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An overview of UKAEA’s integrated fusion technology programmes, emphasising a digital-first strategy

Rachel Lawless, Teuntje Tijssen, Amy Gandy, Kai Zhang, Steven Van Boxel, Jonathan Horne- Jones et al

IAEA FEC – October 2025

UK Programme has unique breadth

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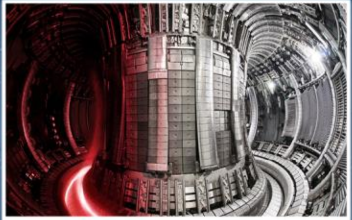
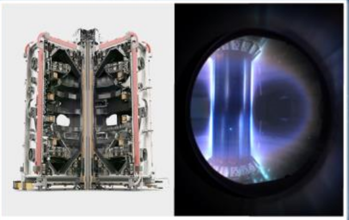
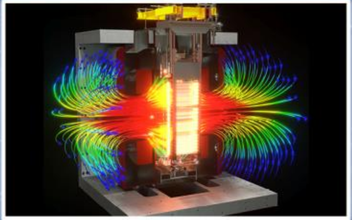


HIGH PERFORMANCE FUSION



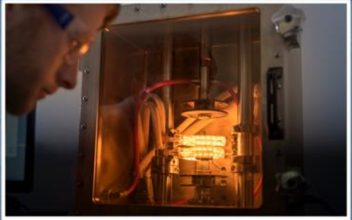
SPHERICAL TOKAMAKS

MATERIALS RESEARCH



FUSION TECHNOLOGY

ROBOTICS



TRITIUM

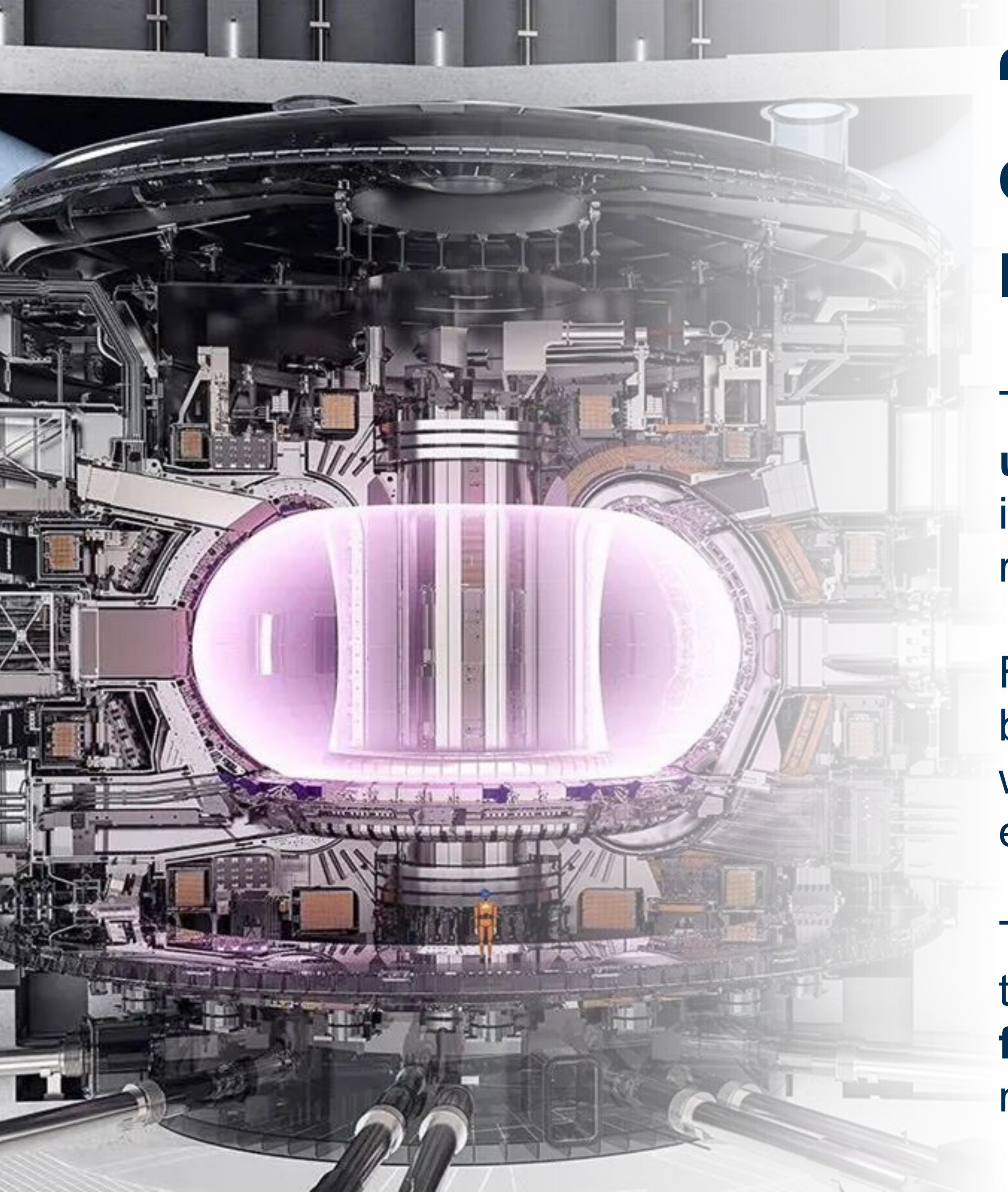
ADVANCED DIGITAL COMPUTING

POWERPLANT DESIGN

INDUSTRY DEVELOPMENT

SKILLS DEVELOPMENT

TECHNOLOGY TRANSFER



‘Digital first’ is critical for achieving near-term milestones

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The in-vessel conditions of a fusion reactor are **unique and extreme**; the combined load is impossible to find anywhere **except** in a fusion reactor.

Fusion has historically been **designed by iteration**, but delivery of a fusion pilot plant in 10 – 20 years will not allow for substantive de-risking by further experimental devices.

Traditional approach is driven by physical testing, this approach must evolve to adopt **simulations as first step**, with experimental testing **confirming** the modelling predictions.

Simulation led experiments

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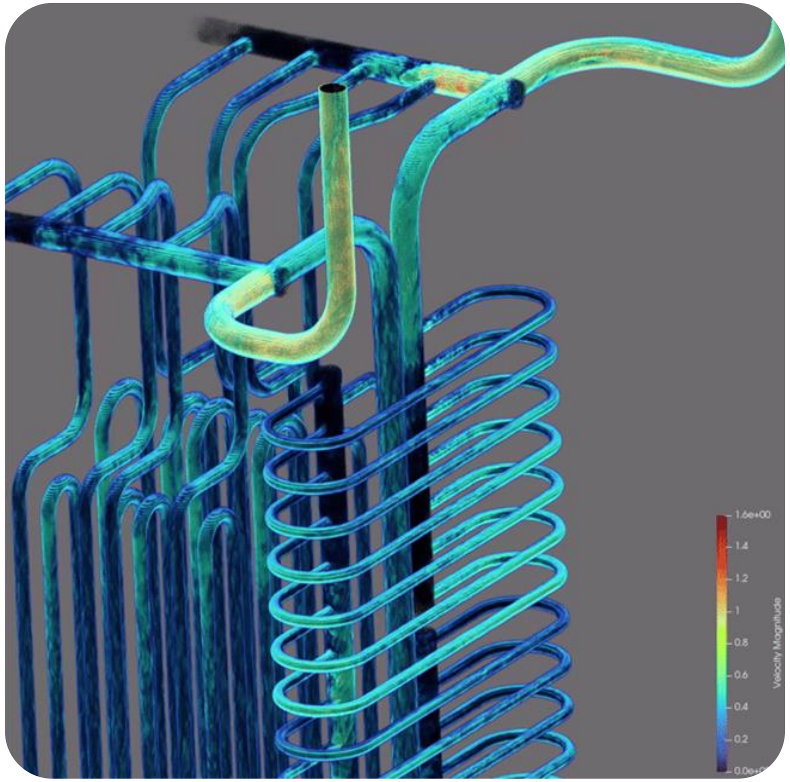
Models must **inform** the selection, design and operation of experimental rigs and facilities

Experiments at a **smaller scale** than a full reactor are still required

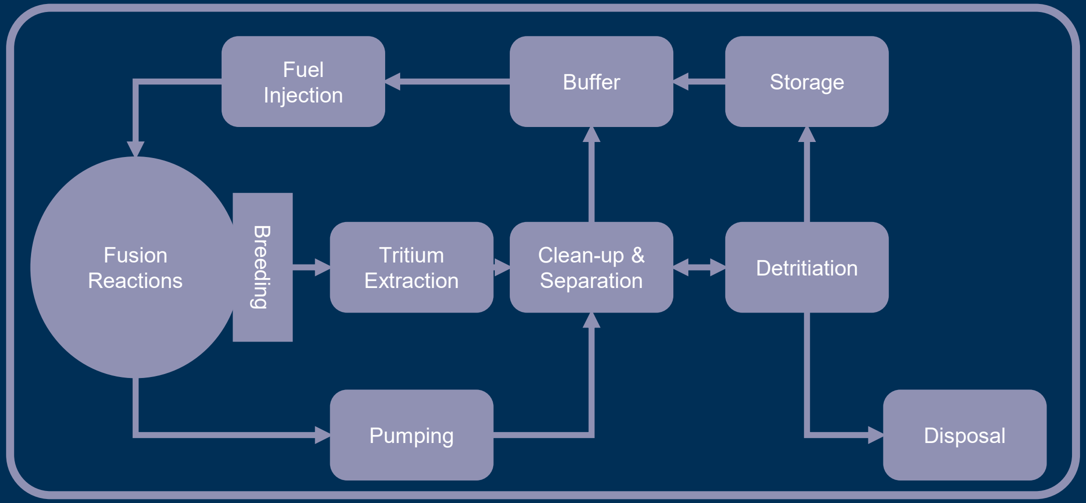
1. Model assumptions
2. Real-world complexity
3. Model validation and calibration
4. Computational complexity

Examples of modelling as a driving force in the delivery of fusion power:

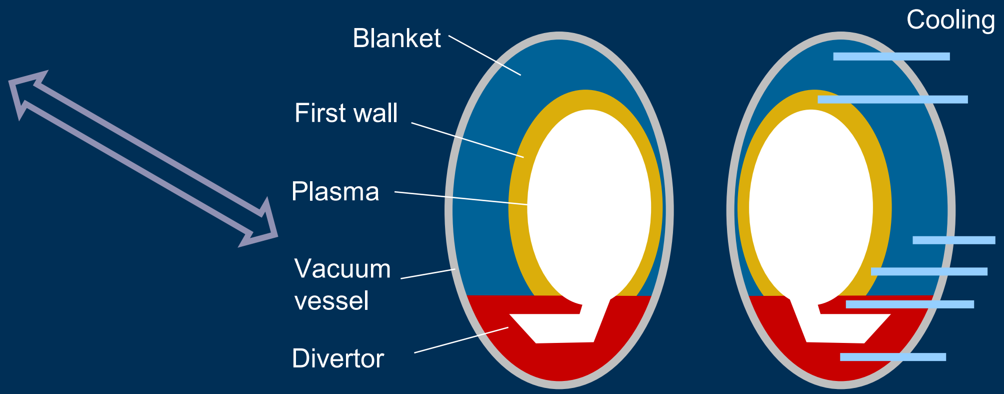
1. Tritium fuel cycle modelling
2. Materials development
3. Robotics and decommissioning
4. Virtual component qualification



Chimera heat transfer simulations – enabling optimised understanding of real-life system performance



Ex-vessel



In-vessel

Tritium fuel cycle modelling

Understanding tritium inventory requirements for a fusion power plant fuel cycle

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Tritium Integrated Modelling

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Aim: Develop models *that will provide tools to determine the* ***time evolution of tritium inventory*** *required to sustain a* ***viable fusion power plant*** *of a given design.*

- Inventory requirements in the literature give inventories in the range of **300g to 22kg** – used mean residence time methodology

UKAEA Approach

- Top-down dynamic models at plant and subsystem levels - no system stands in isolation and an integrated view including time evolution is essential to truly understand the relative contributions and requirements
- Bottom-up: understand dominant physical processes at a fundamental level – data not always available
- Our models utilise and influence data from all our tritium experiments and facilities
- Enable the assessment of design choices through their impact within full fuel cycle context

Tritium Integrated Modelling: Multi³ Approach

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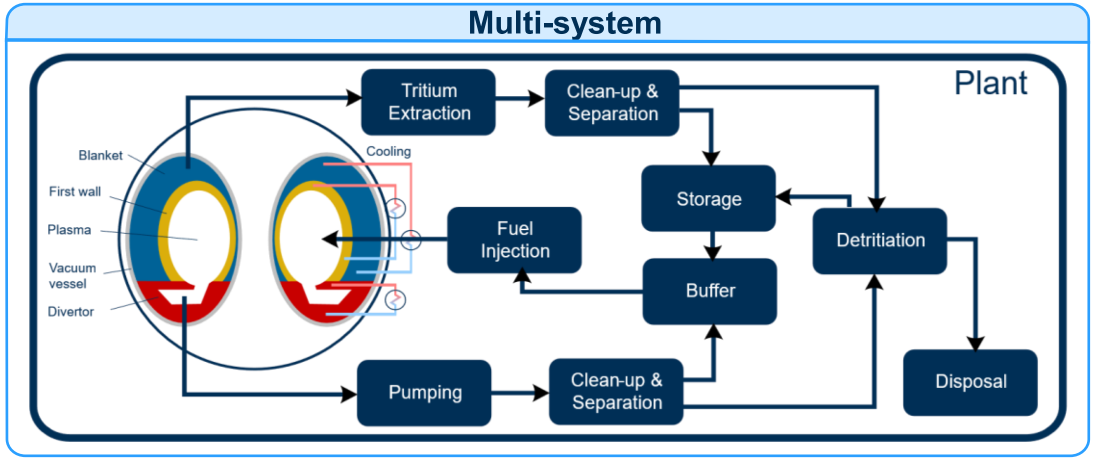
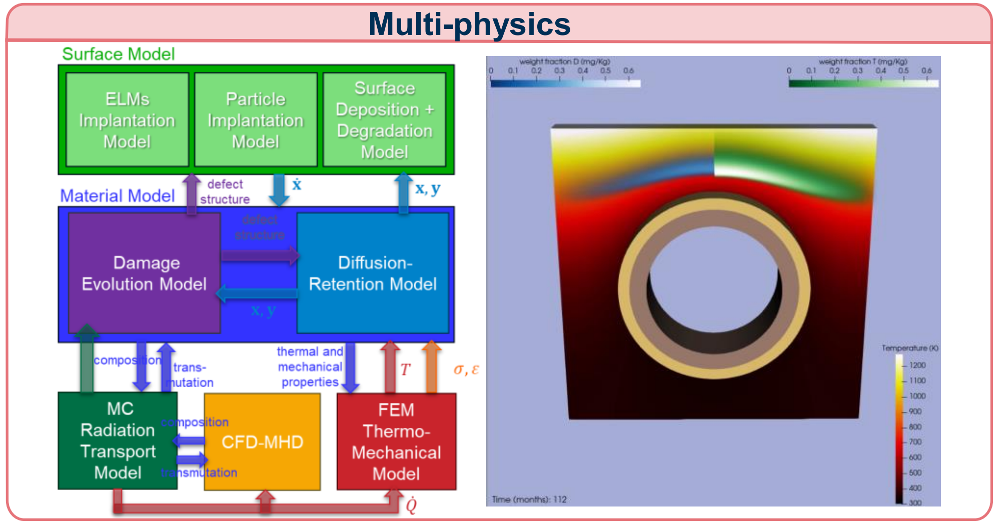
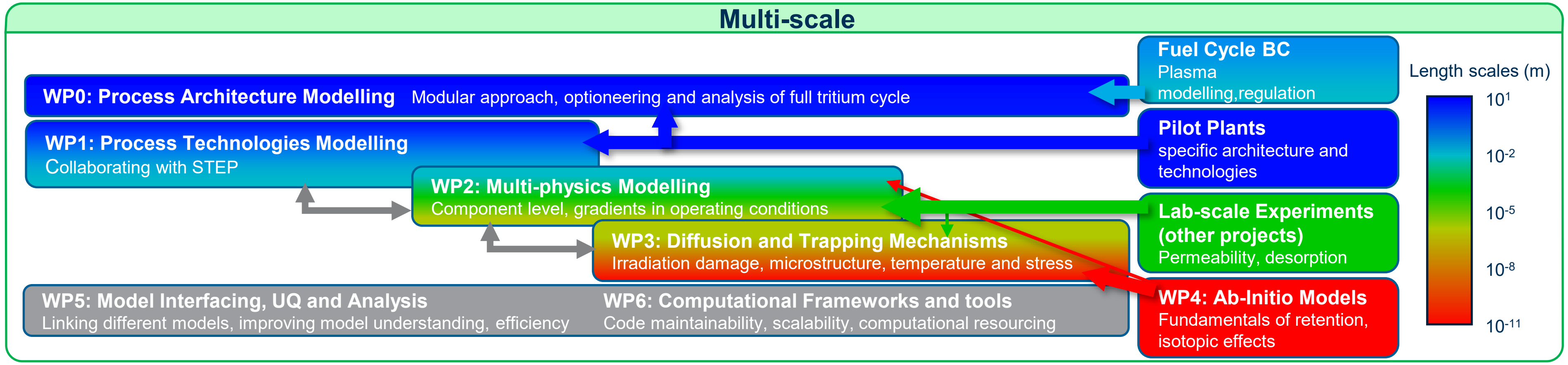
Develop models that will provide the tools to determine the **time evolution of tritium inventory** required to sustain a **viable fusion power plant** of a given design



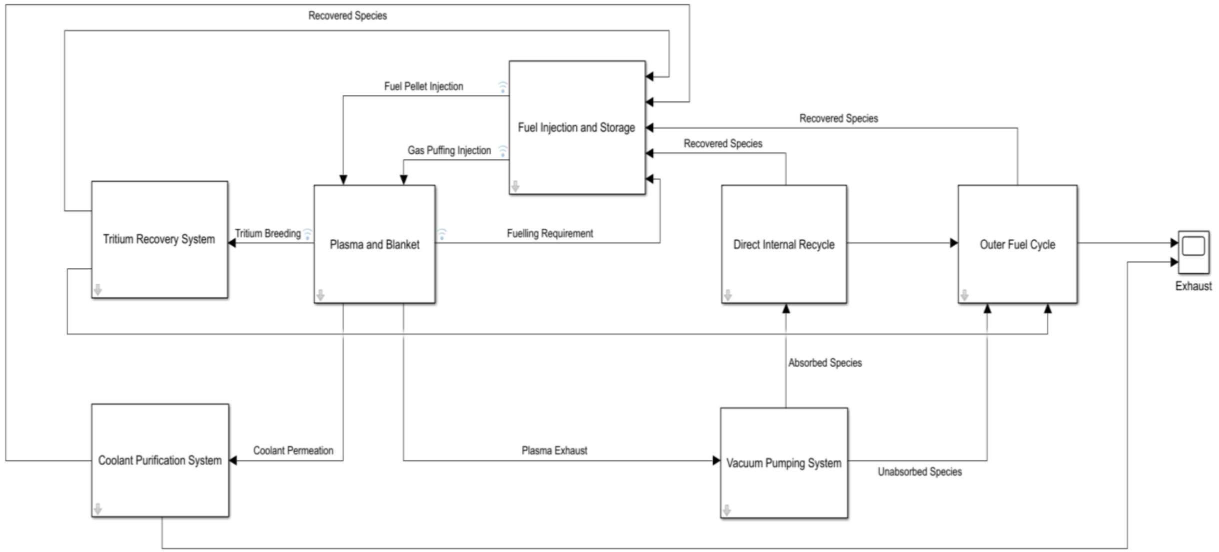


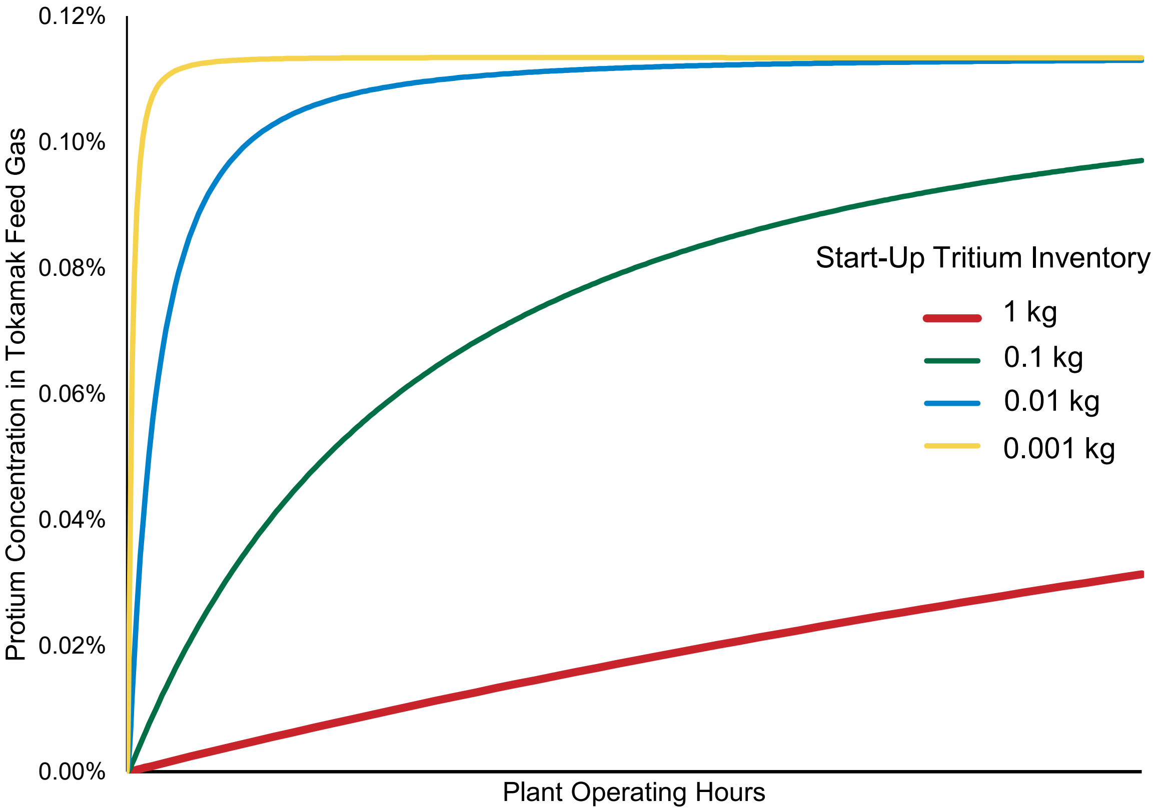


Tritium Integrated Modelling: Process Architecture

Simulink-based tool for modelling various fuel cycle architectures and studying the impact on tritium inventory

- **Multi-species** (H, D, T, He)
- **Dynamic**; each unit inventory changes over time. Batch processes can be modelled
- **Modular**; interfaces allow more complex unit models to be inserted





Materials development

The combined load of temperature, heat flux, neutron flux, magnetic fields and erosion that the in-vessel materials are exposed to is impossible to find anywhere **except** in a fusion reactor

Engineering materials for fusion

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Effects of high energy (14.1 MeV) fusion neutrons on in-vessel materials

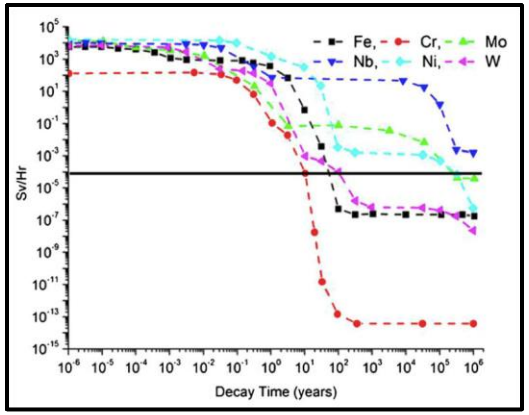
Transmutation:

Ni-58 + n ➔ Ni-59 + γ

Ni-59 + n ➔ Fe-56 + α

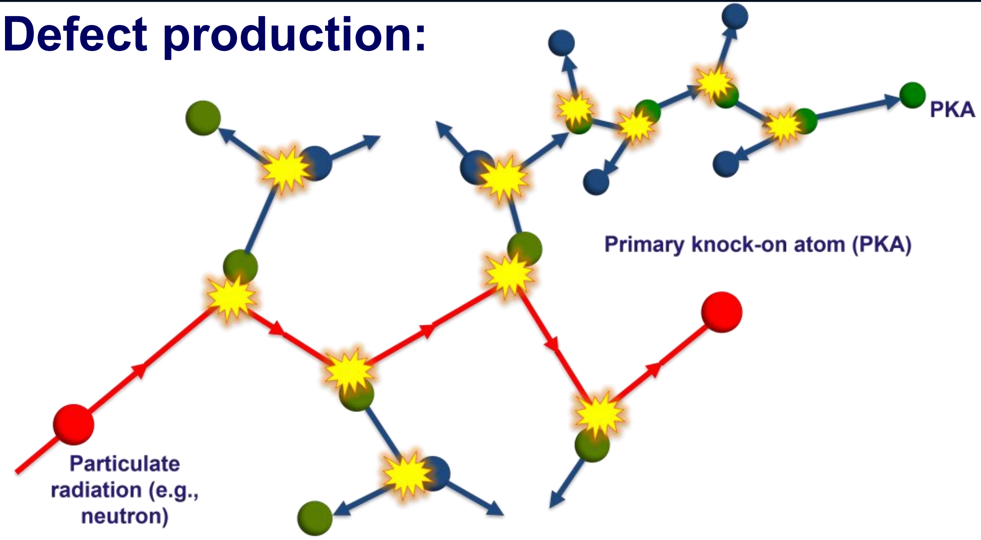
α + 2e⁻ ➔ He-4

→ embrittlement.



"Reduced activation" elements selected to target ILW and LLW production.

Defect production:



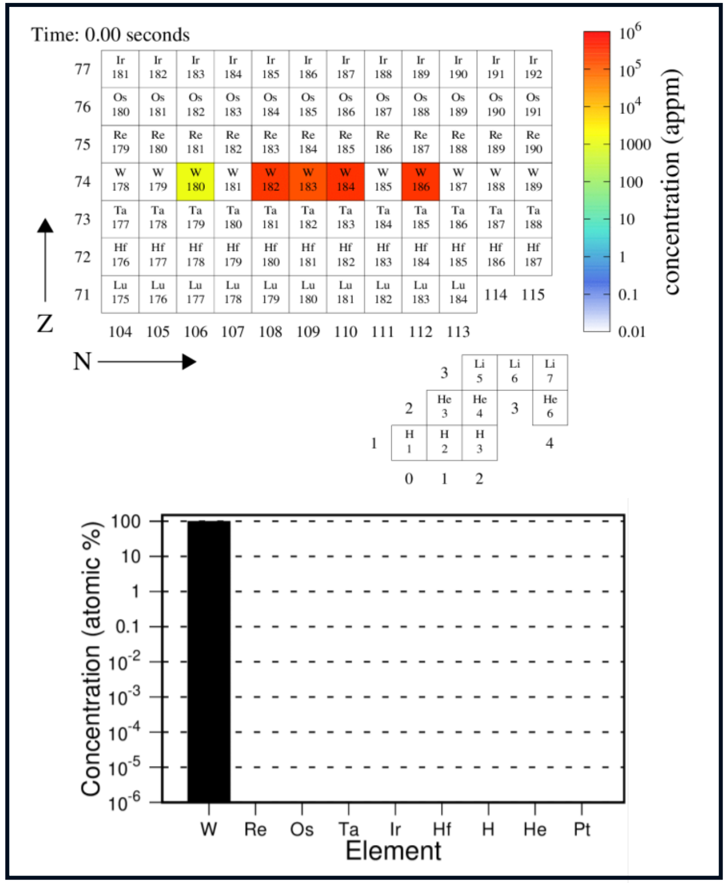
Our research focuses on engineering materials that can withstand these effects without generating high-level, long-lived radioactive waste

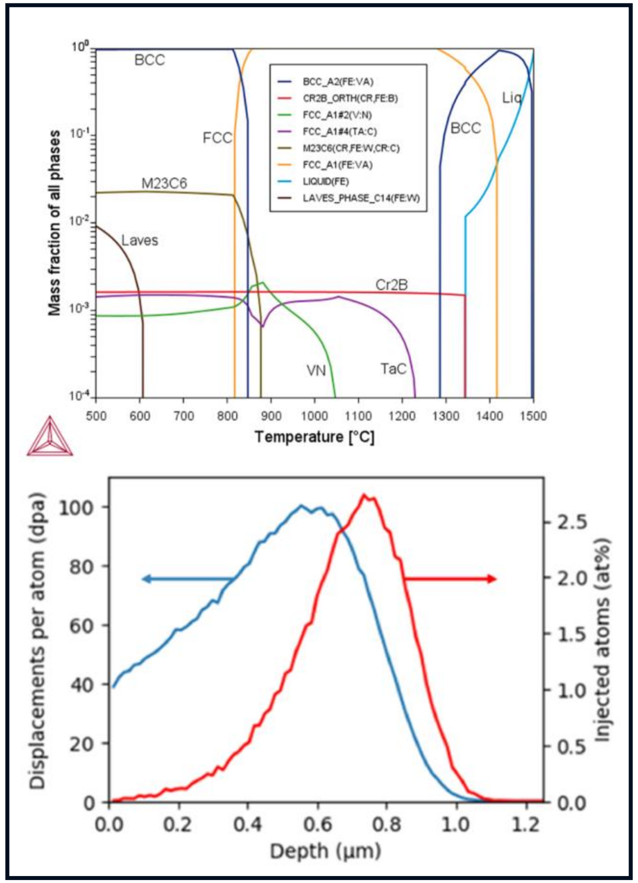
Gorley MJ. et al. Mat. Sc. Tech. **31** 8 (2015) 975-980

Engineering materials for fusion

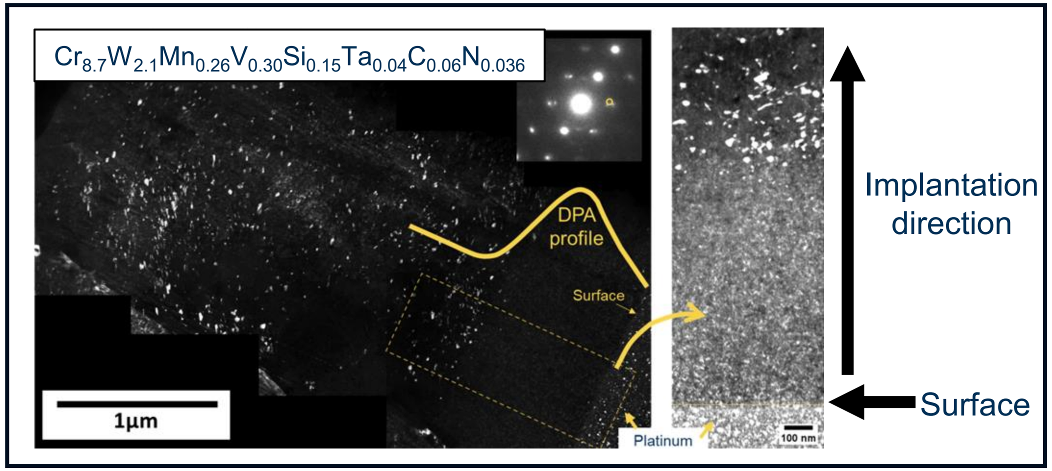
We utilise modelling to:

Inform material design and irradiation experiments





Provide insights into radiation induced material degradation and defect production, observed in experiments



Above: Haley J et. al. J. Nucl. Mat. 596 (2024) 155115.
Middle: Gilbert, M.R. et al., Nucl. Sci. Eng. 177 3 (2014) 291-306
Right: Goodall, R. et al., Ironmaking & Steelmaking 0 0 (2024).

Engineering materials for fusion

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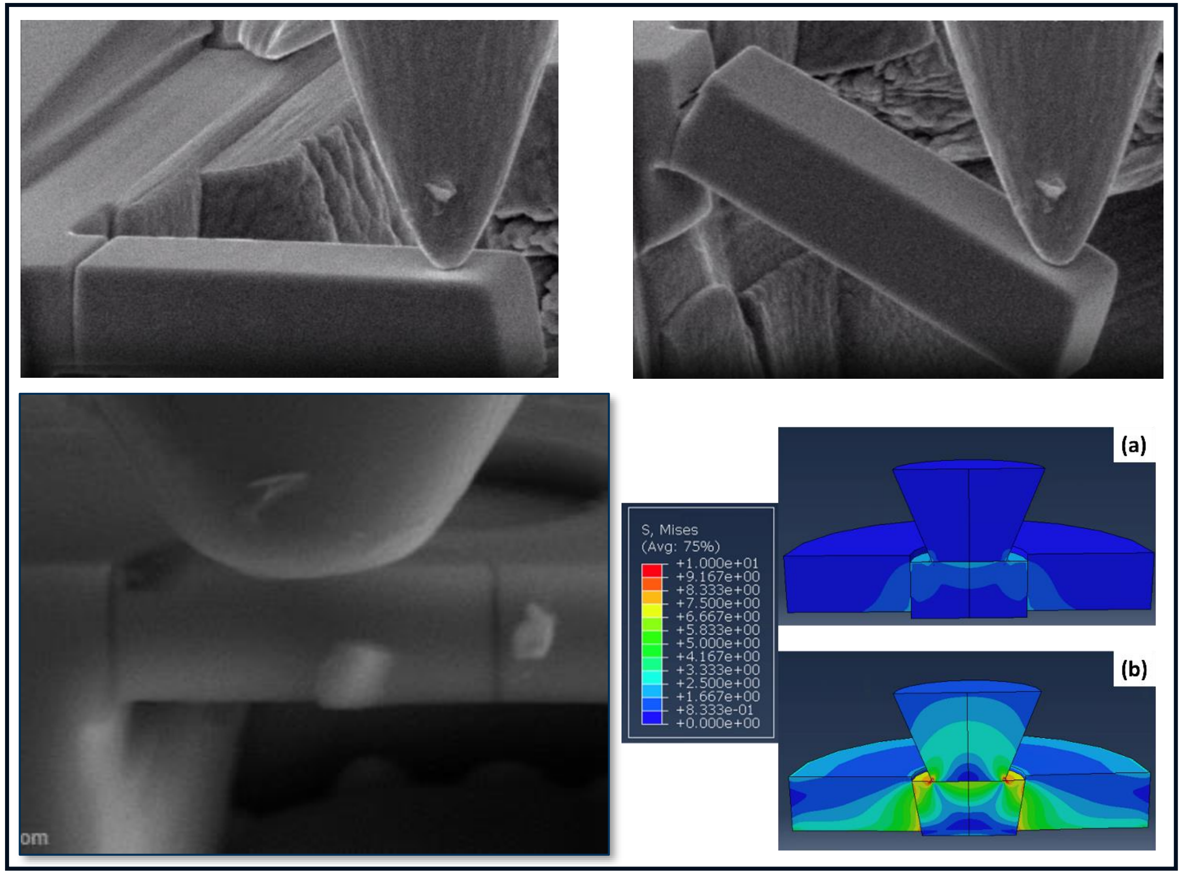
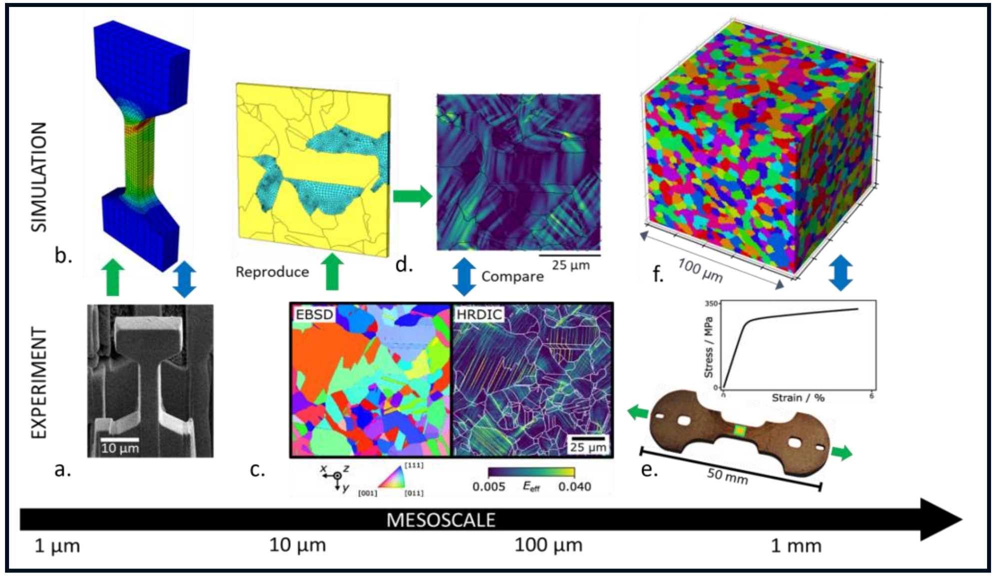
We utilise experimental data to support development and validation of computational models describing deformation and corrosion mechanisms, as well as defect production and evolution





Above: Leide A et. al. J. Eur. Cer. Soc. 45 (2025) 117624

Right: Quadling A. et al., Phil. Trans. R. Soc. A. 382 20230409 (2024)

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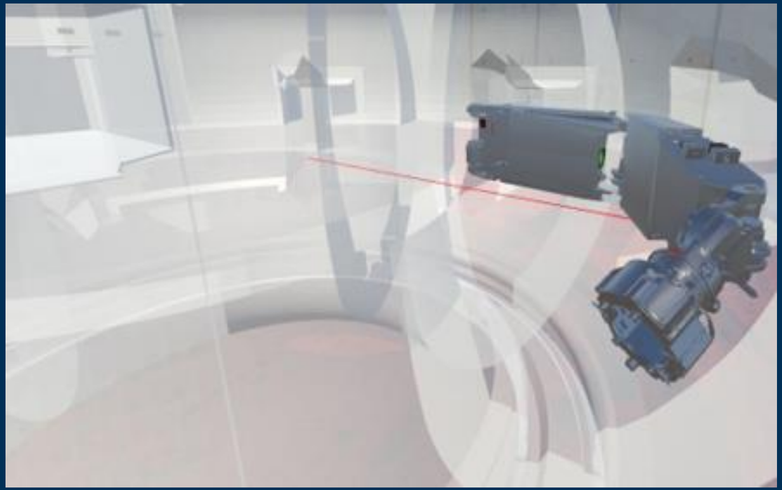

Robotics and decommissioning

Developing and optimising remote handling operations

Robotic Maintenance and Decommissioning

Digital first approach has been central to maintenance and decommissioning operations

Digital platform now at UKAEA

- Remote perception assistance
- Planning tool for operators

→

- Operation concept development
- Motion planning and rehearsals
- Advanced control and operation digital twin

New digitised functions

Robotics - Control & Operational Digital Twin

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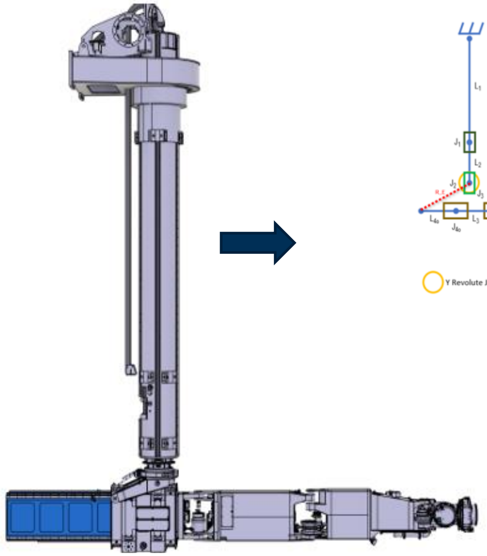
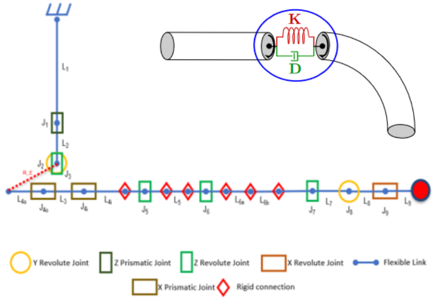
Advanced physics engine to simulate complex nonlinear dynamics

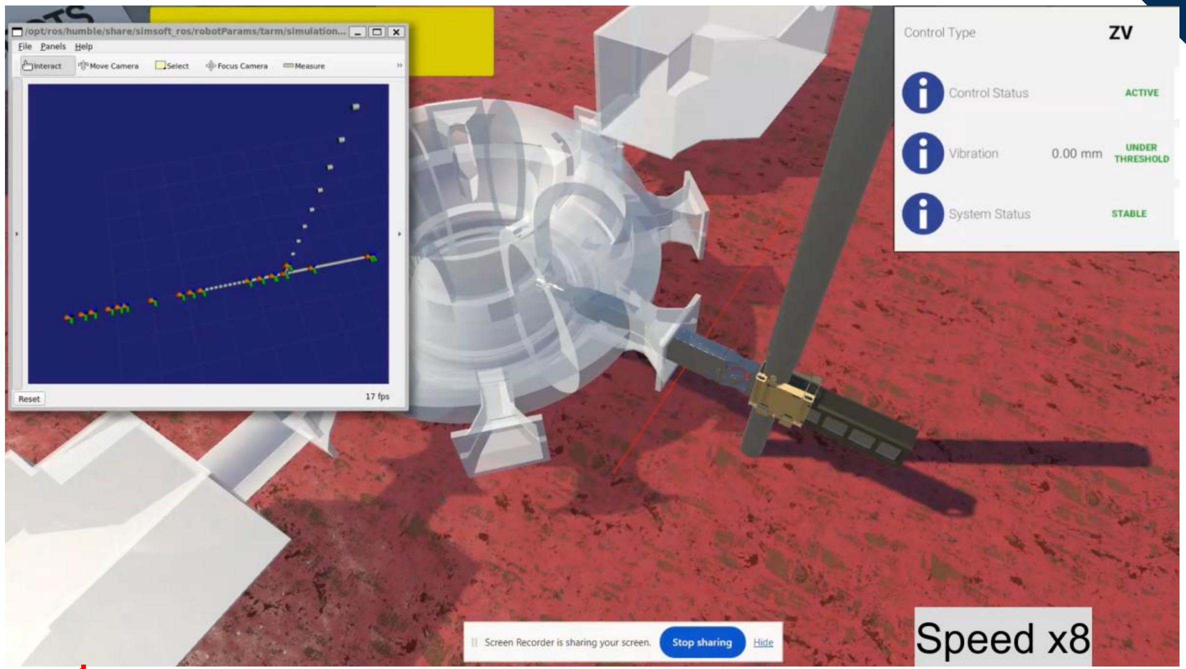
Real-time digital twin (including the robot's vibration & deformation) of operation



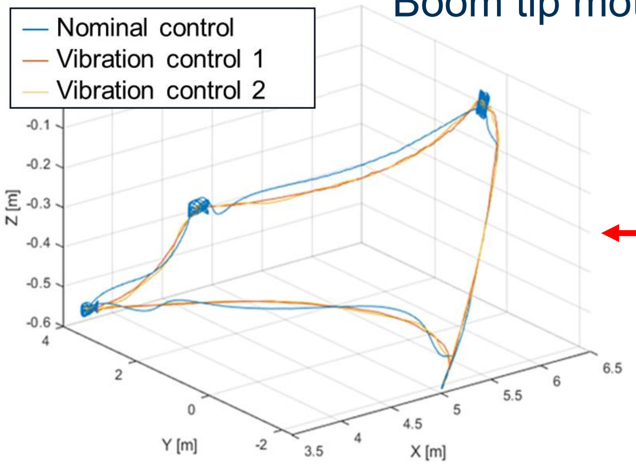


Physics engine

Digital twin

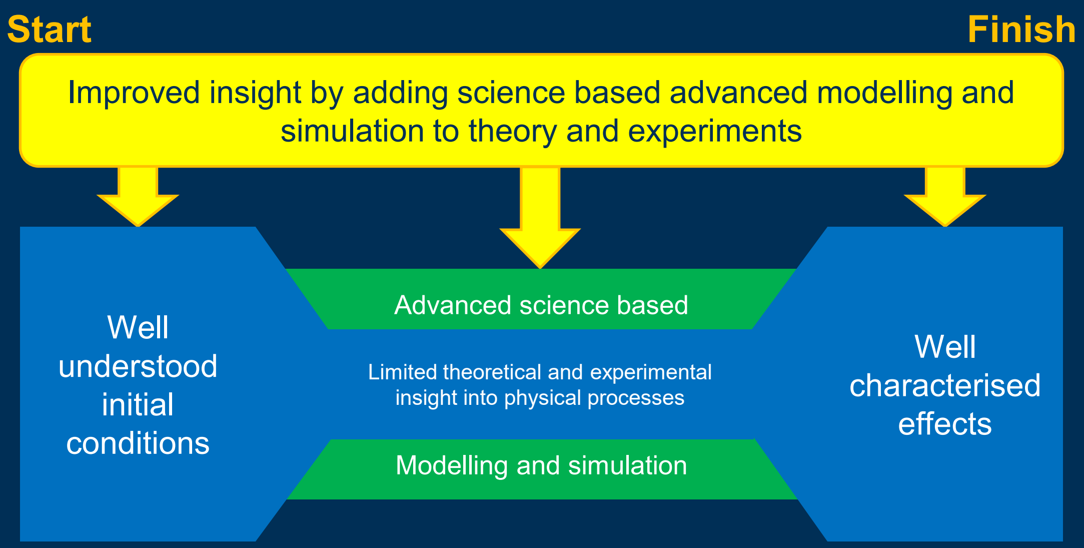


Boom tip motion



Long-reach operation (verified in validated simulation)

- 80% vibration reduction
- 3x faster operation speed
- No safety compromise



Component qualification

How to qualify components for operating in the extreme and untestable environment of a future fusion reactor

Lazelere 2010 DOE-NE

Roadmap to virtual qualification

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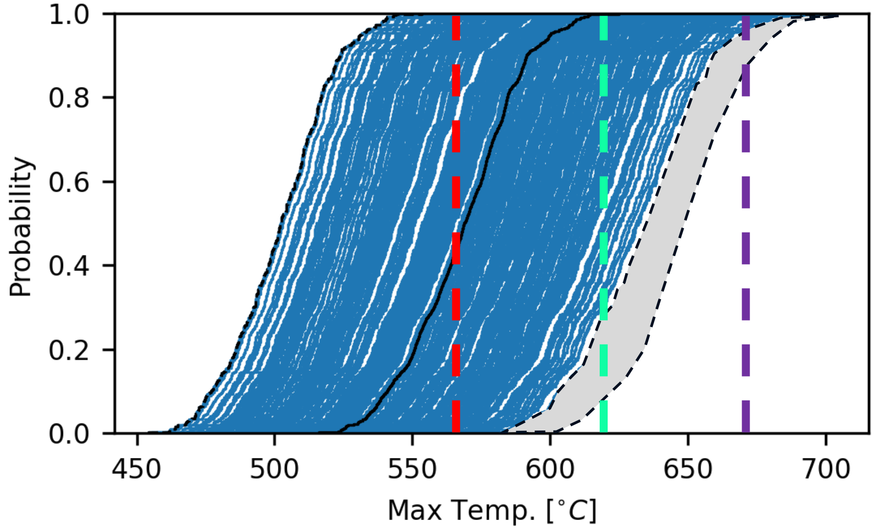
Validation approach incorporating uncertainty

Multiple validation experiments combined to overall model uncertainty

Extrapolation to models of untestable environments

Development of **Credibility Assessment Framework**

Possible failure criteria → 1 2 3



Probabilistic performance prediction, incorporating model validation uncertainty (grey area)

The goal: robust reporting to decision makers and regulators demonstrating predicted component performance and associated uncertainty

Validation example: induction heating of a monoblock

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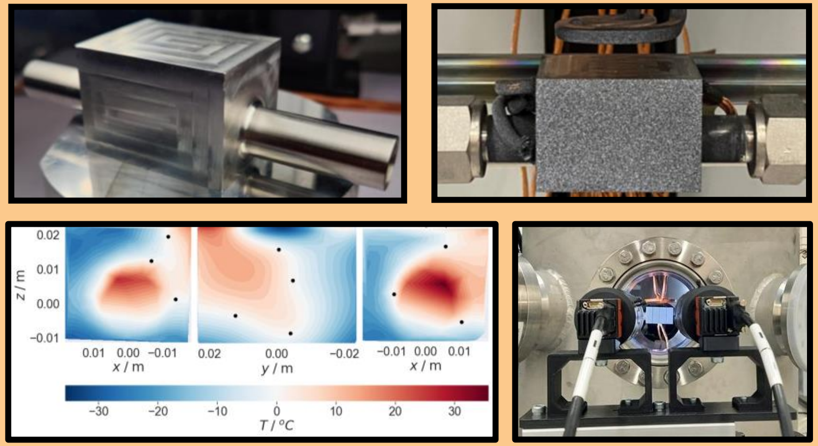
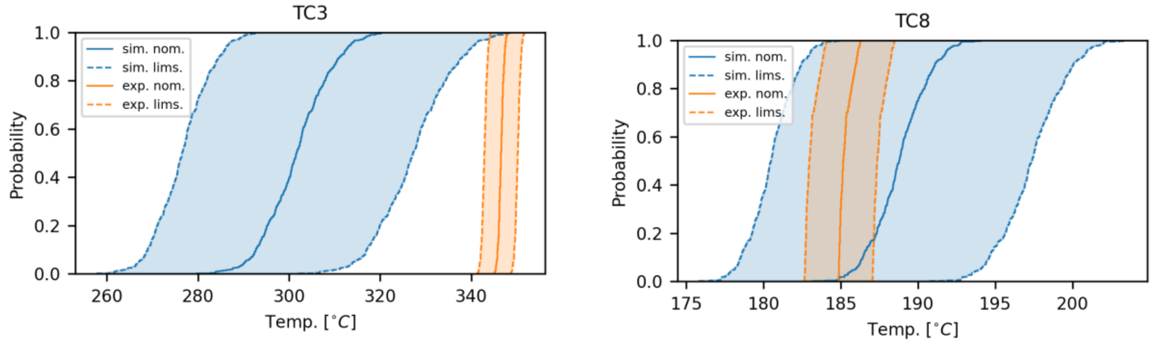
Data-rich experiments



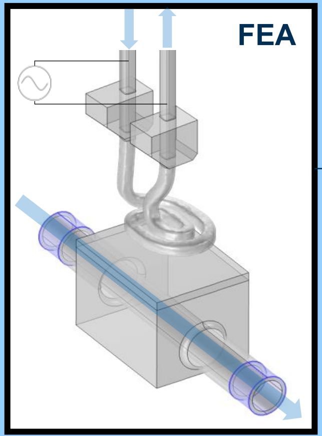
Robust results comparison with uncertainty



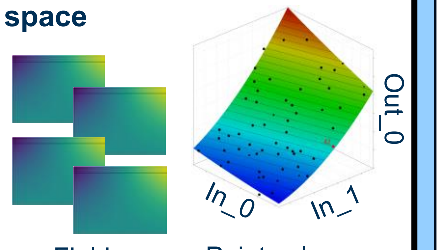
Probabilistic multi-physics model

Optimisation

Sensor uncertainty
Input approximation
Input data statistics

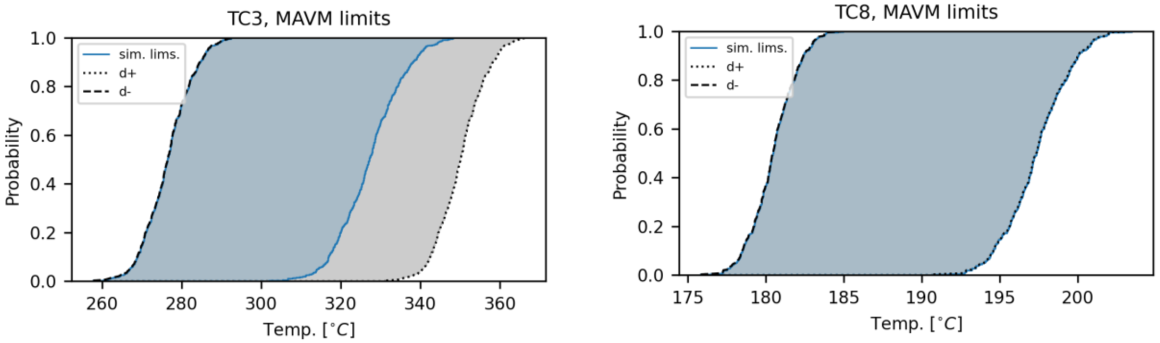


Predictions spanning input space



Statistical surrogate

Quantitative model validation



Probabilistic prediction (blue) + model validation uncertainty (grey)

Delivery of new facilities

Delivering new facilities

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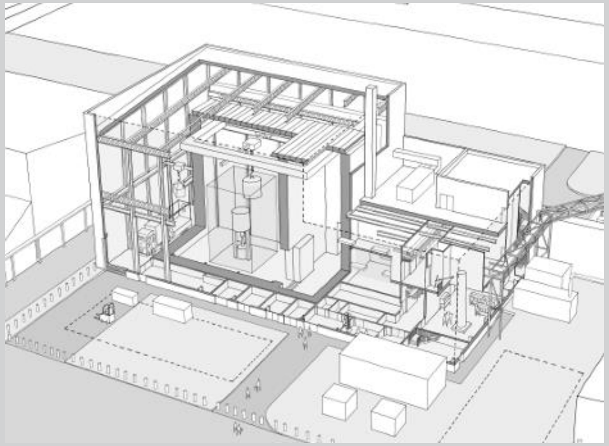
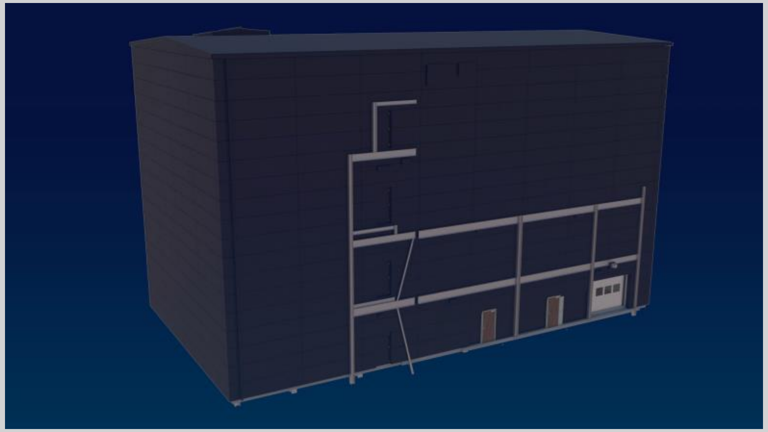
LIBRTI



- Reproducibly achieve tritium production with 14MeV neutron source
- Predict with digital simulations
- Able to handle lithium materials, as solid, liquid or molten salts
- Develop skills and knowledge of Breeder Blanket design and performance

Design process underway

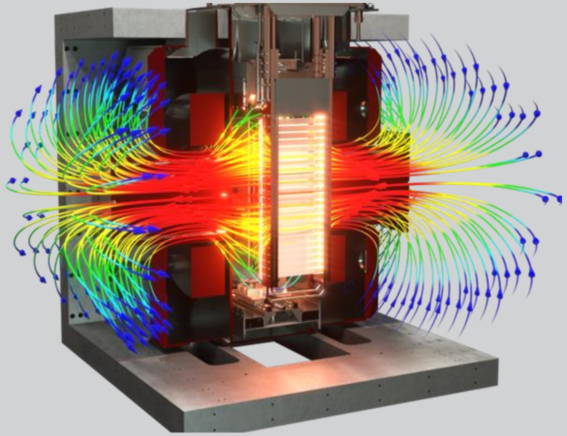
H3AT



- UKAEA is partnering with ENI to deliver a 100g closed loop tritium facility
- Digital twin already operational
- Develop, validate and derisk fuel cycle technology
- Significant space available for experimental work

Procurement underway

CHIMERA



- Testing of prototype components in a fusion relevant environment.
- High temperatures, high heat flux (HHF), high vacuum, static and pulsed magnet loads
- Simulation development will enable virtual qualification
- Key facility within the Fusion Technology Facility in Rotherham.

Under construction

Summary

UKAEA is focused on delivering solutions as quickly and efficiently as possible by utilising a digital first strategy to solve problems and guide strategic use of experimental facilities

This approach has delivered significant benefits across materials, tritium, robotics and many more areas of research

New facilities in delivery have prioritised the development of digital twins to ensure scientific output is maximised

Thank you!