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Towards a fusion component digital twin – virtual test and monitoring of components in CHIMERA by systems simulation

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Critical to the successful design of fusion reactor components is the development of coupled simulation models, capable of conducting efficient whole system design optimisation and virtual component qualification, under conditions which cannot be readily tested. Additionally, successful lifetime monitoring and predictive maintenance of fusion components through diagnostic measurements will be limited due to restricted accessibility and operation in a harsh environment. There is therefore a need for a component digital twin, which combines data from the physical instrumentation with simulation to provide abundant virtual diagnostics in real-time.

CHIMERA (Combined Heating and Magnetic Research Apparatus) is a unique, multi-physics fusion component loading facility under construction at the UKAEA Yorkshire site. CHIMERA will be used as a testing platform to develop and validate the virtual test and digital twin capability. Initial efforts are focussed on the post-commissioning testing, where the first experimental data will come from, with models of the commissioning sample under test (CSUT) being developed.

A systems simulation approach has been adopted covering hydraulic, thermal, electromagnetic, and mechanical domains. Each domain and section of the system are linked through fast-running surrogate models. This model forms the foundation for future developments to include probabilistic simulation, uncertainty quantification and real-time tracking alongside the physical asset.

Keywords: finite element analysis, multiphysics, qualification, thermal, electromagnetic

Glossary:

CHIMERA	Combined heating and magnetic research apparatus
CMS	Component mode synthesis
CSUT	Commissioning sample under test
DEMO	Demonstration power plant
DOE	Design of experiments
EM	Electromagnetic
FEA	Finite element analysis
FMU/(I)	Functional mock-up (interface)
HTC	Heat transfer coefficient
ITER	International Thermonuclear Experimental Reactor
PFC	Plasma facing component
ROM	Reduced order model
STEP	Spherical Tokamak for Energy Production
SUT	Sample under test

1. Introduction

Design validation, operational lifetime monitoring and maintenance of engineering components is a common need across all engineering sectors. In the fission industry, digital frameworks have been suggested to assist with such issues [1]. Fusion has some key challenges which have been discussed in [2], namely the inability to rely on extensive testing, in-operation diagnostics, or periodic inspection. The ability to fully replicate the complete operational component environment and loading conditions of a component is only possible within prototype fusion reactors, which will be limited due to prohibitive costs and timescales. The challenges and implications of regular in-service inspection and the potentially consequences of failures of in-vessel components means that predictive maintenance based on in-situ monitoring will be necessary. However, the harsh environment and challenging access for instrumentation means the data will be sparse and potentially unreliable to some degree. Additionally, the processing of such data to predict maintenance cannot rely on a wealth of historical in-field operational data; a shift away from the need for such data has been highlighted in other industries, such as aerospace as early as 2012 [3]. In line with this, evaluation and validation of fusion component designs and predictive maintenance over the component life must rely heavily on simulation and smaller scale test facilities.

The CHIMERA test facility is one such facility, currently under construction at the UKAEA Fusion Technology Facility in Rotherham. CHIMERA is a unique facility for combined thermal and electro-magnetic load testing of metre-scale prototype plasma facing components (PFCs) or in-vessel hardware. The capabilities and specification for the facility have been detailed in [4].

The key goals for development of simulation capability to support the challenges outlined above are listed below:

1) **Maximise the value of testing campaigns and the data produced**
   As the quantity of measured data from any fusion relevant facility is limited, the value of this data needs to be maximised through an efficient model calibration process that uses this data to continually improve the model predictive capability and reduce the model uncertainty. To ensure the data obtained is of maximum value, the simulations need to be utilised to plan the operations and to optimise the diagnostics strategy.
2) **Enable simulation of components within the context of the full system operational environment with quantified uncertainty of the outputs**
   To capture the component interactions with other component systems and the environment, the simulation must incorporate these and provide a virtual representation of the full system capable of quantifying the uncertainties of the simulated outputs.
3) **Enable the full system operational simulations to be performed live to provide additional diagnostics for fault monitoring and predictive maintenance**
   To allow lifetime monitoring and predictive maintenance the simulations must be capable of running live, and potentially in real-time, to allow the relatively sparse diagnostic data and rich simulation data to be combined to provide enhanced diagnostics with reduced uncertainty. This capability is provided through development of a digital twin of the facility.

This paper provides an overview of the strategy and status of the simulation capability development at UKAEA to achieve the goals outlined above, using the CHIMERA facility as a use case. CHIMERA will be vital for the qualification of PFCs and, within the scope of this work, the simulations will be used directly to maximise the value of the test data and design efficient test campaigns, as well as to provide interpretable and actionable test results.

For the prototype power plant class of tokamaks, such as DEMO [5], [6] and STEP [7], there will be load cases and operating conditions for PFCs which can only be tested in the reactor environment. This means that the design must be developed with state-of-the art simulations supported by available rig-testing validation. CHIMERA will be a key provider of validation data, with representative loading for heat flux and static/transient magnetic loads. CHIMERA testing is a significant step forward for gathering data on PFC behaviour in a representative environment; however, there is missing physics, such as material degradation due to neutron irradiation. Hence, design validation before reactor operations will need to be based on integrated models of all physical predicted effects, which are validated from a variety of test sources; similar strategies are being discussed in aerospace [8]. Once the power plant is operational, simulations used during design will be continually updated with the observed operational history to provide up-to-date predictions of PFC life.

As a precursor to a simulation that can predict component behaviour in a reactor environment, the initial aim of this work is to develop validated simulations of component mock-ups in the CHIMERA environment. These simulations are now in the development phase and will be used to perform virtual tests; currently they can be used in advance of testing for test plan optimisation. Once initial tests are completed, the models will be calibrated against the test data. The aim of this work is to test the simulation capability against multiple CHIMERA SUTs (samples under test) and load cases, to the point where validated simulations can replace the tests altogether, or at least reduce the need for more extensive test campaigns where there is loading/design novelty.

The integrated simulation developed for this purpose forms the foundation of a digital twin of the facility. Although live augmented diagnostics are not essential for CHIMERA, the CHIMERA facility provides an excellent platform to develop this capability in advance of the need on full prototype tokamaks such as STEP and DEMO. A three-phase approach is being taken to work towards this fusion component digital twin: in the first phase, the underlying simulations are being developed; in phase 2, a pseudo-live coupling will be linked to the CHIMERA test database to operate the model as a digital twin; the final phase is to integrate a digital twin to run in real-time alongside CHIMERA testing.

This document is structured as follows. In Section 2, the specific strategy which will be adopted for the initial test case, CHIMERA commissioning, will be described. Section 3 will give an overview of the current systems simulation which has been built for the CHIMERA commissioning sample under test (CSUT). Section 4 will discuss the results generated thus far, and Section 5 will give an overview of the next steps to further develop this capability.

2. Strategy

To provide the simulation platform for conducting virtual operations and form the basis for a digital twin, a systems simulation approach has been adopted. Systems simulation can be defined as [9]:

> *The use of interdisciplinary functional, architectural, and behavioural models (with physical, mathematical, and logical representations) … to specify, conceptualize, design, analyse, verify and validate an organized set of components, subsystems, systems, and processes.*

The systems simulation approach is suited to this application because it is:

- Fast running
- Multi-domain – designed for coupling mechanical, thermal, fluid domains together
- Modular – multiple models are connected into a single simulation, meaning individual parts can easily be updated
- Flexible fidelity – as well as coupling 1D elements, higher fidelity simulations can be coupled into the model

Due to the requirement to run these models probabilistically, there will be thousands of iterations to run. Furthermore, to support the eventual goal of digital twinning, a method that can generate fast running models is essential. To meet this aim of fast running models, the systems model is comprised of multiple reduced order models; these represent different physics/sub-components, which can then be coupled together in a systems simulation software. The method presented in this paper is an initial process which will be continually developed; hence the modularity of systems simulation is appealing, since different sections of the model can be readily replaced without a lot of re-work.

A key technology to enable the linking of multiple solvers/surrogate models in the systems simulation is the functional mock-up interface (FMI) [9]; this is a free standard that defines the interface between many tools. Systems simulation software already has multiple built-in code integrations; however, FMI expands the available toolset to many other commercial and open-source tools. These can run in either model exchange or co-simulation modes [10].

The model which will be presented in this paper utilises 1D elements, multiple reduced order models (ROMs), and decomposes the CSUT geometry into multiple parts. Here ROM refers to a metamodel, surrogate model or emulator of an FEA simulation. These are then connected to create a systems simulation. Loads due to each physical domain in the model, such as fluid, thermal, or electromagnetic (EM), are modelled through separate 1D models or ROMs, but can then be connected through two-way coupling to capture the influence of each system on the other. An initial example of this is presented in Section 3. Utilising this approach reduces the complexity that is captured in each ROM. It is postulated that this will result in a more accurate model compared to building a ROM which combines all these complex multiple relationships. Verification and validation activities to confirm this hypothesis are currently being planned.

There may be assumptions that limit the range of validity of the system simulation; for instance, Joule heating is not accounted for. The benefit of the systems simulation approach is that additional fidelity can be included in the model by coupling to full-physics software where required. An initial model is being developed, which will be compared against test data. If this does not agree within the uncertainty limits of the test and simulation data, then the simulation would need to be revisited.

There are other approaches which can be taken to solve this problem; for instance, full multi-physics codes can be used which can couple fluid, thermal, mechanical and EM loads on the solver level [11]. There are developments in this area to improve solvers, scalability and utilise additional computational power. This capability will likely form part of the solution either through generation of data for ROMs, cross-verification of the systems model or full-physics integration within the systems model. However, in the context of targeting probabilistic simulation in real-time the systems simulation of coupled ROMs will inevitably form the basis for the simulation and any direct integration of full-physics models will be targeted at specific sub-models where this need is identified.

3. CHIMERA Systems Simulation Model

The first data to be generated for the CHIMERA test rig will be during the commissioning phase. For these purposes, a test sample has been developed which is representative in size of an ITER test blanket module [12]. It will generate similar EM loads as a test blanket module and is able to absorb the heating power from CHIMERA (both from the surface heater and simulated volumetric heating), whilst being water cooled at pressurised water reactor conditions (up to 330°C, 155 bar). An overview of the CHIMERA test rig is given in Figure 1. Figure 1 and Figure 3 give an overview of the CSUT design, with the dimensions and separate views showing the fluid circuit and ferromagnetic material. A systems simulation of the CSUT has been developed and will be described in this section. The CSUT design detailed in this study is the concept design; the final manufactured design may differ slightly.

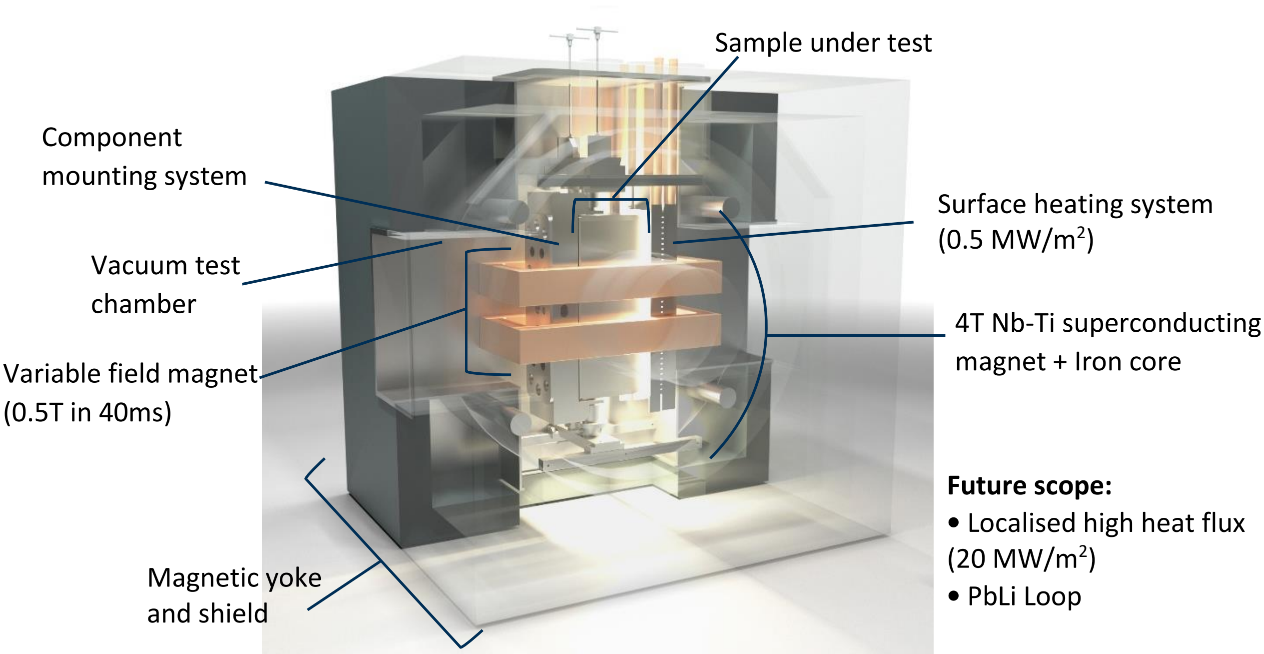

Figure 1: An overview of the CHIMERA test rig and systems

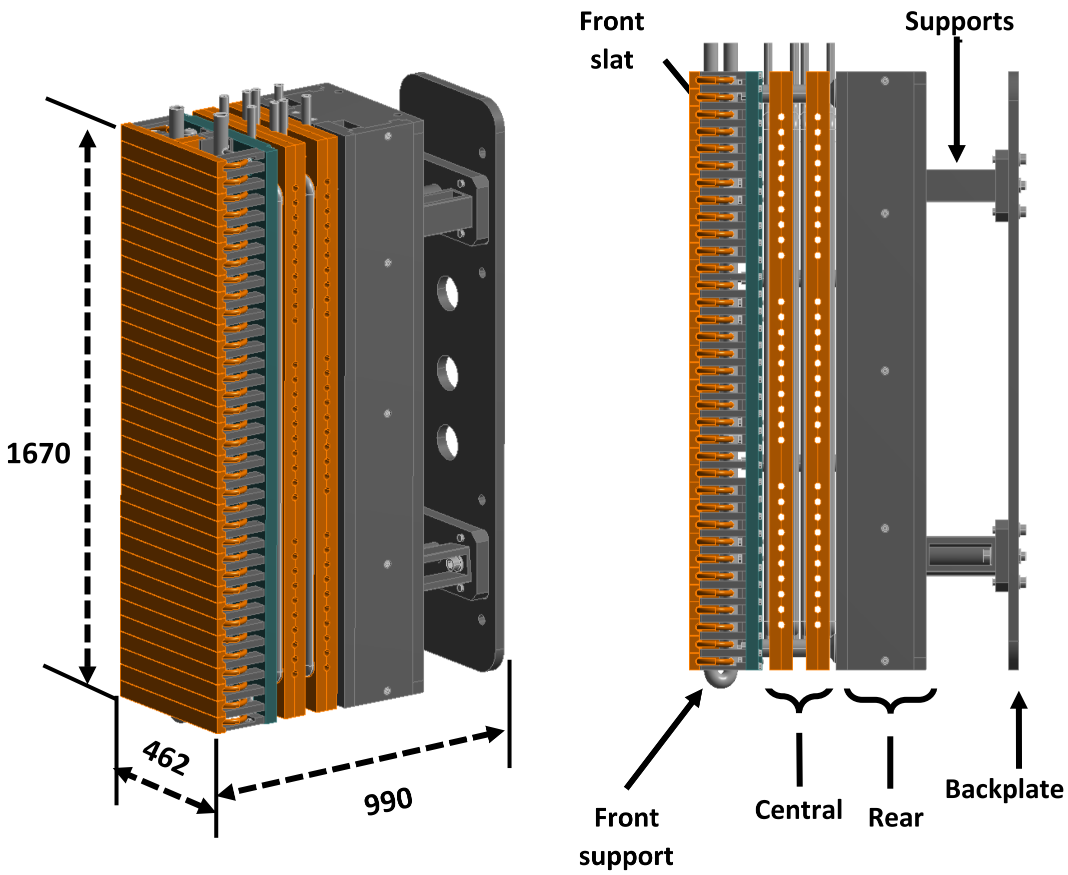

Figure 2: Overview of CSUT-thermal design (dimensions in mm)

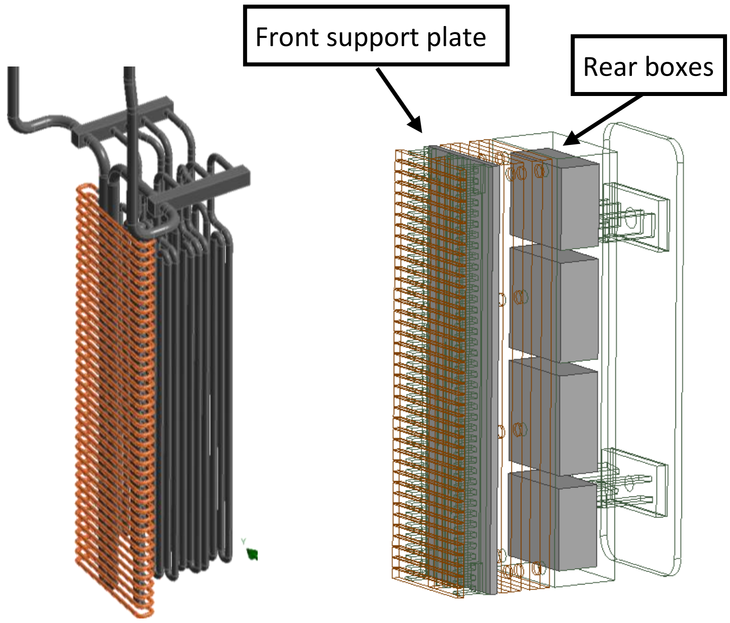

Figure 3: Left: Fluid circuit of the CSUT. Right: Location of ferromagnetic material in the CSUT.

3.1. Reduced Order Model Generation

The same methods have been applied to the generation of ROMs for multiple domains in the systems simulation. The generic process to develop a ROM is to:

- Select input variables and required range of validity for the ROM
- Generate FEA training data using a design of experiments (DOE)
- Train the ROM using machine learning algorithms

The algorithms used in this study to generate a DOE were a combination of central composite design [14] and optimal space filling (a modified version of Latin hypercube sampling [15]) algorithms. This approach was chosen to ensure that the design space and bounding values had been covered by the training data.

The ROMs were then generated using the genetic aggregation algorithm [16]. This ROM fitting algorithm automates the process of selecting a response surface type and finding the best response surface for each design parameter; the final response surface is then a linear combination of multiple response surfaces.

Both scalar and field ROMs have been used in the CSUT systems simulation. For a scalar ROM, the model is trained to output a single value. 3D field ROMs give a prediction for the full field, with an output for every node of the training data. Initially, the field is decomposed into a series of modes and coefficients through use of singular value decomposition [17] (this is documented for a different kind of ROM by Ansys Inc. here [18]). The genetic aggregation algorithm is then applied to train the ROM on the coefficients; the field can then be reconstructed for each point with the predicted coefficients and modes.

3.2. Model Overview

The systems simulation is used to couple the physical domains and sub-components of the CSUT together. The initial version of the model consists of the following components:

- Quasi-1D fluid network
- Static EM load scalar ROMs to predict the loads experienced by the ferromagnetic material in a static magnetic field
- Thermal, stress and strain steady-state 3D field ROMs for each CSUT section

- Component mode synthesis (CMS) [13] based mechanical reduction of CSUT sections

This model does not include loads due to the transient magnetic pulse of the CHIMERA variable field magnet. This is further work which will be discussed in Section 5. Two-way coupling between the thermal and fluid model is included in this simulation, where the increased wall temperature due to the surface heater flux is fed back into the fluid model as a boundary condition.

3.3. Quasi-1D Flow Modelling

The flow model has been developed in Simcenter Flomaster (version 2022.1) with customised modelling elements provided through an in-house quasi-1d flow platform. These customised modelling elements are implemented in Flomaster using the scriptable "N-arm" component allowing many signal inter-change connections to be added to it, such as heat transfer coefficients (HTCs) and wall temperature, not currently available in the default components. The custom elements also contain correlations capturing magneto-hydrodynamic effects which will be required for future CHIMERA SUTs when the PbLi liquid metal loop is operational.

A single model is used to represent the CSUT fluid circuit, which is shown in Figure 3. The fluid model is used to predict the pressure drop, fluid temperature and HTCs throughout the circuit. The HTC values are calculated through use of the Dittus-Boelter correlation [14], and the pressure drops using the Swamee-Jain equation [15].

At multiple spatial locations in the fluid model there are interfaces with the thermal model where the HTC, fluid temperature and wall temperature are exchanged, as shown in Figure 4. The Flomaster model is integrated in the systems simulation as a co-simulation [16] functional mock-up (FMU).

Figure 5 shows a section of the quasi-1D fluid flow model. The flow enters the CSUT through a manifold and is split between the front slat and central sections of the CSUT. The 35 front slat pipes are split into sections of 7-off pipes. As can be seen in Figure 5, the 1D model predicts some differences in HTC in the 7 first wall pipes, due to their flow rate differences. In the systems simulation when the fluid and thermal model are linked, this results in non-uniform temperature predictions across the front face of the CSUT, which will ultimately be validated with thermocouple measurements from CHIMERA testing.

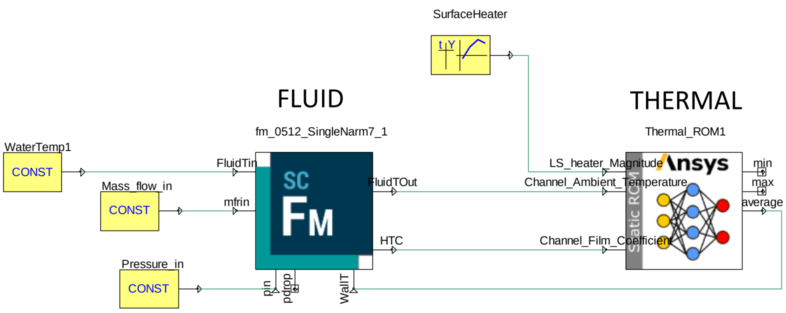

Figure 4: Two-way coupling between 1D fluid model and thermal ROM

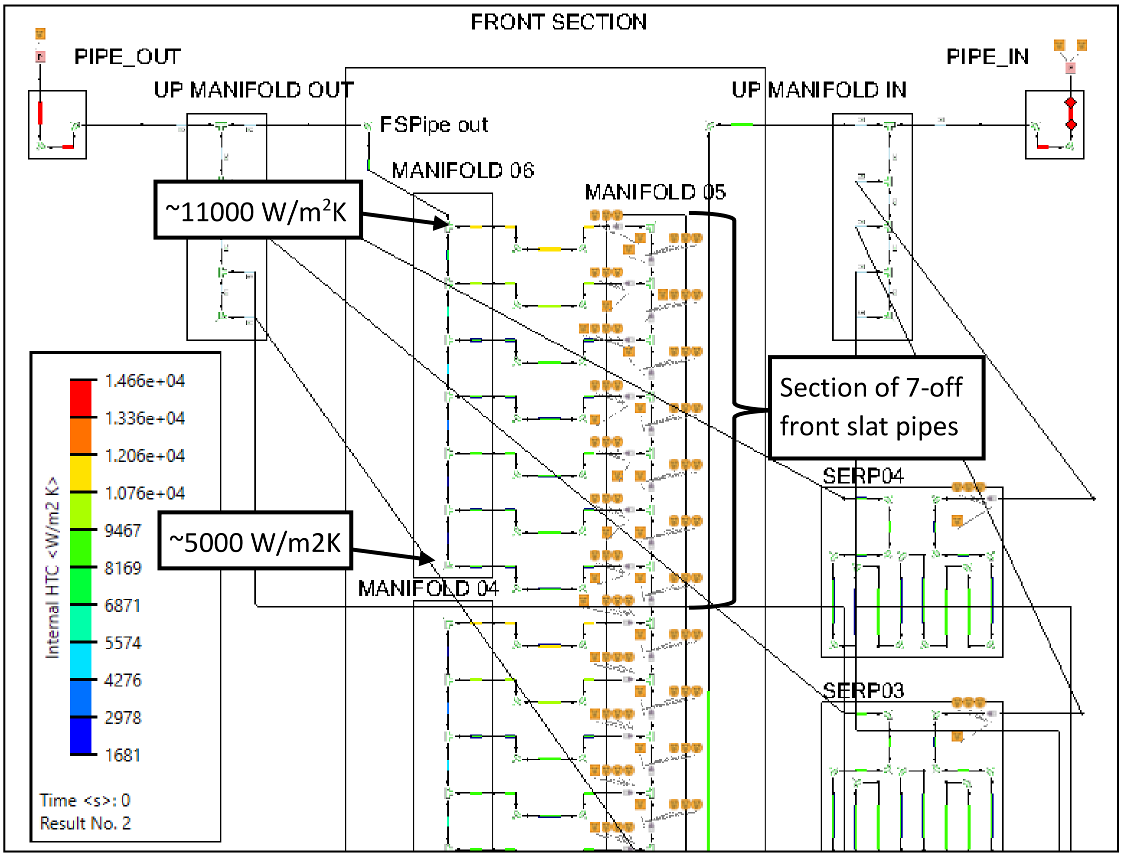

Figure 5: Results of HTC distribution throughout the 1D flow network.

3.4. Static electromagnetic modelling

A static EM analysis has been performed in Ansys Maxwell (2021 R2); a diagram of the model used is shown in Figure 6. In this instance, the analysis was used to calculate the net forces experienced by the ferromagnetic components of the CSUT due to a static magnetic field generated by the superconducting (SC) magnets. In future, this model will also be used for transient EM analysis to capture the effect of a reversing current being driven through the variable field magnet coils.

A set of static EM ROMs was generated from the FE analysis. Two input parameters were varied to build the ROMs, namely the current driven through the SC magnets and the CSUT position in the X-direction. Prior to running an experiment on CHIMERA, the CSUT can be positioned within a total range of 150mm in the X-direction, which gives a variation in net load of approximately 30kN on the front support plate. This variation in net load is caused by a gradient in the magnetic field along the X-direction. These load predictions highlight the importance of capturing potential variations in the experimental setup and the benefit of performing virtual testing prior to operation.

The EM ROMs were built from a DOE of 47 training points, and five validation points (outside of the DOE) were also analysed. The maximum relative error, across all the static EM ROMs, was calculated to be less than 5%; this could potentially be reduced further by adding additional refinement points to the DOE.

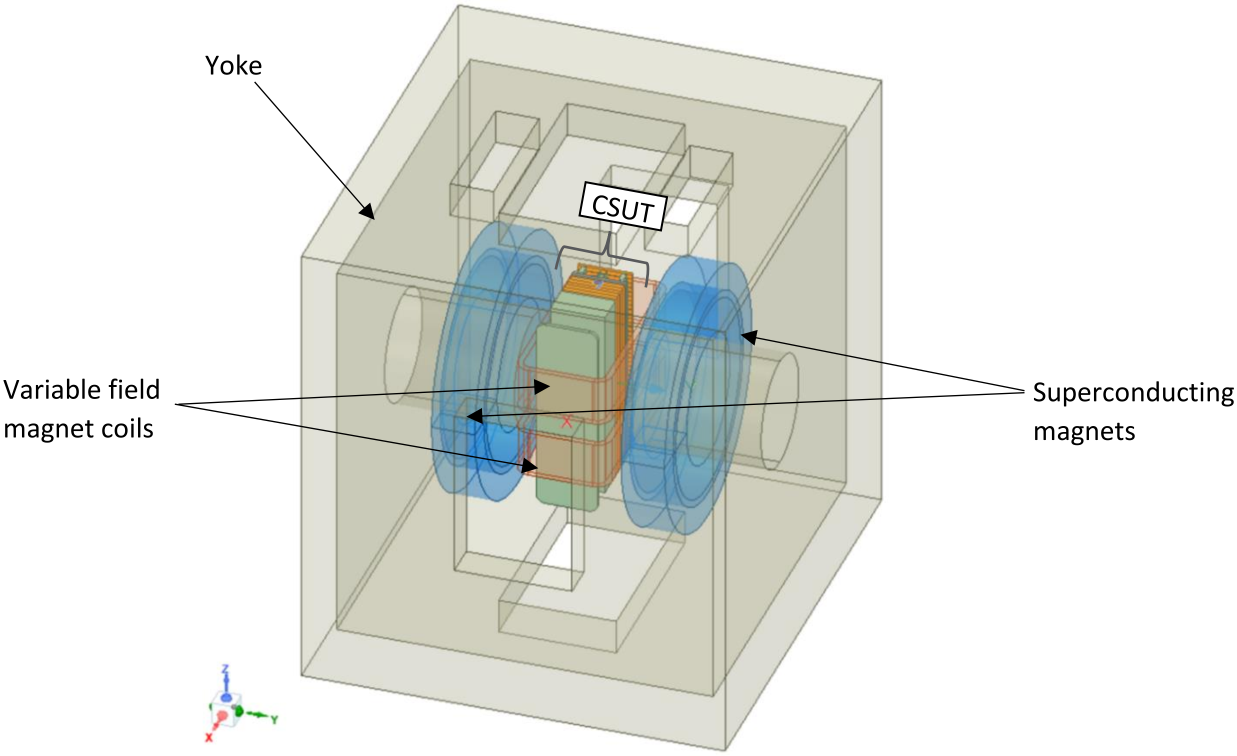

Figure 6: Overview of the Ansys Maxwell model, with vacuum region hidden.

3.5. Thermo-mechanical models

For thermo-mechanical analysis, the CSUT has been split into separate sections, as shown in Figure 7. Thermal and mechanical simulations have been carried out in Ansys Mechanical (2021 R2/2022 R1). An overview of the thermal boundary conditions for the front slat analysis is shown in Figure 8. Equivalent analysis has been completed for the central section, with the relevant boundary conditions for the volumetric heating of the cartridge heaters.

3D static field ROMs have been built in Ansys Twin Builder for both the thermal and stress fields for the front slat, central and rear sections of the model. An example of the output from one of these models is shown in Figure 8. For the front slat example, 100 training points were analysed, with 26 validation points. The peak relative error across the stress field was 6%. For the static ROMs generated for the central and rear sections, the maximum relative errors were all below 6% (for both the stress and temperature field).

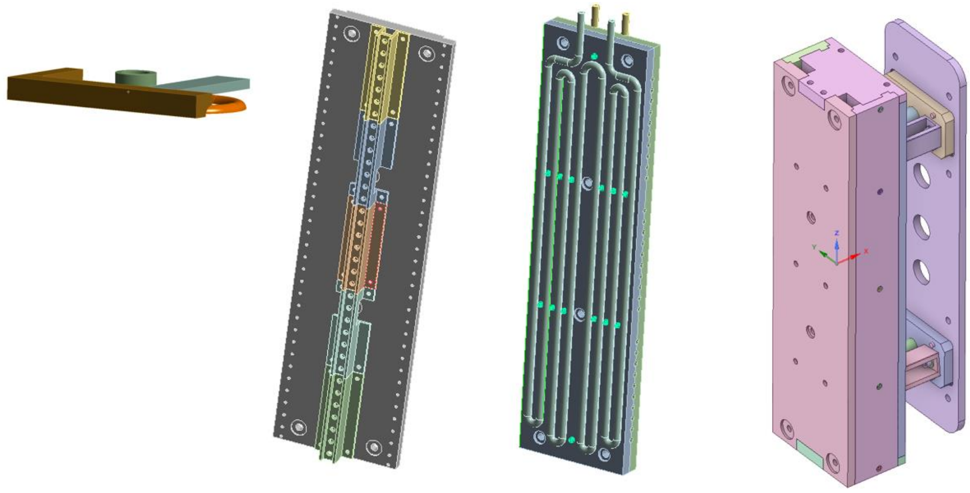

Figure 7: Split of the CSUT into sections for thermo-mechanical modelling. From left – ¼ section of a front slat, front support, central section, and rear section.

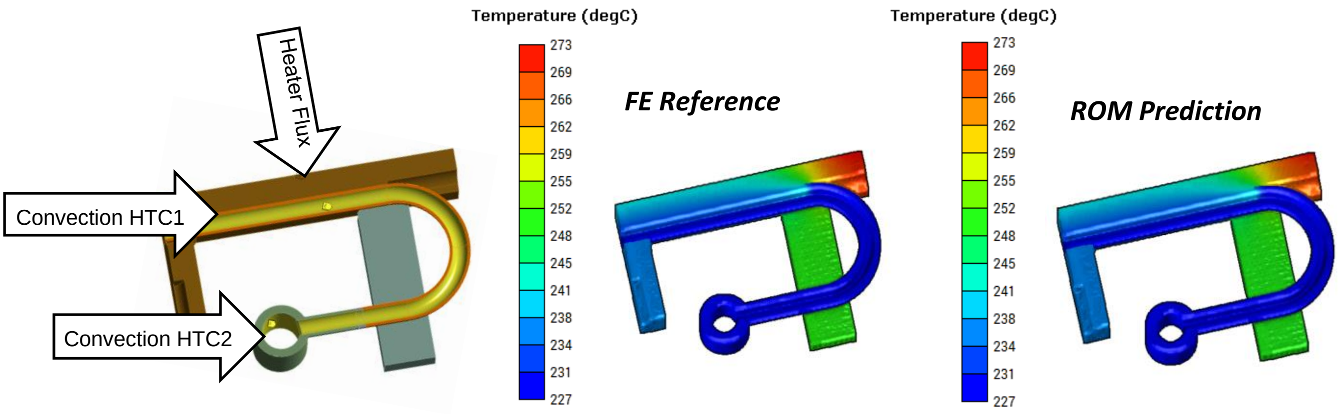

Figure 8: Left – overview of thermal boundary conditions for the front slat analysis. Central – temperature profile prediction from FE analysis. Right – temperature profile prediction from the field ROM.

3.6. Mechanical Reduction

A stiffness representation of the front support, central section and rear section was created to transfer the EM loads through the CSUT systems simulation. The method that has been used is a CMS The front support, central section and rear section are connected by threaded bars; these have not been modelled, but their connections points are used as the interfaces between each section of the model for the CMS.

The front slat loading was modelled in the systems simulation using a scalar ROM for the interface loads; as there is no ferromagnetic material in the front slat, no static EM loads are applied in this section.

3.7. Systems Simulation

An overview of the systems simulation is shown in Figure 9. This model has been assembled in Ansys Twin Builder 2022R1. The inputs which are used to drive the simulation (the yellow boxes), are:

- Fluid inputs – temperature, pressure, flow rate

- Large surface heater flux
- Volumetric heating power
- CSUT position in the X-direction
- Superconducting coil current

Some of the connections are shown schematically in the model; however, since there are many connections to the front slats, some have been omitted for clarity. Each of the front slat thermal/stress/strain ROMs is connected to the fluid simulation at the relevant location. The blue lines on the schematic represent conservative force/displacement connections; these connect the front slat scalar force ROM to the downstream front support, central section, and rear section mechanical reductions. The mechanical reductions are connected to the static EM scalar ROMs. Currently, apart from the front slat, the EM and thermal loads are not combined within the calculation of component deformation or stress; this will be discussed in the future work section.

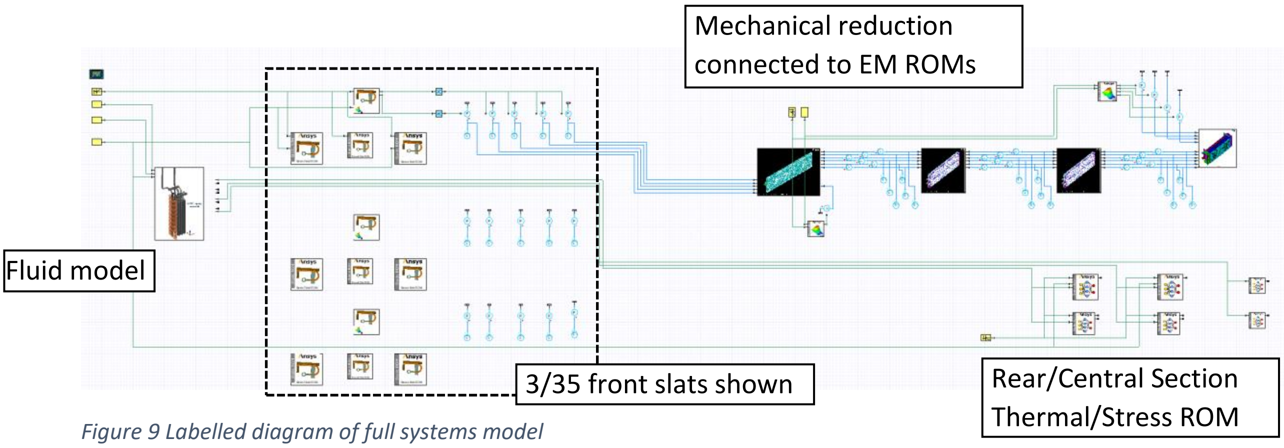

Figure 9 Labelled diagram of full systems model

A run-time comparison has been completed between the systems simulation and the equivalent separate FE models. With the current set of models, the systems simulation is approximately 1600 times faster than the equivalent set of FE solves (in CPU time). This includes solving 35 front slats, the central section and rear section thermal/structural solves and the static EM solves, to an equivalent number of steps as the systems simulation. The FE models are currently able to utilise multiple CPUs, hence their elapsed time would be less than the 1600x quoted. However, the systems simulation was run on 1 CPU, and additional solvers and time stepping schemes have not been investigated to further improve the solve time, although significant scope for improvement is envisaged.

4. Results

The systems simulation in this study is an initial version which will continue to be developed. However, there are already insights which can be gained into the operation of the CSUT which can inform commissioning scenario planning.

In Figure 10, the outputs from the systems simulation field ROMs are presented, showing the full surface temperature response across the front slats of the CSUT. This profile relates to a steady state fluid condition with peak surface heater flux. Due to the varying flowrate through the fluid circuit, the heat transfer coefficient varies for each section of front slats, and because of this there is a temperature variation across the front slats, which in this case is approximately a 20K variation in the peak value. Multiple thermocouples will measure the temperature across the front face of the CSUT during testing, which will be used to validate the model predictions.

Figure 11 shows the outcome of parameter sweeps performed using the fluid model linked to thermal-structural behaviour of the front slat, which includes a CuCrZr pipe. This can be used to identify regions of the operational envelope which should be avoided. For example, there is a large region of the test space in which the temperature exceeds the CuCrZr over-ageing limit (typically 400°C in practice); while individual tests could exceed this temperature, this region should be avoided for a test campaign to maximise the life of the component. Also shown in Figure 11 is the maximum stress over the same operational envelope, revealing a small corner of test space in which the stress exceeds yield (around 180 MPa for CuCrZr), which clearly should be avoided to prevent component damage.

Figure 12 shows the stress vs strain outputs of the front slat for 95 different coolant pressure and surface heater flux combinations. This type of search, made far more practical with the quick-running systems simulation, can be used to identify operating conditions which maximise strain but at the same time limit the risk of damage due to high stress. Experiments involving high component strain will be useful for model validation as well as for developing measurement techniques such as digital image correlation or fibre Bragg gratings.

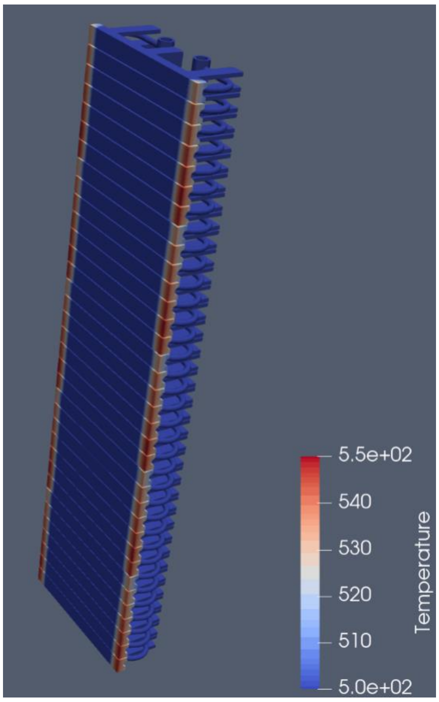

Figure 10: Thermal field across front slats at peak heater flux, temperature in °C

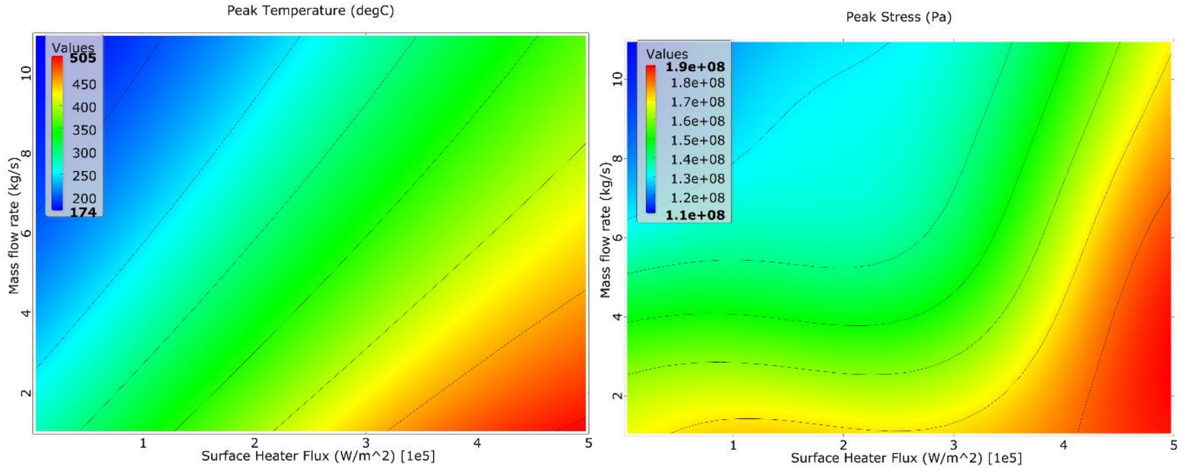

Figure 11: Contour plots of front slat peak temperature (left) and peak Von-Mises stress (right) against water mass flow rate and surface heater flux.

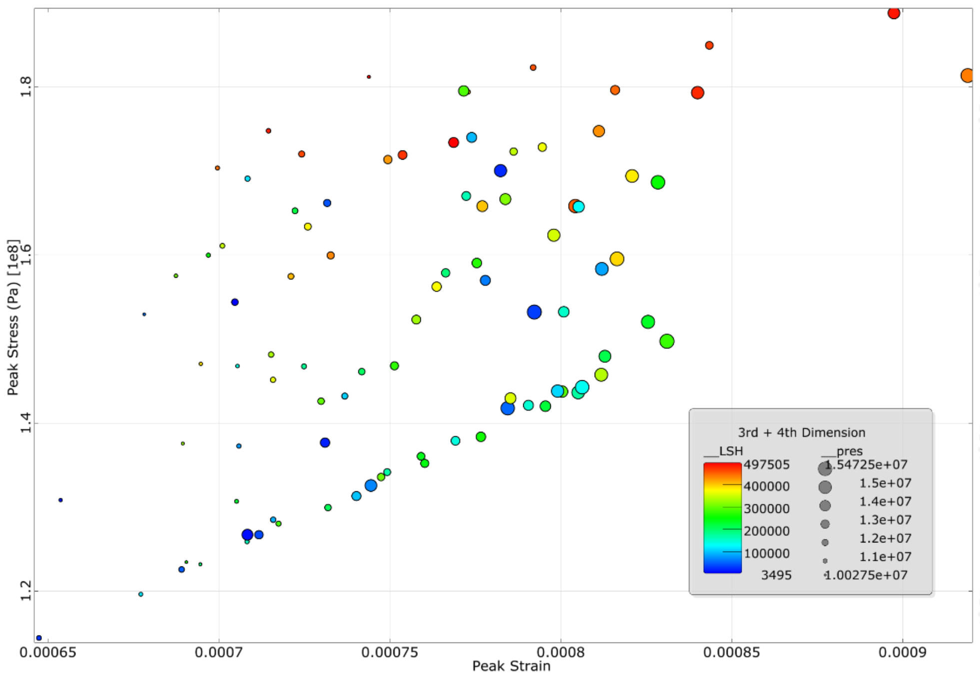

Figure 12: Front slat stress vs strain for a parameter sweep of the CSUT operating conditions. Heater flux [W/m²] is denoted by colour and coolant pressure [Pa] by marker size.

5. Conclusions and Future Work

Initial results from a systems simulation of the CHIMERA CSUT have been presented. The simulation speed, accuracy and complexity have demonstrated the potential of applying this methodology to address the aims of this work, namely, to achieve fast running validated models of fusion components, working towards a fusion component digital twin.

The systems simulation presented here is built from a network of reduced order models, which relate to an individual domain or sub-system of the CSUT. Each of these has been validated against FEA results, with a peak error of 6% across EM, thermal and structural models, although the error is significantly lower for most scenarios. However, further work is needed to verify and build confidence in the results obtained from the systems simulation. Additional test cases where FEA models are coupled together to verify linked reduced order models are in development; this will aid understanding of how errors propagate through the systems simulation. In addition, suitable test cases will be prepared to automatically verify the accuracy of the systems simulation as it develops.

Maximising the systems simulation speed has not been a focus of the work to date, although even before such an effort it is three orders of magnitude faster than the source FEA models in terms of CPU time. Planned work involves identifying bottlenecks in the simulation process, optimising solver settings, and using parallel computing to achieve the required performance.

Key areas for future work will be: (a) the methods of coupling ROMs; and (b) the physics included within each. The thermal and EM models are currently steady state, with the loading from the variable field magnet being neglected. This will be included in the next version of the systems simulation. The methodology presented here will be extended so that it is appropriate for transient modelling. Both the thermal and EM fields are coupled to the structural fields (i.e. stress and strain fields). Hence, a method to map the thermal and EM fields simultaneously is required to get a combined stress/strain response. This will be achieved by extending the use of singular value decomposition to represent both fields as a series of modes and coefficients upon which ROMs can be trained. The training data for transient models will differ from that used for steady state models; rather than an FE solve from a single time point, the transient ROM is trained using a series of excitations. The next step is then to extend the CMS reduction of the CSUT components to have an input load vector, which will enable the application of both thermal and EM fields.

Working towards validated simulations is a key aim of this work, hence one of the next steps is to utilise the systems simulation to optimise the placement of instrumentation, such as thermocouples. Engineering judgement should be enhanced by data-driven information when planning test campaigns. It is possible to create an optimisation loop to minimise the uncertainty in the reconstruction of the thermal field. Moving from a deterministic to a probabilistic understanding of SUTs is a key step in the roadmap for this work; the capability to treat the inputs to the systems simulation as distributions, and hence each output also being treated as a distribution, will be tested in the next phase.

Once the systems simulation can be treated probabilistically and has further verification and validation, the focus of this work will switch to digital twinning; as discussed, the run-time of the simulations will require improvement. Research and development is also required into algorithms which can be used to ensure the simulation continues to track the running test or operating tokamak plant. Early investigations have started and algorithms such as a Kalman filter [17] are being assessed.

This paper has presented an initial demonstration of the process and feasibility of using a systems simulation approach to model fusion components subject to combined loads (in this case heat and magnetic loads). This approach offers many advantages over full-scale multi-physics FEA, including facilitation of robust probabilistic assessments, uncertainty quantification and sensitivity analysis, and the prospect of real-time simulation with a live digital coupling to the physical asset. This work is the first step towards a set of validated simulation models that can be used as the basis for a fusion component digital twin, which will be a key technology to support the design and operation of future fusion power plants.

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