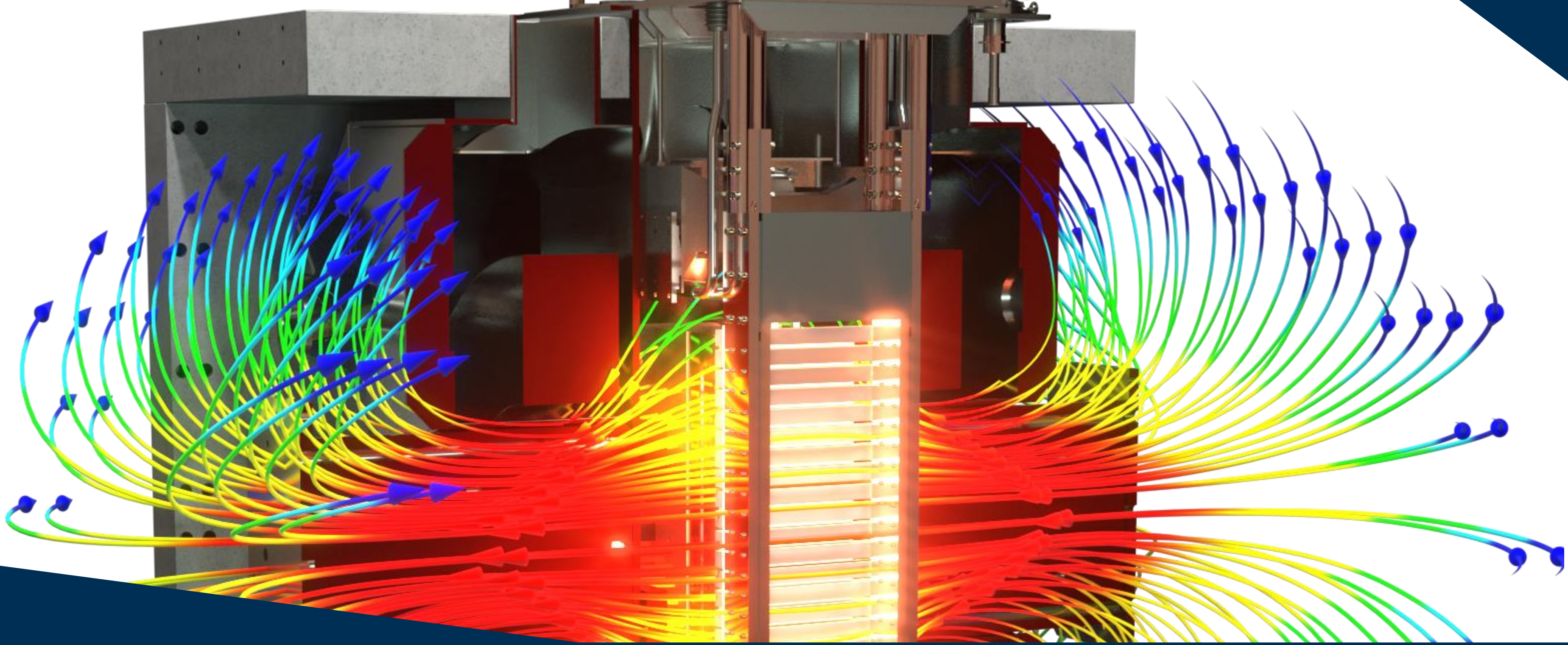

Preparing for the First Integrated Test of a Fusion Breeding Blanket Prototype in the CHIMERA Facility

Tom Barrett

ISFNT-15, Gran Canaria, 11th September 2023

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1. CHIMERA construction

2. Blanket Prototype: specification, design and construction

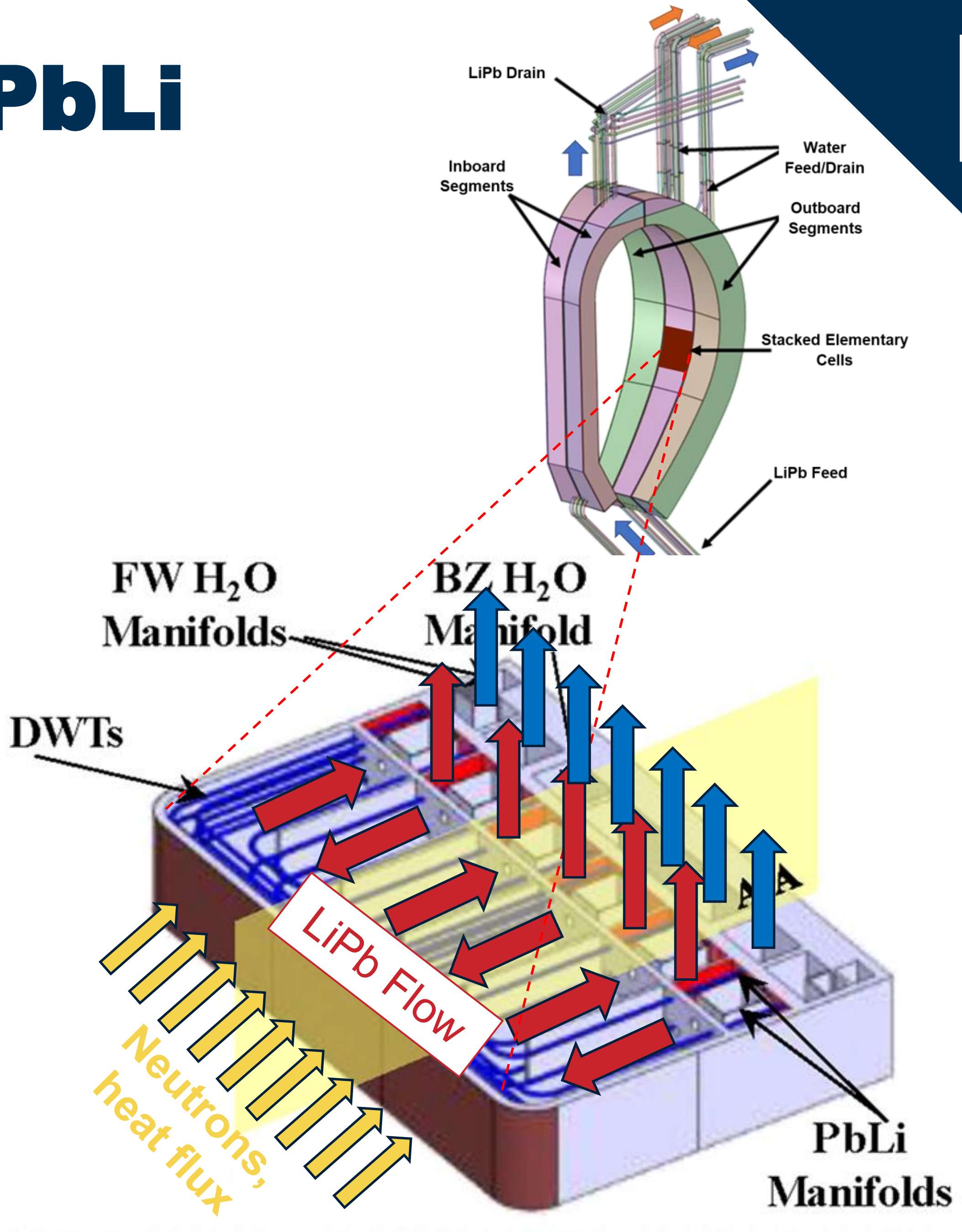
Integrated Blanket Test

3. Development of a simulation Digital Replica / Digital Twin

EU DEMO water-cooled PbLi (WCLL) blanket

EUROfusion

- One of two blanket concepts considered for EU DEMO (and EU ITER TBM)
- Eutectic LiPb at <550°C, bulk flow speed > mm/s
- Water cooling at 15.5 MPa, 328°C
- Decades of development in Europe
  - Integrated design against complex loading
  - Small scale testing
  - Developed closely with EU TBM



F. Cismondi et al., Fusion Eng. Des. 157 (2020) 111640.

Integrated Breeding Blanket Testing

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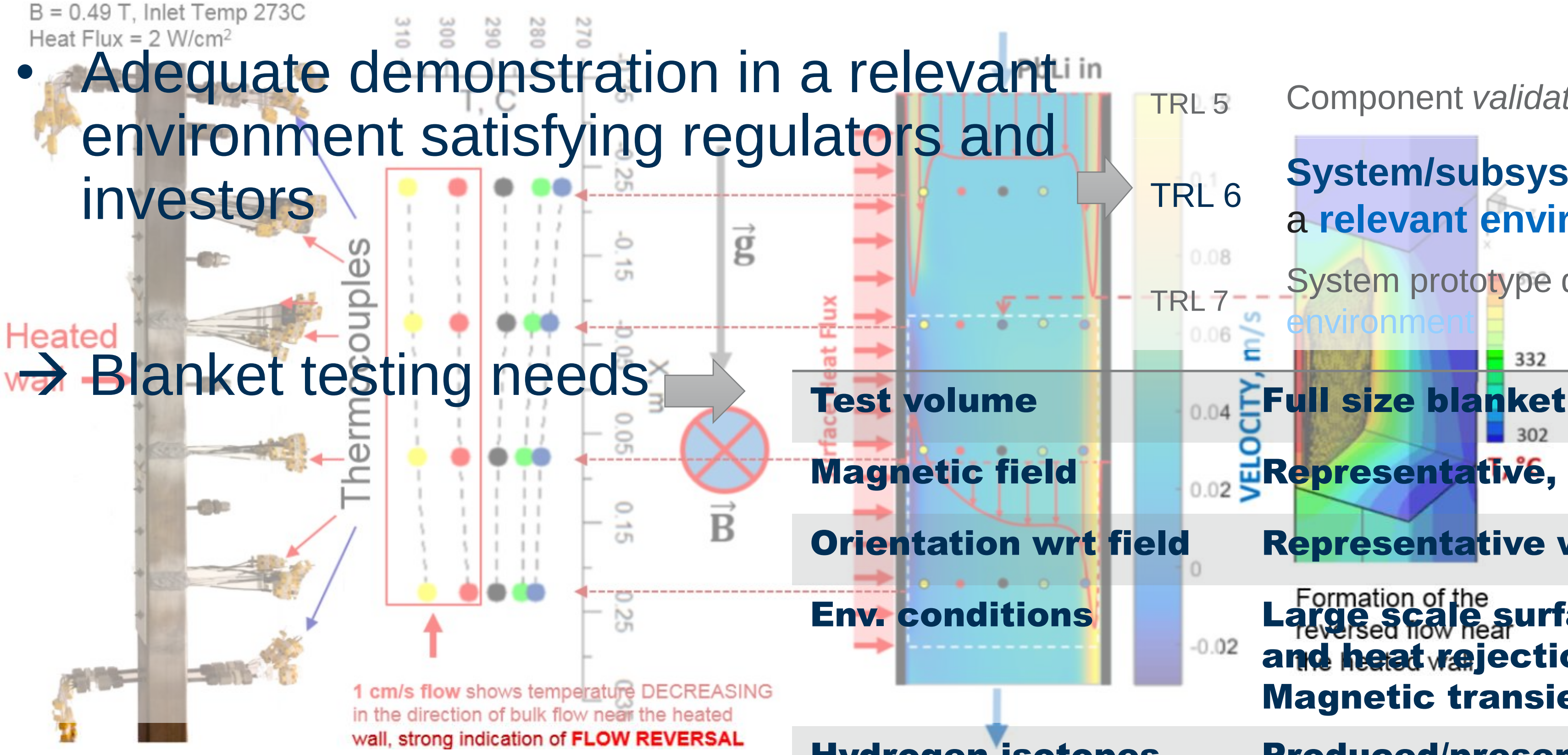
- Importance of multiple-effect testing

- Adequate demonstration in a relevant environment satisfying regulators and investors



TRL 5 — Component *validation* in relevant environment

TRL 6 — **System/subsystem prototype *demonstration*** in a **relevant environment**

TRL 7 — System prototype demonstration in operational environment

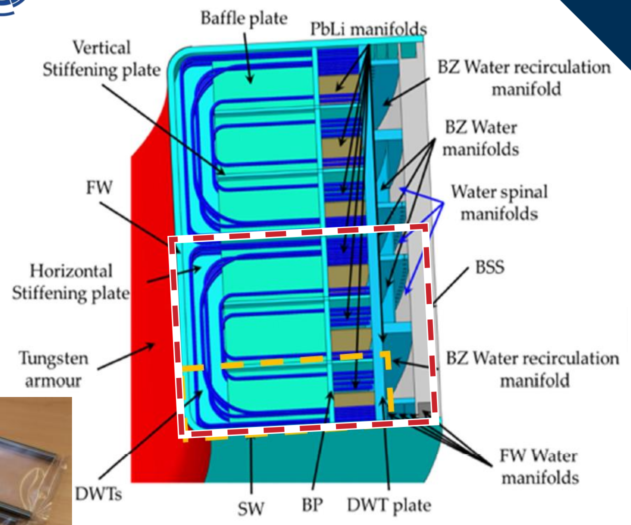
→ Blanket testing needs

Test volume	**Full size blanket module**
Magnetic field	**Representative, >4 Tesla, decay rate > 1/R**
Orientation wrt field	**Representative wrt gravity, field 'horizontal'**
Env. conditions	**Large scale surface and volume generated heating and heat rejection to coolant. Magnetic transient events**
Hydrogen isotopes	**Produced/present and monitored**
Irradiation	**For T production, shielding, sensors, material damage, …**

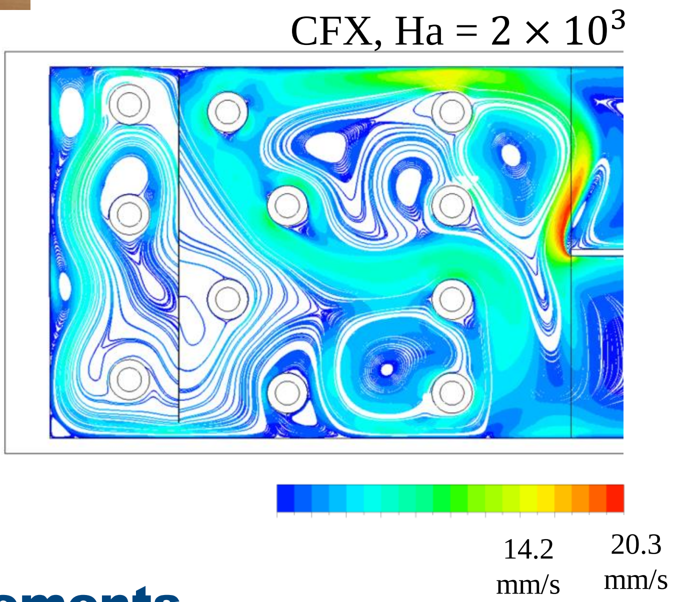
Specific test needs for WCLL

- Results from progressively more complex (geometry and test conditions) **3D magnetohydrodynamics (MHD) analyses need validation.**
  → Flexible experiment platform including PbLi loop
- Measure PbLi pressure drop in WCLL-like mock-up with relevant materials. Role for electrical insulation?
- **Velocity and temperature fields in a WCLL-like mock-up**
  - erosion, corrosion and ACP
  - effect on T transport
  - effect on structural assessment
  - Hotspot effects on double wall tubes (DWTs)
- Thermomechanical and magnetic **stress in mock-up** (magnetic) structure with MHD
- Off-normal events -- safety
  - EM transients effect on PbLi
  - Test in-box LOCA in presence of MHD
- ……

→ **Ongoing work to develop and prioritise test campaign requirements**



← **Example of manufactured DWT**



Tassone, Del Nevo (2022)

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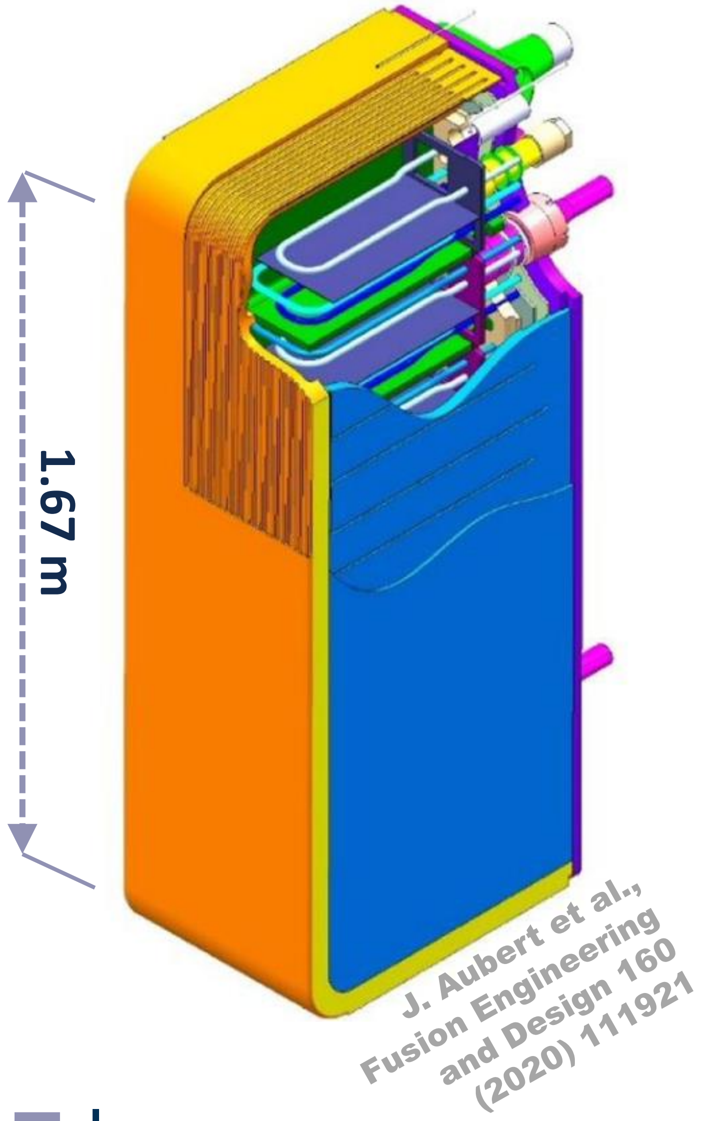
CHIMERA: Integrated testing for fusion

ITER WCLL Test Blanket Module : 1.67 x 0.46 x 0.8 m



	Requirements	CHIMERA
Test volume	Full size blanket module	Y
Magnetic field	Representative, >4 Tesla, decay rate > 1/R	Y
Orientation wrt field	Representative wrt gravity, field 'horizontal'	Y
Env. conditions	Large scale surface and internally generated heating and heat rejection to coolant. Magnetic transient events	Y Y
Hydrogen isotopes	Produced/present and monitored	N
Irradiation	For T production, shielding, sensors, mateiral damage, …	N

PbLi loop specification

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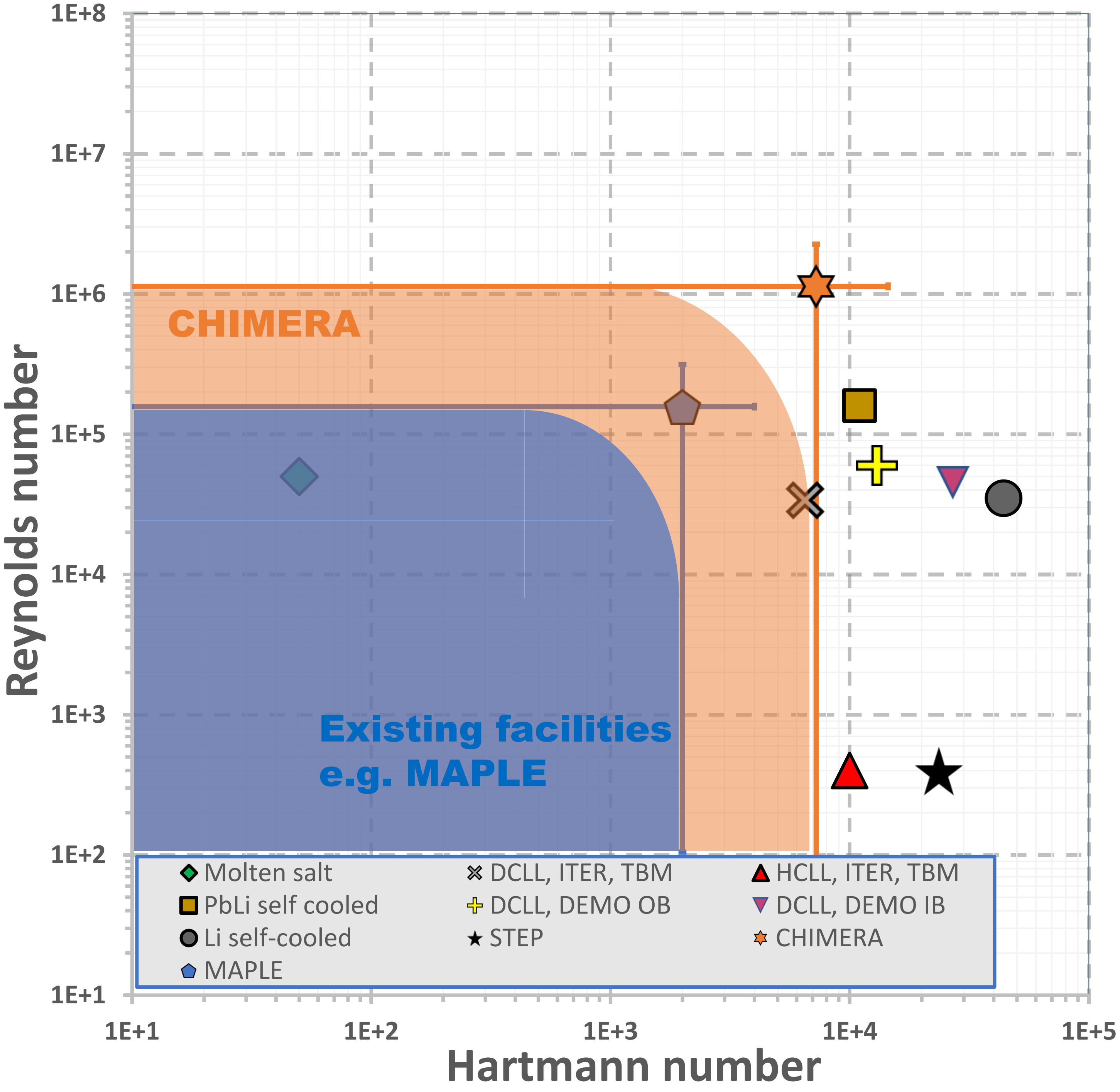
Developed with EUROfusion and design consultant Frazer Nash

CHIMERA		PbLi Loop	
Test Component Size	Up to 1.7m x 0.5m x 0.7m	**Fluid**	83Pb-17Li eutectic
Static Magnetic Field (max.) **(Uniform)**	5 T 4 T	**PbLi Mass Flow**	0.24 m^3/h 17 m^3/h (upgraded)
Transient Magnetic Field	12 T/s	**PbLi Temp. Rang**	290 - 327°C <550°C (max.)
Applied Heat Flux: (radiative) **(laser)**	0.5 - 1.0 MW/m^2 over 1 m^2 20 MW/m^2 over 1500 mm^2 ***or*** 200 MW/m^2 over 100 mm^2	**PbLi Pressure Drop**	3 bar(g) (across PMU) 14 bar(g) (upgraded)
Coolant Parameters (PWR) **Component Cooling System**	Inlet 200 to 333°C @ 15.5 MPa Inlet <150°C @ 5 MPa	**PbLi inventory for mock-up**	270 L
		PbLi Heat Rejection	15 kW



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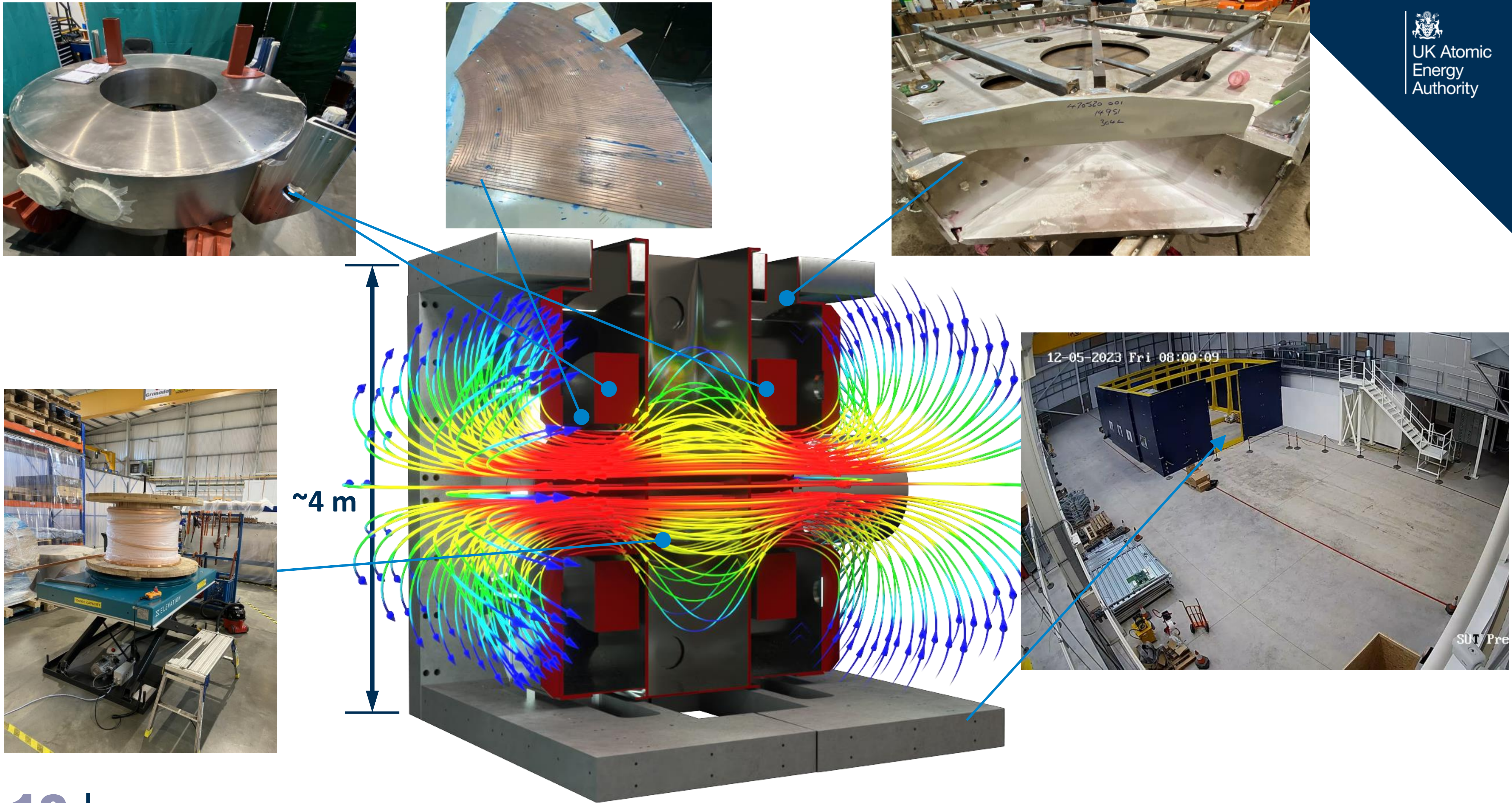
Reactor operating points from: Smolentsev et al, Fusion Engineering and Design 100 (2015) 65–72



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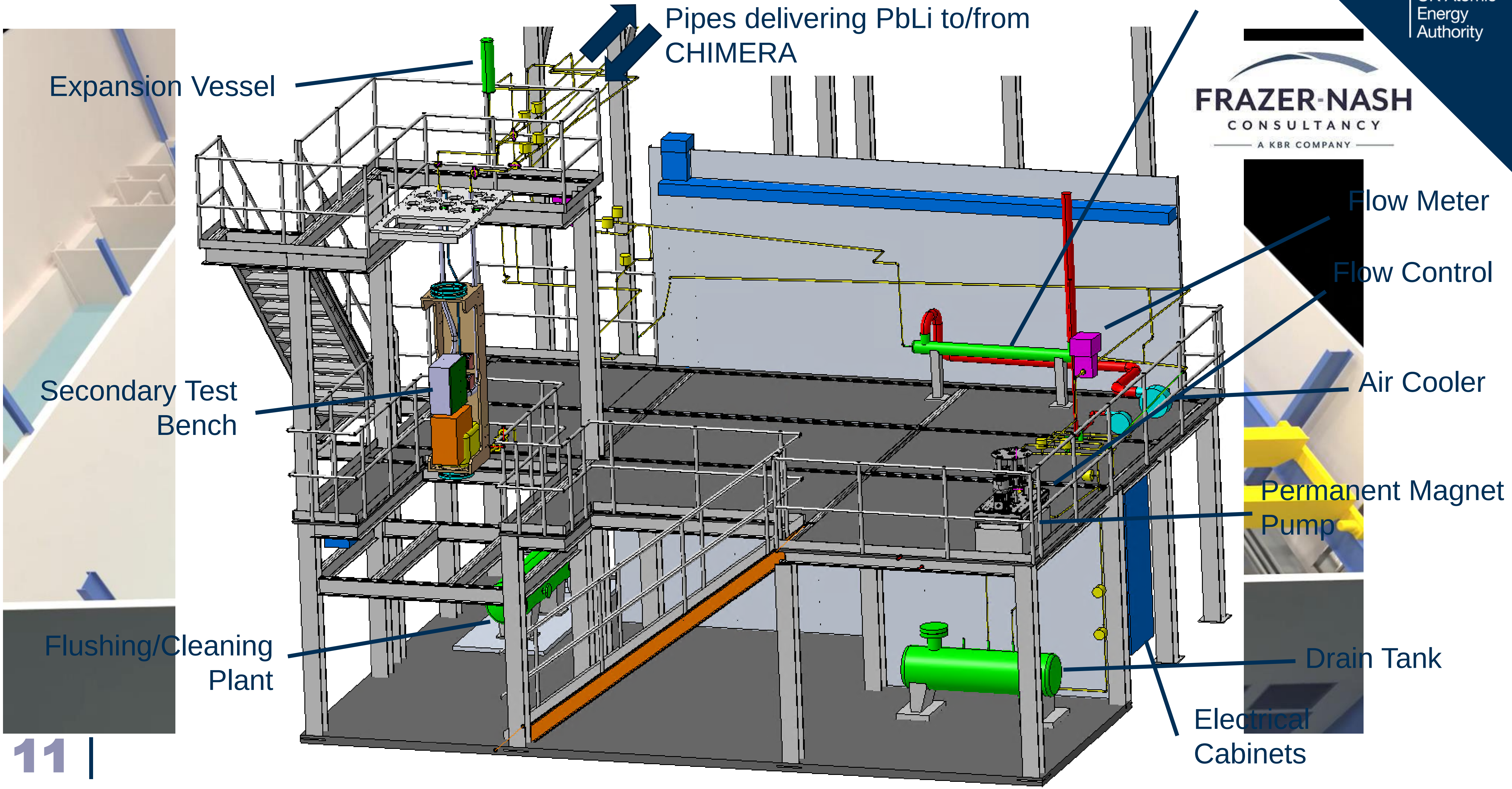
PbLi Loop Facility Concept Design



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Phased approach to integrated testing

Phase 1 – samples containing PbLi only

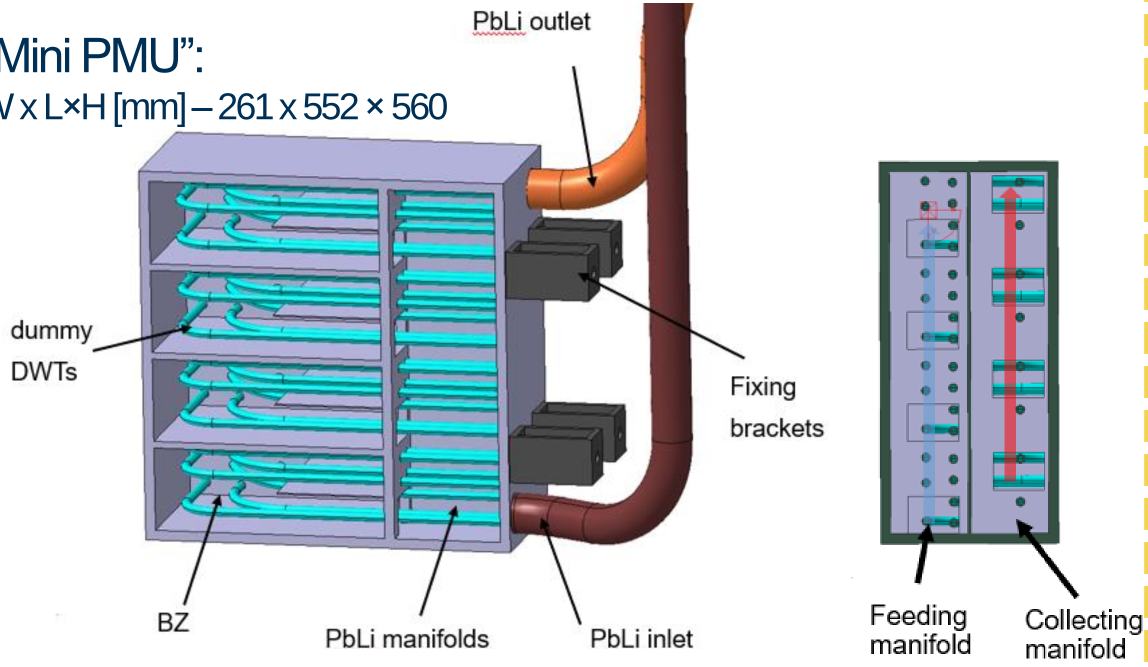
Phase 1a: Benchmarking and simple geometry testing

- Pipe Flow
- Inclined Field
- Fittings
- Non-Uniform Field

→ Develop and calibrate sensors
→ Operational experience
→ Support MHD research

Phase 1b: A single or few WCLL elementary cells

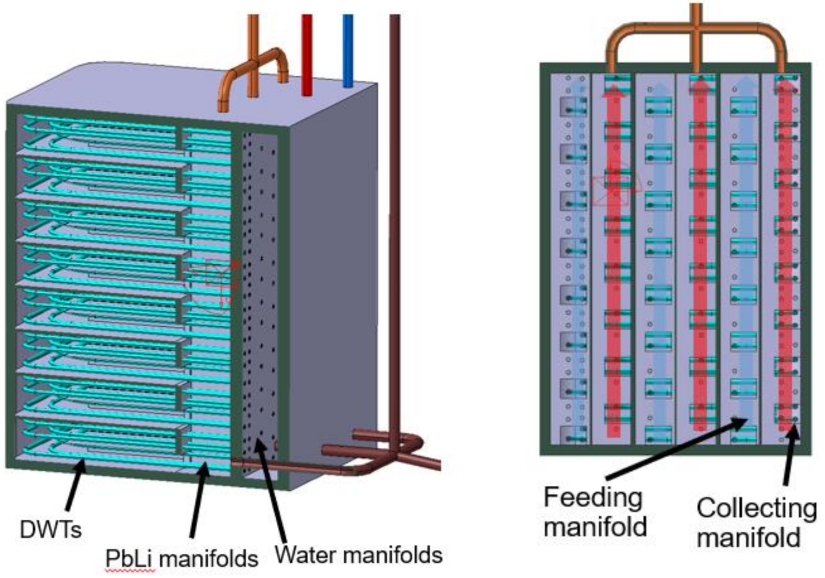
"Mini PMU":
W x L×H [mm] – 261 x 552 × 560



Phase 2 – combined test with PbLi and high temperature water cooling

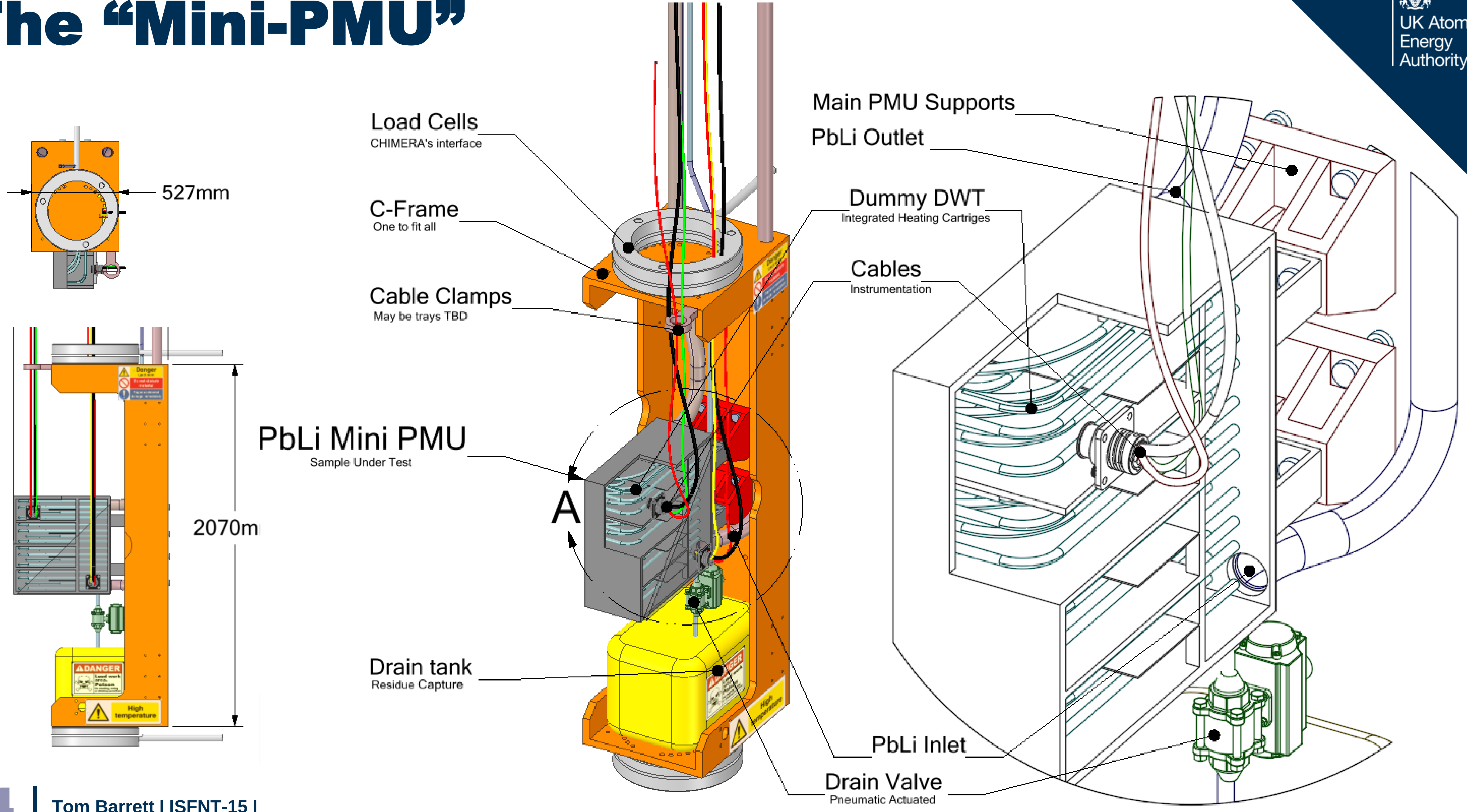
WCLL Prototypical Mock-up Unit, propose 8 elementary cells
Both heaters and cooling DWTs
First wall heating

→ Heat transfer validation
→ High power heat rejection
→ Combined loads/effects



+ Potential to design a mock-up intended to test in-box LOCA event

The "Mini-PMU"



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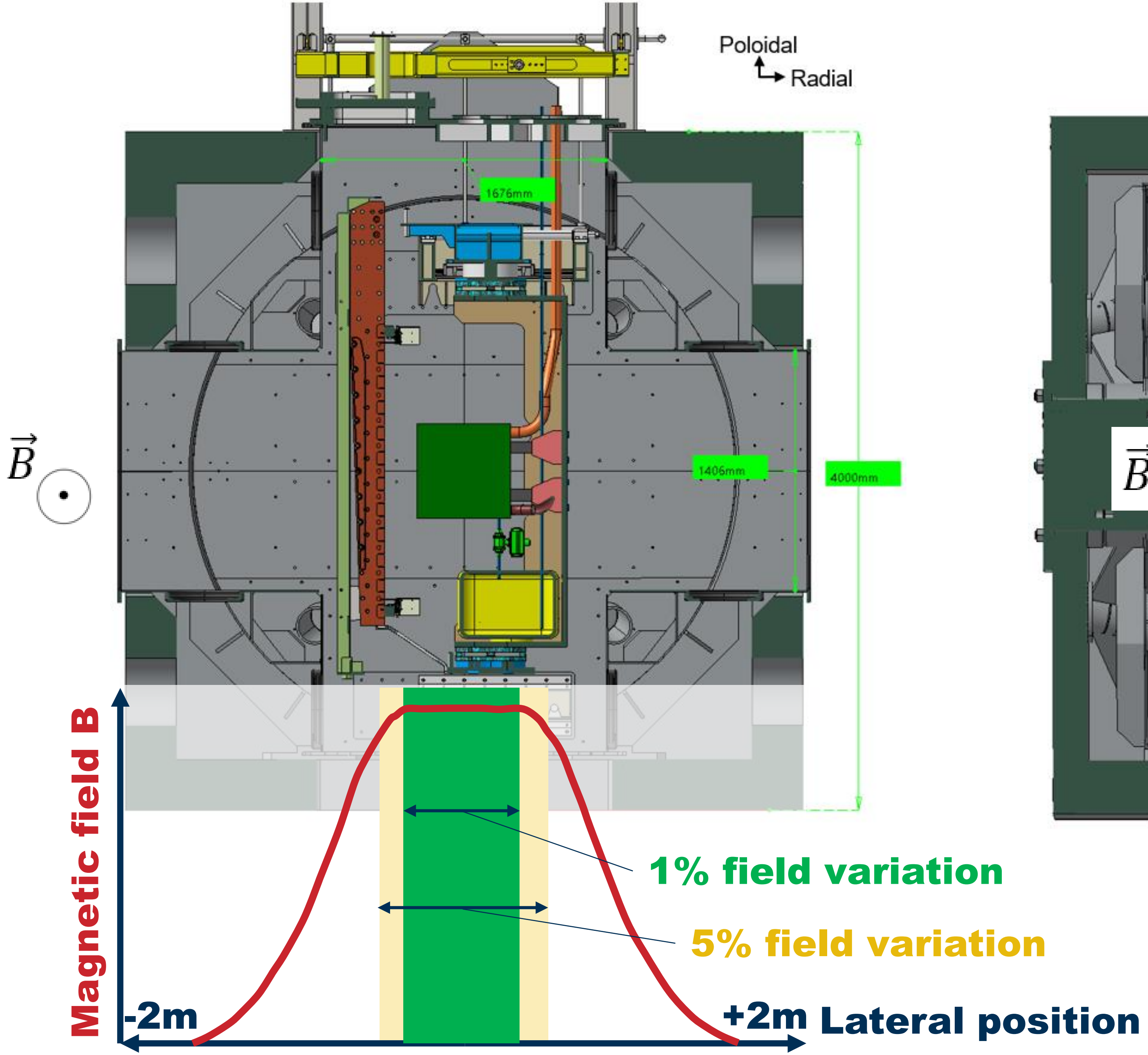

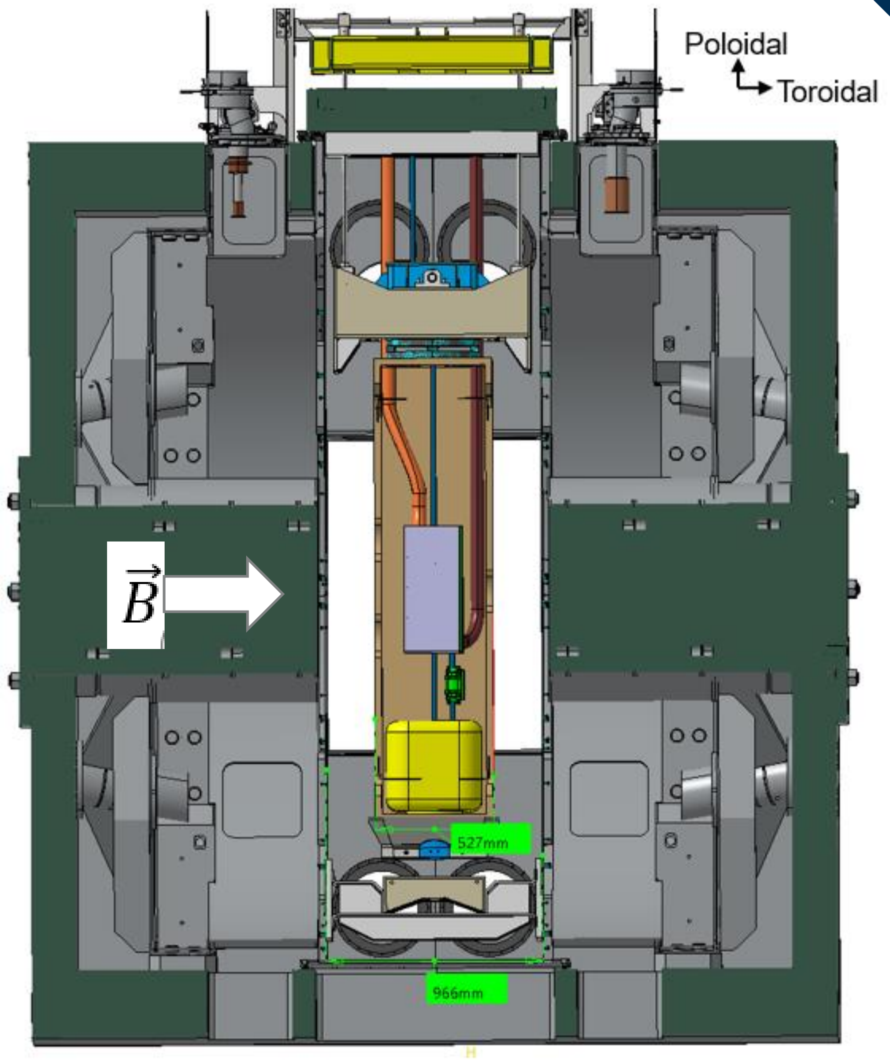

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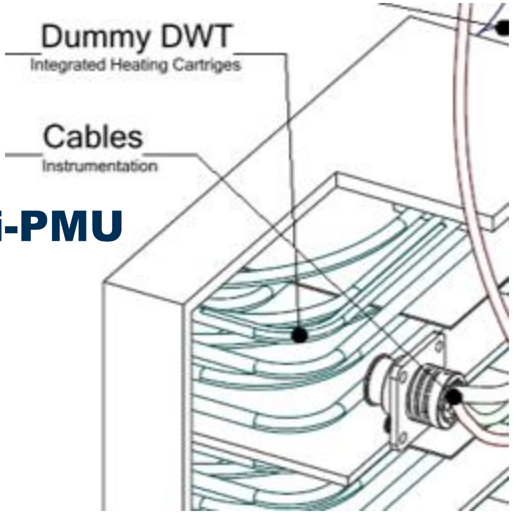
Strategy for ‘virtual test’:

Fusion design assurance relies on simulation to achieve a **‘virtual TRL 6’**

Simulation enables design verification against aspects of the fusion environment ***we cannot test for***

- e.g. exponential distribution of volumetric heating
- Once a suitable full-physics model is developed and validated/calibrated from test data, realistic heat loading can be imposed

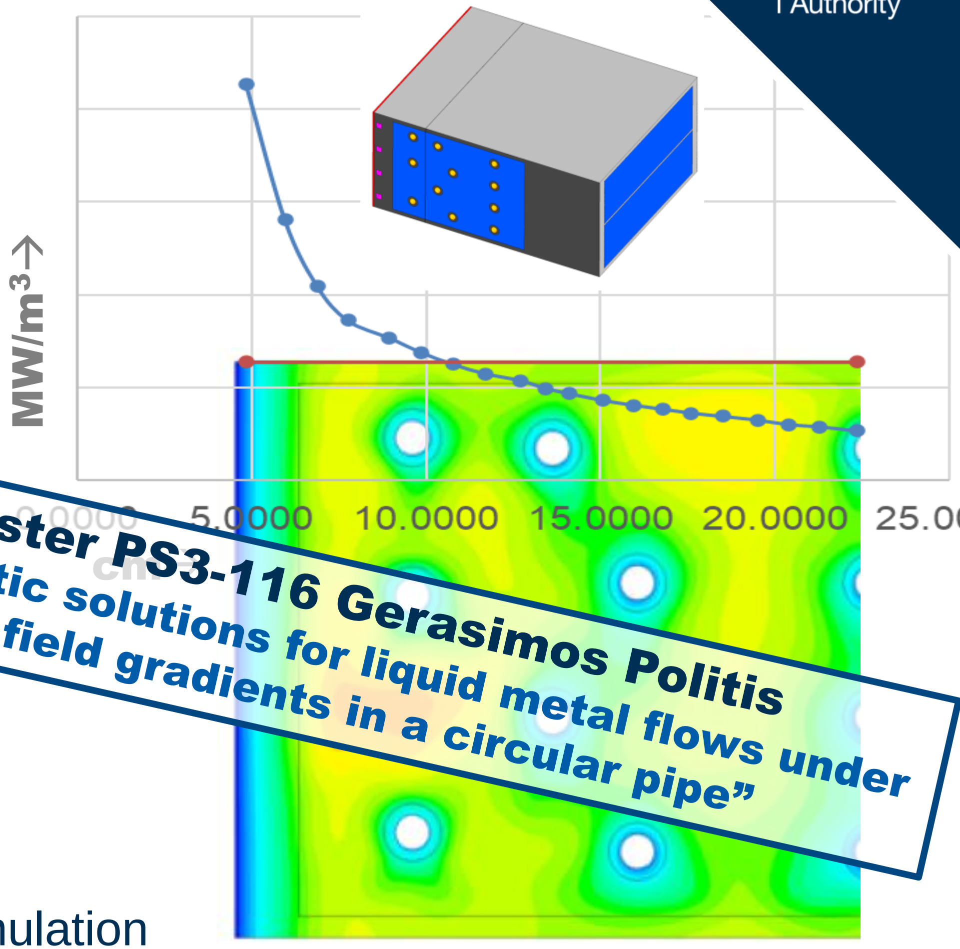
Mini-PMU



Valuable data under **as-tested** heating conditions

Validate/calibrate integrated systems model

Query full systems-simulation under **expected conditions**



Urgorri et al. (2021) 10.3390/en14196192

More information: Poster PS3-116 Gerasimos Politis “Numerical and analytic solutions for liquid metal flows under non-uniform magnetic field gradients in a circular pipe”

→ Strategy must use a combination of test and simulation data in a ‘virtual test’

System simulation development

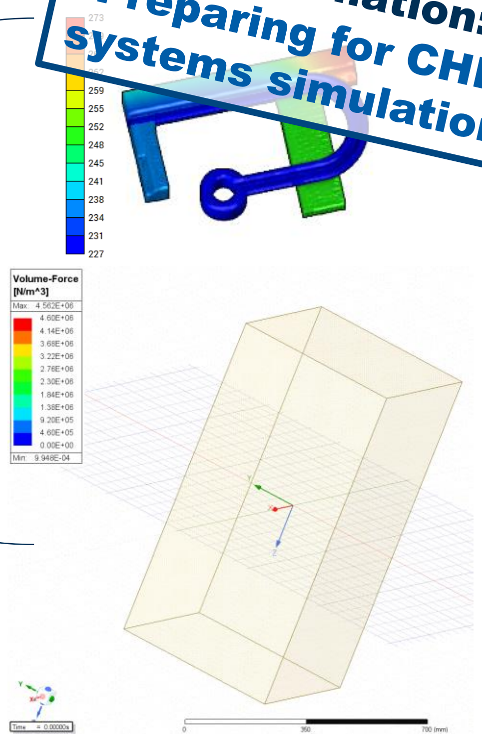
- ✓ Systems simulation = flexible fidelity + modular + fast
- ✓ Series of linked fast running surrogate models for th.hydraulic, thermal, electromagnetic (inc. MHD) and structural response
- ✓ Approach allows highly complex models to be run quickly, important for virtual testing campaigns, stochastic simulation, and ambition for real-rime digital twins

→ **PROJECT PEGASUS**

More information: Poster PS3-116 Michelle Tindall "Preparing for CHIMERA commissioning by virtual testing via systems simulation"

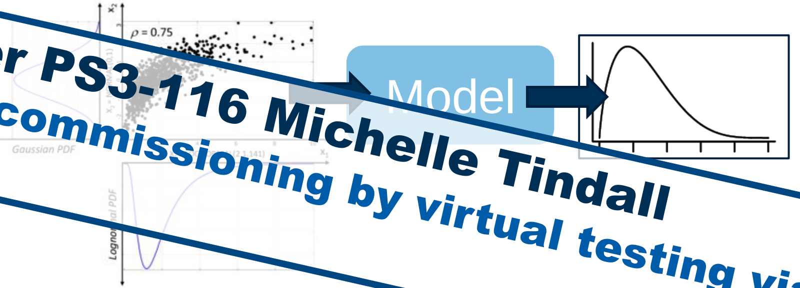
Developing Systems Simulation

Reduced order model (ROM) combining transient EM and thermal loads in systems space



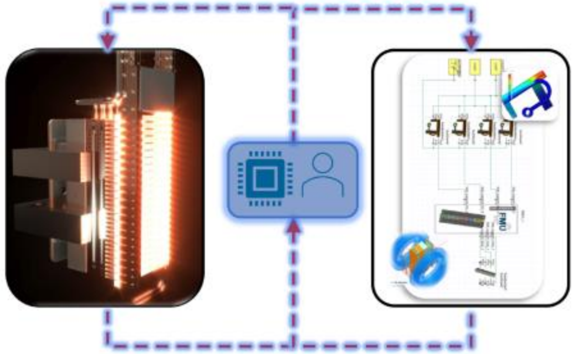
UQ and Model calibration

Running models probabilistically and applying uncertainty quantification



Digital twinning

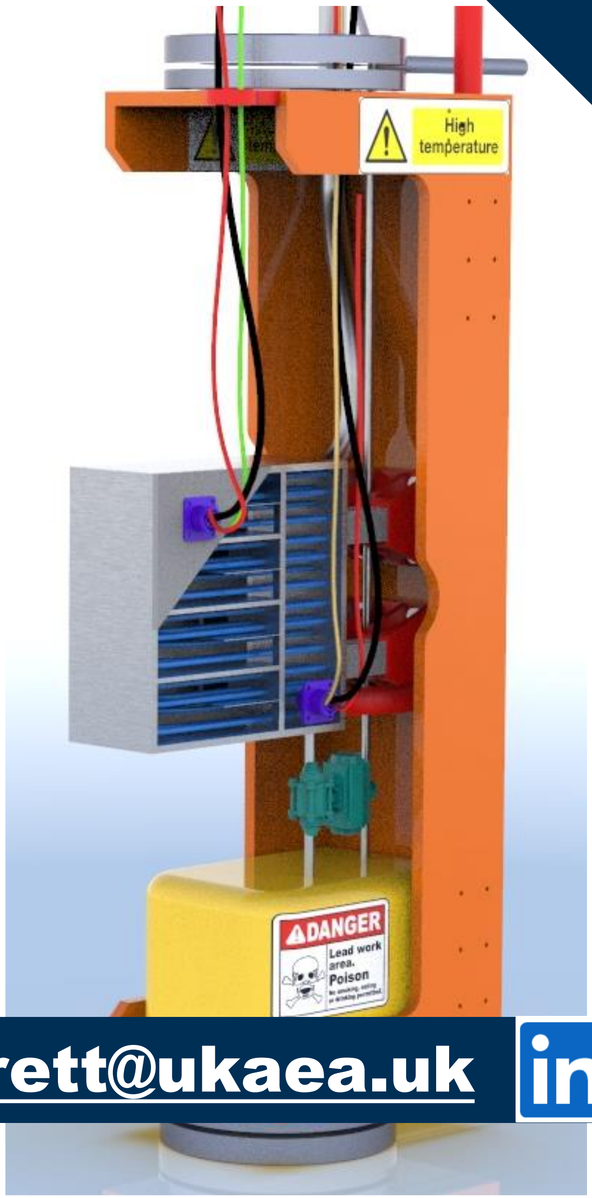
R&D into algorithms for deploying model as digital twin



	Requirements	CHIMERA	+ digital twin
Test volume	**Full size blanket module**	**Y**	**Y**
Magnetic field	**Representative, >4 Tesla, decay rate > 1/R**	**Y**	**Y**
Orientation wrt field	**Representative wrt gravity, field 'horizontal'**	**Y**	**Y**
Env. conditions	**Large scale surface and internally generated heating and heat rejection to coolant.** **Magnetic transient events**	**Y** **Y**	**Y** **Y**
Hydrogen isotopes	**Produced/present and monitored**	**N**	**When mature**
Irradiation	**For T production, shielding, sensors, mtl damage, …**	**N**	**When mature**

Conclusions

- DEMO-class fusion device realisation has to involve integrated blanket testing – **first of a kind design, build and test**
- We need to be ambitious and think **big** on fusion engineering, technology and materials
- UKAEA with other EUROfusion partners are preparing for a **world first fusion blanket test**
  1. CHIMERA construction
  2. Phased approach for blanket prototype design and construction
  3. Digital replica ‘construction’ to augment testing



This presentation is made possible by the whole UKAEA CHIMERA programme team

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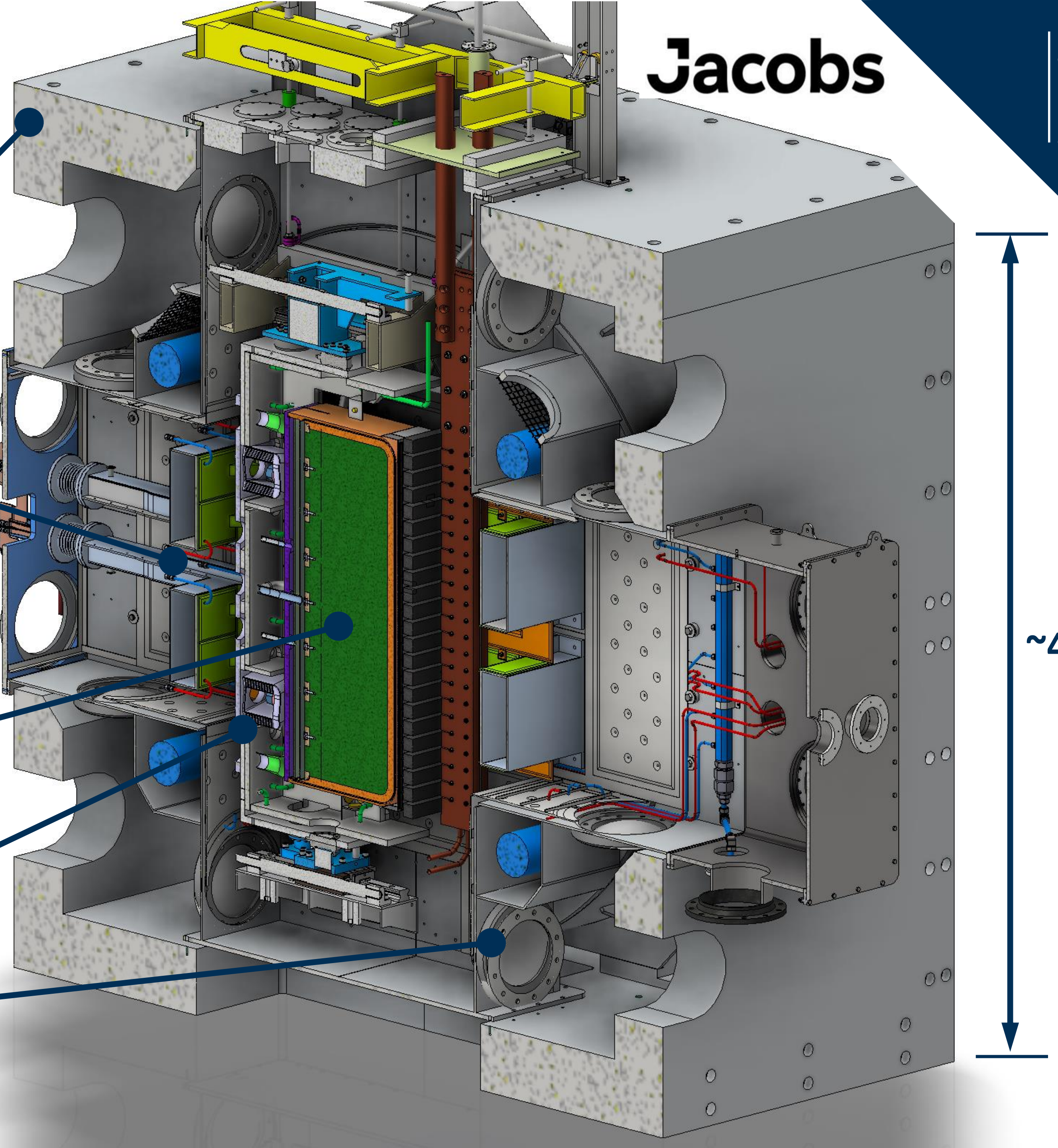
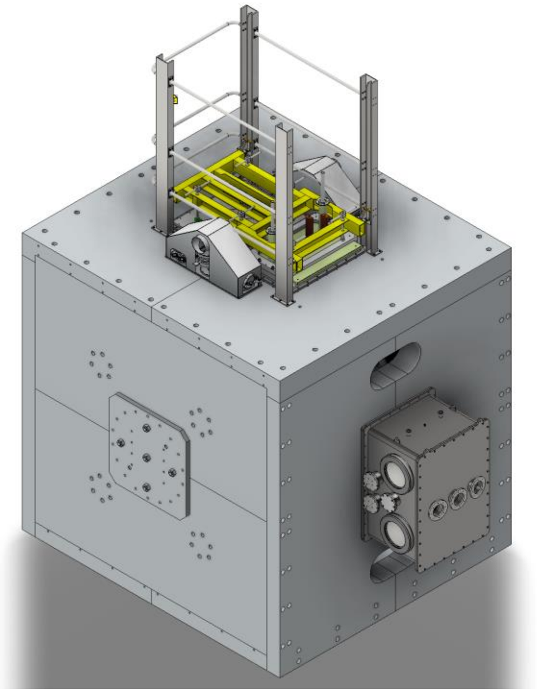
Additional slides

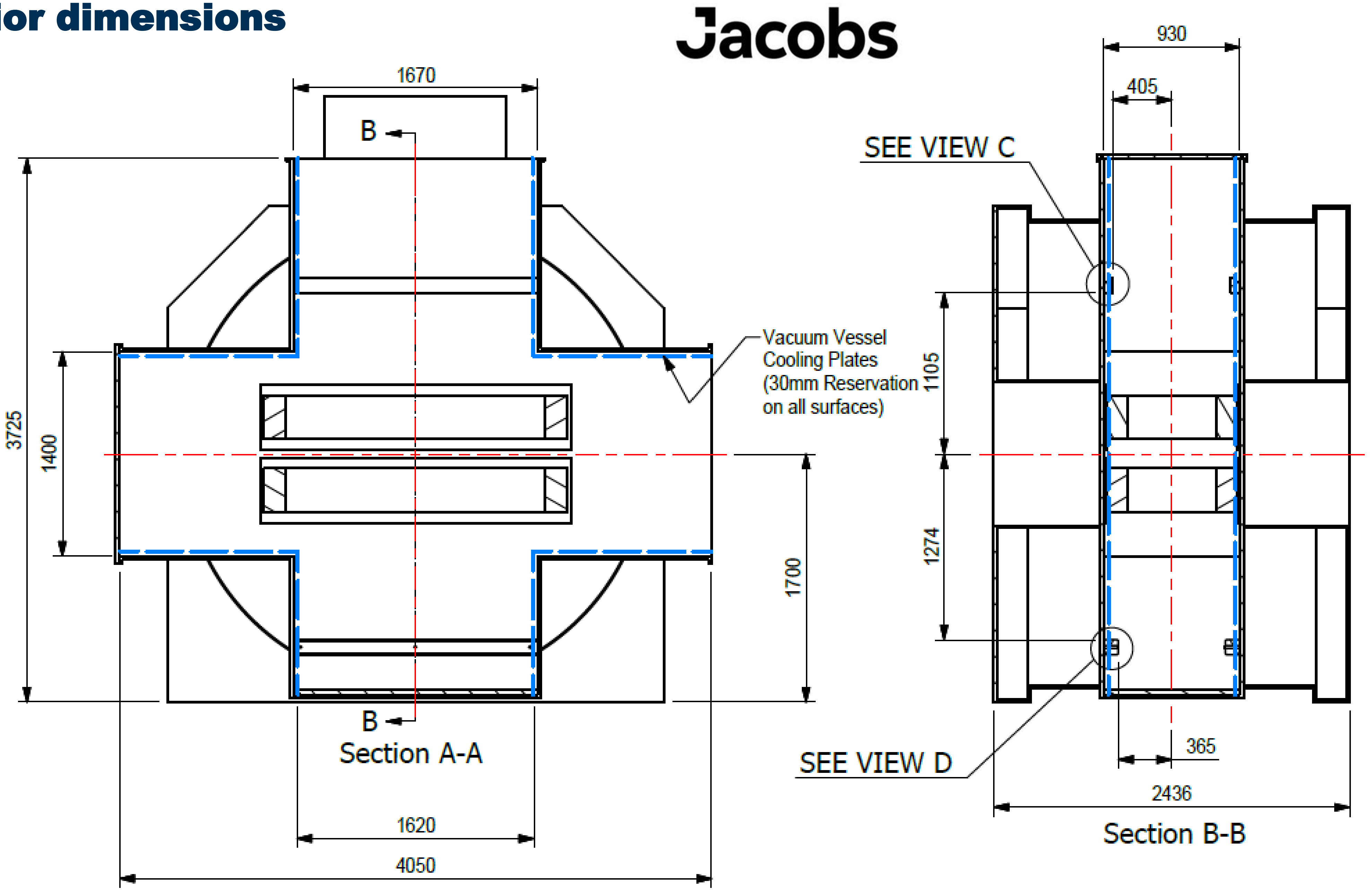
Chimera sectional view





External view of machine

Interior dimensions



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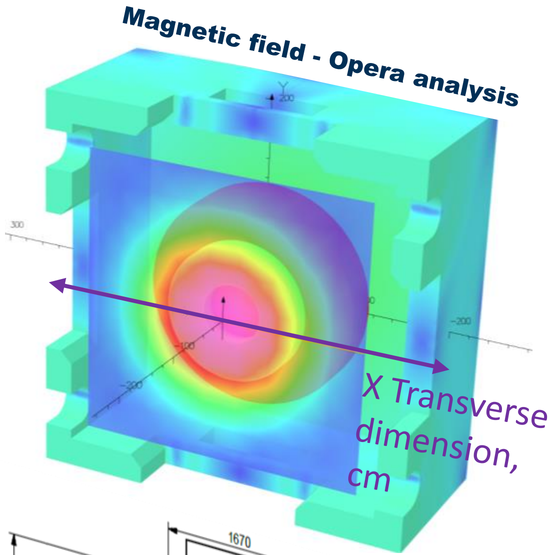
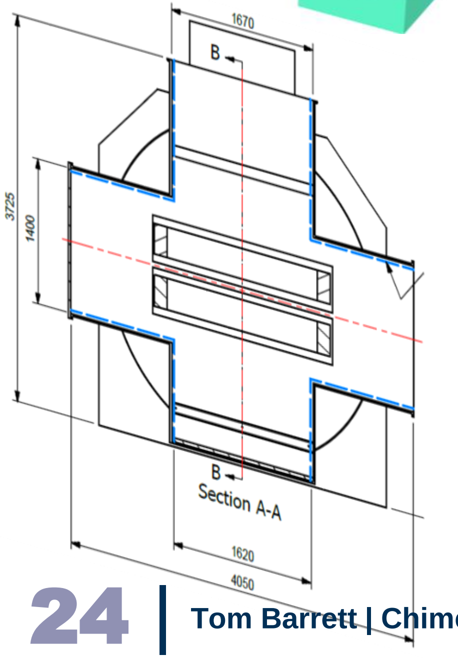
Field Uniformity

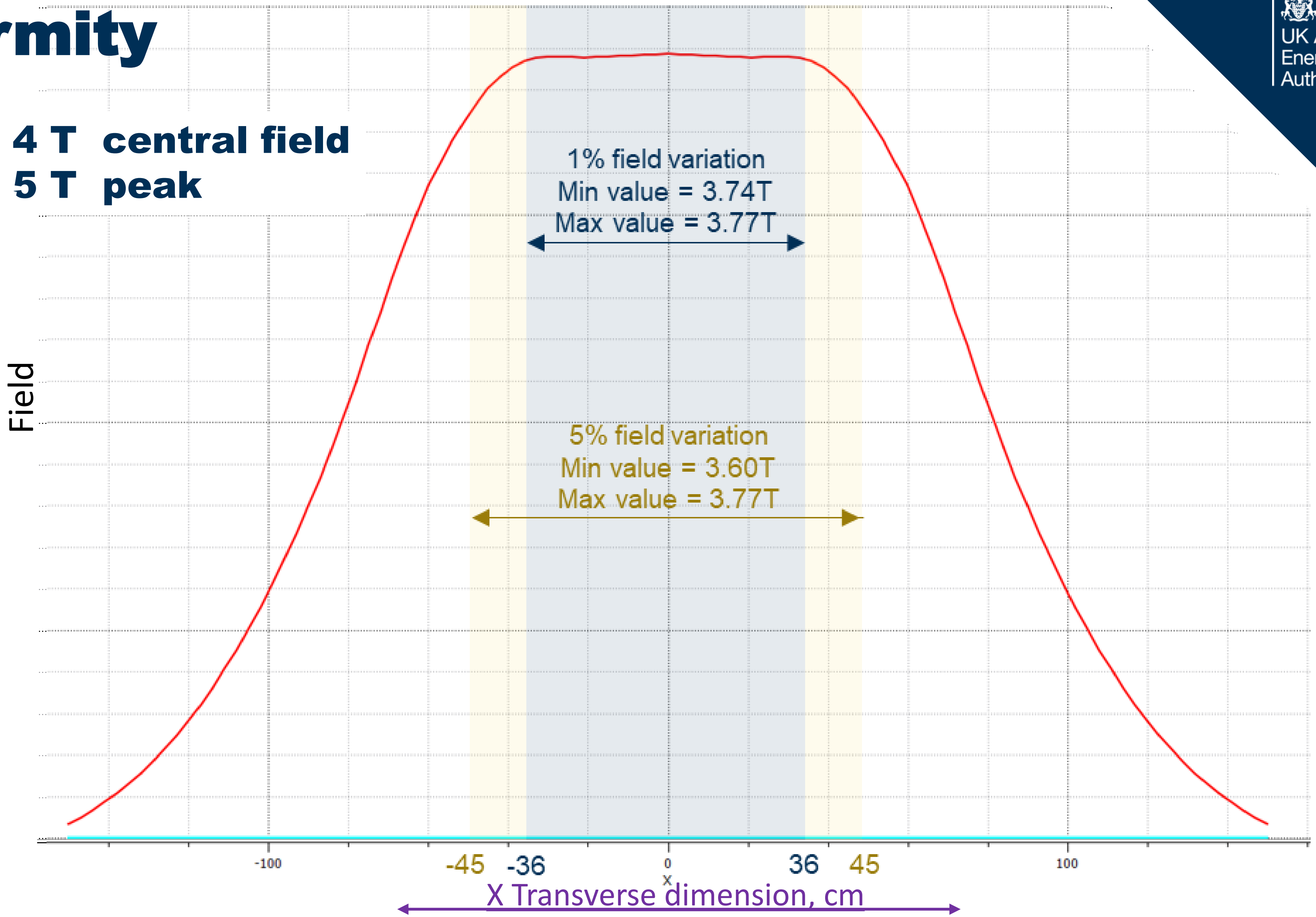
+ with iron annuli

Magnetic field - Opera analysis





4 T central field
5 T peak



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