



# FENIX: Towards a Fully Integrated Multiphysics Framework for Plasma Facing Component Modeling

July 2024

*Changing the World's Energy Future*

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**July 2024**

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**FENIX**

# **FENIX: Toward a Fully Integrated Multiphysics Framework for Plasma Facing Component Modeling**

TOFE 2024

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**VCU**

Battelle Energy Alliance manages INL for the  
U.S. Department of Energy's Office of Nuclear Energy



Idaho National Laboratory



## Overview

1. The need for multiphysics modeling of plasma facing components (PFCs)
2. MOOSE is a flexible platform for multiphysics simulation
3. FENIX leverages MOOSE to model PFCs
  - Capabilities in FENIX
  - Demonstration on divertor monoblock modeling
4. FENIX is open-source and facilitates collaborations
  - High software quality assurance
  - Flexible license
  - Modular capabilities
  - Multiple successful collaborations, including international
5. Getting started with FENIX

# The need for multiphysics modeling of plasma facing components

- Fusion Energy Sciences Advisory Committee (FESAC) report, 2020, Powering the Future, Fusion & Plasmas:

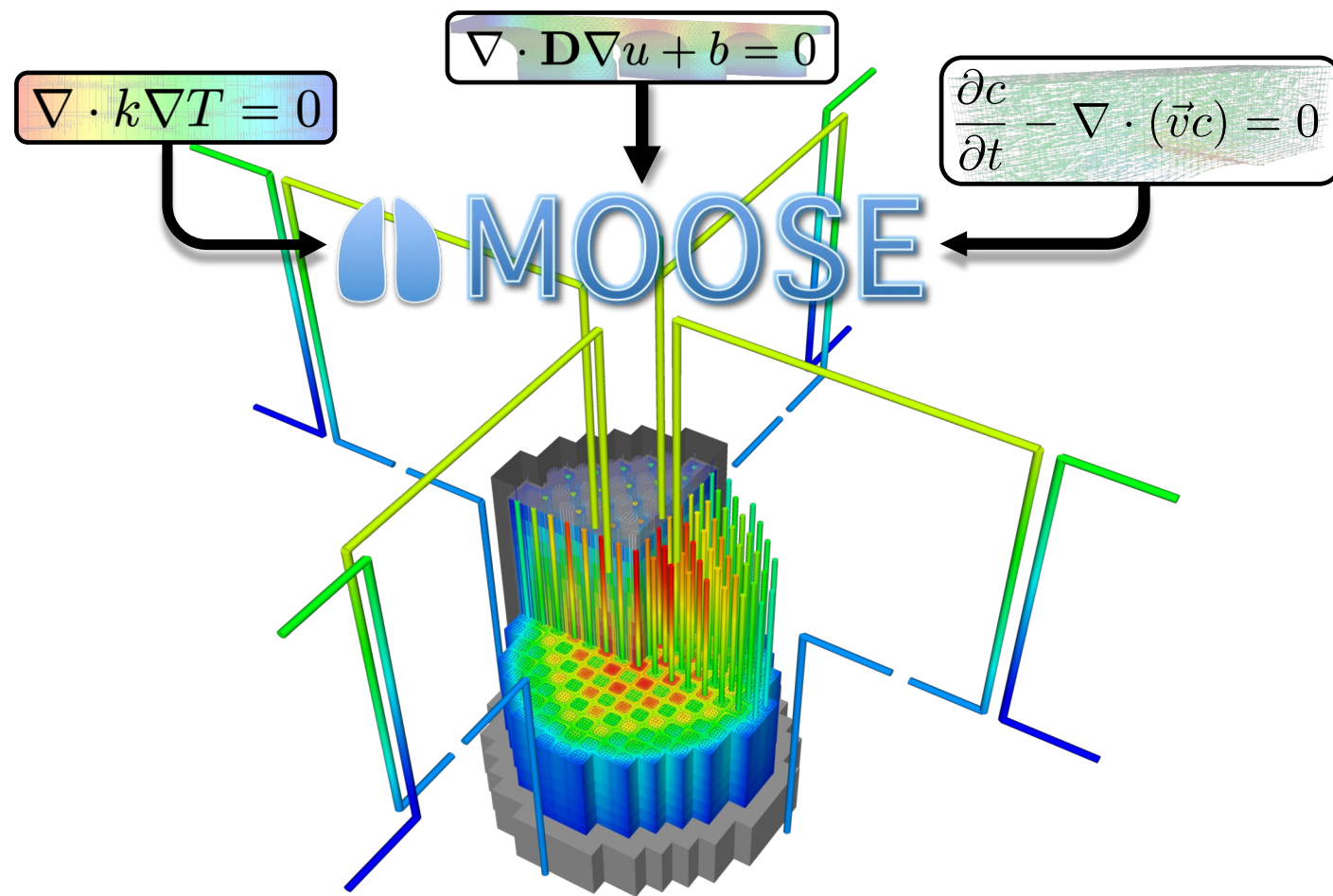


“An essential component underpinning this effort is a strong theory and computation program, including the advancement of **multiscale, multiphysics theory and modeling capabilities** necessary to predict the complex interactions between numerous **plasma, material, and engineering processes**.”

- PFCs are under extreme thermal loads, repeated thermal shocks, and bombardment by 14 MeV neutrons, plasma ions, and neutral particles
- Experimental data is rare and costly to obtain, making PFC design particularly challenging. Predictive computational frameworks need to be an integral part of an accelerated and cost-effective design process by modeling PFC performance in simulated environments.

Modeling neutronics and plasma interactions with Plasma Facing Components in a multiphysics framework with thermomechanics enables an accurate simulation of the environment constraints of PFC

# MOOSE Accelerates Development of High-Fidelity Modeling and Simulation Tools



## What is MOOSE?

- Multiphysics
- Complete Platform
- Open-source
  - Equity, Inclusion
- Massively Parallel
- Flexible
- High Software Quality Assurance

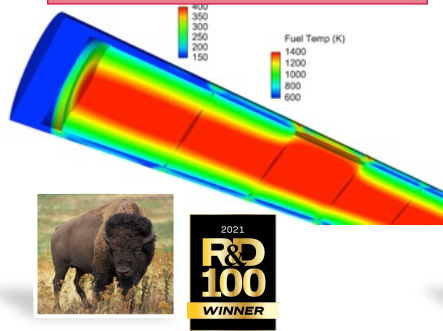
[mooseframework.inl.gov](http://mooseframework.inl.gov)

# Accelerating Advanced Reactor Deployment

## NEAMS

Accelerating Advanced Fission Reactor Deployment

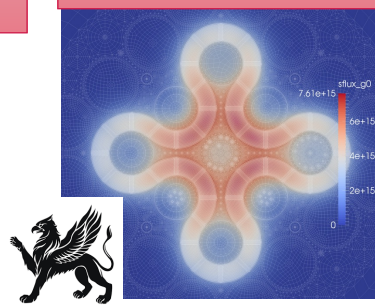
**BISON**  
Nuclear Fuel Performance



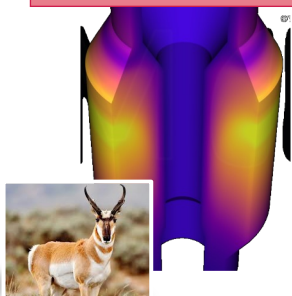
**Grizzly**  
Structural Mechanics for  
Component Aging



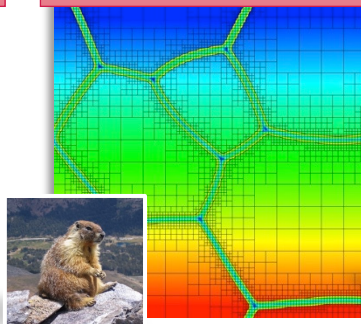
**Griffin**  
Radiation Transport



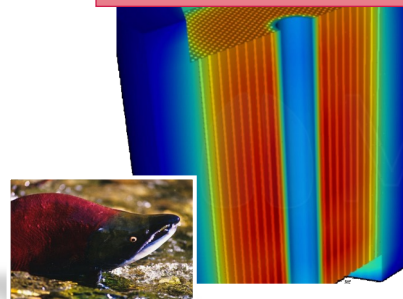
**Pronghorn**  
Medium-fidelity CFD



**Marmot**  
Mesoscale Materials



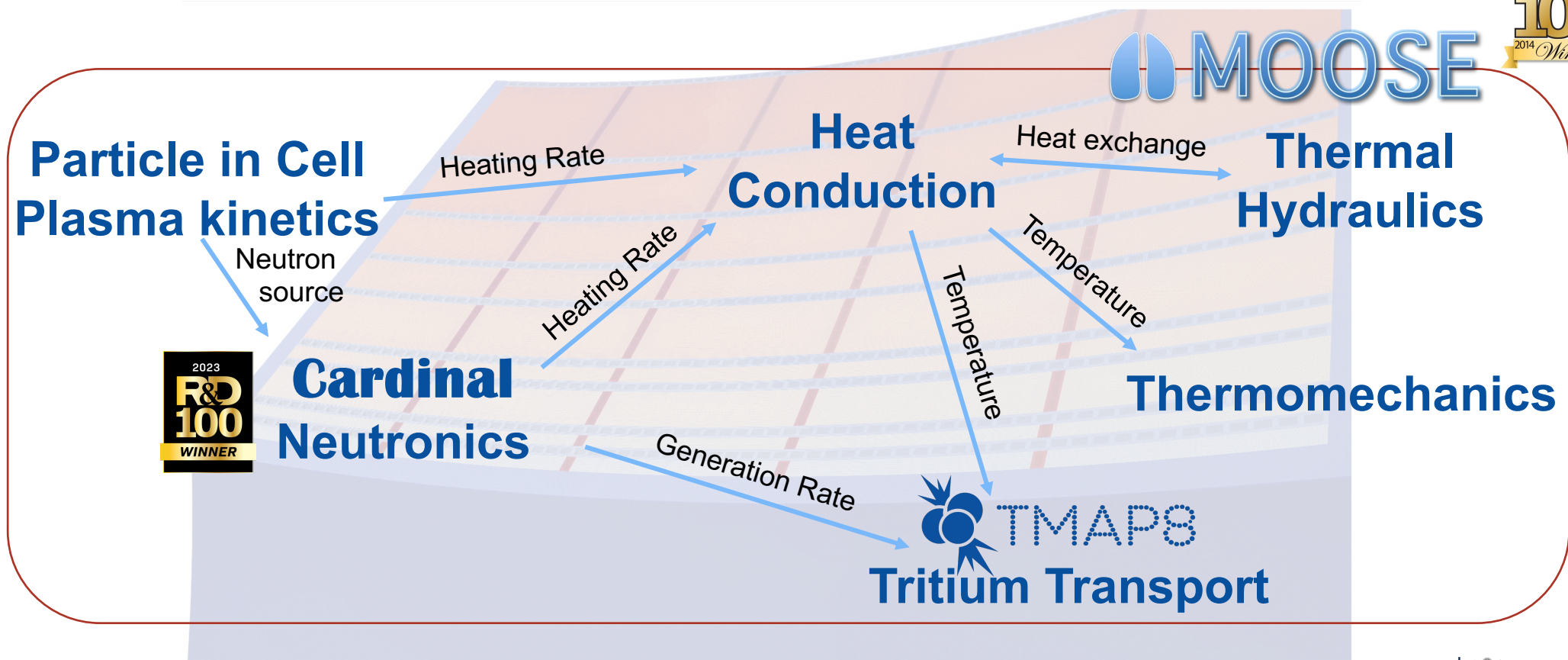
**Sockeye**  
Heat pipe Simulation



The codes' modularity and the selected licenses  
enable public-private partnerships  
Example: KP-BISON



# Understanding multiphysics interactions around PFCs: Fusion ENergy Integrated multiphys-X (FENIX) framework



## FENIX

An open-source, fully integrated, multiscale, MOOSE-based framework facilitating 3D, high-fidelity PFC modeling

FENIX is the product of an ongoing Laboratory Directed Research & Development project



UK Atomic Energy Authority



IDAHO NATIONAL LABORATORY

# Tritium Migration Analysis Program, version 8

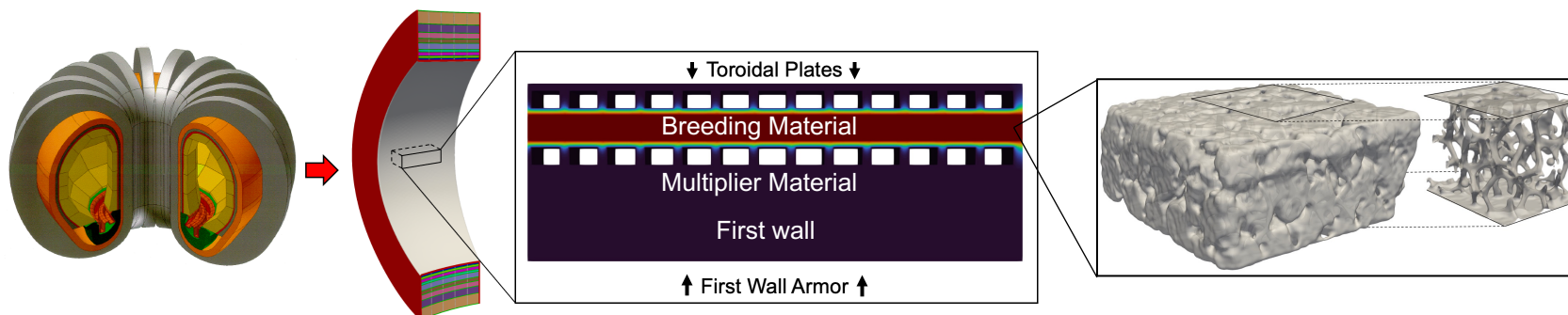


TMAP8



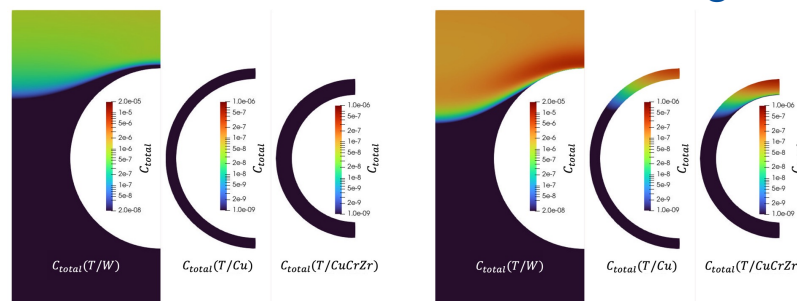
- TMAP4 and TMAP7, although widely used, have significant limitations.
- TMAP8 enables high fidelity, multi-scale, 3D, multiphysics simulations of tritium transport.
- TMAP8 is open source, Nuclear Quality Assurance level 1 compliant, offers user support and massively parallel capabilities.

Model  
Development  
and  
V&V



\* TMAP8 simulations of a ceramic breeder material and of a blanket section

- Modeling tritium transport from the mesoscale to the engineering scale for high fidelity simulations
- Verification & Validation efforts are demonstrating the robustness of the models and code.



UK Atomic  
Energy  
Authority



SAPIENZA  
UNIVERSITÀ DI ROMA



VCU

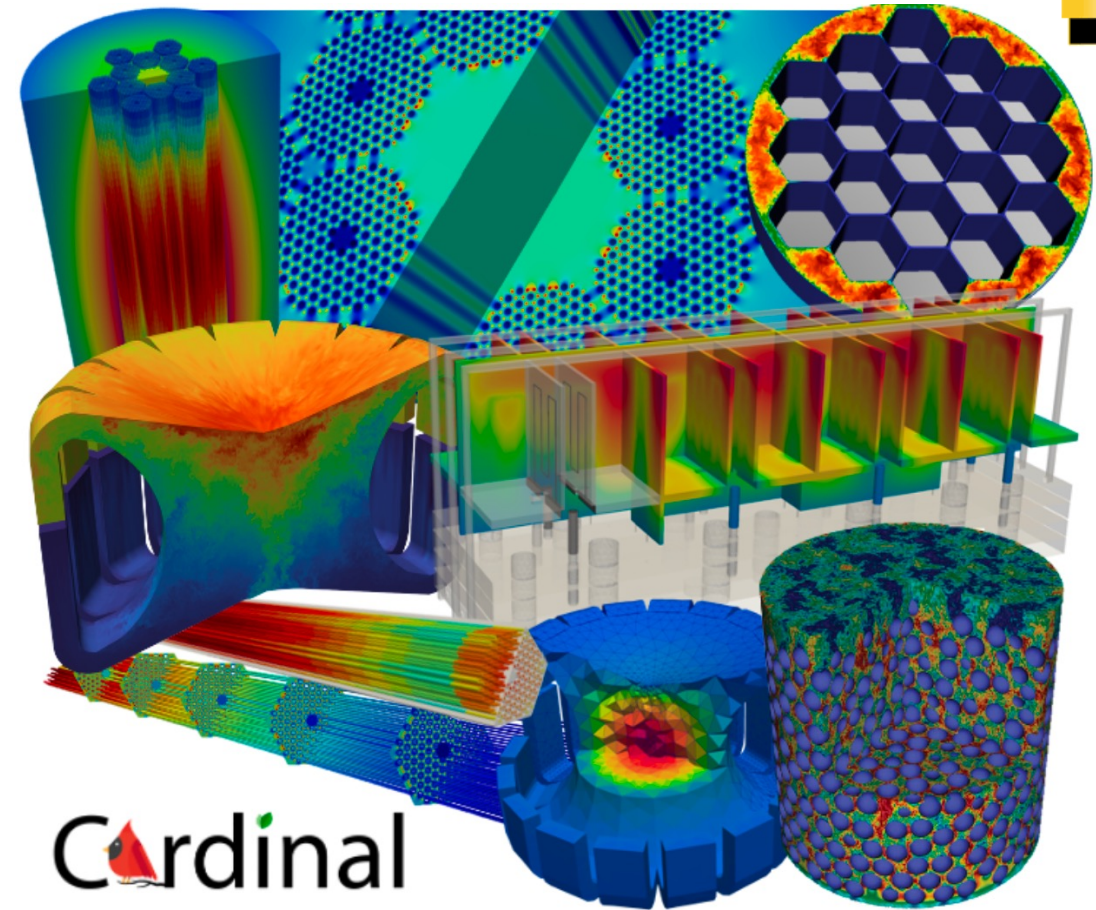


# Cardinal: Exascale Fission and Fusion Simulation



- Cardinal: MOOSE+OpenMC+NekRS
- Showcase for coupling non-MOOSE-based applications
  - MOOSE physics used as “glue”
- Has simulated: gas-cooled microreactors, sodium fast reactors, molten salt reactors, high-temperature gas reactors, and tritium breeder blankets
- Used 27k GPUs on Summit to simulate a full pebble-bed reactor (350k pebbles)

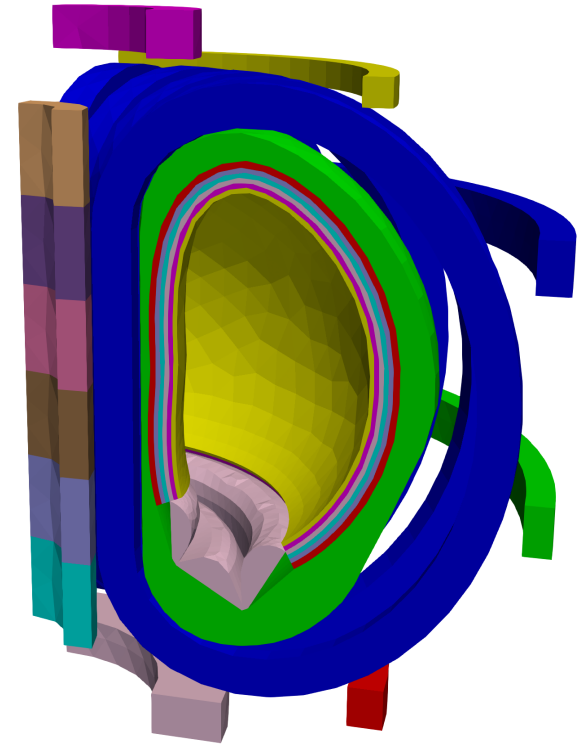
Novak, A. J., D. Andrs, P. Shriwise, J. Fang, H. Yuan, D. Shaver, E. Merzari, P. K. Romano, and R. C. Martineau. "Coupled Monte Carlo and thermal-fluid modeling of high temperature gas reactors using Cardinal." *Annals of Nuclear Energy* 177 (2022): 109310.



Cardinal Applications. Top row: neutron transport, fluid flow, and heat transfer in a gas-cooled microreactor; large eddy simulation in the core of a sodium fast reactor. Middle row: neutron transport and large eddy simulation in a molten salt fast reactor; coupled neutron-photon transport and heat conduction in a tritium breeder blanket module from the EU DEMO fusion plant. Bottom row: fluid flow and neutron transport in a high temperature gas reactor; fission heating simulated in a Computer Aided Design (CAD) geometry; large eddy simulation in a pebble bed reactor with 1568 pebbles.

# Neutronics with Cardinal coupled in FENIX

- Cardinal is used within FENIX to calculate neutronics quantities (i.e., heating, flux, tritium production, ...) using OpenMC Monte Carlo neutron and photon transport code
- We make use of existing capabilities to model fusion systems including CAD-based models using DAGMC and Paramak
- Ongoing objectives:
  - Develop a CAD-based geometry workflows for multiphysics fusion problems in FENIX. OpenMC particle transport runs directly on a DAGMC surface mesh of the geometry.
  - Enable OpenMC simulations with a moving mesh to allow coupling with solid mechanics models
  - Verify multiphysics solver with published analytical solutions for neutron transport coupled with thermal conduction and material expansion
  - Demonstrate importance of coupled multiphysics models for tritium production results

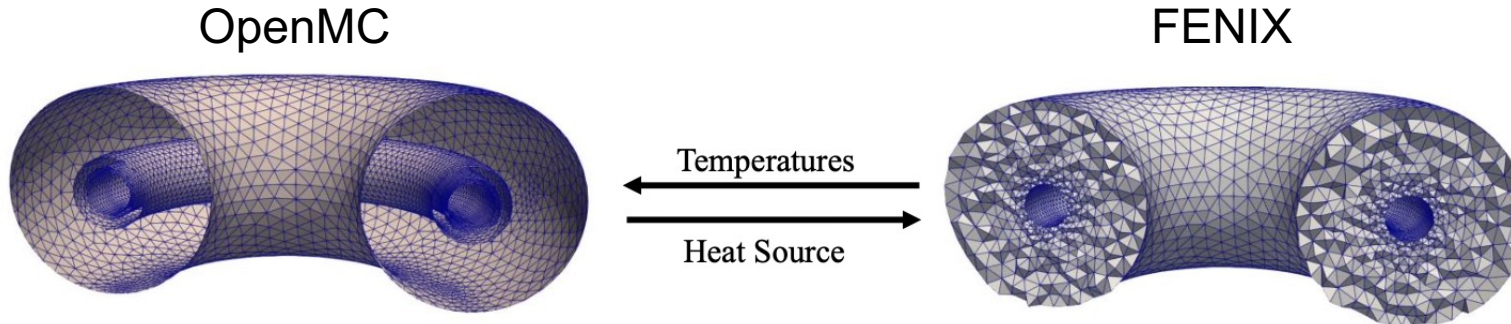
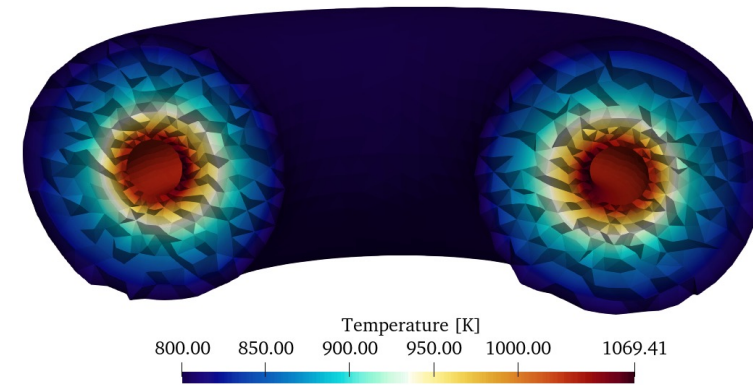
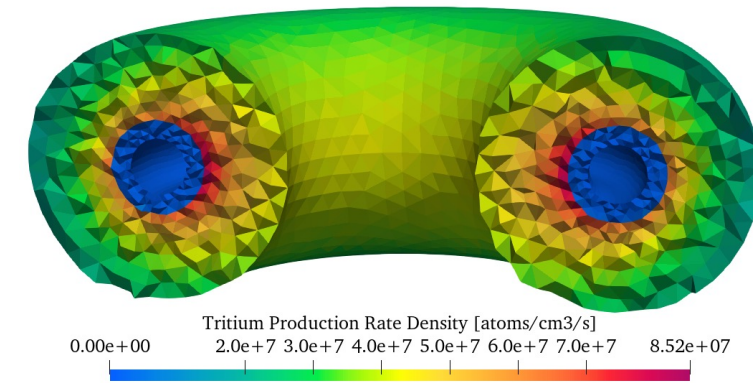


Simplified ITER model  
generated using Paramak



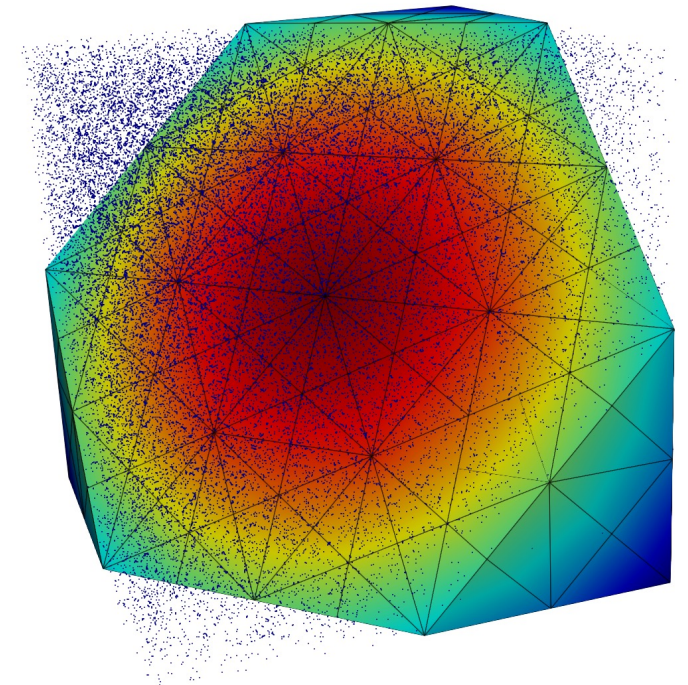
# Neutronics with Cardinal coupled to FENIX

- Investigated CAD-based geometry workflows and performed mesh refinement studies for:
  - DAGMC surface mesh
  - both DAGMC surface mesh and volumetric meshes used for tallying results and solving heat conduction
- Demonstrated that multiphysics results of interest could change as a result of either DAGMC model mesh not conserving the volume of the original CAD geometry, or a mismatch between the tally mesh and DAGMC particle transport mesh
- Cardinal uses MOAB skinner to regenerate DAGMC geometry on-the-fly directly from the volumetric mesh which with recent development also accounts for mesh movement



# MOOSE Based Particle In Cell (PIC) Simulations

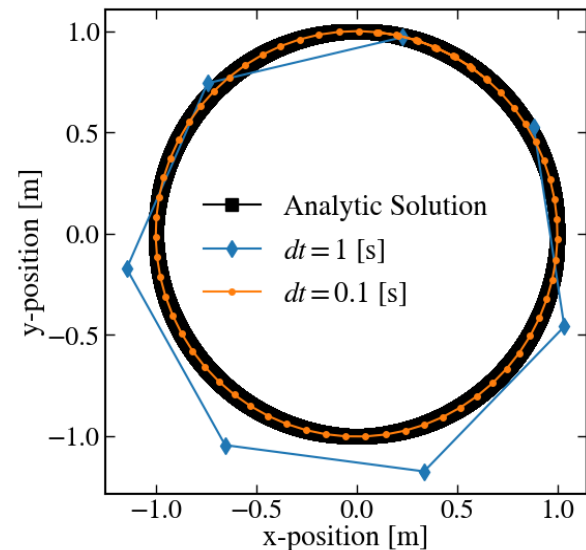
- Leverages the scalability and capability of MOOSE's Ray Tracing module
- PIC simulations can be performed in 1-, 2-, and 3-dimensional geometry with particles tracking 3 velocity components regardless of dimension
- PIC simulations can be performed on unstructured meshes with a wide variety of supported element types
- Flexible Particle initialization within libMesh elements



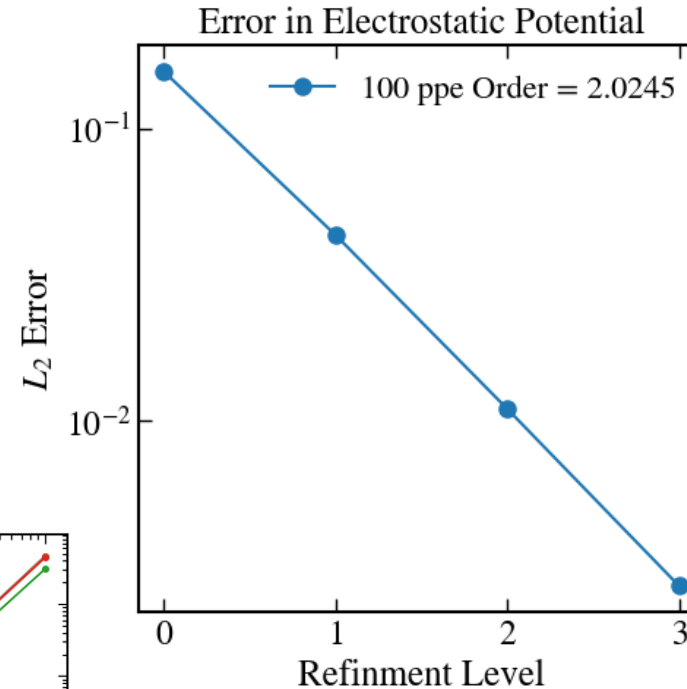
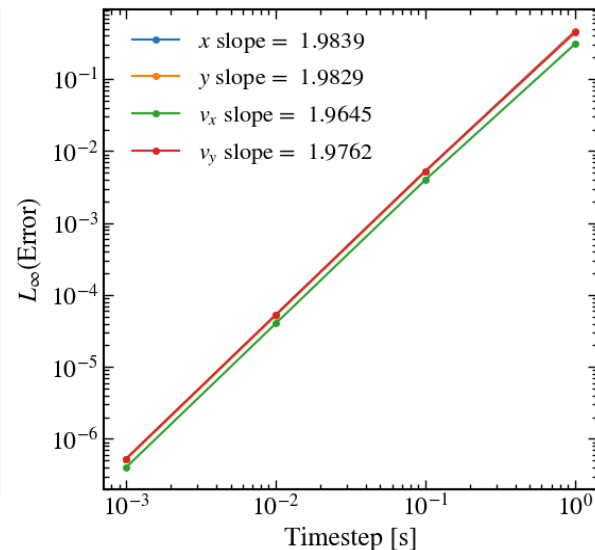
3D electrostatic potential, from a case with 1000 particles per element using tetrahedral elements.

# Verification of Nascent PIC capabilities

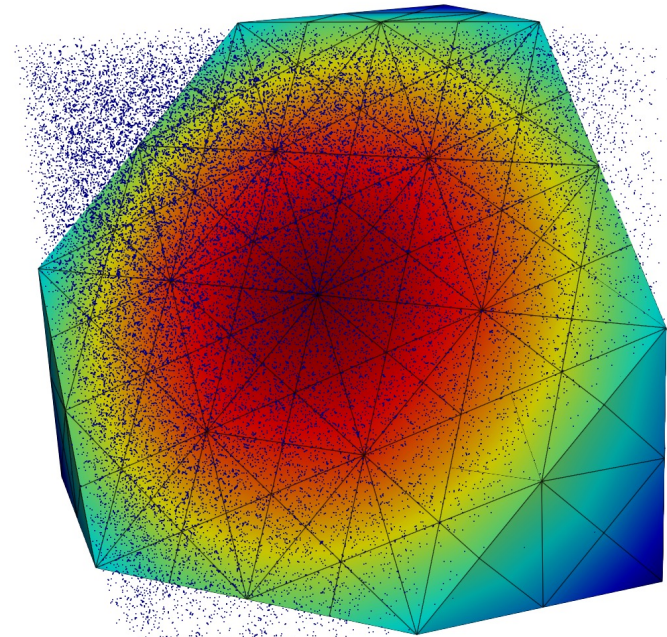
- Implementation of the classical Leapfrog and Boris algorithm for particle motion
- Electrostatic field solves resulting from particle distributions



Cyclotron motion particle paths at various time steps and the corresponding errors



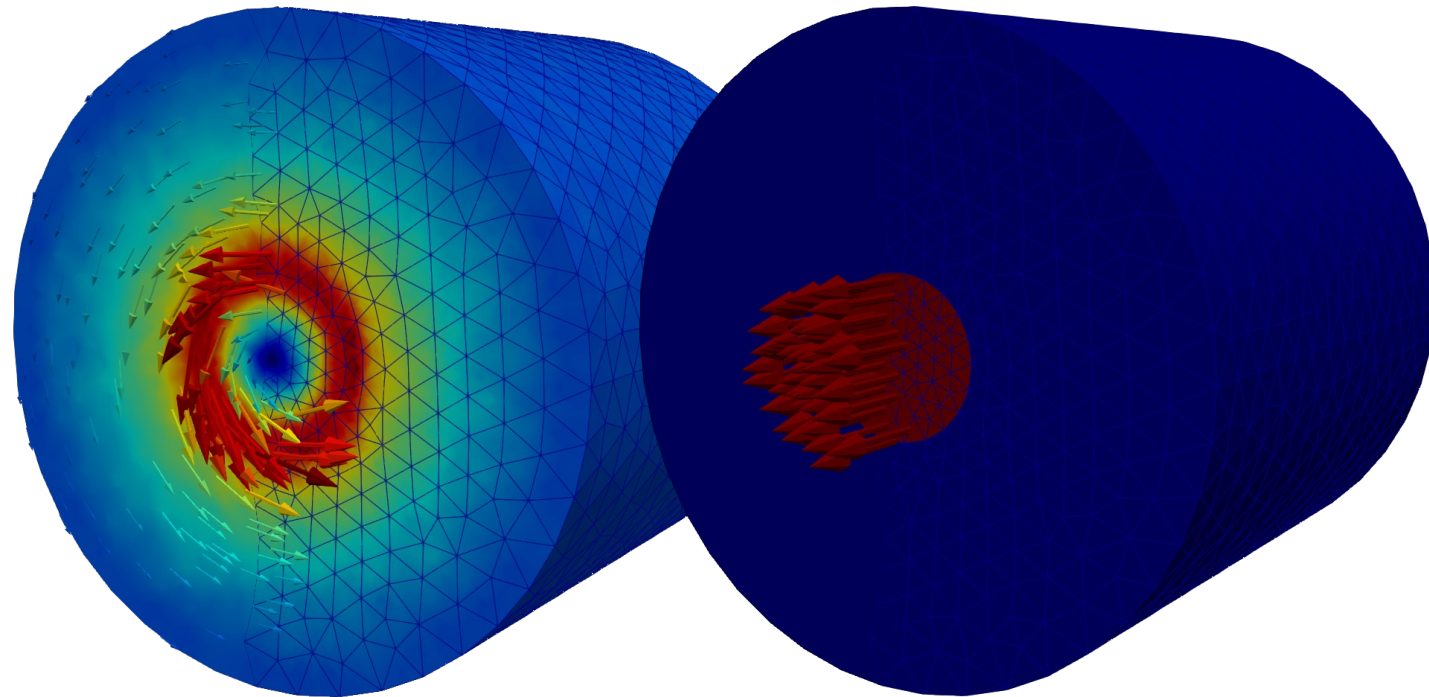
Particle Initialization: Results of a convergence study with a constant number of particles per element and the resulting 3D electrostatic potential, from a case with 1000 particles per element using tetrahedral elements.





# Coupling Particles and Electromagnetics

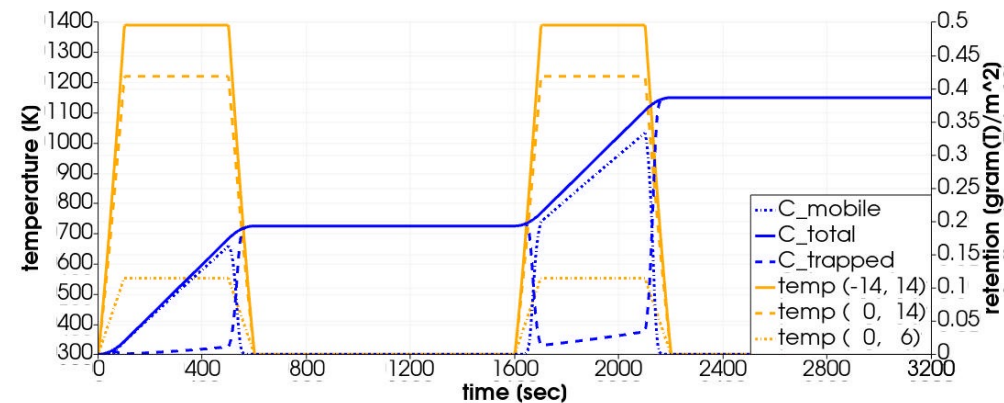
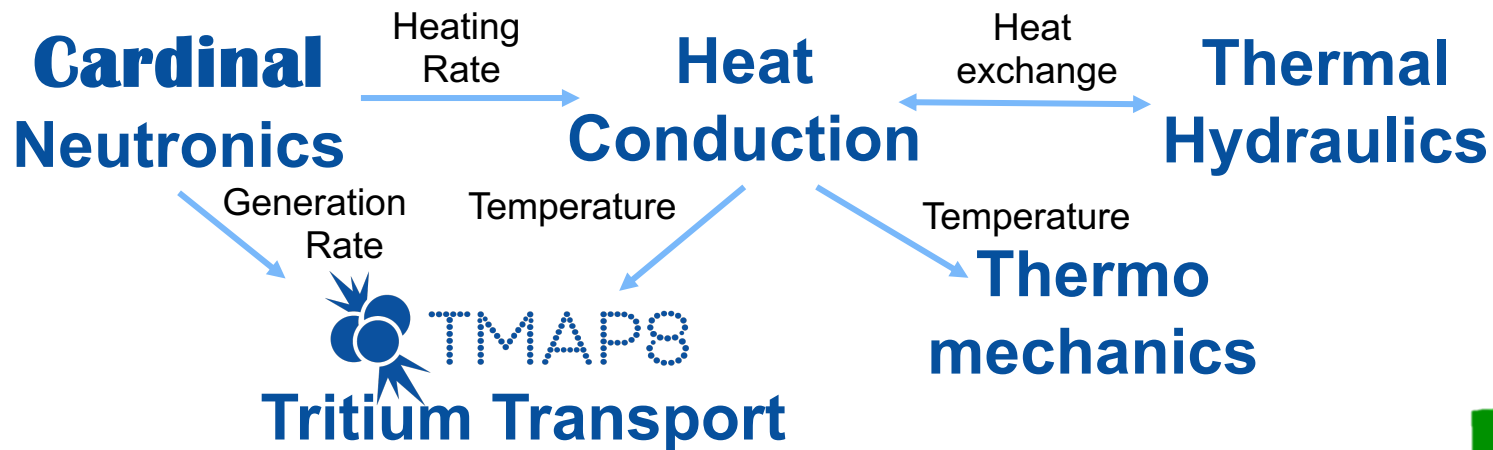
- Implementation of a charge conserving current density scheme is underway [1].
- Verification tests for variational charge conservation are planned.
- Replication of the current density source (left image) using particles and the resulting magnetic field (right image) is planned for demonstration of coupling between the electromagnetics module and particles.



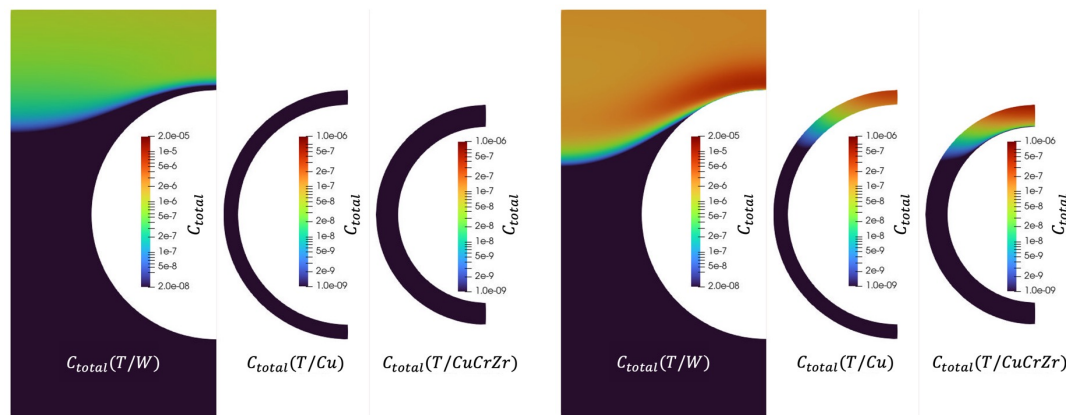
Analytic solution for the magnetic field (left) inside and surrounding a current carrying wire produced by the current density source shown on the right.

<sup>1</sup>Pinto, Martin Campos, et al. "Charge-conserving FEM–PIC schemes on general grids." *Comptes Rendus Mecanique* 342.10-11 (2014): 570-582.

# Multiphysics modeling of a divertor monoblock with FENIX

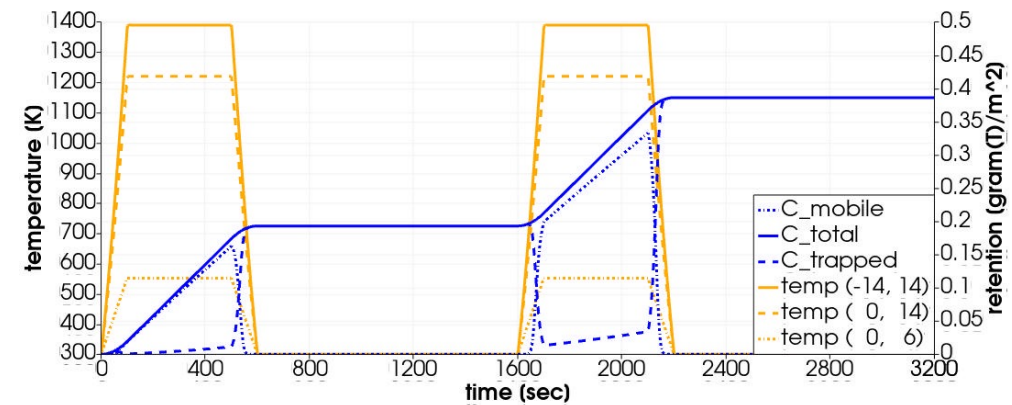
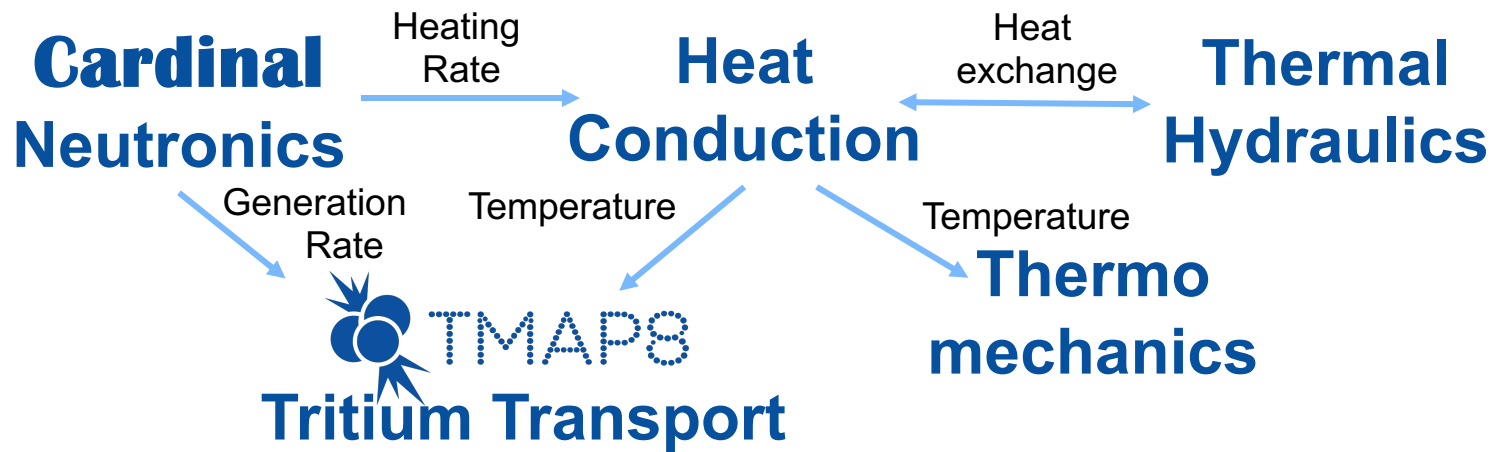


- FENIX enables multiphysics simulation of a divertor monoblock during pulses
- Expanding a case recently published with TMAP8:



Geometry  
ITER-like

# Multiphysics modeling of a divertor monoblock with FENIX



Geometry  
ITER-like



Temperature



Tritium

# Supporting collaborative development through modularity and flexible licensing.

- FENIX is design-agnostic and can be used for a wide variety of systems
- FENIX's follows high software quality insurance
- FENIX, like MOOSE, uses the LGPL 2.1 license, which makes it very flexible

Open collaborations with

universities,  
national laboratories,  
etc.



 **Private FENIX 1**

 **Private FENIX 2**

Private versions developed and controlled by private partners

(local branches can still be private)

# Getting started with FENIX



[FENIX](#)

[Getting Started](#) [Documentation](#) [Software Quality](#) [Help](#) [GitHub](#)

# FENIX

## Fusion ENergy Integrated multiphysi-X (FENIX)

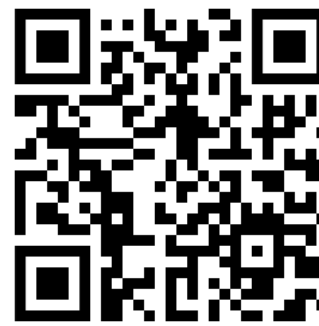
FENIX is designed as an open-source, fully integrated, multiphysics, multiscale, Nuclear Quality Assurance Level 1 (NQA-1) compliant framework facilitating 3D, high-fidelity fusion system modeling.

FENIX is an application based on the [MOOSE framework](#) performing system-level, engineering scale (i.e., at the scale of centimeters and meters), and microstructure-scale (i.e., at the scale of microns) multiphysics calculations related to fusion energy systems. Interfaces to other MOOSE-based codes, including tritium transport ([TMAP8](#)) and neutronics ([Cardinal](#)) are also included to support FENIX simulations.

[Getting Started](#) [Code Reference](#) [Verification, Validation, and Example](#)



## Conclusions



Link to DOE Office of Technology Transition  
talk on FENIX

- MOOSE is a proven system for complex multiphysics analysis to accelerate nuclear research, development, demonstration, and deployment (RDD&D)
- FENIX leverages these capabilities to support high-fidelity, multiphysics modeling of fusion systems
- Open-source enables effective collaborations and promotes inclusion, diversity, and transparency, and a flexible licensing approach enables public-public and public-private partnerships
- We are developing:
  - Flexible plasma kinetics simulations
  - The infrastructure for tightly-coupled multiphysics and neutronics simulations with Cardinal is under development
- Preliminary multiphysics simulations of a divertor monoblock will test multiphysics interactions

# Acknowledgements

- This work was supported through the INL's Laboratory Directed Research & Development (LDRD) Program under DOE Idaho Operations Office Contract DE-AC07-05ID14517.
- This research made use of Idaho National Laboratory's High Performance Computing systems located at the Collaborative Computing Center and supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under Contract No. DE-AC07-05ID14517.



**Check out:**

- 1. PC Simon's talk on IFE chamber dynamics modeling on Tuesday 1:25 PM**
  - 2. Masashi Shimada's talk on Overview of Fusion Safety Program on Tuesday 3:15 PM**
  - 3. Matthew Eklund, talk on MELCOR-TMAP on Wednesday at 10:15**
  - 4. Casey Icenhour's talk on initial development in MOOSE to support fusion magnet modeling and simulation on Wednesday at 2:45 in Assembly**
- And ore talks and posters by Tommy Fuerst, Michael Worrall, and Adriaan Riet.**

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**FENIX**



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