Approaches for the Qualification of Exhaust Solutions for DEMO-class Devices

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Abstract: Plasma exhaust and protection of the plasma-facing components are critical aspects of DEMO-class devices, so there needs to be high confidence in solutions for the plasma and the materials and components. A special feature of fusion is the choice to take large steps (JET to ITER to DEMO in the EU) to control the time and cost of the development of fusion power. Therefore the qualification strategy has to provide adequate confidence without a fully relevant integrated prototype, especially if innovative exhaust approaches that will not be explored on ITER are needed. A strategy is explored that uses theory-based and experimentally validated numerical models for the final extrapolation. Two examples are investigated: the detached plasmas in the divertor and part of a plasma-facing component. These show that uncertainty quantification followed by minimisation will be vital for both optimisation and qualification. Furthermore qualification issues should ideally be considered from the outset and could guide R&D programmes. The approach would need extensive experimental data and also advanced computational tools, which would have synergies with virtual engineering and prototyping (used increasingly in other fields).

1 Introduction

One of the challenging aspects of the step from ITER to DEMO-class devices[1] is the qualification of the scientific, technological and engineering solution to a level that justifies to stakeholders the strategic and financial investment, given that a full scale integrated precursor test is not feasible, almost by definition (although for many plasma aspects ITER can come close). Most other fields take much smaller, shorter timescale, lower cost steps. However an interesting counter-example is the Nautilus programme for the first nuclear submarine in the 1950s [1] which was a very large step, in particular in integration. An empirical approach was adopted for Nautilus, but encouragingly some fields, e.g. automotive and aerospace, are launching products without a full prototype, even if the steps are more incremental than in fusion. Virtual qualification can be done with good confidence and few physical prototypes when based on well-accepted tools and methods. It becomes more challenging when new single or multiple phenomena are involved, or in unstable or singular conditions. Fusion is in this latter category, so virtual and physical prototypes/simulations need to evolve together.

Plasma exhaust (or first wall protection) is a good example of the general challenge, encompassing several state-of-the-art topics: complex plasma & neutral atom physics, advanced engineering, design and use of materials and components in extreme environments, and measurement and control in this same environment. Crucially, the elements need to be integrated into an overall solution that can accommodate significant behaviour uncertainties.

The Technology Readiness Level approach [2], despite some generic limitations [3] is the reference for many technological subsystems and useful for more physics-based elements (e.g. materials [4] and plasmas [5]). However TRLs are traditionally empirically based, especially

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[1] DEMO will be used here as shorthand, *not referring to any specific design or concept*.

at the higher levels, and therefore have limitations as it is not possible to replicate the full environment for all subsystems, and TRLs cannot be used alone for the first complete integrated facility. Recognising this, we explore an approach that exploits modelling for the final step (see Fig.1.), and generally gives a major role to theory and modelling throughout the TRL-like development ladder and especially for the critical integration issues (normally theory and modelling only feature significantly up to about TRL 3). This appears different from other fields at the moment, although there are major modelling initiatives in many areas, for example the EU Human Brain Project, modelling of a human cell, and aircraft modelling (e.g. CRESCENDO, TOICA projects in the EU). These do not yet go as far as qualification/certification, but approach it and are used for pre-screening (e.g. of brain treatments or aircraft layouts). *In silico* qualification of large complex systems is likely to need very large computing power and innovative numerical approaches and has huge potential benefits of cost and time, and design flexibility and optimisation – the associated tools would also provide a platform to test new ideas in a simulated integrated environment.

In this very preliminary study the general issue of qualification is discussed, then the elements of the integrated exhaust system are outlined, with some of the approaches under consideration, and an outline of an overall qualification approach. Two examples are explored: divertor detachment and a plasma facing component (a monoblock).

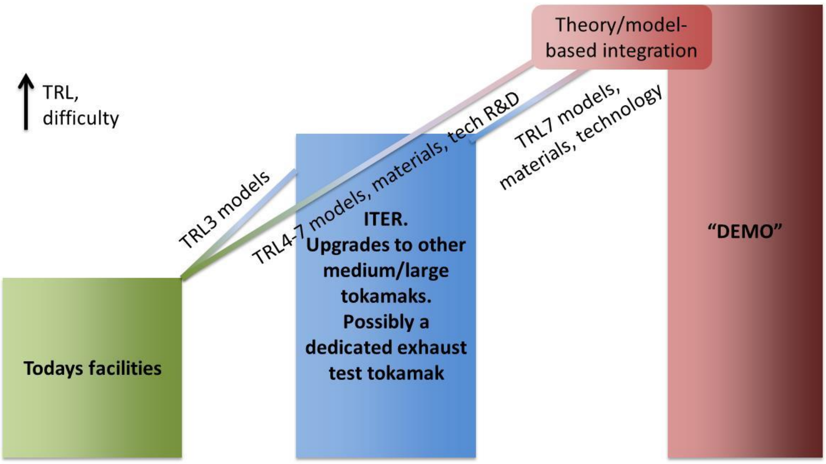


FIG.1. Outline of an empirical + theoretical stepped approach to qualifying integrated exhaust solutions for DEMO-class devices

2 Qualification – general considerations, exhaust context

Qualification in this paper refers primarily to being sufficiently certain that the exhaust scheme will work, and that its failure modes are understood and mitigated. Lower uncertainty may be more important than higher performance. Key points include:

- The new type of stakeholders are likely to need a very rigorous and traceable basis for decisions – primarily empirical extrapolations may not be adequate
- Exhaust requires integration of the main plasma and plasma facing components
- Materials behave differently under combined loads (neutron + mechanical + thermal) and such loads are unlikely to be available in advance, especially for macroscopic components
- Failure modes will be critical, not all will have been experienced or possibly identified
- If it appears that qualifying a particular aspect will be too challenging, then the exhaust scheme may need modifying – hence qualification should be considered at the outset.

"Wind-tunnel" approaches are traditional for extrapolation. They are most reliable when the physics can be completely described by dimensionless parameters (e.g. $\rho*,\beta,\nu*$). For the scrape-off layer and divertor this is unreliable, e.g. due to the critical non-linear role of atomic and molecular physics in plasma detachment. Scalings can be generated from experimental data and theory [6], [7] [8]; these are mainly for attached plasmas so far. Hence models are vital, and their role and use is illustrated in Figs 2 and 3 (and Fig. 1), showing qualification strategies form part of the design optimisation as well as the final decision process.

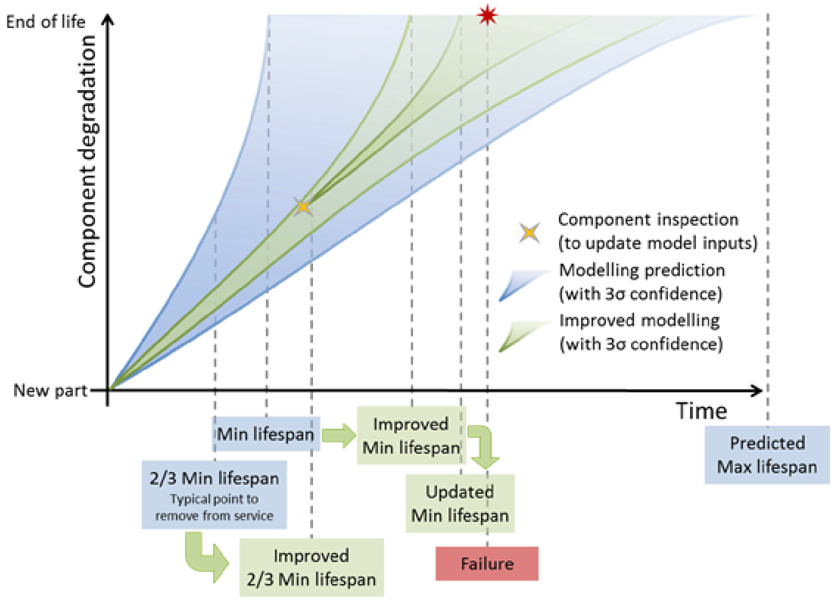
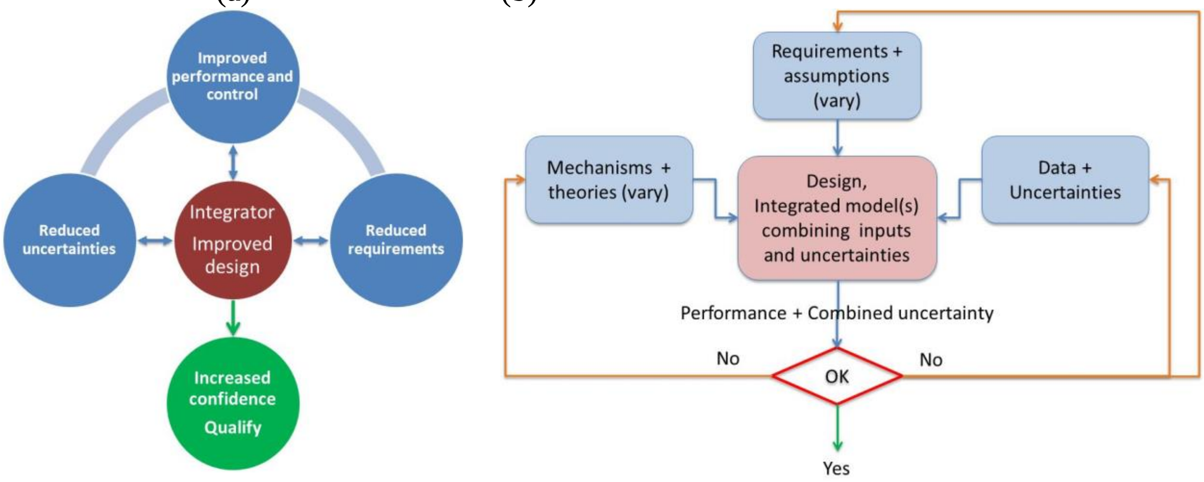


FIG.2. Improved modelling providing reduced uncertainty (green) can allow a solution to be used that would otherwise be rejected due to the risk of too early failure (blue). Component inspection combined with modelling may allow life extension. Better modelling can also allow designs with reduced margin – this may be critical for finding good solutions.



(a) (b)

FIG.3. (a) A design approach showing how qualification factors can enter the design. (b) Use of models and feedback to combine the full spectrum of inputs and uncertainties to give performance predictions and confidence levels to support qualification. These apply to sub-elements (e.g. divertor and SOL, or an irradiated PFC) as well as the whole exhaust scheme.

Models must contain all relevant mechanisms and interactions, from experiments and theory. *Model assumptions* need to be valid in both the final and the test environment. *Model validation* needs special attention: experiments usually involve several mechanisms which generally will combine in different ways compared with the test and may lead to different performance (better or worse). Furthermore since these models will perforce be validated upon reduced scale experiments, it is essential that the models correctly capture aspects of performance that are influenced by physical scale. For *engineering models of components*, the impact of component scale size on failure mechanisms and rates is a key area for attention as it will be necessary to validate these models on reduced scale mock-ups. Similarly, establishing “as built” component models rather than idealised will be important to capture the statistical impact of manufacturing imperfections. Some qualification tools themselves need qualifying; certifying a tokamak or individual experiment as a qualification tool is perhaps a new idea.

Uncertainties, their quantification and propagation including any cancellation, are key. This is a rapidly developing field outside fusion. Models are probably the only tool for estimating systematic and integration uncertainties. Uncertainties can be statistical, but also arise from assumptions/implications made, missing effects, changes in underlying physical mechanisms between the test and final environment, and from integration e.g. pedestal and SOL plasma, or combined radiation and thermomechanical loads in the PFCs. Propagation of statistical uncertainties through models can be addressed in a formal way, although it is complex. Quantifying uncertainties due to model approximations, gaps or simplifications is a different task, especially if it is difficult to do reference calculations with no approximations or simplifying assumptions and a methodology will need to be developed. For example “complete” physics could be included in a model of a part of the system, or in, say, a simplified geometry, and then compared with the simplified model of an integrated simulation in the same situation.

3 Exhaust as an integrated system

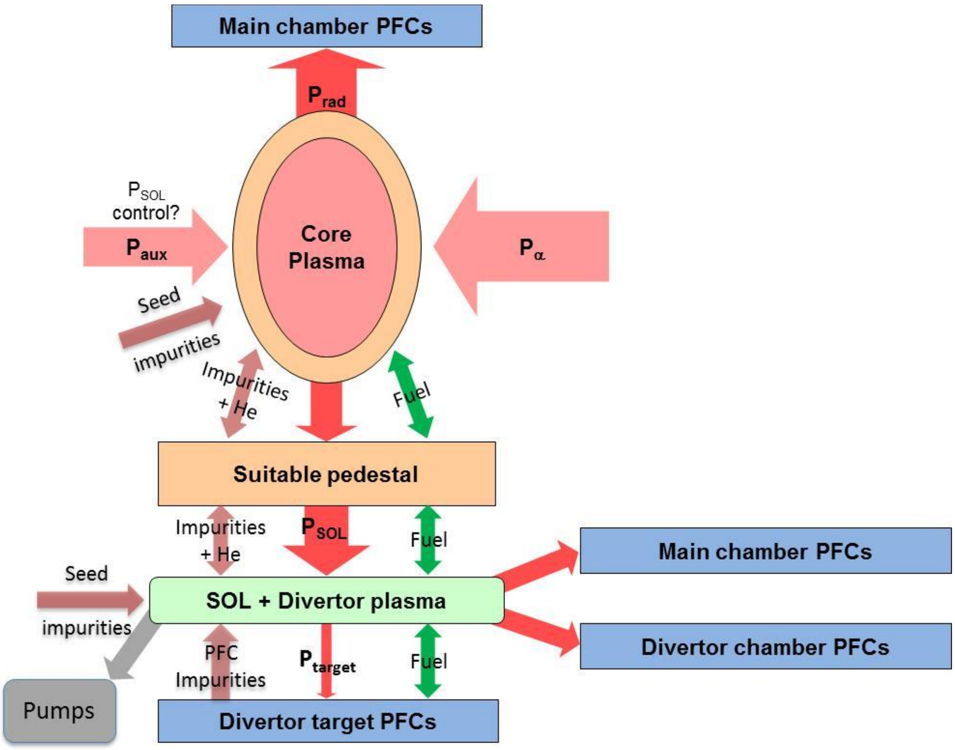


FIG.4. Exhaust as an integrated system, showing the various actors, all of which need to be considered together

The plasma exhaust system comprises many elements (e.g. [9]), most of which are indicated schematically in Fig. 4. A study for the EU DEMO programme [10] with a conventional divertor is given in [11], [12]. It is complex, but the number of elements may in fact help with solutions and confidence in qualification, especially if flexibility is allowed. For example the auxiliary heating power or pellet fuelling change the exhaust power and could be used in exhaust control. The importance of integration can be illustrated by two examples. If a very high fraction of the power deposited in the core plasma has to be radiated in order to reduce the power entering the divertor, then a small change in this radiated power fraction (e.g. due to measurement or control limitations) has a large effect on the divertor, potentially leading to damage by melting. If the detachment front or other radiating region in the SOL and divertor is close to the x-point (by accident or design), then the pedestal can have a substantial two-dimensional perturbation which may change the pedestal structure in a complex way.

There are several strands to an exhaust strategy (e.g. the EU strategy [13]): conventional options and alternatives with more headroom in case the conventional approach is too marginal. For example

- Conventional divertor (like ITER) with high main-plasma radiation, detached divertor
- Alternative configurations, double null, snowflake, X, super-X, or combinations
- Reversed triangularity [14]
- Conventional PFC materials, namely water, gas or molten-salt-cooled tungsten
- Alternative PFCs, primarily liquid metals
- A condensing vapour divertor channel [15]

The main qualification principles apply to them all, but the details would vary and some may be easier to qualify than others (e.g. due to greater margin or extensive tests on ITER). However some alternative approaches introduce additional aspects to qualify, e.g. dedicated systems for liquid metals, or the technology to allow coils inside the vessel.

Control, a research programme in its own right [16] can be a major asset in qualification as it can allow substantial uncertainties to be accommodated.

4 Example 1: Qualification of power attenuation in the divertor plasma

A highly radiating detached plasma region will create most of the attenuation (i.e. power dissipation and erosion reduction) and must survive and attenuate slow transients. Predicting DEMO exhaust will be an extrapolation, in many ways, beyond the physics regimes currently encountered in experiments, e.g. normalized mean free paths for ionization, ion-D_2 collisions, and photon absorption. Together with cross-field transport, combined main-plasma and divertor conditions they can affect the separatrix density, and the pedestal structure may be in a new regime. Extrapolation would be eased from the divertor perspective if P_{SOL} in DEMO is comparable to that on ITER, although this makes the core plasma extrapolation more demanding (higher radiation fraction). The models at present have several gaps [17]. As indicated above if the detachment front moves close to the x-point it will affect the pedestal and core plasma and divertor pumping and it is simpler if this is avoided. Long leg divertors with a large reduction in the total magnetic field between x-point and target give some natural “springiness” to the detachment front and detachment for a wider range of upstream conditions [18] which potentially would help with detachment position control. Fast transients and even small high frequency fluctuations also need to be attenuated adequately to allow long lifetimes for the divertor targets. Some of these issues have underlying uncertainties at present (e.g. the nature of cross-field transport due to turbulence), but some are in principle calculable with confidence (for example parallel transport including kinetic effects with classical collision processes). The main challenge is constructing sufficiently comprehensive numerical models, with advanced enough numerical techniques (and computational facilities), to determine divertor solutions and time dependencies for control. In this sense there is similarity with the PFC example below, i.e. it might be better to have a linked set of models and data rather than a single first-principles model.

The qualification goal is to show the proposed solution meets the requirements for the entire uncertainty range (cf. 3σ in traditional language). Optimising the performance and margin is intrinsic to qualification. The main steps are relatively obvious, even if complex to implement. For the proposed solution (e.g. detached plasma with double null divertor):

- Identify all relevant but uncertain mechanisms in SOL + divertor plasma, understand them enough to implement in models, including uncertainty quantification tools.
- Test these models against experiment and refine.
- Develop measurement and control methodologies and model.
- Develop models to couple to the pedestal and to the PFC surfaces (sputtering, recycling).
- Develop advanced numerical schemes to allow rapid but suitable calculations.
- Develop a framework to include models for all the processes (assuming that it cannot be a single code), including control, which allows performance estimates and uncertainty quantification.
- Calculate performance and the likely uncertainty range, compare with requirements.
- Iterate as needed.

5 Example 2: PFCs under combined neutron and thermomechanical loads

The example chosen is a water-cooled tungsten monoblock. There are gaps and challenges in base materials data, manufacturing, design codes and modelling, and materials data under combined neutron and thermo-mechanical loads and for macroscopic samples (The situation would be transformed if an FNSF [19], or CTF [20] were feasible to expose macroscopic components to all the loads together). Questions include how best to use (a) data from small samples when macroscopic engineering behaviour can differ substantially [21] [22] [23] and (b) data from partial loads, e.g. mechanical tests of unirradiated samples. Presently a number of the important mechanisms which drive failure, such as irradiation creep, are still poorly understood. Furthermore material properties vary significantly depending on their manufacturing route, even for the same chemical compound, and sometimes for nominally the same route. However some powerful techniques are emerging to reduce uncertainty in real samples via high resolution tomography and image-based FEM [24] [25] using advanced FE modelling to capture microstructure compared to using average properties. This is well suited to high levels of parallelisation and can improve component production (reduced uncertainty, Fig. 2) and selection. Fig. 5 shows an example for an ITER-like monoblock.

A single comprehensive multi-scale integrated model of a component does not appear realistic, so an overall package manager would be needed. Many commercial multi-physics codes are not yet suited to parallelisation but open source codes tailored to make efficient use of HPC, are emerging e.g. OpenFoam for CFD or ParaFEM for FEA (already used for IBFEM).

Fig. 6 shows, indicatively, an example approach which brings together a wide range of data, models and requirements with an “integration” box (cf Fig. 3). The qualification process would be a combination of establishing agreed design rules and determining load & geometry boundary conditions, designing the component to these, analysing and testing actual materials and prototypes, and then modelling the performance and uncertainties. An early step would find which uncertainties have the biggest impact. The design would be iterated with the sources of uncertainty to reduce the overall uncertainty (Fig. 3); for example it may even be possible to design the component such that the thermomechanical stress fields are similar in magnitude to those in small samples irradiated in materials test reactors or IFMIF.

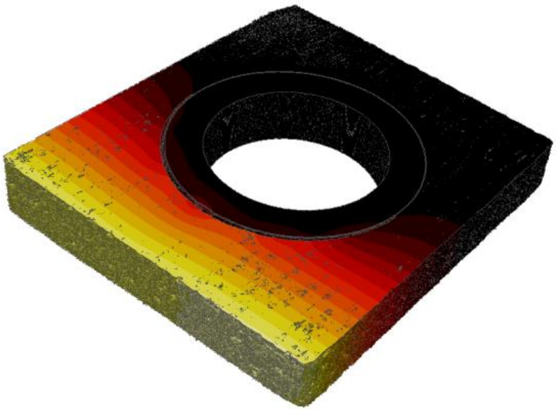


FIG.5. Image-Based FEM analysis of temperature distribution in a CFC-copper pipe monoblock [24]. *Defects in the CFC can be seen (and the FEM is based on the fibre layout in the actual monoblock). Higher resolution would be needed for tungsten.*

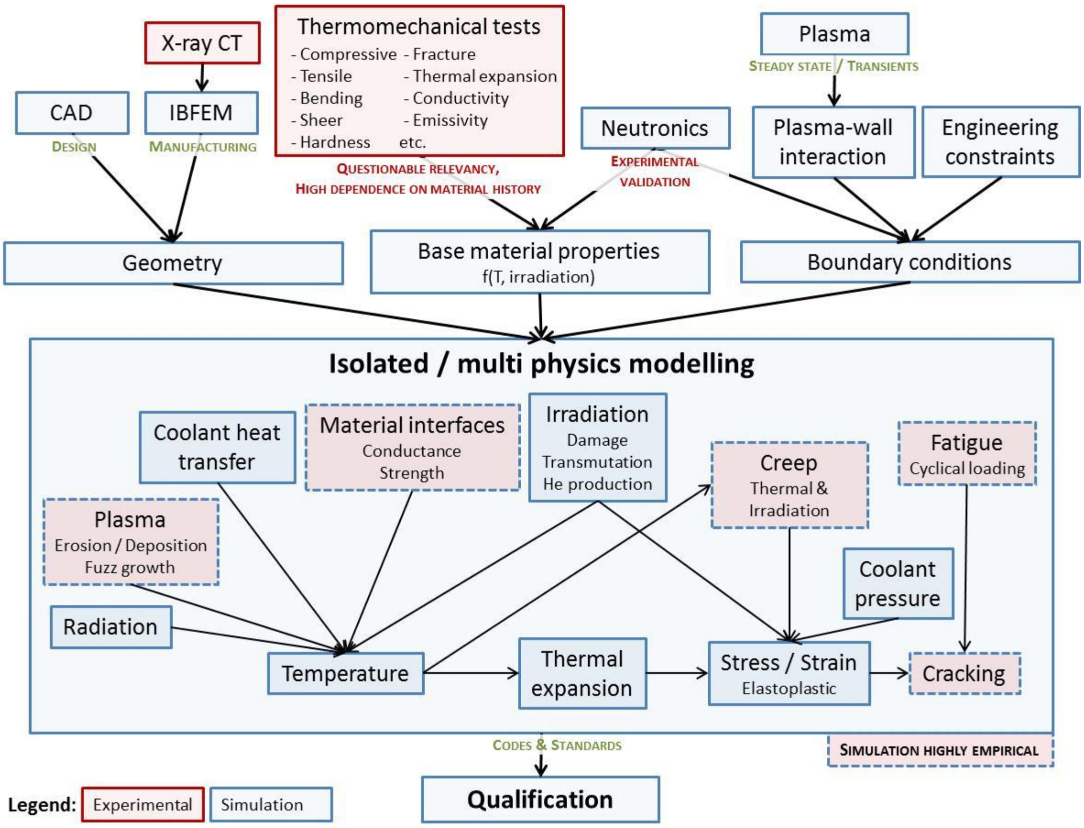


FIG.6. Example approach with traceable performance calculations for a component to assist qualification via performance estimates and uncertainty quantification and propagation.

6 Summary

Developing a qualification stepladder, and the tools to help climb it, is a key part of the path to fusion power plants. This preliminary consideration of the qualification of exhaust solutions for DEMO-class devices implies that qualification factors must be included in the concept and design optimisation stage. Furthermore, theory and modelling have to play a critical role in qualification at all stages, in particular in assessing the final integration and the impact of untested aspects of the final environment (plasma and neutron irradiation in particular). The advanced modelling and computational tools needed could provide a powerful tool for fusion and synergies with other communities wishing to minimise costly and time-consuming prototypes.

Acknowledgements

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