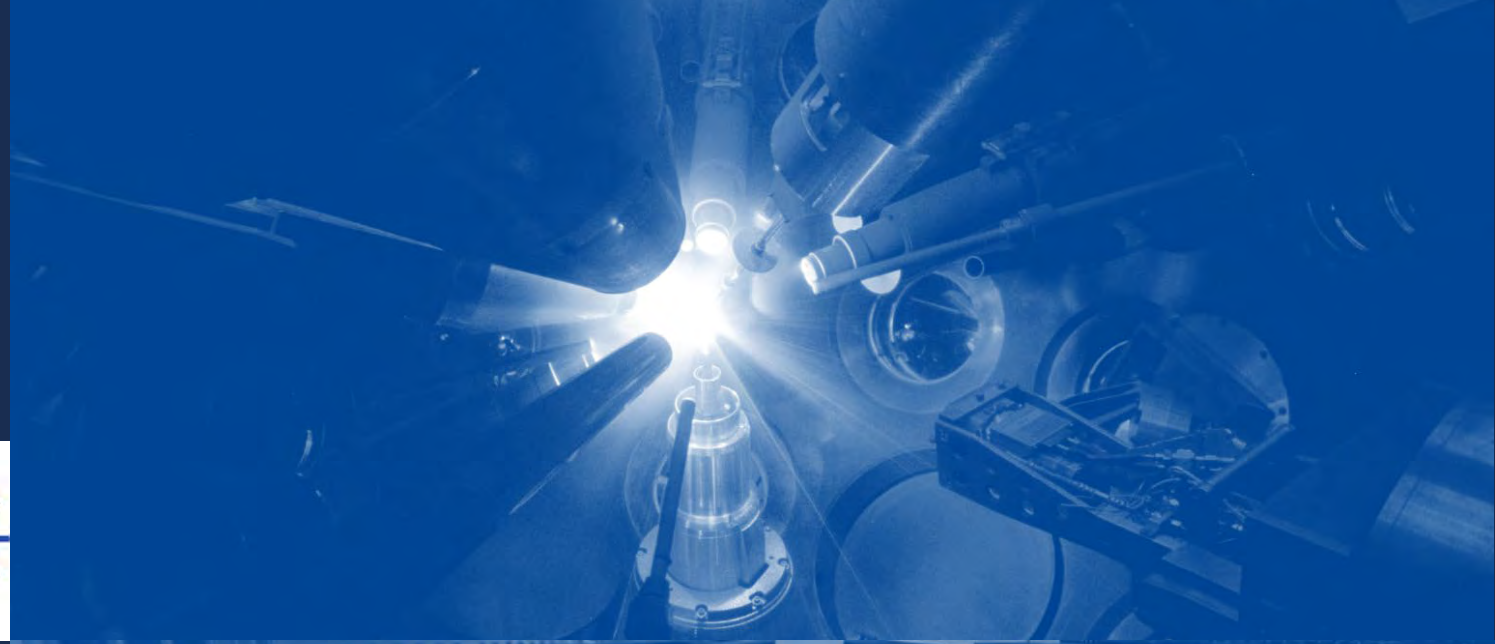
The FLASH code for computational HEDP

Recent additions and improvements



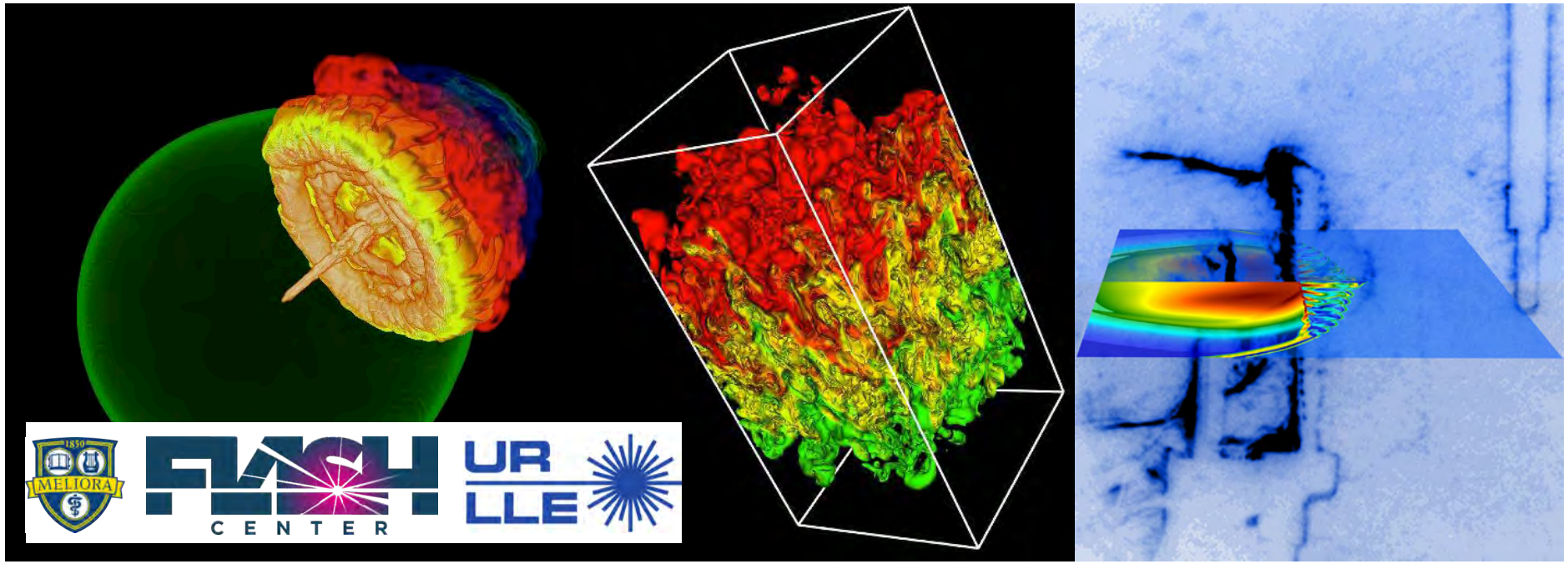
P. Tzeferacos, A. Reyes, E. C. Hansen, F. García-Rubio, Y. Lu, D. Michta, R. Sarkis, M. B. P. Adams, A. Armstrong, K. Moczulski, P. Farmakis, A. Mohapatra, M. McMullan, V. Chang, N. Vanderloo, J. Sauppe, A. Scopatz, and M. Fatenejad

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, 10/17/2022

FLASH is a multiphysics radiation-magnetohydrodynamics simulation code that is being developed at the Flash Center



> 4,000 users worldwide https://flash.rochester.edu >1,300 papers published

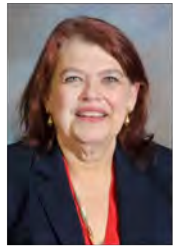
- FLASH (Fryxell et al. ApJS 2000) is a publicly available, HPC, AMR, finite-volume, radiation hydro and MHD code with extended physics capabilities (Tzeferacos et al. HEDP 2015), developed by the Flash Center for Computational Science. The development is supported primarily by the NNSA, LANL, LLNL, and LLE.

The Flash Center for Computational Science: Meet the team!


Petros


Adam


Eddie


Jenni


Rich


Jonathan


Baowei

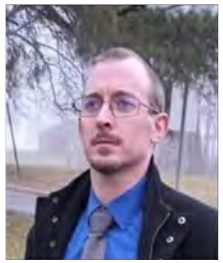

Yingchao


David


Fernando


Milad (VS)


Anthony (VS)


Josh (VS)


Marissa


Abigail

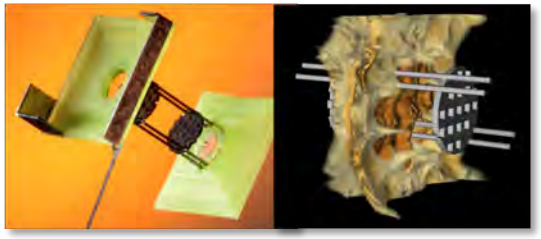

Kasper


Pericles

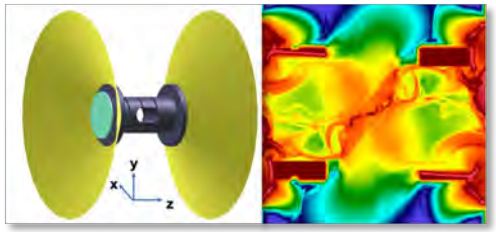

Ananya


Mary

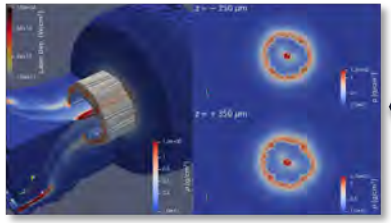
The Flash Center has developed a broad research portfolio at the University of Rochester, in close collaboration with the LLE



Laboratory Astrophysics



High Energy Density Physics



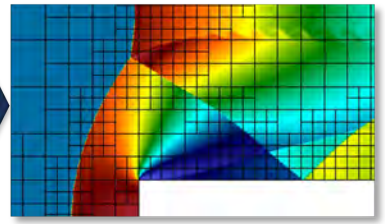
ICF & Fusion Energy

National Nuclear Security Administration

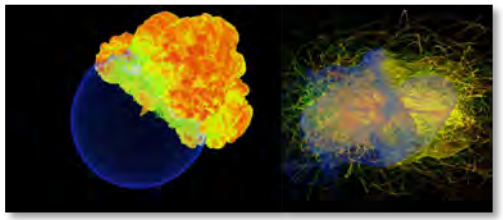
U.S. DEPARTMENT OF ENERGY

Office of Science

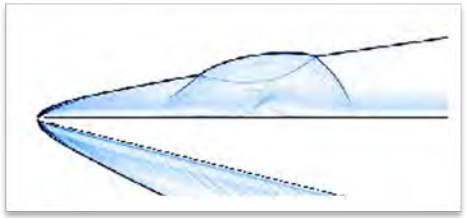
arpa·e CHANGING WHAT'S POSSIBLE



Numerical Methods for HPC



Plasma Astrophysics



Computational Fluid Dynamics

Academic Partners

National Laboratories

Los Alamos NATIONAL LABORATORY

Sandia National Laboratories

Lawrence Livermore National Laboratory

Science & Technology Facilities Council Rutherford Appleton Laboratory

U.S. NAVAL RESEARCH LABORATORY

Small Business & Industry

PRISM Computational Sciences, Inc.

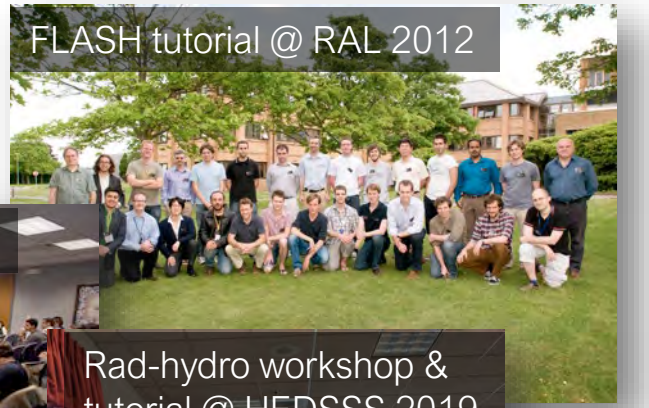
L3HARRIS

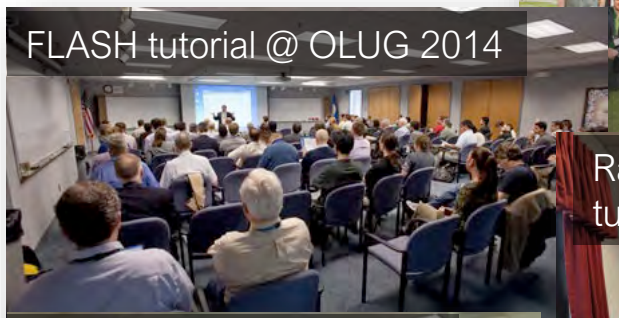
radiasoft

MIFTI

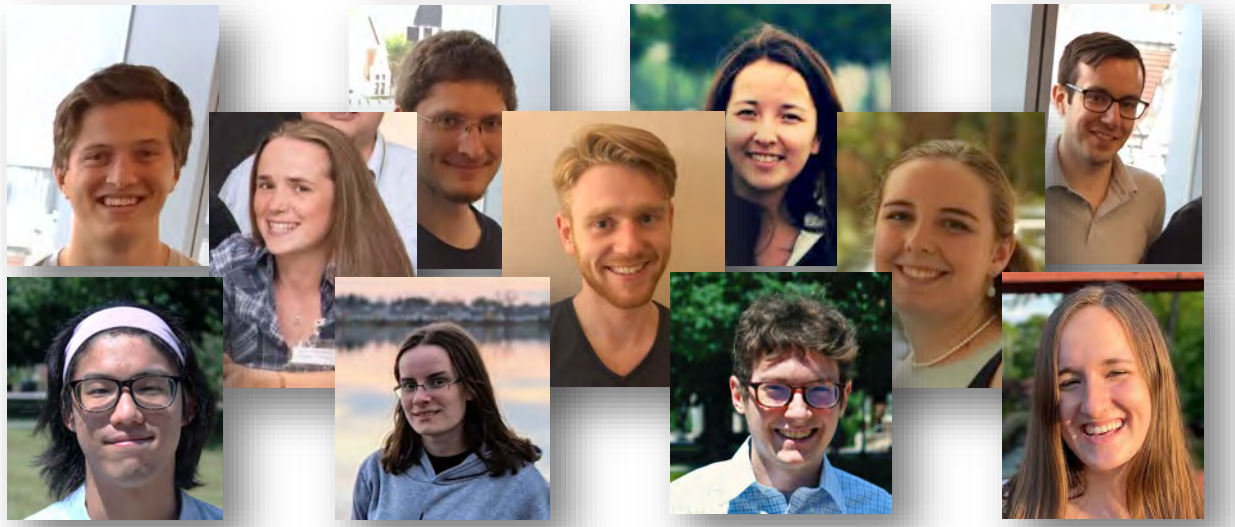
The Flash Center trains the next generation of computational physicists to develop rad-hydro codes and perform validated simulations

- More than 100 graduate students and postdocs trained at the Flash Center
- Workshops and Tutorials

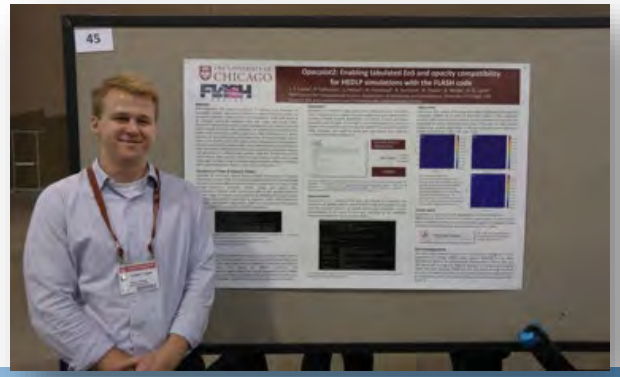


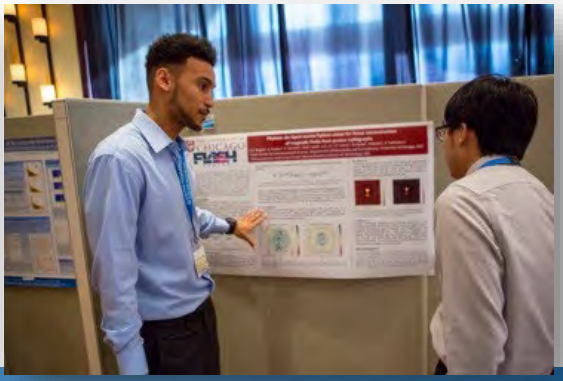


- Apprenticeship in numerical HEDP + Incubator



- Contiguous pipeline and distributed talent pool





FLASH has a broad range of physics capabilities that make the code an ideal tool for modeling magnetized HEDP experiments

- A portable, scalable, application code, composed of units and modules
- Modules are set up and assembled to run different physics problems
- Written in Fortran, C, Python, >1.2 million lines, 75% code, 25% comments

Developed for astrophysics…

- ✓ Hydro, MHD, RHD,
- ✓ Equation of State
- ✓ Nuclear Physics, Source Terms
- ✓ External gravity, Self-gravity
- ✓ Particles, active and passive
- ✓ Material Properties
- ✓ Cosmology

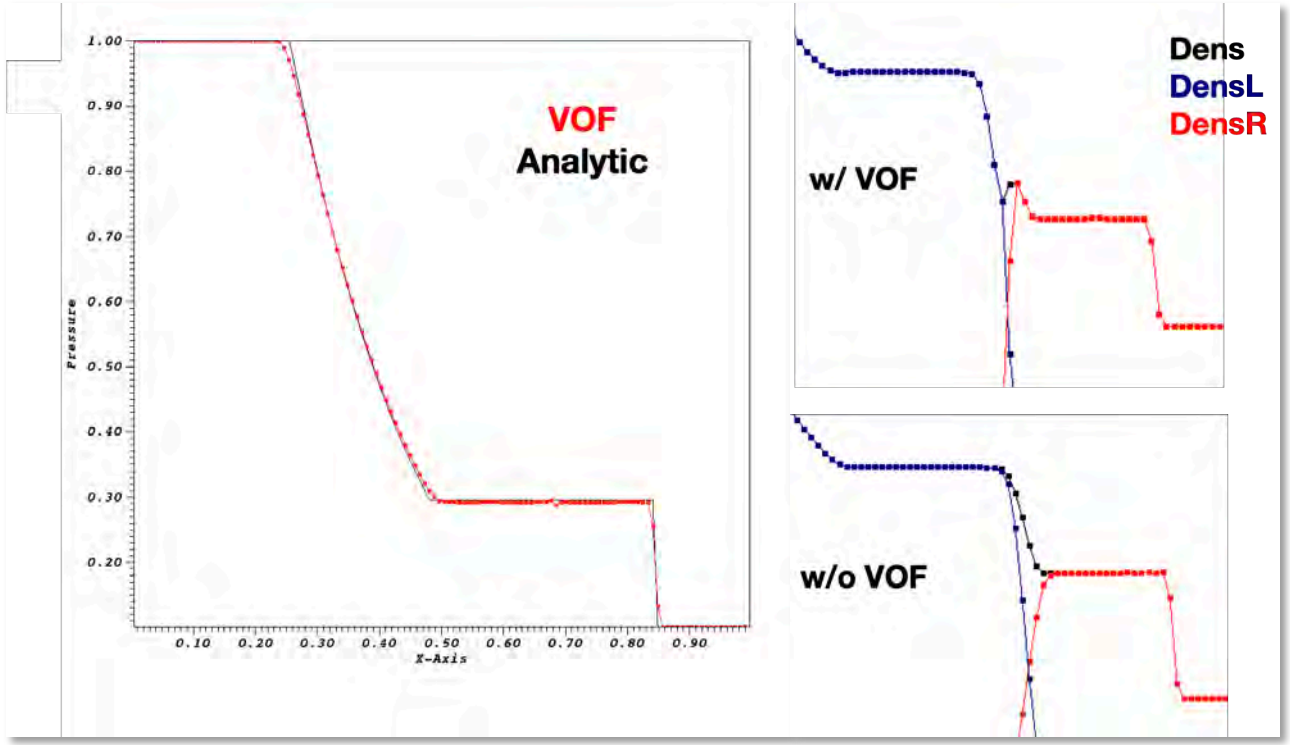
… extended for HEDP & experimentally validated

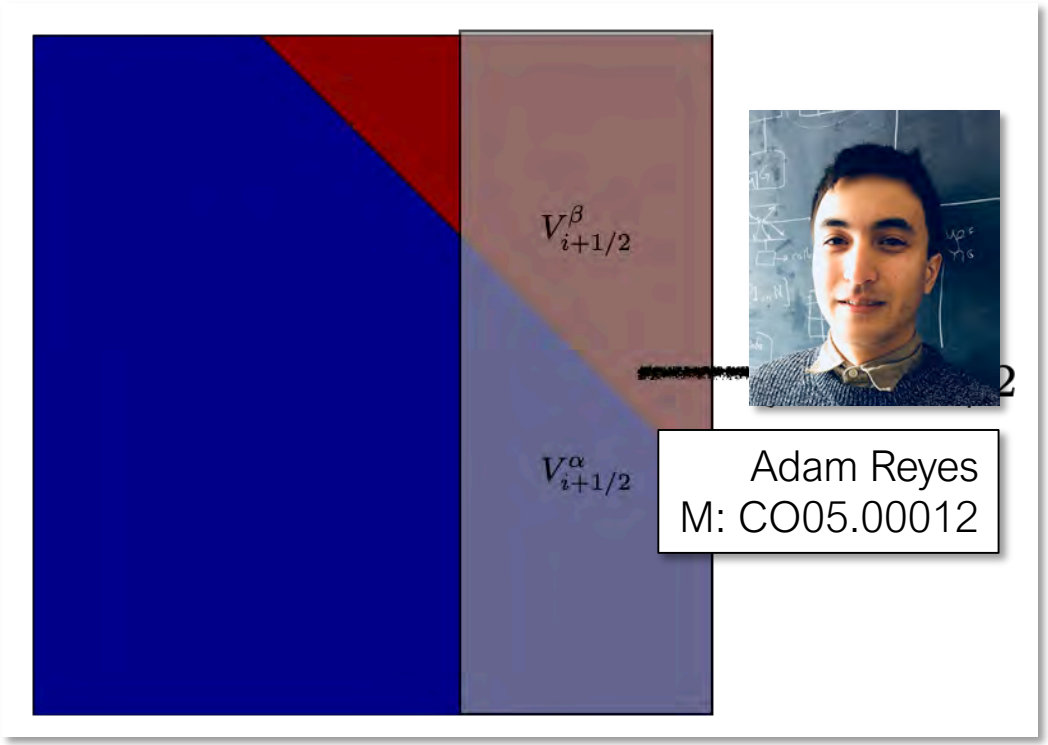
- ✓ 3T HD & MHD
- ✓ High-order methods
- ✓ Heat exchange
- ✓ FL-MGD radiation
- ✓ Laser energy deposition
- ✓ Current drive & circuit models
- ✓ Implicit diffusion solvers
- ✓ Synthetic diagnostics

- ✓ Full Braginskii extended MHD
- ✓ State-of-the-art transport coefficients
- ✓ Multi-material EoS + opacities (SESAME, TOPS, IONMIX, PROPACEOS)
- ✓ Front tracking
- ✓ Solid-gas interfaces

New & improved in FLASH v4.7

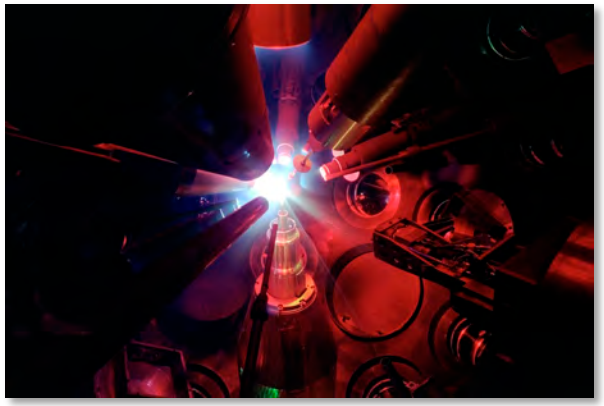
Interface Reconstruction using Gaussian Processes for Volume of Fluid (VOF) methods in 1 & 2 dimensions





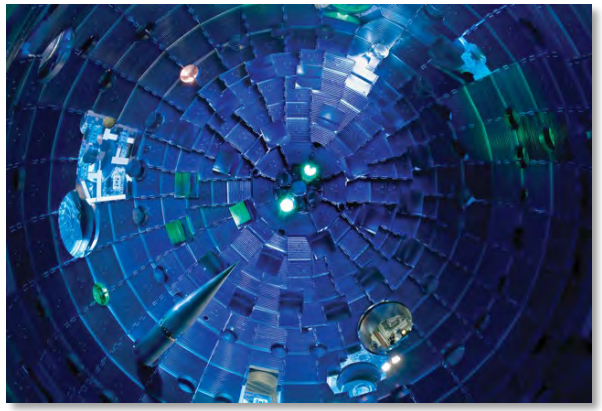
- We have added capabilities in FLASH's hydrodynamics solvers to **capture interfaces in compressible multi-fluid flow using GP-VOF**. Verification on 1D two-fluid Riemann problems shows that FLASH correctly predicts shock speeds while maintaining material interfaces. PLIC reconstruction of interfaces enables VOF advection in two dimensions.

FLASH is a publicly available code being used by numerous academic groups to design and execute laser-driven HEDP experiments



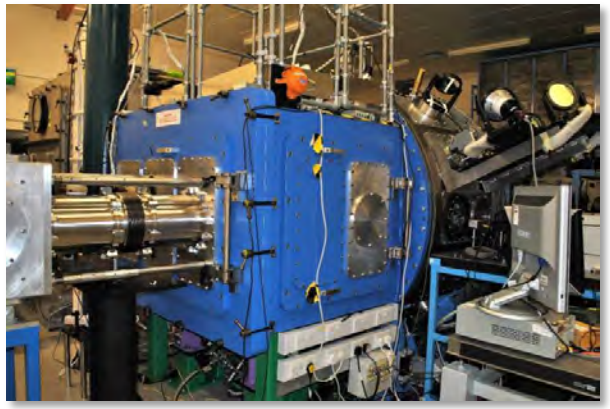
OMEGA-60 Laser Facility, LLE/UR, US

OMEGA-EP Laser Facility, LLE/UR, US

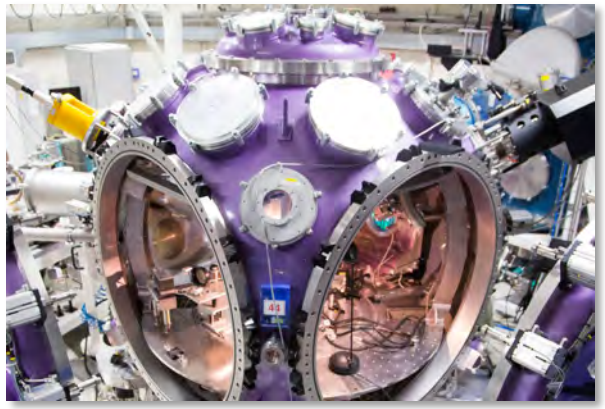


National Ignition Facility (NIF), LLNL, US

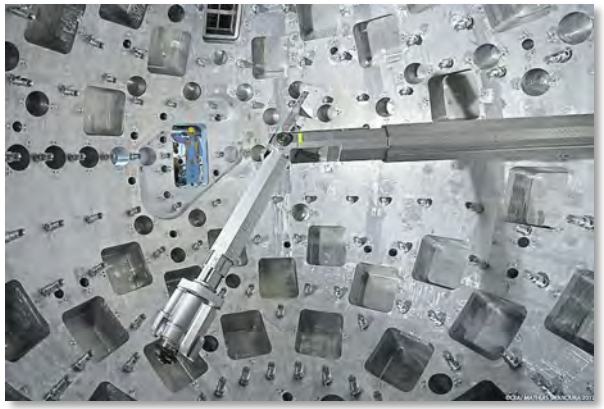
Jupiter Laser Facility (JLF), LLNL, US



Central Laser Facility, RAL, UK



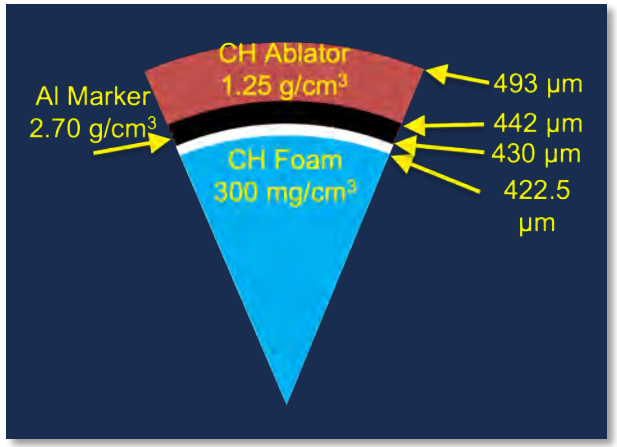
LULI Laser Facility, Ecole Polytechnique, FR

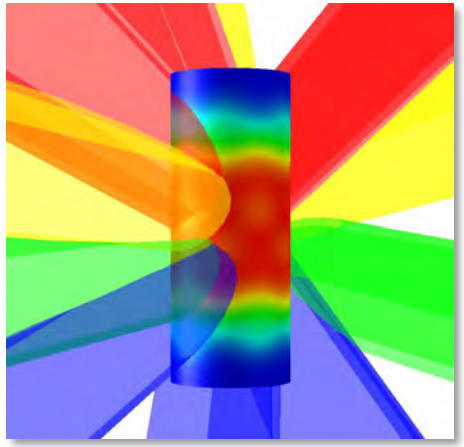


Megajoule Laser Facility (LMJ), CEA, FR

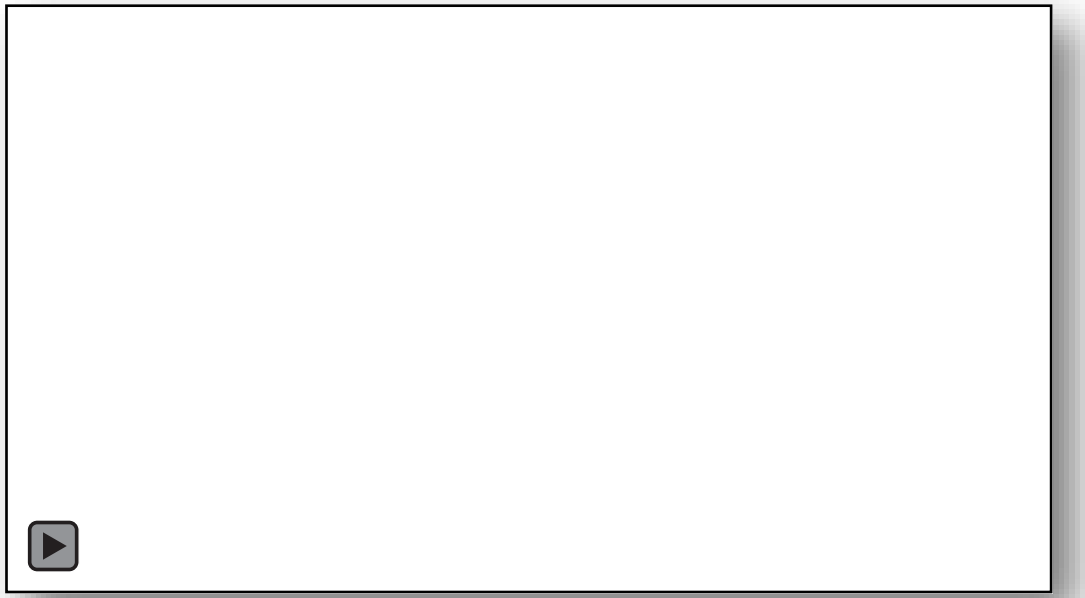
GSI Helmholtz Centre for Heavy Ion Research, DE

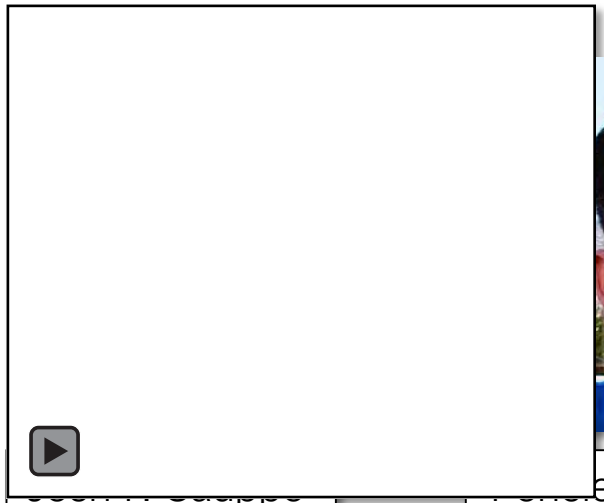
The FLASH code is continuously verified through code-to-code comparisons and validated against experiments – LANL integrated V&V





Courtesy of J. P. Sauppe, LANL



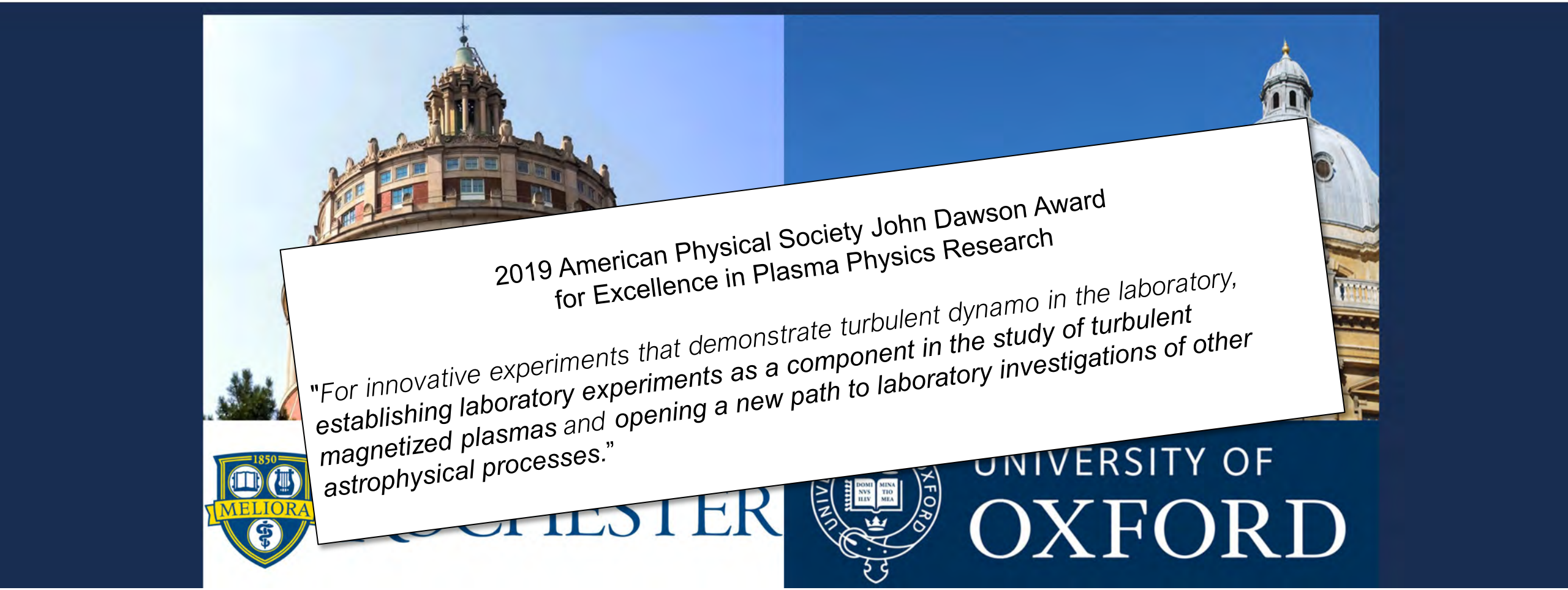


- LANL is fielding cylindrical ICF targets at OMEGA and NIF, using 2D xRAGE and 3D FLASH simulations for platform design
- Excellent agreement with experimental data from both facilities.

F: YI01.00003

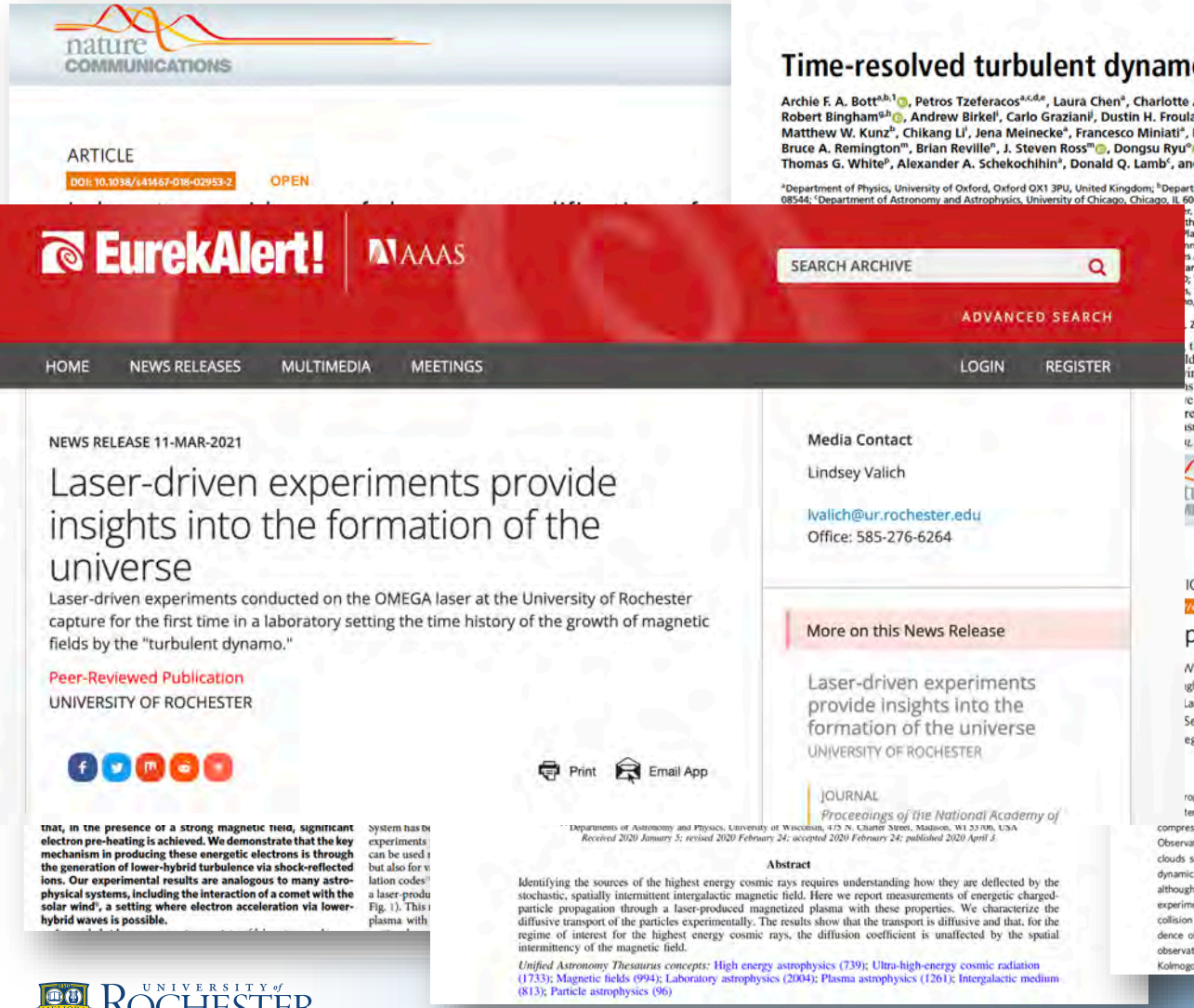
es Farmakis
M: BP11.00121

Laboratory Astrophysics – Turbulent Dynamo Collaboration (TDYNO)

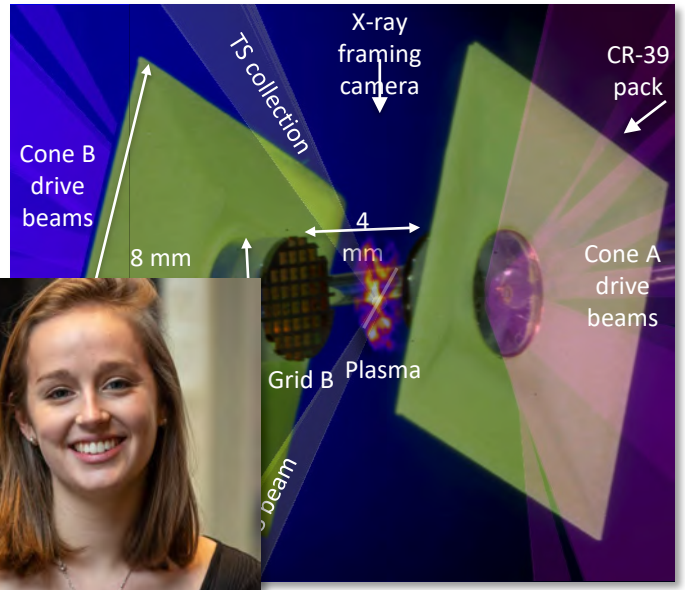


- Magnetized turbulence, fluctuation dynamo, cosmic ray transport and acceleration

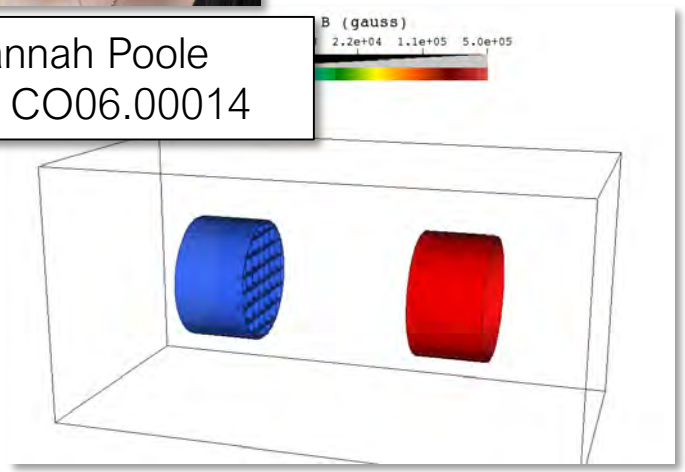
The dynamo breakthrough spring boarded a concerted effort by TDYNO to study astrophysical processes mediated by turbulence

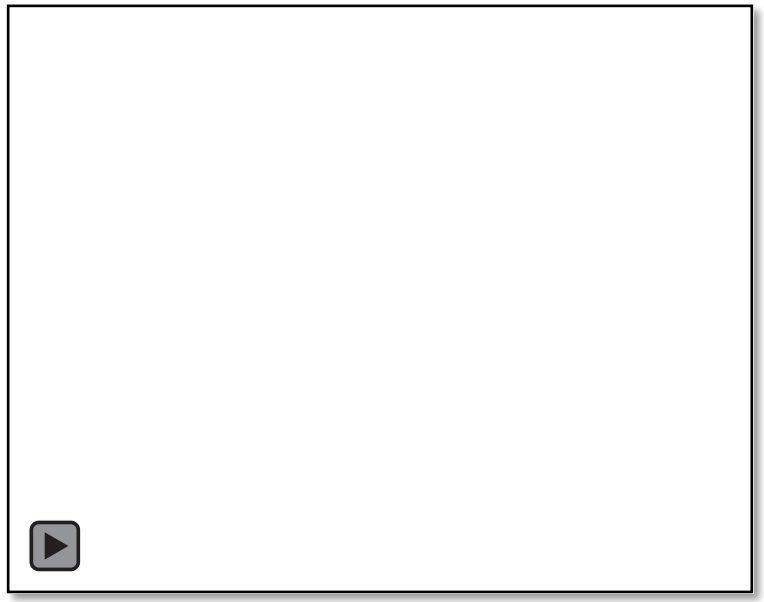


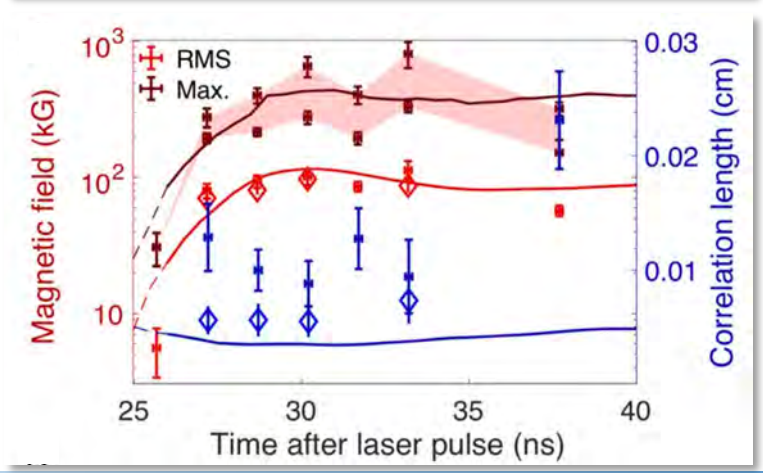
FLASH simulations and TDYNO Omega experiments furnish the first temporal characterization of fluctuation dynamo



Hannah Poole
M: CO06.00014





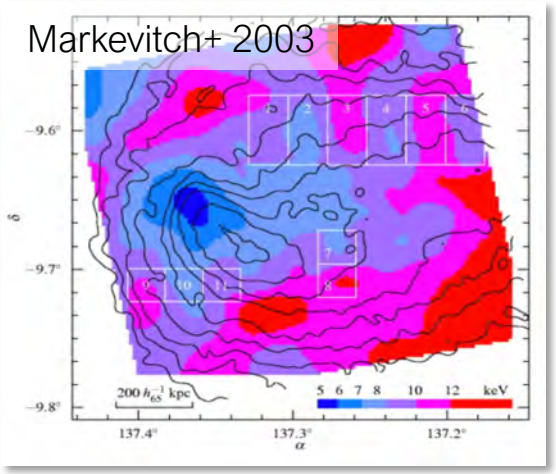


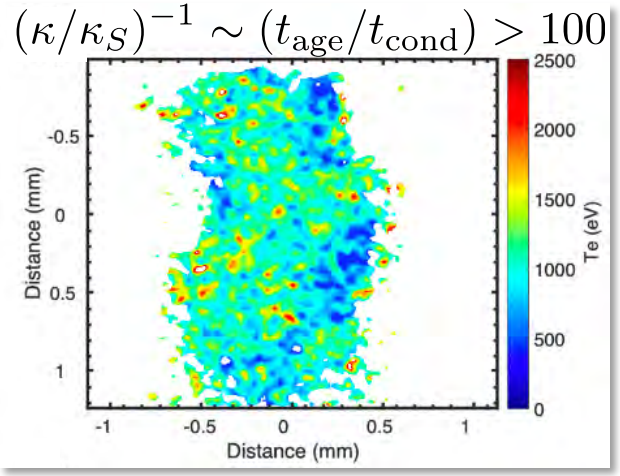

Time-resolved turbulent dynamo in a laser plasma

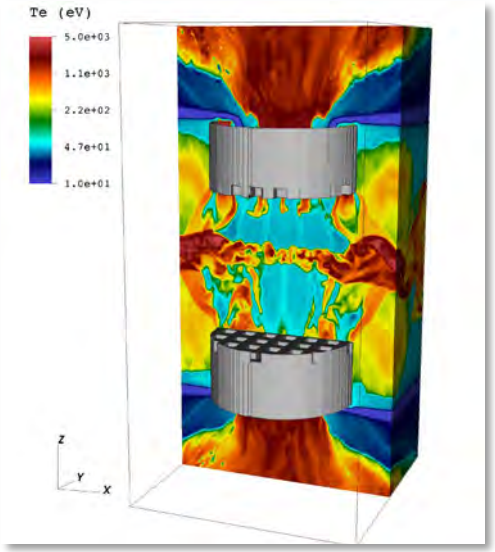

Laser-driven experiments provide insights into the formation of the universe

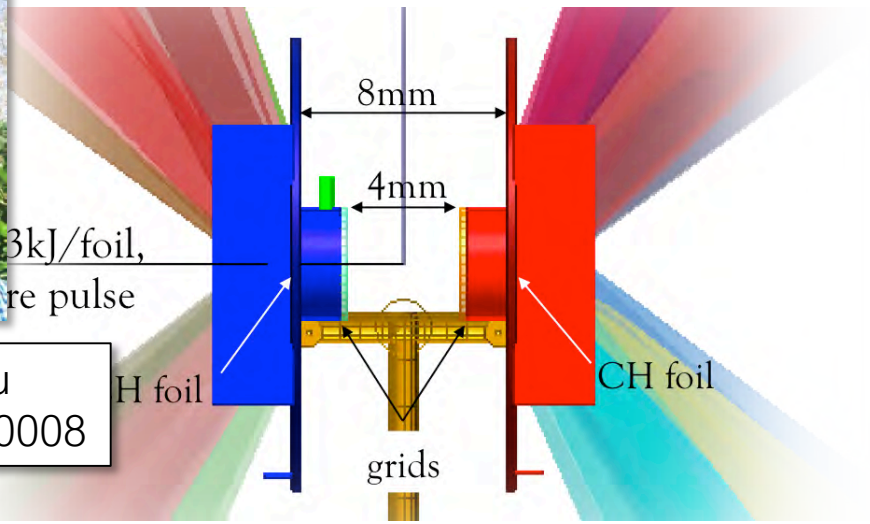
A. Bott+ Proceedings of the National Academy of Sciences 118, e2015729118 (2021)

FLASH simulations and TDYNO NIF experiments help unravel thermal conduction suppression in galaxy clusters

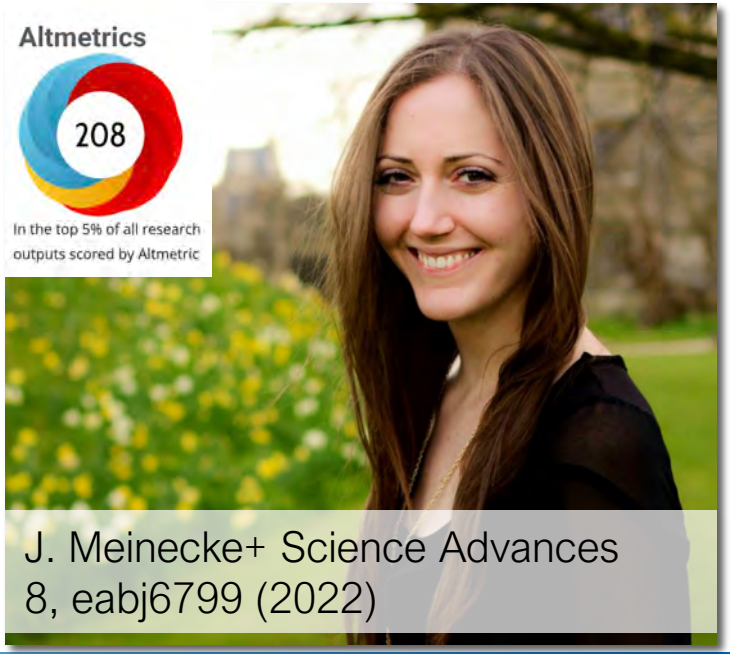






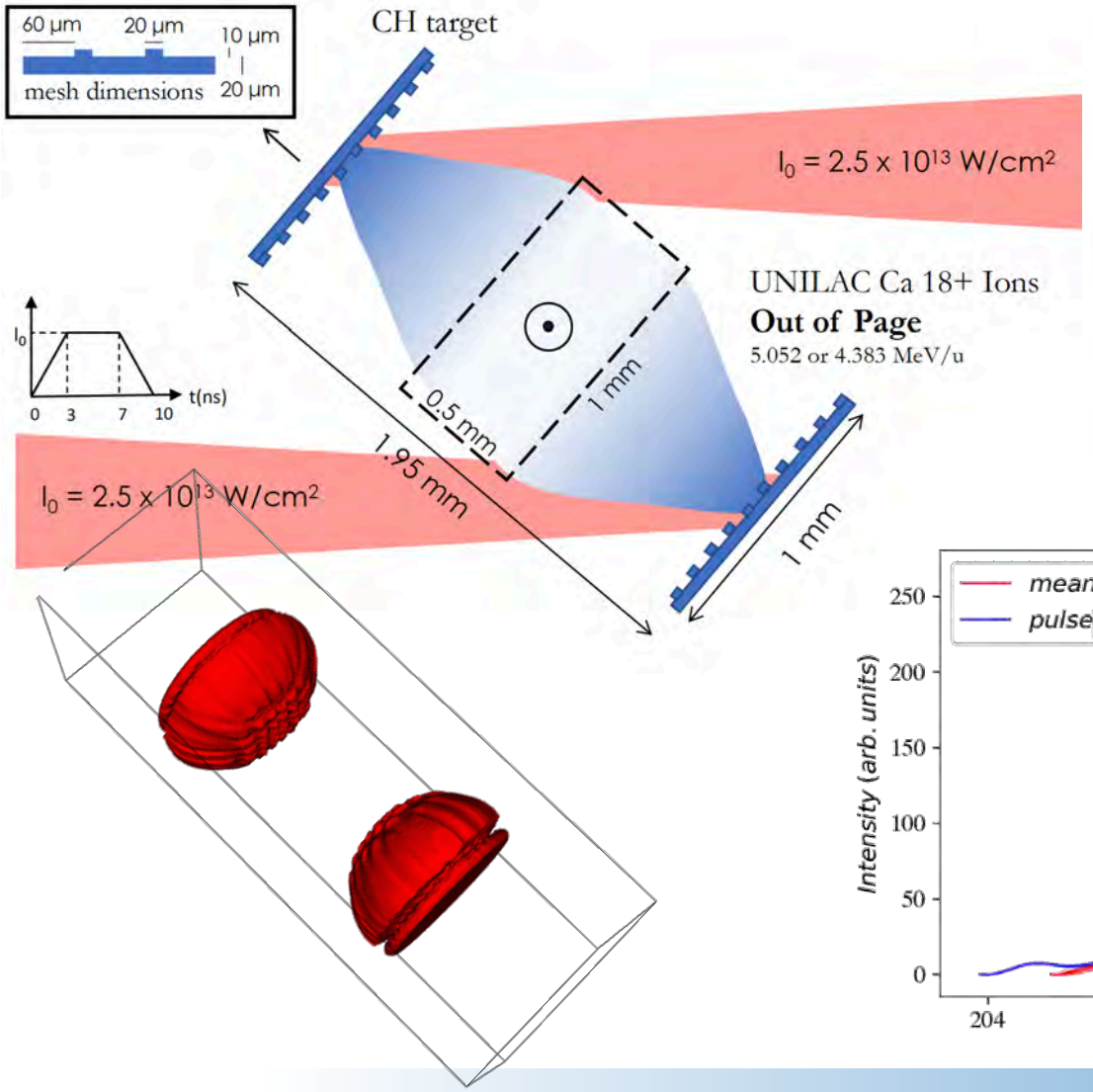


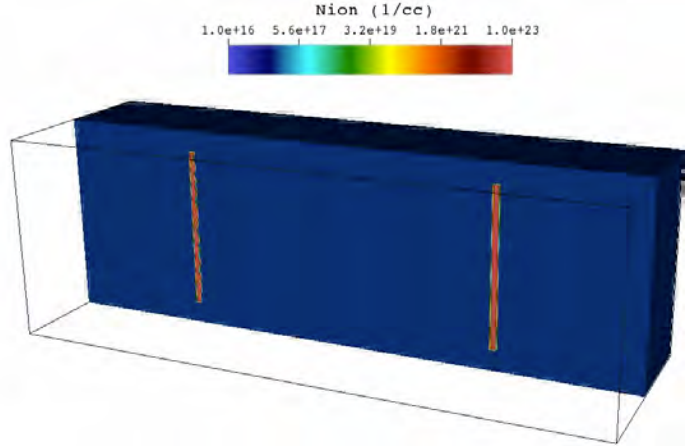
Yingchao Lu
Th: TO06.00008

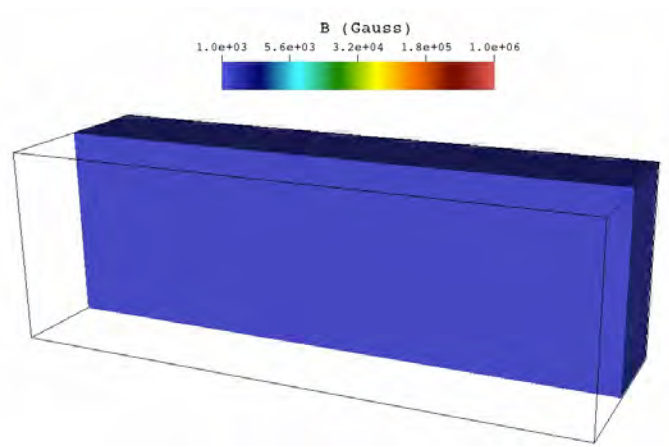


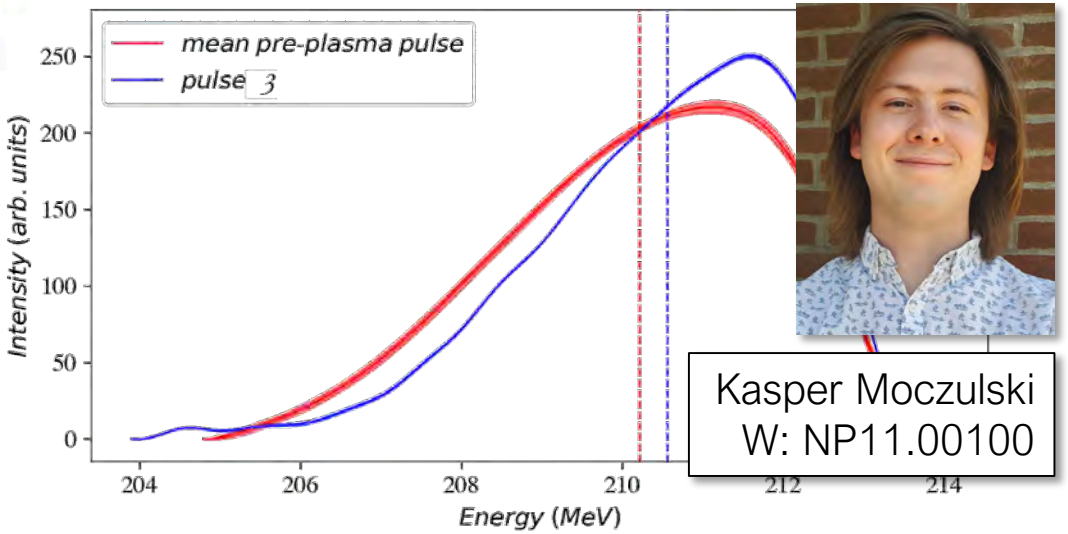
J. Meinecke+ Science Advances 8, eabj6799 (2022)

FLASH simulations and TDYNO GSI experiments study the transport and energization of ions in magnetized turbulence





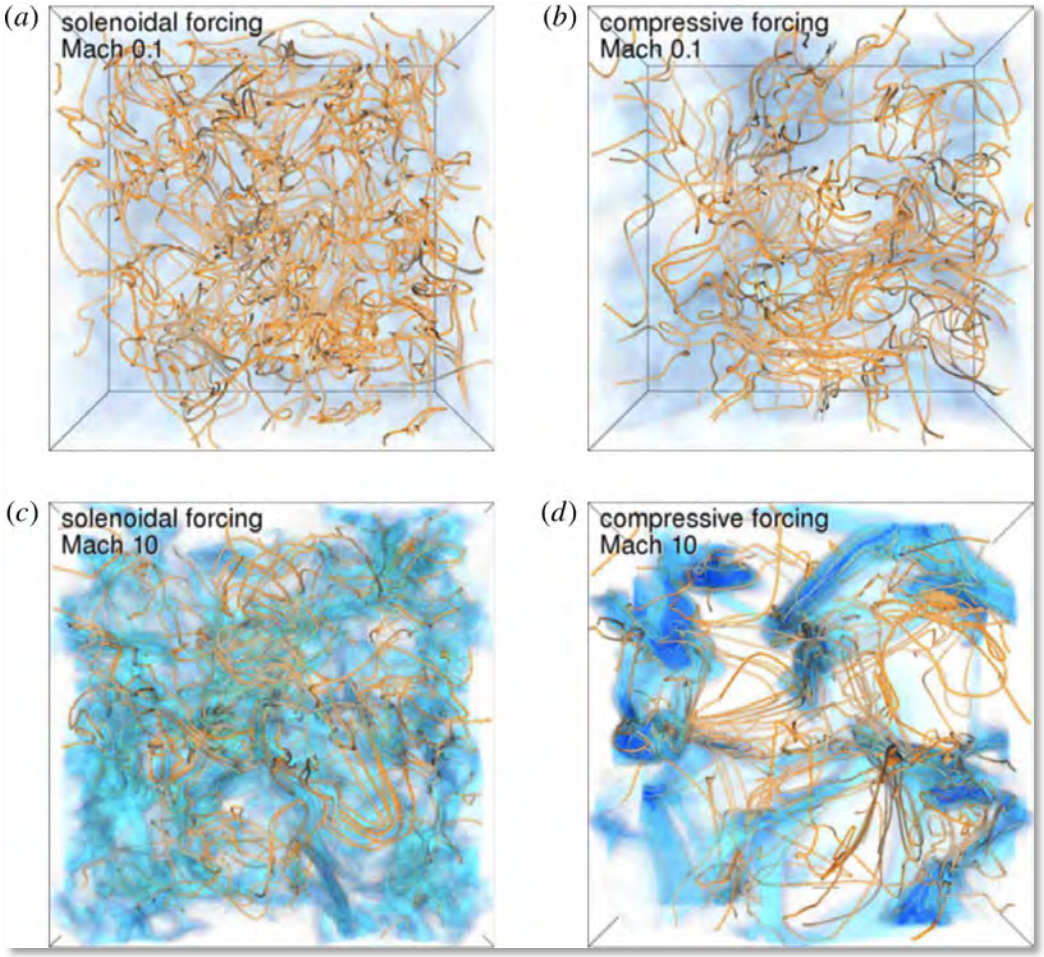




Kasper Moczulski
W: NP11.00100

Thomas Campbell
T: GO07.00009

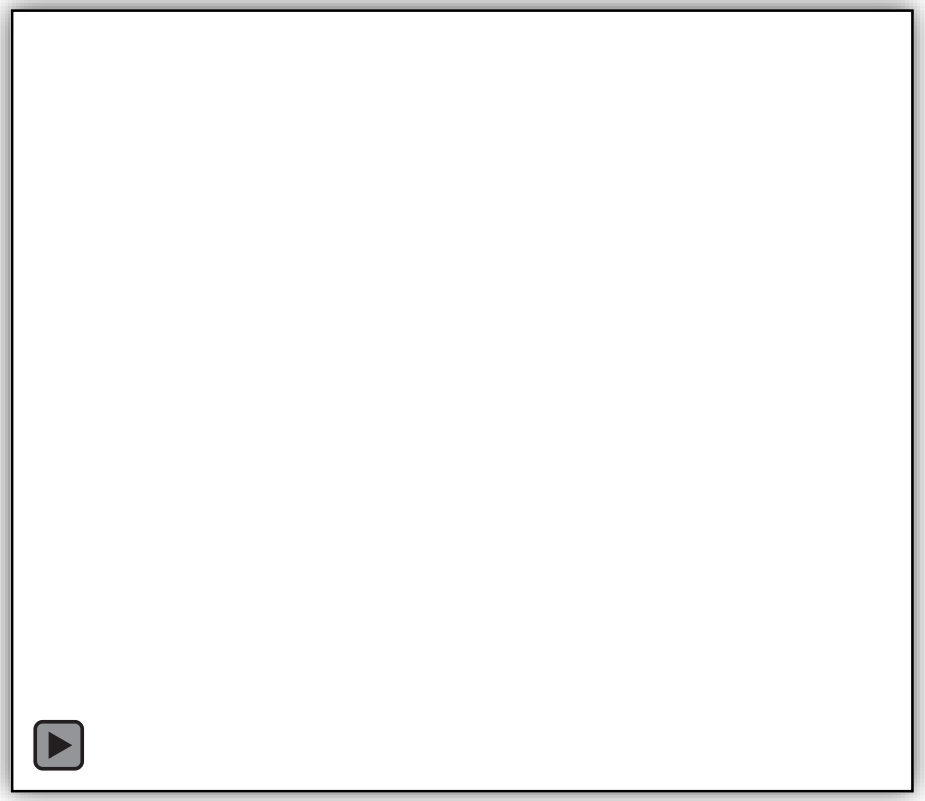
U.S. DOE Office of Science/FES: Driven HED turbulence to design validation TDYNO experiments



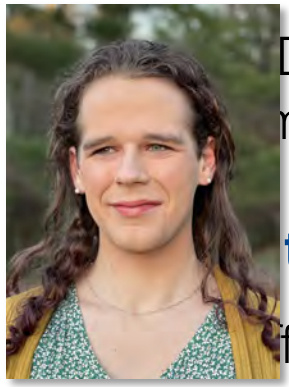
Federrath+ PRL 2011
Federrath JPP 2016

- A new Department of Energy Early Career Research Program Award enables us to study high-energy-density (HED) magnetized plasma turbulence **using driven turbulence simulations with FLASH**.
- This effort will holistically study HED magnetized turbulence **in regimes where plasma physics processes are important** and go beyond the simplified approximations used in current theoretical models and numerical simulations.
- The research combines **theory, high-performance computing simulations with the FLASH code, and experiments** on our nation's **laser facilities** to establish a basis for laboratory astrophysics investigations on the nature of magnetized HED turbulence and fluctuation dynamo.

U.S. DOE Office of Science/FES: Driven HED turbulence to design validation TDYNO experiments



- 3T driven turbulence simulations with the FLASH code. Shown is a 2D slice (density in g cm^{-3}) of the 3D simulation using FLASH's 3T hydro solver.



Abigail Armstrong
W: NP11.00084

Department of Energy Early Career Research
n Award enables us to study high-energy-
(HED) magnetized plasma turbulence **using turbulence simulations with FLASH**.

fort will holistically study HED magnetized
in regimes where plasma physics are important and go beyond the simplified approximations used in current theoretical models and numerical simulations.

- The research combines **theory, high-performance computing simulations with the FLASH code, and experiments** on our nation's **laser facilities** to establish a basis for laboratory astrophysics investigations on the nature of magnetized HED turbulence and fluctuation dynamo.

The Flash Center is part of the NNSA Center of Excellence Center for Matter under Extreme Conditions (CMEC)

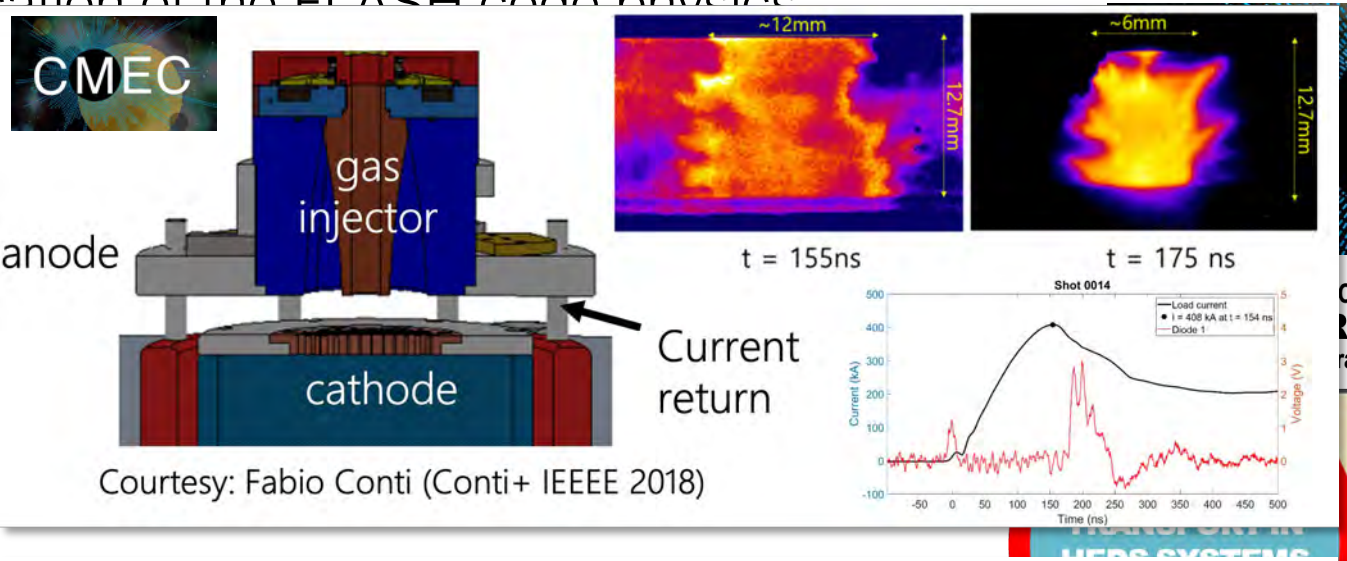
- Expansion and verification of the FLASH code physics capabilities: **extende**

$$\mathbf{E} = \frac{\mathbf{J}}{n_e e} \times$$

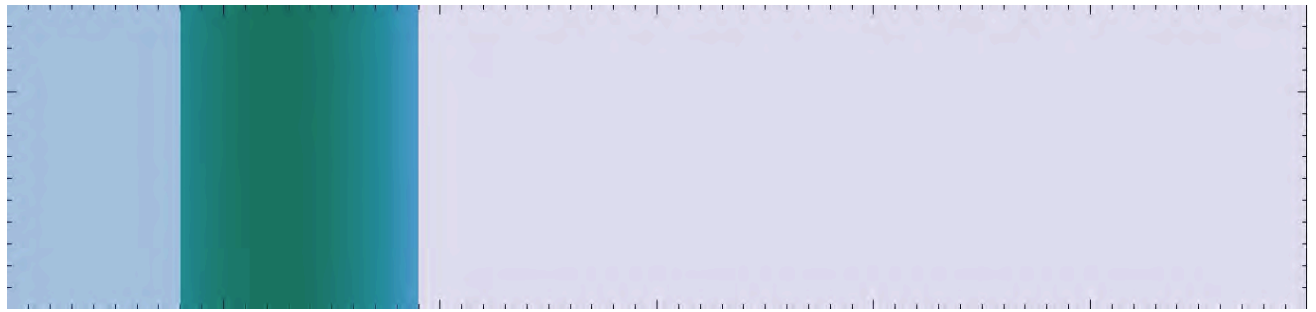
$$+ \quad \cdot \mathbf{J})$$

$$- \quad e) - \beta$$

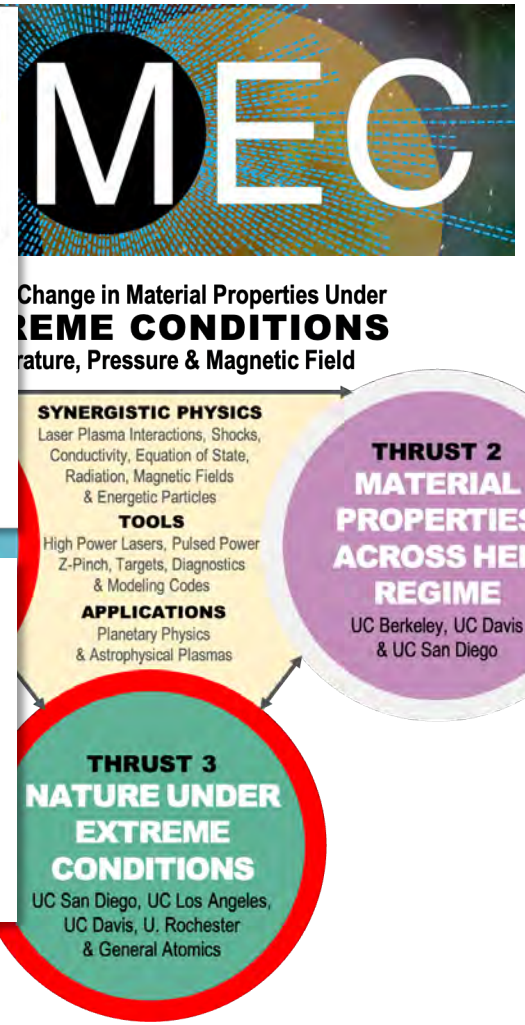
David Michta
F: YO04.00002



- Implementation of **alg** **mod** **bloc**

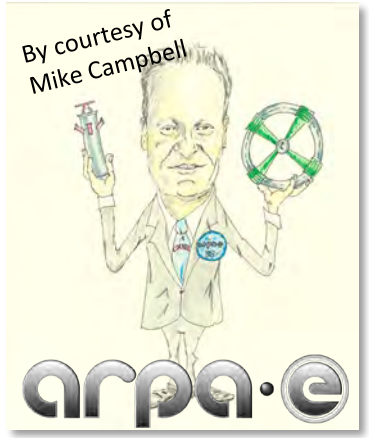


- Numerical modeling **pulsed-power drive**

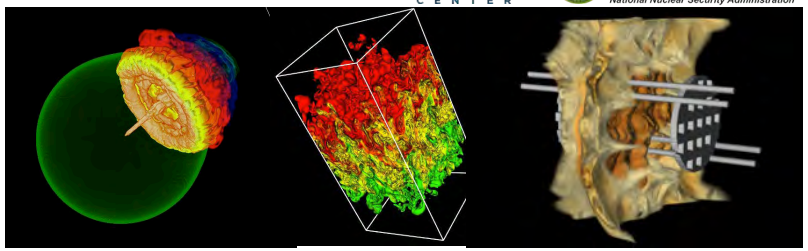


The Flash Center assembles a theory/modeling Capability Team at the University of Rochester for the U.S. DOE ARPA-E BETHE program

- The Capability Team uses **a suite of codes** – fluid, hybrid, and kinetic – 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). **This modus operandi is a good fit for LaserNetUS / other experimental programs.**

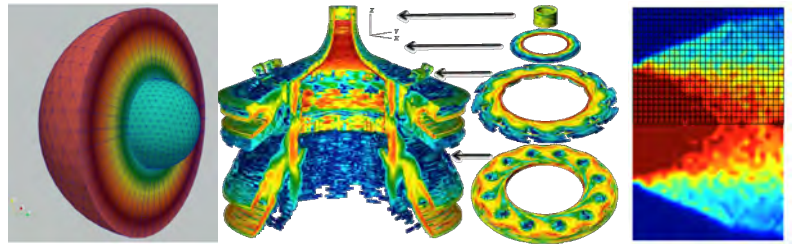


FLASH code



Multi-physics AMR MHD code for HEDP

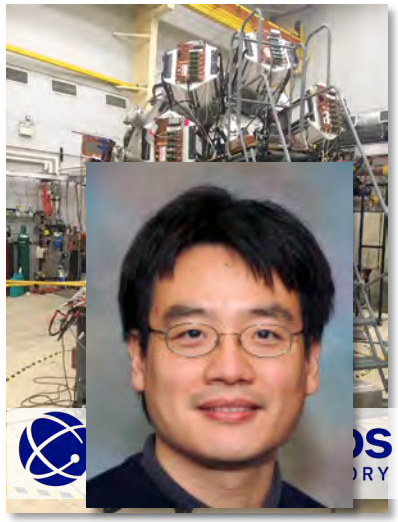
TriForce



Meshless fluid/kinetic hybrid simulation tool

OSIRIS

relativistic, massively parallel PIC code



PLX

Chuang Ren
M: BP11.00118

Ayden Kish
M: BO03.00011

Eddie Hansen
F: YO04.00004

Fernando Garcia-Rubio
W: NO04.00012

Summary

- FLASH is a publicly available multi-physics code with extensive HEDP and extended MHD capabilities, making it **a powerful toolset** for the academic HED community, the national laboratories, and industry.
- The Flash Center, at its new home at the University of Rochester, has added several physics and algorithmic capabilities to **increase simulation fidelity and expand the applicability** of FLASH in new problems and plasma regimes, to study **properties of matter at extremes**.
- Under the auspices of NNSA, and with support from ARPA-E and Office of Science
  - we have turned FLASH into a unique code for **extended-MHD HEDP simulations**, capable of tackling **both laser-driven- and pulsed-power-driven** magnetized HEDP experiments,
  - we have made FLASH into a **sustainable simulation resource** for the HEDP community,
  - we greatly contribute to the **training of the next generation of computational HEDP scientists** to do validated numerical simulations, and
  - we pursue **exciting, cutting-edge science** in several application domains.

Acknowledgements

The Flash Center acknowledges support by the U.S. DOE NNSA under Awards DE-NA0002724, DE-NA0003605, DE-NA0003842, DE-NA0003934, DE-NA0003856, and Subcontracts 536203 and 630138 with LANL and B632670 with LLNL; the NSF under Award PHY-2033925; the U.S. DOE Office of Science Fusion Energy Sciences under Award DE-SC0021990; and U.S. DOE ARPA-E under Award DE-AR0001272.