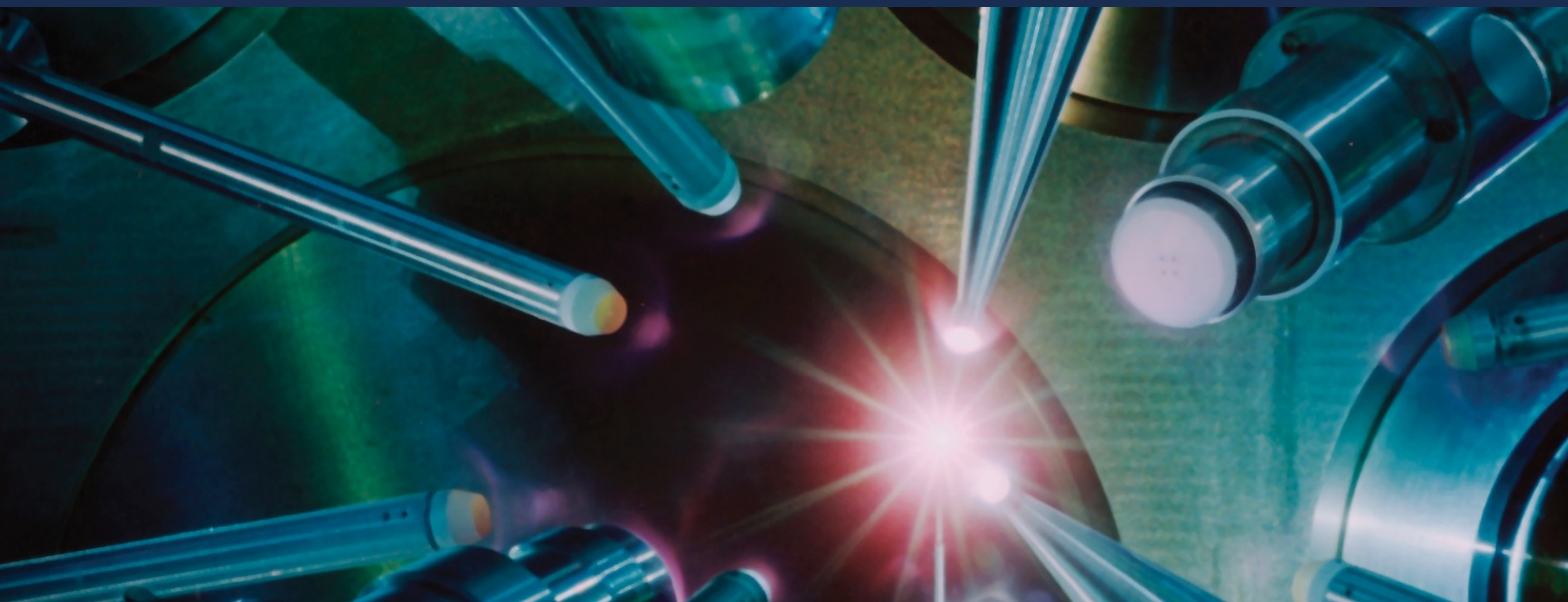
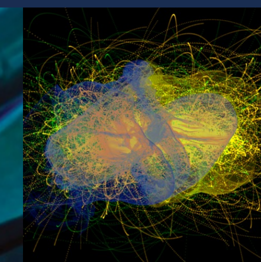
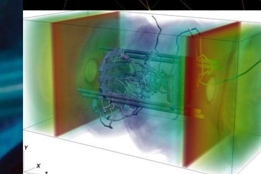
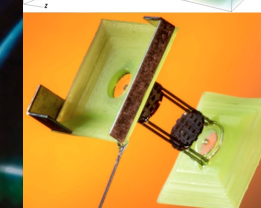
Strong Suppression of Heat Conduction in Laser-driven Magnetized Turbulent Plasmas









Petros Tzeferacos

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

63rd Annual Meeting of the
APS Division of Plasma Physics
November 8–12, 2021
Pittsburgh, PA
Abstract: UO03.00010

TDYNO Collaboration

P Tzeferacos, **A Reyes**, **Y Lu**, A Armstrong, K Moczulski

G Gregori, **J Meinecke**, **H Poole, L Chen**, T Campbell, A Bell, S Sarkar, F Miniati, **A Schekochihin**

D Lamb

D Froula, J Katz, D Haberberger, D Turnbull, S Fess *(and all LLE staff really!)*

H-S Park, **JS Ross**, T Doeppner, J Emig, C Goyon, D Ryutov, B Remington, A Zylstra

C-K Li, A Birkel, R Petrasso, H Sio, F Seguin

A Bott (Princeton), **C Palmer** (QUB), **B Khiar** (ONERA), **S Feister** (CSUCI), **A Casner** (CEA), D Ryu (Unist), B Reville (MP), C Forest (U Wisconsin), J Foster (AWE), Y Sakawa (Osaka), F Fiuza (SLAC),E Churazov (MPIA), R Bingham (RAL), T White (U Nevada Reno), E Zweibel (U Wisconsin)

Thanks to our sponsors

- DOE NNSA, DOE Office of Science, NSF, EPSRC
- DOE's INCITE & ALCC (@ANL), NLUF (@LLE) & DS (@LLNL)
- DOE NNSA NLUF: **DE-NA0002724, DE-NA0003605, DE-NA0003934**
- NSF/DOE Partnership in Basic Plasma & Engineering: **PHY-2033925**
- and General Atomics for target R&D and manufacturing!

Summary

- The advent of high-power lasers has opened **new fields of plasma physics research** and has enabled the reproduction of **astrophysical environments in the laboratory**.

- The TDYNO platform, which was designed with FLASH simulations to **demonstrate fluctuation dynamo in the lab for the first time**, at the Omega Laser Facility at the Laboratory for Laser Energetics (Tzeferacos+ 2018), has been successfully ported onto the **National Ignition Facility** (Meinecke et al. submitted, arXiv:2105.08461).

- The NIF experiments achieve fluctuation dynamo in the **large magnetic Prandtl number regime**, an experimental replica for the magnetized turbulence in the IGM.

- The **strong magnetic fields** generated in the experiments resulted in a **reduction of local heat transport by two orders of magnitude or more**, leading to strong temperature variations on small spatial scales, as is seen in cluster plasmas (Markevitch+ 2003).

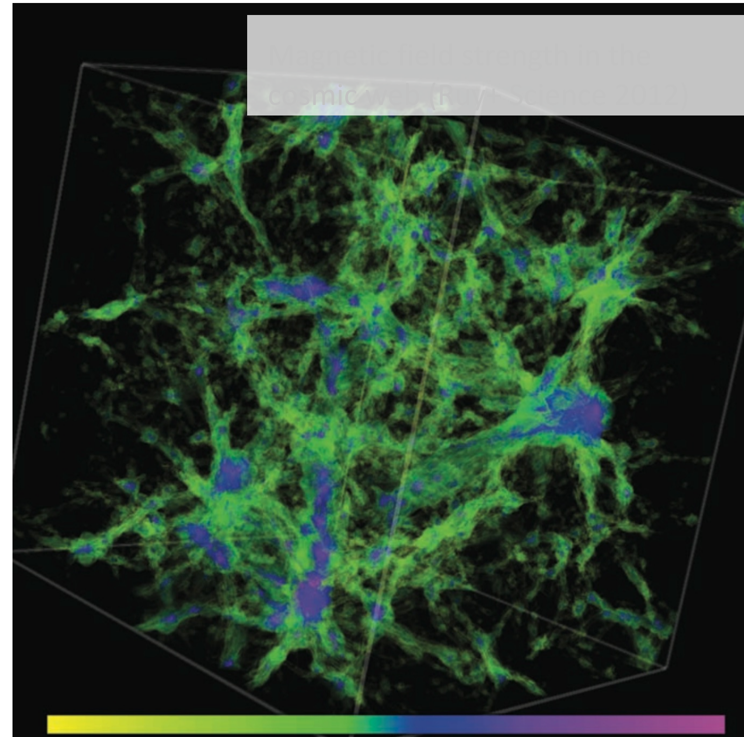
Thermal transport in turbulent magnetized plasmas

- Galaxy clusters are diffuse, turbulent magnetized plasmas.

- In cluster cores, **the temperatures remain anomalously high** compared to what might be expected, given that **the cooling time is short** relative to the Hubble time.

- While feedback from the central active galactic nuclei is believed to provide most of the heating, there has been **a long debate** as to whether conduction of heat from the bulk to the core might help the core reach observed temperatures.

- Thermal conduction in magnetized, weakly collisional plasmas is **a longstanding problem in ICF and fusion research.**



Magnetic field strength in the cosmic web (Ruy+ Science 2012)

Courtesy of NASA/CXC/Un
Chicago, Zhuravleva *et*

TDYNO Collaboration

UNIVERSITY of ROCHESTER

UNIVERSITY OF OXFORD

- ✓ Magnetized turbulence & fluctuation dynamo
- ✓ Cosmic ray physics

TDYNO concerted effort

Astrophysical phenomena & astrophysical systems	*Pm=Rm/Re*	*Cs*	Facility	Dates
Subsonic turbulence: SN shocks, Coma cluster, ISM	< 1	< 1	Vulcan (UK)	2013-2014
Subsonic dynamo: ISM, stars, planets, accretion disks	$< 1, \gtrsim 1$	< 1	OMEGA (USA)	2015-present
UHECR transport in turbulent magnetic fields: CR	< 1	< 1	OMEGA (USA)	2016-2020
Subsonic dynamo: IGM, galaxies, galaxy clusters	$\mathbf{> 1}$	$\mathbf{< 1}$	**NIF (USA)**	**2016-present**
Supersonic turbulence: GMCs, ISM, star formation	< 1	> 1	Vulcan (UK)	2016
Supersonic dynamo: GMCs, ISM, star formation	< 1	> 1	OMEGA (USA)	[illegible]
Supersonic turbulence: GMCs, ISM, star formation	< 1	> 1	LMJ (France)	[illegible]
Second order Fermi: CR	< 1	< 1	GSI (Germany)	[illegible]
NRH instability: CR	< 1	< 1	OMEGA+EP (USA)	[illegible]-present

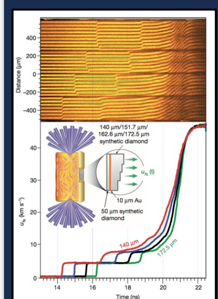
Meinecke et al. submitted (arXiv:2105.08461)

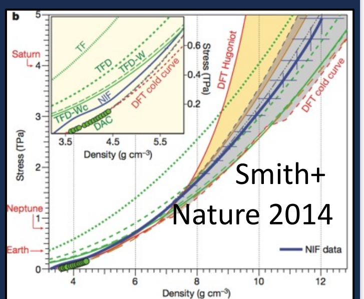
NIF Discovery Science and Laboratory Astrophysics

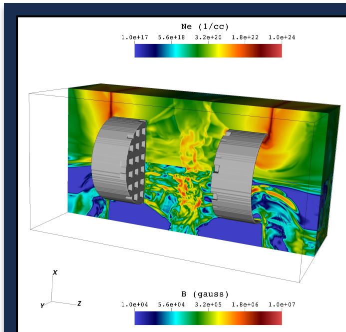
Planetary Science
Planet interiors, equation of state, phase transitions, material properties

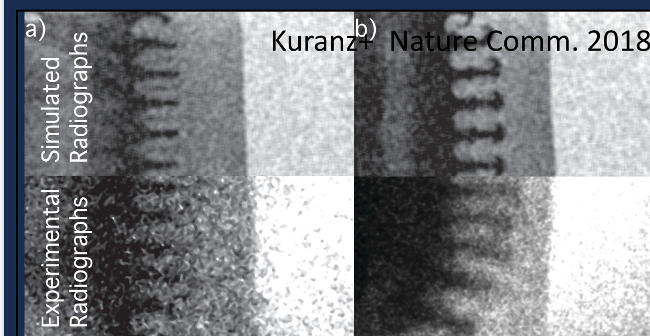
Laboratory Plasma Astrophysics
Shocks, turbulence, particle acceleration and transport, hydro and MHD instabilities

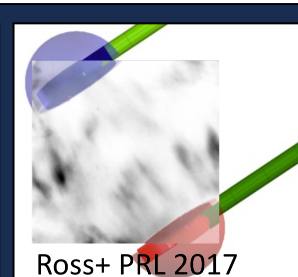
Nuclear Astrophysics
Nuclear reaction rates and cross sections in stellar interiors, s- and r-processes

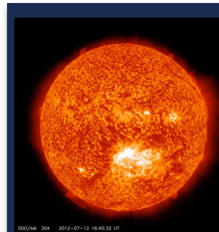


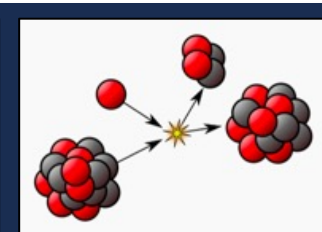


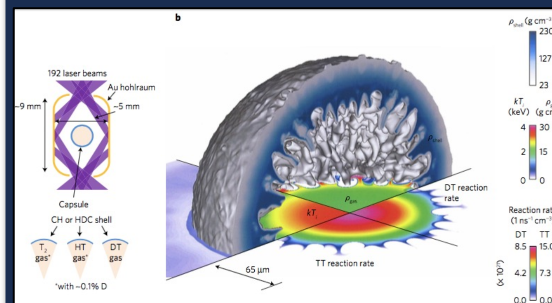


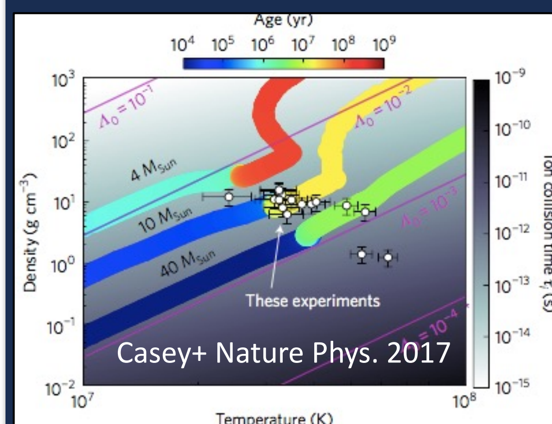








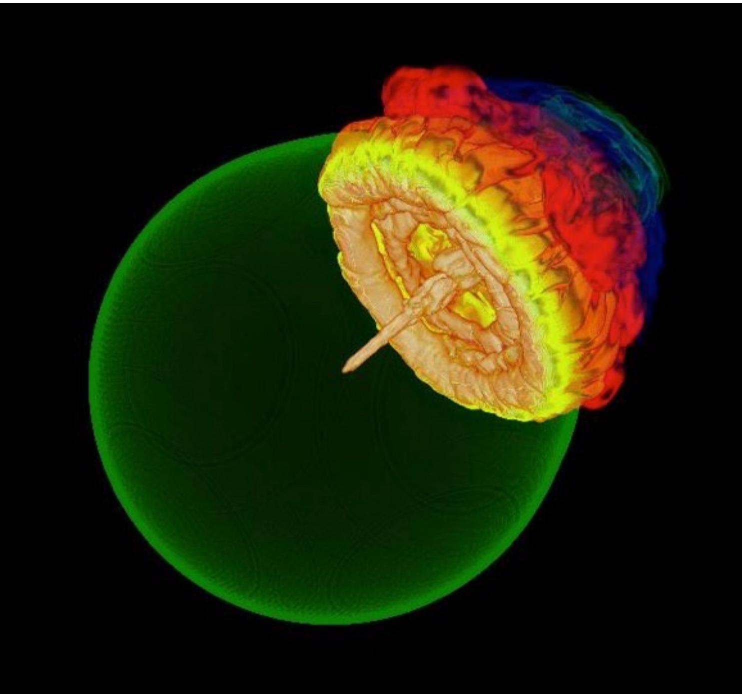


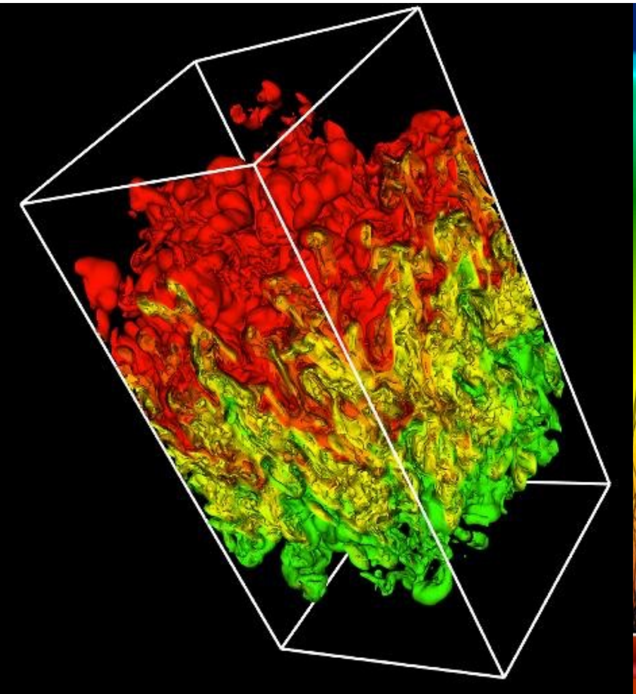


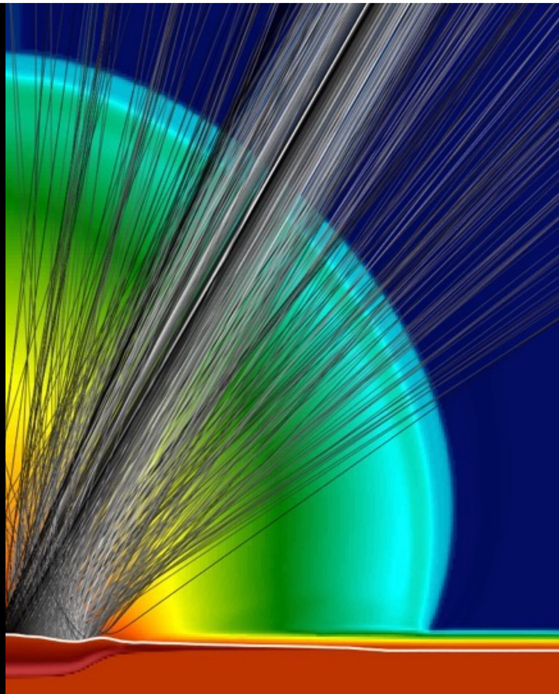
The FLASH code

- FLASH (Fryxell+ 2000) is a publicly available, high-performance computing (HPC), adaptive mesh refinement (AMR), finite-volume, radiation MHD code with extended physics capabilities (Tzeferacos+ 2015). Supported primarily by the **U.S. DOE NNSA, LANL, and LLNL.**
- FLASH is professionally managed software in continuous development for 20 years: coding standards; version control; daily automated regression testing; extensive documentation; user support; integration of contributions from external users.

> 3,500 users worldwide   **flash.rochester.edu**   **>1,200 papers published with FLASH**

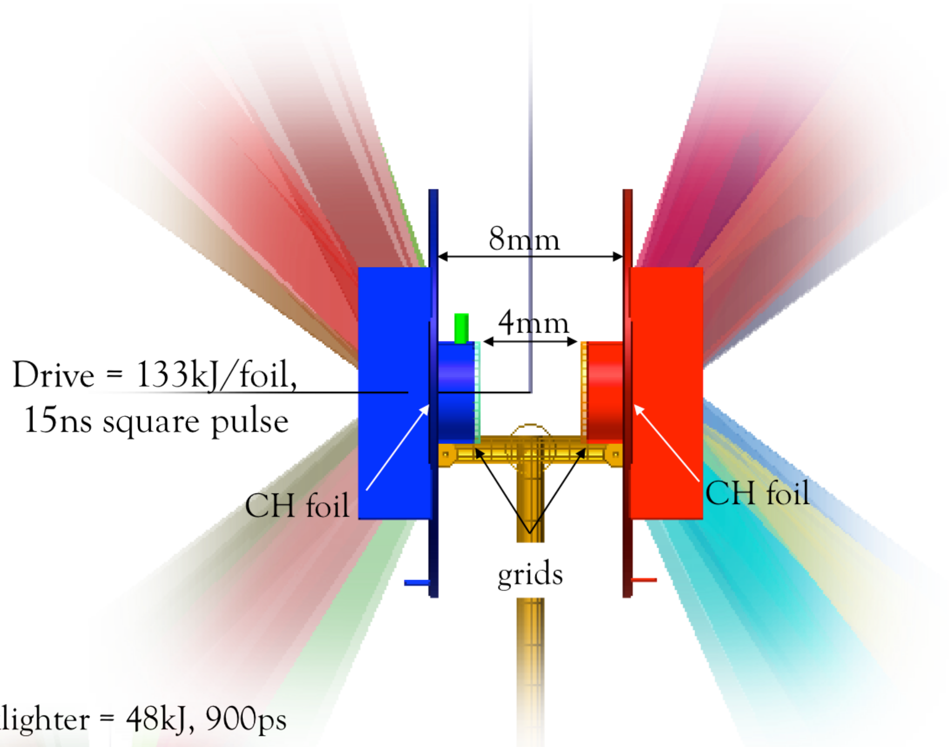


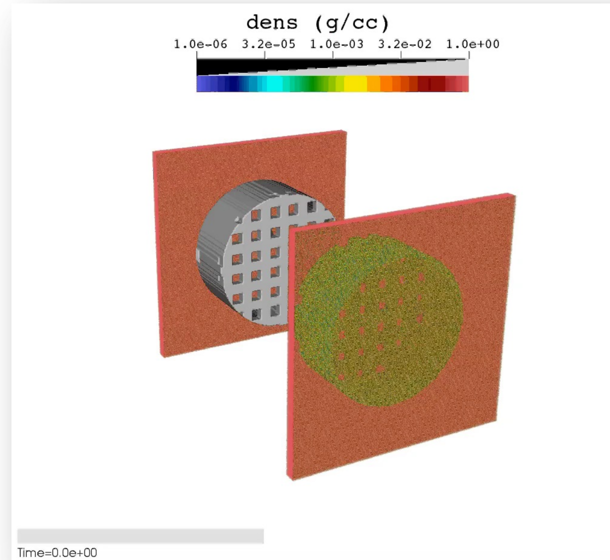


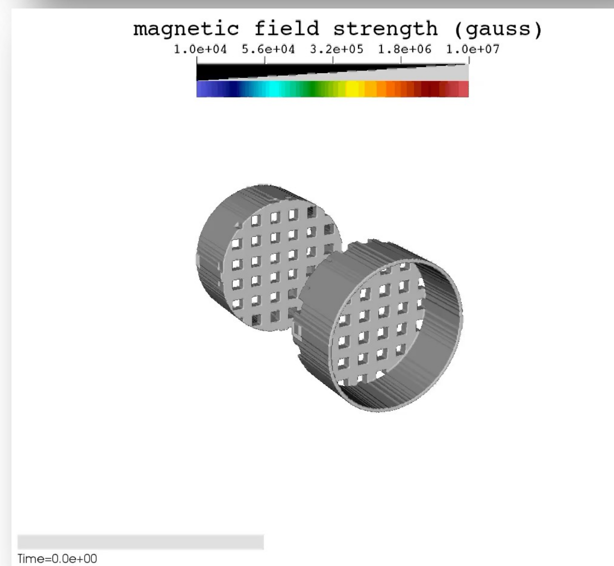


NIF TDYNO platform

Meinecke+ submitted (arXiv:2105.08461)







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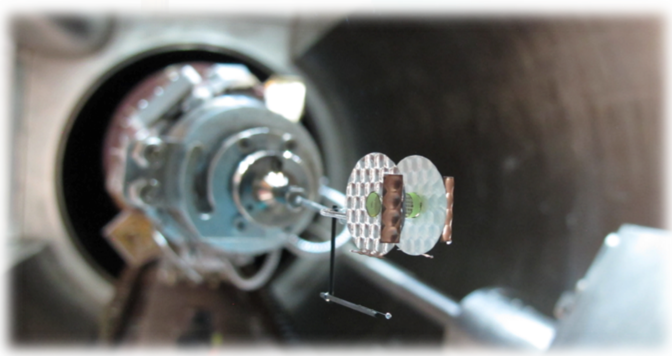
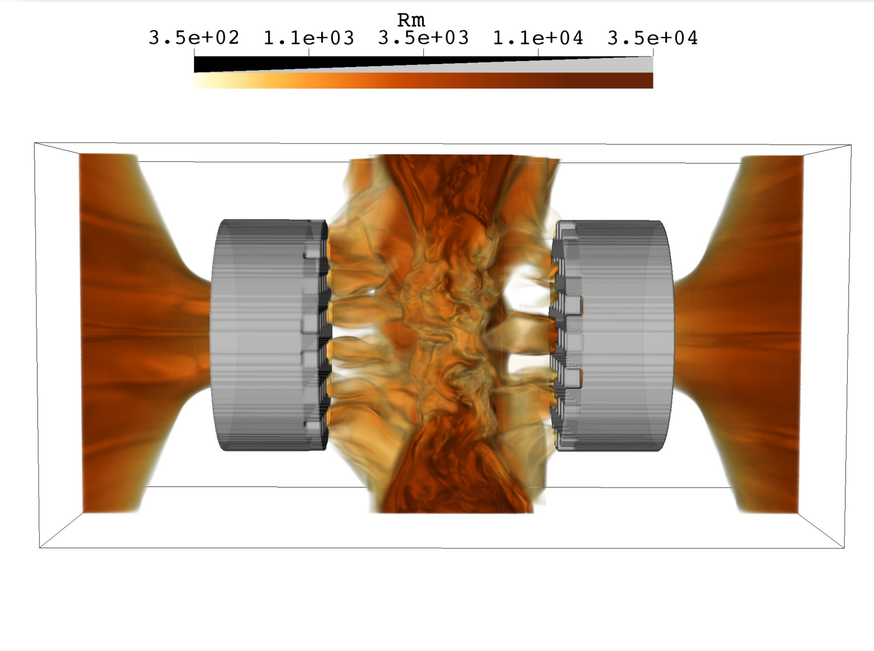
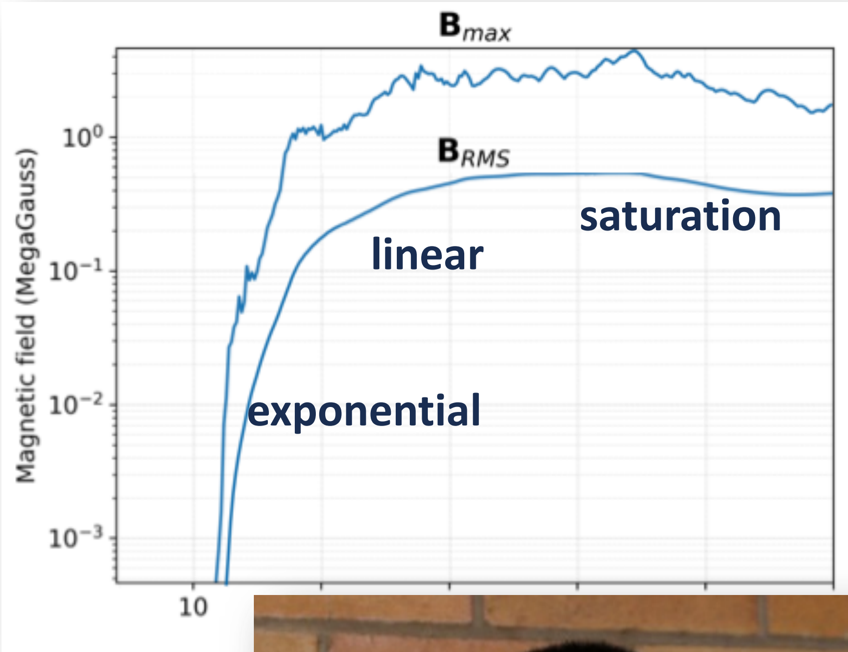


FLASH: plasma state and B-fields

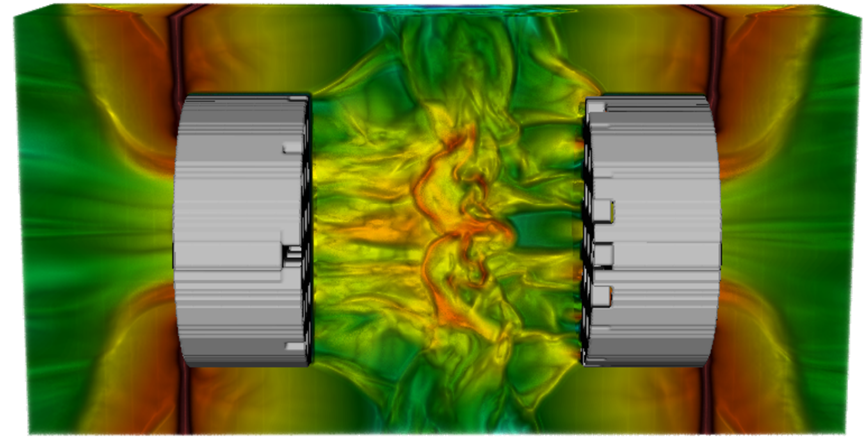


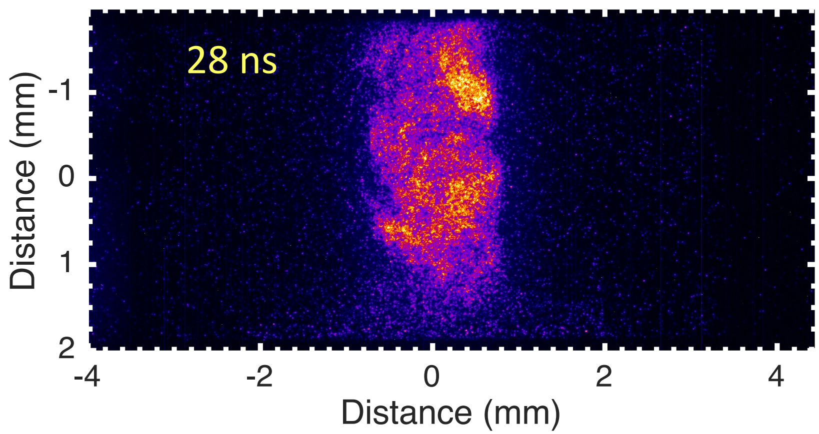


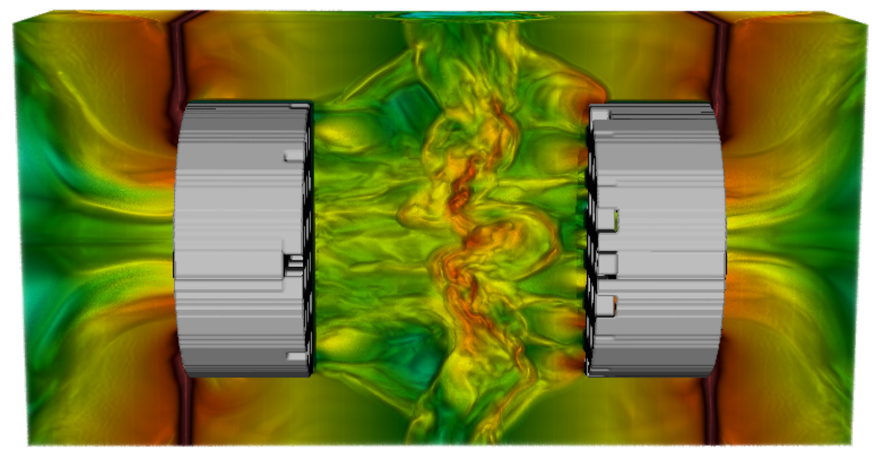
- The FLASH simulations (Feister+ to be submitted) state with $Pm >> 1$ and an outer scale $L \sim 600$ μ characterized by Rm in the **thousands**, orders of (Schekochihin+ 2004)

- Within a few ns ($t_{eddy} \sim L / u \sim$ **3 ns**) the B-field r amplification saturates when the magnetic energ available kinetic energy (RMS)

X-ray imaging



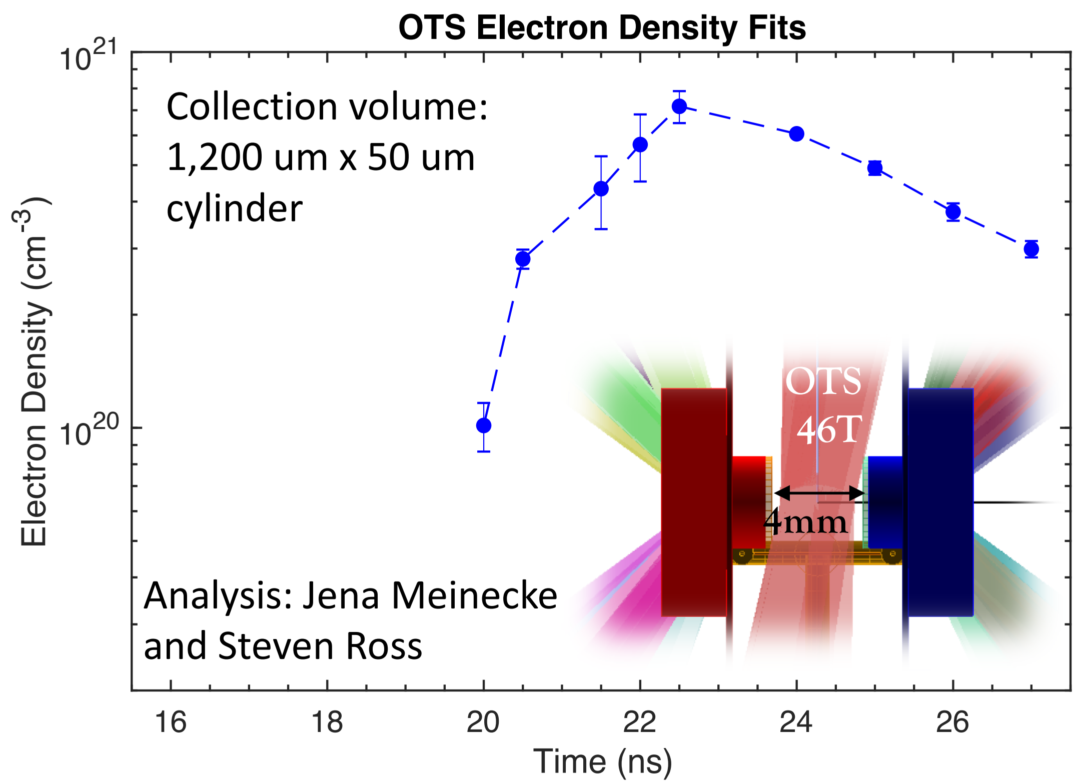




- X-ray imaging shows the formation of a wide (~ 4 mm), thick (~ 1-2 mm), turbulent interaction region after the interaction of the counter-propagating plasma flows

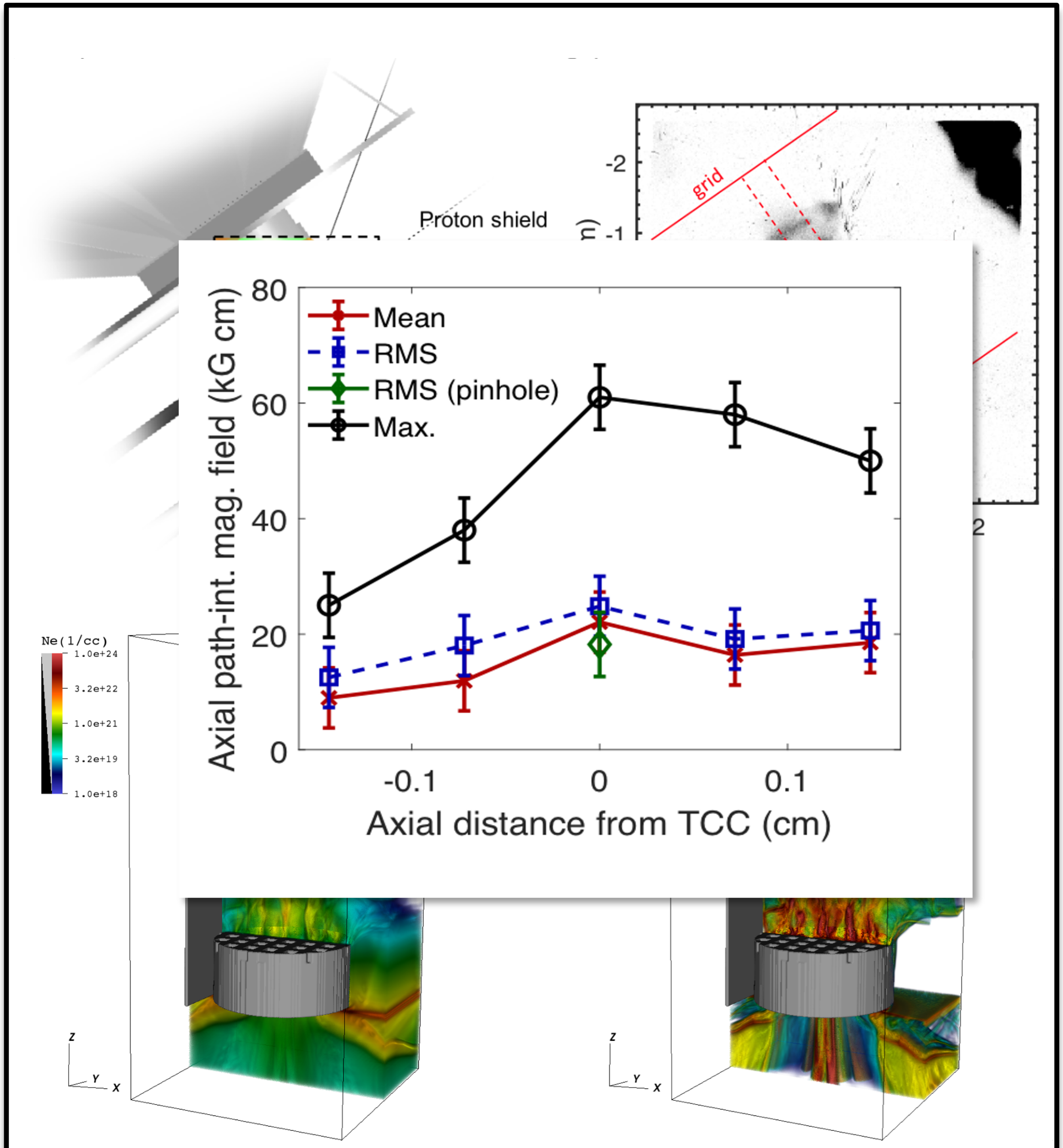
Experimental plasma properties

- The TDYNO campaign fielded NIF's new OTS diagnostic to measure the electron density from the EPW wavelength shifts



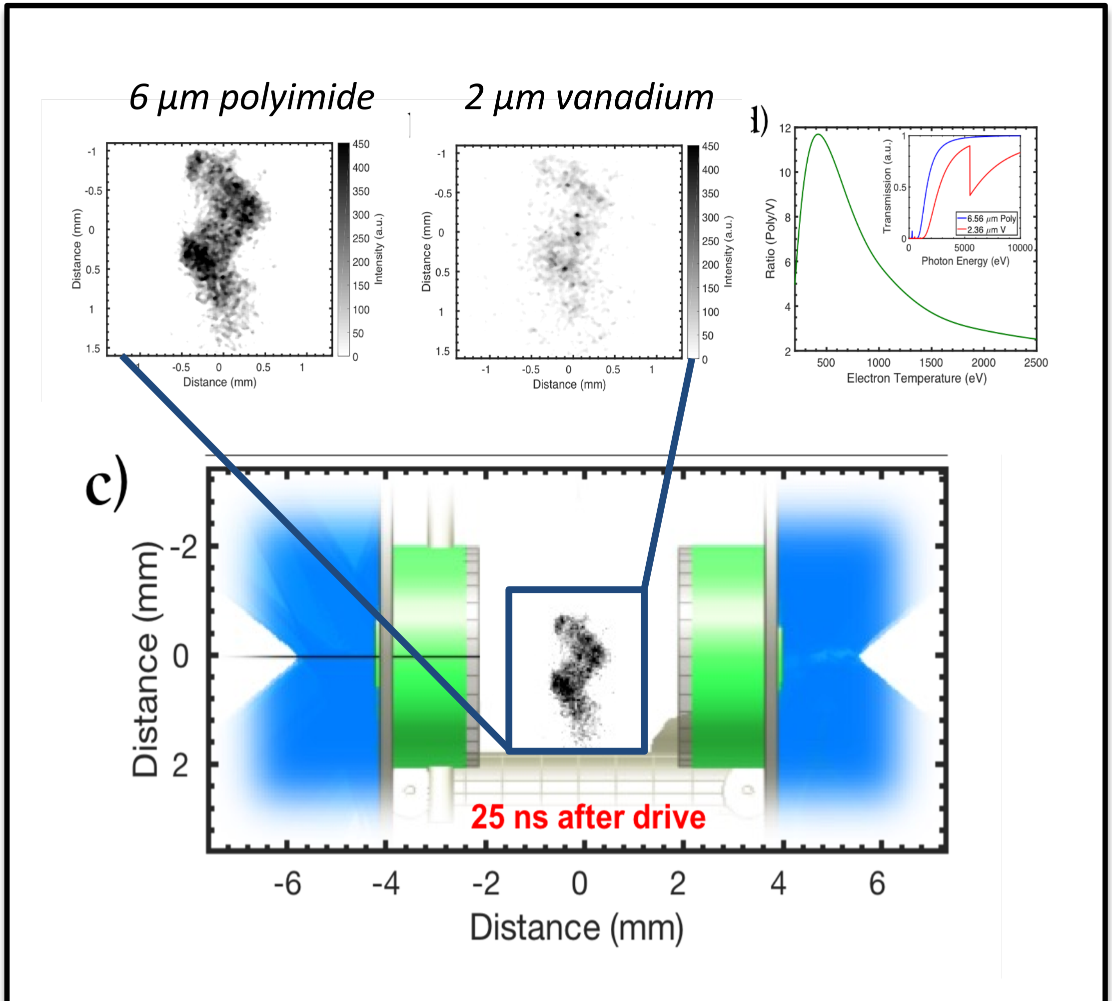
- In the turbulent interaction region, we find N_e**~5x10^{20} cm^{-3}**, which is corroborated by FABS; SRS: N_e~5-8x10^{20} cm^{-3}, SBS: u**~200 km/s**

Proton radiography



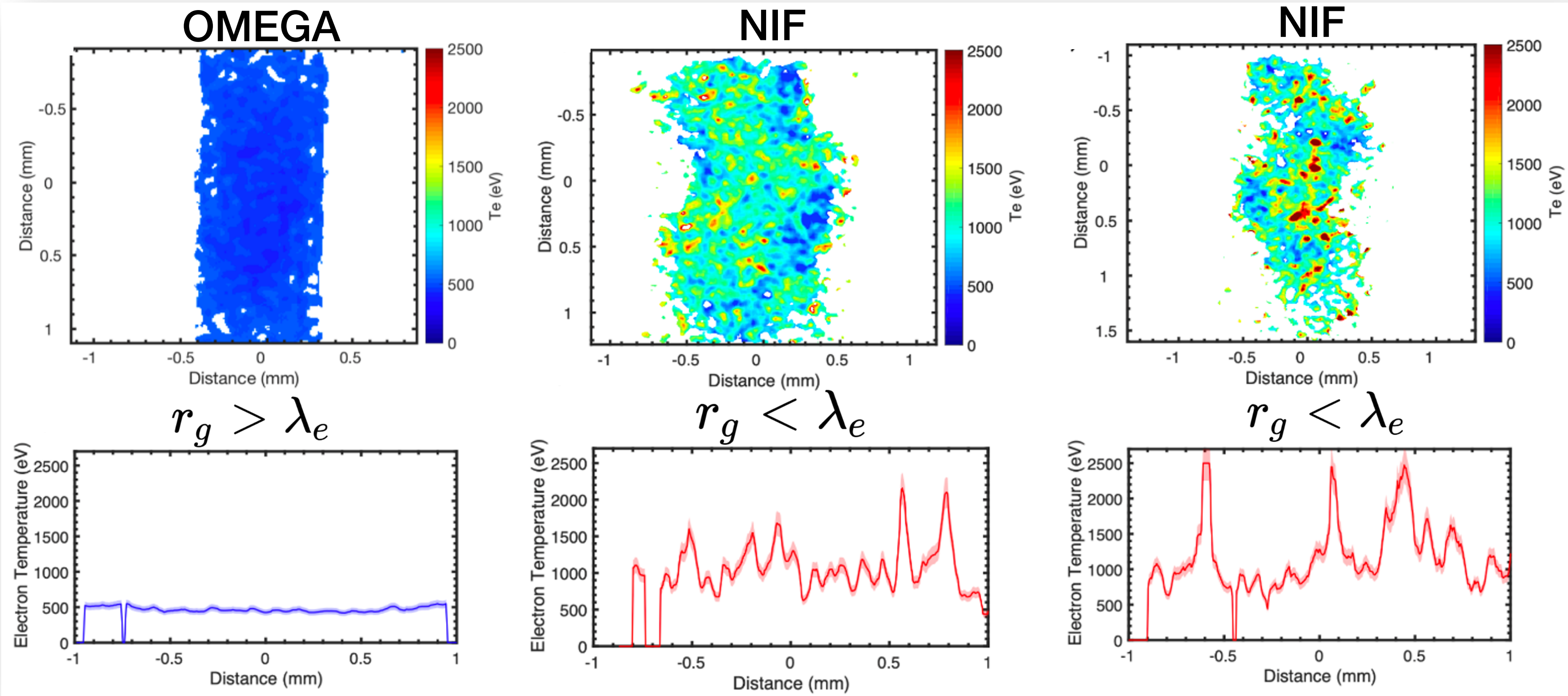
- PRAD shows protons being **strongly deflected** by the magnetic fields in the plasma.
- Analysis suggests B_{rms}~**0.8 MG** and B_{max}~**2-3 MG.**
- The magnetic field is strong enough **to suppress thermal conduction:** data shows hot-spots surrounded by cooler plasma.
- The magnetic field is generated via dynamo action in a turbulent plasma with with magnetic Prandtl numbers $Pm \sim$ **12** and $Rm \sim$ **3.5x10^3**.

Temperature distribution using two-color X-ray emission



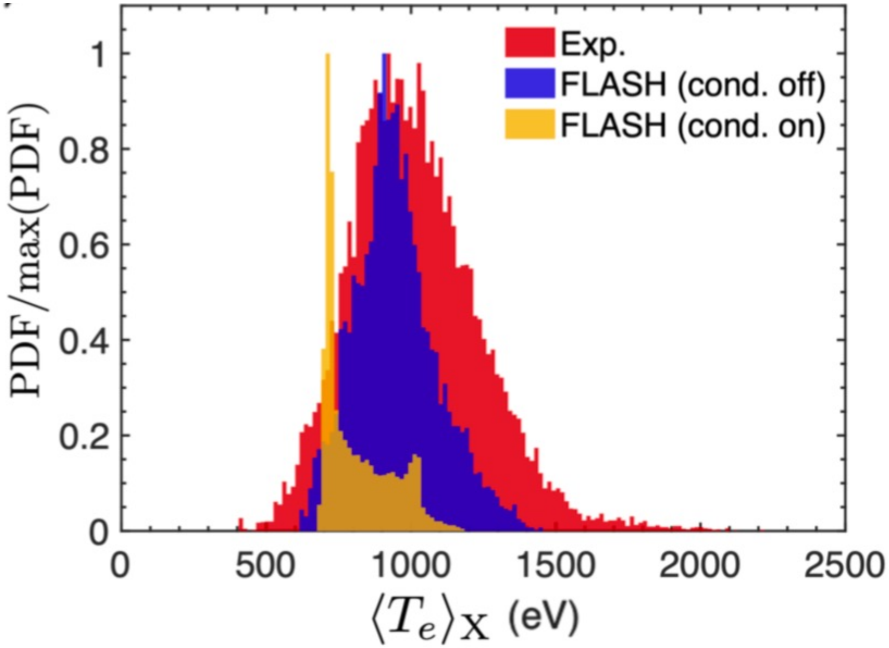
- Plasma temperature is determined by comparing **the X-ray emission in two different energy channels** together with the detector response.
- The technique allows us to create 2D temperature maps of the density weighed path integrated temperature.
- We validated this technique with synthetic post-processing using SPECT3d and FLASH simulations.

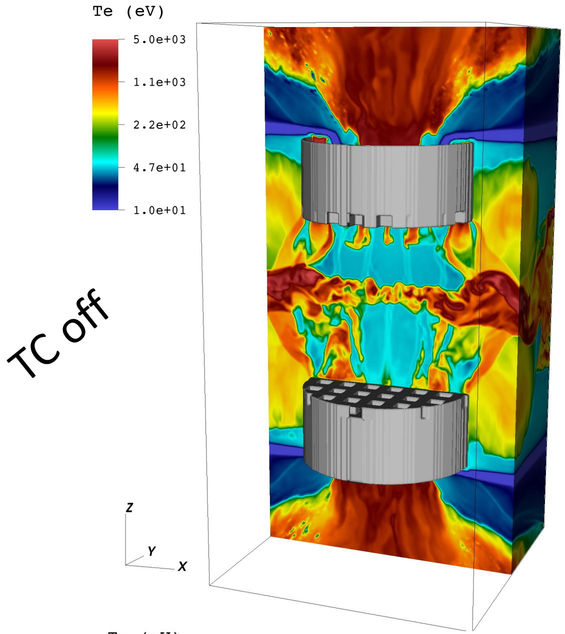
T_e profile controlled by magnetization of electrons

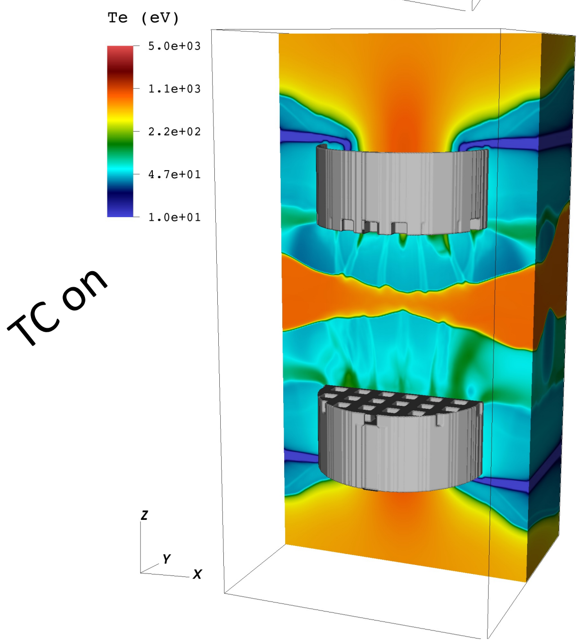


- ❑ NIF data revealed **highly-structured temperature profile** when the Larmor radius, r_g, is smaller than the electron Coulomb mean free path, λ_e
- ❑ The size of hot spots is limited by instrument resolution

The observed temperature is reproduced in simulations only if thermal conduction is off







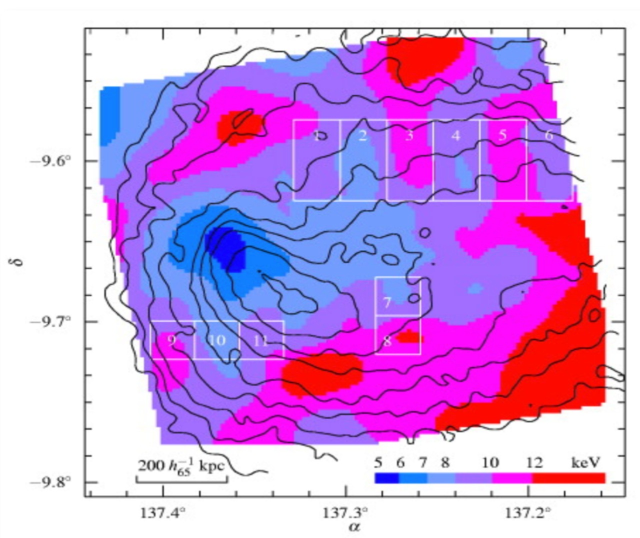
- FLASH simulations show that such a **structured temperature** profile can be obtained **if thermal conduction is uniformly suppressed.**

- What is causing this is **not understood** (maybe micro-instabilities, e.g., Komarov+ 2018 and Roberg-Clark+ 2018, for whistler-unstable plasmas).

We estimate a significant reduction in heat conduction in the NIF experiments

Quantity	NIF t = 23ns	NIF t = 25ns	Omega t = 18ns
$n_e(\mathrm{cm}^{-3})$	7e20	5e20	1e20
T_e (keV)	1.4	1.6	0.4
$l_T(\mu m)$	50	50	200
L (mm)	1	1	0.5
Z_{eff}	5.7	5.7	5.3
t_{cond} (ps)	27	14	1324
t_{age} (ns)	1.7	1.6	1.6
$\frac{t_{\mathrm{age}}}{t_{\mathrm{cond}}}$	63	114	1.2

- An estimate for heat conduction suppression is obtained by comparing the conduction time-scale $t_{\mathrm{cond}} \sim k_B n_e \ell_T^2/\kappa_S$ with the time required for the turbulent structures to persist $t_{\mathrm{age}} \sim L/c_s$.
- Our estimates suggest $(\kappa/\kappa_S)^{-1} \sim (t_{\mathrm{age}}/t_{\mathrm{cond}})$ > 100-200x reduction of heat conduction in the NIF experiments.
- These conditions are, in fact, very similar to what we would expect to see in cluster of galaxies and they would potentially be relevant to the problem of cooling flows.



Projected temperature map of A754 overlaid with CHANDRA X-ray image at 0.8-5 keV (Markevitch+ 2003)

Summary

- The advent of high-power lasers has opened **new fields of plasma physics research** and has enabled the reproduction of **astrophysical environments in the laboratory**.
- The TDYNO platform, which was designed with FLASH simulations to **demonstrate fluctuation dynamo in the lab for the first time**, at the Omega Laser Facility at the Laboratory for Laser Energetics (Tzeferacos+ 2018), has been successfully ported onto the **National Ignition Facility** (Meinecke et al. submitted, arXiv:2105.08461).
- The NIF experiments achieve fluctuation dynamo in the **large magnetic Prandtl number regime**, an experimental replica for the magnetized turbulence in the IGM.
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- DOE NNSA NLUF: **DE-NA0002724, DE-NA0003605, DE-NA0003934**
- NSF/DOE Partnership in Basic Plasma & Engineering: **PHY-2033925**
- and General Atomics for target R&D and manufacturing!

Los Alamos NATIONAL LABORATORY

Lawrence Livermore National Laboratory

Extra slides

Quantity	Experimental Value
Composition of target	48.3% C, 49.6% H, 1.2% O, 0.6% N, 0.1% Mn, 0.1% Co
Average atomic weight ($\langle M \rangle$)	6.7
Mean ion charge ($\langle Z \rangle$)	3.6
Effective ion charge (Z_{eff})	5.7
Hydrogen effective ion charge ($Z_{\mathrm{eff,B}}$)	5.5
Electron temperature (T_{e})	1100 eV
Ion temperature (T_{i})	1100 eV
Electron number density (n_{e})	4.9×10^{20} cm^{-3}
Turbulent velocity ($\mathrm{v_{turb}}$)	2×10^{7} cm s^{-1}
Outer scale (L)	0.06 cm
RMS magnetic field (B_{RMS})	0.8 MG
Maximum magnetic field (B_{max})	3.0 MG
Adiabatic index (γ_{I})	5/3

Table 1: Summary of target characteristics and direct experimental measurements of plasma parameters at t = 25 ns after the start of the drive laser pulse. The outer scale, L, represents the distance between two neighboring grid aperture centers. Values are reported in CGS, except for the temperature that is given in eV.

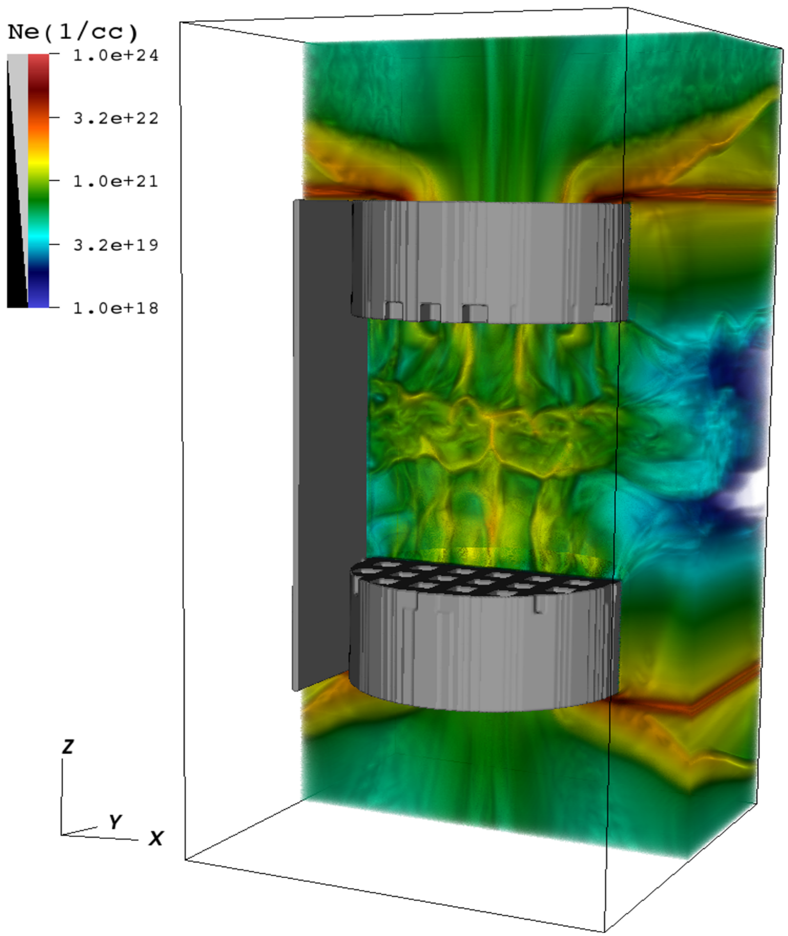
Extra slides

Quantity	Formula	Value
Coulomb logarithm ($\log\Lambda$)	$23.5 - \log n_e^{1/2} T_e^{-5/4} - \sqrt{10^{-5} + \frac{(\log T_e - 2)^2}{16}}$	7.2
Mass density (ρ)	$1.7 \times 10^{-24} (\sum_j M_j n_j)$	1.6×10^{-3} g cm^{-3}
Debye length (λ_{D})	$7.4 \times 10^2 \frac{T_e^{1/2}}{n_e^{1/2}} \left[1 + \frac{T_e}{T_i} Z_{\mathrm{eff}}\right]^{-1/2}$	4.2×10^{-7} cm
Sound speed (c_s)	$9.8 \times 10^5 \frac{[(\langle Z \rangle + 1)\gamma_I T_e]^{1/2}}{\langle M \rangle^{1/2}}$	3.5×10^7 cm s^{-1}
Mach number	$\mathrm{v_{turb}}/c_s$	0.6
Plasma β	$4.0 \times 10^{-11} \frac{n_e T_e + \sum_j n_j T_i}{B_{\mathrm{RMS}}^2}$	44
H-ion mean free path (λ_{Hion})	$2.1 \times 10^{13} \frac{T_i^2}{(Z_{\mathrm{H}}^2 Z_{\mathrm{eff,B}} n_e \log\Lambda)}$	1.3×10^{-3} cm
Electron-ion mean free path (λ_e)	$2.1 \times 10^{13} \frac{T_e^2}{(Z_{\mathrm{eff}} n_e \log\Lambda)}$	1.2×10^{-3} cm
Electron Larmor radius (r_g)	$2.4 \frac{T_e^{1/2}}{B_{\mathrm{RMS}}}$	1.0×10^{-4} cm
Hydrogen Larmor radius (ρ_{H})	$1.0 \times 10^2 \frac{M_{\mathrm{H}}^{1/2} T_i^{1/2}}{Z_{\mathrm{H}} B_{\mathrm{RMS}}}$	4.1×10^{-3} cm
Unmagnetized thermal diffusivity (χ_{S})	$3.0 \times 10^{21} \frac{T_e^{5/2}}{Z_{\mathrm{eff}} n_e \log\Lambda}$	5.9×10^6 cm^2 s^{-1}
Magnetized thermal diffusivity (χ_{m})	$\chi_{\mathrm{S}} r_g / \lambda_e$	4.7×10^5 cm^2 s^{-1}
Suppressed thermal diffusivity (χ)	$\sim \chi_{\mathrm{S}}/150$	3.9×10^4 cm^2 s^{-1}
Turbulent Péclet number ($\mathrm{Pe_{turb}}$)	$\mathrm{v_{turb}} L/\chi$	$\sim$30
Dynamic viscosity (μ)	$4.27 \times 10^{-5} \frac{M_{\mathrm{H}}^{1/2} T_i^{5/2} n_{\mathrm{H}}}{\log\Lambda Z_{\mathrm{eff,B}} n_e}$	7 g cm^{-1} s^{-1}
Kinematic viscosity (ν)	μ/ρ	4.3×10^3 cm^2 s^{-1}
Turbulent Reynolds number ($\mathrm{Re_{turb}}$)	$\mathrm{v_{turb}} L/\nu$	280
Viscous dissipation scale (l_ν)	$L/\mathrm{Re}_{\mathrm{turb}}^{3/4}$	8.8×10^{-4} cm
In-flow Resistivity ($\eta_{\|\|}$)	$3.1 \times 10^5 \frac{Z_{\mathrm{eff}} \log\Lambda}{T_e^{3/2}}$	350 cm^2 s^{-1}
Magnetic Reynolds number ($\mathrm{Rm_{turb}}$)	$\mathrm{v_{turb}} L/\eta_{\|\|}$	3.5×10^3
Magnetic Prandtl number (Pm)	Rm / Re	12
Resistive dissipation scale (l_η)	$L/\mathrm{Pm}^{1/2}$	2.5×10^{-4} cm

Table 2: Summary of derived plasma parameters at t = 25 ns after the start of the drive laser pulse. The values are reported in CGS.

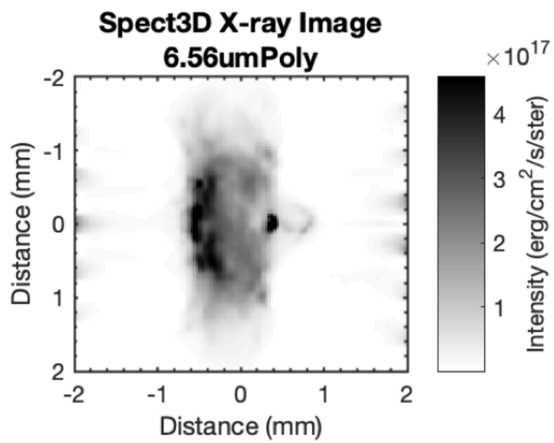
Validation of the two-color temperature diagnostic

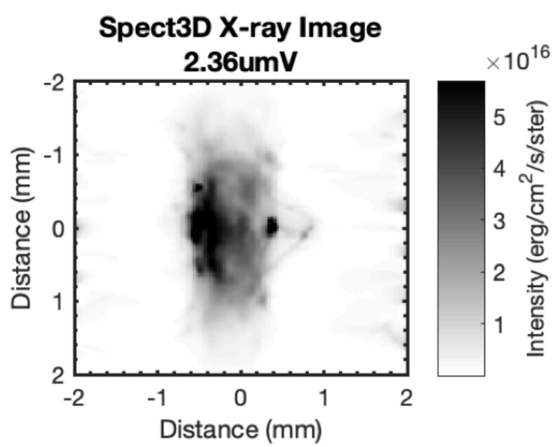
- **Step 1**: We take FLASH simulations results for the interaction region.



Validation of the two-color temperature diagnostic

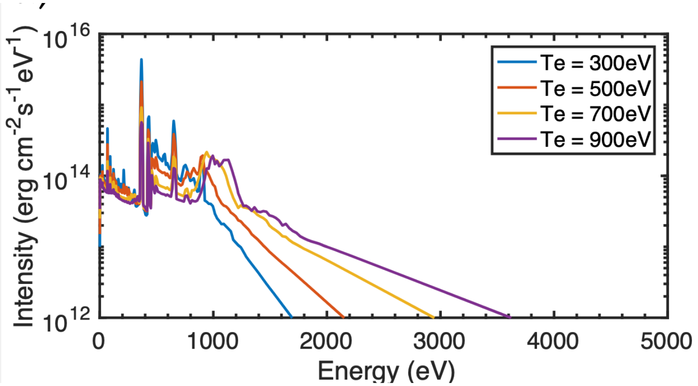
- **Step 1**: We take FLASH simulations results for the interaction region.
- **Step 2**: FLASH simulations are post-processed using SPECT3d to obtain synthetic X-ray maps of the interaction region.

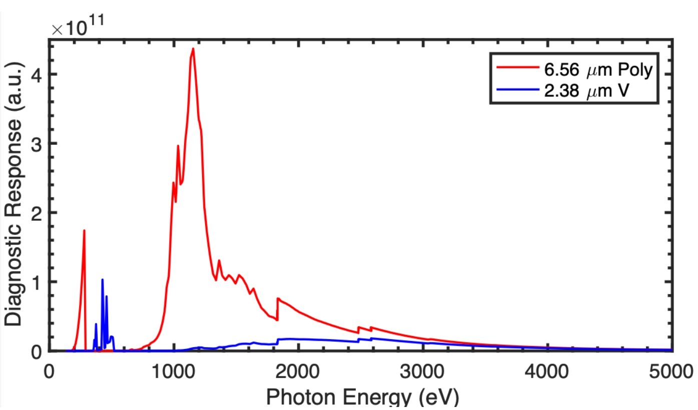


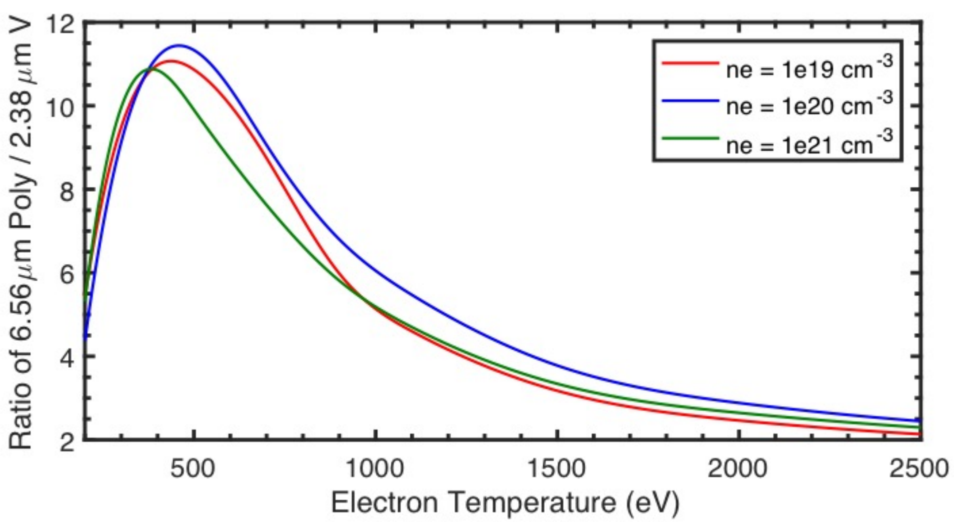


Validation of the two-color temperature diagnostic

- **Step 1**: We take FLASH simulations results for the interaction region.
- **Step 2**: FLASH simulations are post-processed using SPECT3d to obtain synthetic x-ray maps of the interaction region.
- **Step 3**: A relation between filter ratio and temperature is obtained by running PrismSPECT for a range of different plasma conditions.



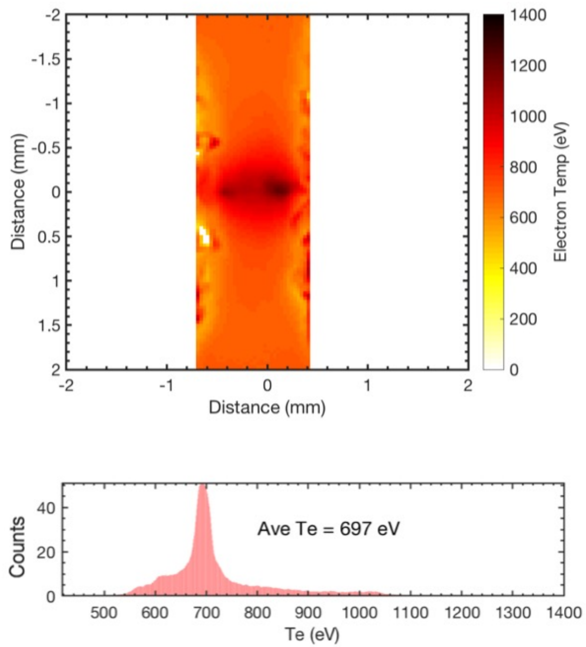




Validation of the two-color temperature diagnostic

- **Step 1**: We take FLASH simulations results for the interaction region.
- **Step 2**: FLASH simulations are post-processed using SPECT3d to obtain synthetic x-ray maps of the interaction region.
- **Step 3**: A relation between filter ratio and temperature is obtained by running PrismSPECT for a range of different plasma conditions.
- **Step 4**: The mass-weighted (along the line-of-sight) temperature map obtained from the filter ratio is compared to the mass-weighted temperature from FLASH simulations.

Filter ratio



Directly from simulation