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# CHIMERA Fusion Technology Facility: Testing and Virtual Qualification

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**Abstract** — *The Combined Heating and Magnetic Research Apparatus (CHIMERA) fusion technology test facility is under construction. The facility will be uniquely capable of semi-integral testing of fusion materials and component modules up to the size of the ITER test blanket module box, under combined conditions of in-vacuum high heat flux, static and pulsed magnetic fields, and high-temperature/high-pressure water cooling. This paper reports the high-level capabilities of the CHIMERA baselined design and the planned program of testing and describes the proposed strategy for use of simulations for virtual testing, qualification, and in-situ monitoring.*

*The first step in testing of a component mock-up is to take data from as-built geometry and other measurements and transmit them to an integrated computational model that can closely mimic the physical asset and form a digital replica. Not only can this digital replica be queried in advance of physical testing in the facility, allowing optimization of the test program, but combined with subsequent test data, it also can deliver much greater insight into experimental results than can be obtained using test data alone. The digital replica is used as the basis for a digital twin, which is live coupled to the running experiment, and is under development as a proposed key facet of fusion reactor surveillance in-service. Physical mock-ups for testing can be subjected to in-vacuum heat flux up to 0.5 MW/m$^2$ over the entire surface while within a strong horizontal magnetic field. The central field can be up to 4 T with a peak in the test region of 5 T. The same component mock-ups can also be subjected to repeated magnetic field pulses with ramp rate 12 T/s, which can simulate loading conditions of a plasma disruption. Facility upgrades are underway to include a liquid metal circulation loop to allow the study of magnetohydrodynamics effects and to add a high-heat-flux system using a very high-power continuous-wave laser to achieve divertor-relevant heat fluxes of 20 MW/m$^2$ over the area of a small-scale mock-up. Four examples are given to illustrate the physical testing program that is currently foreseen.*

**Keywords** — *CHIMERA, test facility, virtual qualification.*

**Note** — *Some figures may be in color only in the electronic version.*

## I. INTRODUCTION

The Combined Heating and Magnetic Research Apparatus (CHIMERA) facility is being built for testing of fusion in-vessel components and systems under combined fusion-relevant loads.[1] The device, once complete, will be unique in being capable of semi-integral testing of fusion component assemblies up to the size of the ITER test blanket module (TBM) box[2] under combined conditions of in vacuo high heat flux, static and pulsed magnetic fields, and high-temperature/high-pressure water cooling. The facility will be needed for the development and qualification of fusion technology as it enables fundamental research on new technologies, design choices informed by testing, validation of computational simulations, and

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functional testing of as-manufactured systems under conditions approaching their intended loads, as well as for the development of the digital twin for reactor monitoring and assurance. At present, engineering and materials testing is widespread in the form of small-scale, single-effect tests on material samples, or even testing on prototype components such as high-heat-flux testing.[3] However, proving of fusion technology in advance of installation in the power reactor itself will also require integrated system and multiple-effect testing at, or near, full component scale. It is this need that the CHIMERA facility helps to address.

Another important aspect of the facility design basis comes from the view that although heat flux testing of fusion components is relatively common, another design-driving fusion load comes from static and time-varying magnetic fields, and there are currently no suitable facilities for testing under relevant combined conditions; hence, this is a major focus of the testing in CHIMERA. As written by the authors in Ref. 1, there is a need for at least three types of magnetic testing: (1) liquid metal magnetohydrodynamics (MHD), (2) static load testing of ferromagnetic components, and (3) combined static and pulsed magnetic field testing. All three will be affected, potentially strongly, by the simultaneous presence of heat flux, and such multi-effect tests will be possible in CHIMERA.

This paper describes the CHIMERA test and research program starting with the overall features and capabilities of the now baselined design, outlined in Sec. II. However, a major feature of the CHIMERA program is that it combines physical and virtual testing. The testing is expected to routinely start with engineering simulation of the proposed test, as this enables both planning of the test campaign in advance of the physical item arriving at the facility and checks for machine and personnel protection. As mentioned, an objective of CHIMERA testing will be to validate computational models, and this contributes to the realization of a digital twin of the facility and mock-up under test. The strategy for virtual qualification and digital twinning is described in Sec. III. In Sec. IV, four examples are given to illustrate the physical testing program that is currently foreseen. Section V gives an outlook statement and conclusion.

## II. CHIMERA OVERVIEW

The CHIMERA specification is reported in Ref. 1; an overview is provided here along with notable changes as the design has evolved. The high-level features and operating parameters are listed in Table I.

TABLE I

CHIMERA Features and Operating Parameters

| Parameter | Specification |
|---|---|
| Maximum test mock-up volume | 1:1 ITER TBM, 1.67 × 0.96 × 0.46 $m^3$ (Ref. 2) |
| Test environment | High vacuum or inert gas |
| Static magnet | Superconducting split pair, recondensing cryostat, NbTi conductor |
| Magnetic field at static magnet center | 4 T |
| Magnetic field peak in available test volume | 5 T |
| Pulsed VFM[a] | Vertical axis split pair, copper rectangular windings |
| Pulsed magnetic field at VFM center | ±0.25 T |
| VFM field reversal time | 40 to 200 ms |
| Large surface heating | 0.5 $MW/m^2$ at surface over TBM first wall |
| Other heating systems | Power available for up to 100 kW simulated volumetric heating (future capacity: 700 kW) |
| Test mock-up cooling | Liquid water |
| Mock-up cooling conditions | Inlet 200°C to 333°C, 650 L/min, 15.5 MPa<br>or inlet <150°C, 1000 L/min, 5 MPa |
| Phase 2 (The following features will not be available in the first phase of operation.) | |
| High heat flux (continuous-wave laser) | 20 $MW/m^2$ over 1500 $mm^2$<br>or 200 $MW/m^2$ over 100 $mm^2$ |
| Liquid metal loop | PbLi (eutectic composition) |
| Liquid metal flow conditions | Flow rate up to 17 $m^3/h$, 280°C to 550°C |

[a] VFM = vertical field magnet.

The CHIMERA facility occupies approximately 800 $m^2$ of purpose-built building space, plus external plant areas for transformers and air-blast coolers. Figure 1 illustrates the facility layout. A dedicated preparation stand is used for the mock-up pretest assembly and fitment of instrumentation and can also be used to apply mechanical loads to the mock-up in order to configure the main load cells before a test. A 20-tonne overhead crane is used to deliver mock-ups from the preparation stand to the CHIMERA vacuum vessel. The CHIMERA machine resides in the center of the area within a 4-m-high magnetic shielding perimeter wall, which ensures that the magnetic field is at safe levels in the building and below 5 G outside the building.

The CHIMERA machine is shown in Fig. 2 in a cross-sectional view to highlight the major internal components. A cuboidal thick magnetic steel yoke surrounds the machine, reducing the stray magnetic field and intensifying the field in the test region. A large test mock-up is shown installed, in this case the commissioning mock-up (see Sec. IV). The large surface heater is shown energized, designed to apply 0.5 MW/$m^2$ heat flux by thermal radiation to a first wall (FW) up to the size of the ITER TBM. The pulsed vertical field magnet (VFM) is also shown. This is a configuration of two coils inside the test vacuum vessel, wrapped around the test mock-up with a vertical axis.

Figure 3 shows the superconducting (SC) magnet windings, a split pair with one coil of approximately 2-m diameter on either side of the vacuum test vessel. The magnet poles are a passive extension of the iron yoke magnetic circuit. Note that the SC magnet coils are within their own dedicated cryostat, a separate albeit adjacent vacuum chamber to the test vacuum vessel.

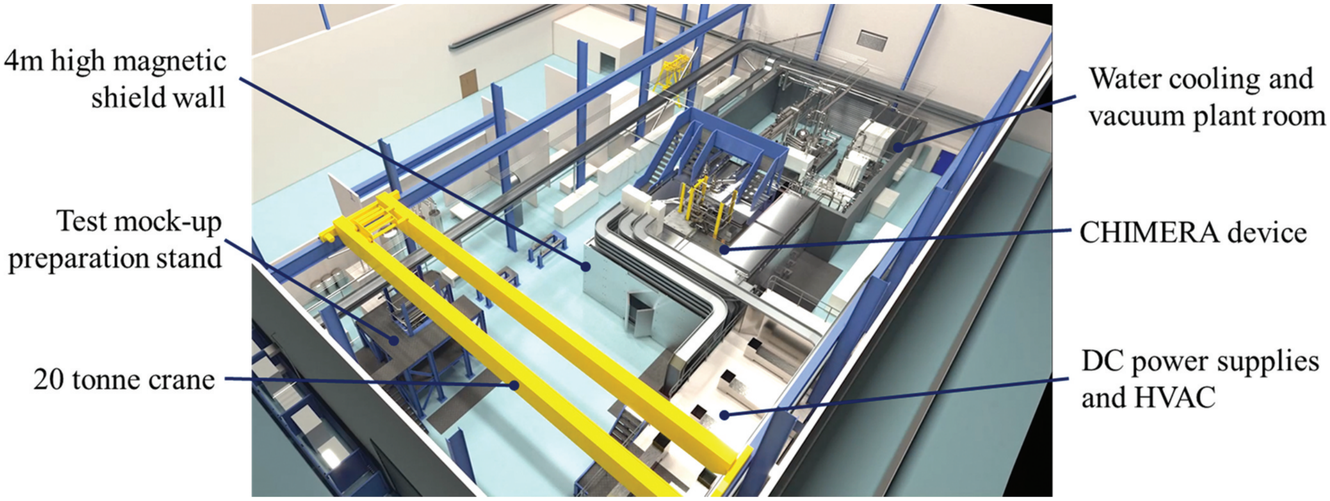

Fig. 1. Aerial isometric view (computer-aided design) above the CHIMERA facility.

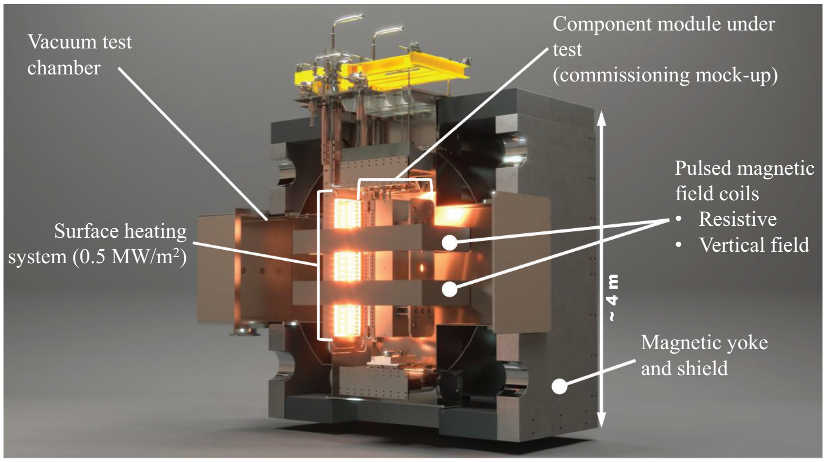

Fig. 2. Vertical cross-sectional view into the CHIMERA vacuum (test) chamber. The large surface heater is shown energized at low power. At full power it will be white hot. The SC magnets are not seen in this view.

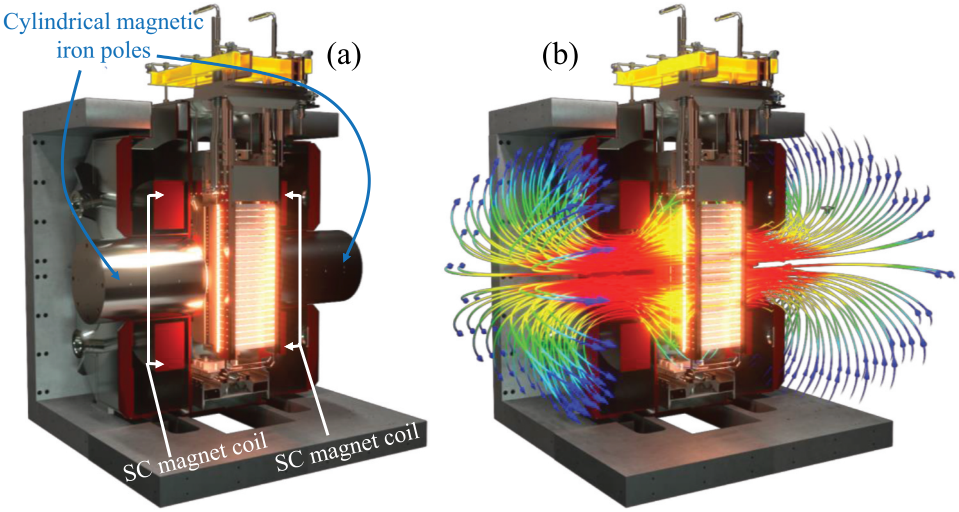

Fig. 3. Vertical cross section along the SC magnet axis showing (a) the two SC magnet coils and low-carbon steel poles and (b) illustration of the SC magnet field lines colored by magnetic flux density. The large surface heater is shown energized and obscures the mock-up under test in this view. The pulsed magnet (VFM) is not shown.

## III. STRATEGY FOR VIRTUAL TEST AND QUALIFICATION

As has been mentioned, testing in the CHIMERA facility will heavily feature virtual testing as part of routine operations, and this aspect of operations is being started in advance of the device itself being available. The strategy is to routinely generate a digital replica of the physical mock-up to be tested, which takes account of detailed data on the as-built condition of the mock-up such as geometry (from three-dimensional surface or even volumetric scans[4]), measured material properties, and other sensor data. The digital replica is a snapshot in time of the mock-up condition, but far more than this, it uses coupled models of multiphysics engineering simulations to accurately predict the component behavior under a set of imposed loads.

Once generated, first, we can use the digital replica to run virtual testing in advance of a real test, to design and plan experiments, therefore maximizing the value of testing campaigns. Second, once testing in CHIMERA is underway, experimental measurements can be used to further validate the outputs of the digital replica, building confidence in the simulations. Simulations are essential for the design of components for a DEMO-class reactor. It is inconceivable to aim to physically test every in-vessel component developed; hence, virtual testing must be relied on (and accepted as a strategy by key stakeholders), and therefore, validated simulations will be essential. Third, once the test campaign is completed, the digital replica is synchronized with respect to measured data from the real mock-up and used in an interpretative mode[5] to provide much greater insight into the state of the mock-up than could ever be inferred by physical measurements alone. Examples might be the component interior strain field (under load, or posttest), stress at the root of a weld, occurrence of cavitation at water-cooling channel bends, risk of fatigue crack initiation/propagation, and induced eddy current density and consequent forces/heating.

This digital replica is a step toward the realization of a component (or complete system) digital twin. Both are an accurate representation of the form and behavior of a physical asset, but further, the digital twin runs live coupled to the running experiment or operating plant, regularly being synchronized and updated using measured data from the asset, potentially in real time. Both replica and twin necessarily require a modeling strategy with the ability to capture high complexity but with a rapid execution time approaching or exceeding real-time capability.

### III.A. Systems Simulation

A fundamental part of the strategy is to employ what is here termed “systems simulation.” The CHIMERA mock-ups, and indeed the assemblies of in-vessel components of DEMO-class reactors, are expected to be geometrically highly complex and will also require coupled multiphysics simulations capturing nonlinear effects and state-dependent materials data. Accurately modeling the

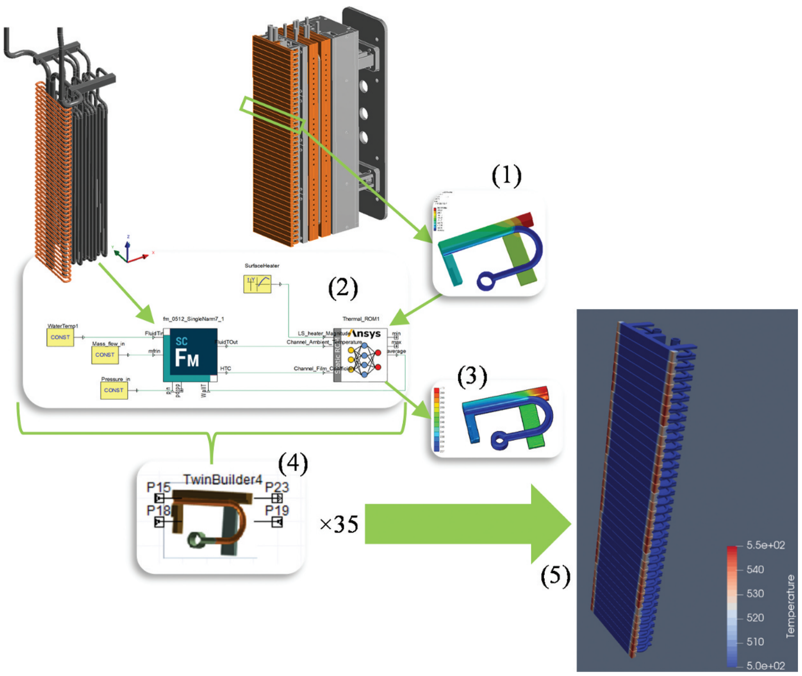

Fig. 4. Systems simulation of the CHIMERA commissioning mock-up FW slat. This is a model coupling the complete fluid, thermal, and structural behavior trained over the CHIMERA commissioning envelope.

complete system behavior by explicitly solving in parallel the underlying equations, with sufficiently low solution time to be useful for engineering design studies or even run in a real-time environment, is expected to be massively computationally expensive and inefficient, although with modern compute power, this ambition is conceivable and is being attempted for a range of industrial sectors.[6]

In contrast, the systems simulation approach involves dividing a complex system into subcomponent parts and domains, each with static or time-dependent engineering fluid, thermal, structural, and electromagnetic simulations [typically, using finite element analysis (FEA)]. Reduced-order-modeling techniques such as machine learning or response surfaces are then used to generate accurate and quick-running models of the simulated behavior. Clearly, key to their accuracy is investing computational effort upfront in generating a sufficient number, and range, of training data for the models. Once trained, these reduced-order models can be coupled together in systems space including using co-simulation to enable rapid prediction of the complete system behavior under a set of loads or other inputs defined by the user.

The systems simulation approach allows handling of highly complex components at high speed while achieving the required accuracy. Depending on the test campaign, it may be sufficient to accept less accuracy (larger model error) in some areas of the model in order to reduce solution time. Low computational expense enables probabilistic simulations; by running not just one simulation but thousands concurrently, we can account for the effect of uncertainty in modeling inputs, which is part of what is termed "stochastic modeling."

The systems simulation method is illustrated in Fig. 4. A complete model of the CHIMERA commissioning mock-up FW slat[a] "(1)" is generated from individual fluid, thermal, and structural FEA analyses from which reduced-order models are trained and then coupled together using Ansys TwinBuilder[7] "(2)" to capture the full component behavior "(3)." There are 35-slat components in the mock-up FW (mimicking the size of the ITER TBM FW); instead of running an expensive high-fidelity simulation of this complete assembly, 35-slat thermal and stress reduced-order models are coupled with a one-dimensional (1-D) fluid model "(4)." Each slat is connected to the associated output from the 1-D flow model and hence assigned different flow boundary conditions. This can be solved using parallel computing giving a rapid solution for the complete FW "(5)." The next step is for this FW coupled systems model to be integrated with

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[a] A brazed assembly of copper heat sink with CuCrZr alloy and stainless steel welded pipes. See Sec. IV for more details.

equivalent models of the other sections of the commissioning mock-up, including the rear magnetic load section, thereby enabling a full virtual test of the commissioning mock-up under different CHIMERA test scenarios.

## III.B. Virtual Qualification

A major motivation for the creation of a digital replica is the ability to perform virtual qualification. In current fusion reactor conceptual designs, the vacuum vessel is the primary containment barrier with respect to release of radiological material, and so, the vacuum vessel is likely to follow a relatively conventional code qualification route and associated requirements.[8] However, the components inside the vacuum vessel are likely to be quite different, as for DEMO-class devices, they are developmental in nature, and so existing codes have limited relevance. But also, the consequences of failure are not thought to be severe in terms of safety, and so verification of in-vessel component integrity is driven by mitigation of device downtime and economic risks (asset protection). This opens up opportunities for designers. First, departing from the stringent verification and integrity assessment requirements of nuclear codes like RCC-MRx (Ref. 9) opens up design and manufacturing options that are not normally available. Second, it promises more freedom in approach to component qualification compared to traditional requirements of a nuclear regulator.

In-vessel component development is faced with a number of challenges when it comes to component qualification, but these can be well mitigated using the approach of virtual qualification, as described below.

### *III.B.1. Poorly Predicted Component Behavior*

The unusual operating conditions, materials, and manufacturing processes of the in-vessel components combined with lack of operational precedence lead to low confidence in absolute performance predictions. Computational simulations are becoming increasingly advanced, and as mentioned, these will require validation under controlled conditions especially when dealing with novel loads like magnetic field or combined loads involving possible synergistic effects (i.e., that do not occur under single-effect testing).

Testing in CHIMERA under combinations of loads will offer an abundance of test data some of which may reveal new phenomena. To enable improved virtual assessments, it is crucial to update the integrated digital replica to account for the experimental observations. A subset of this challenge is the prediction of component structural failure. Researchers are developing improved models for prediction of a whole range of failure modes,[10] and as mentioned, these promise a release from the traditionally stringent safety factors built into code design criteria.

### *III.B.2. No Facility Exists for Testing Under True Fusion Reactor Conditions*

An obvious challenge in engineering design for the fusion in-vessel environment is that no facility exists that is able to fully replicate the extreme conditions at the reactor core. CHIMERA offers semi-integral conditions of heat flux under vacuum, magnetic field gradient, and magnetic field transients but does not faithfully replicate volumetric nuclear heating nor does it account for plasma-surface–interaction effects or effects of neutron irradiation on materials. Indeed, such is the scale and complexity of DEMO-class reactor design that a full-scale integral test facility may only be realizable in the form of a tokamak: a component test facility[11] or the proposed Fusion Nuclear Science Facility.[12]

Engineering design of the fusion reactor will rely fundamentally on in silico design. Development and validation of the models and techniques of the CHIMERA digital replica enable iterative predictive modeling for fusion system design including intelligent design search (using machine learning, surrogate modeling, etc.), reducing the reliance on human experience/judgment to map the design space. Systematic design search and optimization are routine in many engineering sectors, but the need for many thousands of simulations demands rapid run time; this can be realized using the method of systems simulation. At each stage the simulation data and resulting design choices are logged, maintaining design provenance in a digital thread.

Evaluation of designs in silico allows designers to evaluate concepts virtually under conditions and at a large scale that cannot be replicated in a test facility. The systems simulation can also incorporate the effect of other load conditions that are not addressed in experiments, such as irradiation, once their modeling methods are sufficiently mature or adequate experimental data are available.

The virtual design and qualification approach can also account for the uncertainty that must inevitably be managed (and communicated to stakeholders) in the absence of physical testing under real reactor conditions. Stochastic modeling involves treating every input variable to a simulation as a parameter distribution and reporting every output also with a probability distribution. Measured outputs (from CHIMERA or another operational plant) and simulated outputs are utilized together to provide updated model parameters and determine the most probable machine state. Examples of known uncertainties for which we can input a quantified (engineered) distribution are component fatigue life (material s-n data scatter), manufacturing tolerances, surface roughness, joint friction coefficient, or joint contact resistance. Advances in computing hardware, and the systems simulation approach, make it possible to run large numbers of simulations concurrently to explore the parameter distributions. Ultimately, the lack of a fully prototypic test facility means that end-of-life fusion component data are not obtainable, but this approach means that neither should they be required. Virtual assessments with uncertainty quantification enable more effective design, and the risk to in-vessel components is more likely to be made palatable to operators and investors.

### *III.B.3. Undeveloped Manufacturing and Test Acceptance Criteria*

The unusual materials and manufacturing routes likely to be used for fusion in-vessel components are unproven in terms of ability to survive the design loads and will harbor as-yet unrevealed failure modes. Manufactured components, particularly at dissimilar material joints, will include defects or imperfections. A zero-tolerance approach to defects will be extremely costly, not only in developing a flawless manufacturing procedure but also in the cost of quality assurance and inspections during mass production, especially for a system like the divertor, which could have hundreds of thousands of plasma-facing components (PFCs).

X-ray and neutron computer tomography (CT) for nondestructive testing (NDT) is gaining increasing acceptance in many areas.[4] Far more than an image, this technique can generate a highly realistic digital reconstruction of an as-manufactured component, even for components featuring thick tungsten armor; see Fig. 5 for an example.[4] These tomographic models are of sufficient resolution to capture manufacturing defects such as voids or cracks. The digital model is the geometric basis for the aforementioned digital replica, which can then be put under representative loads (heat flux, magnetic field, etc.) in order to develop acceptance criteria for defects, fits, and dimensional tolerance. This approach was demonstrated for a divertor high-heat-flux component by the author in Ref. 13, assisting in improving a defective braze joint; see Fig. 6. This aspect of virtual qualification offers opportunities for development time and cost savings without compromising reactor safety and is a development theme in CHIMERA.

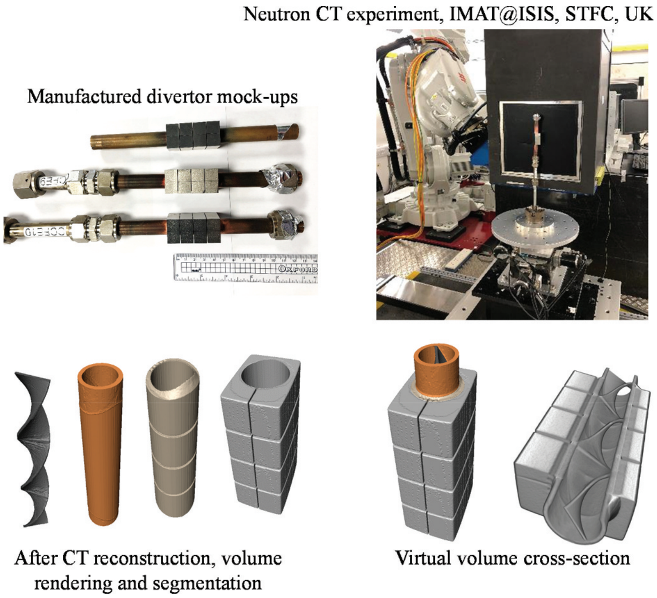

Fig. 5. Example application of neutron CT for divertor component NDT (Refs. 4 and 14).

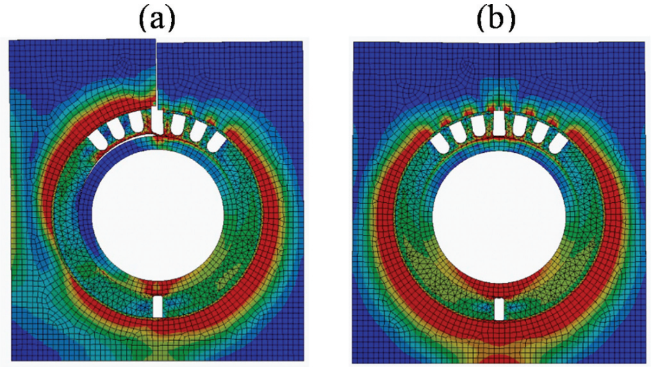

Fig. 6. From Ref. 13, contours of stress (equally scaled) for (a) digital replica using CT scan data with built-in manufacturing defect and (b) same analysis for as-designed part.

Following the as-manufactured CT, the testing of a component in CHIMERA[b] could involve a series of interruptions with repeated CT at each test interval,

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[b] A component of a size for which the CT technique (or another nondestructive imaging technique) is feasible. This is dependent on material choice.

enabling the tracking of progressive cyclic damage to the component. Data on progressive damage under load can be extremely valuable for informing performance predictions and predictive maintenance/replacement once a component is in-service.

### III.C. Digital Twins for In Situ Monitoring

Linked to qualification and asset protection is the strategy for component health monitoring in-service. Diagnostic measurement of reactor components is challenging and, in some cases, will be impossible due to the harsh radiation environment to which any measurement devices would be subjected. This raises the clear need for a digital twin, a digital replica that is live coupled to the operational plant. The digital twin will combine data from the physical hardware instrumentation with simulation models to provide data-rich monitoring of the physical assets in real time. The digital twin can be used for ongoing predictive maintenance given the component loading history, mitigating risk of extreme failures for components under surveillance. In real time the digital twin can be used to provide crucial information on component states and inform operational scenarios for such purposes as improving system performance and even proactive control (interlocks) to mitigate risk of component damage. Models must be updated using data from both physical in-core material surveillance samples, revealing irradiation damage, and also in-situ inspection and NDT of the component during machine shutdown periods. With the inherent lack of fusion lifetime operational data and lack of confidence in ab initio life predictions for fusion components or materials in the fusion environment, the digital twin approach is thought to be essential for in-situ condition monitoring of the reactor and to be an essential part of the assurance strategy for satisfying a regulator, investors, or other stakeholders.

CHIMERA provides an ideal development facility for digital twin technology, and as mentioned earlier, the adopted strategy of using systems simulation lends itself well to the near-term realization of simulations running in real time. Demonstrating an operational digital twin is a key objective of the testing in CHIMERA, logically building on the digital replica simulations that support test planning, test result interpretation, and virtual qualification.

## IV. CHIMERA TEST PROGRAM

Although not a comprehensive account of the planned testing, what follows are four test scenarios that cover the main areas of the CHIMERA test and research program.

### IV.A. Magnetic Field Functional Testing

As illustrated in Sec. II, the CHIMERA static magnet arrangement is a SC split pair, with one coil on either side of the vacuum test vessel. The vacuum vessel is relatively large, as the design basis was to enable testing of fusion blanket and divertor module prototypes at full scale. A side elevation sectional view of the vacuum vessel is shown in Fig. 7, showing the major dimensions of the vessel. In most cases, mock-ups for testing are expected to be installed into the vessel via the top lid, which is a limiting factor on the maximum size of the mock-up. Also, the full vessel width of 850 mm between the poles of the magnet (*Z* direction) is available only when the pulsed magnet is removed from the vessel.

Figure 8 presents the magnetic field from the static magnet (numerical analysis using the Opera code).[15] The maximum field is 4 T at the center of the magnet, and approaching 5 T can be achieved in lateral regions away from the magnet center. The field is relatively uniform near the magnet center, especially if iron inserts are used (at the expense of space available in the test chamber), as shown in Fig. 8. This level of field is similar to that expected at the outer-equatorial ports in ITER or EU-DEMO. It is anticipated that in such high magnetic field, the functional performance of components and systems is a risk, for example, operation of diagnostics, instrumentation, and hardware with moving parts such as shutters. The CHIMERA magnet and vessel will allow component developers to test the functioning of items or systems to de-risk their operation in advance of costly installation into the tokamak.

Another key issue is resilience of in-vessel instruments to magnetic field transients. Addressing this issue is very important to account for the current quench phase of a mitigated or unmitigated plasma disruption and may also be important for smaller transient magnetic field effects resulting from intentional or unintentional variations in plasma position. A transient magnetic field induces eddy currents in conductive components, with consequences that are difficult to predict with confidence. The CHIMERA pulsed magnet (VFM) is intended to enable testing of hardware under such conditions. Crucially, the device is designed and being constructed so that the full field reversal (maximum rate 12.5 T/s) can be pulsed simultaneously with the full 4-T static field, with consequent large Lorentz forces generated on components under test. CHIMERA can also perform such testing with the components under heating, which could be essential if operating temperature or heat flux are major factors in qualifying equipment. The VFM can be pulsed every 100 s, enabling repeated cyclic testing under the transient magnetic load.

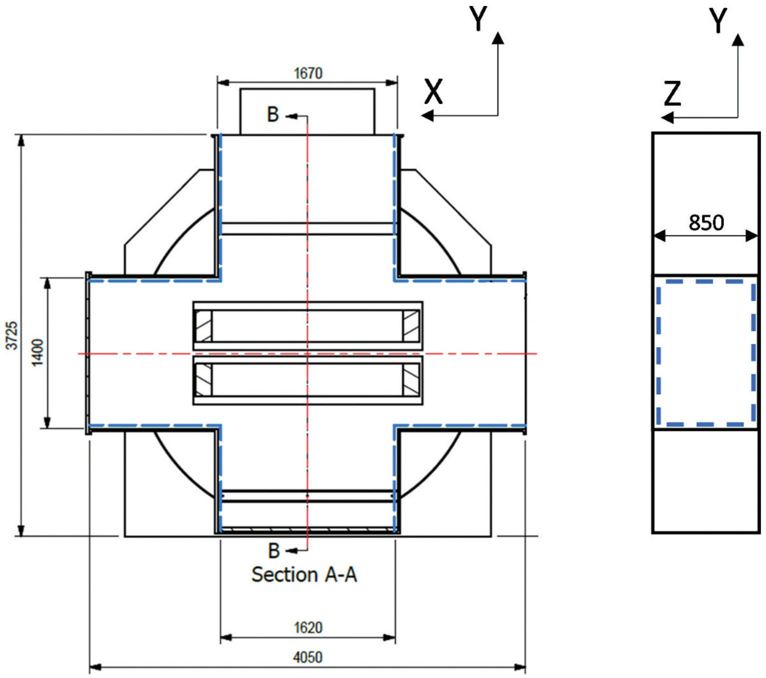

Fig. 7. Side elevation sectional view of the CHIMERA vacuum vessel. The envelope of the test vessel is within the blue dashed lines. Dimensions are in millimeters.

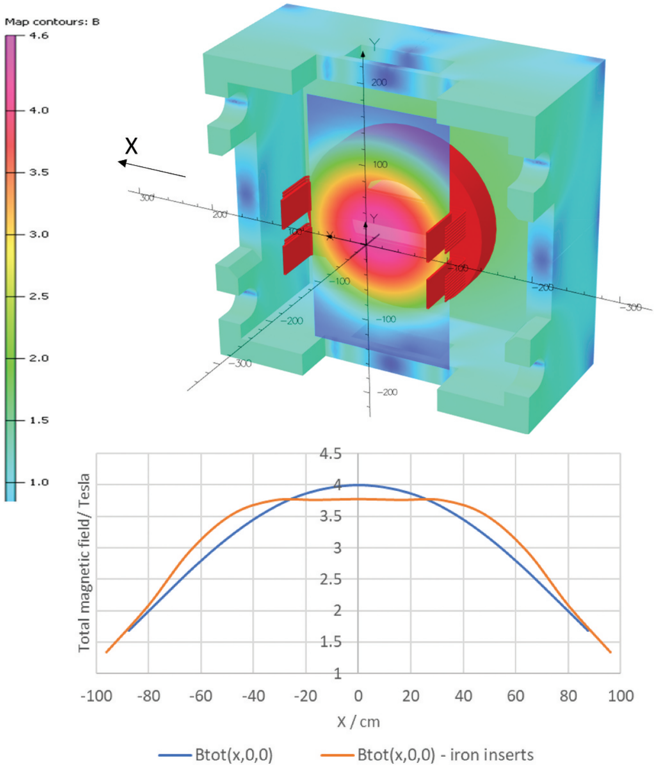

Fig. 8. Magnetic field map plotted on the *X*-*Y* plane at $Z$ = 30.6 cm (note that only one SC magnet and half the VFM are shown due to model symmetry). Graph of total field at $Y = Z = 0$, moving through the magnet in *X*, including a plot when using iron inserts to improve field uniformity. Dimensions are in centimeters, and field units are in teslas.

## IV.B. Semi-Integral PFC Test

The term “semi-integral” is used because as already described, CHIMERA can replicate simultaneously some of the major design-driving loads of the fusion core environment, but not all, with the main remaining gap being irradiation. This is why the overall strategy must include simulation. CHIMERA has been designed to enable representative magneto-thermal-hydraulic testing of the full-size ITER TBM box, to discharge residual risks from the design process, to enable validation of computational models, and to functionally qualify component prototypes in advance of their installation in a tokamak.

To prove this combined-load testing under ITER-relevant conditions, the mock-up that will be used for commissioning and first operations deliberately approximates the TBM in terms of size and also operational envelope. This commissioning mock-up, shown in Fig. 9, is divided into three sections. The FW section is made up of 35 copper slats, each cooled via a CuCrZr cooling pipe with water at up to pressurized water reactor (PWR) conditions (328°C, 155 bars). The FW area mimics that of the ITER TBM, and it is designed to sustain 0.5 MW/m$^2$ in steady-state. The FW surface may be coated in order to improve emissivity and power absorption from the radiative CHIMERA heater. The mock-up midsection is composed of copper panels with an inlaid serpentine water-cooling

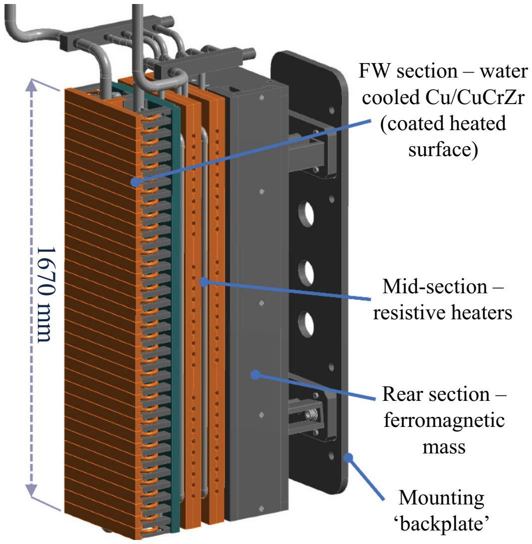

Fig. 9. CHIMERA commissioning mock-up, computer-aided design.

tube and includes embedded resistive heaters for volumetric heating of the section up to 100 kW. Last, the rear section is composed of ferromagnetic steel plates within an austenitic steel casing and is designed to replicate the magnetic forces that will be experienced by the ITER TBM. The mock-up will be fitted with on-board thermocouples, strain gauges, and magnetic instrumentation. Mock-ups as complex as this will require significant effort in their preassembly and integration with CHIMERA, particularly ensuring safe connection of high-temperature water-cooling pipes, fitting and wiring of instrumentation to the lid, and assembly with the CHIMERA load cells.

Large component mock-ups can undergo thermal-hydraulic testing with FW surface and internal heating loads. The mock-up water-cooling loop is designed to exhaust up to 1.7 MW with water up to PWR conditions. In parallel with these thermal loads, CHIMERA can operate with the SC magnet energized, with consequent high magnetic forces or torque on ferromagnetic mock-ups. The commissioning mock-up, similar to the ITER TBM, undergoes a static horizontal pull force up to 160kN at a 4-T central field. Depending on the objectives of the test, the pulsed magnet may be used simultaneously with heating and the SC magnet field to simulate the operating conditions at the point when a plasma disruption occurs. The pulsed field induces large eddy currents in the mock-up structure, which cross the static field from the SC magnet and so generate Lorentz force and net torque on the mock-up.

To develop and prove the performance of an engineering system as complex as a fusion breeding blanket will require testing of prototypes under combined loads as close as possible to the final conditions. CHIMERA is designed with this type of test as a design basis. With the large SC magnet, high-temperature water loop, and later upgrade to include a lead-lithium circulation loop, it is well suited to testing of water-cooled lithium lead (WCLL) blanket technology, as outlined next.

## IV.C. Liquid Metal MHD

It is widely known that a magnetic field fundamentally changes the flow regime and heat transfer behavior of flowing liquid metals, undergoing MHD effects, and also that this modified behavior is highly challenging to predict.[16] If liquid metals are to be adopted in reactor concepts, then the ability to adequately predict and design for MHD-affected flow will be critical. Because of the relatively (compared to hydrodynamics or structural mechanics) immature readiness of numerical simulations, cross validation and even fundamental science by experiments are even more important. Experiments in MHD-affected flows also enable tests on complex geometries and development of requisite instrumentation technology. Important liquid metal MHD experimental facilities already exist,[17] although these are relatively limited in achievable scale and Hartmann number and do not consider heat exchange with high-temperature water, that will need to be verified in the development of the EU DEMO WCLL blanket.

The large test chamber of CHIMERA is well suited for testing liquid metal MHD effects at component scale. A eutectic PbLi circulation loop is under conceptual design, and a preconcept is shown in Fig. 10 illustrating the main features. The loop will be skid mounted and enable a flow up to 17 m$^3$/h at up to 550°C. The loop uses a permanent magnet pump. By use of a counterflow heat exchanger, most of the components in the skid can operate below 380°C, reducing corrosion and so improving

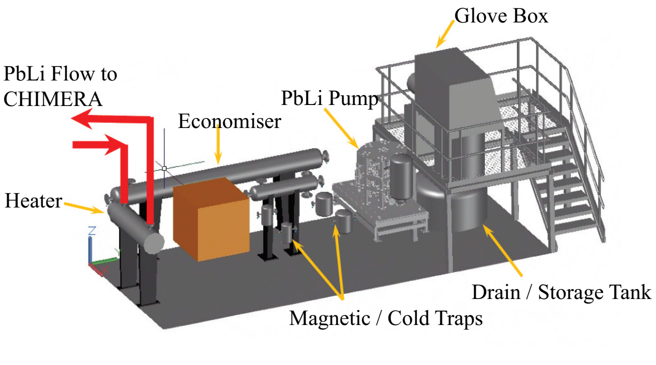

Fig. 10. Preconceptual design of the PbLi circulation loop skid, computer-aided design.

facility life. Within the CHIMERA vessel, PbLi-filled mock-ups will be heated by surface-mounted or internally mounted resistive heaters. Operation of the CHIMERA pulsed magnet brings potentially important experiment possibilities either to study the effects of rapid transients or to use the VFM to vector the magnetic field to study the varying field line angle (tokamak pitch angle).

Last, in collaboration with EUROfusion, a DEMO WCLL blanket mock-up is currently under design in preparation for experiments on CHIMERA. This MHD testing will be an important step forward in capability for the fusion community, particularly the testing of components at full scale and at relatively high field and so previously unachievable Hartmann numbers.

### IV.D. Combined High Heat Flux and Magnetic Field

The design for high heat flux is a critical and design-driving issue, both for the divertor target PFC normal steady-state operation and for FW and limiter PFCs against extreme plasma transient events.[18] There are a large number of facilities worldwide for water-cooled thermal-hydraulic testing of PFCs. Many of these enable testing under high-heat-flux conditions and use either high-energy neutral particle beams or electron beams. The unique offering of CHIMERA is the capability for thermal-hydraulic and high-heat-flux testing in combination with the magnetic loads described above, potentially revealing previously unknown synergistic effects or failure modes, but this precludes the use of conventional electron or ion beam heating. Instead, CHIMERA will use a high-power continuous-wave fiber laser of the type used for commercial laser cutting and welding. The laser is a modular construction and has a maximum 125-kW output. Fixed optics are foreseen initially although concept studies and have shown that complex heat flux distributions may be achievable with development of bespoke scanning optics. The system specification is to provide an absorbed heat flux of at least 20 MW/m$^2$ over a mock-up area of 1500 mm$^2$ (representing the conditions expected at the divertor vertical targets) or 200 MW/m$^2$ over 100 mm$^2$ (representing the conditions of FW extreme transient loads). In practice, there will be a heat pulse duration limit, but the use of a commercially available laser will reliably allow long experiments reaching steady-state conditions.

A key and unique capability is that this high-heat-flux testing can be combined with the static and pulsed magnetic fields. For divertor vertical target component concepts, the Lorentz forces resulting from a plasma disruption or vertical displacement event will impose greater stress onto a PFC already highly stressed from steady-state thermal loading. Additionally, this combined high-heat-flux and magnetic field testing will be especially useful for the development and qualification of liquid metal surface PFCs, either of the capillary porous structure type or free surface liquid metal, since the tokamak magnetic field fundamentally affects (or in some cases may facilitate) the operation of these components. Last, the ability to focus the laser for a heat flux of the order of 100 to 1000 MW/m$^2$ enables studies of PFC surface melting and vaporization as a function of magnetic field as well as impact of exposed leading edges and castellations.

## V. CONCLUSION

Proving fusion technology in advance of installation in a power reactor will require integrated system and multiple-load testing at, or near, full component scale. The CHIMERA facility is being built to help address this need and will enable fundamental research on new technologies, design choices informed by testing, validation of computational simulations, and functional testing of as-manufactured systems under conditions approaching their intended loads, as well as address the development of the digital twin for reactor monitoring and assurance.

CHIMERA is intended to be a flexible test bed capable of combined heat and magnetic loads in vacuum. This paper has outlined the planned test program; however, this is not a comprehensive list of potential tests, and there can be many other applications. CHIMERA is designed with flexibility as a user facility for the fusion community and adjacent sectors.

A major theme of the CHIMERA program is the development of the digital replica and digital twin. The design of fusion systems will critically rely on coupled computational multiphysics simulations, which require validation using a suitable facility. There is no available facility that fully recreates the conditions in the fusion reactor core; hence, a strategy of virtual component qualification is proposed adopting the digital replica augmented with enhanced models or boundary conditions representing full integral fusion reactor conditions. A natural step from this is a digital twin that is live coupled to the operational plant, enabling data-rich real-time monitoring of high technical risk components, proactive maintenance and replacement, and active control to prevent component failure.

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