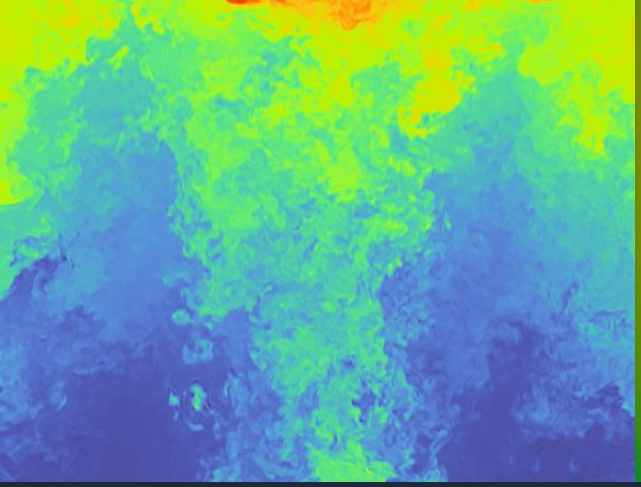
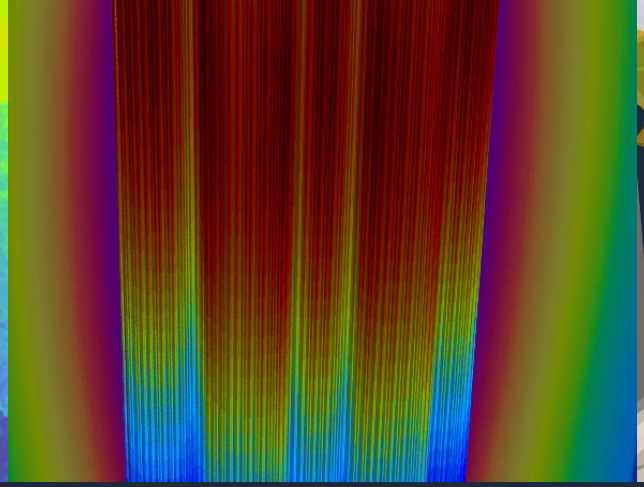
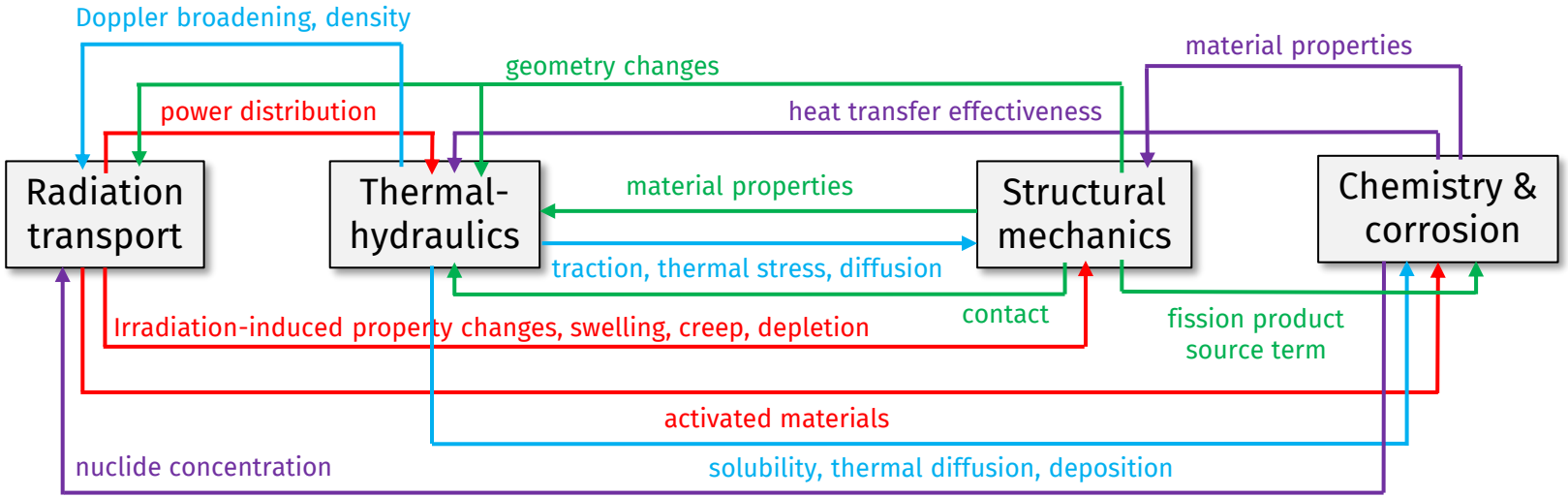




Cardinal: Multiphysics and Multiscale Simulation for Fusion Applications

A. Novak[1], A. Hegazy[1], K. Sawatzky[1], M. Eltawila[1], M. Reji[1], S. Schott[1], P. Shriwise[2], P. Romano[2], W. Ahammed[3], P. Wilson[3], H. Brooks[4], P.C. Simon[5], G. Giudicelli[5], C. Icenhour[5], C. Taylor[5], J. Pacheco Duarte[3], B. Lindley[3], J. Quinn[6], S. Coleman[7]

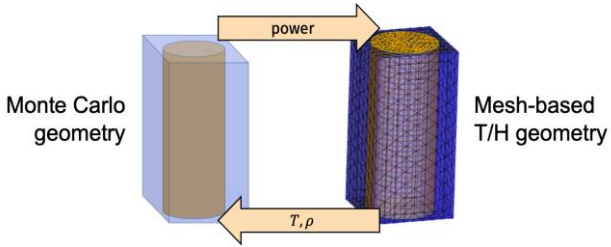
[1]University of Illinois, Urbana-Champaign
[2]Argonne National Laboratory
[3]University of Wisconsin, Madison
[4]United Kingdom Atomic Energy Authority
[5]Idaho National Laboratory
[6]Colorado State University
[7]RadiaSoft

Multiphysics in Fusion

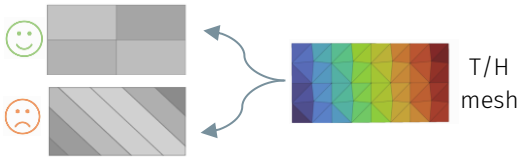


R&D Challenges

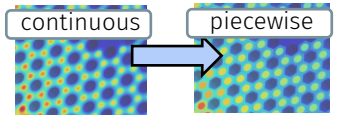
Data Transfers



Highly manual process to build geometries and exchange data



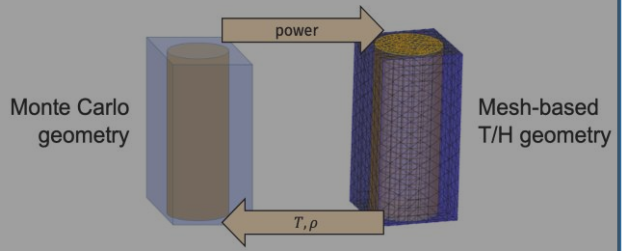
Limitations on distance-to-collision sampling



Need a general-purpose capability

R&D Challenges

Data Transfers



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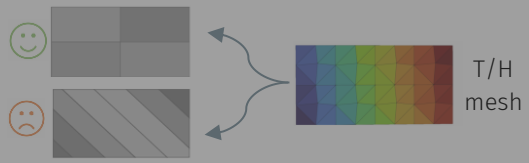
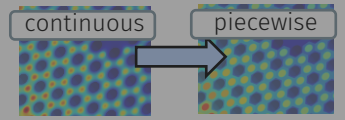


Limitations on distance-to-collision sampling

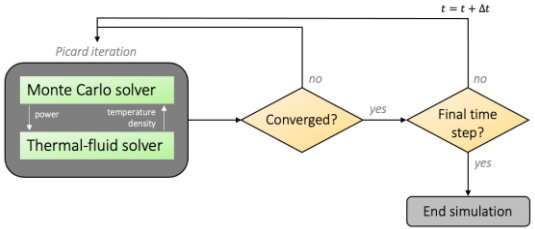


Need a general-purpose capability

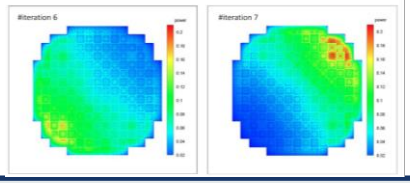
Iterative Methods

combine stochastic and matrix-based methods

Monte Carlo $Ax = b$



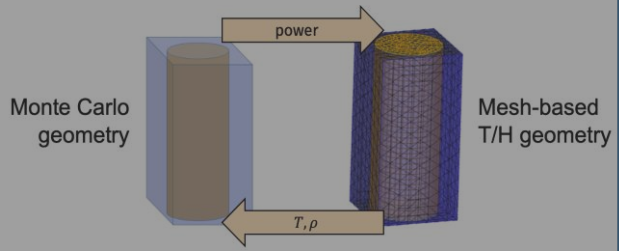
Operator splitting and/or poor statistics can cause instabilities



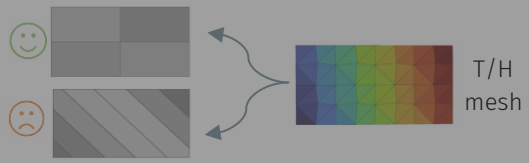
Need control over iteration scheme

R&D Challenges

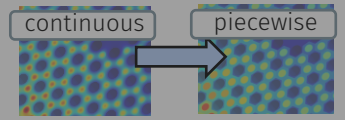
Data Transfers



Highly manual process to build geometries and exchange data



Limitations on distance-to-collision sampling



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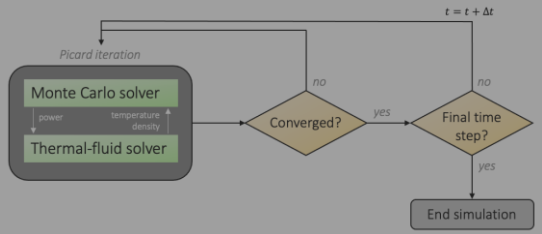
Monte Carlo $Ax = b$



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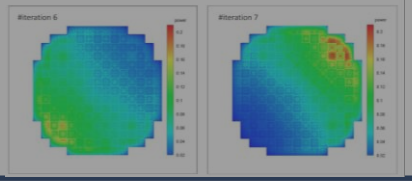


Need control over iteration scheme

Software and Parallelization

Need to leverage GPUs and be designed with performance in mind

Scarce open-source high-fidelity multiphysics software

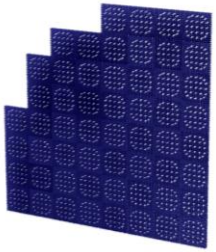
Performant & open source important

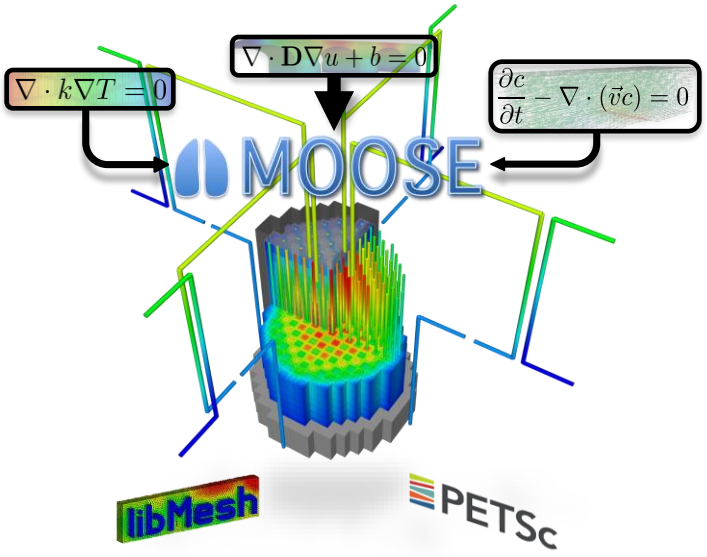
- Cardinal: High-fidelity Multiphysics for Fusion

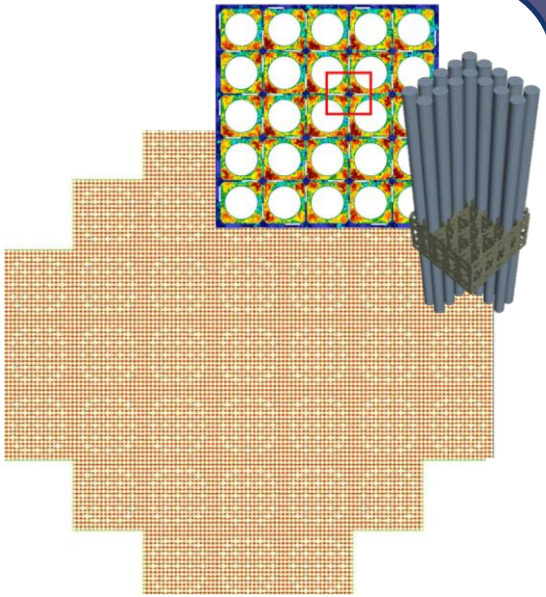
- Adaptive mesh refinement for breeder blankets
- Neutronics to accelerate fusion materials development
- Liquid metal MHD experiments
- Reticulated foam extraction systems

- Conclusions

Cardinal







OpenMC

C++ Monte Carlo radiation transport + depletion

NekRS

C++ spectral element turbulent incompressible flow; induction & inductionless MHD

MOOSE: multiphysics framework

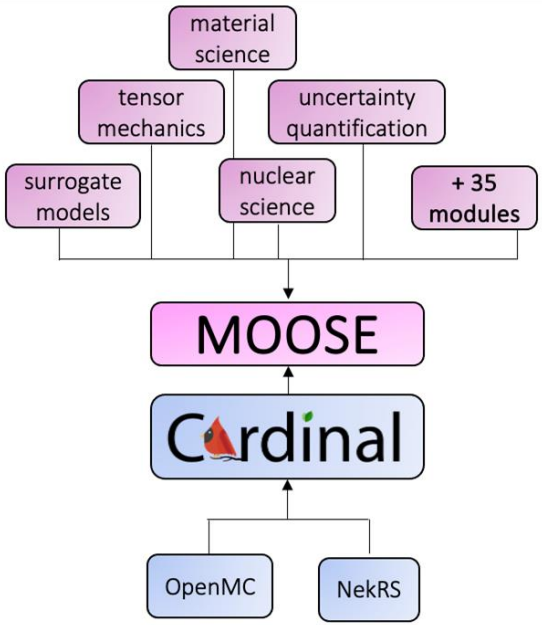
Extensible, modular C++ classes to define physics model components (parallel communication, mesh-to-mesh data transfers, kernels, materials, …)

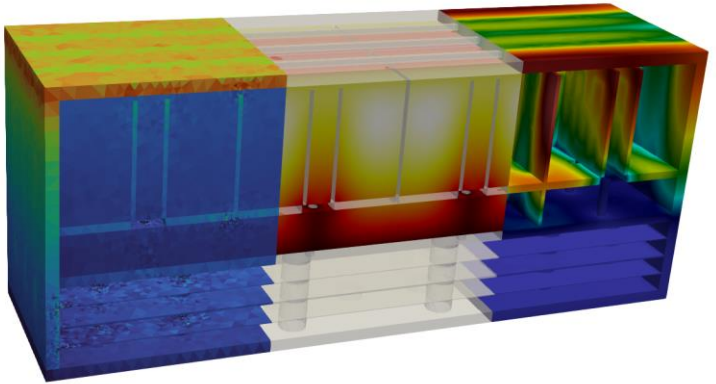
Argonne NATIONAL LABORATORY · INL Idaho National Laboratory · University of Illinois Urbana-Champaign · PennState · UK Atomic Energy Authority

B. Wirth, A. Novak, E. Merzari, W. Brinkley, K. Sawatzky, "Developing a Science-Based Predictive Simulation Capability for the Design and Analysis of Advanced Nuclear Fuel Concepts Operating in a Virtual Reactor Environment," SBIR (2025)

J. Fang, D. Shaver, A. Tomboulides, et al., "Feasibility of Full-Core Pin Resolved CFD Simulations of Small Modular Reactor with Momentum Sources," Nuclear Engineering and Design (2021)

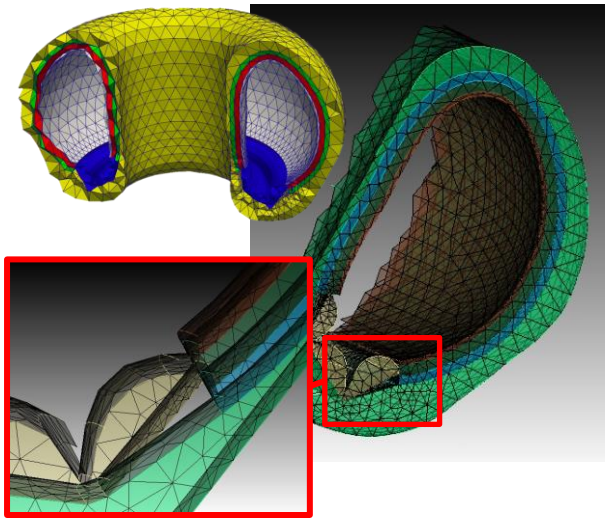
Big-Picture: *Add OpenMC and NekRS to a large "toolbox" for fusion simulation*





MOOSE framework	MOOSE modules	MOOSE applications
data transfers	solid mechanics	**OpenMC $n-\gamma$ transport**
solution postprocessing	**heat transfer**	**NekRS CFD and MHD**
mesh adaptivity	**stochastic tools**	**TMAP8 tritium**
checkpointing	thermal-hydraulics	SALAMANDER PIC

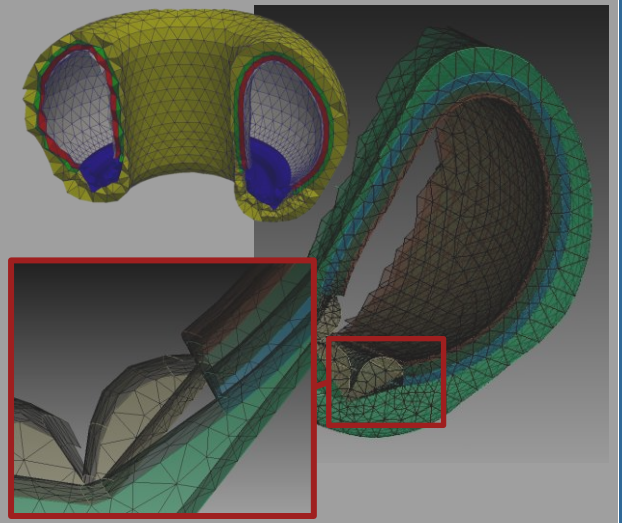
Some Notable Software Features



surfaces bounding each cell

Automatic re-generation of CAD geometries to capture feedback

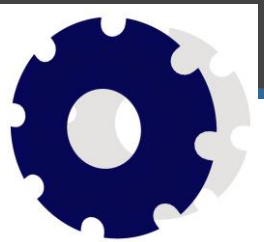
Some Notable Software Features

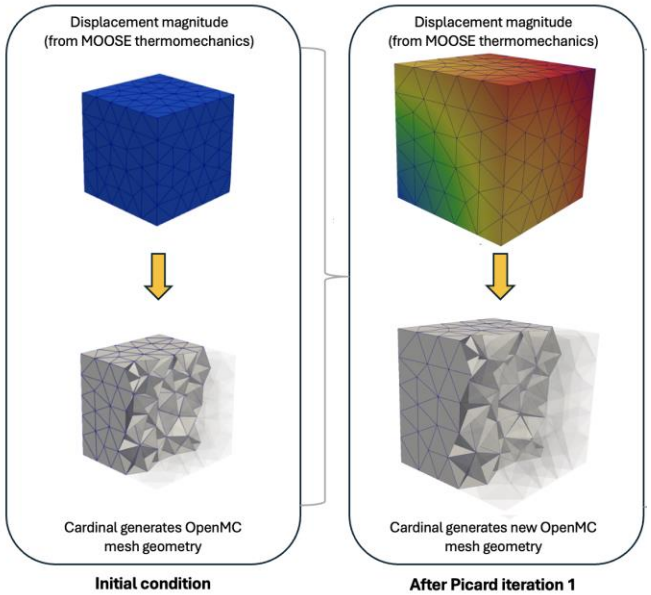


surfaces bounding each cell

Automatic re-generation of CAD geometries to capture feedback

Continuous geometry deformation is directly used in OpenMC

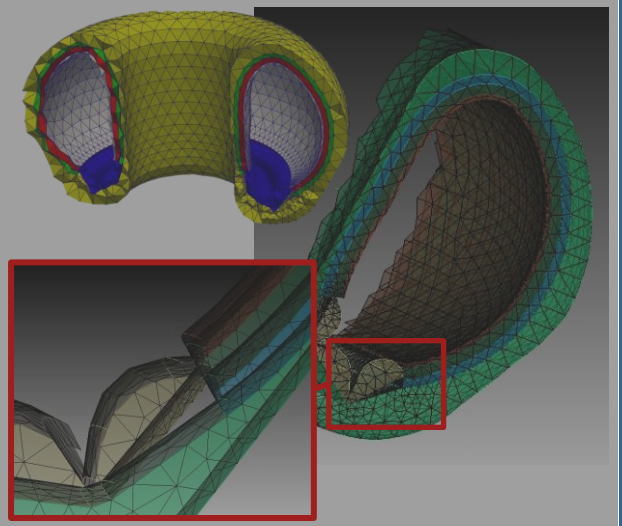




Thermomechanics feedback to Monte Carlo neutronics

Some Notable Software Features

Sandia study quantified ~80% of CFD engineers' time spent on mesh generation!



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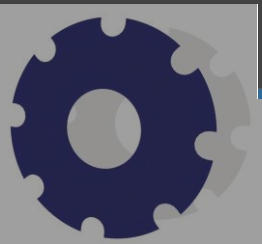
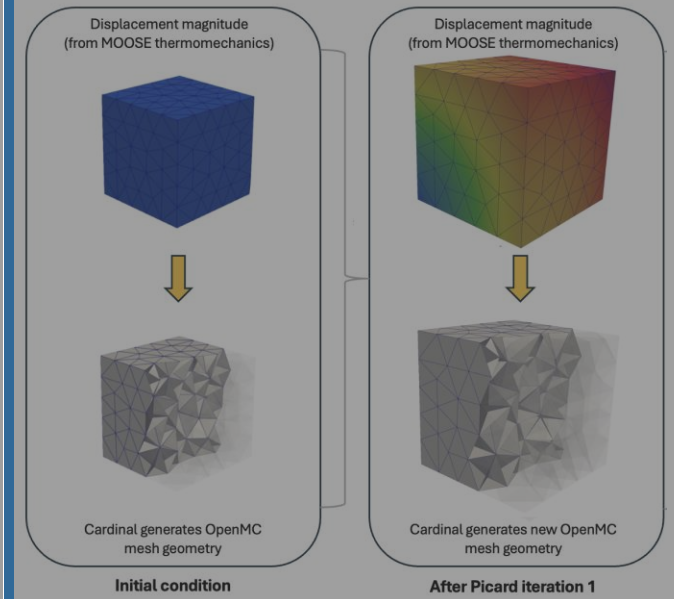
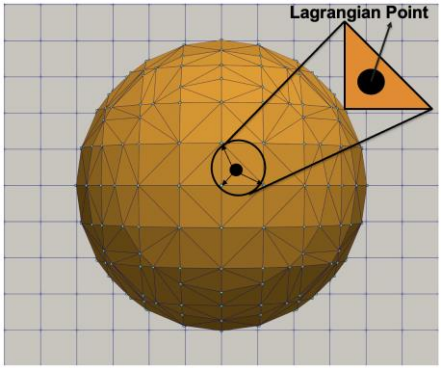
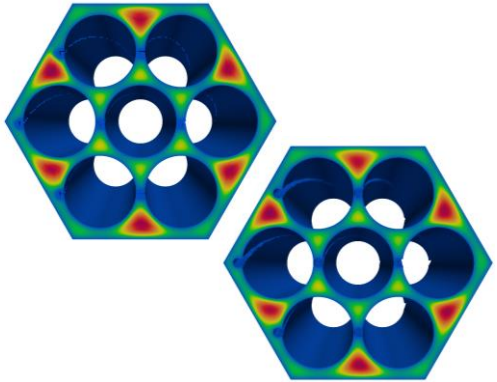




Thermomechanics feedback to Monte Carlo neutronics





Immersed boundary methods for CFD of complex geometries

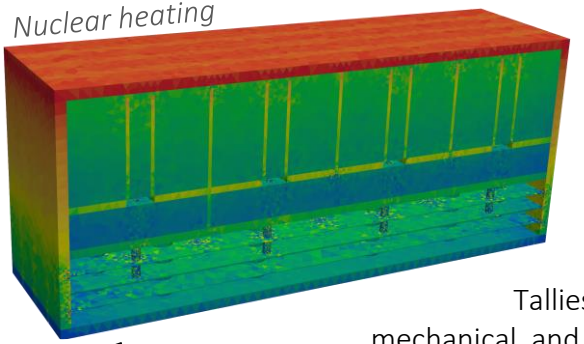
- Cardinal: High-fidelity Multiphysics for Fusion

- Adaptive mesh refinement for breeder blankets
- Neutronics to accelerate fusion materials development
- Liquid metal MHD experiments
- Reticulated foam extraction systems

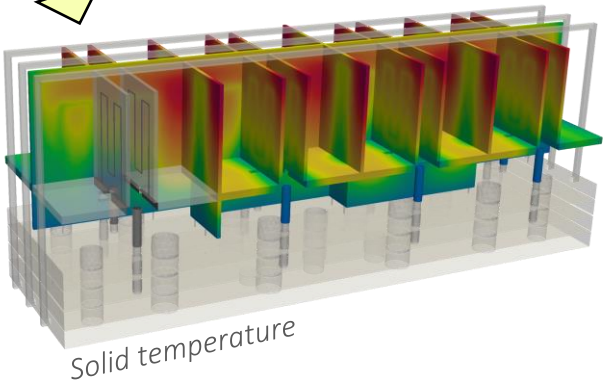
- Conclusions

Monte Carlo Tallies

Spatial resolution

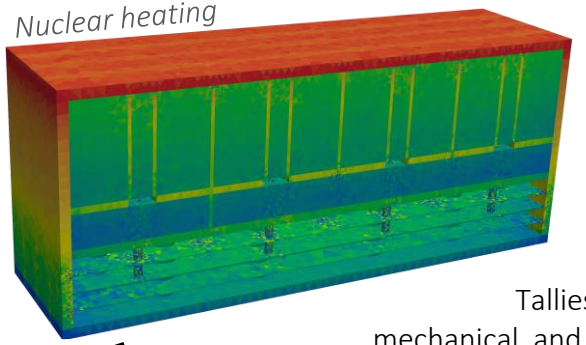


Tallies are inputs to T/H, mechanical, and material analysis... on different length scales



Monte Carlo Tallies

Spatial resolution



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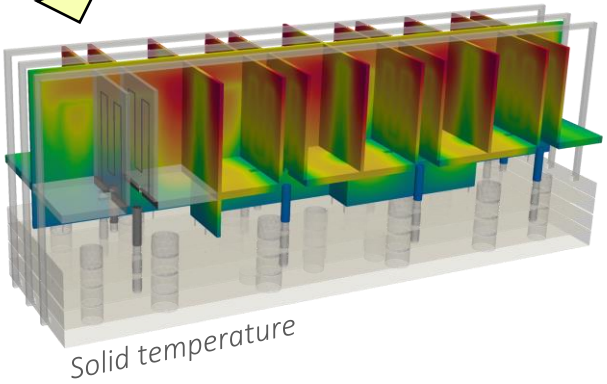
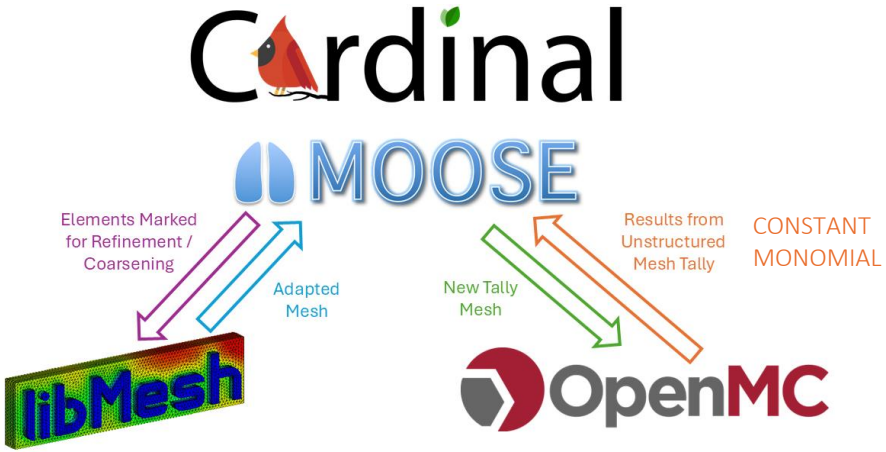


Runtime, Statistical Error, and Stability

Refinement is penalized by $\sigma \sim \frac{1}{\sqrt{N}}$

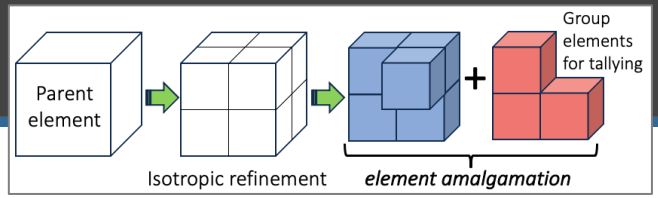
Statistical error and/or finer resolution can also destabilize Picard iteration

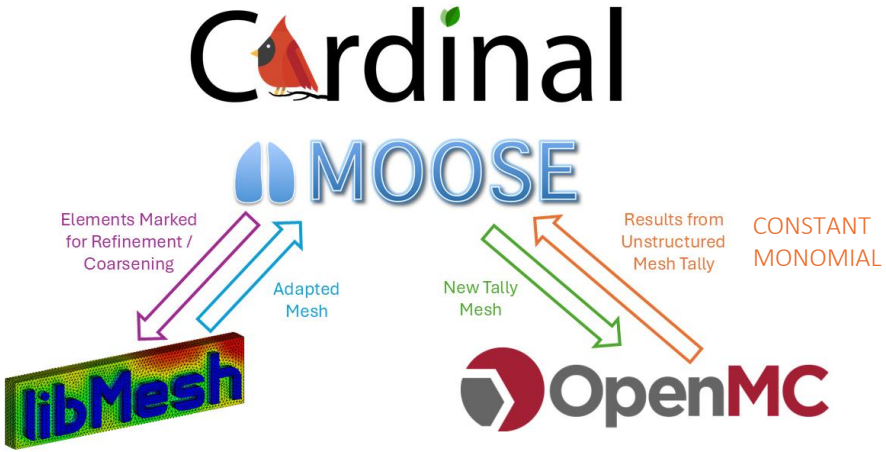
Adaptive Mesh Refinement in Cardinal

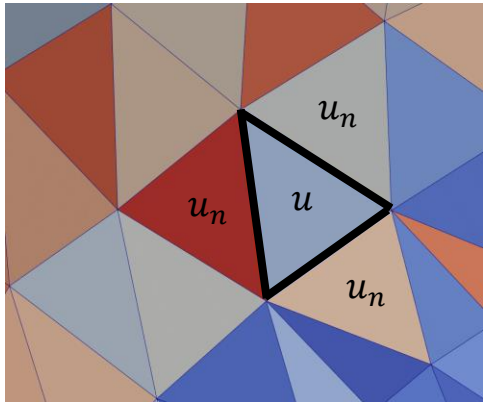


- `Indicators:` estimate of error in each element
- `Markers:` decide which elements to refine/coarsen

Adaptive Mesh Refinement in Cardinal







- An OpenMC unstructured mesh tally is re-initialized on each adaptivity cycle
- Any number of adaptivity cycles are allowed within a single Picard iteration – AMR subcycling
- Tallies are constant monomials (for now)

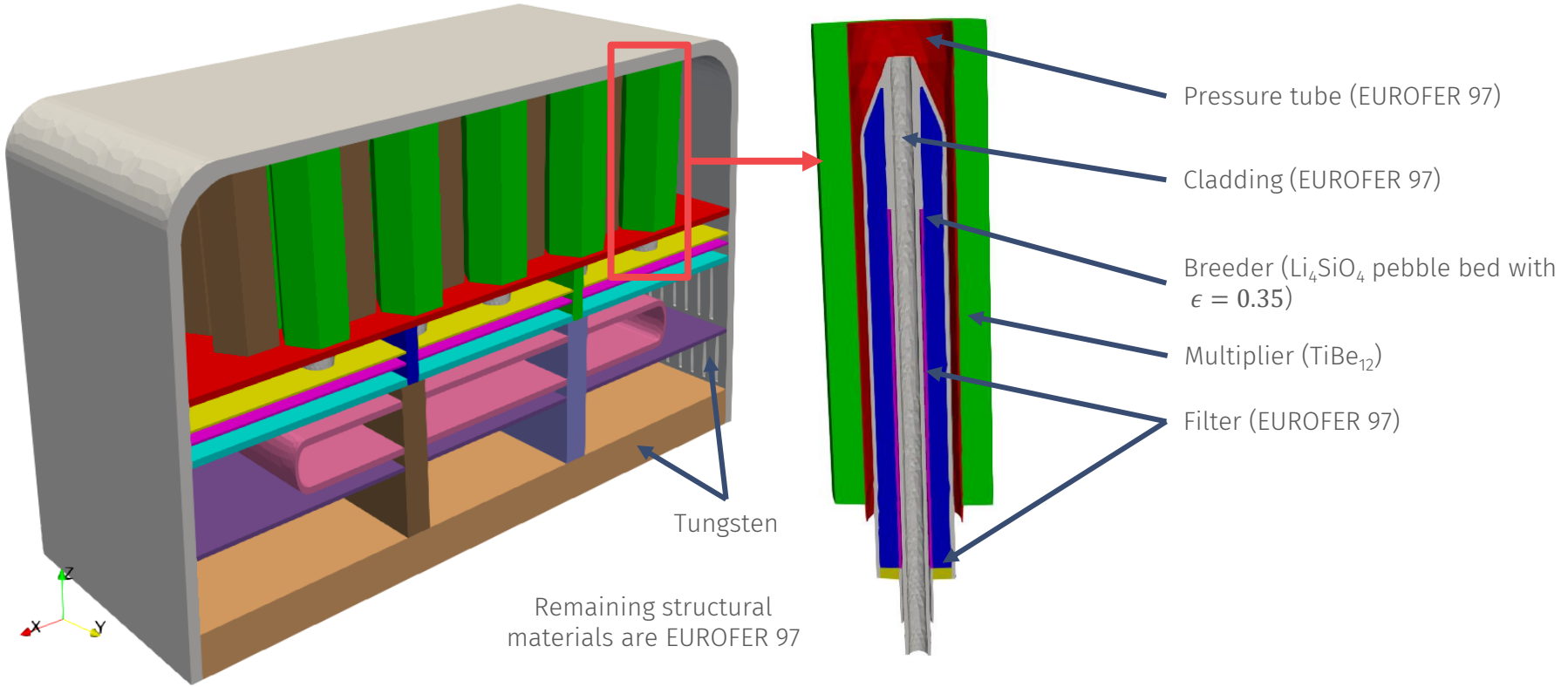
`ValueJumpIndicator`: $\sqrt{h\int(u-u_n)^2dS}$

`VectorMagnitudeIndicator`: $\sqrt{h\int\|\vec{u}\|dV}$

`VectorJumpIndicator`: $\sqrt{h\int(\vec{u}-\vec{u}_n)^2dS}$

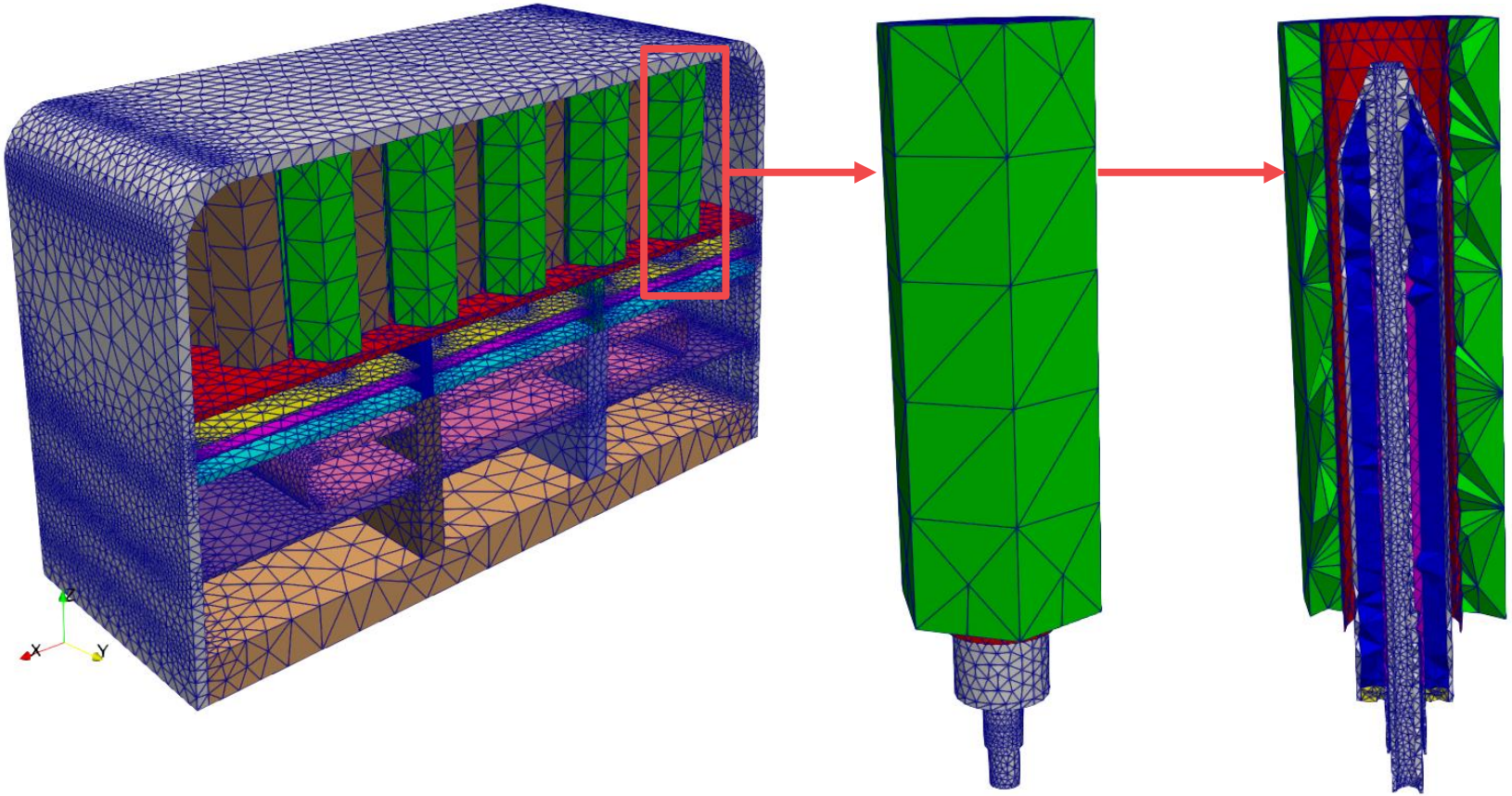
`ElementOpticalDepthIndicator`: $\Sigma_x h$

HCPB Outboard Blanket Module



CAD generated with Hypnos, a parametric geometry engine for blanket design developed by the UKAEA: https://github.com/aurora-multiphysics/hypnos

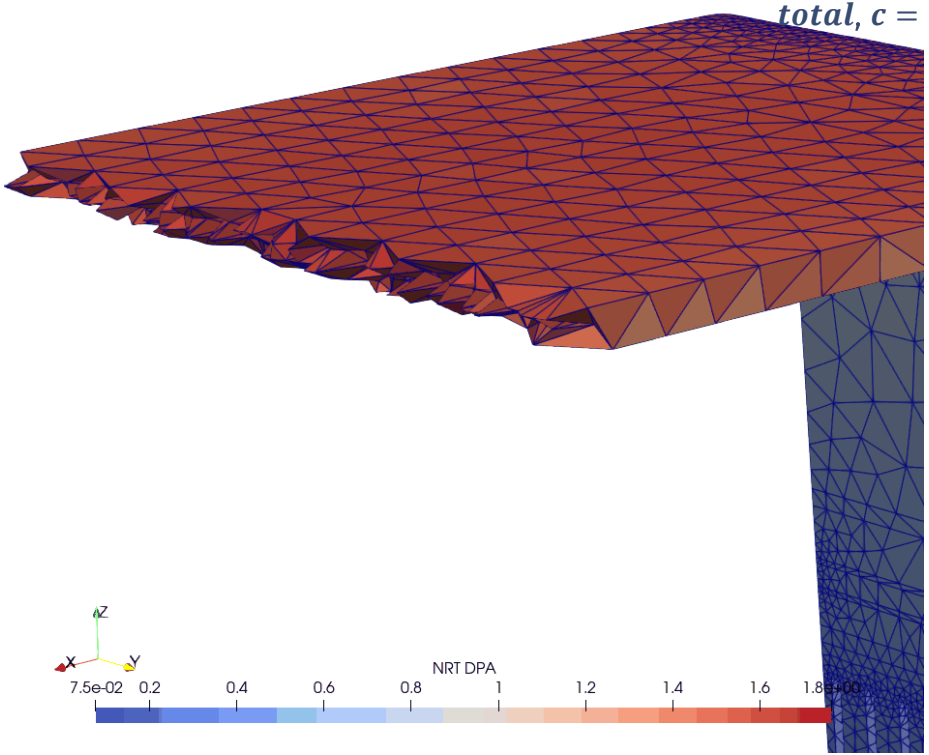
Initial Mesh



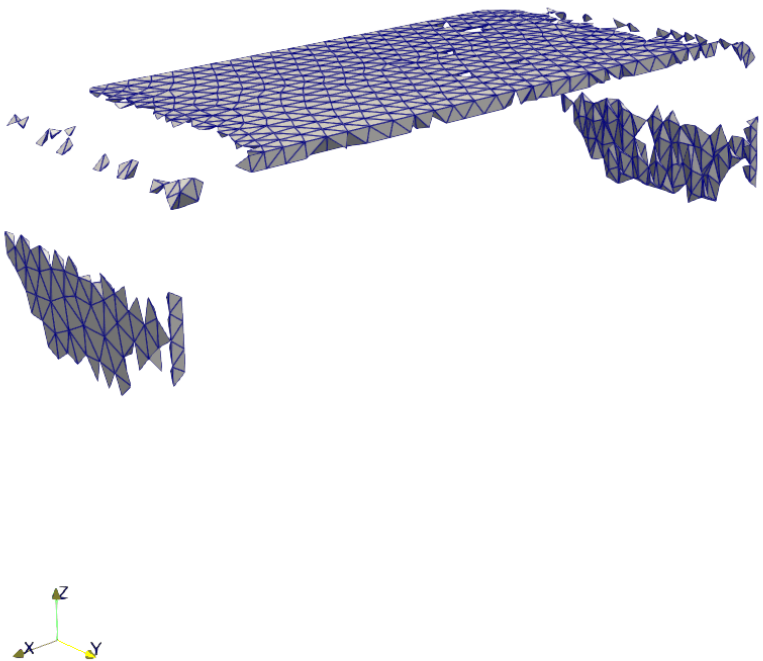
Applying AMR to DPA on the First Wall

Combining an inverted `ElementOpticalDepthIndicator` with the `ErrorFractionLookAheadMarker`

$$total,\ c = 0.3,\ t = 1\%$$



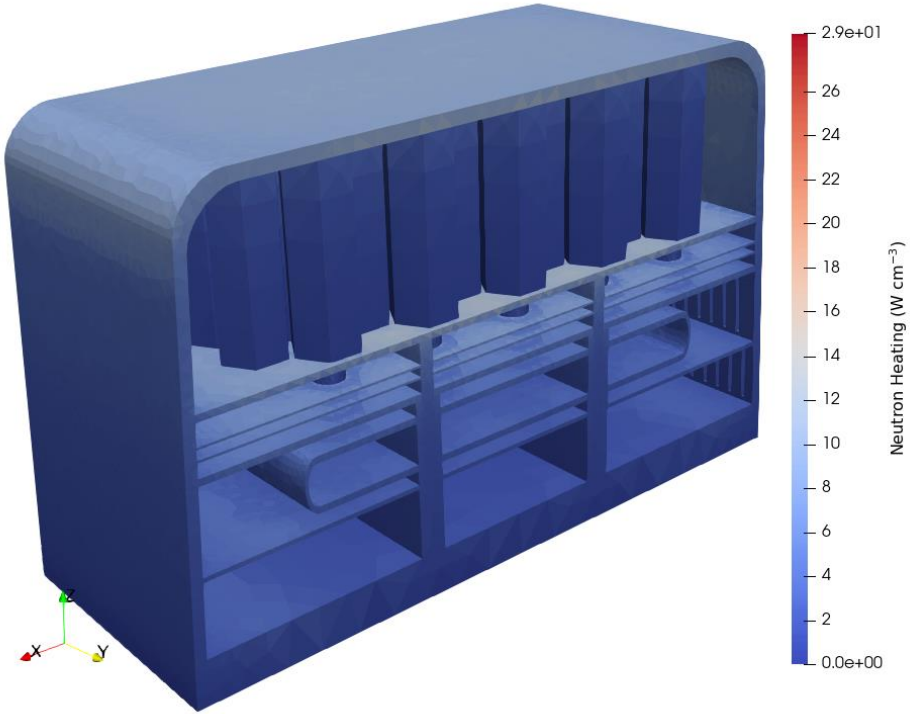
NRT DPA



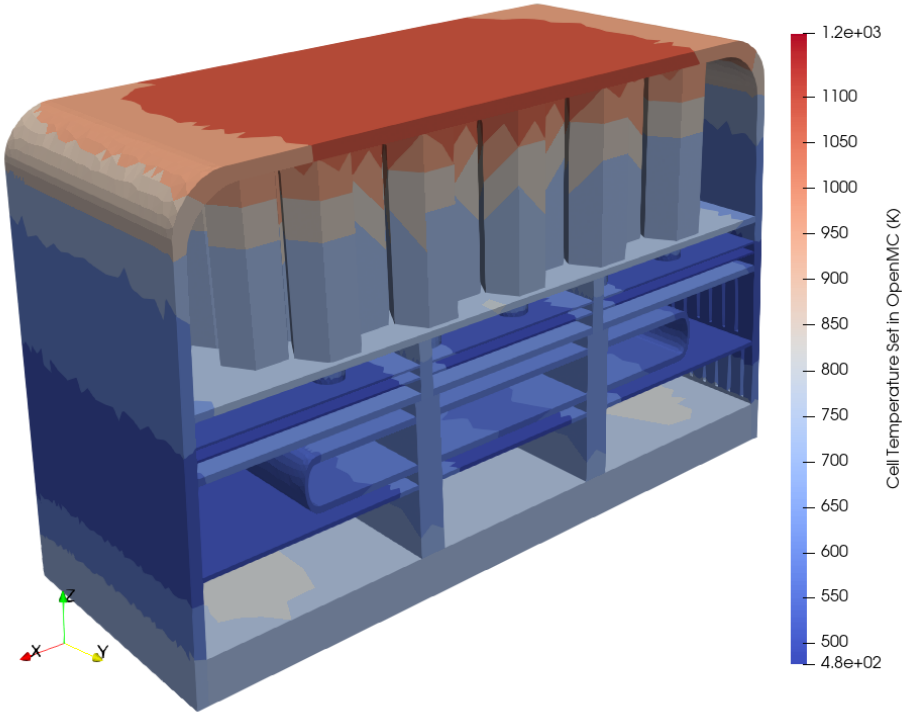
Elements Marked for Refinement

Refinement Cycle: 0.000000

Next Step: Multiphysics-Driven Adaptivity



Neutron Heating



Temperature

- Cardinal: High-fidelity Multiphysics for Fusion

- Adaptive mesh refinement for breeder blankets
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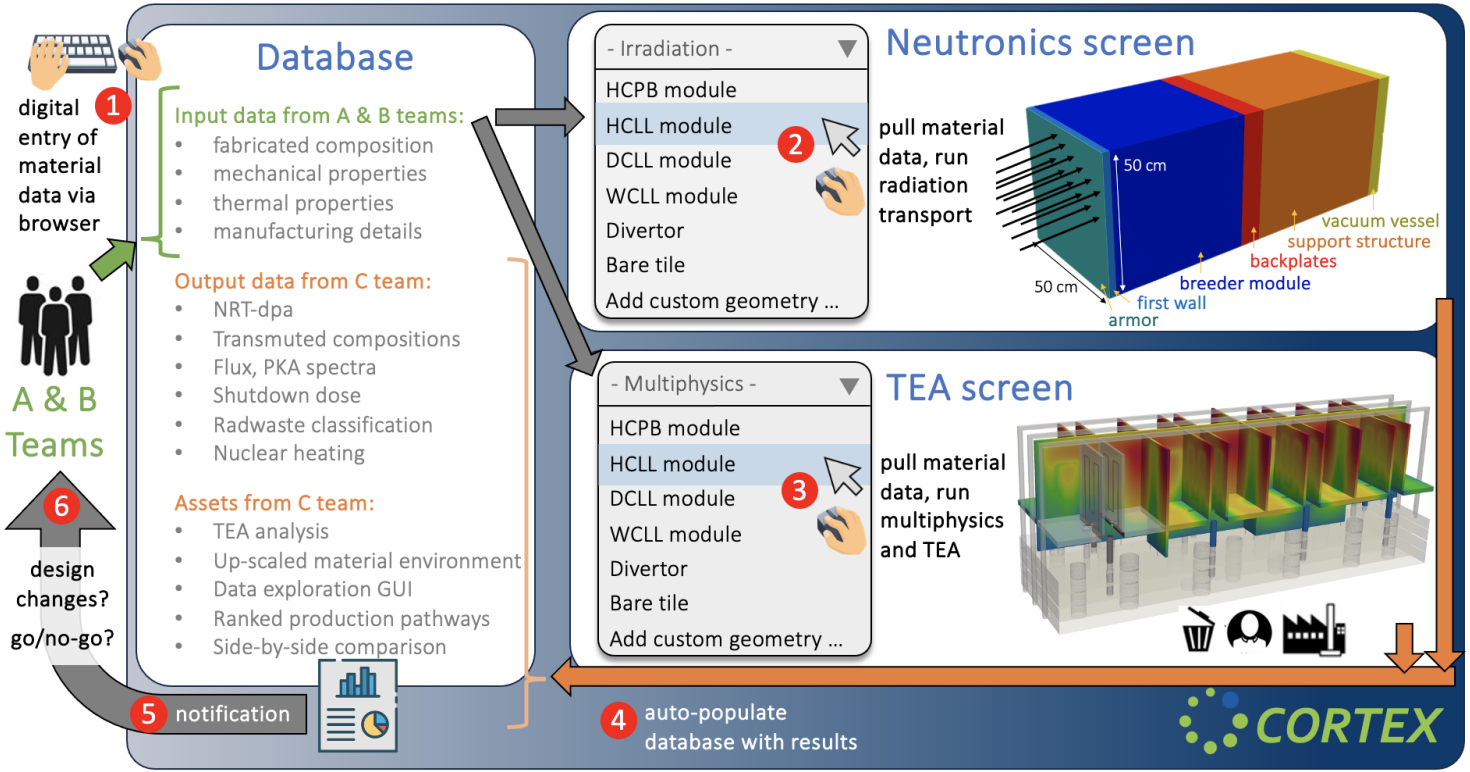
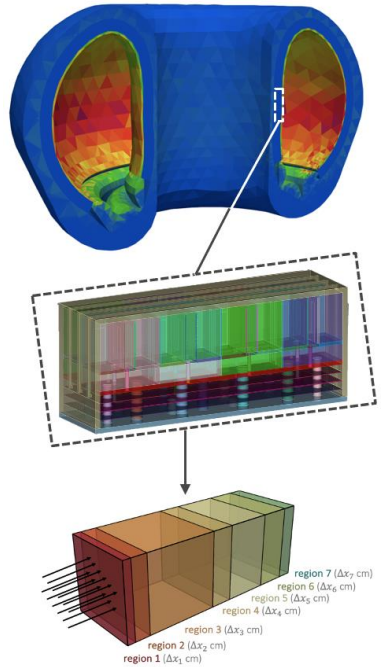
- Reticulated foam extraction systems

- Conclusions

CORTEX: *Fusion Materials Database + Neutronics/TEA Analysis*





CORTEX Materials Database

example

Materials | Operating Conditions | Geometry

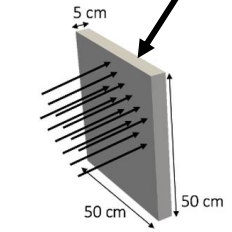
Name	Eurofer 97	string between 1 and 100 characters	*Enter the name of your material*	
Density	19	number of f g/cm3 between 1 and 25	*Enter the density of your material during in-service conditions.*	

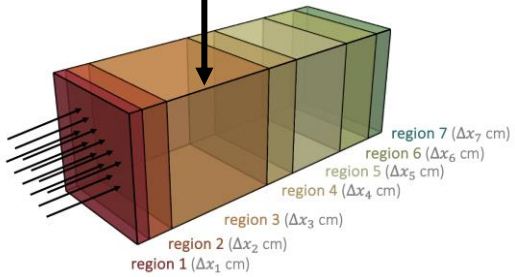
Composition

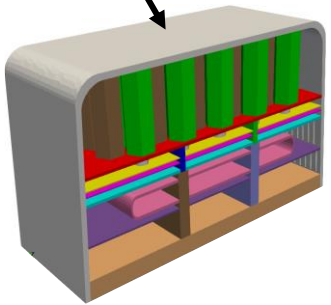
Enter the composition of your material. The components of a material must ALL be given in weight % or ALL be given in atomic percent. Neutronics simulations will use the "target" value if provided. If the "target" value is not provided, the midpoint of the max/min range will be used, unless the "min" value is zero in which case the maximum is used (assuming a conservative approach for impurities). One element or nuclide can be indicated as "balance" in order to fill the remaining material components to 100% weight percent or 100% atomic percent.

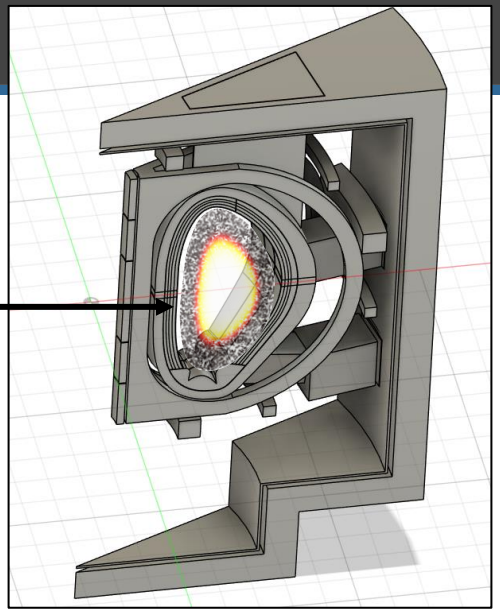
	Weight %			Atom %		
Element or Nuclide	Target	Min	Max	Target	Min	Max
C	0.11					
Cr	9.00					
W	1.10					
Mn	0.40					
V		0.15	0.25			
Ta	0.12					
N	0.03					
P	0.01					
S	0.01					
B	0.00					
O	0.01					
Fe	balance					
Nb		0.00	0.01			
Mo		0.00	0.01			
Ni		0.00	0.01			

Text | balance



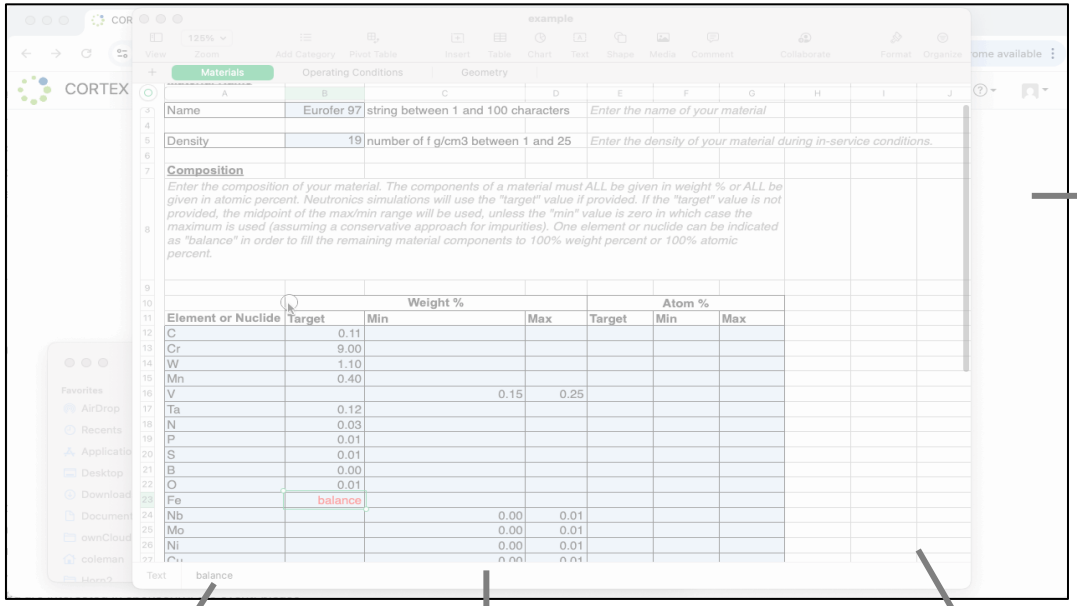


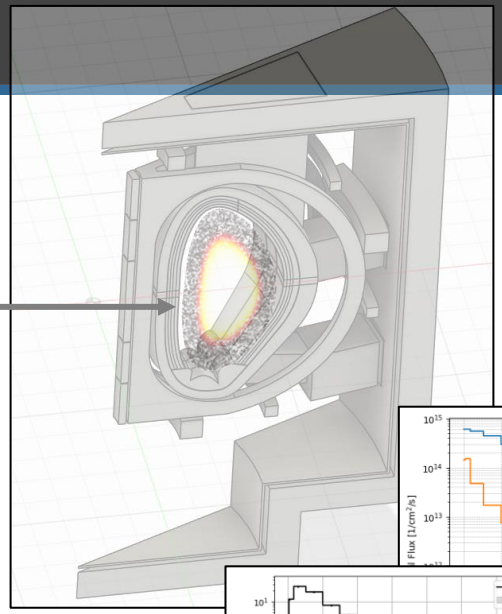


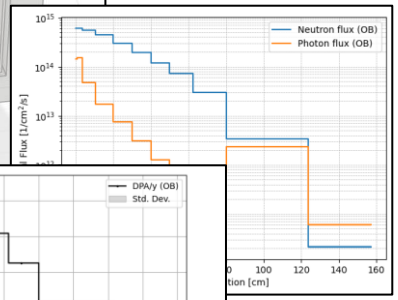


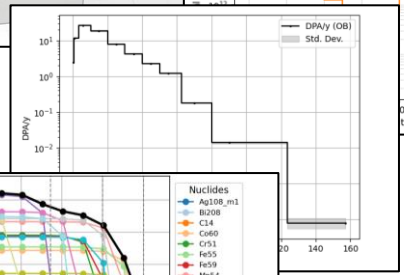
https://sirepo.com/cortex

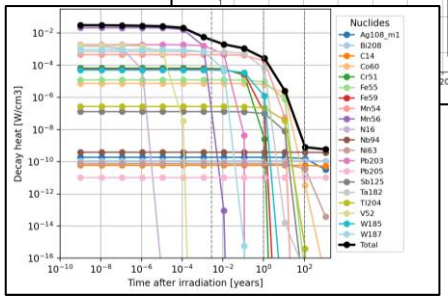
CORTEX Materials Database

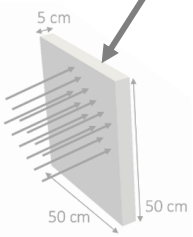


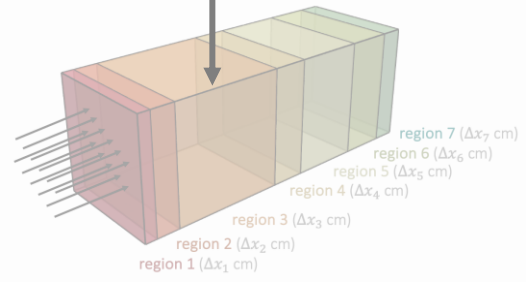


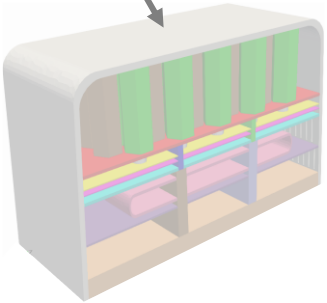












OpenMC predictions of NRT-dpa, He/H production, heating, transmutation, …

PbLi MHD Experimental Facility: MAGNES

Engineering significance of MHD:

- MHD pressure drop
- Suppression of turbulence
- Flow distributions: cooling, recirculation, stagnation
- Mass transfer: tritium permeation, plate-out/collection of high-melting point impurities

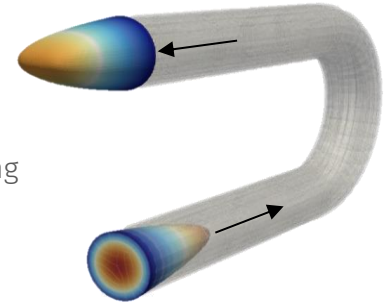
Computational challenges:

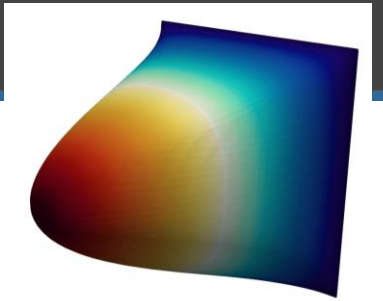
- Hartmann and side layers scale as $1/Ha$, $1/\sqrt{Ha}$
- Numerical stiffness, $\Delta t \sim 1/Ha^2$

New MHD facility being commissioned at Univ. of Wisconsin, Madison through FIRE using ~5 T field near WHAM magnets.

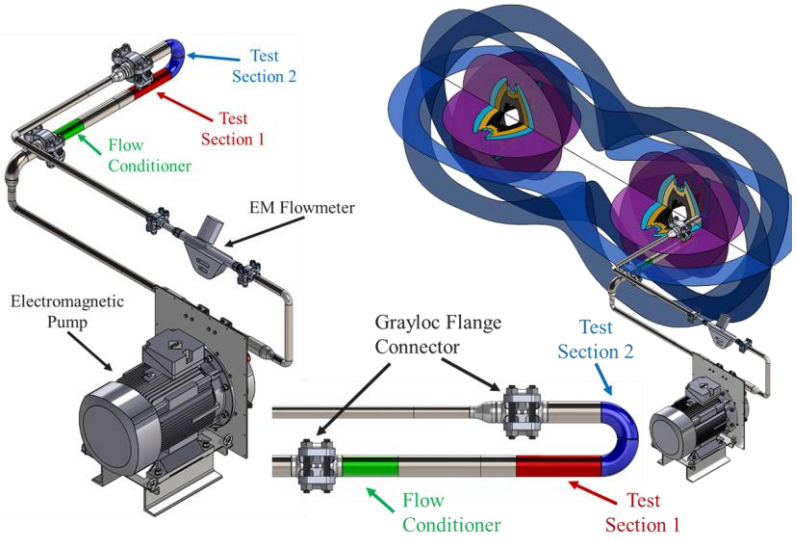
- Develop open-access benchmark data for isothermal PbLi MHD flows (up to Ha ~ 4000): insulations, advanced heat exchange surfaces, ….
- Validate MHD codes
- Develop MHD pressure drop library to facilitate systems-level design

NekRS MHD simulations of experimental test section.





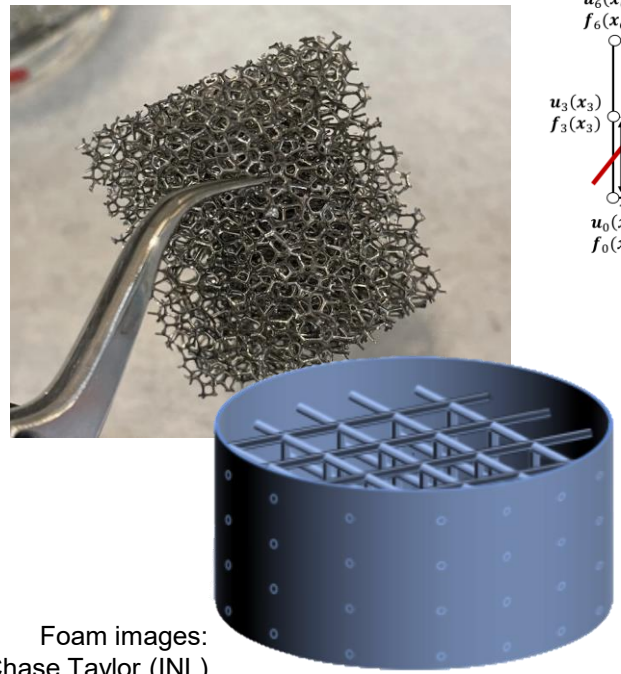
Evolution from hydrodynamic flow to Hunt MHD flow



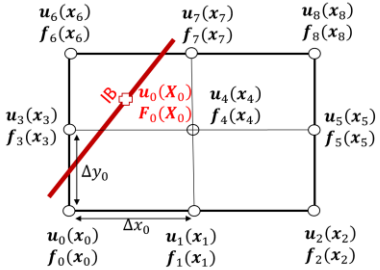
Experimental team: Juliana Pacheco-Duarte (UW), Craig Jacobson (Realta Fusion)
Computational team: April Novak (UIUC), Rogerio Jorge (UW)

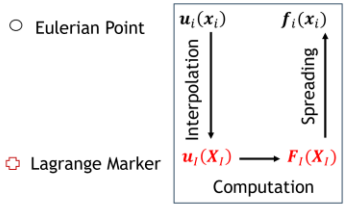
Reticulated Foams for Tritium Extraction

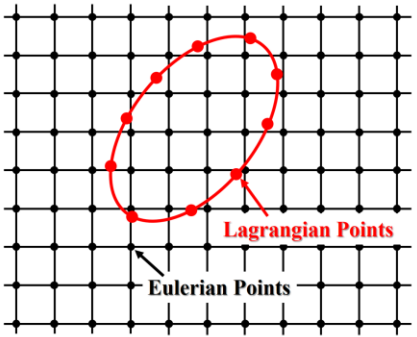
- High surface area capillary foams for tritium extraction
- NekRS immersed boundary method based on direct forcing approach with overlapping meshes

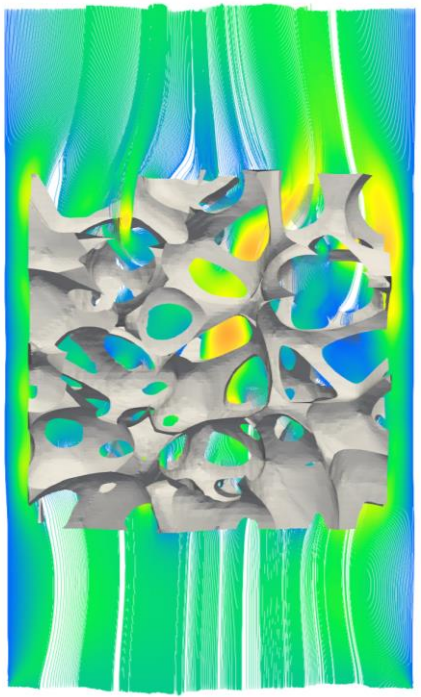


Foam images:
Chase Taylor (INL)









Preliminary NekRS immersed boundary simulation of reticulated foam

Concluding Thoughts

- Code interoperability will benefit multiphysics simulations, multiscale techniques, and UQ/SA. But code-specific workflow challenges remain for
  - CAD-based neutronics modeling
  - Meshing for CFD

  } *Hard to "parallelize"*

- Software quality assurance (SQA) will be important for fusion and is a huge undertaking – we are QA'ing non-MOOSE codes via MOOSE (e.g. NekRS)

- We are building an open-access fusion materials database (https://sirepo.com/cortex) which is linked to fusion neutronics device/component models
  - Suggestions for this tool to support your needs?
  - We welcome material data contributions – do you have datasets you'd like us to upload?

- Community requests for MHD test sections for MAGNES?

Questions?

https://cardinal.cels.anl.gov

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