Nuclear Technology Activities under ECO-Fusion Project

What is needed to design a fusion power plant?

Antti Hakola

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Special thanks…

… to the entire ECO-Fusion team, in particular:

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- Business Finland
- VTT
- FinnFusion Consortium

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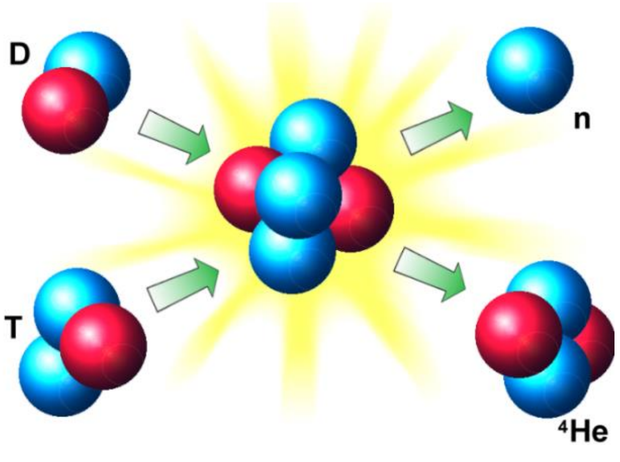
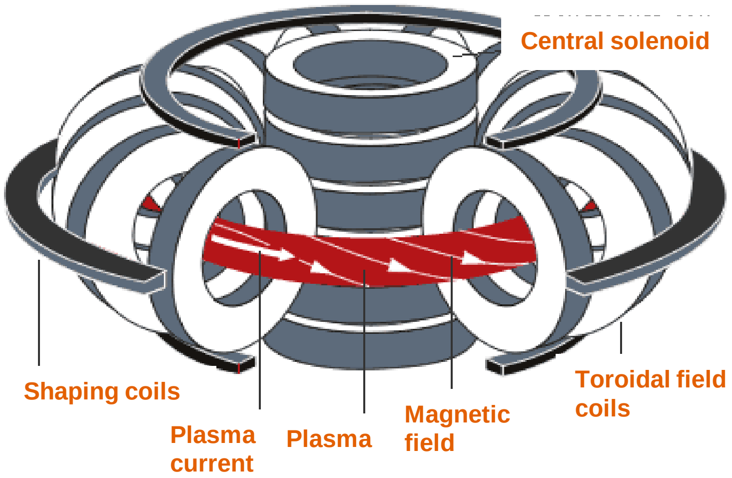
Basics of energy production via nuclear fusion

- In fusion reactors, light elements **fuse together and release energy** → 95,000 kWh from 1 g of typical fusion fuel (mixture of D and T)
- Fusion requires such extreme conditions that the **fuel transforms into plasma**
- Plasma can be kept confined with the help of magnetic fields
  - **Most promising concept is a tokamak** on which the next generation fusion devices ITER and DEMO are based





What is needed to construct a fusion power plant – and how Finland is involved

- Besides **passion for research and innovations**, one needs
  - A credible **roadmap** with a clearly defined strategy with intermediate steps and decision points
  - Sufficient **funding** to promote the necessary R&D efforts and a critical mass of experts involved
  - A functional and versatile **ecosystem** consisting of a variety of networked stakeholders
  - Strong **involvement of companies** at each stage of the process

All these are mandatory to meet the ambitious goal of producing baseline energy by nuclear fusion for the growing need of clean electricity of society by the end of the century

- Generally, all these are being **addressed in the ECO-Fusion project**
  - We follow the European roadmap – ITER and DEMO to demonstrate scientific and technical feasibility of nuclear fusion in energy production – but also keep a close eye on the efforts made by private companies
- ECO-Fusion aims at
  - **Strengthening the existing national fusion network** - FinnFusion Consortium - in targeted research areas and with a subset of FinnFusion contributors
  - Provide the participants with improved understanding on how to best **utilize the tendering opportunities** becoming available (e.g., ~20 G€ for ITER) → growth in business and export

Research project 6/2021 – 12/2023+

VTT | HELSINGIN YLIOPISTO HELSINGFORS UNIVERSITET UNIVERSITY OF HELSINKI

EU funding | Own funding | BF funding

EUROfusion | BUSINESS FINLAND

VTT and university's own funding

COMATEC	EOS	LUVATA	PLATOM
Development of Expertise and Service Portfolio for International Markets	*Novel AM materials for Energy Segment*	*Fuusiokuparit*	*International Licensing Framework in Challenging Environments*
Company own work	Company own work	Company own work	Company own work
Research and/or SME subcontracting	Research and/or SME subcontracting	Research and/or SME subcontracting	Research and/or SME subcontracting

Domestic public stakeholders

Työ- ja elinkeinoministeriö Arbets- och näringsministeriet | BUSINESS FINLAND | ACADEMY OF FINLAND

International and domestic industry stakeholders

finnfusion | FUSION FOR ENERGY | FINNUCLEAR® | iter china eu india japan korea russia usa

International public stakeholders

EUROfusion | European Commission

Special features of ECO-Fusion @ VTT

- Financing comes from **three different sources** → also goals set in three different levels
- Besides ECO-Fusion, VTT is also the Finnish Beneficiary in the EUROfusion Consortium, **requiring co-ordination of all Finnish fusion research activities**
  - Implemented via FinnFusion
- Business Finland and the home institute (VTT) provide the necessary national funding required for contributing to the EUROfusion tasks
- ECO-Fusion is **more like a research programme** than a traditional project: large volume and broad spectrum of R&D strands:
  - Physics of fusion plasmas
  - Robotics and remote handling/maintenance
  - Advanced materials and 3D printing
  - Magnet technology
  - Development of ecosystems and business models
  - Power plant modelling
  - Analyses of activated samples and components
  - Nuclear waste management
  - Fire safety
  - High-power computing and artificial intelligence & machine learning

Structure of the ECO-Fusion @ VTT

VTT

Project manager
Antti Hakola

Research project

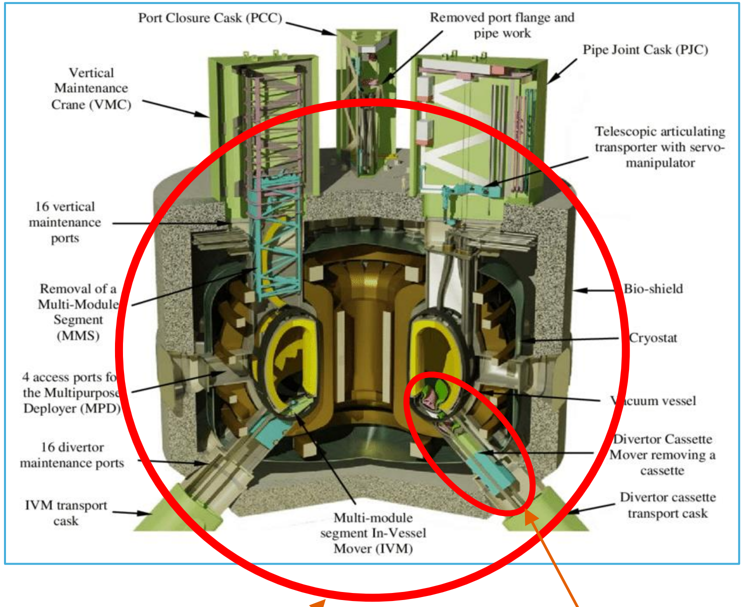
WP VTT-1	WP VTT-2	Advanced Computing Hub – jointly with University of Helsinki	WP VTT-3	WP VTT-4	WP VTT-5	WP VTT-6
Power plant lifetime and maintenance	Novel materials		Power plant analysis	Licensing and safety	Fusion tech. ecosystems and business models	Project management and dissemination
31%	13%		35%	8%	7%	5%

Budget 11,6 M€ (~700 PM)	
EU	33%
VTT	34%
BF	34%

- WPs and their volumes defined on the basis of funding and human resources available for the different activities
- Advanced Computing Hub is a joint activity with University of Helsinki (actual work under WP VTT-2 and -3)

ECO-Fusion advances: remote maintenance

- WP VTT-1 focuses on **remote and automated maintenance of components** in fusion reactors
  - Detailed assessment of existing and new concepts for plant architecture and designing solutions for maintaining components inside the reactor and the bioshield
  - **Integration of human control** into the systems and development of algorithms based on artificial intelligence for condition monitoring
  - Laying the foundations for **hosting a digitized fusion test-rig facility** in Finland beyond 2023



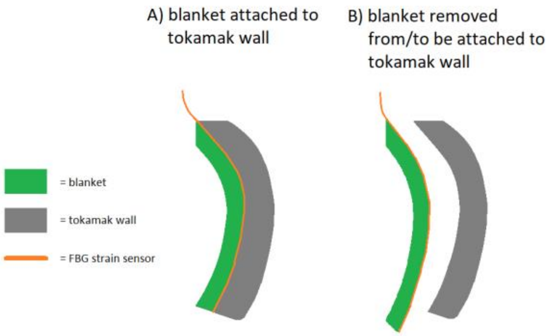
Focus now

Research focus before ECO-Fusion

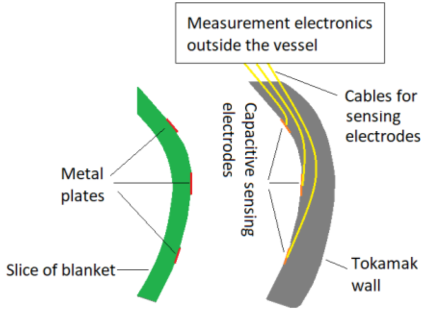
- ❑ Opportunities for Finnish companies to become involved (e.g., Comatec)
- ❑ The solutions can be utilized in other complex or hostile environments to manipulate heavy structures at a high precision

ECO-Fusion advances: remote maintenance

- **Examples of tasks** - novel sensors for **controlling the positions/movements of heavy reactor components** in complicated geometries and with small tolerances
  - Based on
    - ✓ radiation-tolerant optical fibers (FBG, Fiber Bragg Gratings) to measure strains or joint angles of the components or manipulators
    - ✓ Capacitive proximity sensors to measure the exact position and shape of the components when moved using manipulators
  - Preliminary test systems being realized



Implementation of FBGs to detect changes in the strains of the blanket structures during manipulation

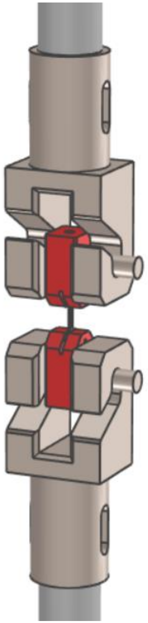


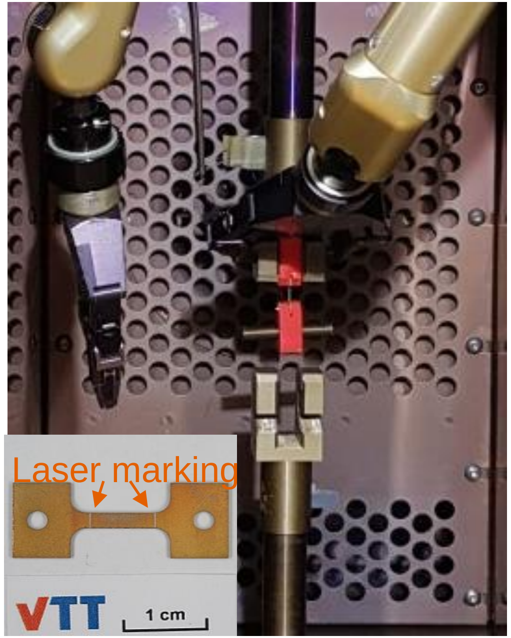
Capacitive proximity sensors to position the blanket structures precisely during manipulation

ECO-Fusion advances: materials and analyses

- WP VTT-2 deals with development of **novel materials for fusion-reactor components and magnets** and analyses of irradiated/activated structures
  - Utilized the unique modelling expertise of the **VTT ProperTune team** and the **state-of-the-art hot cell facilities** at VTT Centre for Nuclear Safety (CNS)
  - In addition, **additive manufacturing** (=3D printing) is a key in prototype manufacturing

- ❑ Strong collaboration with Finnish companies (e.g., Luvata, EOS Finland) with also subcontracting opportunities
- ❑ At a later phase also cleaning of exposed structures will be adopted

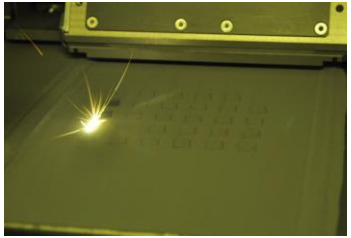


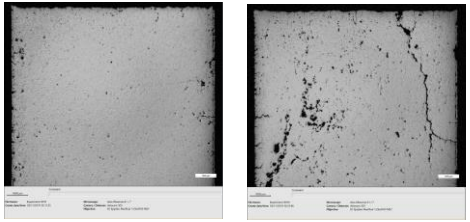


Novel tension grips designed and manufactured to manipulate fusion-specific samples at CNS

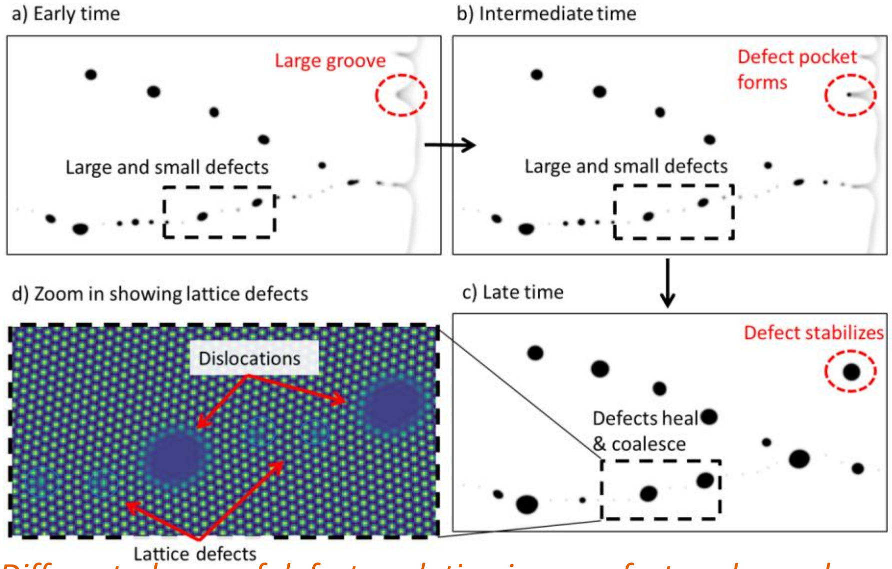
ECO-Fusion advances: materials and analyses

- **<u>Examples of tasks</u>** – optimizing **modeling workflow for the entire additive manufacturing chain** from raw materials to the final product (incl. casting, drawing, annealing, forging,…)
  - Good understanding of the evolution of defect structures during manufacturing – consistent with experiments
  - Several prototypes made to minimize sample porosity and cracking





Production of ”sugar cubes” and two examples of samples with good (left) and bad (right) quality

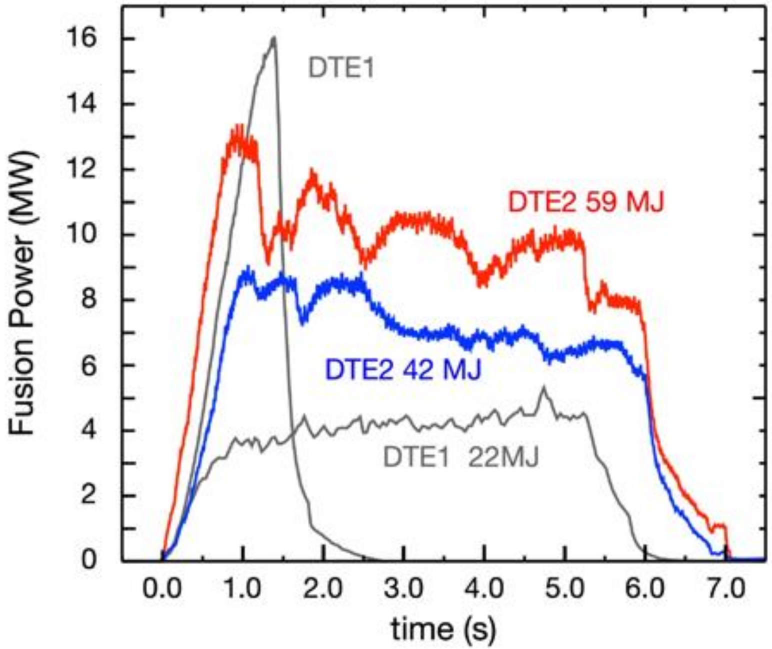


Different phases of defect evolution in manufactured samples

ECO-Fusion advances: power-plant operation

VTT

- WP VTT-3 will promote operation of the entire fusion power plant – from **physics understanding of the hot plasma to full-scale balance-of-plant (BoP) simulations**
  - Exploitation of **existing fusion facilities** (participation in experiments, analysis of the results, and modelling)
  - Development of **novel diagnostics** for the reactors
  - Detailed assessment of technical feasibility, safety, licensing issues and lifecycle costs of **downselected BoP configurations for DEMO using Apros**



- ❑ Lays the foundations for new types for projects with industry

UK Atomic Energy Authority

JET

Landmark results – 59 MJ of sustained fusion energy – by EUROfusion scientists and engineers at the world-leading Joint European Torus (JET) facility in Oxford, UK (December 2021)

ECO-Fusion advances: power-plant operation

- **<u>Examples of tasks</u>** – **steady-state magnetic field sensor** for high radiation environment
  - Novel idea: Silicon-on-Insulator (SOI) miniature sized chip with coiled silicon waveguides to measure Faraday rotation from which magnetic field can be derived
  - Simulation model for the method is being built, the feasibility of the concept is being analysed, and several prototypes are being constructed

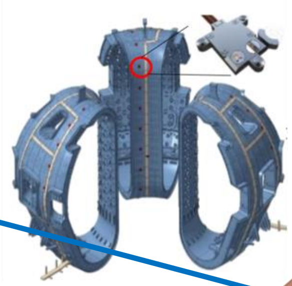
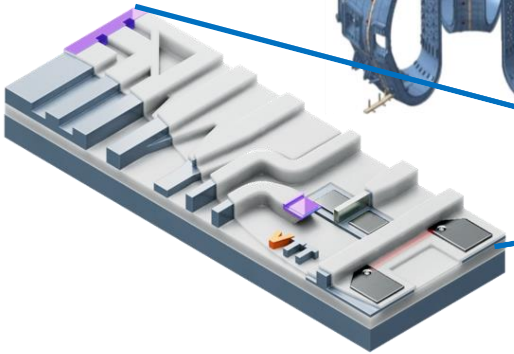
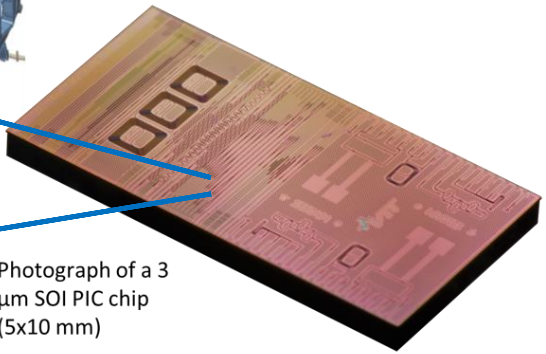


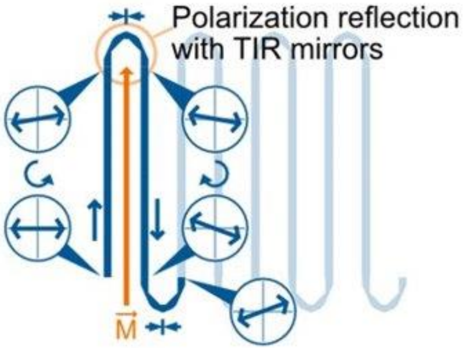
Illustration of a tokamak reactor with a (conventional) magnetic field sensor in one potential place for magnetic field measurement

3 µm SOI PIC platform with passive and active functions (schematic)





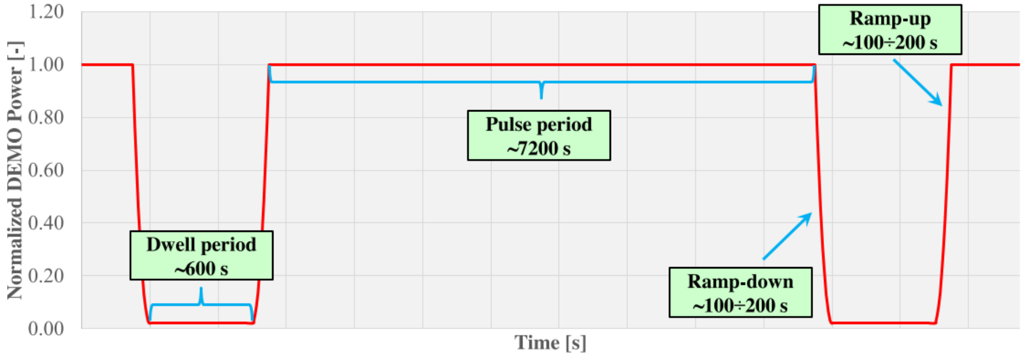
Photograph of a 3 µm SOI PIC chip (5x10 mm)



Measuring Faraday rotation requires straight waveguides with dimensions and coatings optimized for zero birefringence and folded waveguides with U-turns based on total internal reflection (TIR) mirrors → development needed

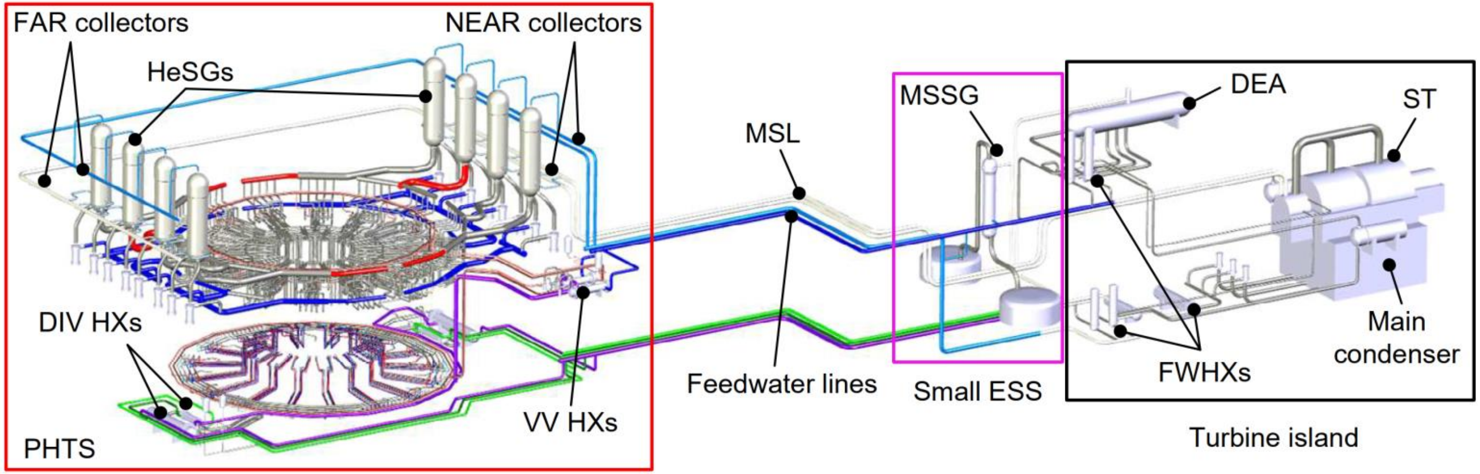
ECO-Fusion advances: power-plant operation Apros analyses for DEMO

- Development of DEMO towards a power plant requires an extensive integrated plant model with interaction from different systems – both in the physics level and through automation systems
- Thermal-hydraulic models have been developed for **two breeding blanket (BB) concepts**
  - Helium-Cooled Pebble-Bed (HCPB) and Water-Cooled Lithium-Lead (WCLL)
  - BB takes care of **tritium production for the fusion reactions** during the plant operation
- Main challenge of the heat transport chain in DEMO will be the **pulsed nature of plasma operations** → special constraints on all components of the BoP system



ECO-Fusion advances: power-plant operation Apros analyses for DEMO

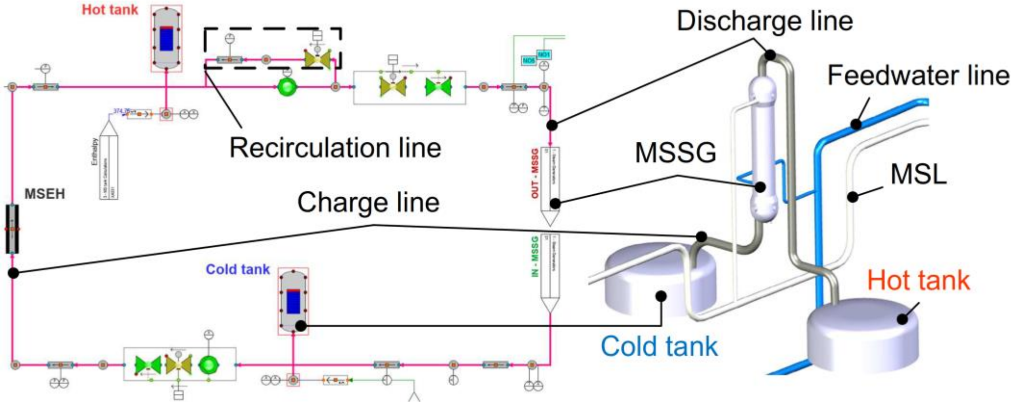
- Recently investigated plant concepts for both HCPB and WCLL equipped with **a small energy storage** system (ESS)

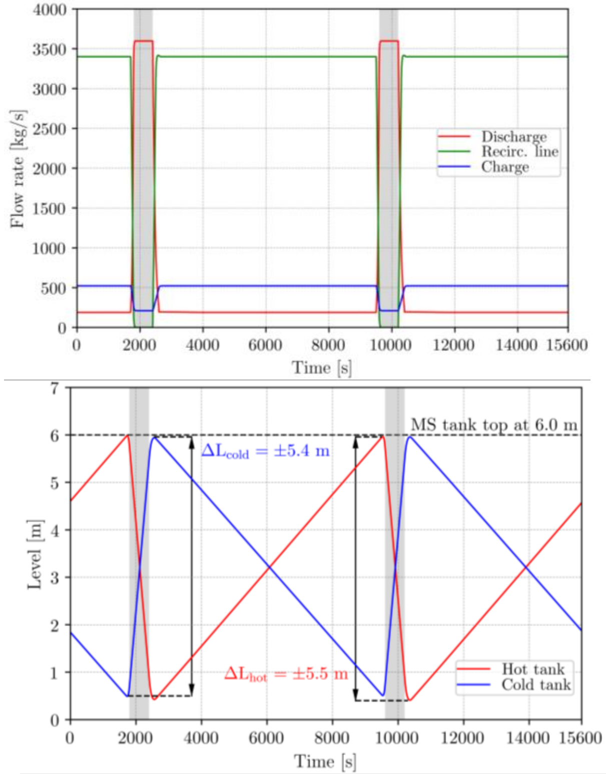


HCPB breeding blanket concept with an ESS

ECO-Fusion advances: power-plant operation Apros analyses for DEMO

- The **small ESS is a buffer energy source** for mitigating the pulsed nature of DEMO
  - Based on using molten salt electrical heater (MSEH) to regulate the salt temperature
- Similar layout in HCPB and WCLL, differences mainly in the enthalpy demands of the molten salt steam generator (MSSG)
  - Working medium HITEC®, eutectic mixture of water-soluble, inorganic salts of $NaNO_3$–$NaNO_2$–KNO_3

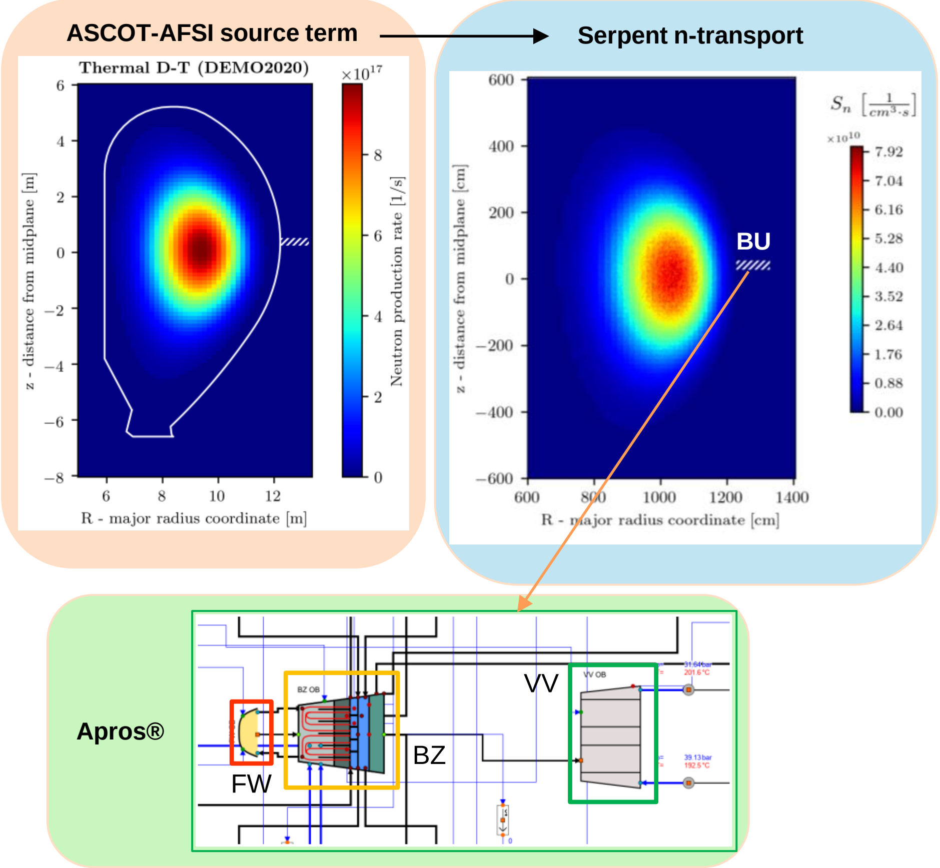




Control schemes for the salt flow rate and levels of the hot and cold tanks

ECO-Fusion advances: power-plant operation Apros analyses for DEMO

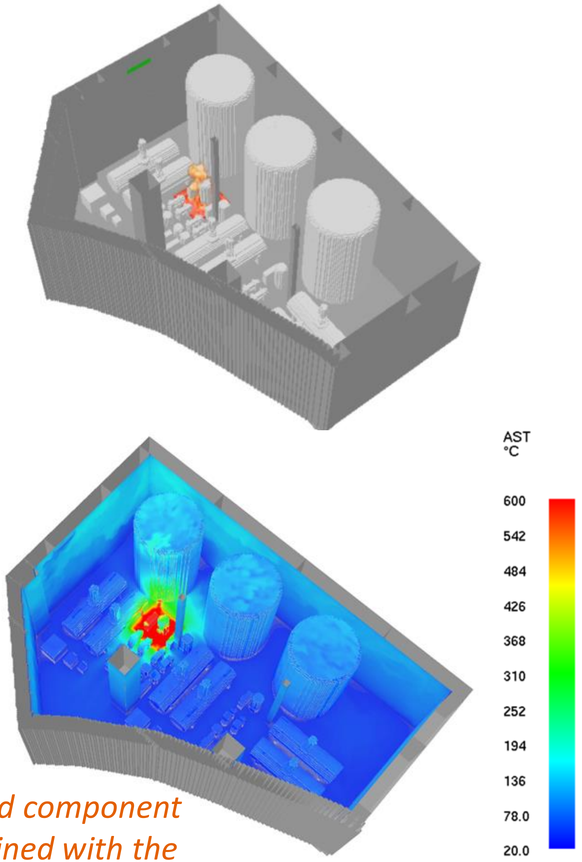
- Development of a **novel calculation chain** ongoing
  - Establish an analytical chain starting with source term calculations and ending with plant-level analyses by Apros
- **ASCOT-AFSI neutron source integrator** code (developed by Aalto University and VTT) utilized to obtain 4D product particle distributions from various reactions.
- Thermonuclear source terms imported and used by the **Serpent MCNP neutron transport** code in hybrid calculations featuring CAD-based geometry file
- Power deposition curves during the fusion pulses and ramp-up phases handled by **Apros breeding unit models**



ECO-Fusion advances: plant safety

- WP VTT-4 is the **link between fusion and fission** communities in the fields of (nuclear) safety, radiation doses, waste management, licensing, and decommissioning
  - Benefits from **existing networks within the fusion and fission communities** and long traditions of Finland in relevant fields of nuclear engineering
  - Good example of **new openings are fire accident analyses**: Identification of fire hazards, assessment of consequences, and evaluation of the protection of personnel and property

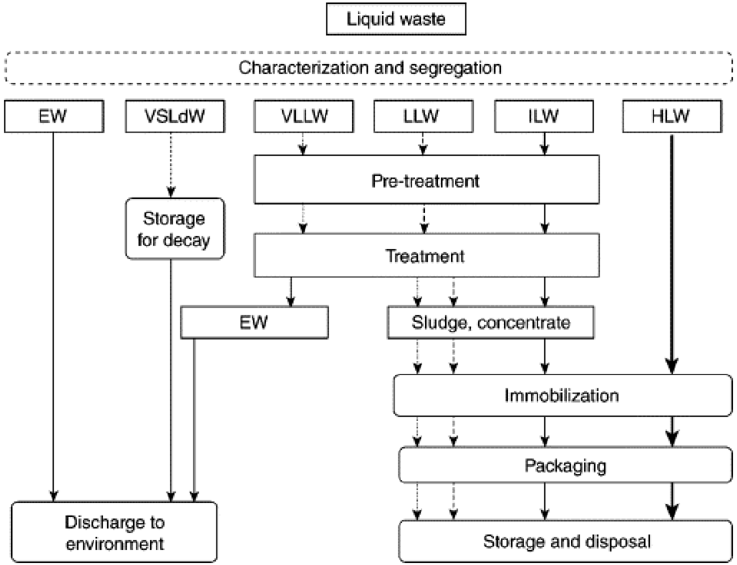
- ❑ Expected to grow in importance towards the end of the project with more subcontracting opportunities to arise
- ❑ Already a number of companies (e.g., Platom) involved



Results of fire-risk simulations for a lithium-lead component room: acceptable fire safety levels can be obtained with the designed fire protection systems

ECO-Fusion advances: plant safety

- **Examples of tasks** – **Nuclear waste management for DEMO**: VTT estimates liquid waste streams
  - Generation of radioactive waste (volume & active inventory) shall be considered before the construction of the power plant facility
  - What has been done and what will be done in the liquid-waste front?
    - ✓ Identified and classified the most important waste streams and process options, including processing-technology readiness estimates and quantified estimates against ITER experiences
    - ✓ Synergies with pre-disposal treatment of radioactive waste in fission (EU-Predis)
    - ✓ Using analogies from design and licensing of modern nuclear power plants



Categorization of liquid waste from Exempt Waste to Short Living, Low Level, and High Level Wastes together with proposed procedures.

ECO-Fusion advances: growing fusion network

- WP VTT-5 is about **growing the Finnish fusion network** – especially deepened inclusion of companies
  - Several interviews made and workshops arranged to understand the **underlying challenges and needs of the potential company members**

Challenges in Big Science projects

- Offer phase
- Lack of resources and resource intensity
- Not recognizing possibilities
- Gap between research and participation of companies

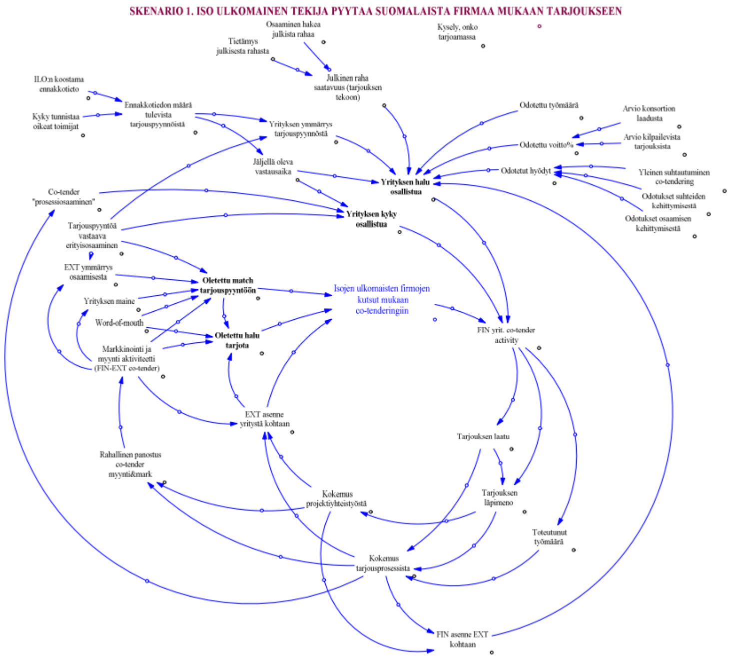
Needs in Big Science projects

- Companies need better understanding from customers and their needs
- Companies need better communication in Big Science context
- Interest towards open data base where companies could present their skills and competences

ECO-Fusion advances: growing fusion network

VTT

- WP VTT-5 is about **growing the Finnish fusion network** – especially deepened inclusion of companies
  - Several interviews made and workshops arranged to understand the **underlying challenges and needs of the potential company members**
  - Motivation and participation can be improved via…
    - ✓ ***System dynamics* modelling** to understand leverage points in situations where
      - o Big foreign companies ask Finnish partners to take part in tendering
      - o Number of active partners in the fusion ecosystem is to be increased
    - ✓ ***Foresight work* and delphi questionnaire** for international experts to understand
      - o Future of fusion and parallel forms of energy production
      - o Alternative paths for fusion commercialization



Concluding remarks

- The Finnish ECO-fusion project promotes high-quality research in the field of nuclear fusion with the aim of **building a top ecosystem for Finnish companies, research organizations and universities**
- Key objective is to **activate all participants of the network** to become involved in in Big Science projects including ITER and DEMO
- Work carried out on several fronts, including
  - Development of remote maintenance tools and novel materials
  - Analyses and modelling of fusion reactors and power plants
  - Plant safety
  - Ecosystem research
- **Strong links to nuclear technology** as evidenced by
  - Application of Apros for transient analyses in DEMO with its novel analysis chain for the source and neutron transport modules
  - Identification of fire risks in the power plants and estimates for various streams of liquid nuclear waste
  - Analysis programme for neutron-activated fusion reactor materials in VTT hot-cell facilities
- The project will continue until 2024 and further progress will be regularly reported

beyond the obvious

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