

UK Atomic Energy Authority

SOFT2026

Progress towards high-fidelity multi-physics simulation of fusion breeder blankets

2026-09-22

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Overview

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Motivation

Challenges

Solution

Recent Developments

Summary

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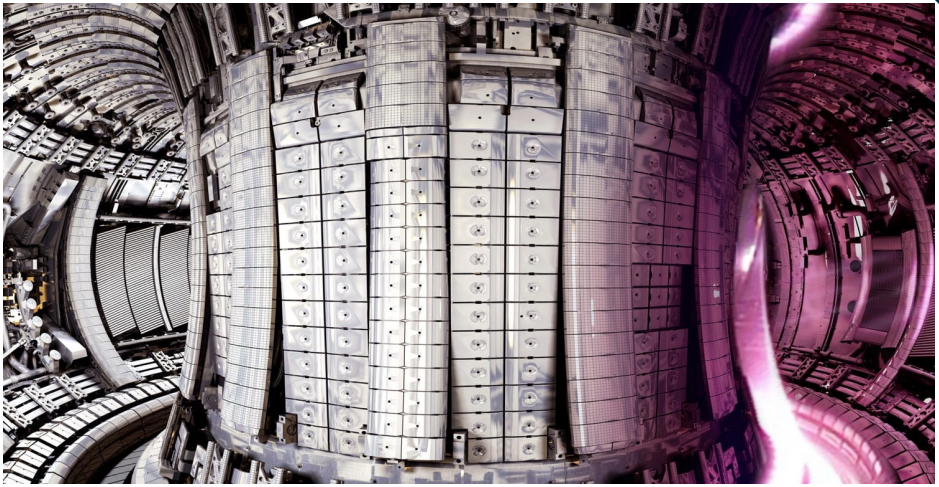

ITER

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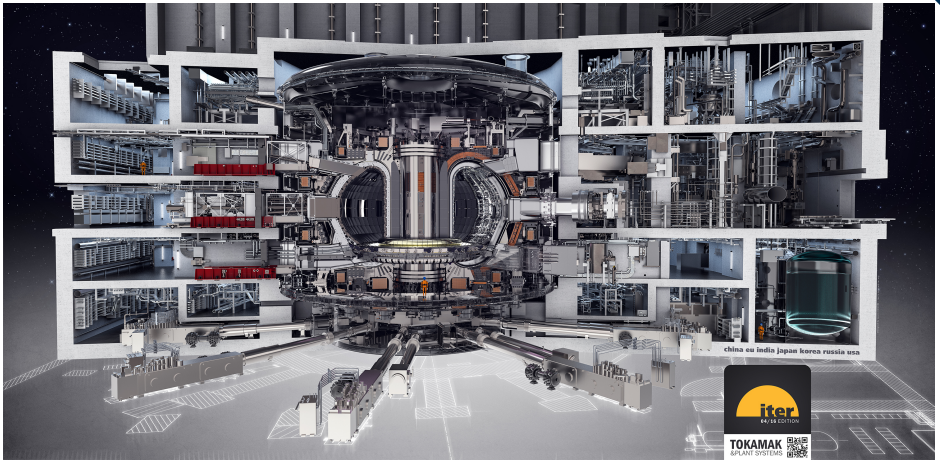

FOAK

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STEP, DEMO, ARC etc.

For first of a kind demonstrators to be successful, we need to demonstrate not just that fusion energy works but a pathway to commercial viability exists.

Building a full plant costs billions of pounds, but we can iteratively improve designs *in silico*.

High-fidelity multi-physics and multi-scale computational analysis is the pathway to successful fusion energy.

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Multiphysics

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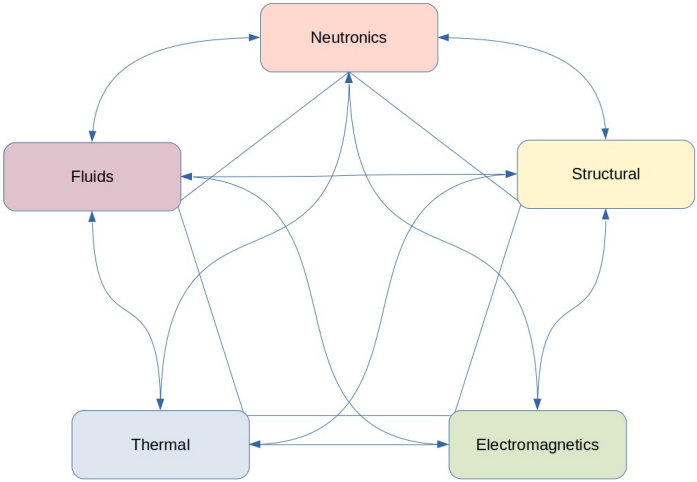

Multiscale

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- Atomistic scale - neutron damage, transmutation
- Material scale - crystal plasticity, evolving properties
- Micro scale - turbulence, Hartmann layers
- Component scale - blankets, divertors
- Powerplant scale

Uncertainty

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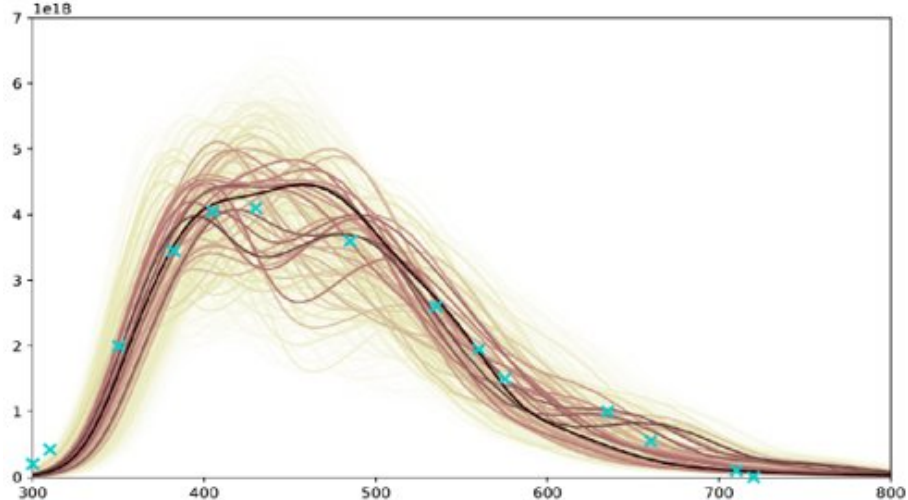

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Requirements

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We are going to need a big computer...

Requirements

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We are going to need a big computer...

...and some scalable software to run on it.

Requirements

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- Parallel first - targetting exascale
- Permissively licensed - any location, any size
- Portable - any computational architecture
- Extensible - open to contribution, good software engineering practices
- Supported - active community, user and developer documentation
- Compiled language - high-performance software

Scale Up

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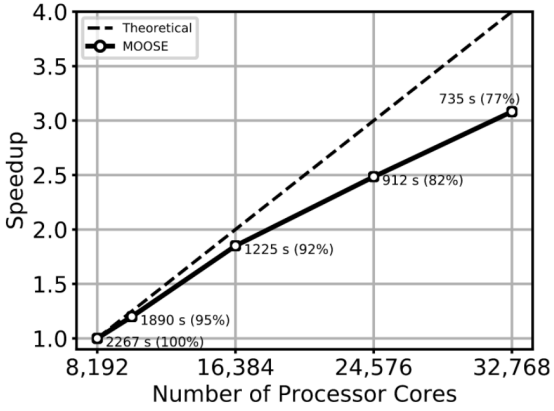

Figure: Strong scaling of MOOSE up to 32,768 cores, annotated by compute time and parallel efficiency.

Scale Out

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- Scale to multiple concurrent simulations
- Computational design of experiments
- Uncertainty quantification
- Surrogate modelling and active learning
- Robust simulation driven design

Software Stack

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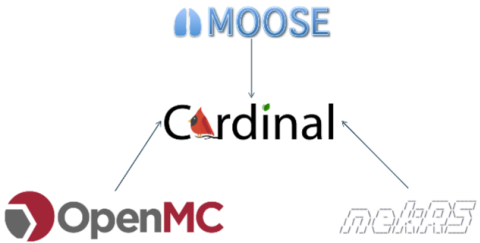
- MOOSE Framework - core solvers, glue
- Proteus - MOOSE native fusion digital twins
- OpenMC - neutronics
- NekRS - high-performance fluids on GPU
- Cardinal - Coupling MOOSE, NekRS and OpenMC
- OpenFOAM - mature finite-volume library
- Hippo - Coupling MOOSE and OpenFOAM



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CHIMERA

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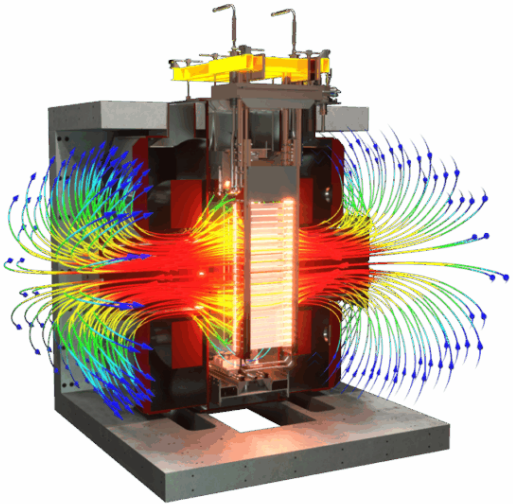

CHIMERA Thermal-Hydraulic System

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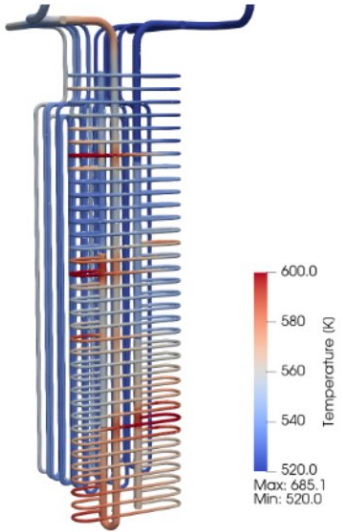

Simulation at Scale

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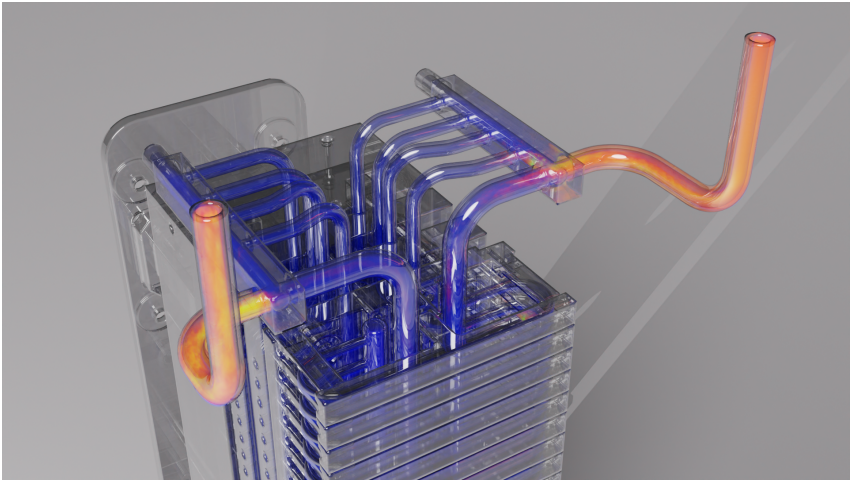

Heat Transfer

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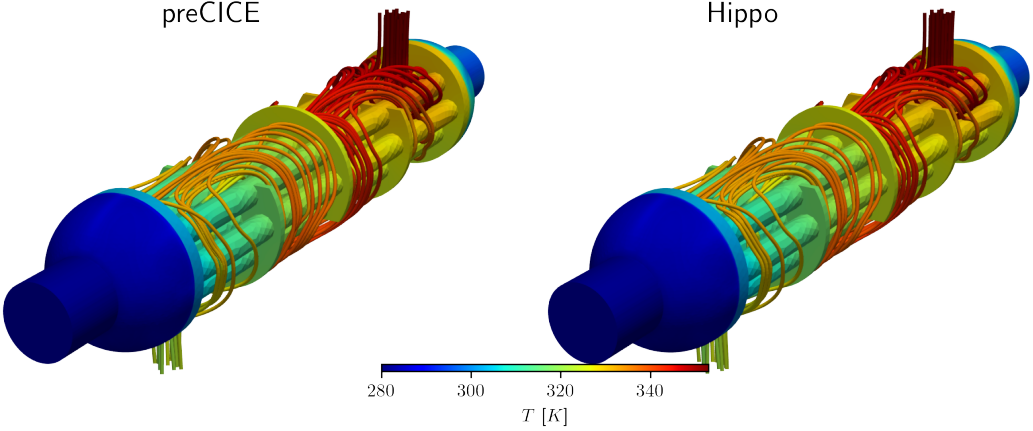
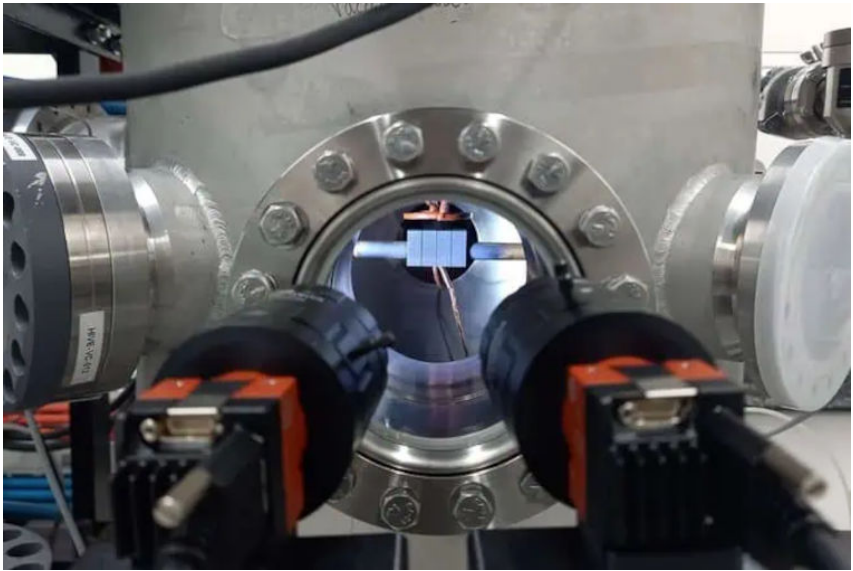
preCICE

Hippo





HIVE Divertor Monoblock

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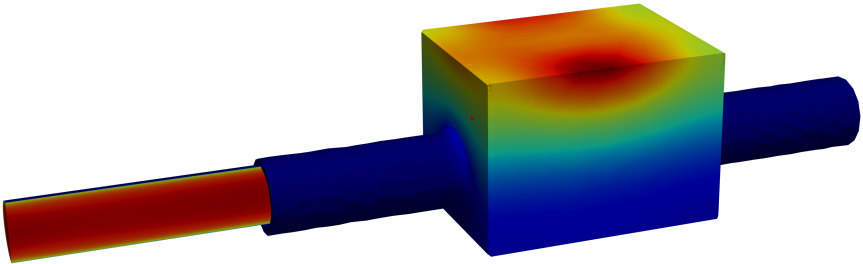
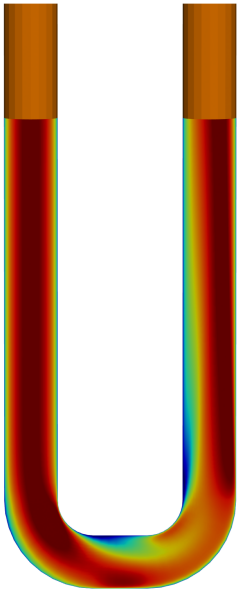


Multiscale



Hypervapotron

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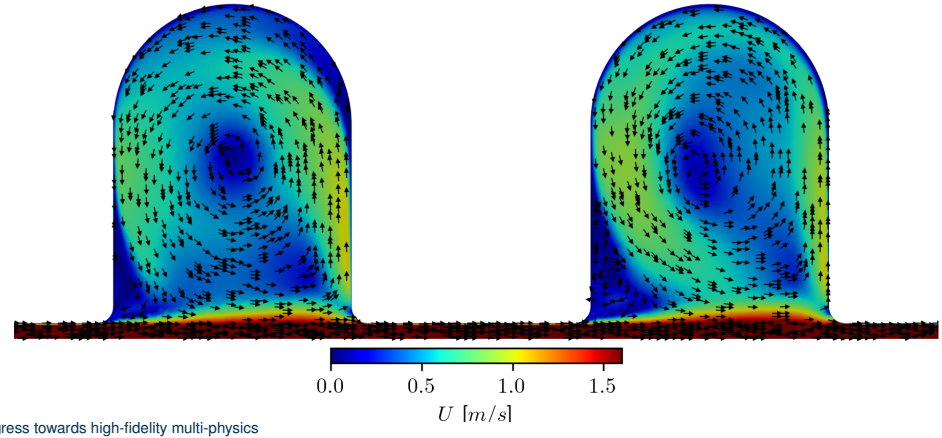

Multiphase

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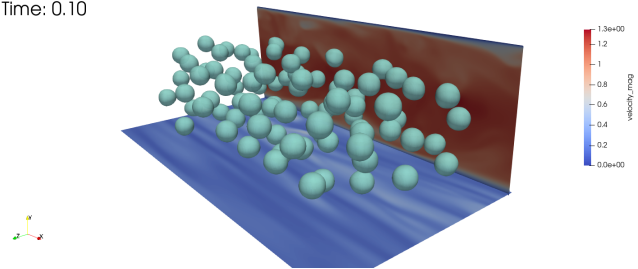
Time: 0.10



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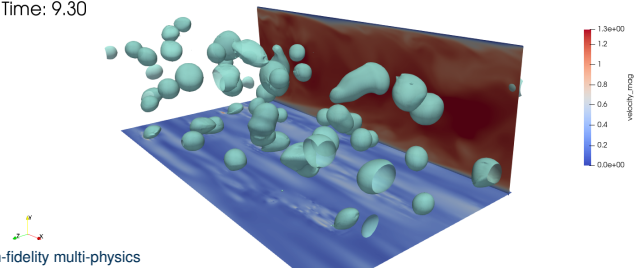

Multiphase

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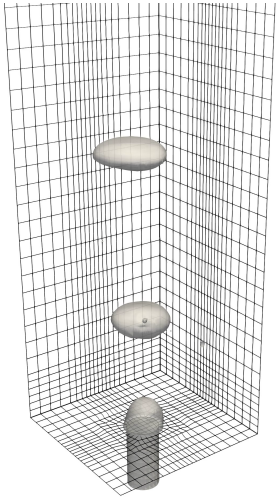

Magnetohydrodynamics

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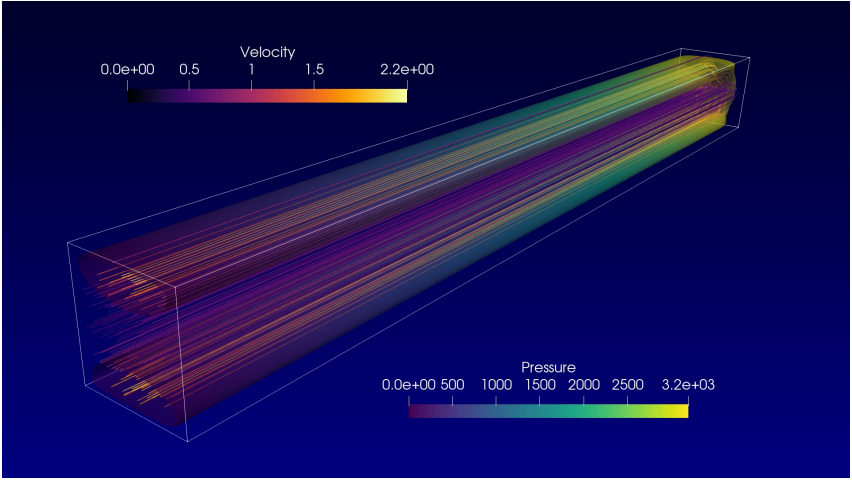

Magnetohydrodynamics

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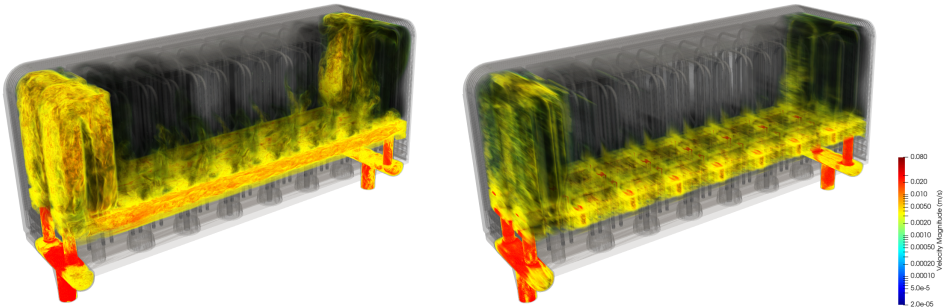

Multiphysics at Scale

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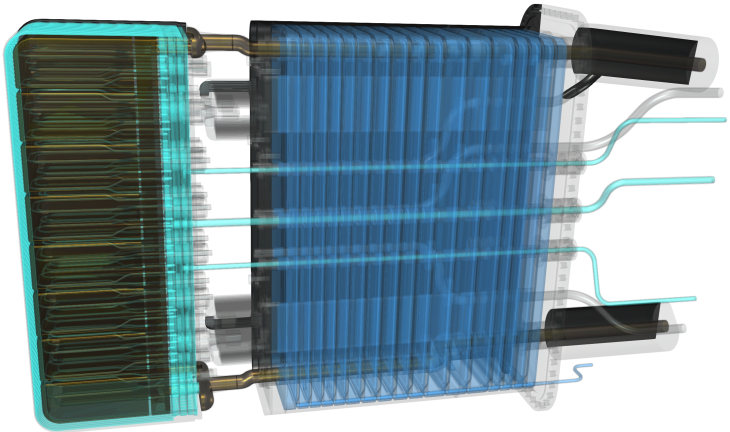

Multiphysics at Scale

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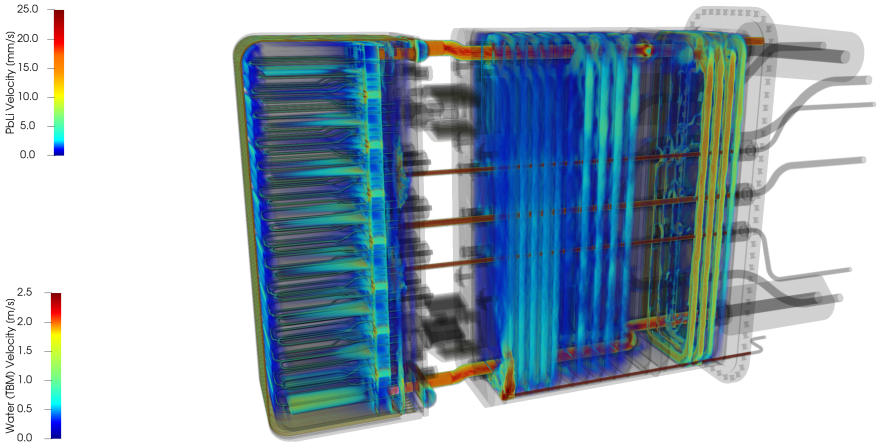

Multiphysics at Scale

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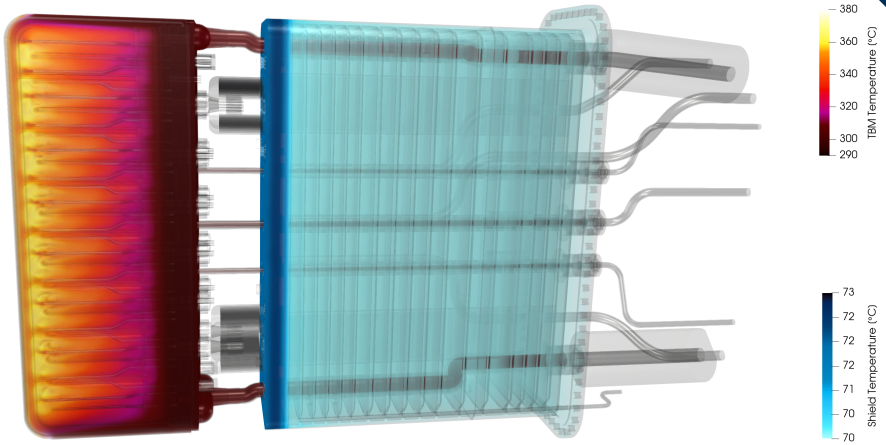

Multiphysics at Scale

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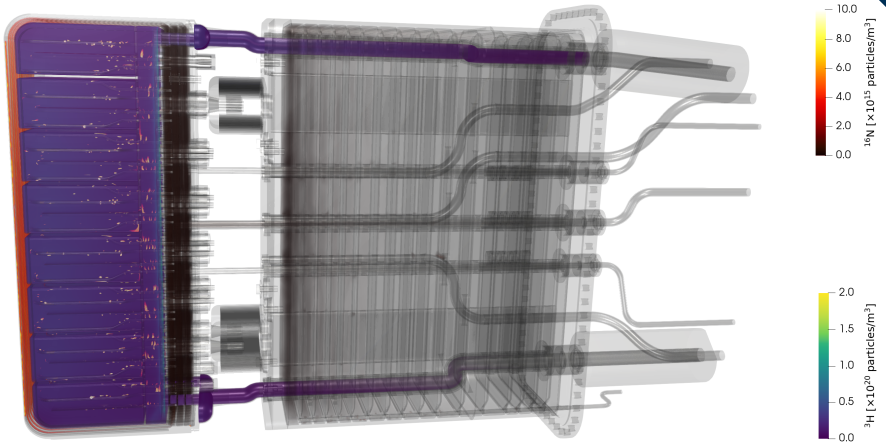

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Can I Get Involved?

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Of course!

Free to download and run, use cases can help drive improvements (doesn't have to be fusion).

MOOSE Framework: `https://mooseframework.inl.gov`
Proteus: `https://github.com/aurora-multiphysics/proteus`
OpenMC: `https://openmc.org`
NekRS: `https://github.com/Nek5000/nekrs`
Cardinal: `https://cardinal.cels.anl.gov`
OpenFOAM: `https://openfoam.com`
Hippo: `https://github.com/aurora-multiphysics/hippo`

Summary

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- Fusion power plants are a complex multi-physics, multi-scale problem with high uncertainty.
- Commercial viability of fusion energy depends on being able to make cost-effective, optimised systems.
- High-fidelity coupled simulation is the best way to analyse the complexity of designs in the face of uncertainty.
- Progress has been made in high-fidelity heat transfer simulations, liquid-metal magnetohydrodynamics simulation, multi-phase flow simulation and doing so at scale.
- We now have a strong capability to simulate a large number of coupled physics at the component scale.
- Next step: power plant scale?

Thank You For Listening

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