A Simulation Resource Team for Innovative Fusion Concepts in the BETHE program

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Abstract

Computer simulations are indispensable tools in the development of all areas of science and engineering. For any innovative fusion scheme, simulations are essential to help **interpret data** and to extrapolate from the first experiments to a **prototype design.**

Here we present a project that assembles **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 theoretical analysis of the physics underlying leading Concepts.

We discuss the suite of simulation codes – fluid, hybrid, and kinetic – we use in this effort, and how they are applied to engage with Concept Teams that focus on **Plasma-Jet-Driven Magneto-Inertial Fusion (PJMIF), Field-Reversal Configurations (FRC)**, and the **staged Z-pinch (SZP).**

The codes central to this project are **FLASH, TriForce, and OSIRIS**, chosen because they are flexible, high-performance computing codes, capable of one-, two-, and three-dimensional simulations, and can be used by Concept Teams to sustainably continue their modeling efforts. The Capability Team also leverages OSHUN, a Fokker-Planck code to develop models of magnetized transport.

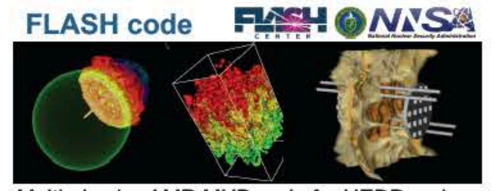
Meet the Team at the University of Rochester!

- **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.**

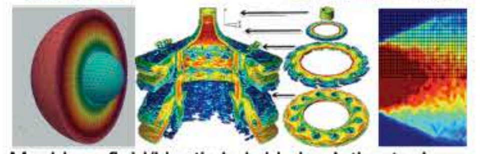
UR Theory & Modeling Capability Team provides simulation support for Concept Teams and assesses leading Concepts

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

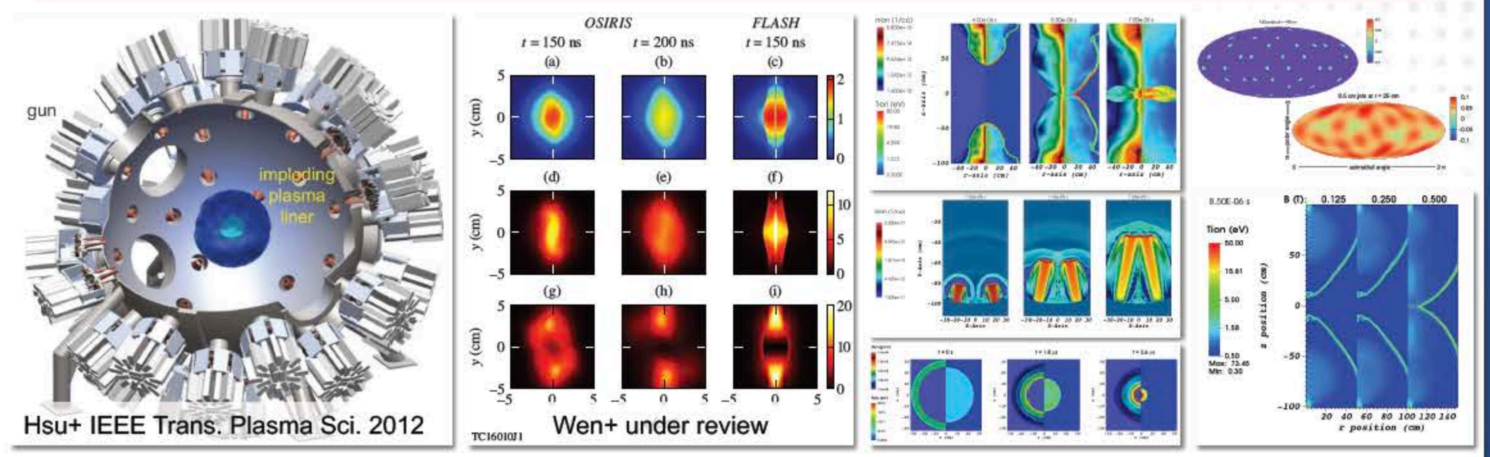
PLX device at LANL

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-Reversal Configurations **(FRC)**, and the staged Z-pinch **(SZP)**.

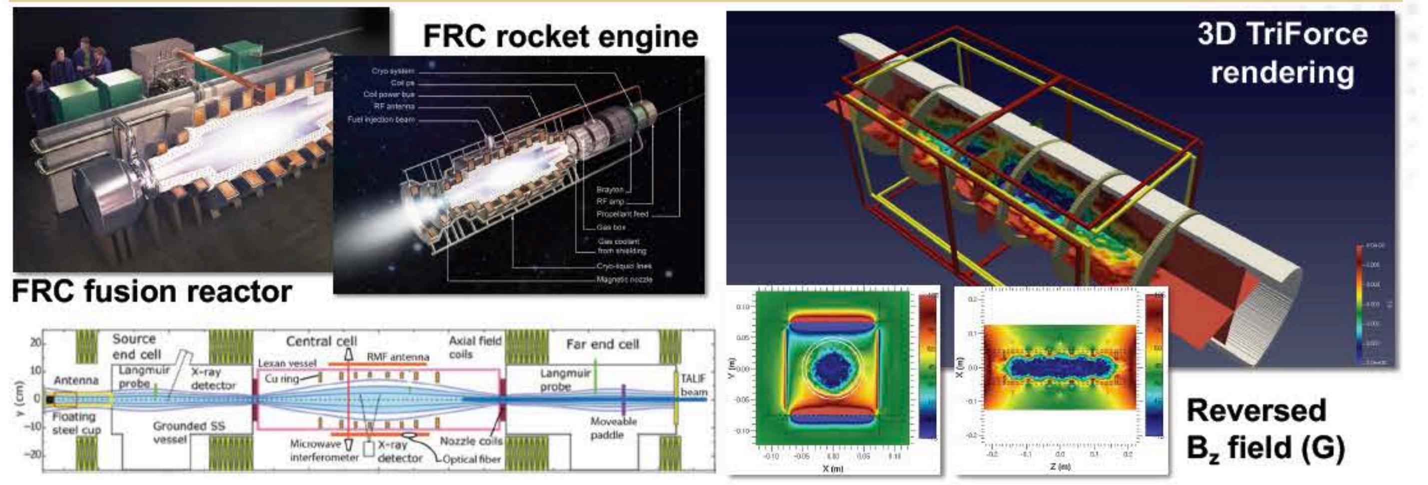
PLX-LANL



Hsu+ IEEE Trans. Plasma Sci. 2012 — Wen+ under review

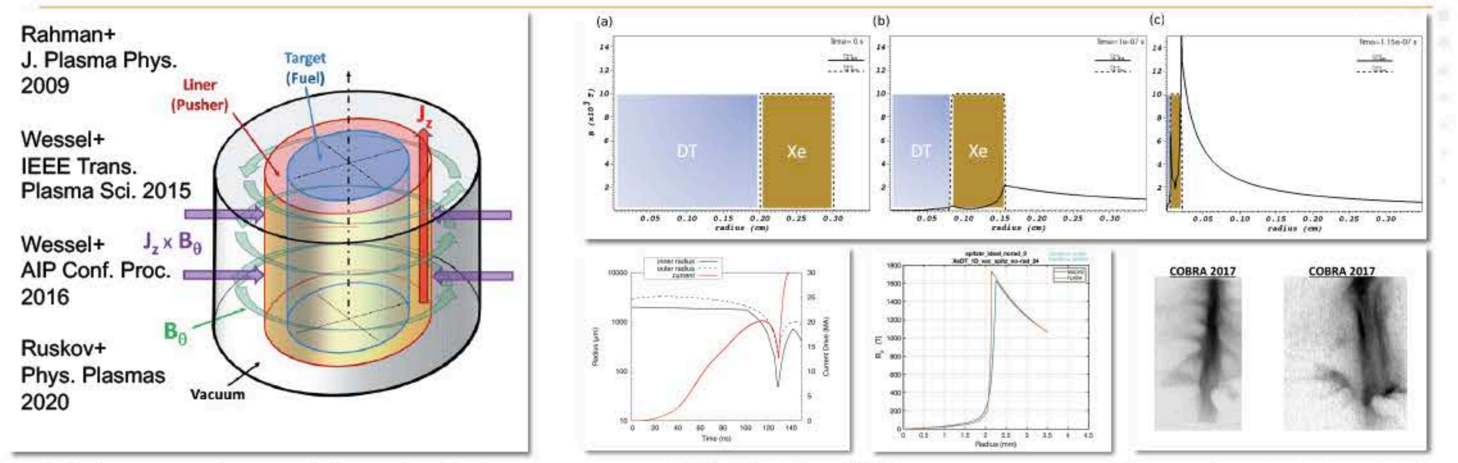
- We provide simulation support for the PJMIF project at **LANL**, the Plasma Liner Experiment (**PLX**). The LANL team explores magneto-inertial fusion through the concept of a **spherically imploding plasma liner**, formed via the **merging of plasma jets** launched by a spherical array of **plasma guns**.
- FLASH and OSIRIS simulations of the target formation indicate that a **strongly magnetized plasma** regime with $\chi_e \approx 100\text{–}1000$ (electron Hall), $\chi_i \approx 1\text{–}10$ (ion Hall), and $\beta \leq 1$ (plasma beta) can be achieved. We are currently using 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.

Princeton FRC-PPPL



- The team is providing simulation support to the **Princeton Field-Reversal Configurations** (FRC) team (FRC with RMF-o) at **Princeton** (PI Sam Cohen). The **TriForce** team members are working closely with **PPPL** to test the algorithms in TriForce for very long timescale FRC simulations.
- TriForce is undergoing **development and benchmarking efforts** to reproduce the previously published PFRC particle-in-cell results and will now be employed to help the effort of **demonstrating ion heating in the PFRC-2 device.**

SZP-MIFTI



- The team is providing simulation support to **MIFTI**. The SZP concept expands on the traditional Z-pinch to overcome the deleterious effects of MRTI. MIFTI's SZP uses a **high atomic-number liner** to compress a fusion fuel, **shock-aided** to to reach fusion-relevant conditions.
- New code development in **FLASH** includes implicit anisotropic magnetic resistivity and a circuit model (McBride+ 2010) making the code highly suitable for Z-pinch simulations. The team is conducting **thorough 1D code-to-code comparisons of FLASH and MACH2** using analytical test problems and simplified-physics Z-pinch models (Hansen+ in preparation) to **assess the feasibility of the concept.**

Impact of the project

- 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 will provide will ensure a **sustainable simulation resource**, for the ARPA-E BETHE Program and beyond, to enable **novel disruptive technologies.**

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