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A New Facility for Combined-Load Testing of Fusion Reactor In-Vessel Components

Thomas R. Barrett, Carlo Carrelli, Tom Grant, Michael Kovari, Nicolas Mantel, Alex Muir and Elizabeth Surrey

***Abstract*—Meeting the challenge of realising fusion power production will require considerable and increasing investment in facilities for testing and development of fusion technology. Particularly important will be testing of components destined for the harsh in-vessel environment of the reactor. To help address this need the UK Government is investing in major new fusion technology facilities, which will offer integrated laboratories covering the complete development life cycle from materials to manufacturing processes and load testing of components. A major part of these facilities shall be a test device, named CHIMERA, offering testing under fusion relevant loads for metre-scale in-vessel component mock-ups. Among the major challenges addressed are electromagnetic loads, high heat flux, and proving complex and high-risk manufacturing. The ability to test technology in magnetic fields will be unparalleled and could prove vital for breeding blanket designs featuring a ferromagnetic structural material or a liquid metal breeder. The CHIMERA magnet system uses a split-pair NbTi superconducting magnet, combined with a vertical-axis pulsed resistive solenoid to simulate plasma disruptions. Further, in order to provide semi-integrated testing including possible synergistic effects, CHIMERA will enable tests of resilience against magnetic and thermal loads in combination. The heating systems will deliver at least 0.5 MW/m^2 at the module surface, high heat flux in localized areas, and power for volumetric heating of a module. This paper introduces the CHIMERA device, reports the motivation and technical basis, describes the system specification, and outlines the future plan.**

***Index Terms* — experimental devices, fusion technology, fusion power generation, high heat flux, superconducting magnets**

I. Introduction

CURRENTLY, the major facilities for nuclear fusion research, at least by investment, are focused on the plasma physics challenges of achieving power reactor conditions, with technology an important but lesser element. ITER [1] will address, and in its construction is already overcoming, some of the key fusion technology issues [2] but ultimately its exploitation will be dominated by its physics mission. However, to harness fusion power will require considerable and increasing investment in dedicated facilities for testing and development of fusion engineering and technology. This will be essential to close current technology gaps, discharge key risks in proposed technology, prove a viable route to a reactor design and to satisfy a nuclear regulator. Most critical of all will be to address the design, technology and materials of fusion in-vessel and plasma-facing components, as these present the major unresolved challenges in the realisation of a fusion reactor [3]. To help address these needs, the UK government is investing in a National Fusion Technology Platform [4] which will deliver a new facility for tritium research as well as a suite of fusion technology facilities. The fusion technology facilities are divided into three laboratories that together cover the full lifecycle of fusion component development [4]: materials technology, advanced manufacturing and component module testing. The third of these laboratories is the focus of this paper. The aim is to provide a facility for design development and risk mitigation for component modules, such as a fusion blanket module or divertor target plate, addressing the critical challenges of high heat flux, electromagnetic loads, components with complex or unusual materials and manufacturing methods, and their consequent specific failure modes. The facility will operate a unique component loading device named CHIMERA (combined heating and magnetic research apparatus), which will enable testing of components under conditions anticipated in a reactor [2][5]. Because of the difficulty of accounting for the effects of multiple loads computationally, and because of the possibility of revealing previously unknown synergistic effects or failure modes, it will be crucial to test components under a combination of loads. As such, CHIMERA is designed to test component prototypes in the semi-integral environment of simultaneous extreme temperature, heat flux and electromagnetic conditions representative of a fusion power reactor. Plasma surface interaction and component irradiation will not be in scope (as a non-nuclear and non-radioactive facility), although CHIMERA can contribute via the development of digital twins which can be enhanced to simulate these additional effects.

This paper introduces the CHIMERA device, reports the motivation and technical basis (Section II), describes the system specification (Section III), and outlines the future plan (Section IV).

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II. Technical Basis for the Facility

The testing in CHIMERA has a range of objectives. Although the emphasis is not qualification *per se*, the ability to characterise or validate as-manufactured component performance will be essential. For a component which is nearing the end of the design (and manufacturing) development phases, combined loading tests in CHIMERA could be used to prove performance predictions and discharge key risks in a component before committing to costly installation on a device like ITER. A second major objective is to perform experiments on component mock-ups of varying complexity and realism in order to improve and validate computational modelling and develop digital twins. This is elaborated further in Section II.C.

The major, and unique, offering of CHIMERA is testing of large components in magnetic fields and the ability to perform tests using a combination of thermal and magnetic loads, and yielding a high volume of diagnostic and test data suitable to enable virtual engineering. These key features are addressed below.

A. Magnetic testing

The concept of testing component mock-ups in a magnetic field environment is not new [6][7][8], but there have been few facilities offering this and none at the scale of a complete module. There can be a number of types of magnetic testing as follows.

1) Liquid metal magnetohydrodynamics (MHD) experiments

Many fusion breeder blanket design teams internationally are considering liquid metals (chiefly LiPb eutectic) as tritium breeder, neutron multiplier and in some cases as a coolant, as they have a number of important advantages over solid breeder blankets. All liquid metal blanket designs are heavily impacted by MHD effects caused by the reactor magnetic field. The metal flow velocity profile is altered dramatically [9], affecting heat transfer, tritium transport, corrosion rate and increasing channel pressure drop in some situations by orders of magnitude [6]. Accurate prediction of all of these effects will be critical for liquid metal blanket design and successful integration with the reactor. However, current computational analysis codes are unable to simulate 3-D MHD affected flows under fusion-relevant conditions with sufficient accuracy [6]. One of the main difficulties is simultaneous calculation of effects happening at wildly different scales, from very thin near-wall layers to variations on the scale of the channel width. Interaction with conducting walls is also a critical uncertainty. The extreme number of grid cells required to resolve very thin boundary layers at high Hartmann numbers forces the use of parallel and high-performance computing, even for relatively simple flow path geometries.

Experiments in MHD affected flows are therefore essential to provide a database for analysis validation, to test complex geometries and to develop the requisite instrumentation technology. Existing experiments include MEKKA at KIT [6], MaPLE-U at UCLA [9] and DRAGON-IV and -V at INEST, China [8]. DRAGON-V offers semi-integral MHD-affected thermal-hydraulic experiments with LiPb and (in future) helium cooling, and is designed for testing of one-third scale ITER DFLL-TBM (dual functional lithium lead test blanket module) mock-ups [8]. The peak magnetic field is 2 T. For experiments on MHD effects, facilities need to try to achieve the parameters in the range anticipated in fusion blanket conditions (e.g. Hartmann, Grashof and Nusselt numbers), enable testing in uniform and non-uniform magnet fields, at relevant scale, and include the ability to test the effects of gravity. A high level of instrumentation is needed to assist in validating computational analyses and digital twinning.

2) Static magneto-mechanical testing

Tokamaks feature strong magnetic field and field gradients. For most prototype fusion power reactor designs, including EU DEMO [3] and CFETR [10], the baseline structural material for in-vessel components (mainly the breeding blankets) is a reduced activation ferritic-martensitic (RAFM) steel [11], which is strongly ferromagnetic. This situation creates very strong forces on the components; for the ITER TBM between 150-200 kN net inward force is expected [12]. Even when net forces are low, there may be internal magneto-static stress which makes a significant contribution to overall primary and secondary stress in a blanket, which are already near to code allowable limits, necessary to minimise cost.

Existing numerical modelling and analysis are perfectly adequate for sufficiently accurate calculation of net loads on component attachment points [13]. However, calculation of the internal distribution of force with confidence is much more difficult or even impossible with current analysis methods, for a number of reasons. First, because of the geometrical complexity of fusion blankets, and because of the present need for sensible computational cost, the geometry in a model is often simplified and where multiple material domains are combined their material properties are *smeared*. This does not tend to sacrifice accuracy of body forces but will alter the stress distribution in a component. An example of smearing is demonstrated in the next Section. Second, for calculation of internal force distributions, it is well known that numerical force formulations disagree fundamentally, giving sometimes wildly differing results. Third, there can be uncertainty over the magnetic material properties of materials as a function of temperature, particularly the behaviour at material discontinuities or joints, including welds, of which there will be a large number in foreseen blanket designs. Determination of magneto-static stress is clearly critical for engineering design of fusion blankets and the current shortfalls of modelling can be addressed or mitigated with the advent of appropriate and carefully designed experiments.

3) Combined static and time-varying magnetic field testing

Tokamak magnetic fields are not static, and by far the most dramatic time-varying field is caused by a plasma disruption, a sudden (less than 300 ms [5]) collapse of the plasma and the current it carries. Disruptions impart very large forces and heat loads on in-vessel components such as the first wall, as experienced in current tokamaks [14]. The ITER wall and other in-vessel components are being designed to cope with a certain number of disruptions as an off-normal load type. Attempts are also underway to design the EU-DEMO wall for disruptions and the associated high heat loads [15].

Disruptions induce eddy currents in components which lead to demanding and design-driving loads, but these loads are difficult to predict computationally. As well as uncertainty over magnetic properties, calculation of stress in a component under a disruption requires knowledge of electrical properties as a function of temperature and methods for accurate calculation of current density distribution. Simplifications such as material property smearing are typically used to avoid very large model size [13].

The effect of material property smearing is demonstrated using an analysis of an ITER-like first wall component [16]. The model is not an accurate or absolute prediction for the ITER first wall component but it is used solely as a relevant comparative demonstration of modelling methods. The model dimensions and boundary conditions of the analysis are arbitrary.

The analysis uses the ANSYS finite element analysis code. A linear electromagnetic analysis is used to calculate current distribution caused by a time-varying magnetic field and the resulting force distribution in the presence of a uniform orthogonal static field. The model geometry is shown in Fig. 1; there are 40 beryllium tiles perfectly bonded to a CuCrZr heat sink which is perfectly bonded to a stainless steel carrier. The model is constrained by imposing zero displacement at three points at one end of the component as shown in Fig. 1. A static uniform magnetic field is held at 4 T in the X direction and 0.6 T in the Z direction (with reference to the axes shown in Fig. 1) while the field in the Y direction is initially zero ramping linearly to 0.5 T in 16 ms.

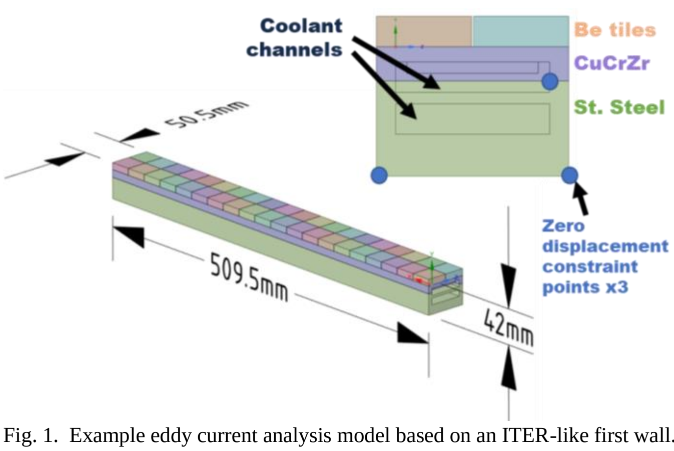

Fig. 1. Example eddy current analysis model based on an ITER-like first wall.

The 'detailed' model in Fig.1 is compared with results using a simplified geometry and two types of material property smearing. The CuCrZr, stainless steel and cooling channel (void) parts are combined into a single body. The properties of the single material are determined using a volume weighted average of the properties of the constituents parts. This weighted averaging can be either 'parallel' (assumes materials behave electrically as resistors in parallel) or 'series' (resistors in series), depending on the *expected* direction of current flow with respect to the material boundaries. In this example current is driven parallel to the material boundaries, but results are compared from both methods. Fig. 2 presents magnetic flux density contours at a cross-section through the component. Compared to the model with full detail, the model with parallel smearing gives a result within 15% for total Mz moment and peak stress, although the magnetic flux distribution is considerably altered with the peaks reduced and shifted in location. However, the opposite is true for the result using series smearing; the total Mz is highly overestimated compared to the full model at +80%, and the distribution has accentuated peaks (exceeding the original contour scale in the grey regions seen in Fig. 2).

In this example the parallel smearing model approximated well the overall moment, deformation and stress of the component, and so could be used for global assessment and calculation of loads on e.g. attachments. However because the current distribution is grossly simplified this model could not be relied on for detailed stress results especially at the boundary between materials, which is where failure tends to occur in components. The direction of current flow here is intuitively known *ab initio*, but there will be many cases where the current direction is not obvious and may be a mix of series and parallel contributions. In these situations a fully detailed analysis may not be practical, and the analyst may need to use various simplification approaches and quantify the result uncertainty. Clearly, an experiment using an appropriate mock-up may be used to reduce this uncertainty.

In summary, disruption loads are a serious concern for ITER and other fusion reactor components and prediction of their response is very sensitive to modelling methods and assumptions. Experiments using a rapid field reversal in combination with a static field could allow functional testing of components as well as development of improved modelling.

B. Combined load testing

As described and demonstrated above, accurate absolute prediction of component behaviour and failure is challenging computationally, even for individual loads. In the case of the divertor target, even advanced analyses can not be solely relied on and small-scale high heat flux (HHF) tests in facilities such as GLADIS [17] are routine with analysis taking an 'interpretative' role [18]. ITER took this 'design by test' approach in the qualification of the divertor plasma-facing components [19].

In reality, fusion in-vessel components will suffer a harsh environment and mix of combined loads. Analysis methods are even further challenged and computationally costly when loads are combined. Outputs from linear analyses can be superimposed readily, but simulations will increasingly rely on non-linear models and material data. As an example of the importance of considering temperature dependent material data, we return to the component analysis presented in the previous Section. As an electromagnetic analysis, this was initially run with room temperature material properties. However, CuCrZr resistivity more than doubles between 20°C and 400°C (Fig. 3). When material data for CuCrZr at 400°C are used, the moment Mz, maximum deflection, and maximum stress are reduced by 45%. In reality, the heat receiving area of CuCrZr is at perhaps

400°C, but the area below the cooling channel is at the water temperature. Thus heat flux changes the current density distribution to focus more current in the hot region.

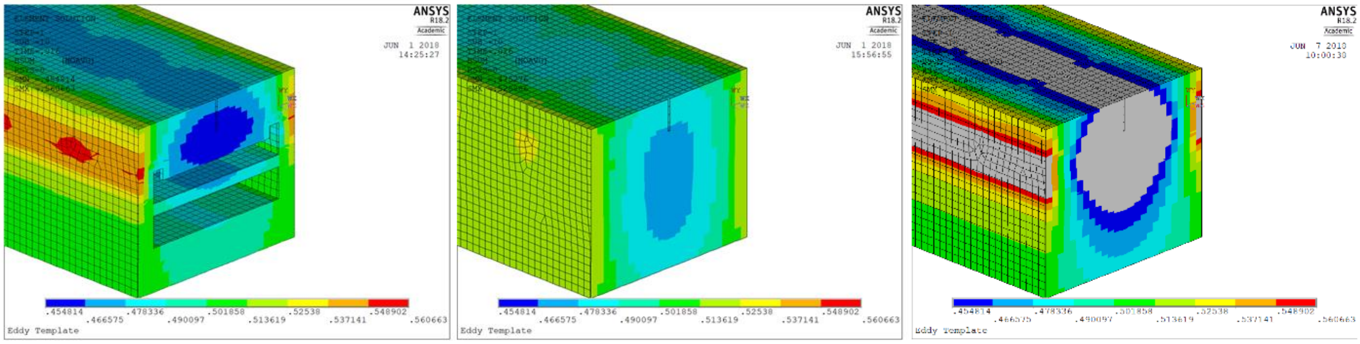

Fig. 2. Comparison of magnetic flux density (Tesla) results for the detailed model (left) and two-material simplification with parallel (middle) and series (right) methods of material property smearing. For interpretation of colour the reader is referred to the online version of this article.

Note that the resistivity of the beryllium armour tiles varies by a factor 8 between 20°C and 800°C (Fig. 3). Accounting for temperature and temperature gradient (heat flux) is vital in correct determination of current distribution including current crossing the Be-CuCrZr structural joint.

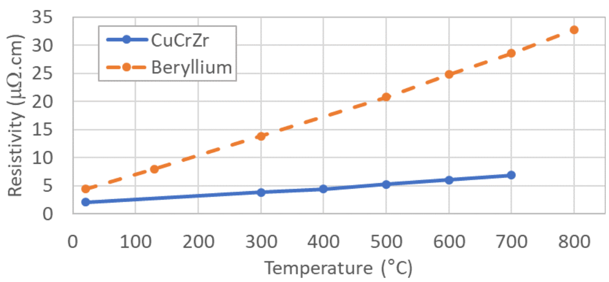

Fig. 3. CuCrZr and beryllium resistivity as a function of temperature. Data source: ITER material properties handbook ITER-AK02-3202 G 74 MA 16 and ITER-AL02-3201 S 74 RE 1.

Accounting for combined loads raises the possibility of synergistic effects or failure modes, i.e., effects that do not occur when accounting for the loads individually. This was demonstrated in the early experiments on MaPLE-U [9], in which researchers proved that combining a liquid metal temperature gradient, buoyancy, and magnetic field dramatically changes the velocity field compared to the case of these three conditions in isolation. Mixed convection and even flow reversal against the direction of forced flow was deduced.

The multiple-effect results in MaPLE-U supported previous analysis predictions. However, the physical processes occurring at the surface and within plasma-facing components are highly complex and inter-linked, and there may be unknown synergies and failure modes arising. This may be especially true of electromagnetic phenomena, which are relatively unexplored by physical testing to date. The ability to account for multiple effects and combined loads is thought to be crucial to advancing fusion technology, not least by the validation of modelling.

C. Instrumentation and virtual engineering

The Sections above have highlighted some of the shortfalls and challenges of current computational modelling approaches. However, the vast scale and complexity of the DEMO-class reactor design challenge means that heavy reliance must be made on predictive computational modelling and design *in-silico*. Integral experiments on full-scale DEMO blanket segments, for example, are unlikely. Instead, simulations are advancing towards a virtual test or even virtual reactor [20], but these models can only be relied on if the data, modelling methods, material models, etc., have provenance in high quality experimental data. A key objective in CHIMERA will be highly instrumented testing, enabling thorough diagnosis of performance and failure modes and delivery of abundant engineering data for model validation and digital design.

Related to this, a major theme is to perform experiments on component mock-ups of varying complexity to develop digital twinning and real-time and lifetime monitoring. Such techniques will be vital for DEMO-class devices as component conditions (and health) will need to be deduced and controlled using data from a very limited set of diagnostics and actuators within the harsh environment of the reactor core. The principle is to strive for a numerical model "twin" of the component which mimics the real response and can predict accurately the behaviour that is experienced in the fusion environment [21][22]. Such models will be developed with and tested against detailed data from CHIMERA and could in time be used to simulate the effect of other load conditions which are not addressed in experiments, such as irradiation, once modelling methods are sufficiently mature.

III. CHIMERA Specification

A. Overview

The high-level system specification is presented in Table 1, and the overall device concept and topology is shown in Fig. 4. The test chamber is designed to contain a test article up to the size of a 1:1 ITER TBM module. A divertor vertical target plate can also be accommodated. Because accounting for gravity will be critical in liquid metal blanket experiments, the primary (static) magnet axis is horizontal, representing a tokamak toroidal field. Additionally, to simulate in CHIMERA the rapidly changing field of a disruption, a pulsed magnet will be used, with its current fully reversed to drive induced current with constant direction in the test module with minimal peak field and so the least resistive loss and power requirement. This pulsed magnet surrounds the test module as a solenoid within the experiment (test) vacuum vessel (Fig. 4). To maximise space for experiments, the test vacuum vessel is integrated as part of the static magnet cryostat. The test vessel and cryostat do not share a vacuum space, but the test vacuum *shell* wraps around the outside and features large port tubulations for vertical sample loading, services and diagnostics. The vessel overall diameter is approximately 3.5 m. The major CHIMERA sub-systems are described further below.

TABLE I
OVERVIEW OF CHIMERA SYSTEM SPECIFICATION

Parameter	Specification
Maximum test module volume	1:1 ITER TBM, 1.67×0.96×0.46 m^3 [12]
Test environment	Vacuum or inert gas
Static magnet	Superconducting split pair, NbTi
Peak magnetic field at static magnet centre	4 T
Pulsed Vertical Field Magnet (VFM)	Vertical axis split pair solenoid, copper
Peak magnetic field at VFM centre	±0.25 T
VFM field reversal time	40-200 ms
Global surface heating	0.5 to 1 MW/m^2 at surface over ~1 m^2
High Heat Flux	20 MW/m^2 over 1500 mm^2 or 200 MW/m^2 over 100 mm^2
Other heating systems	Power available for up to 700 kW simulated volumetric heating
Test module cooling	Liquid water
Cooling conditions	Inlet 200-333°C, 650 litre/min, 15.5 MPa or Inlet <150°C, 1000 litre/min, 5 MPa

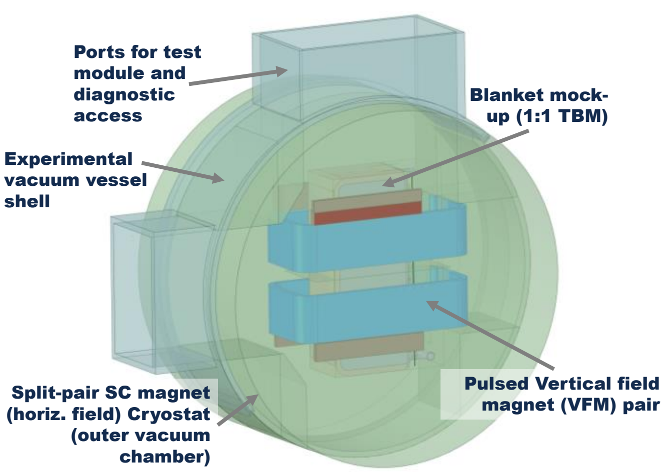

Fig. 4. Overall CHIMERA device topology.

B. Magnet system

The magnet system is the unique feature of CHIMERA and is integral to the device. The static magnet is a split-pair topology using NbTi superconducting coils in liquid helium baths. The coil diameter is sufficiently large to saturate Eurofer steel at every point in the 1:1 TBM test module. This magnet in principle uses technology taken from NMR/MRI magnets. However, key challenges are the large forces and heat load to be transmitted to the cold mass, and the interaction of this magnet with the pulsed field from the VFM.

The pulsed VFM is a resistive split-pair solenoid (Fig. 4), inter-pulsed water cooled, with a clear bore large enough for the test module plus surface heating system(s). If the test module uses ferromagnetic materials, these will be saturated by the static horizontal field, and so their behaviour will be approximately linear. Time-dependent phenomena will then be linear in the fields and currents. On the other hand, there are characteristic timescales that should be preserved. The VFM has therefore been specified to maintain realistic field collapse timescales, but with reduced fields compared to ITER and DEMO in order to limit the device power and magnetic loads. The flat-top field at the centre of the VFM can be up to 0.25 T, and can be between 0.15 and 0.35 T within the volume 462 × 400 × 800 mm. To enable stable field measurements, a field flat top of at least 100 ms is held before and after the field reversal (Fig. 5).

Computational simulations for ITER are available for a so-called “major disruption” at different locations around the wall [12]. The most extreme variation in field is in a major disruption near the inboard midplane, with a change of 2 T in 40 ms. In addition to a field ramp, the simulations predict rapid smaller field fluctuations, and we do not attempt to reproduce them in the VFM. For the VFM the shortest full-field reversal time is therefore 40 ms, giving a central ramp rate of up to 12.5 T/s (Fig. 5). In ITER the largest change occurs in the poloidal component of the field. In CHIMERA the test modules are likely to correspond to equatorial blankets, hence the poloidal direction and therefore pulsed field are initially specified as vertical.

Note that although the test module mechanical attachments can be the same as used in the tokamak installation, tests in CHIMERA enable study of the effects of a given rate of change of field on current and load distribution but do not represent the realistic current paths in the tokamak vessel or other structures. For the purpose of design development CHIMERA experiments will need to be supplemented by modelling of the remainder of the tokamak, but they will also serve to validate the models of the sample under test. Induced currents in the CHIMERA vacuum vessel and the test module will apply a reverse emf to the VFM. This will be compensated in the power supply design to ensure the correct current profile in the VFM.

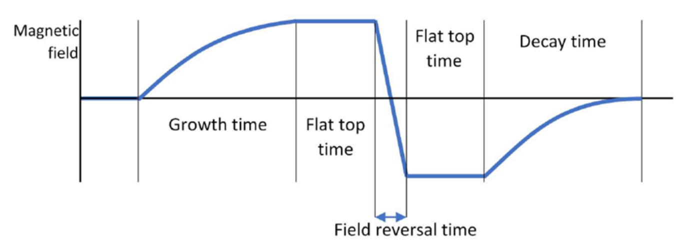

Fig. 5. Pulsed magnet field profile (magnetic field vs. time).

C. *Heating systems*

A range of test module heating systems are specified as listed in Table 1. The global surface heating system simulates thermal radiation from the anticipated ITER or EU-DEMO plasma with heat fluxes at the target surface of at least 0.5 MW/m^2 [5]. This system is likely to use black-body infrared heating elements, which have been used with success in other facilities such as HELOKA [23].

Design for high heat flux (HHF) is one of critical challenges in fusion technology development, occurring at the divertor and first wall or limiters. There can arise situations, such as plasma vertical displacement events, when a fast magnetic transient is accompanied by extreme wall heat fluxes. It is therefore essential to include a HHF heating system either for plasma facing component development and/or combined load testing. The requirement for concurrent HHF and magnetic fields precludes electron or ion beam heating. The concept design for CHIMERA uses a high-power continuous laser of the type used for commercial laser cutting and welding. In practice there will be a time duration limit but the use of a commercially available laser will allow long experiments of many hours or even days. Fixed optics are foreseen initially although concept studies have shown that complex heat flux distributions may be achievable with development of bespoke optics.

As well as surface heat flux, the design-driving heat load for fusion blankets, and required for thermal-hydraulic testing, is volumetric nuclear heating. The facility will include power sufficient for up to 700 kW internal heating of a test module via embedded trace heaters or infrared heaters.

Water-cooled thermal shields will be installed on the cryostat interior walls to minimise heat transfer from these heating systems and the test module to the superconducting magnet.

D. *Water cooling system*

The choice of primary coolant in fusion reactor design studies is usually between high pressure liquid water and helium gas [3], the former having nuclear power heritage and the latter enabling higher temperature and cycle efficiency. There are existing facilities which deliver helium cooling, such as HELOKA and DRAGON-V [8][23]. For this reason and because of relevance to ITER, CHIMERA will use liquid water for sample cooling with parameter ranges as shown in Table 1. The ability to test up to PWR-like conditions and ambition for liquid metal testing raises the potential for testing water-cooled lithium lead (WCLL) blanket technology, a candidate blanket concept in EU-DEMO and a concept for the EU-TBM [12].

IV. Status and Future Plan

The current schedule for the fusion technology facilities is to have an initial capability operating in early 2022. At the time of this paper, CHIMERA is at the stage of engineering design. Three initial device concept designs were produced by different engineering consultancies, this being narrowed to two integrated concept designs, only one of which is taken forward to detailed design and construction starting at the end of 2019. Because of the long lead time of the magnet system, the procurement of this critical element has been launched in parallel with the ongoing design of the rest of the system. This requires robust application of systems engineering including rigorous requirements and interface management to ensure compatibility and appropriate design maturity of the magnet system and other critical sub-systems.

It is anticipated that the CHIMERA test capabilities will be commissioned in phases over time, with highest priority being on the global surface heating, thermal-hydraulics and static magnet, and the VFM and high heat flux being lower priority.

Initially experiments may include liquid metal natural convection, but to maximise exploitation of the magnetic field capabilities and ability to test WCLL technology it is expected that a LiPb circulation loop will be added as a future upgrade. Subject to demand from blanket and reactor design programmes, a gas cooling loop may also be added in the future.

V. Conclusion

The pathway to the realisation of a fusion power reactor will require considerable and increasing investment in facilities for testing and development of fusion technology. Integrated computational modelling will be increasingly relied on in future for design of DEMO-class reactors, but such models can only be relied on if they have provenance in high quality data from testing. Physical testing is currently essential to address the many uncertainties in modelling, and to functionally test components for which modelling is not viable. Also essential for DEMO will be the development of digital twinning for lifetime/realtime monitoring.

The new fusion technology facilities in the UK will include a unique component loading device named CHIMERA which will enable testing of components under conditions anticipated in a reactor. A key feature of the device is the capability for testing large component modules, up to the scale of a 1:1 ITER TBM, under static and rapidly pulsed magnetic loads simulating a plasma disruption. Further, CHIMERA is capable of testing component modules under combined magnetic and thermal loads. CHIMERA heating systems are a global surface heater simulating plasma thermal radiation, high heat flux heating in localised areas, and power available for simulated internal volumetric heating of a test module. Test modules are water cooled, making the facility suitable for testing ITER components as well as WCLL blanket technology.

Currently CHIMERA is under engineering design, and the procurement of the magnet system has been launched. Detailed design and construction will start at the end of 2019.

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