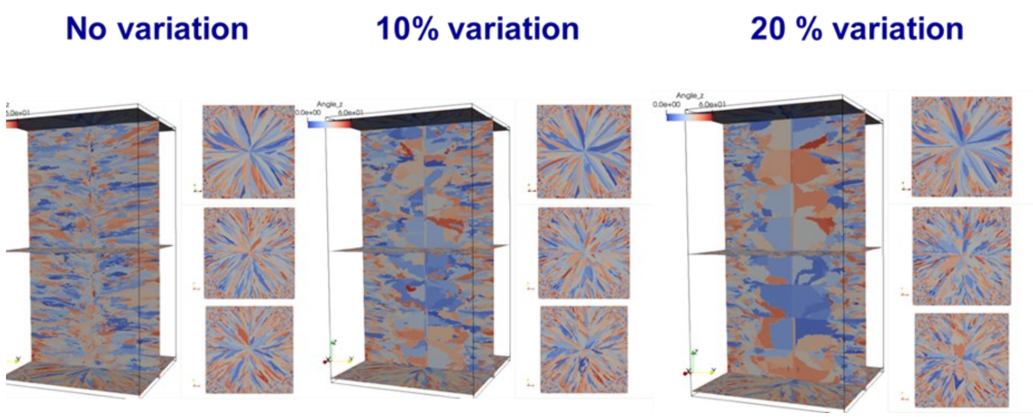

Figure 15. Example of the effect of perturbations on the microstructure of the cast.

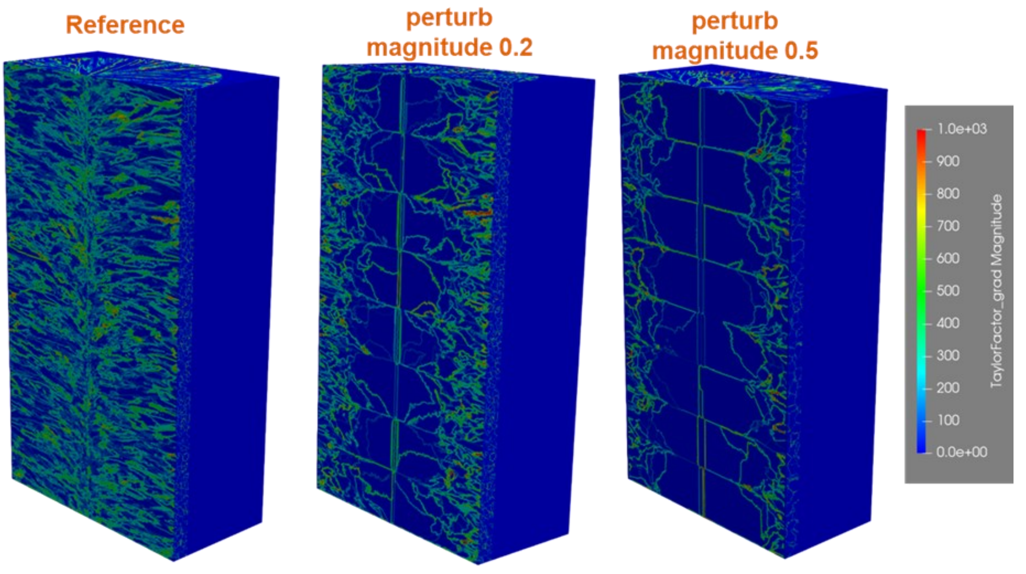

Figure 16. Example of the effect of perturbations on the Taylor Factor.

CA and PF process-structure models were used as a direct input for CP-based property and performance models. Examples of the workflow for Cu-based materials are presented in Figure 17 and Figure 18.

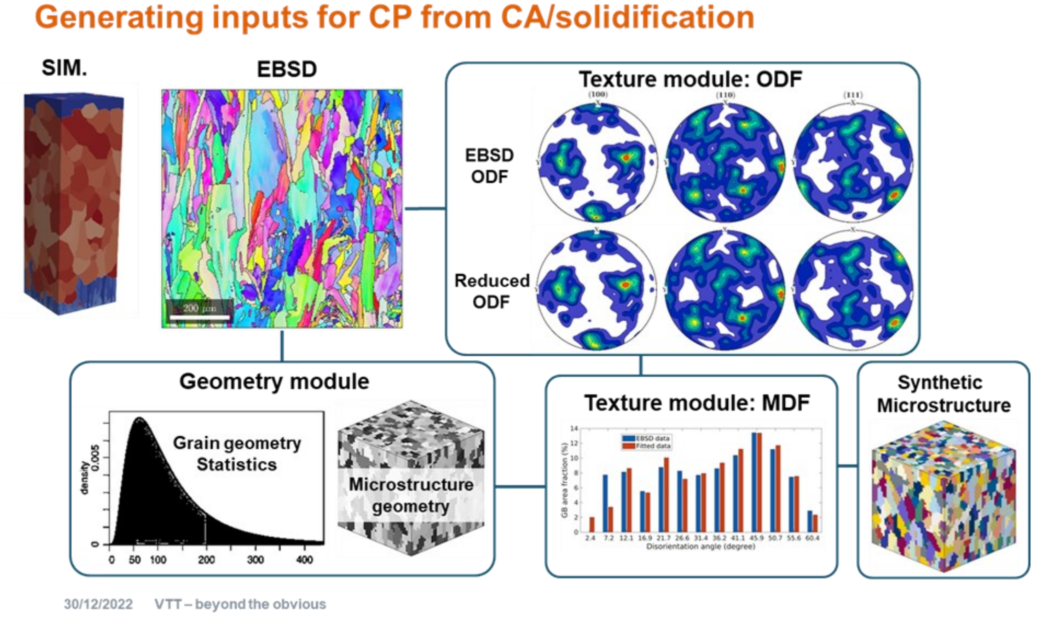

Figure 17. Inputs for CP from CA/solidification models in the ICME framework.

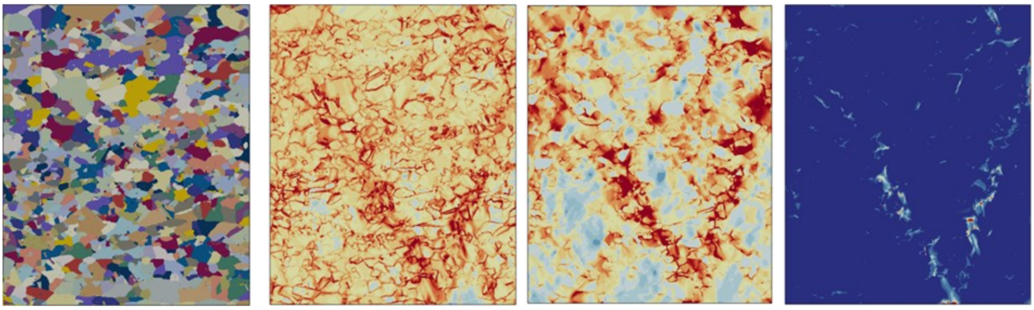

Figure 18. (Left) EBSD (Electron BackScattering Diffraction) based microstructural analysis (porous crystal damage model) and (right) V. Mises Stresses, dislocation density and "porosity fraction” (ductile damage model – crystal plasticity) for a CuCrZr sample under tensile stress.

Three different CP-based damage approaches were developed, so-called porous damage, crystalline damage and phase field damage (example of porous damage in Figure 18). These local damage analyses can address grain-boundary-type damages (e.g., void nucleation and growth, intra-grain damage as observed in the simulations). Special points of interest include grain-boundary damage, orientational effects, triple points, precipitate effect, as well as all size and scale effects.

Emphasis was also given to the precipitates in CuCrZr and a framework how for treating inter-and intragranular precipitates was created (Figure 19).

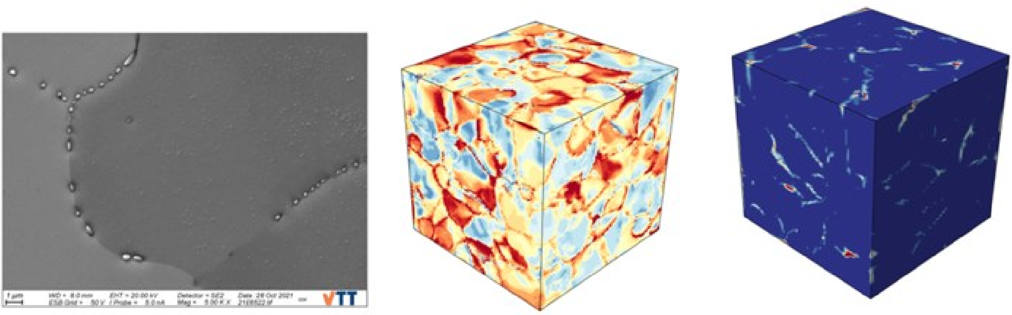

Figure 19. (Left) Electron microscopy image of the CuCrZr microstructure showing larger precipitates at the grain boundaries as smaller ones inside the grain. (Right) Modelled effect of the precipitates: V. Mises and damage nucleation sites.

The work in 2023 enriched the material portfolio as well as the modeling framework to consider also the damage and performance of CuCrZr. As a result, a detailed process-structure-property-performance ICME framework is now available for various Cu-and CuCrZr-based alloys, Figure 20.

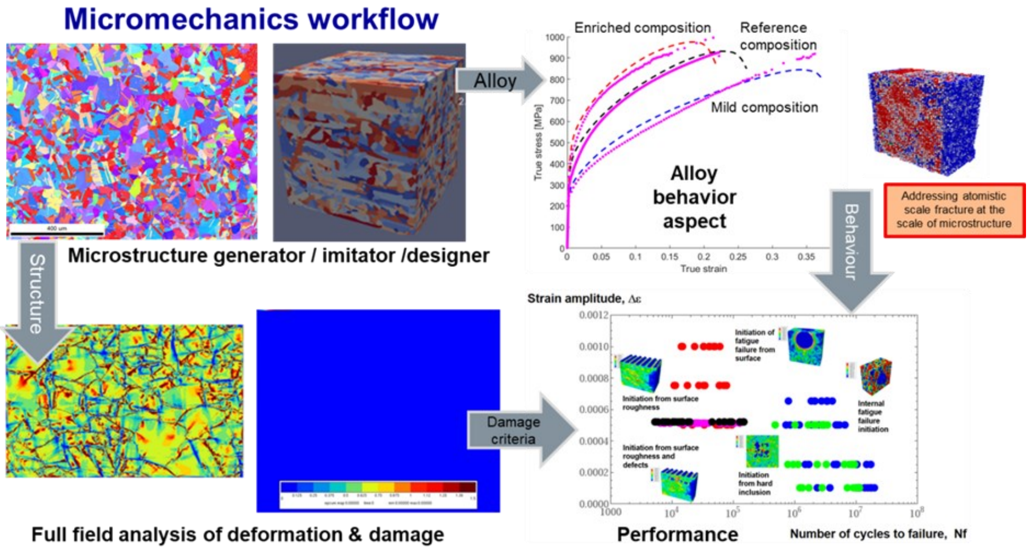

Figure 20. Framework for structure-property-performance linkage.

The framework was used to generate a direct input for CP-based property and performance models. Three different CP-based damage approaches were developed, so-called porous damage, crystalline damage and phase field damage in order to model the performance metrics. New mechanical testing stage for compression, tension, and cyclic loading from nominal to elevated temperatures (up to 1000˚C) was installed in the microscopy facilities of VTT.

3.2.3 Tungsten and refractory alloys for HHFM

Activity coordinator: A. Laukkanen, T. Suhonen
Related task: VTT-2.1

Research in collaboration with three EUROfusion partners was started to fully characterise the behaviour of W- and W-based novel plasma-facing alloys under fusion-reactor conditions. VTT mainly focused on the development of a computational framework which was particularly based on phase-field-crystal models and molecular dynamics (MD) to support additive manufacturing processes such as powder bead fusion (PBF) and electron beam melting (EBM) activities. This way enhanced understanding was obtained on the following experimental activities:

- Laser beam melting of tungsten and beam shaping for improving printability and subsequent properties of the outcomes.
- Laser PBF of W-W2C materials.
- Electron beam melting (EBM) of tungsten-based materials.

For the first activity, computational trials were completed, and the work will continue with parametric studies and comparisons to experimental findings. Concerning the second topic, an initial thermodynamical work was carried out and development work was performed on a full-field microstructural simulator. The thermodynamical work will first be completed and comparisons to experimental and characterisation results then be pursued, followed by parametric studies. Finally, the third topic was pursued by studying the effect of process parameters on the outcomes and validating the developed models. Examples of the outcomes from each of the three research areas can be seen in Figure 21.

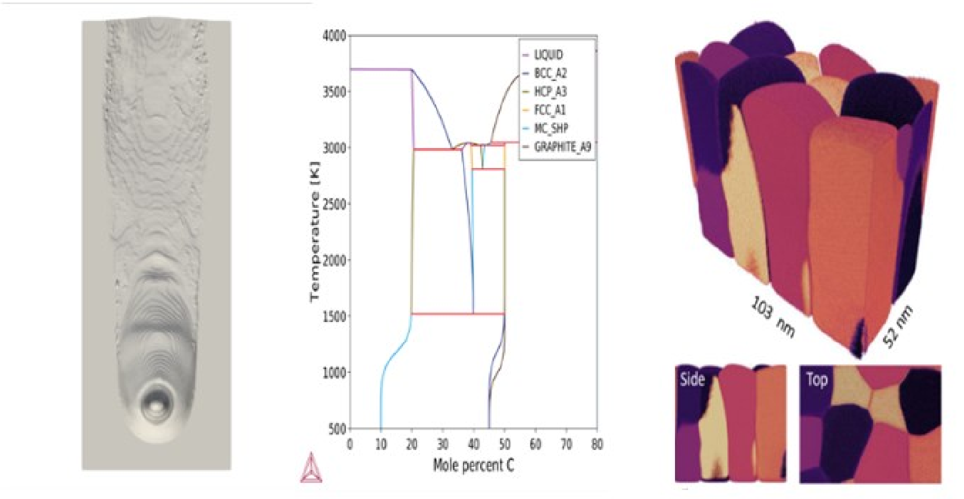

Figure 21. (Left) Examples of laser beam melting computations and beam shaping; (Middle) Effect of oxygen content/impurities in the W-W_2C-system (10mol-%O) and (Right) Phase-field-crystal model of directional solidification of W in EBM.

3.2.4 Analysis of fusion samples in VTT hot-cell facilities

Activity coordinator: P. Lappalainen
Related task: VTT-2.2

Significant progress was made in developing and validating test methods to determine the mechanical properties of highly activated specimens used in fusion reactors. The tests, including fracture toughness, tensile strength, and low-cycle fatigue, were designed to be conducted in a hot-cell environment, where handling and testing of radioactive materials are required. The key achievements of this task can be summarized as follows:

- *Designing and Preparing Test Setups:* Necessary test setups to be integrated into the hot-cell environment of VTT were designed. This involved careful planning and engineering to ensure that the equipment could operate under the stringent safety and operational requirements of a hot cell, where radioactive materials are handled. The design included considerations for remote handling, radiation shielding, and precise control of test conditions.
- *Installation of Test Equipment*: The installation of the test equipment within the VTT hot cell was successfully completed. This included precise positioning of the dynamic testing rig and ensuring that all systems were operational and compatible with the remote-handling

capabilities of the hot cell. This setup enabled the execution of fracture toughness, tensile strength, and low-cycle fatigue tests.

- *Validation of Test Methods*: Selected test methods were validated to ensure they met the required standards in such a specialized environment. This validation was crucial to guarantee the accuracy and reliability of the data obtained from the mechanical tests. The process involved rigorous testing under various conditions to confirm that the methods could consistently produce reliable data. The validated methods are now ready for future use.
- *Commissioning Tests*: Commissioning tests were conducted to ensure that all systems were functioning as intended. Following these, the actual tests – fracture toughness, tensile strength, and low-cycle fatigue – were carried out on both reference and specimens irradiated in nuclear test reactors. These tests provided valuable data on the mechanical properties of the materials.

The achievements in this task represent a significant advancement in the ability to test and understand the mechanical properties of materials used in fusion reactors. The successful development and validation of these test methods within a hot cell environment not only enhances our knowledge but also contributes to the overall safety and efficiency of future fusion reactors. This work has also laid the groundwork for future research and development in the field of fusion energy. An example of tensile test results of irradiated CuCrZr alloy at various test temperatures and irradiation doses is shown in Figure 22.

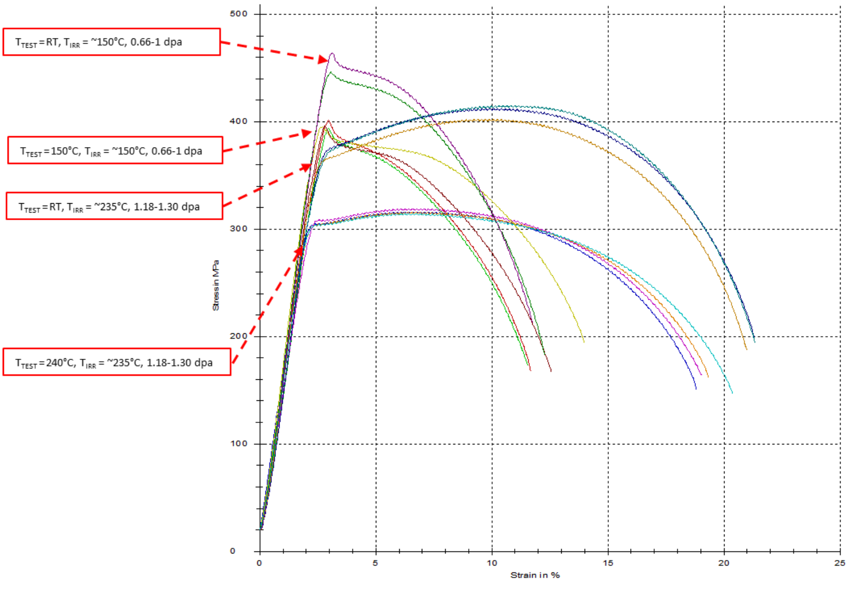

Figure 22. Stress-strain curves of the irradiated CuCrZr alloy at various test temperatures and irradiation doses.

3.2.5 Microstructural characterization of tungsten components at elevated temperatures in a hydrogen atmosphere

Activity coordinator: J. Heikinheimo
Related task: VTT-2.2

Investigating the microstructural mechanical behavior of ITER-grade tungsten monoblocks at elevated temperatures, with and without hydrogen atmospheres, is crucial for ensuring the long-term performance and safety of fusion reactors. Tungsten is chosen for plasma-facing components (PFCs) due to its exceptional thermal and mechanical properties, such as high melting point and low erosion rate. In the extreme environment of a fusion reactor temperatures are high and hydrogen isotopes, including tritium, are present. In these conditions the microstructure of tungsten may degrade, leading to embrittlement, cracking, or material failure. Understanding these effects under different conditions is essential for optimizing material performance, ensuring the structural integrity of reactor components, and advancing the development of safe and efficient fusion energy.

Preparatory work for testing ITER-grade tungsten monoblock samples has been done within the scope of ECO-Fusion. The work included the characterization of monoblock materials IGW (A.L.M.T. plates) and IGP (Plansee W) with scanning electron microscopy electron backscatter diffraction (SEM-EBSD) imaging, virtual microstructure generation based on the imaging, tensile test simulations and comparison with the real tests in the literature. Results of the first tests along different crystallographic orientations indicate a strong dependency on the sample morphology, which is also observed in the experiments, see Figure 23 for details.

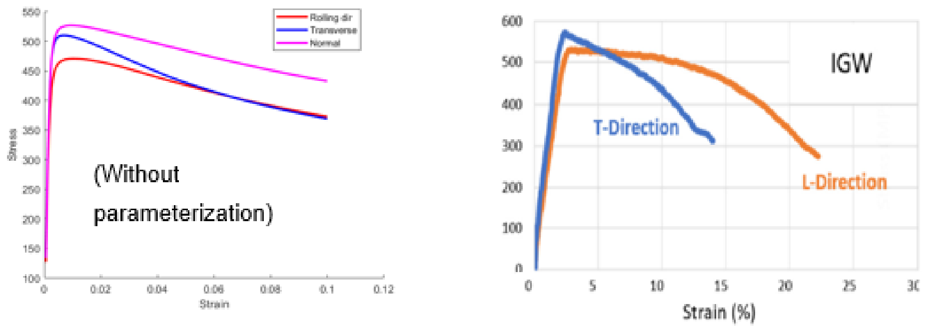

Figure 23. (Left) True stress vs strain curves from IGW modeling. (Right) Experimental tensile stress vs. strain curves at 500°C.

Baseline small punch testing (SPT) of IGW samples without hydrogen was carried out (EN10371 standard 2021). The tests were conducted at room temperature and at elevated temperatures from 300 to 600°C. Due to the small sample size and compact experiments, these kinds of tests enable in the future introduction of H_2 atmosphere for the mechanical testing and mechanical testing of irradiated radioactive samples.

3.2.6 Artificial Intelligence and Advanced Computing Hub

Activity coordinator: A. Järvinen
Related task: VTT-2.3

Artificial intelligence and efficient data science approaches for parameter inference were investigated in connection with the Advanced Computing Hub (ACH) and Enabling Research projects funded by EUROfusion. The focus of the ACH work was on developing efficient inverse uncertainty quantification methods to accelerate validation of computationally expensive tools, connected to the work plans of the different Tasks and activities under WP VTT-3. Furthermore, in 2024 development of efficient forward uncertainty quantification methods with SparseGrids was started, also connected to the same Tasks. In activities outside the ACH, but within the broader artificial intelligence applications for fusion, research was directed towards state representation learning algorithms as well as for efficient surrogate modelling strategies, see Figure 24. These aim to build methods for fast, high-fidelity, physics-data hybrid AI methods for fusion plasma scenario predictions.

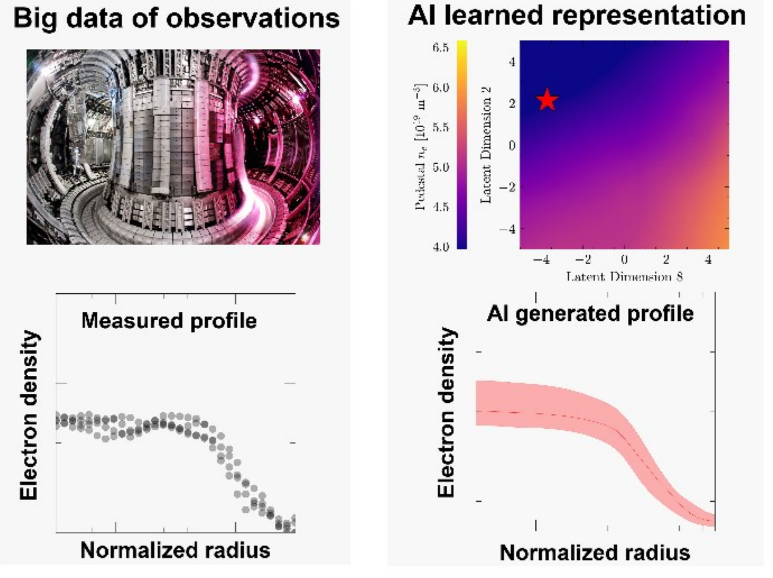

Figure 24. Illustration of the state representation learning research, where a low dimensional representation for the plasma state is learnt (Left) based on a large database of observations. (Right) AI-generated profiles can then be produced from the representation.

The main outcomes from this work within the timespan of the project are:

- Development of Bayesian optimization framework, released in GitHub, for the usage of the model development teams to accelerate model validation: https://github.com/aejarvin/BO_FOR_RE_SIMULATIONS
- Publication related to the above framework in Journal of Plasma Physics: A.E. Järvinen, et al. Journal of Plasma Physics **88** (2022) 905880612.

- Extension of the framework towards amortized inference capabilities through neural-network type posterior estimation methods. Publication is expected in 2025.
- Development of the SparseGrid approaches for efficient forward uncertainty quantification. Publication is expected in 2025.
- Four publications on data-driven methods for tokamak edge plasma predictions: A. Kit, et al. Plasma Physics and Controlled Fusion **65** (2023) 045003; A. Kit, et al. Nuclear Materials and Energy **34** (2023) 101347; A. Kit, et al. Physics of Plasmas **31** (2024) 032504; A.E. Järvinen, et al. Physics of Plasmas **31** (2024) 032508.
- Code framework to generate databases for surrogate models: https://github.com/DIGIfusion/enchanted-surrogates
- Surrogate model for linear magnetohydrodynamic (MHD) stability analysis for tokamak edge plasmas. Publication is expected in 2025.

3.3 Main achievements in WP VTT-3

Within WP VTT-3, the main part of the performed activities was related to participation in experiments and analyses in international fusion devices as well as measurements and modelling carried out at the VTT facilities (Task VTT-3.2). The project team also contributed to the balance-of-plant simulations of future fusion reactors, and this goal was promoted by integrating several individual codes – Apros, Serpent2, and ASCOT – into a single modelling entity such that now it is possible to understand the entire plant operation: from energy production in the core up to the point where electricity is generated for the grid (Task VTT-3.1). All these goals were met. Apros received a prestigious position within the European fusion community, and the number of Apros activities allocated to VTT increased almost by a factor of two from 2021 to 2024 (section 3.3.1). Apros was applied to a variety of possible configurations for the conceptual design of the European DEMO reactor, utilizing here also the new ASCOT-Serpent2-Apros workflow (sections 3.3.1 and 3.3.2). The involvement of Platom in the co-innovation project will further increase the balance-of-plant modelling efforts in the future, both under EUROfusion and as separate commercial contracts. Thanks to ECO-Fusion, Finland is now prominently present in different European and international organizations relevant for fusion research and many of the Finnish focus points show up on their agendas, in particular remote maintenance and materials research. The Finnish community has carried out high-quality scientific research and reported the results in various conferences, other events, and as published journal articles. Results from the JET tritium campaign and general lifetime considerations of plasma-facing components have been the ultimate highlights of ECO-Fusion in these fields (sections 3.3.3 and 3.3.4). Diagnostics was also developed for varying purposes including laser-based techniques to analyse the accumulation of material and radioactive tritium on reactor walls (section 3.3.5) and measuring static magnetic fields in fusion reactors (section 0).

3.3.1 Balance-of-plant investigations for the DEMO reactor using Apros

Activity coordinator: M. Szogradi
Related task: VTT-3.1

As part of the Balance-of-Plant (BOP) efforts, transient analyses were performed using the integral thermal-hydraulic plant models of the Helium-Cooled Pebble Bed (HCPB) and Water-Cooled Lithium-Lead (WCLL) Breeding Blanket configurations implemented in the Apros code package. The 1D lumped-parameter models were based on high-fidelity 3D CAD data describing the Primary Heat Transfer Systems (PHTSs), the Intermediate Heat Transfer Systems (IHTSs) and the Power Conversion Systems (PCSs), see Figure 25. For single-phase coolant domains (helium, HITEC®, argon) the homogeneous flow model of Apros was used while the water-steam nodes relied on the heterogeneous 6-equation solution.

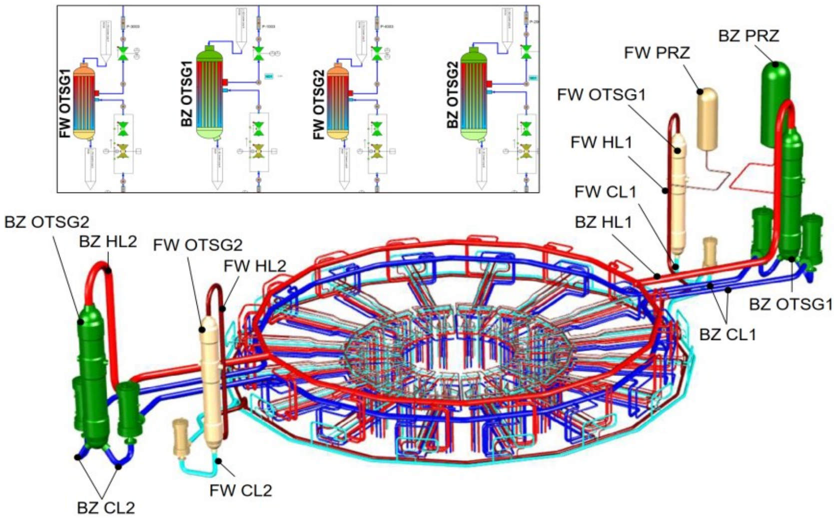

Figure 25. OTSG model in the WCLL primary circuit Apros vs. CAD drawings.

Besides normal operation, cycling between pulse and dwell, the models allowed us to develop various control schemes whilst assessing the direct impact of actuations and geometry on the behaviour of the system (revealing instabilities e.g. flashing in condensate lines due to large pressure losses). The effects of plasma power fluctuations, due to imperfect pellet injection, were assessed with respect to heat structures in both HCPB and WCLL blankets utilizing the necessary plasma physics reference data.

The HCPB IHTS evolution focused on the optimization of the layout for piping systems on both charge and discharge sides, concerning tank and SG bypasses, pressure control and Intermediate Heat Exchanger (IHX) design (see Figure 26). Earlier concepts relied on a pressurized molten salt system with tank pressures up to 8 bar, using an Ar-based control system. To alleviate the complexity of the IHTS, the pressure was reduced to 1.2 bar meaning that new control valves and orifices had to be implemented to prevent subatmospheric pressures at the highest sections of the system. In 2024 a new circular HCPB PHTS layout was adopted in the integral Apros model, where the 8 vertical

IHXs were replaced by 8 horizontal heat exchangers to improve the transient system behaviour. This work entailed the complete refurbishment of the IHTS and the PHTS piping, along with the conception of the new horizontal IHX Apros user component.

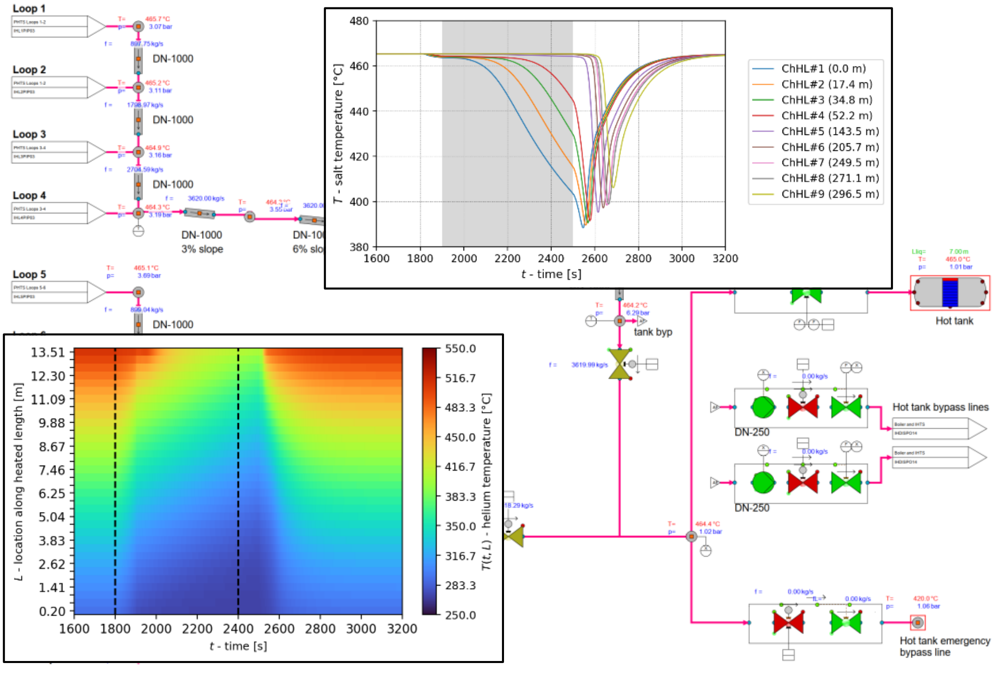

Figure 26. Apros IHTS charge loop model with IHX tube-side axial temperature profile (Bottom left) and thermocline propagation via the charge loop hot leg (Top).

Benchmarking activities, led by Ansaldo Energia, were performed to investigate system code capabilities in relation to various steam generator concepts. For the WCLL plant, various water-water Once-Through Steam Generator (OTSG) models were compared in low-load (dwell) and full-power working points. Each of these conceptual OTSG designs required a corresponding user component which was later compared to its RELAP5 counterpart (results provided by the University of Rome). The studies focused on the secondary (shell) side of the heat exchangers with emphasis on mesh sensitivity in the lower port regions, pressure and temperature profiles and recirculation rates between the riser and downcomer compartments. For the helium-HITEC® vertical IHXs another set of benchmark calculations were performed using a scaled-down version of the IHTS.

To bring different disciplines of fusion engineering closer to each other, the ASCOT-Serpent2-Apros calculation chain development was initiated, based on the WCLL small IHTS case. ASCOT was used to generate a baseline D-T fusion product distribution in a toroidally symmetric 2D Cartesian space. This source term was utilized by Serpent2 to perform particle transport calculations relying on the 3D heterogeneous CAD model for the equatorial cells in the outboard segment of the WCLL BB. Equipping the breeding unit domain with the appropriate detectors, relevant parameters could be recorded, e.g., nuclear heating profiles and neutron spectra. The volumetric and radiative heat deposition schemes can be translated into power distribution profiles using the internal heating attribute of the solid-state heat structures of the Apros bleeding blanket models (see Figure 27).

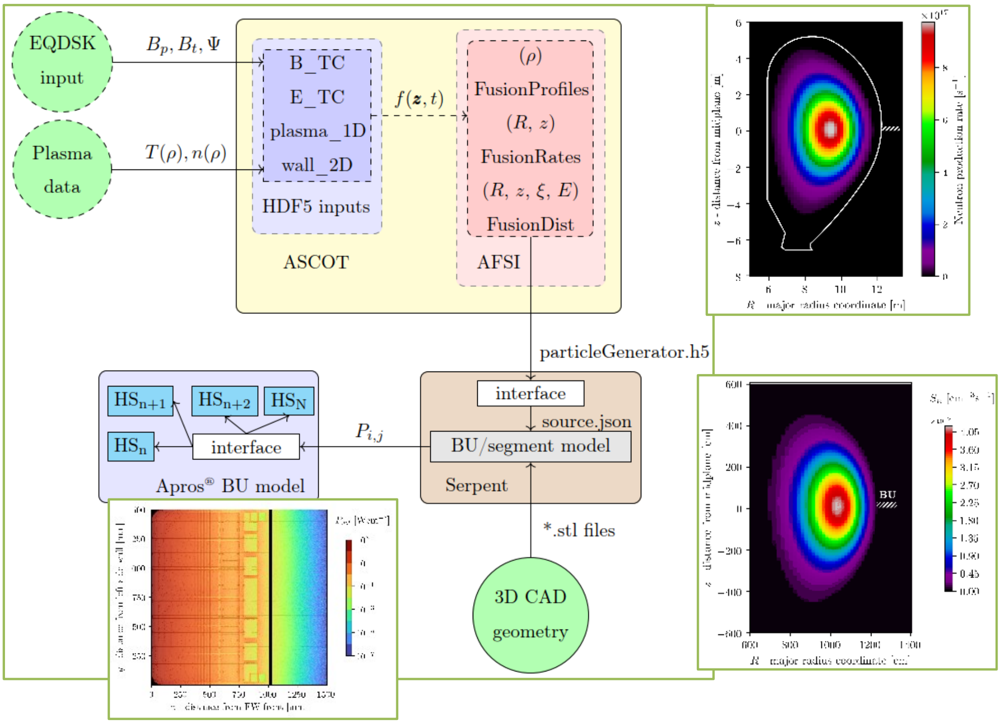

Figure 27. The multiphydics calculation chain featuring ASCOT/AFSI, Serpent and Apros.

Looking back at the original task goals and deliverables, all of them have been met as described above. These efforts to elevate the usage of Apros within the fusion community has opened discussions of using the code in even wider context, including design of privately funded fusion machines. While there has not been a commercial project to carry out such work, the work carried out within the ECO-fusion project has made this extremely likely soon.

3.3.2 Development of ASCOT-Serpent2 toolchain

Activity coordinator: A. Snicker
Related task: VTT-3.1, VTT-3.2

The ASCOT code has been developed at Aalto University for >30 years while during ECO-Fusion the code package including its development activities were transferred to VTT. The code is widely used for fast-ions studies within public and private fusion research, including predictive studies for existing machines to assist in their experimental planning, interpretative studies for existing machines to understand the underlying physics, design studies for future machines, and for integrated modelling studies as a part of numerical tools to simulate the full tokamak system.

The strategy implemented in the ASCOT research group of VTT is the constant development to keep up with the pace of research but also software and hardware development of high-performance computing. To this end, the latest revision of the code tool package, the ASCOT5 code has been developed further to meet the needs of user community. The main achievements during ECO-Fusion include publishing an open-source (LGPL 3.0) version of the code under GitHub (https://github.com/ascot4fusion/ascot5). This modification allowed all users to freely use the code for their studies and increased the user community dramatically. Furthermore, the code base has undergone six minor releases, all containing important physics or hardware developments including but not limited to: enable usage within the Conda coding environment, compatibility with the IMAS family of software, and very recently also GPU implementation with partial physics (full physics to be added in the future). Especially the latter has been worked with the help of HPC specialists including NVIDIA GPU experts. The code is one of the first implementations of single-source software that can employ with a single binary both CPUs and GPUs.

The highlights of the usage of the ASCOT code within ECO-Fusion include the design of the FILD (Fast Ion Loss Detector) diagnostics for ITER, as illustrated in Figure 28, design studies of the volumetric neutron source (VNS), and supporting the tomographic reconstructions that use ASCOT-calculated distribution functions as a key prior information for the tomographic inversion. Besides these jointly funded projects, ASCOT work has initiated multiple commercial projects with international customers. As it stands, ASCOT is the golden standard code in the field of fast-ion orbit-following studies and the future development of code is aimed to keep this frontrunner position in the future.

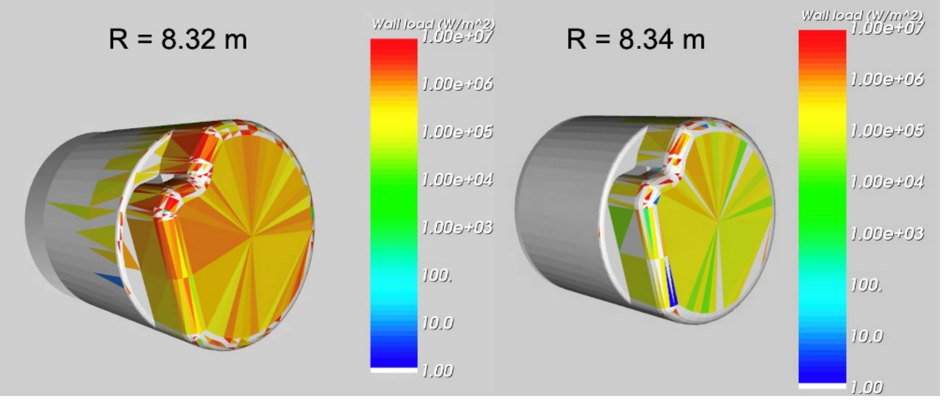

Figure 28. Alpha particle heat flux on the ITER FILD probe head calculated by ASCOT for two different insertions of the head.

Serpent2 code has been applied for fusion studies in the last decade. However, a dedicated program to elevate the usage of the code within the community has not been launched until the last two years. During ECO-Fusion, the emphasis on the usage of Serpent2 code has been for the stellarator geometries under related EUROfusion tasks. This allows to fully utilize the CAD-based transport routine of Serpent2, which has allowed for the first time to estimate the neutron flux in the full non-planar coil system of the HELIAS stellarator plant design as shown in Figure 29. Moreover, Serpent2 has been used to estimate the tritium breeding ratios over a wide range of parameter space, including different thicknesses of the breeding blankets, breeding blanket material options, and different shielding material layer thicknesses. The simulations have been extended to include possible openings in the breeding blankets due to, e.g., heating and current drive ports and divertor structures. The reduction of tritium breeding ratio has been for the very first time estimated extensively using Serpent2. While currently there is no commercial project with the Serpent2 code, several discussions in this direction have been undergone and extremely likely the first commercial project using Serpent2 for fusion design will be opened within a year. The plan is the use the developed competencies, similarly, as has been done with the ASCOT work, soon to integrate fully into the private fusion sector also with the Serpent2 code. As was mentioned in section 3.3.1, integration of ASCOT and Serpent2 to Apros is ongoing, potentially providing a comprehensive modelling package for private fusion companies.

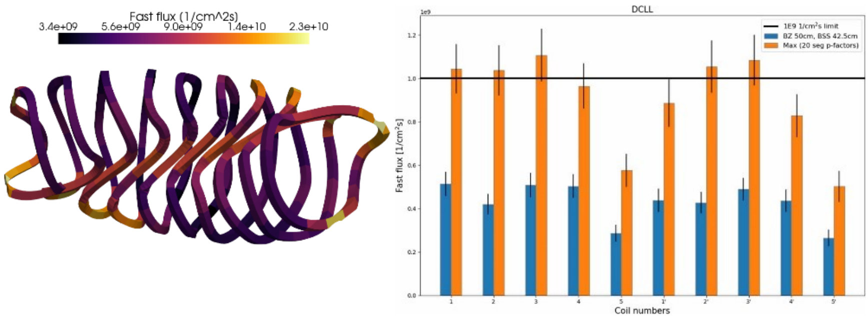

Figure 29. Left: Fast flux heatmap of the coil winding pack calculated in 20 poloidal cells per coil using a uniform thickness dual-coolant lithium lead (DCLL) blanket. Average fast flux in the coils (blue) using a high blanket thickness configuration together with the peak flux (orange) estimated using the peaking factors from the heatmap. The threshold flux is shown in black.

3.3.3 Transport studies during tritium operations at JET

Activity coordinator: T. Tala
Related task: VTT-3.2

The dimensionless isotope mass scaling experiment between pure deuterium and pure tritium plasmas with several plasma parameters matched, including ρ_*, ν_*, β_n, q and T_e/T_i has been achieved in L-mode discharges at JET with dominant electron heating (NBI+ohmic) conditions. Some 28% higher scaled energy confinement time $\tau_{e,th}\times B_t/A$ (where B_t is the toroidal magnetic field and A is the isotopic mass number) is found in favour of the tritium plasmas. This can be cast in the form of the dimensionless energy confinement scaling law as $\Omega_i\,\tau_{e,th} \sim A^{0.48\pm0.16}$. This significant isotope mass scaling is consequently seen in the scaled one-fluid heat diffusion coefficient $A\chi_{eff}/B_t$ which is around 50% lower in the tritium plasma throughout the entire plasma radius, see Figure 30. The isotope mass dependence in the particle transport channel is negligible, supported also by the perturbative particle transport analysis with gas puff modulation. The comparison of the edge particle fuelling or ionisation profiles from the EDGE2D-EIRENE simulations show that the absolute density differences that are necessary for the dimensionless match in the confined plasma dominate over any isotope mass dependencies of particle fuelling and ionization profiles t the plasma edge. Local GENE simulation results indicate a mild anti-gyroBohm effect at ρ_{tor} = 0.6 and thereby a small isotope mass dependence in favour of tritium on heat transport and a negligible effect on particle transport. These results were summarized and reported in the IAEA Fusion Energy Conference in London in October 2023 and in the Nuclear Fusion Special Issue on the JET DT campaigns.

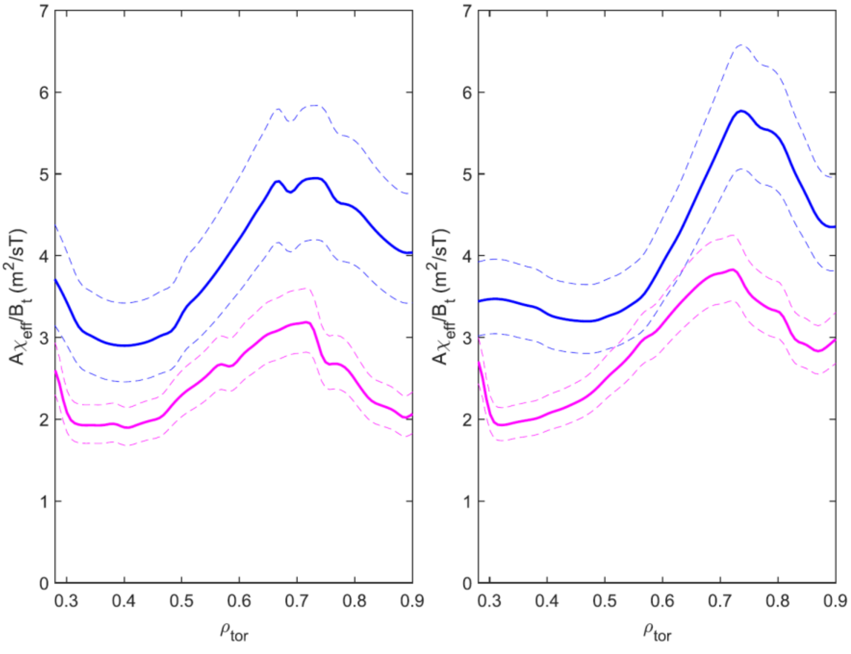

Figure 30. Scaled one-fluid effective diffusion coefficients for the Deuterium ischarge (blue) and the Tritium discharge (magenta) at two different NBI power levels, P_{NBI}=0.8/1.4 MW (Left) and P_{NBI}=1.8/3.4 MW (Right), with the larger NBI power level referring to the tritium pulse and the smaller one to the deuterium pulse. The dashed lines indicate the error bars.

3.3.4 Surface analyses of JET wall components

Activity coordinator: J. Likonen
Related task: VTT-3.2

The divertor is a region at the bottom of a tokamak-type fusion reactor to receive and mitigate the highest heat and particle loads during plasma operations. The plasma-facing components at the JET divertor are made of tungsten-coated carbon fiber composites (CFC), except for the PFCs receiving the highest head loads, being produced of solid tungsten (W). For the most recent JET campaigns, a few special marker tiles with a sandwich-like configuration of successive W and Mo layers on top of the CFC substrate were produced. JET has also beryllium (Be) PFCs elsewhere in the machine, and their erosion can lead to the formation of beryllium-based deposits also on the marker tiles. JET has now completed three operating periods, called ILW-1 (2011-2012), ILW-2 (2013-2014) and ILW-3 (2015-2016), giving an opportunity to make comparisons between tiles exposed for different operating periods.

Figure 31 shows Secondary Ion Mass Spectrometry (SIMS) depth profiles measured from a sample cut from the apron of an inner divertor tile 14IWG1A exposed in 2011-2016. Tile 14IWG1A was coated with ~4 μm of W and ~3 μm of Mo on top of ~12 μm of W (and a thin Mo interlayer) to act as the markers to measure the erosion/deposition during ILW campaigns. Depth profiling was stopped at the interface between the Mo and W layers. It can be observed that the co-deposited layer (thickness ~30 μm) contains mainly beryllium in addition to hydrogen isotopes and carbon with considerable deuterium inventories.

The main result obtained with SIMS is that deposition on the divertor tiles is not necessarily linear, i.e., the thickness of the co-deposited layer and deuterium amount do not increase as a function of the exposure time, but the dependence is much more complex. This shows the urgency in also determining the amount of radioactive tritium on the wall components after the most recent deuterium-tritium campaigns on JET to provide data for assessing the operational safety of future fusion reactors.

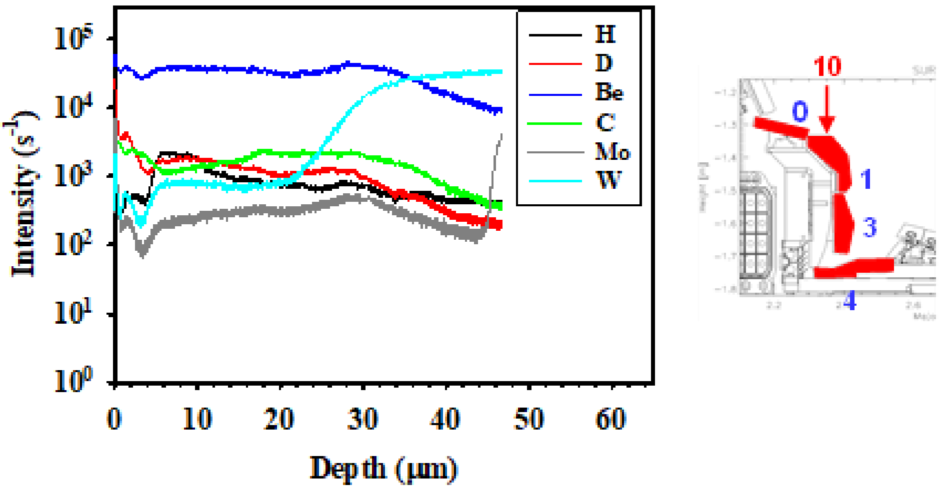

Figure 31. (Left) SIMS depth profiles for sample 14IWG1A/10 cut from the apron of inner divertor tile 14IWG1A and (Right) JET inner divertor.

3.3.5 Development of LIBS as a tritium monitoring tool at JET

Activity coordinator: J. Likonen
Related task: VTT-3.2

Laser-Induced Breakdown Spectroscopy (LIBS) is one of the few techniques available for monitoring the tritium content of co-deposited layers during the maintenance breaks of fusion reactors. At VTT, together with EUROfusion collaborators, we have developed LIBS to accurately assess the amount of deuterium and tritium on PFCs removed from JET. Based on this experience, we have designed a compact LIBS system for surveying the inner wall structures of JET, see Figure 32. The system will be mounted on the MASCOT remote-handling arm of JET (see Figure 33) and operated for a limited period in 2024 to obtain information on tritium retention in various parts of the vessel. In 2024, the design was completed and test measurements using actual JET samples were completed successfully at VTT. Additional test measurements were performed at UKAEA before mounting the LIBS enclosure on the remote-handling arm. The LIBS experiment at JET will be executed in September-October 2024.

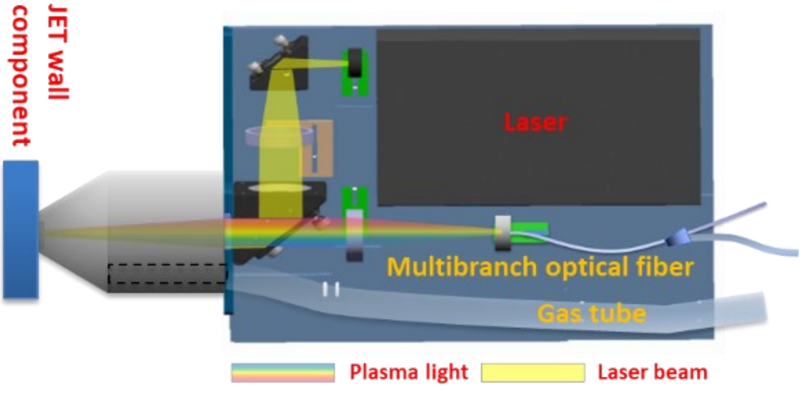

Figure 32. Schematic illustration of the LIBS system designed for JET. The system will be mounted on MASCOT to access different regions of the vessel.

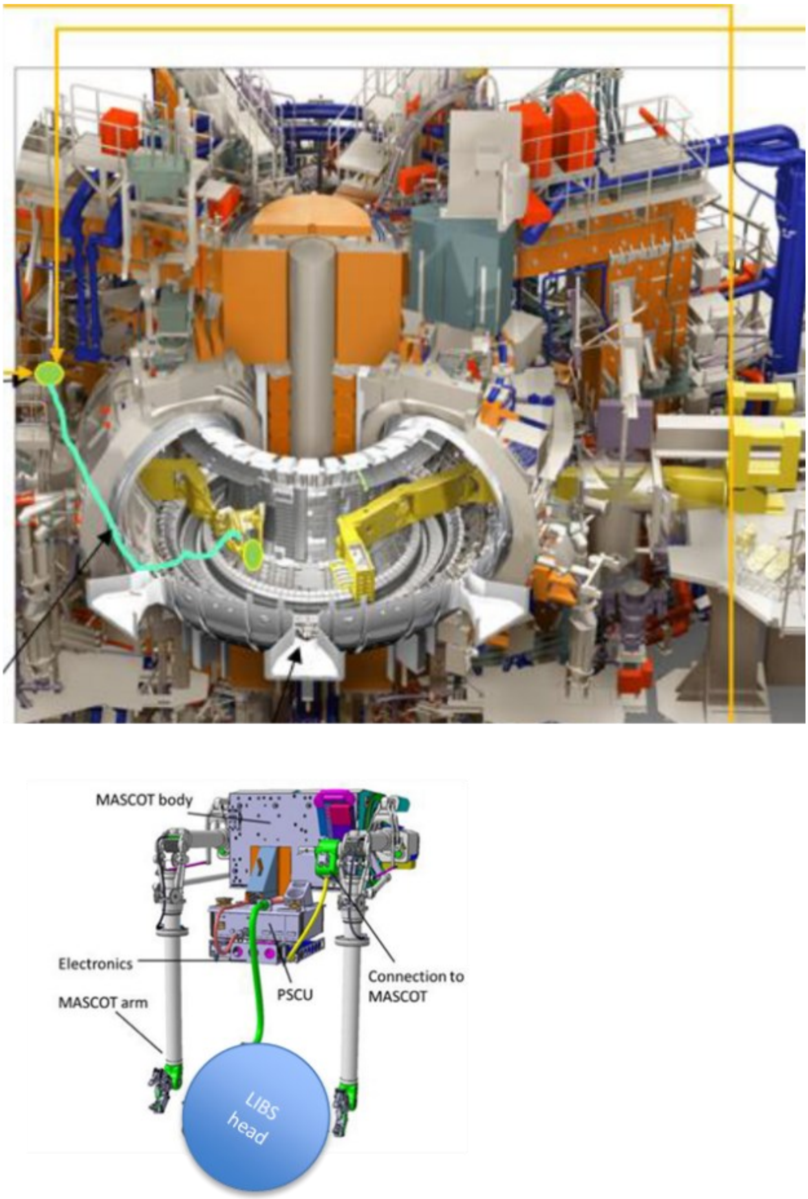

Figure 33. Operating a LIBS system using the remote-handling arm at JET.

3.3.6 Silicon-on-Insulator based magnetic field sensor development

Activity coordinator: A. Salmi
Related task: VTT-3.2

The ability to accurately measure magnetic field strength over extended periods in a harsh neutron environment is essential for fusion power plants. Flux-based techniques are prone to noise-induced integration drifts, which can accumulate over time and lead to significant errors. This degrades the reliability of magnetic field reconstructions, potentially resulting in suboptimal control or unscheduled discharge restarts. This activity explored a novel concept based on silicon photonics and using coiled 3-µm strip waveguides to detect the strengths of steady-state magnetic fields through field-induced Faraday rotation of the ~1.5-µm light. Bulk silicon, with a high melting point (>1000°C) and excellent radiation tolerance, could be an ideal material for such challenging environments. Additionally, integrated circuits can fit on a 2 cm x 2 cm chip, enabling localized measurements. Light can be transmitted to the sensor via radiation-hardened optical cables, making the sensor and its vicinity entirely free of electronic components while sensitive polarization measuring equipment can be placed far away in shielded laboratories.

Given the novelty of the concept, we needed to design and manufacture several key components and integrate them seamlessly for a working sensor. All this was done in-house at the VTT co-hosted Micronova facility in Espoo where the multitude of lithography steps, chip cutting, and interface polishing were meticulously performed and verified at each step down to a 10-nm accuracy. The final characterization was conducted using advanced measurement techniques after submicron-precision alignment of fiber and lens-focused light coupling. In parallel, we advanced the three major components required to realize the sensor at the ambitions ITER specifications

i. Near zero birefringence ($\Delta n_{\mathrm{eff}} < 10^{-6}$) straight strip waveguides
ii. Phase flipping U-turns
iii. Polarisation splitters

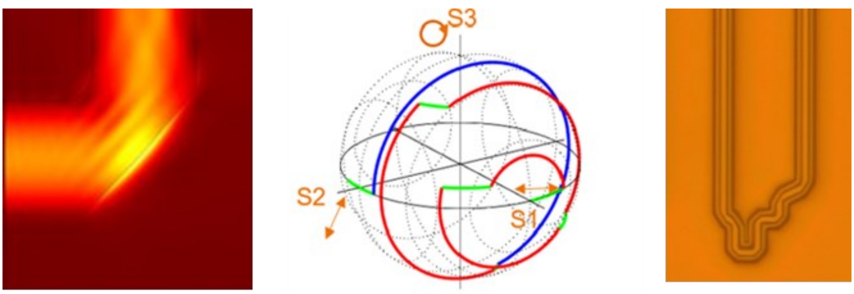

Figure 34. (Left) 45-degree TIR turn with wavefield intensity pattern overlaid; (Middle) Poincare sphere illustration of polarization non-idealities at the simple bend (see green displacements) and (Right) optical image of the exact 3π 8 TIR mirror design.

We designed and manufactured two variations of the phase-flipping U-turns, which, on a small turning radius, rotate the relative TE/TM polarization angle by an odd-π amount, thereby enabling polarization rotation accumulation as light travels both with and against the magnetic field. The simpler, less lossy solution uses only two 45-degree total internal reflection (TIR) mirrors to reverse the light path. However, this design does not perfectly induce an odd-π polarization turn, requiring more advanced modeling to compensate for this (see Figure 34). The second variation is more complex to design and manufacture, involving more reflections (eight per U-turn), resulting in higher losses. Consequently, this version allows fewer total U-turns before the signal level becomes too low but achieves exactly the 3π phase flip and thus is simpler to calibrate (see Figure 34). The optical properties of the components were measured and, while they did not fully meet the required levels for signal purity and sensitivity, the results were promising. Losses as low as 0.26 dB per mirror were achieved, placing them among the best reported for TIR mirrors. Further modeling will help pinpoint the areas for improvement, with initial indications suggesting that even small 3D imperfections may lead to mode coupling and increased scattering losses.

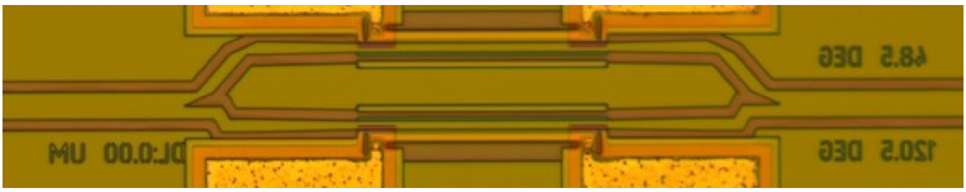

Figure 35. Optical microscope image of the MZI type polarization splitter. Light is split in two brances and combined to yield a single polarization state.

To ensure a known polarization state at the input of the sensing waveguides, we designed and successfully manufactured multiple MZI-based polarization splitters at the VTT Micronova facility (see Figure 35). Given the optical fibers are exposed to strong magnetic fields and, consequently, uncontrolled Faraday rotation, the splitters are crucial in converting random polarization into a desired, highly pure polarization state (~99%), well within the sensor specifications.

The development of the fundamental building block, a straight waveguide with minimal birefringence, proved more challenging than anticipated. As part of the characterization process, we enhanced our measurement setups, including upgrades to our neodymium magnets and holders, to maximize measurement sensitivity and Faraday rotation magnitude. Dedicated structures such as arrayed waveguide gratings (AWGs) were designed to measure both group index and effective index birefringence. Extensive COMSOL modeling provided a deeper understanding of the relationship between geometry, 2D imperfections, and material stresses in the waveguide, the cladding and the substrate. We succeeded in aligning these findings with our experimental results, allowing us to closely pinpoint how to achieve zero birefringence. This work was published in the Journal of Lightwave Technology, with highlights shown in Figure 36.

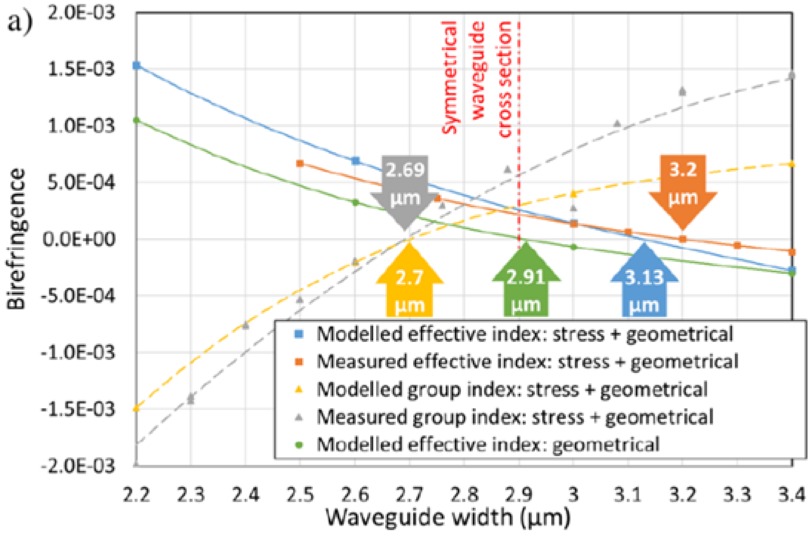

Figure 36. Comparison between the measured and the simulated birefringence as a function of the waveguide width. Waveguide depth is kept constant at 2.9 µm. The asymmetric material stresses shift the zero-crossing away from the perfect square shape.

However, we also found that birefringence dispersion is not negligible and plays a significant role, complicating the interpretation of the Faraday rotation effect. It likely dampens the polarization rotation as well. Further work is needed to refine our models and fully account for this, enabling a more accurate evaluation of the magnetic field. As a result, the targeted integration of components to realize the sensor has been postponed until these issues are resolved, ensuring that the final implementation meets the necessary performance specifications.

3.4 Main achievements in WP VTT-4

The emphasis of WP VTT-4 was put on various safety analyses of fusion reactors. The work performed included determining safety against fires and assessing the probabilities of various incidents and the functionality of different monitoring equipment in fusion devices (Task VTT-4.1) as well as laying the foundations for the decommissioning of fusion power plants at the end of their lifetime and handling radioactive waste formed (Task VTT-4.2). On the safety side, the DEMO-relevant work was carried out for the fire analyses (section 3.4.1) while probabilistic assessments and development of camera solutions were performed for IFMIF-DONES (sections 3.4.2 and 3.4.3). In both cases, several recommendations were put forward and various risks and design issues were identified. Licensing of fusion power plants was promoted by discussions with Finnish authorities and decision-makers, also in connection with the ongoing process of renewing the Finnish legislation connected to nuclear facilities. Platom was included in the process, to also support their own company project under the co-innovation framework. First steps in drafting decommissioning and waste-management plans for DEMO were taken during ECO-Fusion (section 3.4.4) which would put Finland in a good position for making similar plans to other future fusion reactors. Also, here Platom was strongly involved via subcontcracting projects under EUROfusion. Finally, first attempts were made to determine tritium retention on fusion relevant materials but progressing the task further requires analysis of wall components from the JET tokamak after its experimental campaign in deuterium-tritium plasmas. This is foreseen to take place from 2025 onwards. Only then, also the proposed detriation approaches can be further pursued. Concerning the ITER opportunities, no new satefy-related tenders were launched but more opportunities are to emerge now that a new ITER baseline has been officially released.

3.4.1 Fire accident analyses for the DEMO reactor

Activity coordinator: T. Hakkarainen
Related task: VTT-4.1

Fire accident analyses ensure the fire safety of fusion power plants. The research work included the identification of fire hazards, the assessment of fire consequences, and the evaluation of the needs to protect personnel and property. Areas of primary interest are high-risk areas, such as those including critical equipment, radioactive material inventories or large fire loads. As an outcome, it is demonstrated that acceptable fire safety levels can be obtained with the designed fire protection systems.

This task concentrated on the fire safety of the DEMO reactor. During 2021–2024, the reactor building was the focus of the work. The rooms and spaces studied included lithium lead (LiPb) component rooms, vacuum pumping rooms, vertical cable shafts, galleries, and the cryostat. The work mostly mapped failure risks of fire sector partitions depending on space dimensions and fire load densities. Parametric studies were performed to produce quick-to-use tables and graphs for fire hazard assessment and design of fire sector partitions. Also, the thermal penetration time using randomized concrete properties was calculated, and the probability that it is greater than a given time was estimated, resulting in a quick-reference table for various concrete thicknesses.

The work done gives insight into the applicability of different tools with varying levels of complexity for different use cases. Simple analytical models can be used for parametric studies with low input data. When overconservative assumptions are used in these models, the lack of detailed DEMO design does not affect significantly. In the future, the overconservatism of the design can be reduced to cut costs. Zone fire models are well suitable for fast screening since they are less time-consuming and computationally less costly than computational fluid dynamics (CFD) simulations. CFD simulations (using e.g. Fire Dynamics Simulator (FDS) software) are needed for detailed analyses of complex fire scenarios and geometries, as well as for validation of results of analytical methods and zone fire models to check if these simple methods are applicable and sufficiently reliable.

The work done will support fire safety analyses of DEMO when its design becomes more mature. Though several calculations and simulations need to be re-run with updated input parameters, the same principles, tools, and procedures can be utilized. In the short run, fire safety analyses help to check that there are no showstoppers due to fire safety issues. In the long run, they will ensure the safety of people and the environment, as well as the property protection and operation continuity of the plant.

An example of the progressive design for the DEMO reactor is introduced in Figure 37. In 2021, fire risk analysis of LiPb component rooms was performed. At that time, there were two separate rooms. In 2023, the design had considerably changed. Now the equipment was placed to one larger room. Therefore, the fire risk analysis was repeated to check whether the conclusions made are still valid for the new geometry.

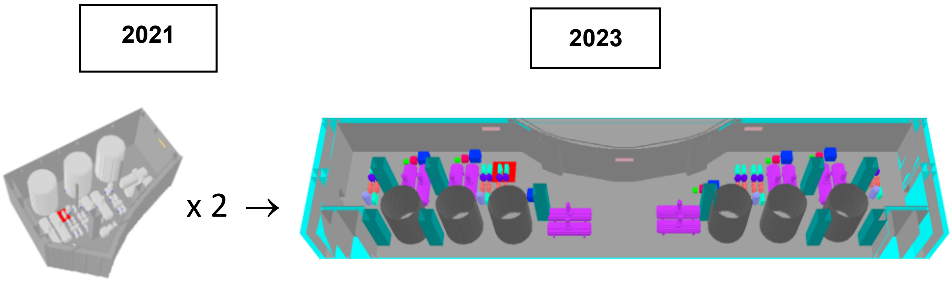

Figure 37. Development of LiPb component room geometry. 2021: two smaller rooms; 2023: one larger room.

3.4.2 Probabilistic risk assessment for IFMIF-DONES operations

Activity coordinator: A. Helminen
Related task: VTT-4.1

During ECO-Fusion, probabilistic risk assessment (PRA) was developed for the International Fusion Material Irradiation Facility - DEMO Oriented Neutron Energy Source (IFMIF-DONES). The PRA approach can be used to provide insights on the strengths and weaknesses of the design and operation of IFMIF-DONES but also those of a fusion reactor. The PRA model of internal events covers 11 event trees reflecting the different responses of the facility to accident scenarios initiated by internal events. The following accident scenarios are included in the current model:

- Large lithium leak to the lithium loop cell
- Small lithium leak to the lithium loop cell, hot trap cell or cold trap cell
- Lithium leak to the test cell
- Loss of lithium flow at target
- Loss of cooling of lithium
- Loss of high flux test module cooling
- Air ingress in beam duct
- Water ingress in beam duct
- Fire inside vent gas detritiation subsystem (VDS) glove box
- VDS leaks to the glove box
- Small radioactive gas or water leak to an air-filled room.

The model can be further developed as the design of IFMIF-DONES proceeds and updated as new data becomes available. PRA results can be compared to national and international risk goals and licensing objectives. Based on the results from the current PRA model, the estimated frequencies of some consequences are above the desired risk goals. The high-risk estimates are mostly related to scenarios with a failed shutdown of the irradiation beam. The results should be considered only as preliminary, calculated with strong assumptions based on incomplete information about the design and accident phenomena, and using expert judgements in many situations. A large number of modelling uncertainties have been identified and the model should be developed further to decrease these uncertainties.

In addition to the PRA, a literature review on the integration of PRA with organizational factors/ safety culture assessment was conducted. The integration may open a novel way of applying PRA and the probabilistic model to improve the organizational factors/ safety culture of IFMIF-DONES. The mapping of PRA elements on the iceberg model of safety culture is shown in Figure 38.

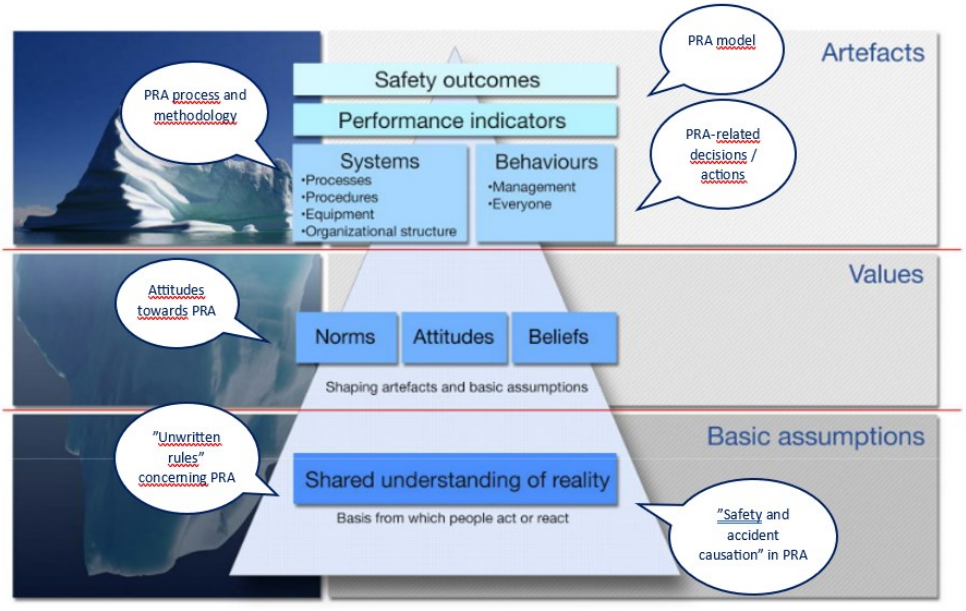

Figure 38. Mapping of PRA elements on the iceberg model of safety culture.

3.4.3 Design of a radiation-resistant monitoring camera system for IFMIF-DONES remote operations

Activity coordinator: K. Rainio
Related task: VTT-4.1

Some parts of the IFMIF-DONES facility are under such strong radiation that maintenance procedures must be carried out by robots. The operations must be monitored remotely using radiation-resistant cameras. A few dozen cameras are needed to comprehensively monitor these maintenance procedures. Most of the cameras are overview cameras, which must have Pan-Tilt-Zoom capabilities, whereas some cameras will be attached to moving parts, and the light weight of these cameras is essential.

Color cameras based on semiconductor technology are available in the market, which can withstand high radiation, some models up to 1 MGy. The price of the cameras is a few tens of thousands of euros, and most camera models have Zoom-Pan-Tilt capabilities, and often lighting. The cameras require supporting parts, including fixed cables (up to 100 m) and camera controllers, which must be placed in radiation-protected spaces.

The camera model(s) to be used are being selected, and the locations and wiring of the cameras are being planned. The work uses Virtual Reality (VR) animations, which show maintenance procedures in facilities under radiation. The characteristics of the cameras of the virtual models (e.g., Field of View) were set to be as similar as possible to the characteristics of the prime candidate camera model, and the size (width x height) of the visualization windows was set to be the same as the output images of the prime candidate camera model. Thus, the VR animations show as realistically as possible what the IFMIF-DONES facility maintenance operators will see in the future when the facility is in operation. An example of the VR model screenshots can be seen in Figure 39.

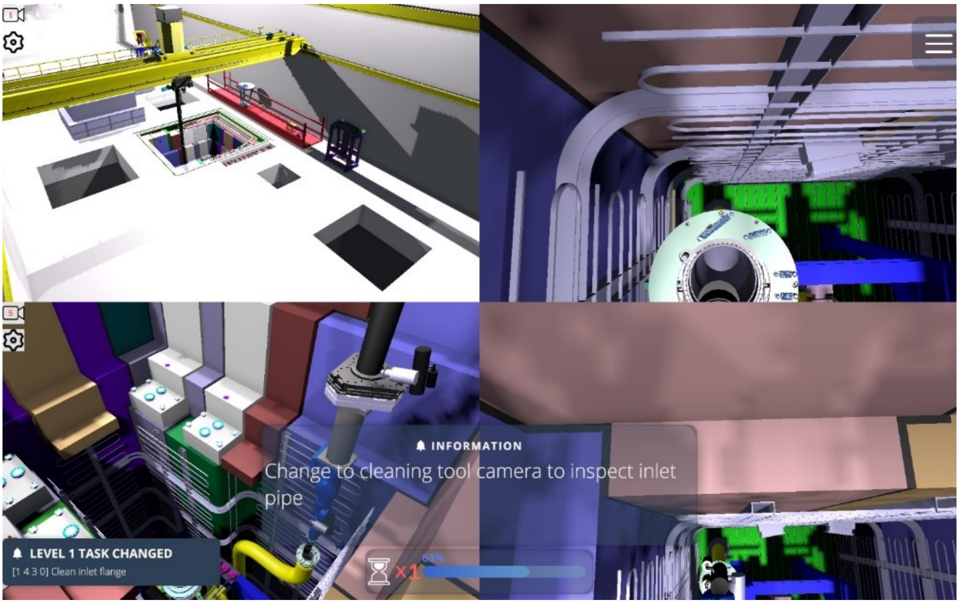

Figure 39. Screenshot of VR model with 4 partial images showing views from different cameras.

3.4.4 Decommissioning and nuclear waste management

Activity coordinator: M. Airila
Related task: VTT-4.2

Today's licensing requirements for a new nuclear facility include early preparation for decommissioning after the service life of the facility. Figure 40. General phases for a nuclear facility taking place after the operational phase. illustrates that decommissioning is a multi-phase activity, taking several years, sometimes decades, which means huge opportunities for optimization and cost saving, if all necessary reservations critical for smooth decommissioning are implemented in advance. This is also accounted for in DEMO, for which Platom developed the first draft of a decommissioning plan in 2024 as part of VTT's scope in the EUROfusion programme and with an integrated link to the ECO-Fusion project. The plan outlines Finland's extensive experience in nuclear energy, nuclear waste management, and decommissioning. Finland's regulatory framework, led by the Radiation and Nuclear Safety Authority (STUK), is highly regarded and considered demanding.

The document emphasizes the importance of incorporating decommissioning considerations from the design phase to avoid complications and increased costs. Also, several practical means to enforce the decommissioning expertise and its inclusion in the planning processes are presented.

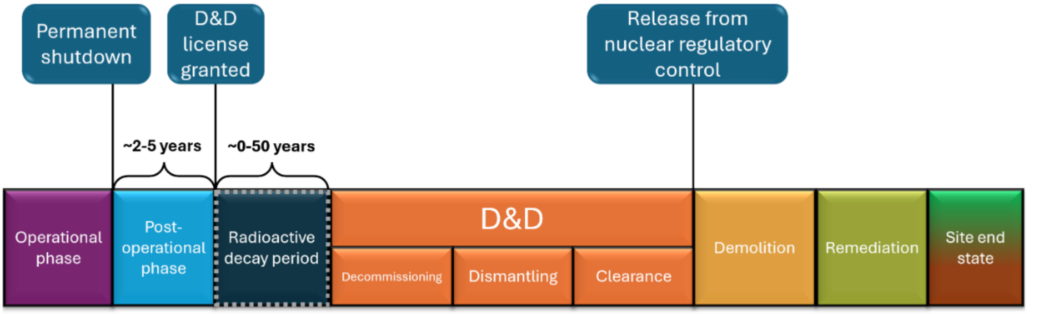

Figure 40. General phases for a nuclear facility taking place after the operational phase.

The generation of radioactive waste, in terms of volume, radioactivity content, and frequency of batches generated, must be considered before the construction of a facility. In the project, VTT investigated liquid radioactive waste streams from the DEMO design so that the Generic Site Safety Report (GSSR) can be developed further. We identified and classified the most important waste streams and listed process options identified so far, including a processing technology readiness estimate. Examples of liquid waste streams include waste water from the process systems and ion-exchange resins, lithium-lead related waste, contaminated lubricants, laboratory waste, as well as several types of secondary waste. Most liquid wastes produced are similar to those in fission power plants, which have plenty of industry experience in handling radioactive wastes. In the DEMO design, the same waste management procedures should be primarily considered.

3.5 Main achievements in WP VTT-5

One of the primary focal points of the project revolves around fusion ecosystems and business models. Throughout ECO-Fusion, efforts persisted in delving deeper into this realm, with the objective of comprehending the interconnection and potential synergy between international fusion projects and their implications for Finnish companies. Various research methodologies were employed not only to amass pertinent information but also to facilitate knowledge dissemination among companies, thereby enriching their understanding of the fusion industry.

In 2023, a Delphi research method was used to gather experts' views on the future of fusion technology up to the year 2080. The goal was to engage experts in active discussions and thereby initiate new understandings and viewpoints for everyone. The Delphi study involved two rounds of inquiries and pre-understanding workshops, with the second one building upon the answers from the first round. Several organizations participated in the research, including research institutions, companies, and government organizations. These organizations represented multiple countries, such as Finland, Italy, Germany, the United States, Hungary, France, the Netherlands, and Estonia.

These interviews were conducted to better understand the needs and challenges of Finnish companies in participating in commercial fusion-related projects. Companies seem to prefer commercially viable projects that match their core business over lengthy uncertain research projects.

They are not that ready to develop new technologies or services but to provide those already existing and applicable across industries. Also, small companies expect information to come to them, e.g., from VTT, but larger companies make their own market intelligence and scouting. This can be interpreted as need for activities and actors like ILO and FinnFusion/ECO-Fusion to activate SMEs to expand their search for business opportunities into Big Science realm.

Also, interviews in Finland and abroad were conducted with a focus on business potential through an ambidexterity perspective. Based on this an academic article was published: "Insights into the buyer-supplier cooperative relations in big science", CInet, 2023.

Companies had no readiness to open or co-develop their business models, thus making it not possible to formulate the case-based business models as originally planned in the project plan. This discussion remained on the level of implementing generic business models of companies instead of creating any new ones for fusion.

In the area of modelling, work focused on understanding and identifying leverage points to increase the participation of Finnish companies in fusion-related commercial projects. This was done by building systems-based views on fusion tenders. Three different approaches were used: systems thinking, modelling and agent-based modelling. Work was divided into three phases:

- Phase 1: Systems mapping (qualitative modelling) – goal to provide common understanding.
- Phase 2: System dynamic modelling – goal to understand system's behaviour on a high level.
- Phase 3: Simulation with agent-based model – goal to model the behavior of individual agents (companies) who are faced with decisions to participate in fusion ecosystem, fusion tenders and projects.

Due to the restrictions in the data collected, the models were built more on the learning about needs and requirements level than on the ecosystem level. However, the results are the first step in the process that will continue in future projects.

The results were disseminated and discussed e.g. in FinnFusion meetings and joint Big Science seminars, bringing together and networking people and companies interested across opportunities in SMRs, fusion and decommissioning.

This work, with a focus on fusion foresight and cross-industry ecosystem building, will continue in the next project; the project proposal has been submitted to Business Finland.

3.6 Main achievements in WP VTT-6

The activities within WP VTT-6 concentrated on managing the VTT research project, promoting collaboration with the co-innovation partners and other Finnish companies, and disseminating the project outcomes to the Finnish fusion ecosystem, the FinnFusion Consortium, and the general public. On the project management side (Task VTT-6.1), the main achievements were:

- The project was completed on time and within the allocated budget; a minor deviation of <0.5% was reported. All the main deliverables were achieved as reported in sections 1.4 and 3.1. The human resources consumed for the project were in line with the initial estimates within 10%.
- Steeering Group meetings were held after every tertile during the period from August 2021 until the end of 2024. These were accompanied by regular intermediate reports towards Business Finland. In addition, internal team meetings were held on an annual basis. All the material of the meetings has been stored on relevant Teams pages.

Considering facilitating collaboration (Task VTT-6.2), the project has resulted in the following highlights:

- Interaction with FinNuclear ILO has taken place on a regular basis and selected project members have attended various Business Fora (Big Science Business Forum, ITER Business Forum, and Nordic ITER Business Focum) during 2022-2024. This has expanded existing networks and provided new opportunities for Finnish companies to become involved in large fusion projects.
- VTT has facilitated discussions and separate project initiatives with private fusion companies and international research institutes, including the US, UK, and Korea. The partners have been particularly interested in Finnish expertise in the fields of fusion physics, remote maintenance, and materials modelling. Recently the VTT ProperTune® group has received DOE/Arpa-E funding from the US for 3 years, starting in 2025, to progress the materials modelling tools, largely as a result of the efforts initiated and promoted under ECO-Fusion.
- Several meetings have been arranged between VTT and Finnish companies to extend the existing fusion ecosystem. Around 50 companies have been contacted, either during round-table discussions or private discussions and more than 5 of them have joined the FinnFusion Consortium and/or become part of the new co-innovation project proposal submitted to Business Finland in May 2024.
- Finnish companies have been involved in large separate project initiatives due to their involvement in ECO-Fusion. Several subcontracting opportunities have been provided by the EUROfusion Consortium to the co-innovation partners, including Comatec and Platom, and other Finnish companies, like Coresbond, Fulvisol, and Qualifin. In addition, work done within WP VTT-2 has helped Luvata in increasing export deals on Cu alloys.

The dissemination and communication activities (Task VTT-6.3) are summarized in section 6, where the key conclusions are:

- The project website has been established at https://finnfusion.fi/ to inform the stakeholders about the project and its achievements. Also, messages communicated via the communications channels of the EUROfusion Consortium have been linked on the web and shared via social media channels.
- Project has been visible in several national and international conferences and events and synergies between various nuclear ecosystems of VTT have been strengthened via Open Business Days in 2022.
- Several journal articles and conference contributions (>150) have been produced during the project lifetime 2021-2024 and more are expected to appear in the next couple of years. Several PhD or MSc. Theses have emerged with more in the pipeline for 2025.

4. Status of fusion ecosystem and business model development

The ECO-Fusion project has been a step forward in activating Finnish companies into fusion and in general the Big Science realm. New companies were brought into the FinnFusion family and many more became aware of fusion activities in Finland. Joint seminars with decommissioning and SMR projects made also people outside fusion but in the nuclear industry aware of the opportunities in fusion.

Big Science, both research and commercial projects, is a challenging business for Finnish companies, especially SMEs, to enter. Although also from the Big Science side there are more and more developing activities to support participation, only some Finnish companies are actively benefitting these services. A good example is the biannual Big Science Business Forum (BSBF), where Finland participates with a small amount of visibility, while Sweden, for example, participates with a tenfold investment supported by their government.

Projects like ECO-Fusion are facilitating this development in Finland by disseminating information and communicating with companies. The technological know-how is really being pushed forward by research organizations and it is available for companies to benefit from, but to raise business activity to the same level as, e.g., in other Nordic countries, change in attitudes towards Big Science must take place at the national level.

The transition from Big Science research-driven projects into more private fusion business is opening new opportunities. The exponential growth in these investments multiplies the market, but currently most of the investments go into highly specialized high-tech development. However, this market is developing, and the more it moves into piloting and first-of-a-kind phase, the more opportunities open to the companies outside the proprietary technology. But to capture this value, Finnish companies need to be visible, known, and communicating with the core ecosystem players in the field. And this requires support that opens communication channels and transfers market information to Finnish companies, especially SMEs with niche knowledge.

Understanding the future of fusion and communicating it to the companies is probably the most important result. For this the Delphi method was used.

The Delphi method intended to engage fusion experts in an active conversation about the future of fusion. The study aimed at understanding the factors affecting the future of fusion, and its development paths. The Delphi consisted of two rounds of inquiries: the first round received 21 responses and the second round 32 responses, e.g. from research, companies, and governmental organizations. Despite Finland being well represented among respondents, the Delphi reached respondents also in countries such as the UK, Germany, Hungary, Italy, the US, Spain, France, the Netherlands, and Estonia.

As discussing the future of fusion, especially two topics divided opinions among fusion experts. The first one related to the overall timeline of fusion commercialization, and the other one to fusion's ability to contribute to the 2050 climate goals, similarly highlighting the timeline perspective. The majority of the views on the timeline of connecting fusion energy to the grid ranged from 2040 to 2080, and consideration of the larger share of fusion in the energy mix also received a range of views on the timeline. Time constraints paired with technical challenges and scaling were considered as reasons for the impossibility of fusion to contribute to the 2050 climate goals. This was also supported with, e.g., regulatory issues. However, the statements supporting the possibility of contribution highlighted the involvement of private companies, technological development steps, progression of fusion research, increasing interest and financing, in addition overall boost in climate emergency.

The findings also provided views on supporting the development and expansion of fusion. Finding synergies between different development paths, communicating and demonstrating the message that fusion brings along, and collaboration on issues such as supply chain, grid resilience, community acceptance, and workforce development were considered as supporting aspects. The role of public and private collaboration, and attraction of public and private funding was highlighted. The challenges regarding the development and expansion related to the same issues where the solutions were considered to be targeted: for example, lack of sufficient funding and investment attraction, insufficient sharing of information, and lack of human resources.

The Delphi study and findings from fusion experts formed a foundation for three “future of fusion in 2050” scenarios. The scenarios were formed based on multiple attributes stemming from the findings (e.g. fusion’s competitiveness, technical readiness, lead time of building fusion plants, industry collaboration, private company activity), thus aiming to represent different challenges and/or solution leaps introduced in findings to describe different 2050 worlds towards which fusion has progressed via alternative paths. The outlines of the three scenarios are as follows:

- Fusion fast track: A 2050 world in which the technological development for fusion takes leaps, and fast scaling enables fusion contributing to 2050 climate goals.
- Commercial fusion takes time: A 2050 world in which fusion’s technology challenges are resolved, but the scaling of fusion is slow and thus the commercialization timeline is long.
- Urgency for fusion diminishes: A 2050 world in which other sources of energy experience major leaps, and fusion research, funding and urgency decrease.

As a summary it can be said that Finnish companies are interested in fusion and Big Science as an opportunity, but still, especially SMEs, suspect that the investment required to participate in tenders is not worthwhile, considering the uncertainties. This might change when the potential of private fusion projects in the market starts to realize, but support both from Big Science side and from national organizations is still needed to connect and network companies and especially people.

One goal to set to push Finnish knowhow to the Big Science market, could be broad and active participation in BSBF2026, both as high-tech country and as growing business ecosystem. As said in the BSBF website: “*Belgium and the Netherlands will jointly organise the so-called European Big Science Business Forum (BSBF) at the MECC in Maastricht in October 2026. An expected 1,000 participants from leading high-tech companies will meet Europe’s larger research organisations at this conference to share knowledge on high technology and innovation. They will also engage in research and development collaborations.*”

5. Work performed under Advancing Computing Hub

An Advanced Computing Hub (ACH) was formed at the University of Helsinki in 2021 to provide broad expertise on data science, algorithms, scientific computing, GPU programming, and database management for the wide range of scientific tasks within the community connected to EUROfusion. The ACH has achieved a solid footing within the EUROfusion program within the past years and is ready to perform for the entire duration of Horizon Europe as well as to continue to operate until 2035 as part of the EU Research FP10.

The development of new AI solutions was at the forefront of the work conducted by the ACH, including the development of data-efficient forward and inverse uncertainty quantification methods, as well as surrogate modelling projects ranging from materials physics to aspects related to relativistic plasma physics. Outreach and dissemination were practiced, for example, through public webinars on aspects, such as Bayesian optimization for data-efficient inverse uncertainty quantification. Aspects on GPU programming were carried out related to the optimization of one of the plasma codes through the development of a GPU-accelerated quadruple precision solver to be used for challenging numerical problems. Industrial collaboration was conducted by developing plasma fluid solvers with the Sparselizard finite element C++ library in collaboration with the Finnish company Quanscient. This activity both provided new problem-solving approaches for the EUROfusion community as well as supported the plasma physics relevant expertise development at Quanscient to address the needs of the growing fusion industry.

The ACH has successfully addressed the deliverables of establishing a centre of expertice on data-science, algorithms, scientific computing, GPU programming, and database management. This has been demonstrated by the large number of completed projects, requested by the linked EUROfusion projects. The details of those projects where the VTT members are active were already documented in section 3.2.5. The ACH is also linked to the FCAI (Finnish Center for Artificial Intelligence) and a new Virtual Laboratory of Fusion and Plasma Physics was established within the FCAI Virtual Laboratory scheme to further accelerate the dissemination of the established AI methods for other fields of sciences as well as to enhance the learning of the relevant ACH team members on the relevant novel AI methods. The established expertise in AI methods is expected to have a positive impact to digital engineering and modelling tasks also outside the fusion domain.

6. Communication and dissemination activities

Communication with various stakeholders and dissemination of project results have been an integral part of ECO-Fusion throughout its lifetime in the period 2021-2024.

ECO-Fusion has been very visible both nationally and internationally. This has resulted in expanded networks and including new Finnish companies to fusion research, either as members of the FinnFusion Consortium or as active partners in commercial contracts (e.g., funded via the subcontracting activities of the EUROfusion Consortium). The visibility was gained thanks to several research visits, conference participations, or targeted face-to-face meetings. Overall, 253 business trips, corresponding to 1325 travel days were completed. Of these, >90% were trips abroad and further around 200 research visits were paid to fusion facilities worldwide; typically the research visit consisted of periods of 1-2 weeks but also some longer-term visits were completed.

Participation in conferences and workshops increased towards the end of the projects: some 20 people attended these events during the last year of the project (July 2023 – June 2024) once the restrictions induced by Covid had been lifted. Of these, the most important was the IAEA Fusion Energy Conference (FEC) in London in October 2023, with more than 1000 participants from around the world. Besides scientists, the IAEA FEC attracted political decision makers, representatives from various companies including private fusion enterprises, as well as leaders of international organizations. The conference was a unique opportunity to establish novel collaborations, especially towards the US and UK. A major achievement was a meeting with representatives from the Department of Energy (DOE), US, where mutual needs for strengthening collaboration in the fields of fusion technology, materials, and remote maintenance were identified.

Overall >75 conference contributions were published during the project on top of the more than 90 articles in refereed scientific journals: a testament of the multitude of scientific achievements made within just 3.5 years. A full list of publications can be found in FinnFusion yearbooks, accessible online at (the 2024 data to be added in early 2025):

- https://cris.vtt.fi/en/publications/finnfusion-yearbook-2023 (2023)
- https://cris.vtt.fi/en/publications/finnfusion-yearbook-2022 (2022)
- https://cris.vtt.fi/en/publications/finnfusion-yearbook-2021 (2021)

ECO-Fusion organized a large event called Open Business Day (https://www.openbusinessday.fi/) together with the other nuclear ecosystem projects of VTT, the EcoSMR (https://www.ecosmr.fi/) and dECOmm (https://www.decomm.fi/) in May 2022, to enhance their collaboration and identify further business opportunities for participating companies. The event was a big success: several people found the program and discussions therein useful. ECO-Fusion was also prominently present in the Nuclear Science and Technology Symposium in late 2022 (https://finnuclear.fi/nuclear-science-and-technology-symposium-2022-syp2022/) as well as in the annual FinnFusion meetings in June 2023 (together with Sweden and Denmark) in Gothenburg, Sweden, and in May 2024 (organized by University of Helsinki). In the latter event, all the co-innovation partners of ECO-Fusion were present to summarize the main lessons learnt of their company or research projects.

The main results obtained within ECO-Fusion and by the international fusion community were collected on the FinnFusion web page at https://finnfusion.fi/. Several blog articles and news flashes appeared there and the most important of them were also shared via different social media channels, in particular via LinkedIn.

7. Summary

The ECO-Fusion project has concentrated on creating a functional fusion ecosystem in Finland both by carrying out high-quality scientific research and by identifying prospects of Finnish companies to become involved in ongoing and future international fusion projects. The project has consisted of five scientific work packages (from WP VTT-1 to WP VTT-5, see section 3) as well as project management and dissemination activities (WP VTT-6). The project was co-funded by Business Finland, VTT, and European Union via the EUROfusion Consortium, all contributing roughly at equal shares.

The focus of WP VTT-1 was on designing and developing solutions for remote maintenance of the European DEMO and other future fusion reactors, in addition to which preparations for a Finnish test platform (consisting of various test rigs) of different RM solutions were initiated. To the latter end, several novel measurement and sensor approaches were investigated, of which one patent application has already been filed. All the studied methods will ensure safe and stable operation of future fusion power plants. Under, WP VTT-2, for its part, significant effort was put into designing novel materials for structural and wall materials of fusion reactors and thoroughly modelling their properties using the ProperTune® simulation framework. The work also covered analyses of irradiated fusion materials in the hot-cell facilities of VTT and development of novel measurement techniques for mechanical properties of such materials at high temperatures and upon exposure to fusion-relevant hydrogen environment. Promising results have been obtained, strengthening the role of VTT in international R&D projects and helping in winnng new commercial contracts, but also in extending the palette of offerings in the field of materials solutions for challenging environments. The work package WP VTT-3 concentrated on broad participation into experiments and analyses in international fusion devices, thus providing the community with state-of-the-art information to support conceptual design of fusion reactors. The project team also contributed to the balance-of-plant simulations of future fusion reactors, and this goal was promoted by integrating several individual codes into a single modelling entity such that now it is possible to understand the entire plant operation: from energy production in the core up to the point where electricity is generated for the grid. The emphasis of WP VTT-4 was on various safety analyses of fusion reactors. The work performed included determining the formation of radioactive waste and safety against fires, assessing the probabilities of various incidents and functionality of different monitoring equipment in fusion devices, and laying the foundations for the decommissioning of fusion power plants in the end of their lifetime. The information achieved can be utilized for planning safe and economical operation of fusion powere plants. Finally, under WP VTT-5, the existing fusion ecosystem was studied and recommendations were formulated for its further expansion. The main tools were comprehensive interviews of representatives from Finnish companies, analysis of the obtained results, development of dynamic models to better understand the needs and opportunities of various companies in the field of fusion energy, as well as scenario work for the role of fusion energy in society. The results are expected to be published in the near future and thereby encourage more companies to join the existing fusion network. The role of AI was prominent in the project and many of the project activities under WP VTT-1, WP VTT-2, and WP VTT-3 benefited from novel methodology and improved computational tools that AI brought along.

The key results have been regularly presented in the project steering group meetings, organized after each tertile since August 2021. A large number of peer-reviewed journal articles (>90) and conference presentations (>75) were published during the project accompanied with 7 completed PhD or MSc. Theses and more to come in the next couple of months.

ECO-Fusion has been a highly international project, maximally making use of the possibilities for international collaboration provided in particular by the EUROfusion Consortium. The project team has participated in experiments in all major fusion facilities worldwide, including the experiments at th JET tokamak where the real fusion fuel (deuterium-tritium mixture) was used in two distinct campaigns in 2021 and 2023. More than 250 travels, research visits or participation to conferences, were accomplished during the project, of which 90% were trips to abroad and some 200 involved participation in experiments or data analyses. Thanks to active travelling, VTT was able to expand the existing fusion network and establish new contacts with foreign companies along with the international research institutes.

In additional to international collaboration, co-operation with co-innovation partners (Luvata, EOS Finland, Comatec, and Platom) and other Finnish companies was actively pursued. In the ECO-Fusion network, the companies could benefit from subcontracting projects offered by the EUROfusion Consortium as well as from tendering opportunities as members of larger consortia. ECO-Fusion was fully integrated to the FinnFusion Consortium that combined all the actors and stakeholders in the field of fusion research: Finnish universities and research institutes together with companies, decision makers and funding bodies. This collaboration intensified during the project lifetime, manifested by ECO-Fusion attracting new companies as members to the FinnFusion Advisory Board and varying project initiatives being launched within the consortium.

The R&D work performed, and the results obtained will have a huge impact on the design and operations of ITER and varying DEMO reactors, including those conceptualized by private fusion companies. Links to SMEs and start-up fusion companies from the US and the UK have been established during the project, and VTT has now several commercial contracts running with them, with more in the negotiation and tendering phases. This has provided benefit to the entire co-innovation project. Inside VTT, ECO-Fusion has facilitated interactions between different research and business areas and, as a result, more than 120 people have worked at least part-time for the project during 2021-2024.

The project results were disseminated by organizing an Open Business Day event in 2022 together with other VTT nuclear ecosystem projects, providing visibility for the participating companies and opportunities for networking. ECO-Fusion was strongly present in FinnFusion annual seminars in 2023 and 2024, the former being organized together with Sweden and Denmark as well as in various business fora. The final seminar will be arranged in December 2024 to review the project results and give an overview of planned future activities and the new VTT fusion roadmap. The role of VTT as the ECO-Fusion coordinator has brought along several fruitful contacts with Finnish companies: more than 50 discussions were held during the project.

The project was completed on time and within the agreed budget. New members joined the fusion ecosystem during ECO-Fusion in 2021-2024 and five out of the present members of the co-innovation project have recognized the need to continue fusion research in Finland beyond 2024; a new co-innovation proposal was submitted to Business Finland in May 2024.

Series title and number

VTT Technology 433

Title	**ECO-Fusion: Finnish Ecosystem for Industrial Fusion Technology** Final report
Author(s)	Antti Hakola & Tommi Lyytinen (Eds.)
Abstract	This report summarizes the work done under the VTT part of the ECO-Fusion co-innovation project (Finnish Ecosystem for Industrial Fusion Technology, 40962/31/2020), co-funded by Business Finland, VTT and the European Union (under EUROfusion Consortium). The co-innovation partners were VTT, University of Helsinki, Luvata Oy, Electro Optical Systems Finland Oy, Insinööritoimisto Comatec Oy, and Platom Oy. The main goals of the project were establishing a functional fusion ecosystem in Finland, facilitate growth and export of Finnish companies in fields related to fusion technology and take part in emerging tendering opportunities on the international arena, as well as increasing the competences of the participants in targeted research areas. For VTT, the latter included remote maintenance of components and sub-systems in fusion reactors, design and characterization of novel materials for the harsh environment inside fusion reactors, providing the scientific community with new information to guarantee successful operation of future fusion power plants, as well as ensuring safe operation of the plant, handling of the produced radioactive waste and final decommissioning of the fusion reactor. ECO-Fusion was part of the FinnFusion Consortium, a network for Finnish universities, research institutes, companies, and decision-makers, which ensured large visibility for the key achievements of the project and offered novel ways for collaboration. Thanks to the EU involvement, ECO-Fusion was a highly international programme and during its lifetime in 2021-2024 links and and new contracts were established with several foreign companies and organizations, including the US, the UK, and South Korea.
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Nimeke	**ECO-Fusion: Finnish Ecosystem for Industrial Fusion Technology** Loppuraportti
Tekijä(t)	Antti Hakola & Tommi Lyytinen (Eds.)
Tiivistelmä	Tässä raportissa esitetään yhteenveto VTT:n tutkimusprojektin keskeisistä tuloksista, jotka on saatu ECO-Fusion-yhteisinnovaatiohankkeen (Finnish Ecosystem for Industrial Fusion Technology, 40962/31/2020) aikana. Hanketta rahoittivat Business Finland, VTT ja Euroopan unioni (EUROfusion-konsortion alaisuudessa). Yhteisinnovaatiohankkeen kumppaneita olivat VTT, Helsingin yliopisto, Luvata Oy, Electro Optical Systems Finland Oy, Insinööritoimisto Comatec Oy ja Platom Oy. Hankkeen päätavoitteina olivat toimivan fuusioekosysteemin luominen Suomeen, suomalaisyritysten kasvun ja viennin edistäminen fuusioteknologiaan liittyvillä aloilla sekä osallistuminen kansainvälisiin fuusioalan tarjouskilpailuihin. Lisäksi tavoitteena oli hankkeeseen osallistuvien osapuolten osaamisen lisääminen valituilla tutkimusalueilla. VTT:n osalta nämä alueet kattoivat fuusioreaktorien komponenttien ja osajärjestelmien etähuollon, uusien materiaalien suunnittelun ja karakterisoinnin fuusioreaktorien vaativiin olosuhteisiin sekä uuden tiedon tarjoamisen tiedeyhteisölle tulevien fuusiovoimaloiden menestyksekästä käyttöä varten. Lisäksi selvitettiin voimalan turvallisen käytön, syntyvän radioaktiivisen jätteen käsittelyn ja fuusioreaktorin lopullisen käytöstäpoiston erityisvaatimuksia. ECO-Fusion oli osa FinnFusion-konsortiota, joka on suomalaisista yliopistoista, tutkimuslaitoksista, yrityksistä ja muista alan toimijoista koostuva verkosto. Konsortio varmisti hankkeen keskeisten saavutusten laajan näkyvyyden ja tarjosi uusia yhteistyömahdollisuuksia. EU:n mukanaolon ansiosta ECO-Fusion oli erittäin kansainvälinen ohjelma, ja sen toteutuksen aikana vuosina 2021–2024 luotiin yhteyksiä ja uusia avauksia useiden ulkomaisten (ml. Yhdysvallat, Iso-Britannia ja Etelä-Korea) yritysten ja organisaatioiden kanssa.
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ECO-Fusion: Finnish Ecosystem for Industrial Fusion Technology

Final report

This report summarizes the work done under the VTT part of the ECO-Fusion co-innovation project (Finnish Ecosystem for Industrial Fusion Technology, 40962/31/2020), co-funded by Business Finland, VTT and the European Union (under EUROfusion Consortium). The co-innovation partners were VTT, University of Helsinki, Luvata Oy, Electro Optical Systems Finland Oy, Insinööritoimisto Comatec Oy, and Platom Oy. The main goals of the project were establishing a functional fusion ecosystem in Finland, facilitate growth and export of Finnish companies in fields related to fusion technology and take part in emerging tendering opportunities on the international arena, as well as increasing the competences of the participants in targeted research areas. For VTT, the latter included remote maintenance of components and sub-systems in fusion reactors, design and characterization of novel materials for the harsh environment inside fusion reactors, providing the scientific community with new information to guarantee successful operation of future fusion power plants, as well as ensuring safe operation of the plant, handling of the produced radioactive waste and final decommissioning of the fusion reactor. ECO-Fusion was part of the FinnFusion Consortium, a network for Finnish universities, research institutes, companies, and decision-makers, which ensured large visibility for the key achievements of the project and offered novel ways for collaboration.

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