

# *The FLASH code for computational HEDP*

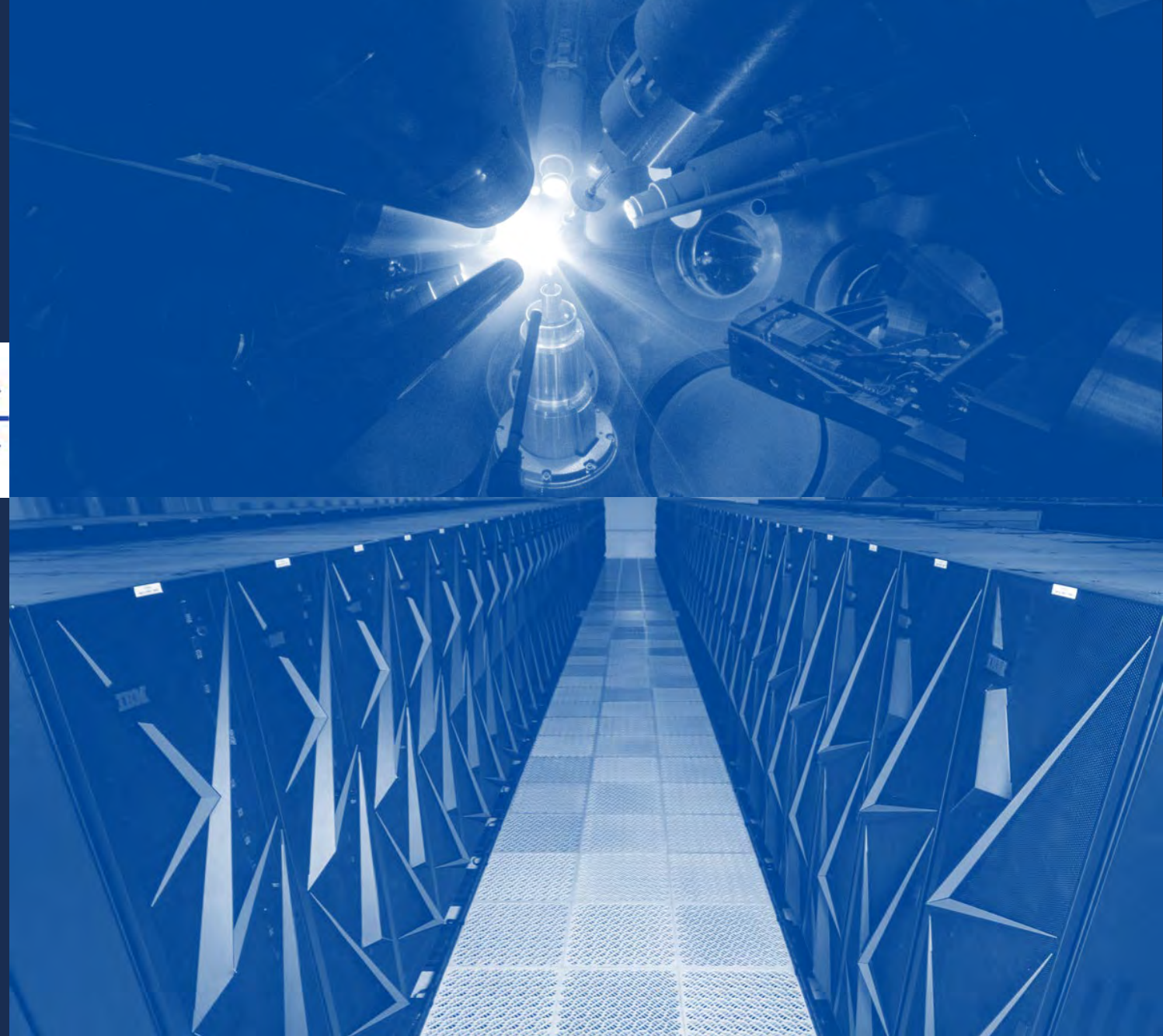
*Recent additions and  
improvements*



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

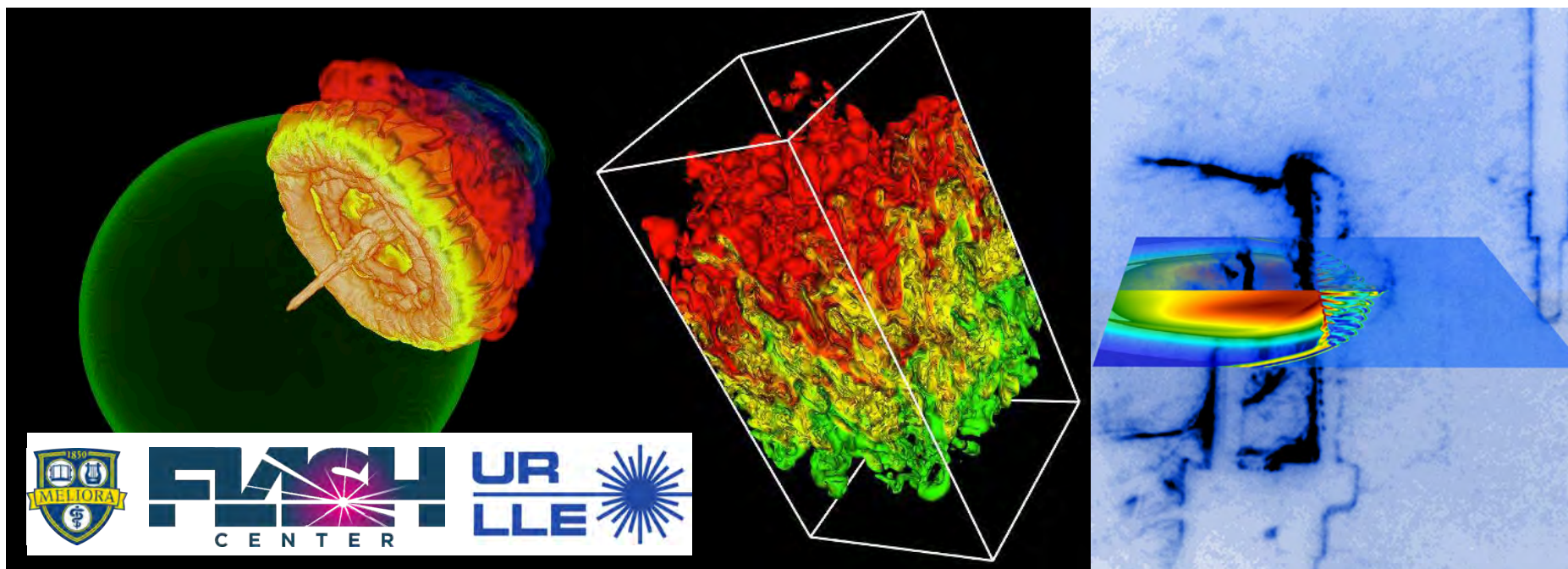
Flash Center for Computational Science  
Department of Physics and Astronomy  
Laboratory for Laser Energetics  
University of Rochester

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

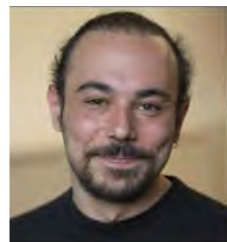


**> 4,000 users worldwide <https://flash.rochester.edu> >1,300 papers published**

- 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



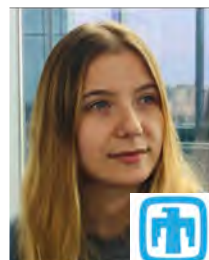
Milad (VS)



Anthony (VS)



Josh (VS)



Marissa



Abigail



Kasper



Pericles



Ananya



Mary

### Astrophysical Processes



We study media are co generate cosmic interst

### The FLASH Code



code, an mulation code astrophysics. ical methods complex



### High



We carry out simulation campaigns on the largest supercomputers in the world and are on the cutting edge of high performance computing, leveraging emerging technologies that revolutionize research.

### physics

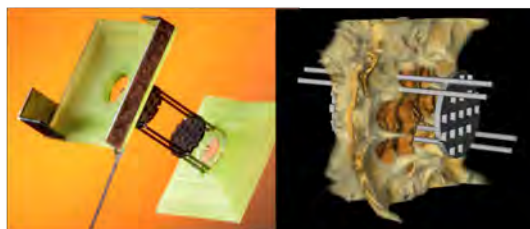


We conduct our breakthrough experiments at the largest laser facilities in the world, such as the Omega Laser Facility at LLE, the National Ignition Facility at LLNL, and the Megajoule Laser in France.

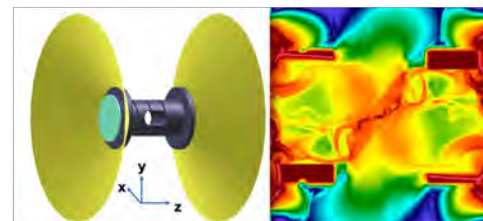
[p.tzeferacos@rochester.edu](mailto:p.tzeferacos@rochester.edu)



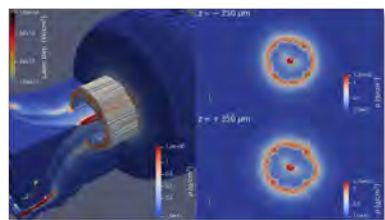
# The Flash Center has developed a broad research portfolio at the University of Rochester, in close collaboration with the LLE



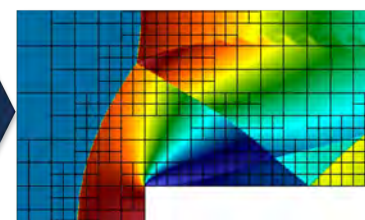
Laboratory Astrophysics



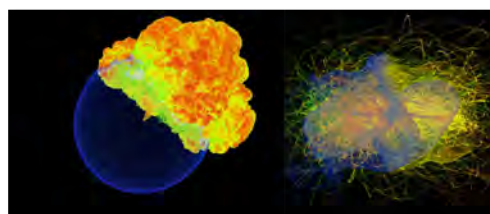
High Energy Density Physics



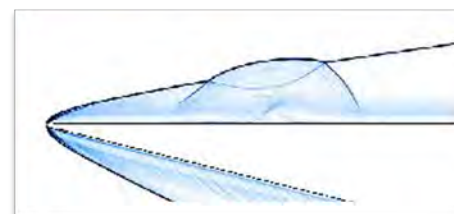
ICF & Fusion Energy



Numerical Methods  
for HPC

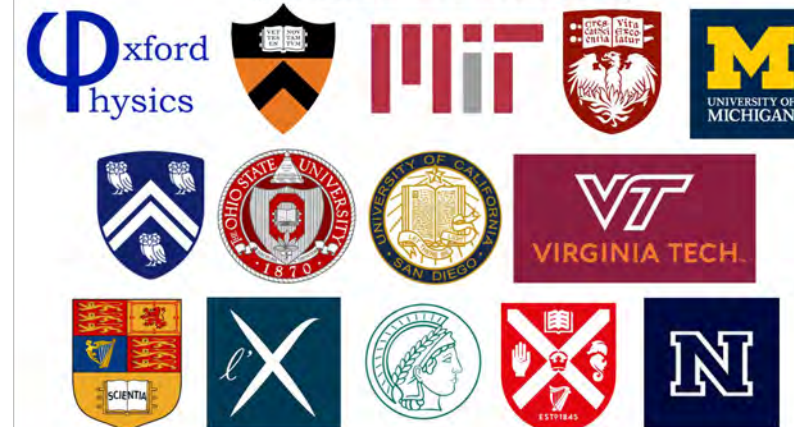


Plasma Astrophysics

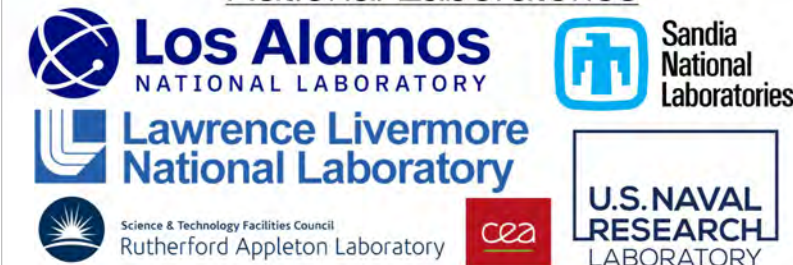


Computational Fluid Dynamics

## Academic Partners



## National Laboratories



## Small Business & Industry





# 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

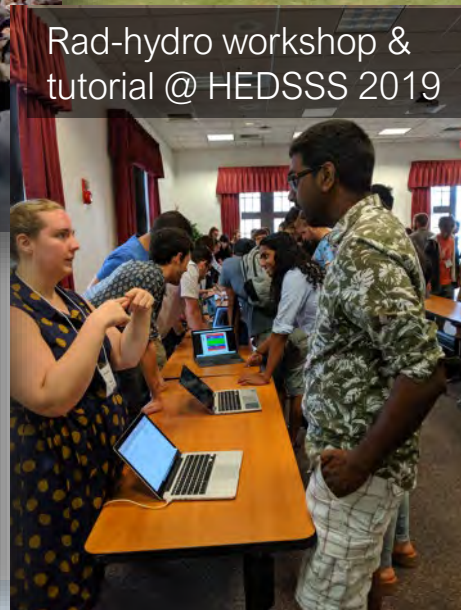
FLASH tutorial @ RAL 2012



FLASH tutorial @ OLUG 2014



Rad-hydro workshop & tutorial @ HEDSSS 2019



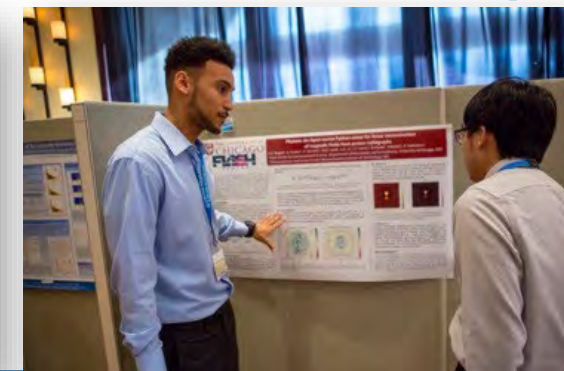
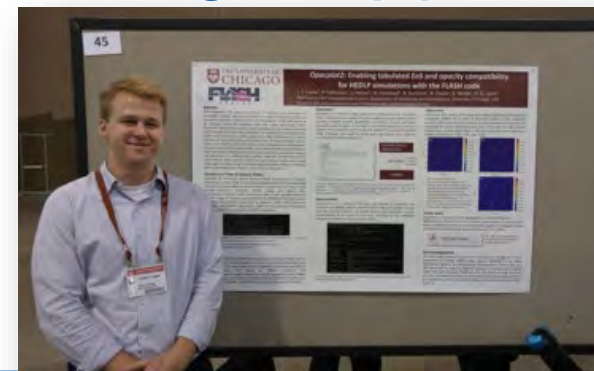
Rad-hydro workshop & tutorial @ HEDSSS 2017



- 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

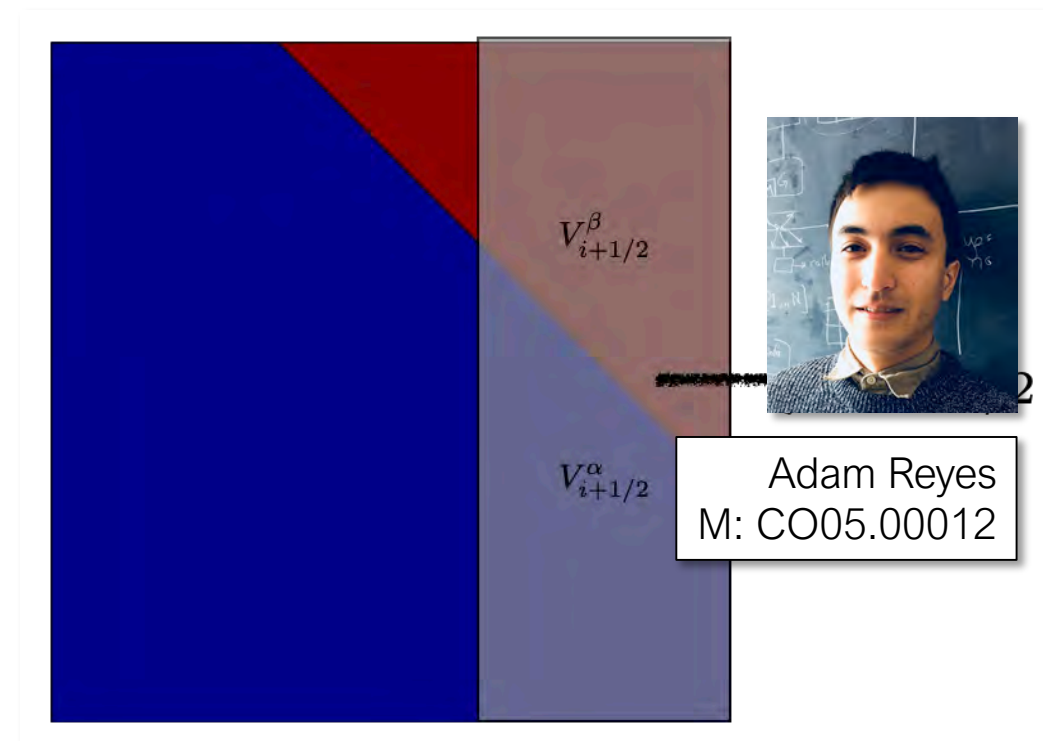
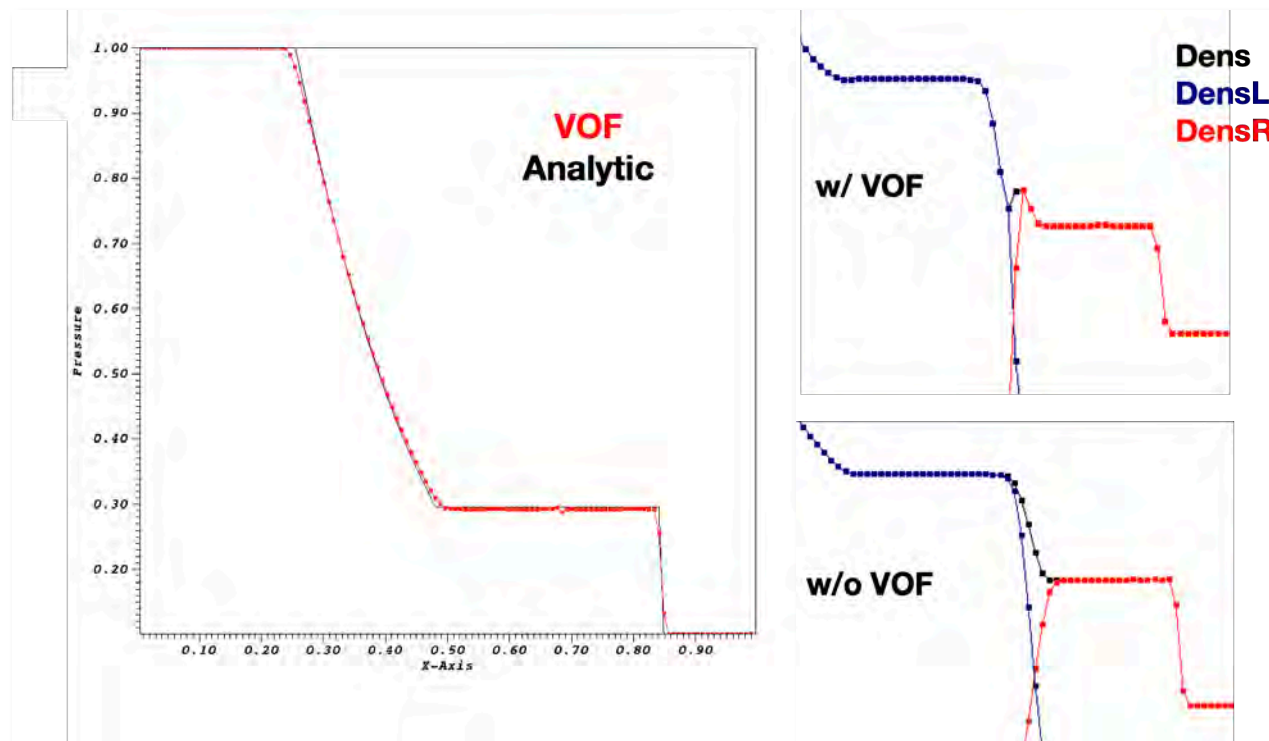
## ... extended for HEDP & experimentally validated

- ✓ 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

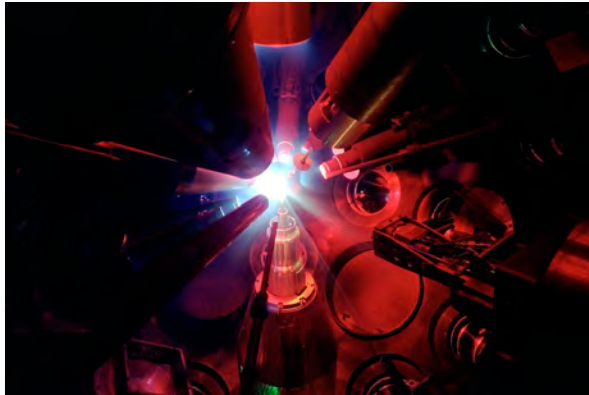


Adam Reyes  
M: CO05.00012

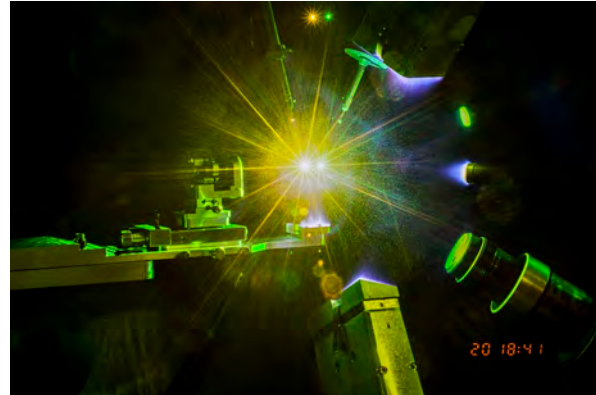
- We have added capabilities in FLASH's hydrodynamics solvers to **capture interfaces in compressible multi-fluid flow using GP-VOF**. Verification on 1D two-fluid Riemann problems shows that FLASH correctly predicts shock speeds while maintaining material interfaces. PLIC reconstruction of interfaces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



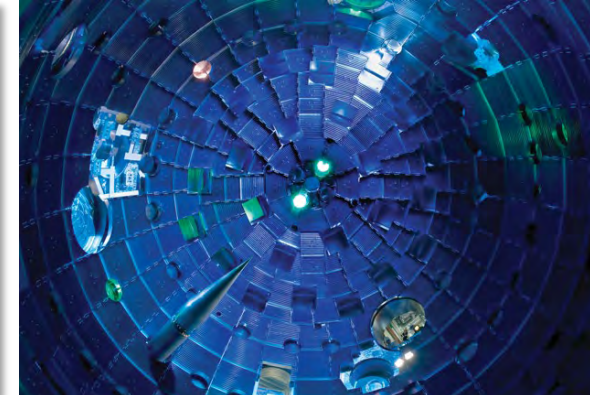
# FLASH is a publicly available code being used by numerous academic groups to design and execute laser-driven HEDP experiments



OMEGA-60 Laser Facility,  
LLE/UR, US



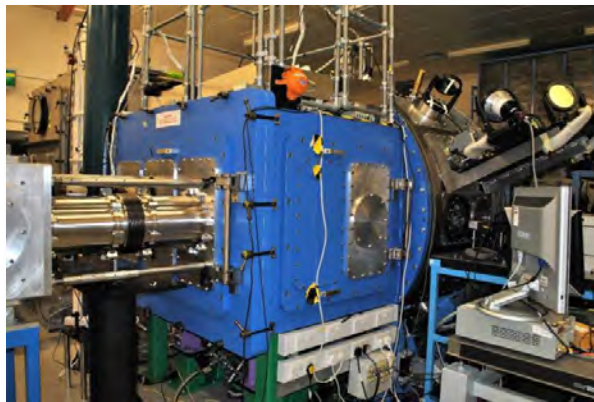
OMEGA-EP Laser Facility,  
LLE/UR, US



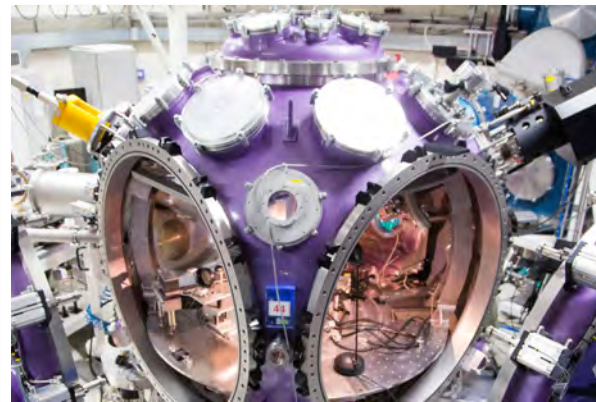
National Ignition Facility (NIF),  
LLNL, US



Jupiter Laser Facility (JLF),  
LLNL, US



Central Laser Facility,  
RAL, UK



LULI Laser Facility, Ecole  
Polytechnique, FR



Megajoule Laser Facility (LMJ),  
CEA, FR

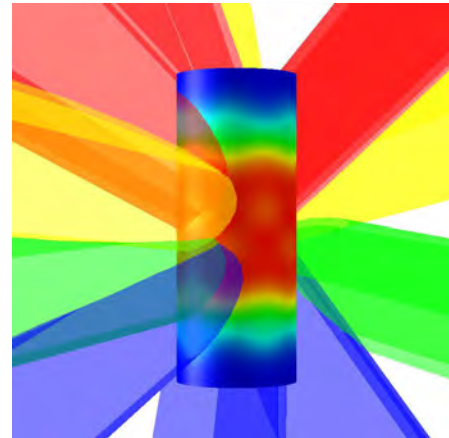
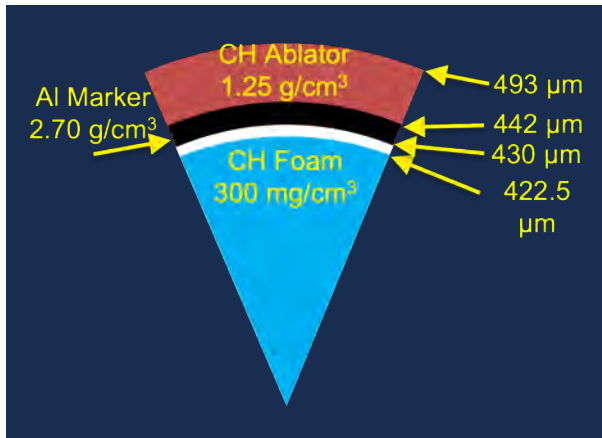


GSI Helmholtz Centre  
for Heavy Ion Research, DE

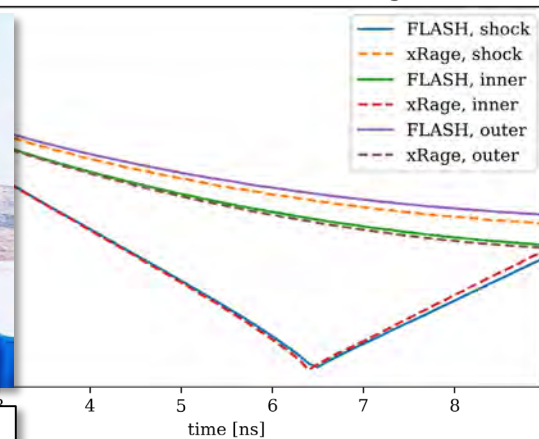


# The FLASH code is continuously verified through code-to-code comparisons and validated against experiments – LANL integrated V&V

Courtesy of J. P. Sauppe, LANL



FLASH (Sesame table, T0=290K) vs xRage (3720)



- 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



ARTICLE

DOI: 10.1038/s41467-019-02953-2

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NEWS RELEASE 11-MAR-2021

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

Laser-driven experiments conducted on the OMEGA laser at the University of Rochester capture for the first time in a laboratory setting the time history of the growth of magnetic fields by the "turbulent dynamo."

Peer-Reviewed Publication  
UNIVERSITY OF ROCHESTER



that, in the presence of a strong magnetic field, significant electron pre-heating is achieved. We demonstrate that the key mechanism in producing these energetic electrons is through the generation of lower-hybrid turbulence via shock-reflected ions. Our experimental results are analogous to many astrophysical systems, including the interaction of a comet with the solar wind, a setting where electron acceleration via lower-hybrid waves is possible.

System has been used in experiments can be used but also for simulation codes a laser-produced plasma with

Departments of Astronomy and Physics, University of Wisconsin, 475 N. Charter Street, Madison, WI 53706, USA  
Received 2020 January 5; revised 2020 February 24; accepted 2020 February 24; published 2020 April 3

### Abstract

Identifying the sources of the highest energy cosmic rays requires understanding how they are deflected by the stochastic, spatially intermittent intergalactic magnetic field. Here we report measurements of energetic charged-particle propagation through a laser-produced magnetized plasma with these properties. We characterize the diffusive transport of the particles experimentally. The results show that the transport is diffusive and that, for the regime of interest for the highest energy cosmic rays, the diffusion coefficient is unaffected by the spatial intermittency of the magnetic field.

Unified Astronomy Thesaurus concepts: High energy astrophysics (739); Ultra-high-energy cosmic radiation (1733); Magnetic fields (994); Laboratory astrophysics (2004); Plasma astrophysics (1261); Intergalactic medium (813); Particle astrophysics (96)

## Time-resolved turbulent dynamo in a laser plasma

Archie F. A. Bott<sup>1,2,\*</sup>, Petros Tzeferacos<sup>3,4,5,6,\*</sup>, Laura Chen<sup>1</sup>, Charlotte A. J. Palmer<sup>1,2</sup>, Alexandra Rigby<sup>1</sup>, Anthony R. Bell<sup>1</sup>, Robert Bingham<sup>1,2,3</sup>, Andrew Birkel<sup>1</sup>, Carlo Graziani<sup>1</sup>, Dustin H. Froula<sup>1,2,3</sup>, Joseph Katz<sup>1,2,3</sup>, Michel Koenig<sup>1,2</sup>, Matthew W. Kunz<sup>1,2</sup>, Chikang Li<sup>1</sup>, Jena Meinecke<sup>1</sup>, Francesco Miniati<sup>1</sup>, Richard Petrasso<sup>1</sup>, Hye-Sook Park<sup>1,2</sup>, Bruce A. Remington<sup>1,2</sup>, Brian Reville<sup>1,2</sup>, J. Steven Ross<sup>1,2</sup>, Dongsu Ryu<sup>1,2</sup>, Dmitri Ryutov<sup>1,2</sup>, Fredrick H. Séguin<sup>1</sup>, Thomas G. White<sup>1</sup>, Alexander A. Schekochihin<sup>1</sup>, Donald Q. Lamb<sup>1</sup>, and Gianluca Gregori<sup>1,2,3,4,5,6</sup>

<sup>1</sup>Department of Physics, University of Oxford, Oxford OX1 3PU, United Kingdom; <sup>2</sup>Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544; <sup>3</sup>Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637; <sup>4</sup>Department of Physics and Astronomy, University of

at Rochester, NY 14623; <sup>5</sup>Lawrence Livermore National Laboratory, Livermore, CA 94550; <sup>6</sup>Department of Physics, University of

the fluctuation dynamo number  $Rm \equiv u_l \tau \eta$  is at a given scale  $l$ , and some critical threshold depends on the plasma (21, 27, 28), defined  $u_l/\nu$  is the fluid Reynolds



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DOI: 10.1038/s41467-019-02953-2

personic pl

White<sup>1,2</sup>, M.T. Oliver<sup>1,2</sup>, Bingham<sup>1,2,3</sup>, R. Clarke<sup>1,2</sup>, J. F. Lamb<sup>1</sup>, J. Meinecke<sup>1</sup>, Th. Selwood<sup>1</sup>, J. Squire<sup>1,2</sup>, Gregori<sup>1</sup>

properties of supersonic, cold terrestrial and astrophysical

compressible turbulence plays a vital role in star formation and the evolution of our galaxy. Observations of the density and velocity power spectra in the Orion B and Perseus molecular clouds show large deviations from those predicted for incompressible turbulence. Hydrodynamic simulations attribute this to the high Mach number in the interstellar medium (ISM), although the exact details of this dependence are not well understood. Here we investigate experimentally the statistical behavior of boundary-free supersonic turbulence created by the collision of two laser-driven high-velocity turbulent plasma jets. The Mach number dependence of the slopes of the density and velocity power spectra agree with astrophysical observations, and supports the notion that the turbulence transitions from being Kolmogorov-like at low Mach number to being more Burgers-like at higher Mach numbers.

## Inefficient Magnetic-Field Amplification in Supersonic Laser-Plasma Turbulence

A. F. A. Bott<sup>1,2,\*</sup>, L. Chen<sup>1</sup>, G. Boutoux<sup>1</sup>, T. Caillaud<sup>1</sup>, A. Duval<sup>1</sup>, M. Koenig<sup>1,2,3</sup>, B. Khair<sup>1</sup>, I. Lantuejoul<sup>1,2</sup>, L. Le-Deroff<sup>1</sup>, B. Reville<sup>1,2,3</sup>, R. Rosch<sup>1</sup>, D. Ryu<sup>1,2</sup>, C. Spindloe<sup>1,2</sup>, B. Vauzour<sup>1</sup>, B. Villette<sup>1</sup>, A. A. Schekochihin<sup>1,11</sup>, D. Q. Lamb<sup>1</sup>, P. Tzeferacos<sup>1,6,12,13</sup>, G. Gregori<sup>1</sup>, and A. Casner<sup>1,3,14</sup>

<sup>1</sup>Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom  
<sup>2</sup>Department of Astrophysical Sciences, University of Princeton, 4 Ivy Lane, Princeton, New Jersey 08544, USA  
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<sup>4</sup>LULI, CNRS, CEA, Ecole Polytechnique, UPMC, Sorbonne Universités, Institut Polytechnique de Paris, F-91128 Palaiseau cedex, France

<sup>5</sup>Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan

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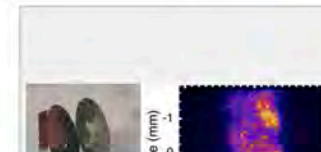
## Researchers unravel the inner workings of heat conduction in galaxy clusters

Peer-Reviewed Publication  
UNIVERSITY OF OXFORD



University of Oxford Press Release

The inner workings of heat conduction in galaxy clusters have been unravelled by a collaboration of international researchers led by the University of Oxford, University of



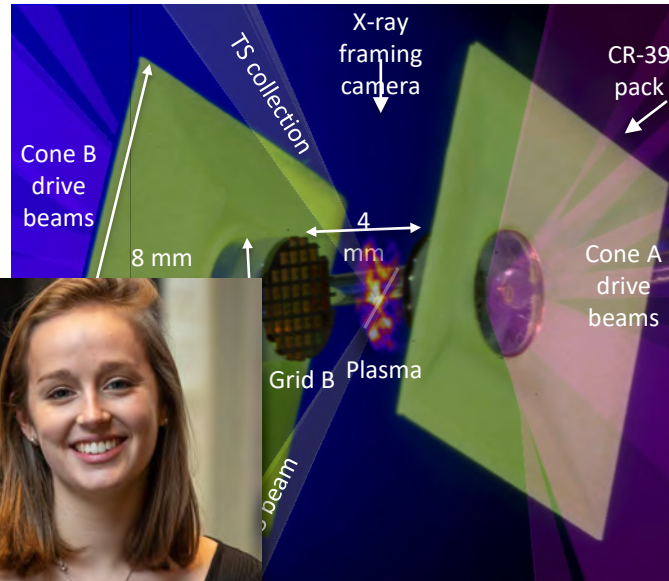
Galaxy clusters, where observed temperature profiles are explainable only in the presence of a strong suppression of heat conduction compared to Spitzer's theory. To address this problem, we have created a replica of such a system in a laser laboratory experiment. Our data show a reduction of heat transport by two orders of magnitude or more, leading to large temperature variations on small spatial scales (as is seen in cluster plasmas).

### INTRODUCTION

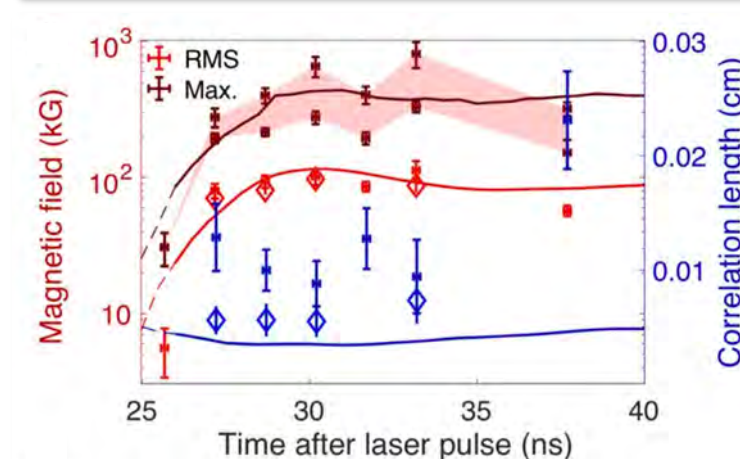
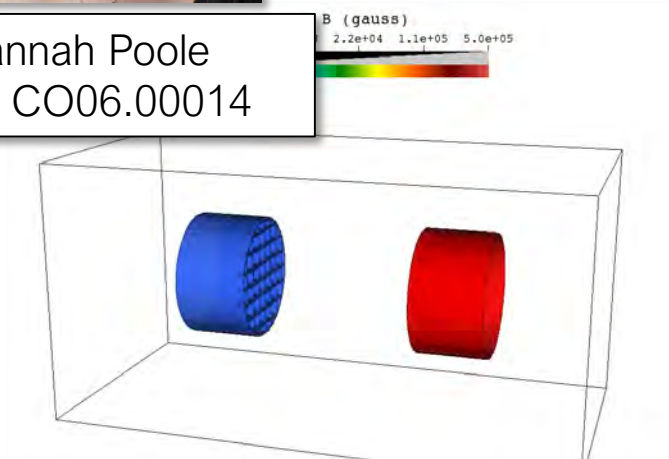
Galaxy clusters are filled with hot, diffuse x-ray emitting plasma, with a magnetically tangled magnetic field whose energy is close to equipartition with the energy of the turbulent motions (1, 2). In the cluster cores, the temperatures remain anomalously high compared to what might be expected considering that the radiative cooling time is short relative to the Hubble time (3, 4). While feedback from the central active galactic nuclei (AGN) (5–7) is believed to provide most of the

stack, in local magnetic mirrors (12), alignment of local temperature gradients perpendicular to magnetic fields (13), and plasma instabilities such as whistler waves (14, 15). For these processes to occur, the electron's Larmor radius must be small compared to its gyroviscosity mean free path, enabling microscale changes in the electron heat transport to alter the global properties of the plasma dynamics. Numerical simulations are able to address these issues fully (16, 17), as comprehensive modelling of all the physical processes present at different scales

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



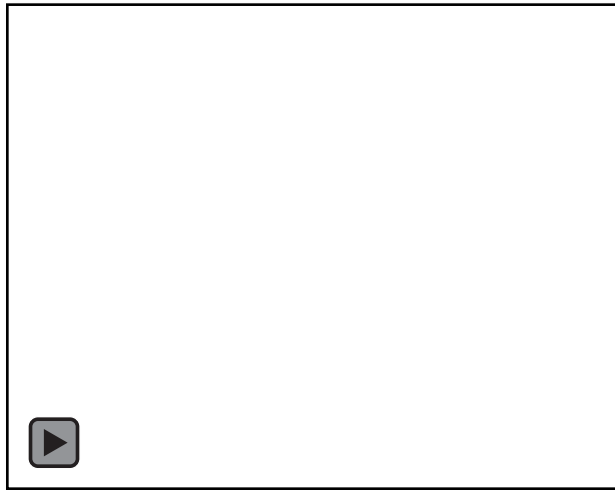
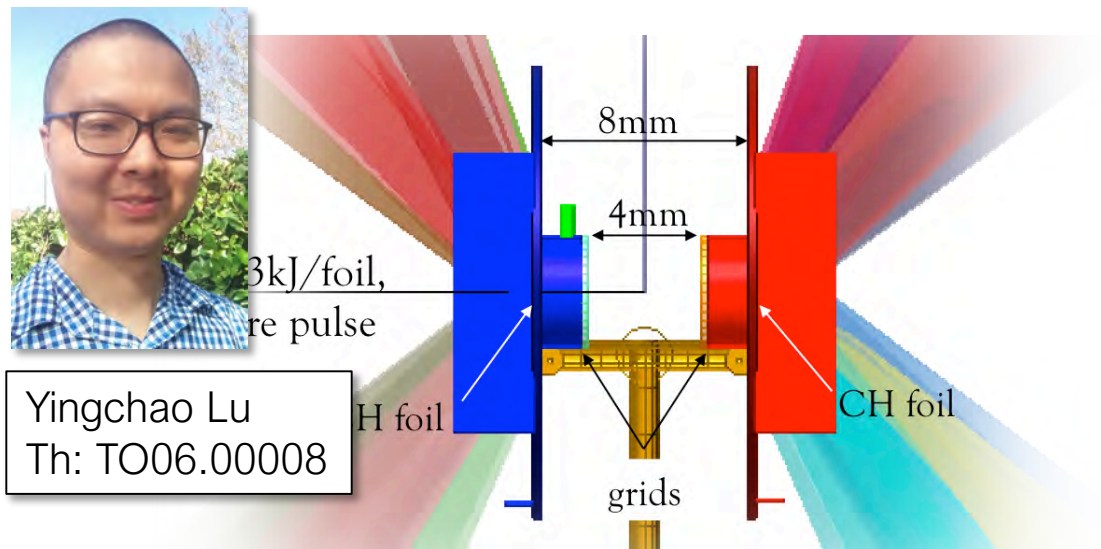
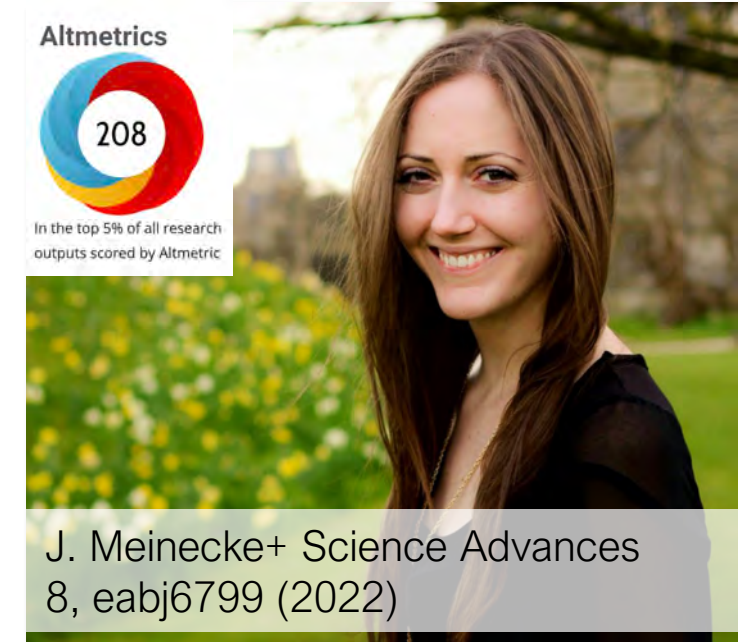
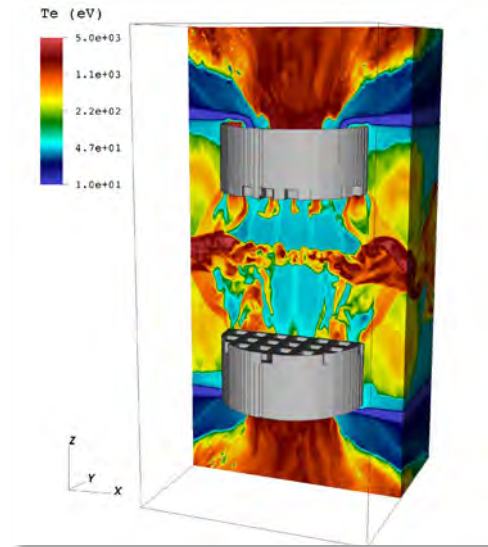
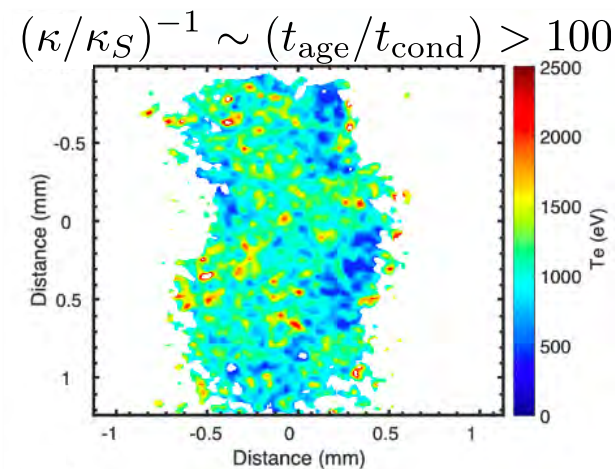
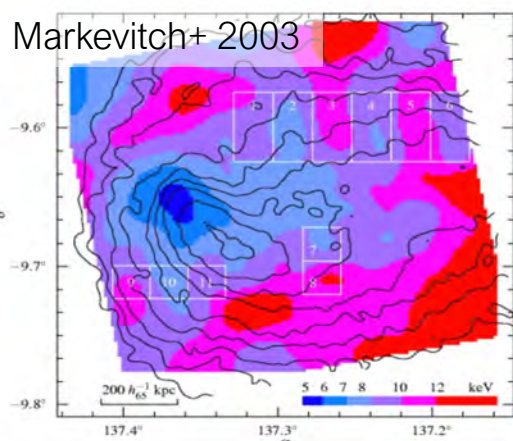
Hannah Poole  
M: CO06.00014



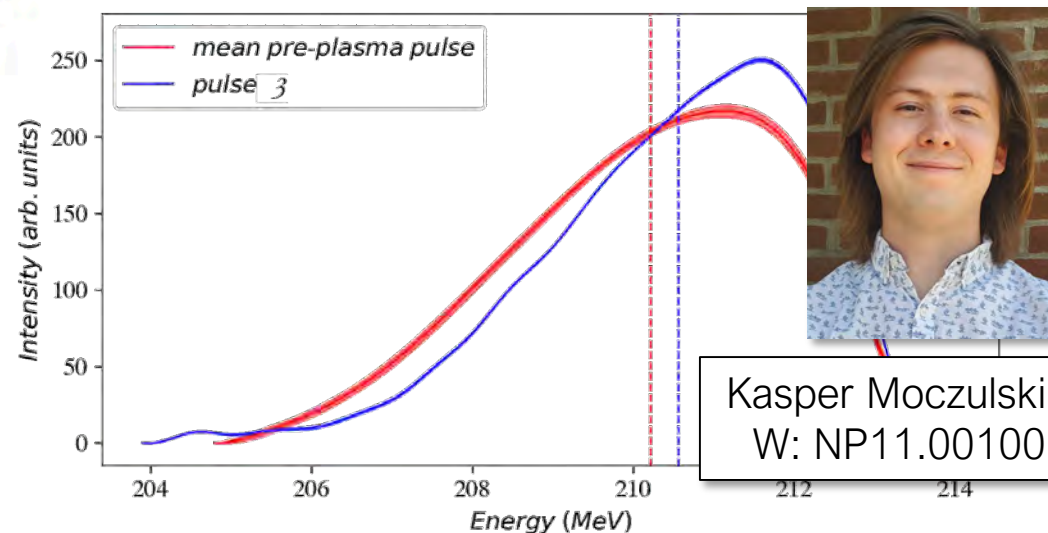
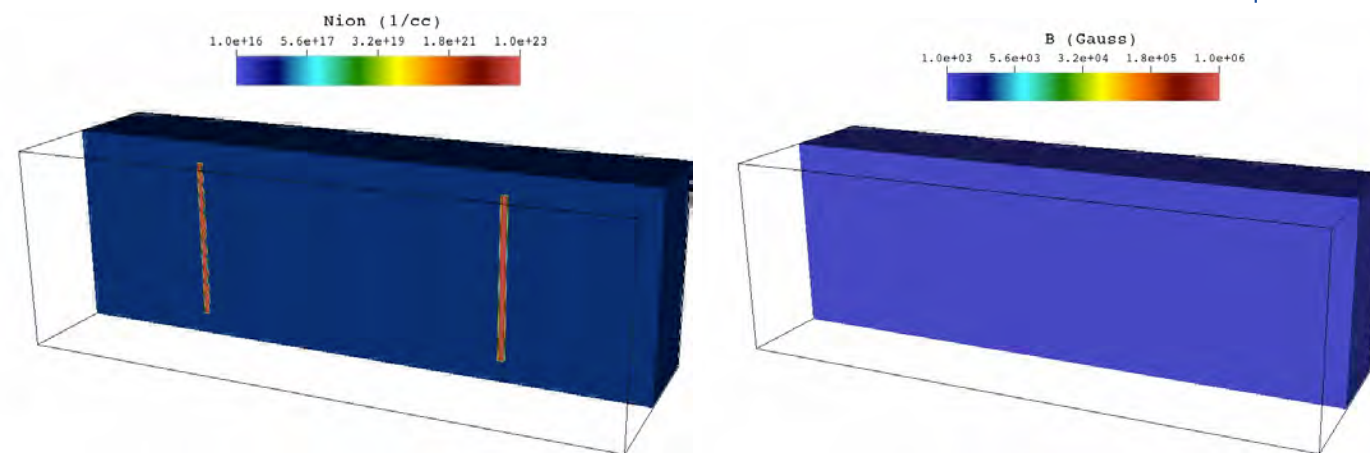
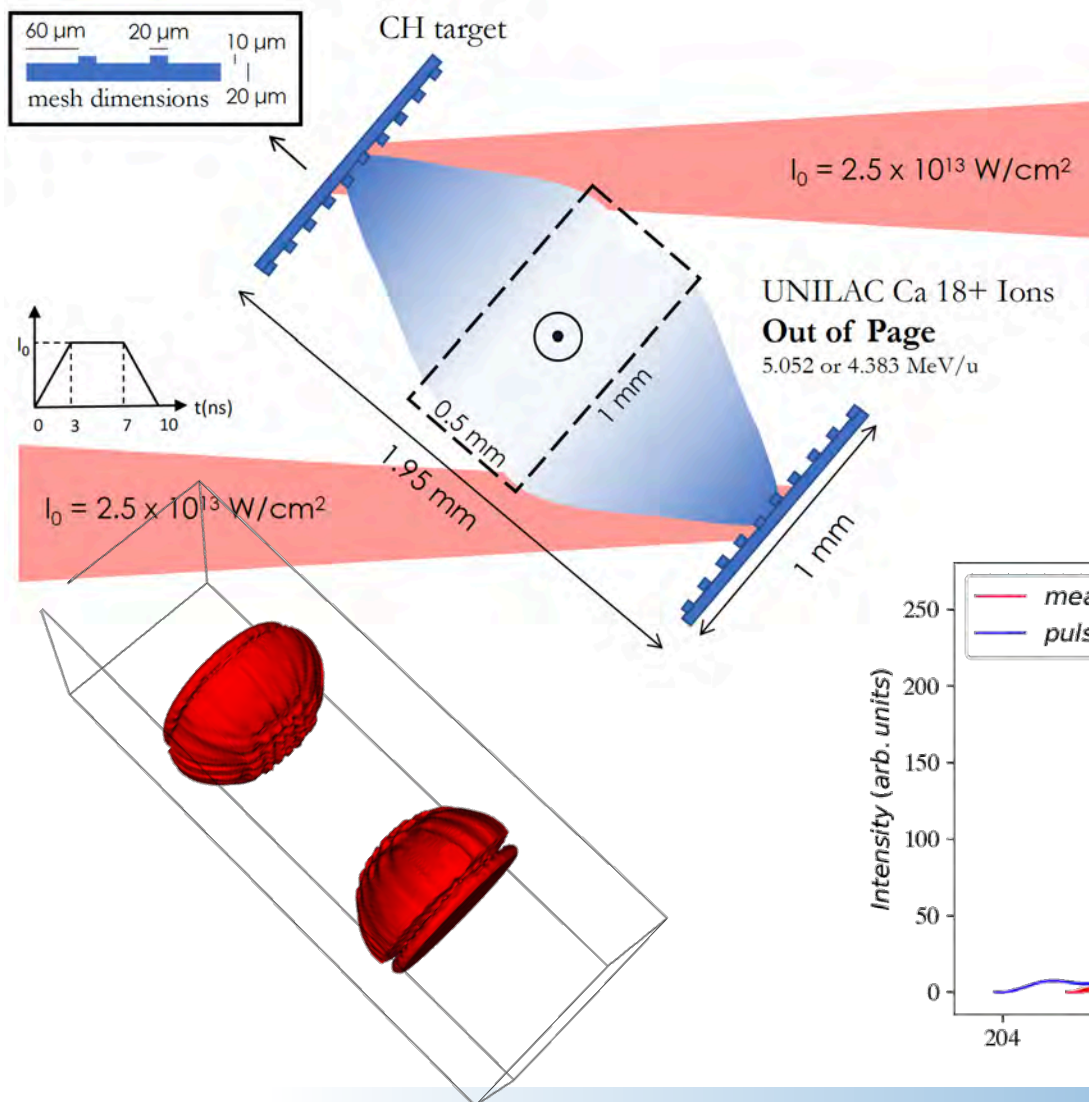
A. Bott+ Proceedings of the National Academy of Sciences  
118, e2015729118 (2021)



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



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



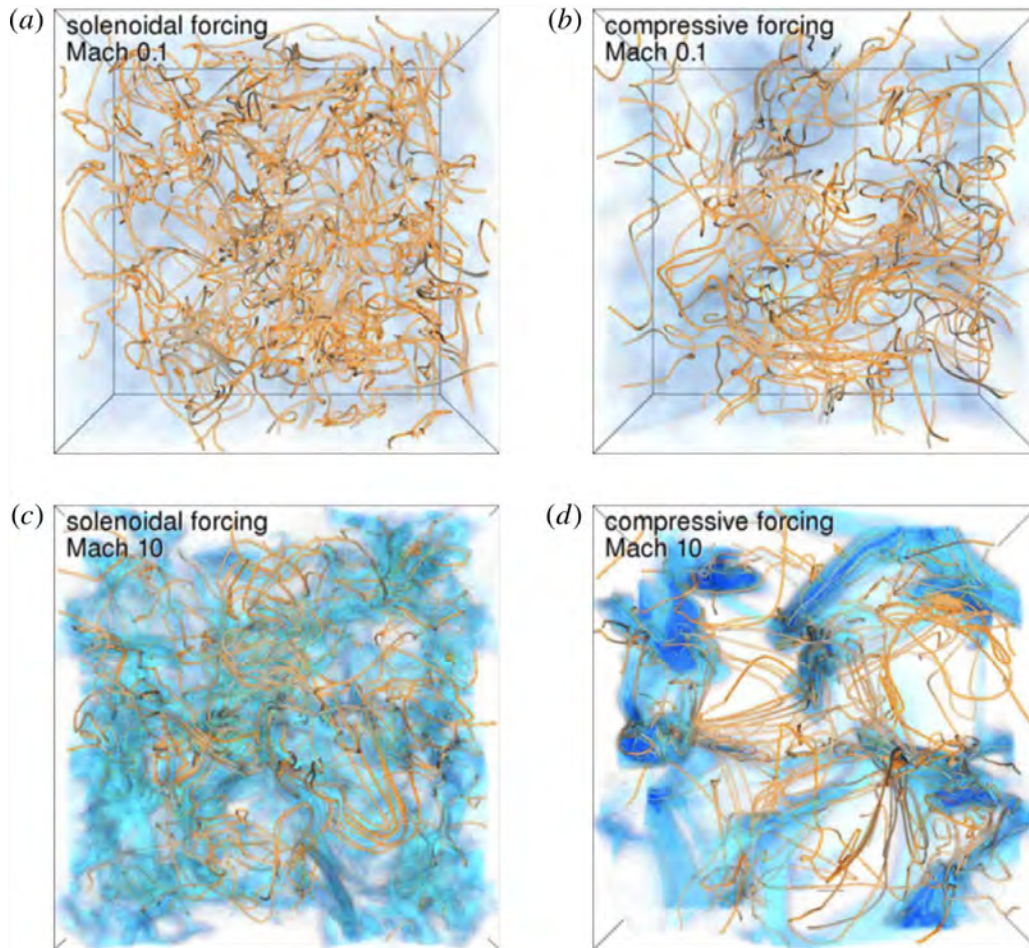
Kasper Moczulski  
W: NP11.00100



Thomas Campbell  
T: GO07.00009



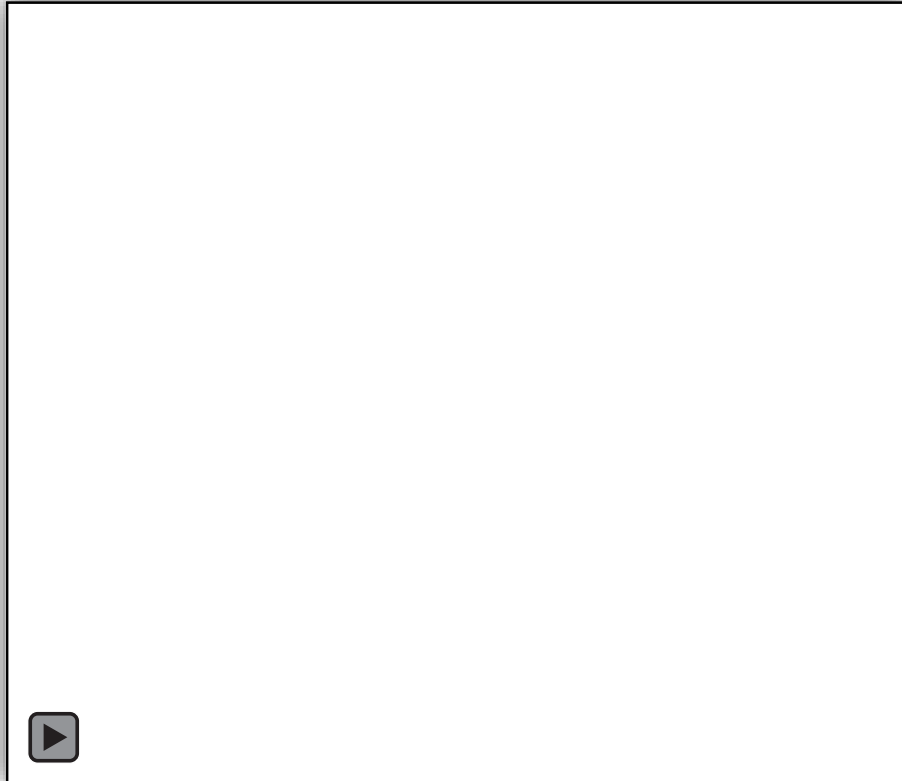
# U.S. DOE Office of Science/FES: Driven HED turbulence to design validation TDYNO experiments



- 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.

Federrath+ PRL 2011  
Federrath JPP 2016

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



Abigail Armstrong  
W: NP11.00084

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

effort 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.

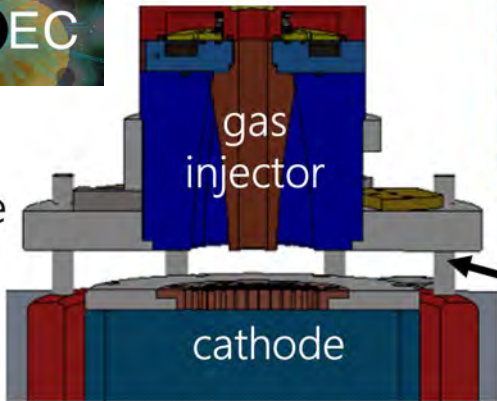
- 3T driven turbulence simulations with the FLASH code. Shown is a 2D slice (density in  $\text{g cm}^{-3}$ ) of the 3D simulation using FLASH's 3T hydro solver.

- 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.

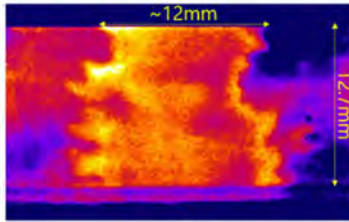


# The Flash Center is part of the NNSA Center of Excellence Center for Matter under Extreme Conditions (CMEC)

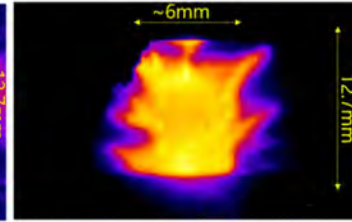
- Expansion and verification of the FLASH code physics capabilities: **extended CMEC**



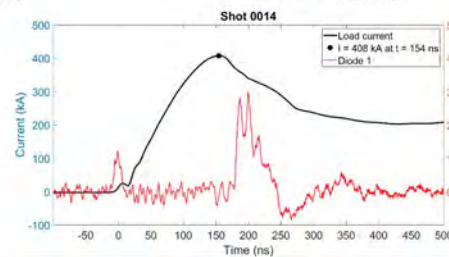
Courtesy: Fabio Conti (Conti+ IEEE 2018)



t = 155 ns



t = 175 ns



Change in Material Properties Under  
**EXTREME CONDITIONS**  
Temperature, Pressure & Magnetic Field

**SYNERGISTIC PHYSICS**  
Laser Plasma Interactions, Shocks,  
Conductivity, Equation of State,  
Radiation, Magnetic Fields  
& Energetic Particles

**TOOLS**  
High Power Lasers, Pulsed Power  
Z-Pinch, Targets, Diagnostics  
& Modeling Codes

**APPLICATIONS**  
Planetary Physics  
& Astrophysical Plasmas

**THRUST 2**  
**MATERIAL**  
**PROPERTIES**  
**ACROSS HED**  
**REGIME**  
UC Berkeley, UC Davis  
& UC San Diego

**THRUST 3**  
**NATURE UNDER**  
**EXTREME**  
**CONDITIONS**  
UC San Diego, UC Los Angeles,  
UC Davis, U. Rochester  
& General Atomics



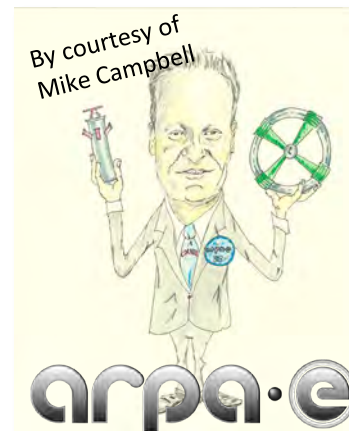
David Michta  
F: YO04.00002

- Implementation of **algorithmic modeling**
- Numerical modeling of **pulsed-power drive**

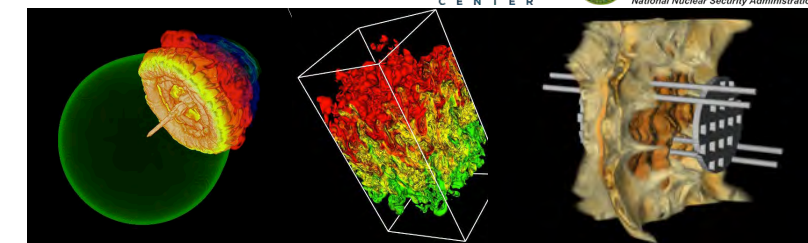


# The Flash Center assembles a theory/modeling Capability Team at the University of Rochester for the U.S. DOE ARPA-E BETHE program

- 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.**

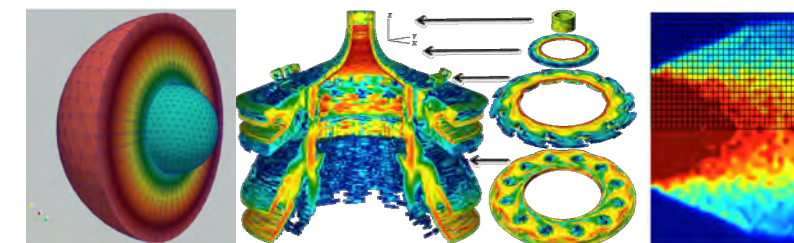


FLASH code



Multi-physics AMR MHD code for HEDP

TriForce

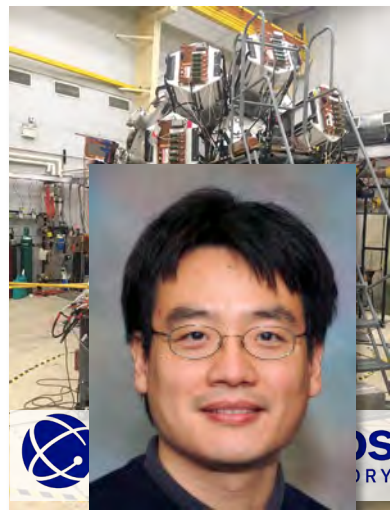


Meshless fluid/kinetic hybrid simulation tool

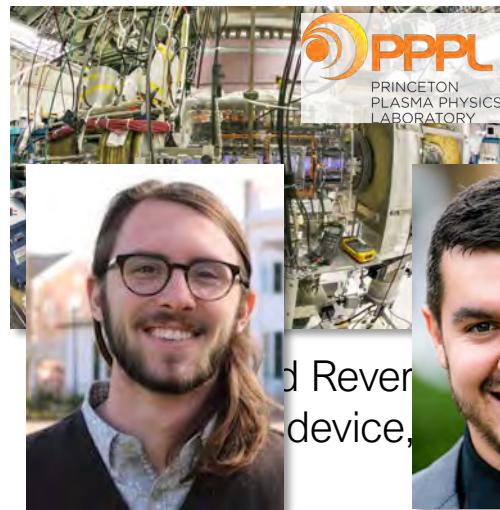
OSIRIS



relativistic, massively parallel PIC code



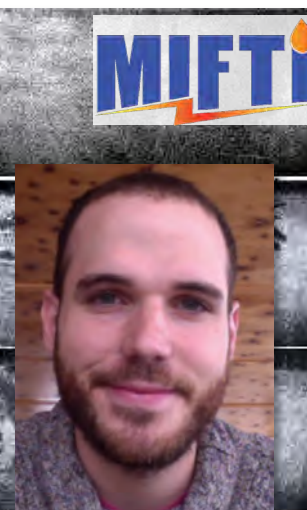
PLX  
Chuang Ren  
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F: YO04.00004



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.

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