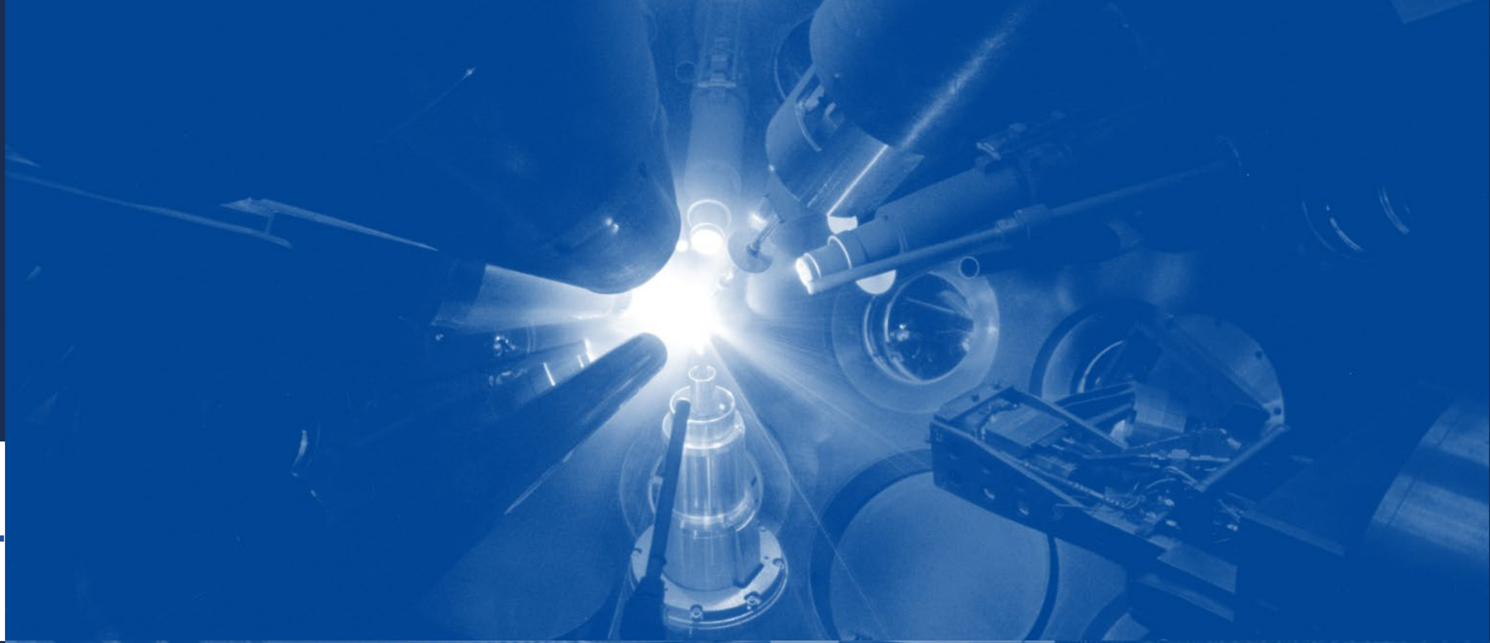
Numerical modeling of innovative fusion concepts within the BETHE program



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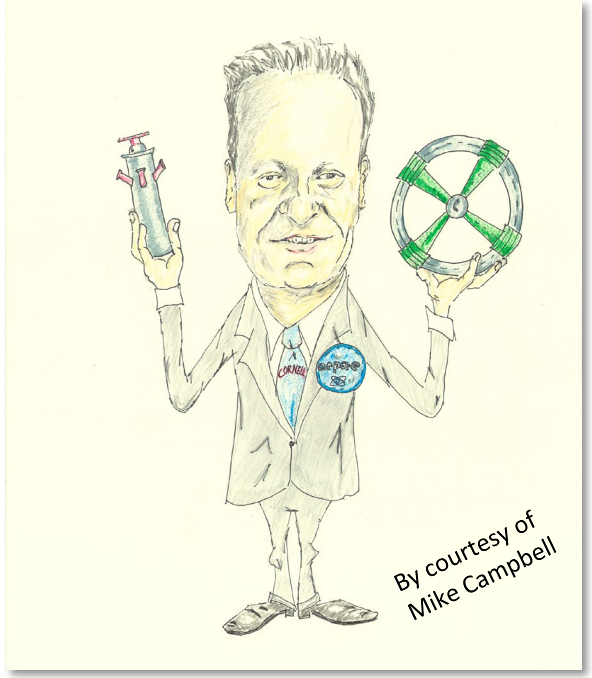
Flash Center for Computational Science
Department of Physics and Astronomy
Laboratory for Laser Energetics
University of Rochester

64th Annual Meeting of the APS DPP

Spokane, WA, 10/18/2022

Summary

- Computer simulations are **indispensable tools** in the development of any innovative fusion scheme, from the formulation of a new concept to prototype design, data interpretation, and reactor scale modeling.
- We have assembled a **theory/modeling capability team** at the University of Rochester to provide, under the auspices of the DOE ARPA-E BETHE program, **simulation support** for concept teams, and **independent assessment** of the physics underlying leading fusion concepts.
- We discuss the suite of simulation codes we use in this effort – **fluid, hybrid, and kinetic**, and how they are applied to model a broad range of fusion concepts, from Plasma-Jet-Driven Magneto-Inertial Fusion (**PJMIF**), to Field-Reversed Configurations (**FRC**) and the staged Z-pinch (**SZP**).
- We showcase a model of engagement that **bridges academic teams with national lab and industry partners**, providing the latter with sustained state-of-the-art capabilities and forging long-lasting collaborative efforts.



Meet the Team at the University of Rochester!

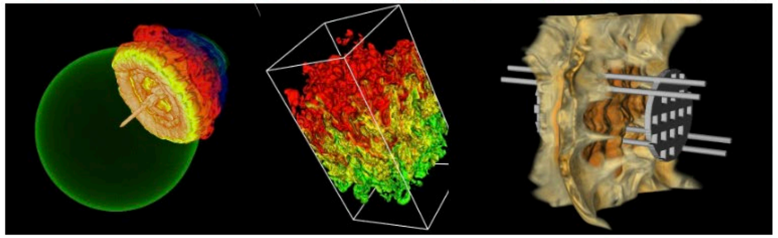
- Petros Tzeferacos - PI, project lead, FLASH lead
- Adam Sefkow - co-PI, TriForce lead
- Chuang Ren - co-PI, OSIRIS lead
- Riccardo Betti - co-PI, theory & simulations support
- Jonathan Davies - co-PI, theory & liaison
- Han Wen - Scientist, OSHUN & OSIRIS
- John Shaw - Scientist, TriForce
- Robert Masti - Postdoc, TriForce
- Eddie Hansen - Postdoc, FLASH
- David Michta - Postdoc, FLASH
- Fernando García-Rubio - Postdoc, theory
- Ka Ming (Jack) Woo - Postdoc, theory & simulations

Charge:

1. Carry out simulations for Concept Teams;
2. Independent simulations of key fusion Concepts;
3. Assist Teams in the use of simulation codes;
4. Modest development to enhance fidelity.

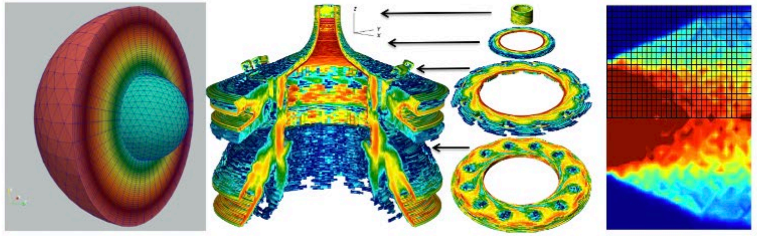
UR Theory & Modeling Capability Team provides simulation support for Concept Teams and assesses leading Concepts

FLASH code



Multi-physics AMR MHD code for HEDP and plasma astrophysics https://flash.rochester.edu

TriForce



Meshless fluid/kinetic hybrid simulation tool
https://hajim.rochester.edu/me/sites/sefkow/about/index.html

OSIRIS

Fully relativistic, massively parallel PIC code
https://picksc.idre.ucla.edu

Codes	**FLASH, TriForce, OSIRIS**
Physical models used	**Fluid, hybrid, and kinetic simulations** **FLASH** is a finite-volume Eulerian, radiation extended-MHD code with extensive HEDP capabilities. **TriForce** is a C++ framework for open-source, parallel, multi-physics, 3D, particle-based hybrid fluid-kinetic simulations. **OSIRIS** is a massively parallel, fully relativistic PIC code with binary collisions and a QED module.
Fusion concepts/types that can be modeled	MIF, ICF, MCF, with an emphasis on laser-driven and pulsed-power-driven plasma and fusion experiments.
Key physical processes that can be modeled	Multi-temperature hydro & MHD, SPH, EM-PIC, heat exchange & transport (local/non-local), radiation transport, laser deposition, extended MHD (full Braginskii), multi-material EoS and opacities, material properties, nuclear physics, burn, gravity, self-gravity, EM solvers, current circuit, QED, synthetic diagnostics.
Dimensionality	1D, 2D, 3D simulations in multiple geometries.
Meshing details	**FLASH:** Block-structured (oct-tree) adaptive mesh refinement (AMR) and uniform grids. **TriForce:** Meshless approach for fluid dynamics and Lagrangian particle-based description – integration of nonpolar geodesic polyhedral, as well as rectangular and triangular AMR. **OSIRIS:** EM-solves on a Cartesian mesh with advanced dynamic load balancing.
Scalability and portability	All three codes are high-performance computing (HPC) codes that scale well on > 100,000 cores, on modern architectures. This is achieved through MPI, threading, vector parallelism, and GPU accelerators to optimally utilize compute resources.

Supported fusion concepts

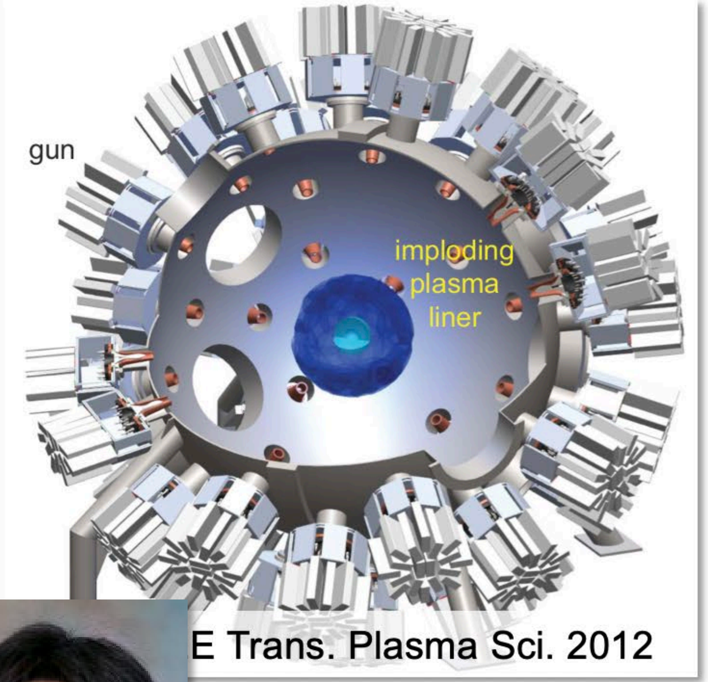
PLX device at LANL

Princeton Field Reversed Configuration device, the PFRC-2

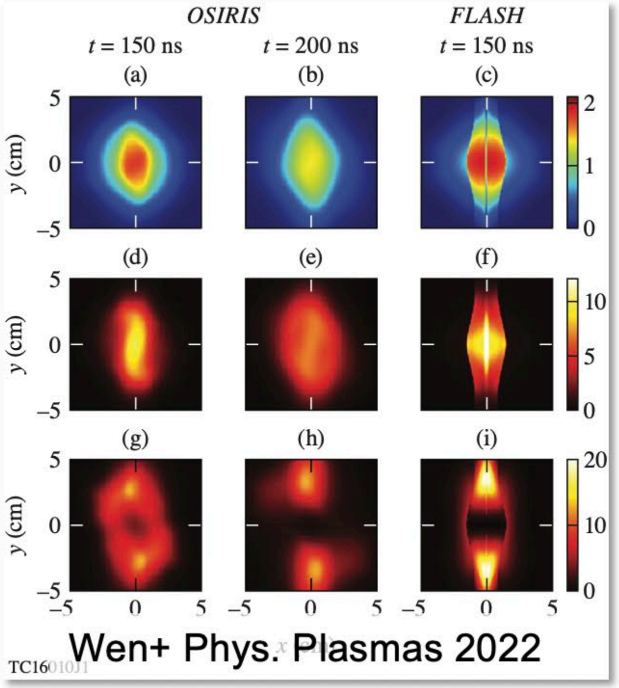
Staged Z-Pinch concept of MIFTI

- Partner and engage with ARPA-E-supported concept teams that focus on Plasma-Jet-Driven Magneto-Inertial Fusion **(PJMIF)**, Field-Reversed Configurations **(FRC)**, and the staged Z-pinch **(SZP)**.

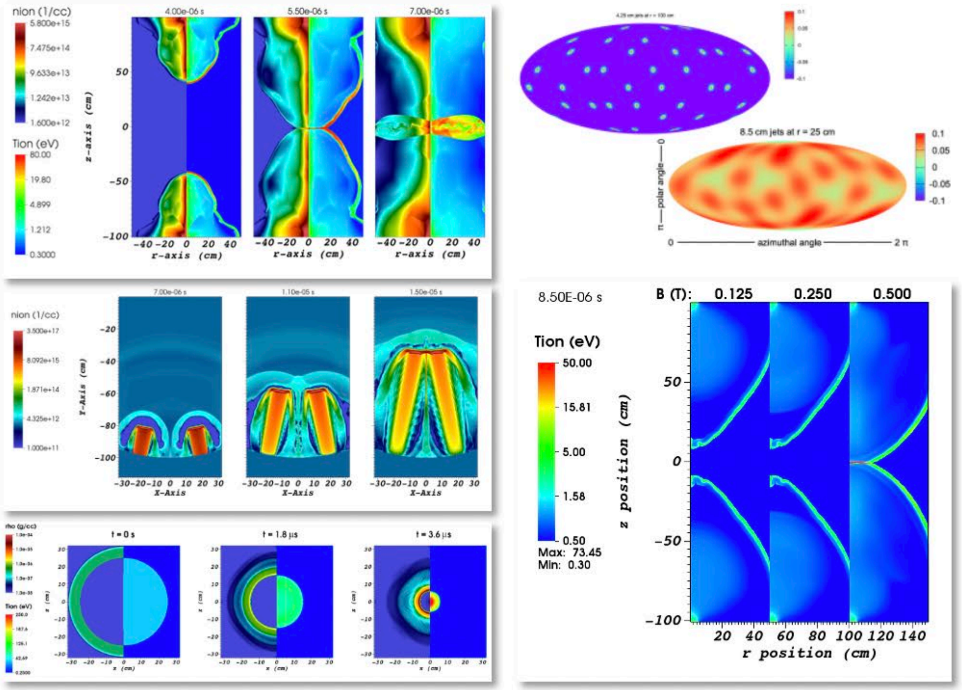
PLX @ LANL – PJMIF *ab initio* simulations

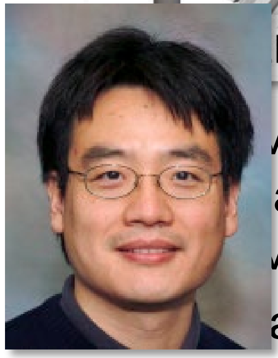


E Trans. Plasma Sci. 2012



Wen+ Phys. Plasmas 2022





Chuang Ren
M: BP11.00118

...vide simulation support for the PJMIF project at **LANL**, the Plasma Liner Experiment (**PLX**). The ...am explores magneto-inertial fusion through the concept of a **spherically imploding plasma liner**, via the **merging of plasma jets** launched by a spherical array of **plasma guns**.

...and OSIRIS simulations of the target formation indicate that a **strongly magnetized plasma** regime ...00−1000 (electron Hall), $\chi_i \approx$ 1−10 (ion Hall), and $\beta \le 1$ (plasma beta) can be achieved. We are ...ing concerted **FLASH and OSIRIS** simulations to **model all phases** of the experiment, from the ab-initio target and liner formation to the composite fuel implosion.

PFRC @ PPPL – FRC full device simulations

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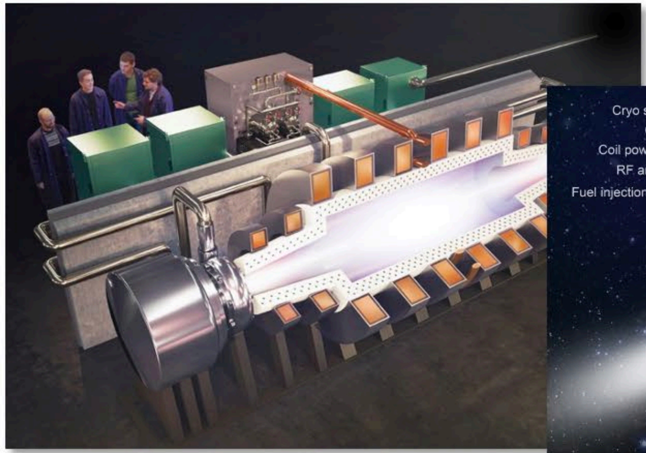
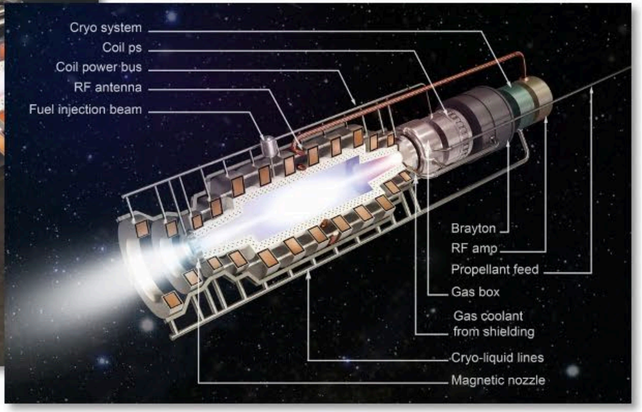
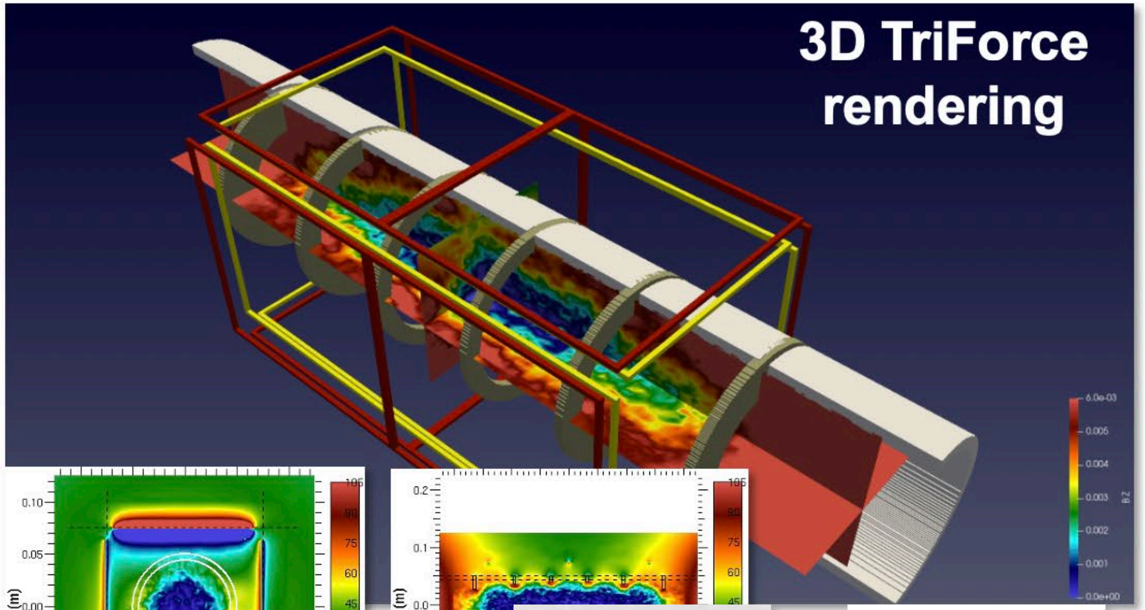
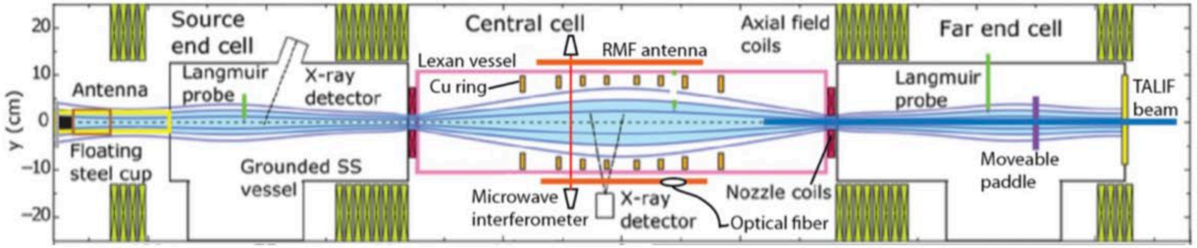


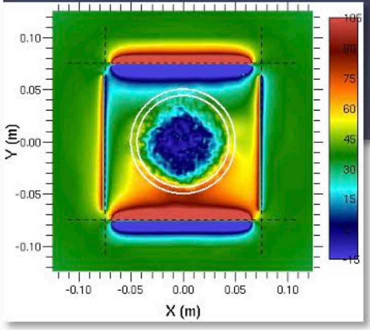
FRC rocket engine

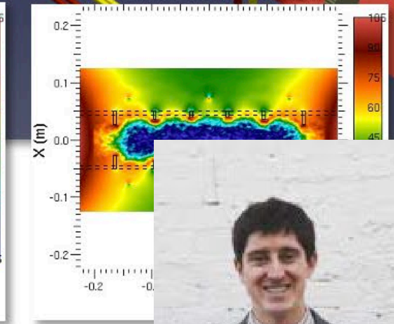


FRC fusion reactor









Re

B_z

Mike Lavell
M: BO03.00012

Ayden Kish
M: BO03.00011

- The team is providing simulation support to the **Princeton Field-Reversed** … **ions** … m (FRC with RMF-o) at Princeton (PI Sam Cohen). The **TriForce** team memb… …rking …th **PPPL** to test the algorithms in TriForce for very long timescale FRC simulation…
- TriForce is undergoing **development and benchmarking efforts** to rep… …viou… PFRC particle-in-cell results and will now be employed to help the effort… …ng i… **the PFRC-2 device**.

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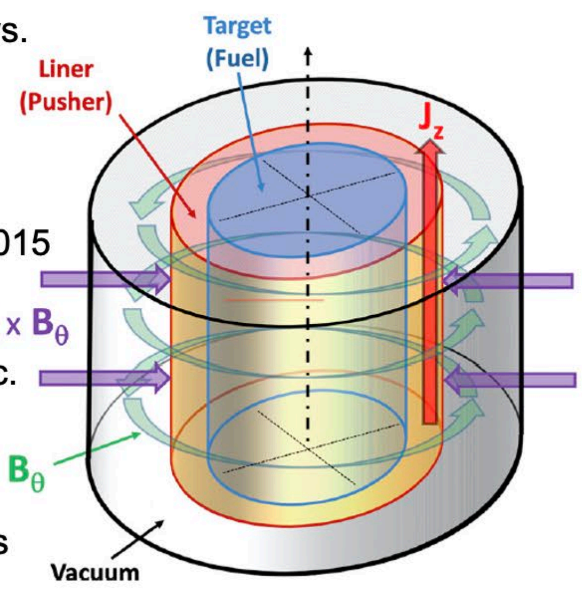
SZP @ MIFTI – Feasibility study

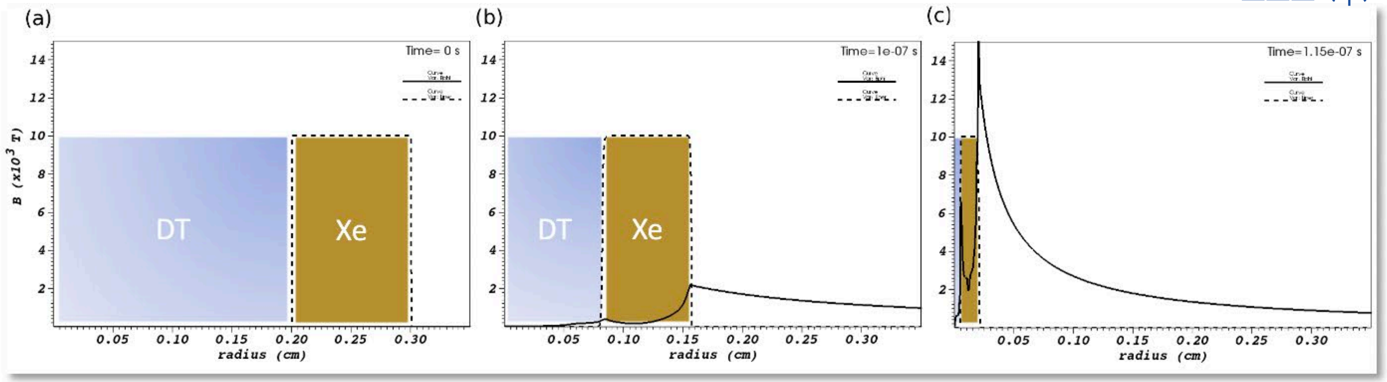
Rahman+
J. Plasma Phys.
2009

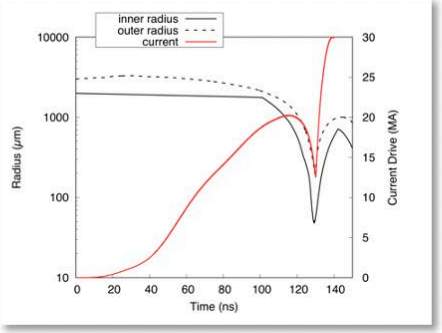
Wessel+
IEEE Trans.
Plasma Sci. 2015

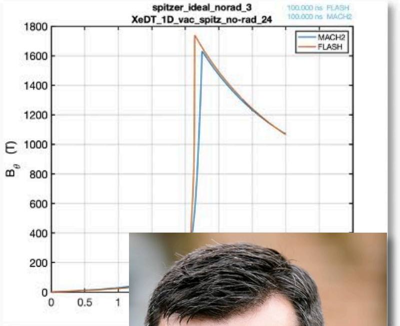
Wessel+
AIP Conf. Proc.
2016

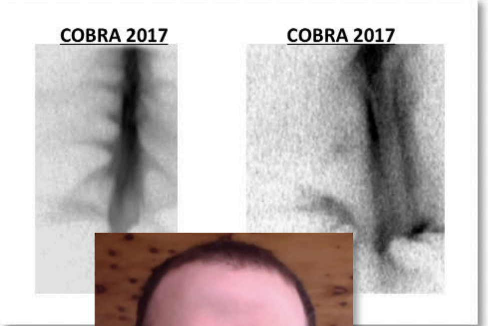
Ruskov+
Phys. Plasmas
2020





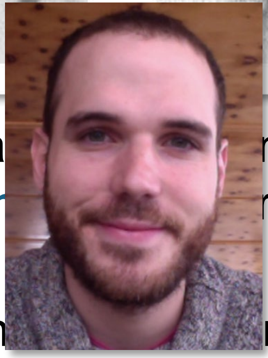






- The team is providing simulation support to **MIFTI**. The SZP concept e… the tra… nch to overcome the deleterious effects of MRTI. MIFTI's SZP uses a **high a… ber lin…** ress a fusion fuel, **shock-aided** to to reach fusion-relevant conditions.
- New code development in **FLASH** includes implicit anisotropic magn… vity an… model (McBride+ 2010) making the code highly suitable for Z-pinch simulation… con… **1D code-to-code comparisons of FLASH and MACH2** using anal… blem… physics Z-pinch models (Hansen+ in preparation) to **assess the feasibility of the concept**.

Eddie Hansen
F: YO04.00004



Fernando Garcia-Rubio
W: NO04.00012

Sustained partnerships through INFUSE and paradigm expansion for LaserNetUS

INFUSE Innovation Network for Fusion Energy

FLASH CENTER

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"**3D modeling of the Staged Z-pinch with the FLASH code**" will expand FLASH's capabilities to execute high-fidelity, three-dimensional FLASH simulations of various SZP configurations, in collaboration with MIFTI.

MIFTI

"**Stabilizing PFRC plasmas against macroscopic low-frequency modes**" will allow PPPL and University of Rochester staff to set up and perform needed simulations of PFRC-2 using TriForce.

PPPL PRINCETON PLASMA PHYSICS LABORATORY

"**Simulating RF antenna designs for PFRC plasma heating and sustainment**" will allow PPPL staff to use TriForce simulations to help analyze RF antenna performance parameters critical to the viability of PFRC-type fusion reactor designs.

PPPL PRINCETON PLASMA PHYSICS LABORATORY

The SimNet Executive Committee is the newest addition to LaserNetUS

LaserNetUS

Charter of SimNet

"We aspire to make the LaserNetUS Simulation Group (SimNet) an organization that will assist LaserNetUS researchers in ***computational tools*** *and in* ***establishing connections*** *among researchers and simulation teams to design, execute, and interpret experiments carried out at LaserNetUS facilities."*

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Project impact

- Numerical simulations are critically important for the design and interpretation of Innovative innovative fusion schemes. However, **establishing adequate simulation capabilities** for new fusion concepts can easily be **more expensive** and **time-consuming** than building the first experiment.

- The Simulation Resource Team overcomes this “entry-barrier” in a **cost-effective manner** by developing a flexible, multi-purpose, multi-physics simulation capability suitable for many innovative fusion concepts.

- The **broad availability** of the simulation codes involved and the **training** the Simulation Resource Team provides ensures a **sustainable simulation resource**, for the ARPA-E BETHE Program and beyond, to enable **novel disruptive technologies**.

We acknowledge support from the U.S. DOE ARPA-E under Award No. DE-AR0001272, the U.S. DOE SC/FES under Award No. DE-SC0017951 and DE-SC0021990, and the U.S DOE NNSA under Award No. DE-NA0003856 and DE-NA0003842, and Subcontract No. 536203 and 630138 (LANL) and B632670 (LLNL). We thank the UCLA-IST Consortium for the use of OSIRIS.