INL/CON-24-77008-Revision-0

Challenging Common Assumptions of Thick-Wall Chamber Dynamics in Inertial Fusion Systems using MOOSE

July 2024

Changing the World's Energy Future

Pierre-Clement A Simon, Mauricio Eduardo Tano Retamales, Nahom Habtemariam, Carlo Fiorina, Susana Reyes

INL/CON-24-77008-Revision-0

Challenging Common Assumptions of Thick-Wall Chamber Dynamics in Inertial Fusion Systems using MOOSE

Pierre-Clement A Simon, Mauricio Eduardo Tano Retamales, Nahom Habtemariam, Carlo Fiorina, Susana Reyes

July 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

July 23, 2024

Pierre-Clément Simon
pierreclement.simon@inl.gov
Nahom Habtemariam, Mauricio E. Tano,
Susana Reyes, Carlo Fiorina

Challenging Common Assumptions of Thick-Wall Chamber Dynamics in Inertial Fusion Systems Using MOOSE

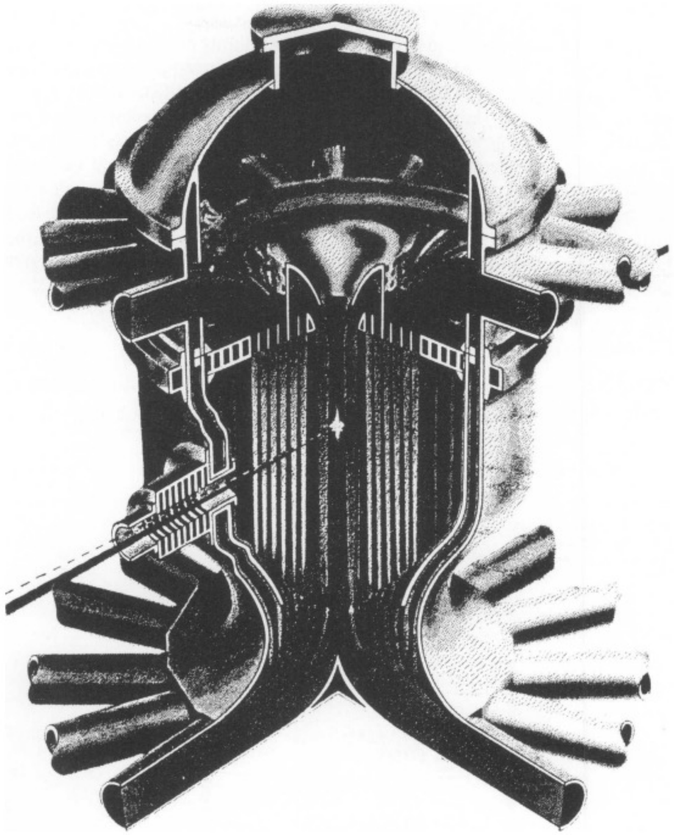
TOFE 2024

Overview

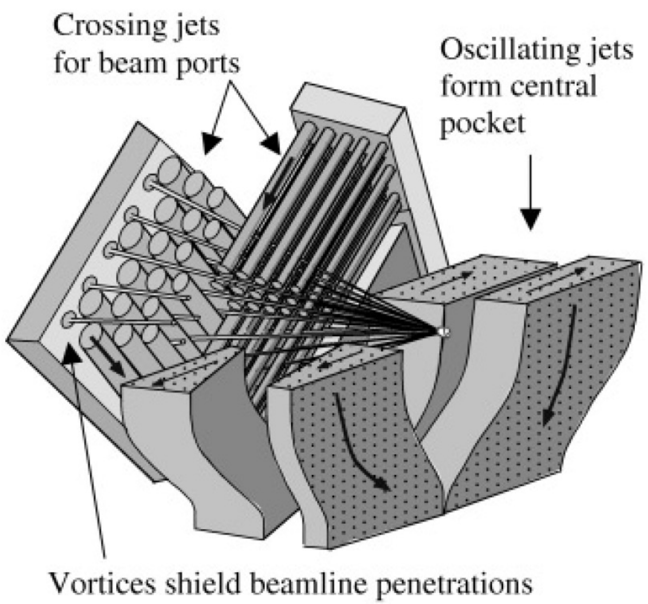
1. The need for thick-wall chamber dynamics modeling for Inertial Fusion Energy
2. Preliminary capability development and benchmarking
3. Reference simulation of thick-wall chamber dynamics in HYLIFE-like design
4. Challenging common assumptions and quantifying their effects
5. Conclusions and future work

Thick-wall chamber design for IFE

- Several companies are developing commercial **Inertial Fusion Energy** (IFE) designs, and there is a pressing need to **understand the physics of thick-wall chamber dynamics**.
- The thick liquid wall approach:
  - reducing the radiation damage rate
  - extending the lifetime of chamber structures
  - increased plant availability and reduced waste streams



HYLIFE-I chamber design.

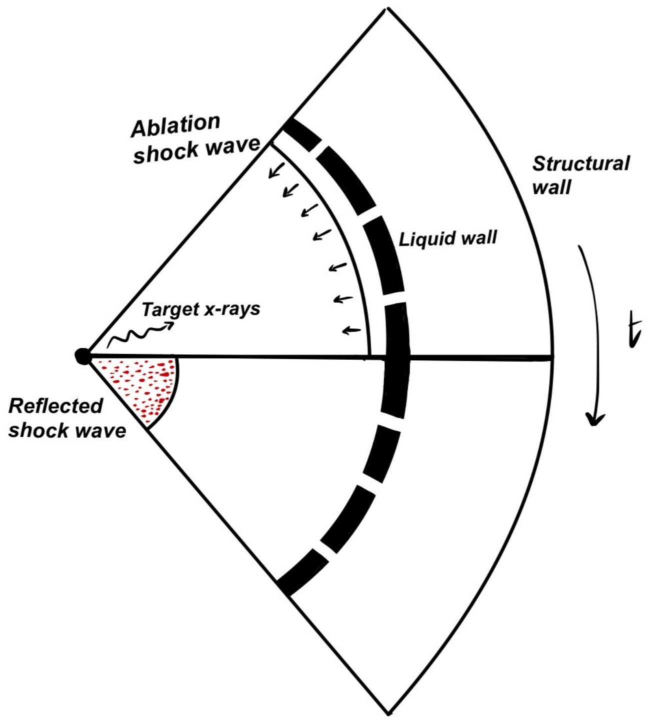


HYLIFE-II chamber design, a fundamentally 3D system.

Raffray et al., Fusion Science and Technology, 49:1, 1-27, 2006
Habtemariam et al., ANS transactions, 2023.

Modeling of post-ignition hydrodynamic phase of thick-wall chamber dynamics

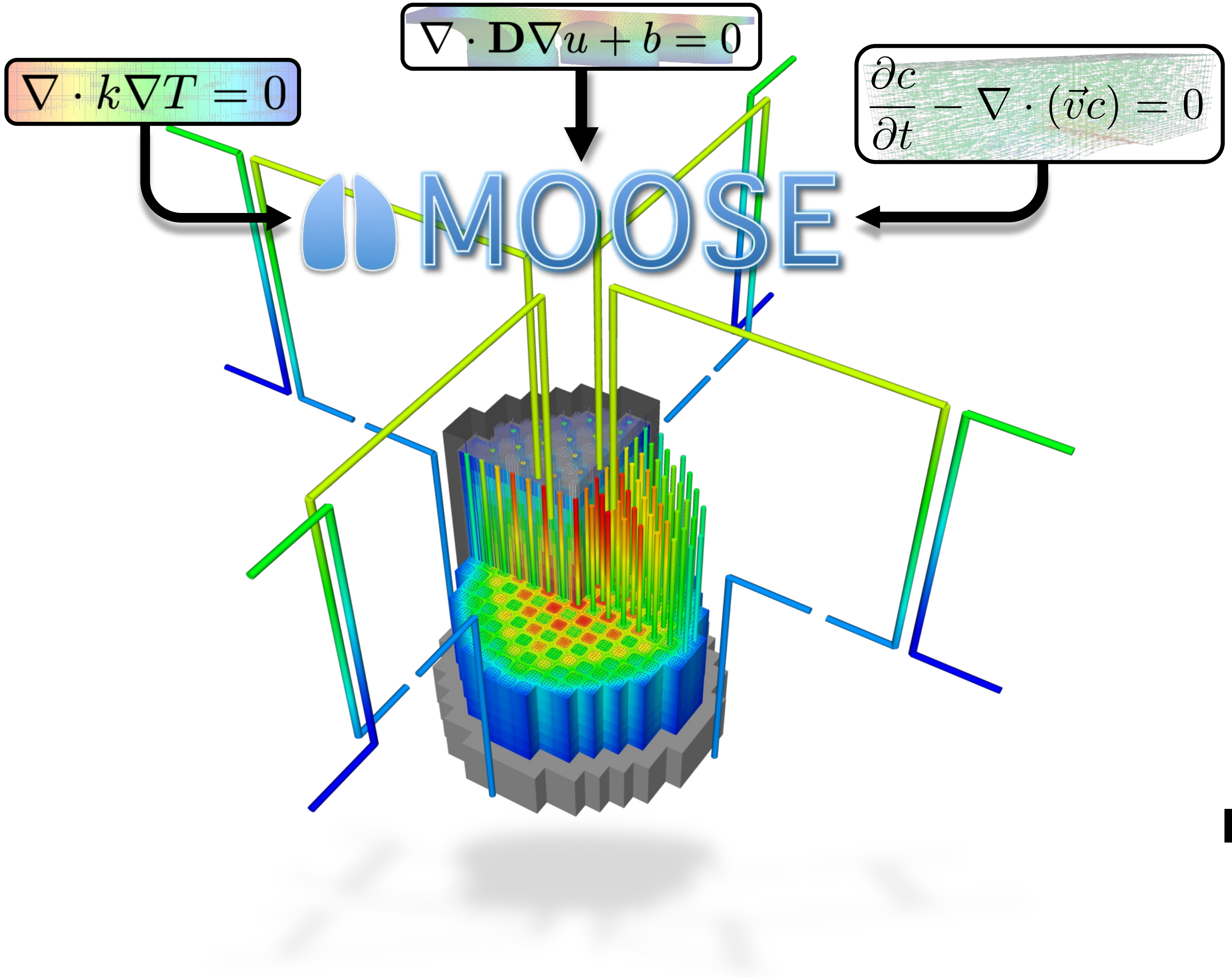
- **Most studies were performed decades ago** with limited computational capabilities and significant assumptions. These modeling results are only partly available, and assumptions have not been re-assessed with modern computational tools and approaches.
- **Common assumptions** include:
  - The IFE designs are modeled as **2D** systems, but many aspects are fundamentally 3D
  - The impact of **radiative heat transfer** is neglected, even at high temperatures.
  - **Ideal gas** behavior is assumed, even for partially ionized gases
  - Jets are assumed to remain **cylindrical**, which can be affected by turbulence, heating, etc.
- These assumptions could be **limiting** and potentially **mislead the design of thick-wall IFE chambers**.



Schematics of the gas dynamics within the chamber

Raffray et al., Fusion Science and Technology, 49:1, 1-27, 2006
Habtemariam et al., ANS transactions, 2023.

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

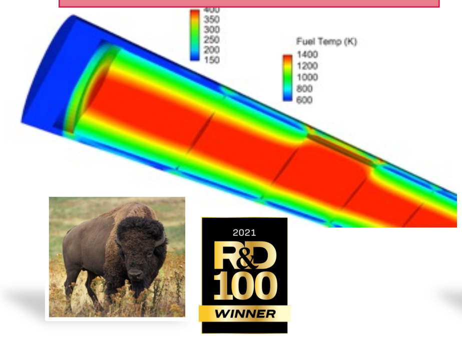
mooseframework.inl.gov

Accelerating Advanced Reactor Deployment

NEAMS

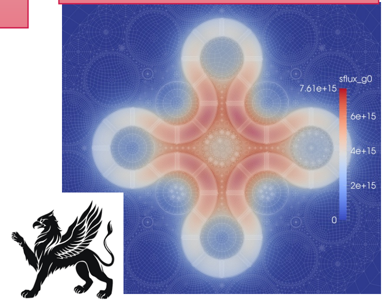
Accelerating Advanced Fission Reactor Deployment

BISON
Nuclear Fuel Performance



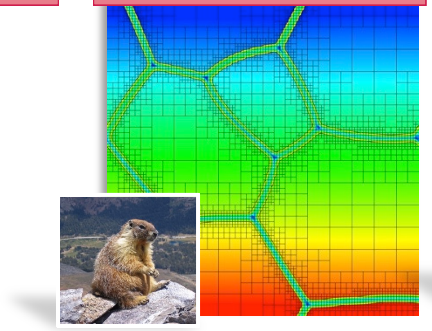
Grizzly
Structural Mechanics for Component Aging

Griffin
Radiation Transport

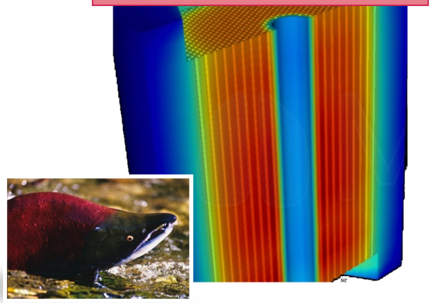


Pronghorn
Medium-fidelity CFD

Marmot
Mesoscale Materials



Sockeye
Heat pipe Simulation



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Kairos Power

RADIANT

Westinghouse

BWXT
Nuclear Energy Canada Inc.

Structural Integrity Associates, Inc.®

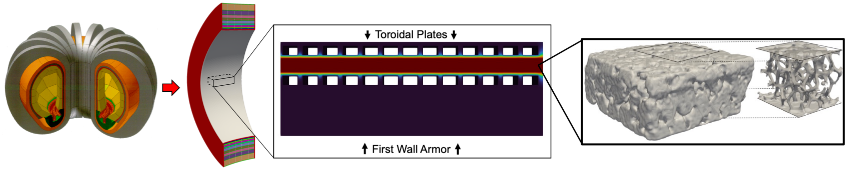
EPRI

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

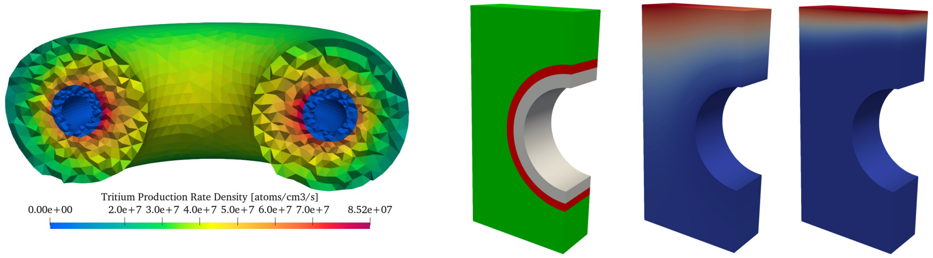
Link to DOE Office of Technology Transition talk

MOOSE-based applications for Fusion

- TMAP8
  - TMAP4 and TMAP7, although widely used, have significant limitations.
  - TMAP8 enables high fidelity, multi-scale, 3D, multiphysics simulations of tritium transport.



- FENIX (Fusion ENergy Integrated multiphys-X)
  - An open-source, fully integrated, multiscale, MOOSE-based framework facilitating 3D, high-fidelity PFC modeling
  - Couples plasma kinetics, neutronics, heat conduction, thermal hydraulics, thermomechanics, and TMAP8

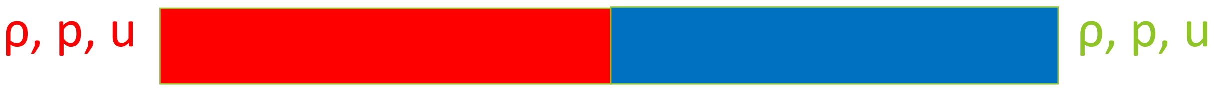


- MOOSE Fusion Module
  - Blanket multiphysics modeling
- These capabilities are open-source, Nuclear Quality Assurance level 1 compliant, offers user support and massively parallel capabilities.

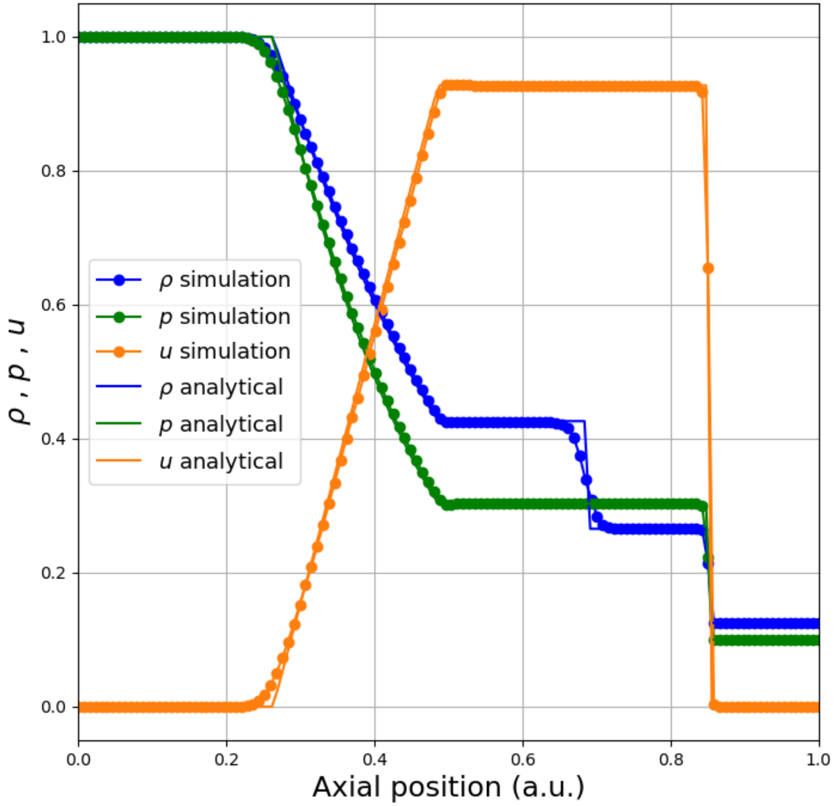
See Casey Icenhour's talk on initial development in MOOSE to support fusion magnet modeling and simulation on Wednesday at 2:45 pm in Assembly

Preliminary capability development and benchmarking

- Sod-Shock tube case

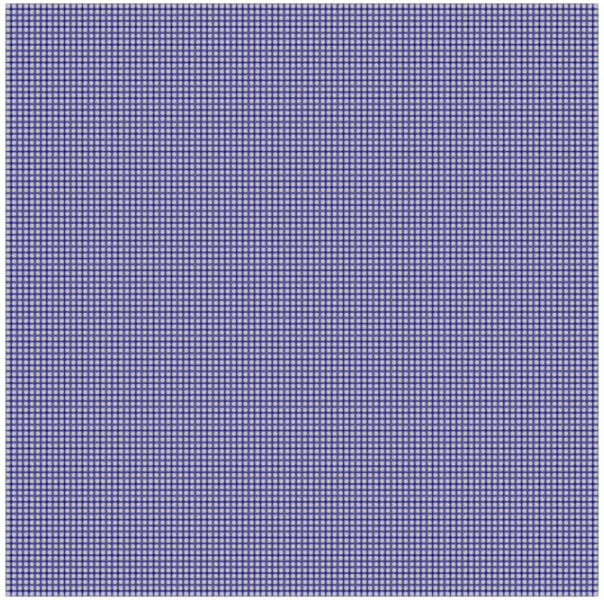


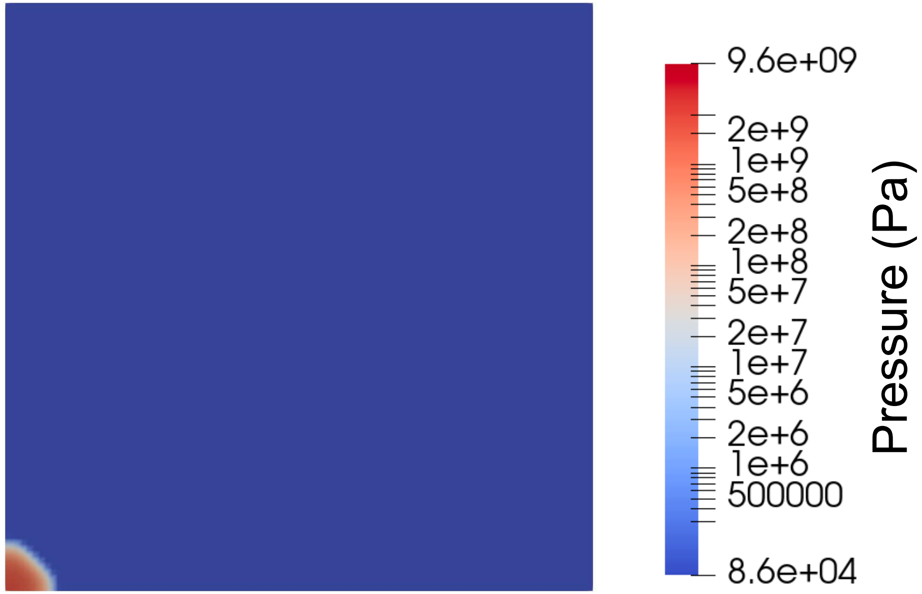
- The simulation results match the analytical solution



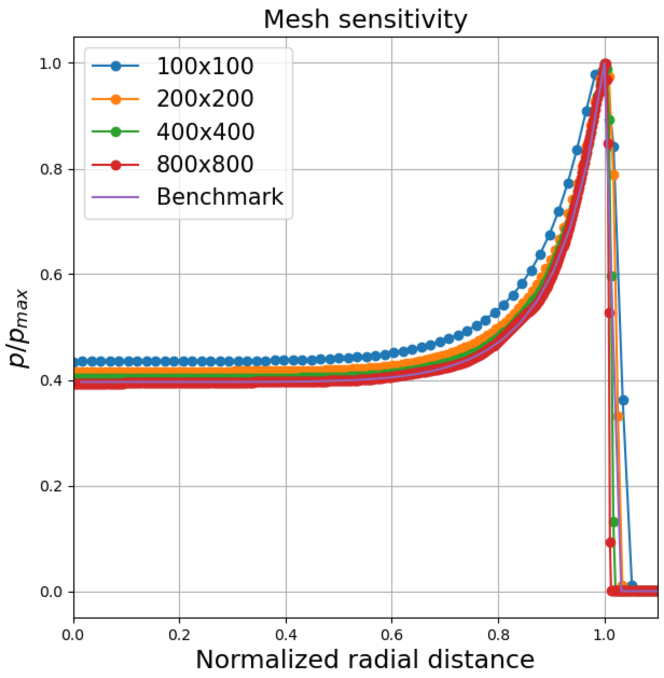
Preliminary capability development and benchmarking

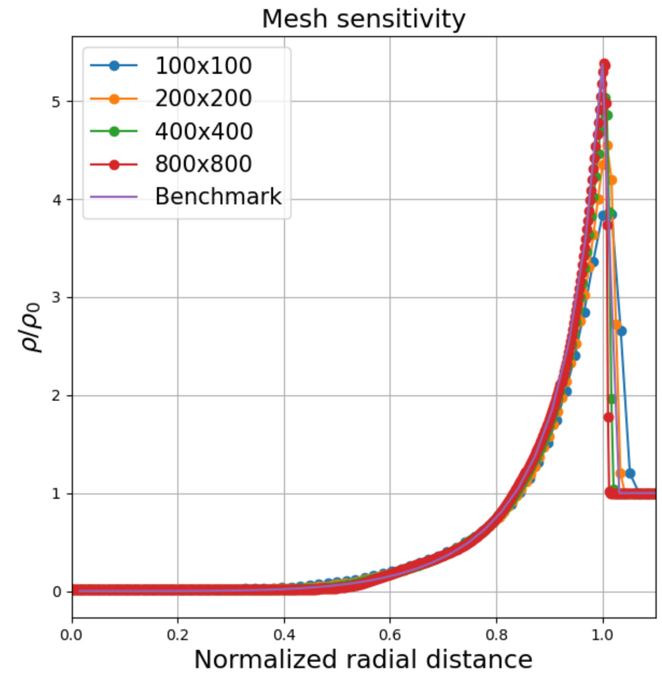
- Cylindrical Sedov blast-wave





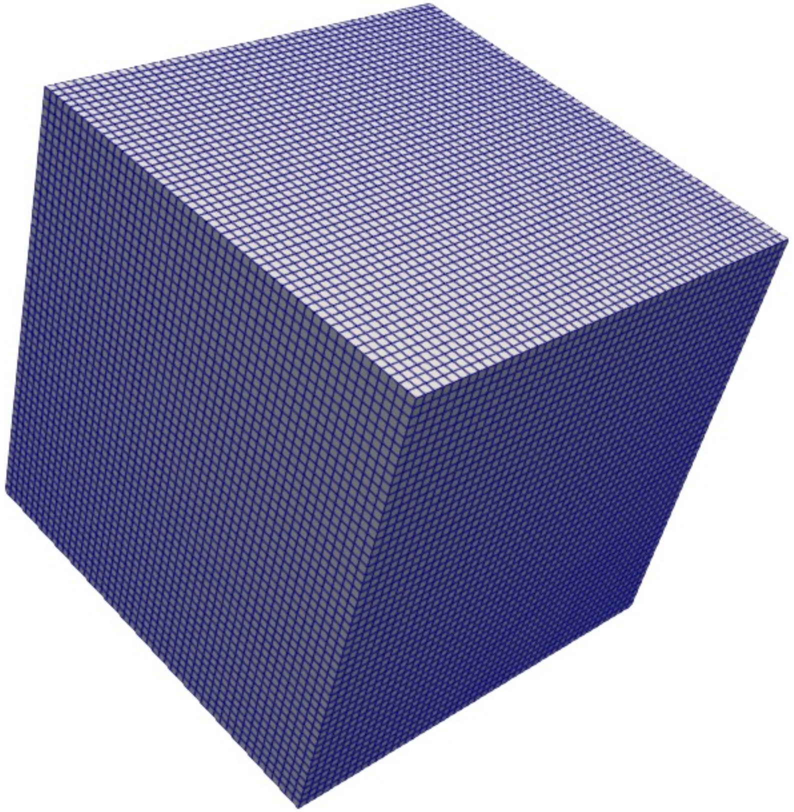
- The simulation results match the analytical solution

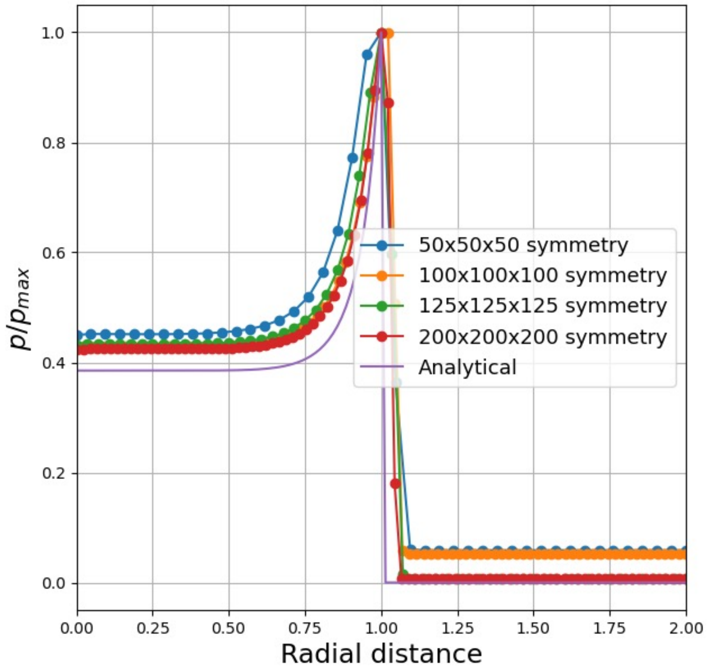


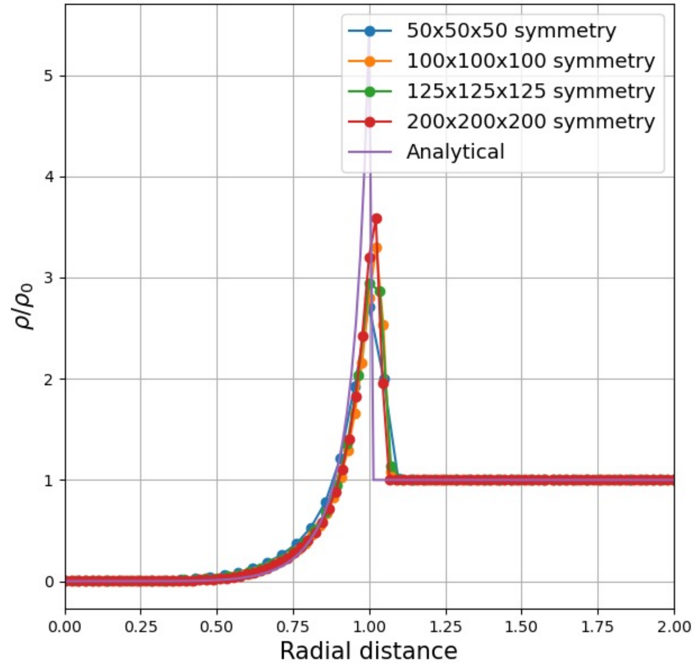


Preliminary capability development and benchmarking

- Spherical Sedov blast-wave



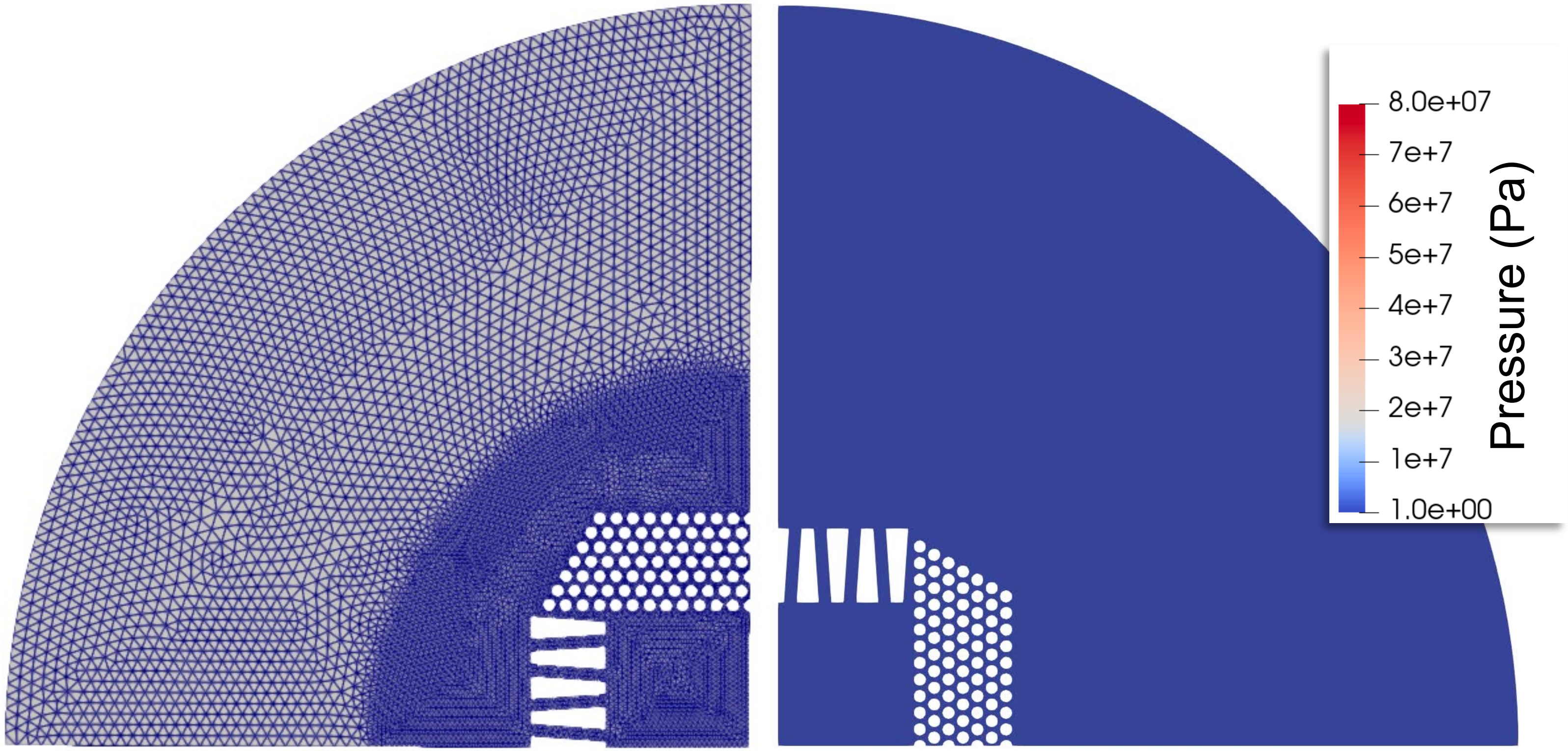


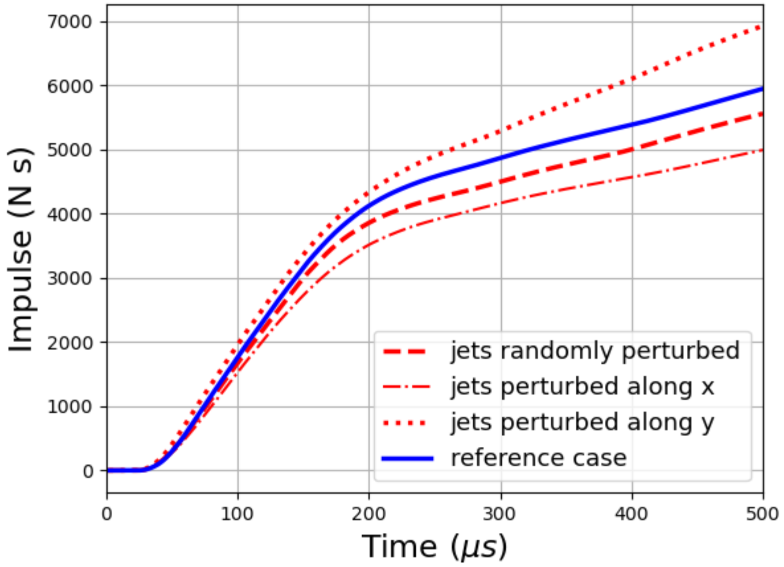


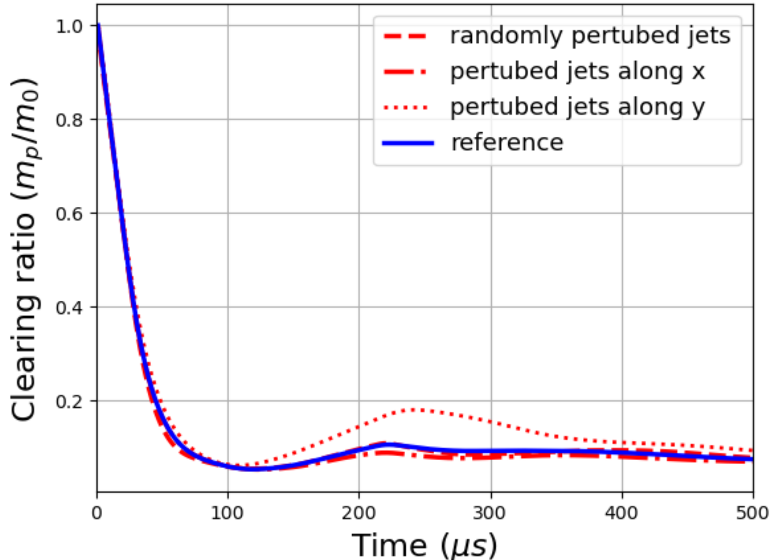
- A finer mesh leads to a better match between the simulation prediction and the analytical solution

Reference simulation with common assumptions

- Initial conditions from Glenn (linearly extrapolated from HYLIFE-I based on lower yield)
- Engineering metrics: Momentum transferred to jets, and mass clearance
- This forms the bases to quantify the effect of each

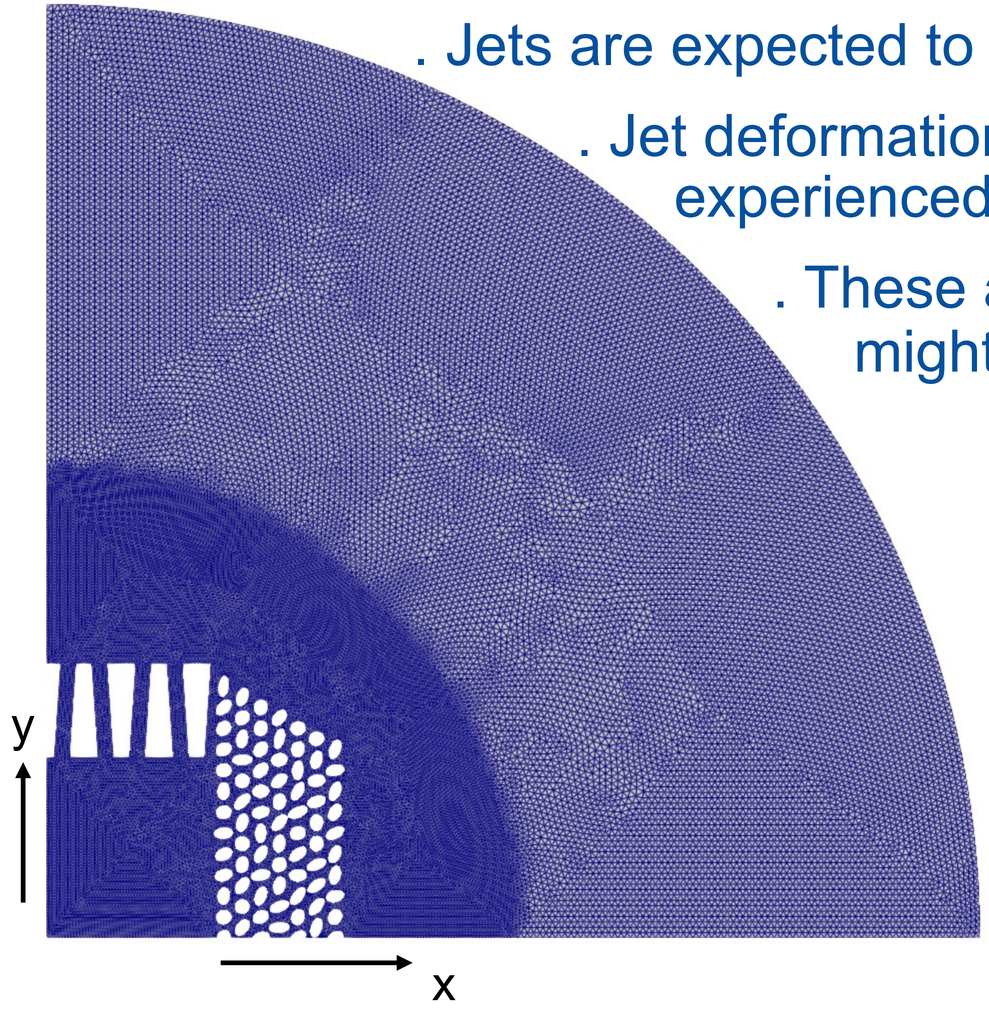


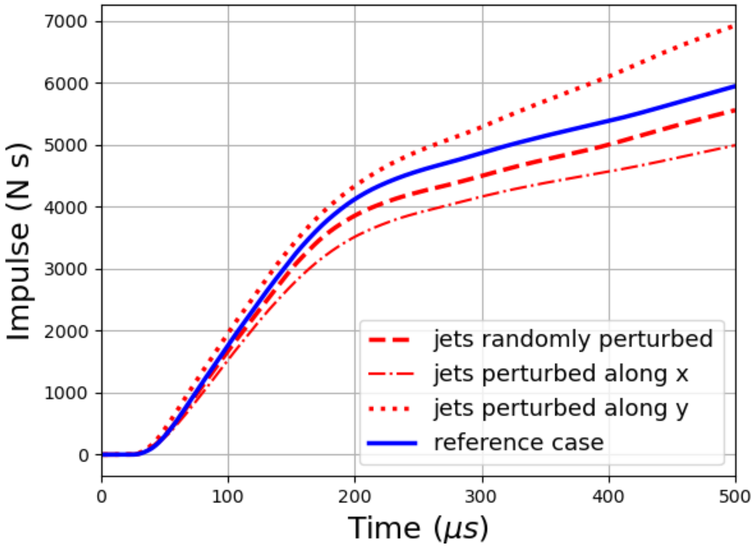


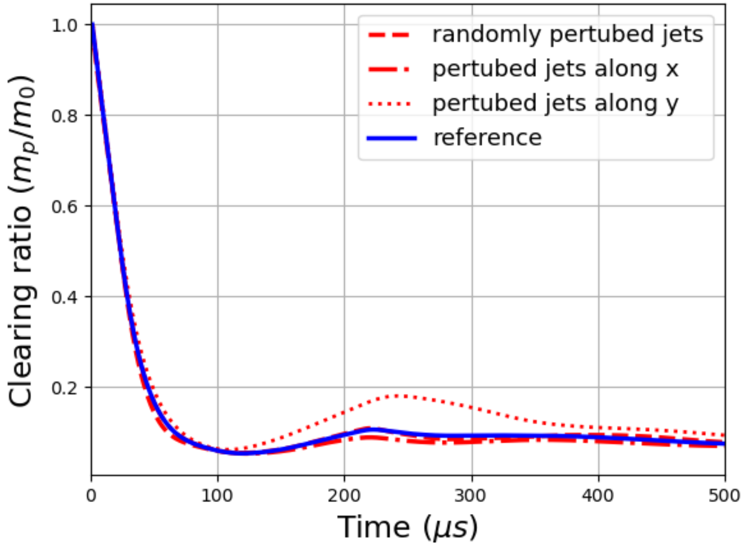


Effect of jet deformation

- Jets are expected to deform due to turbulence, heating, etc.
- Jet deformation does not significantly impact the force experienced by the jets (in 2D, with random deformation)
- These are just preliminary results, but jet deformation might not have a large impact.

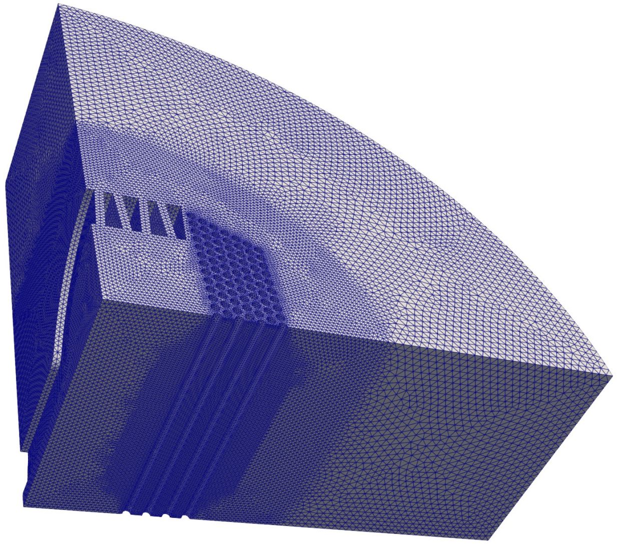


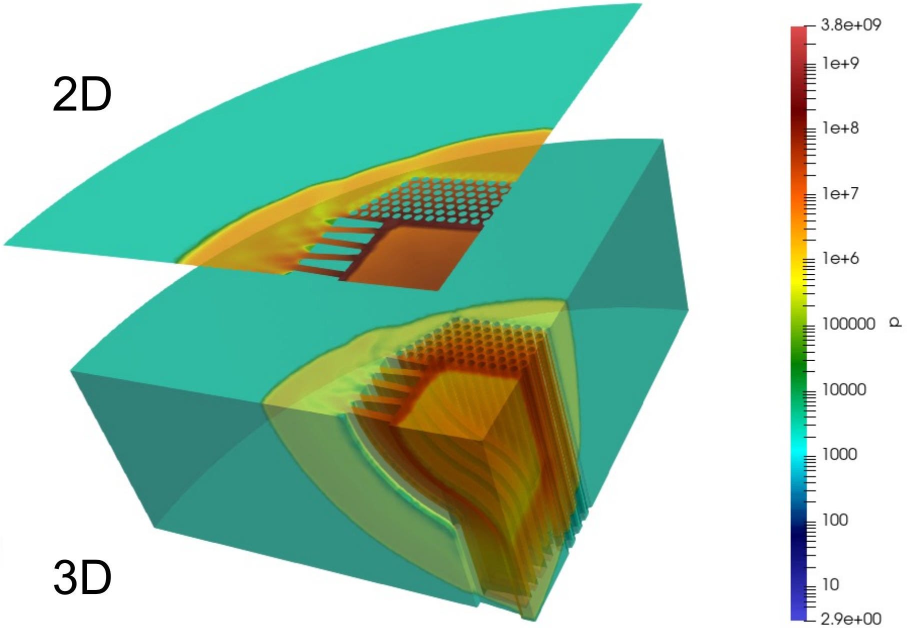


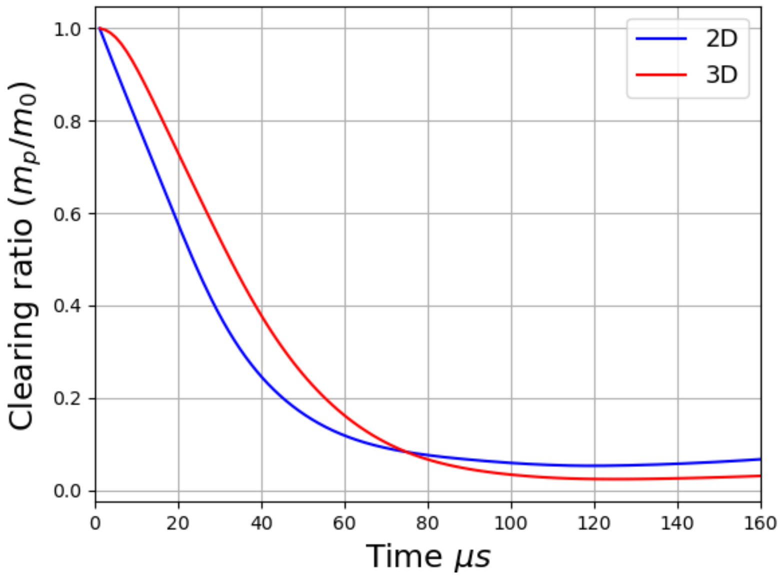


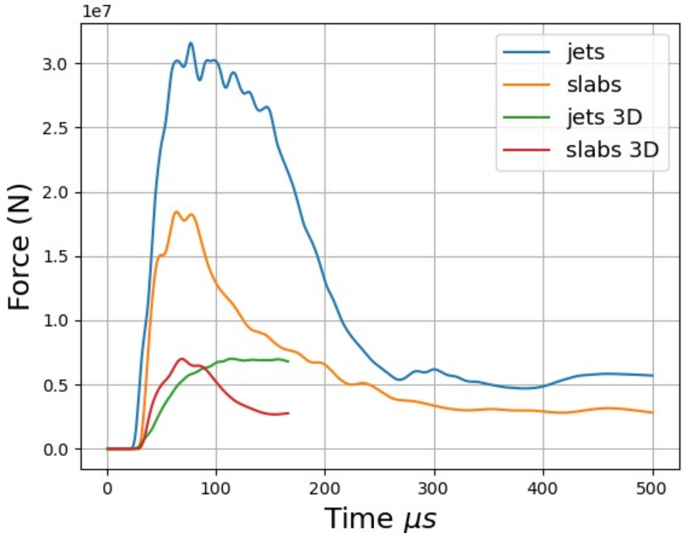
Three dimensional effects

- Many features of the thick-wall chamber designs are fundamentally 3D – the blast itself is spherical
- The calculated force in 3D are smaller than for the 2D simulations
- These results suggest that 3D simulations lead to lower engineering constraints.



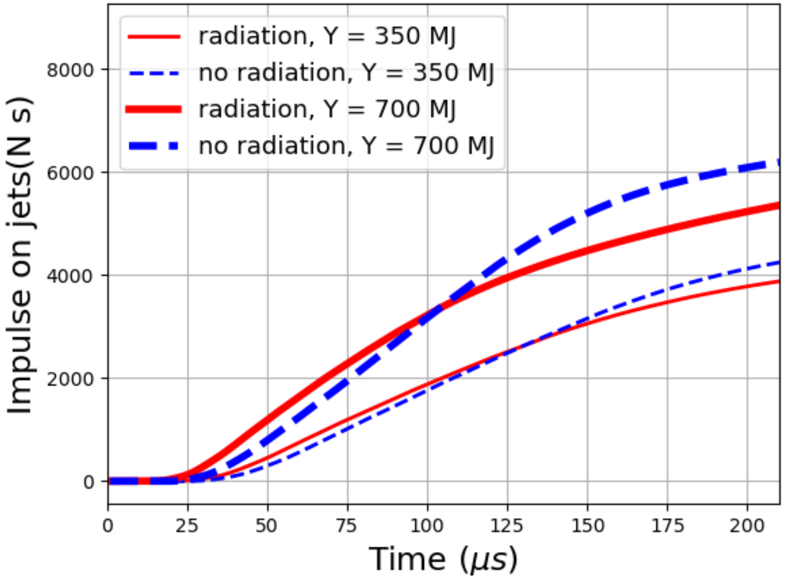


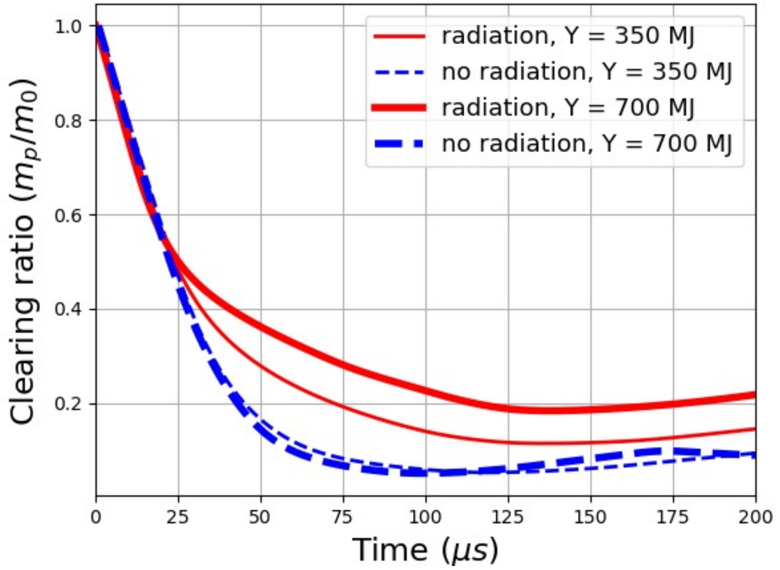




The impact of radiative heat transfer (P1)

- Radiative heat transfer is expected to contribute to energy dissipation and reduce engineering constraints
- Simulations at higher yield utilize a linear extrapolation of the initial condition
- The effect of radiative heat transfer is higher at higher yields
- Clearing seems to be slower when accounting for RHT





- Accounting for radiative heat transfer could affect engineering conclusion

Conclusions and future work

- MOOSE was used to model the hydrodynamic phase of the post-ignition physics in thick-wall chambers
- The different assumptions were tested using new MOOSE capabilities
  - Jet deformation might not significantly affect chamber dynamics
  - 3D simulations reduce some of the engineering constraints
  - Radiative heat transfer can help dissipate energy at higher yield
  - An appropriate equation of state is expected to provide more accurate results
- Future work:
  - Study the impact of ideal gas assumption
  - Study interactions between different phenomena currently studied independently
  - Expand current approaches and challenge remaining assumptions
  - Improved initial conditions
  - Use these capabilities for design and engineering of thick-wall IFE chambers
  - Code validation
  - Upload cases to Virtual Test Bed

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.

Pierre-Clément (PC) Simon, Ph.D.
pierreclement.simon@inl.gov