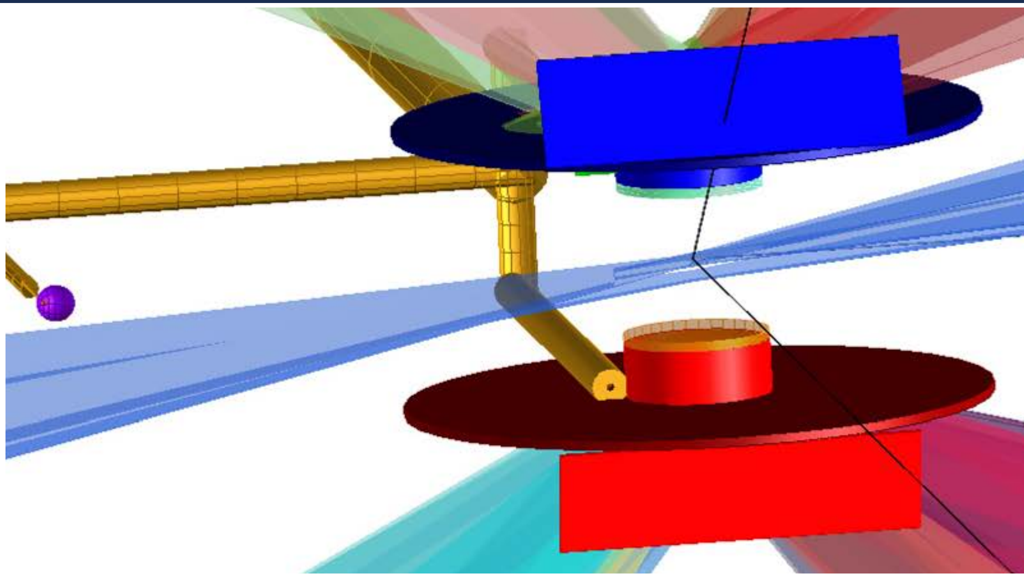
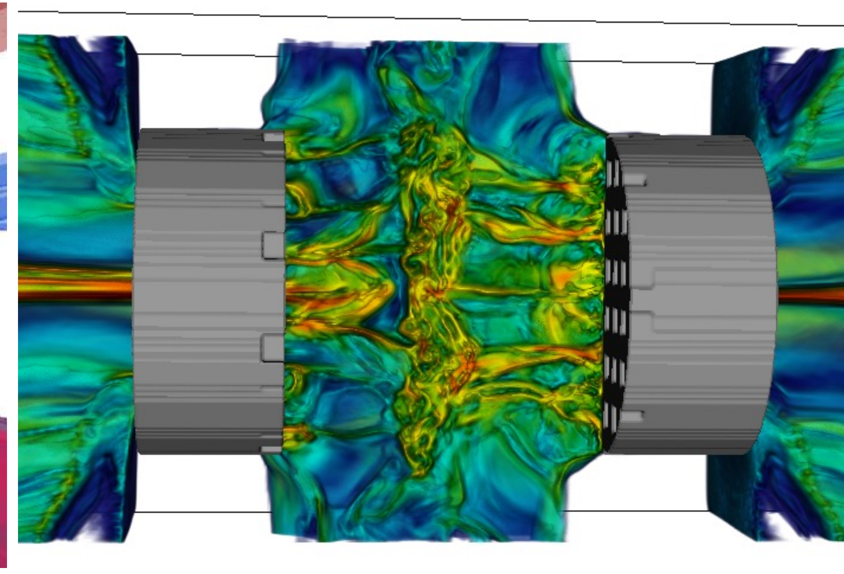
Numerical Modeling of Laser-Driven Plasma Experiments Aiming to Study Turbulent Dynamo and Thermal Conduction at the National Ignition Facility





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Collaborators

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Summary

- We design the experiment using FLASH simulations and create a turbulent plasma on NIF with magnetic field amplification under magnetic Reynolds number $\mathrm{Rm} > 10^3$ and magnetic Prandtl number $\mathrm{Pm} > 1$ condition.

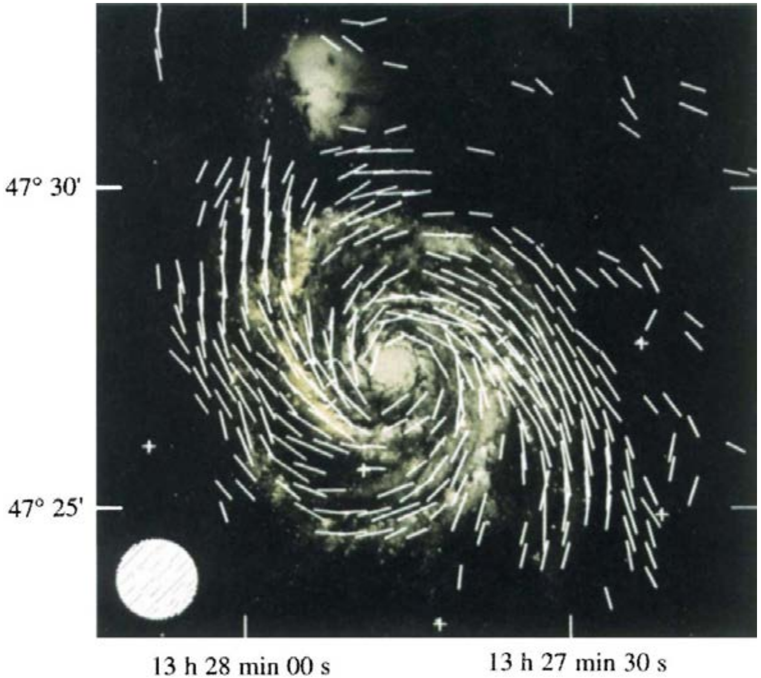
- Fluctuation dynamo operates under these conditions and amplifies magnetic fields to the experimentally measured amplitude.

- Such a plasma with $\mathrm{Pm} > 1$ is relevant to hot low-density plasmas found in astrophysical accretion disks and the intracluster medium (ICM).

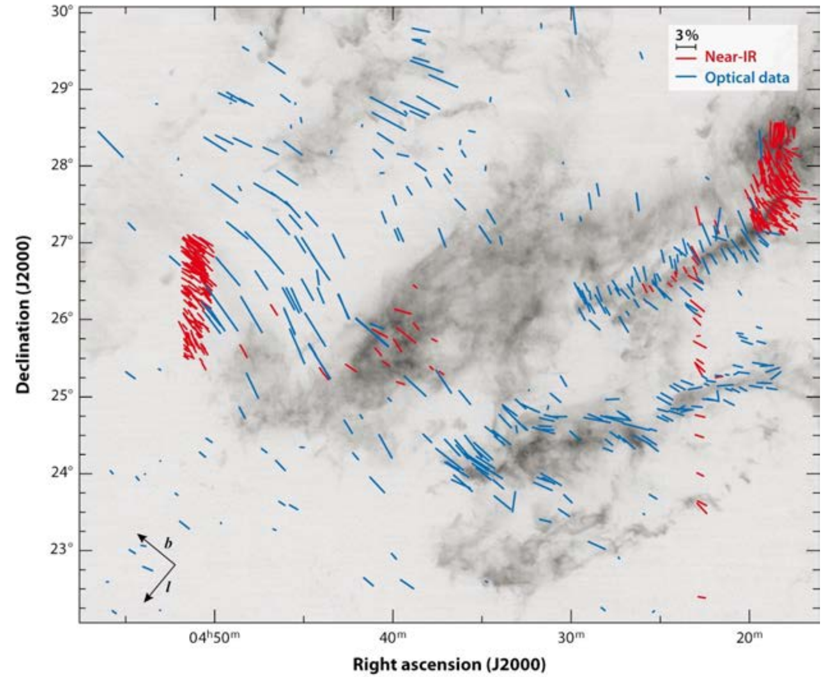
- The magnetization is large enough for the electron Larmor radius to be less than mean free path, which can affect thermal conduction. Using FLASH simulations, we have created an experimental platform to study thermal conduction suppression as seen in active galactic nuclei (AGN) feedback.

- Synthetic proton radiography and X-ray self-emission images reveal characteristics of the turbulent plasma, e.g., electron temperature and magnetic field distributions, and enable direct comparison with the experiments.

Magnetic fields in the Universe



B-field vectors of M51 (Zweibel 1997)

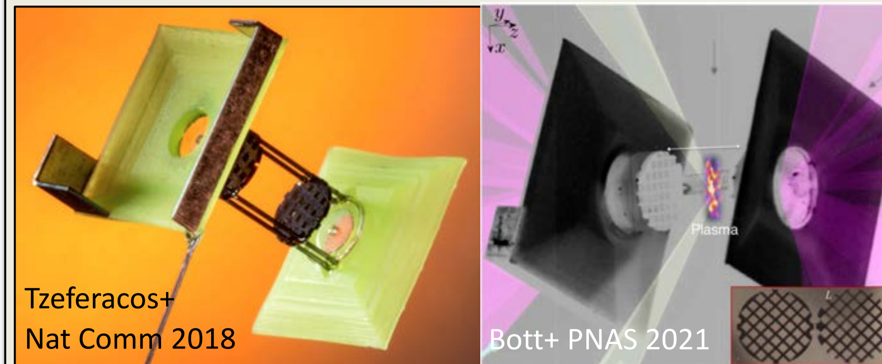


B-field in the Taurus dark-cloud complex (Crutcher 2012)

- ❑ Seed magnetic field generation by Biermann battery effect (Biermann 1950) or Weibel instability (Weibel 1959)
- ❑ Turbulent dynamo: small-value seed fields amplified to observed values (Parker 1979, Moffatt 1978, Kulsrud 1997)

Dynamo amplification experiments in Laboratory

Turbulent Dynamo at Omega Laser

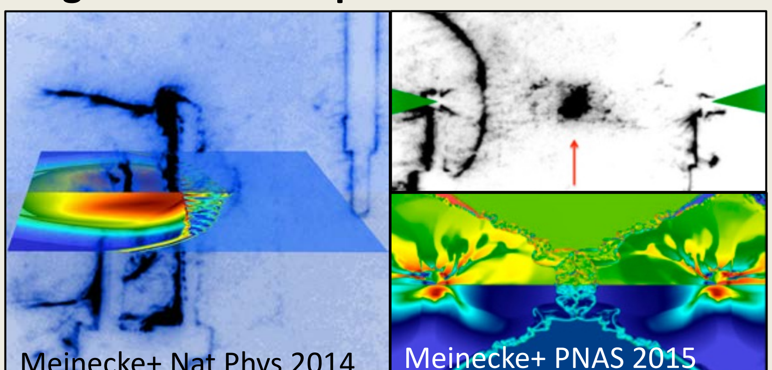


Tzeferacos+ Nat Comm 2018

Bott+ PNAS 2021

Rm ~ 600

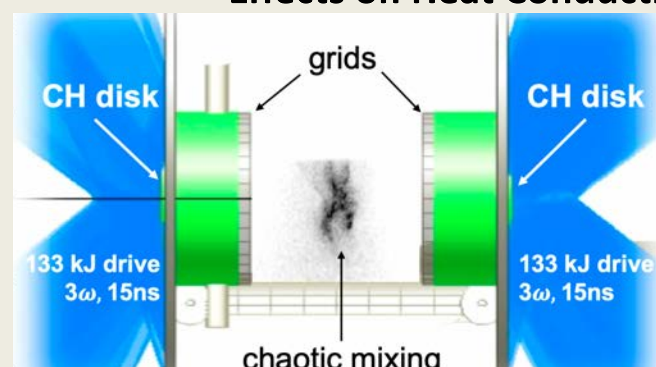
Magnetic Field Amplification at Vulcan Laser


Meinecke+ Nat Phys 2014

Meinecke+ PNAS 2015

Rm ~ 3 - 6

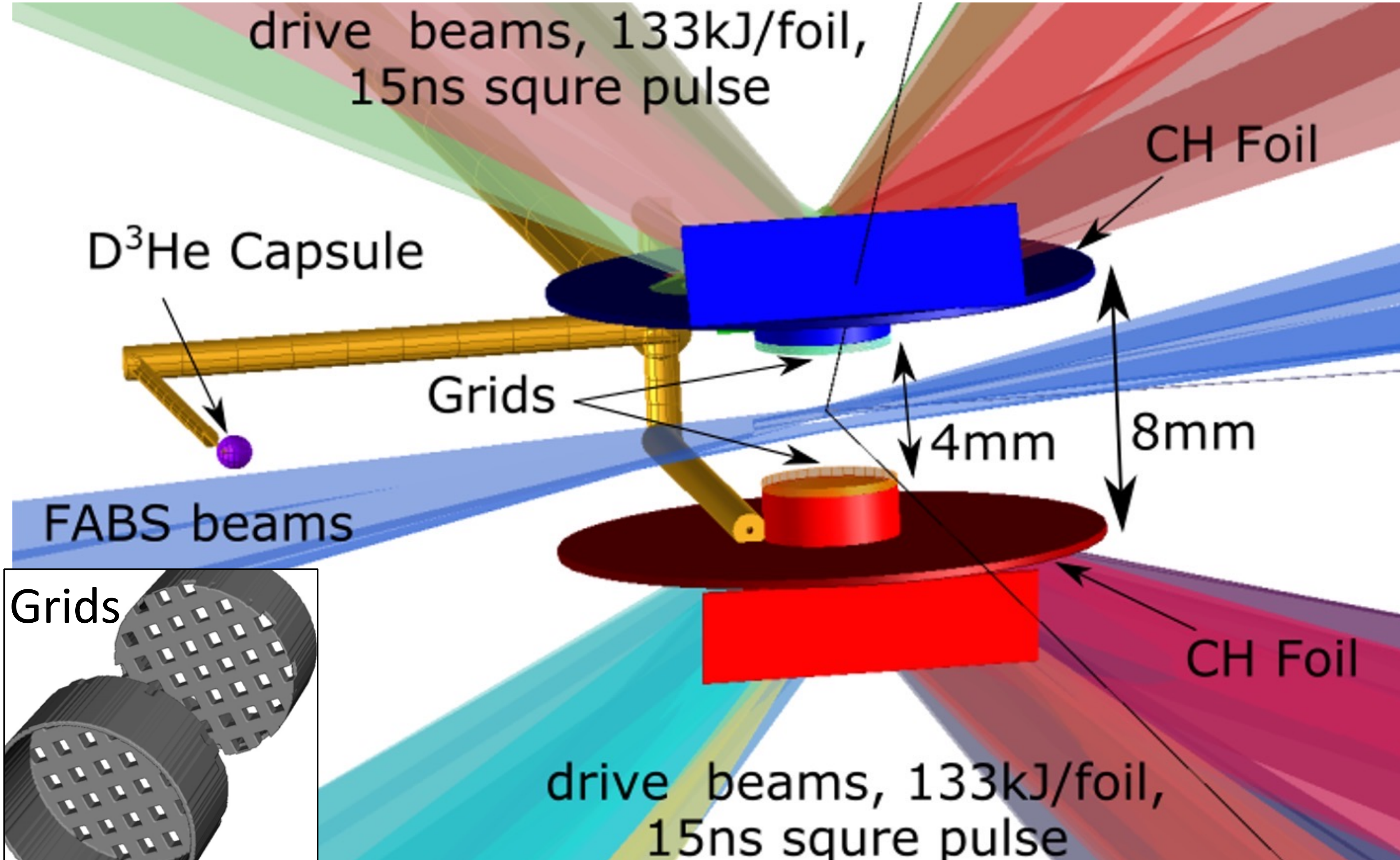
NIF Dynamo Experiments and Effects on Heat Conduction



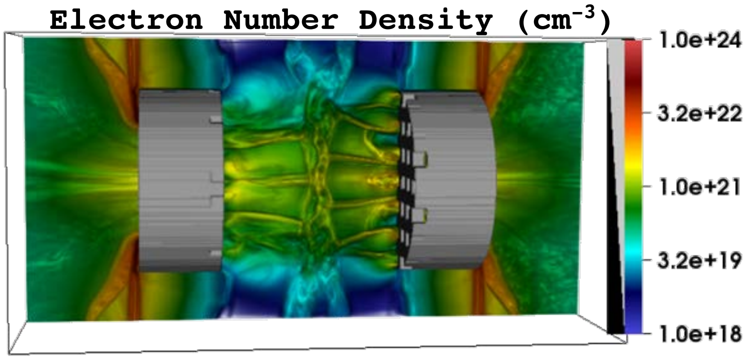
Rm ~ 3500

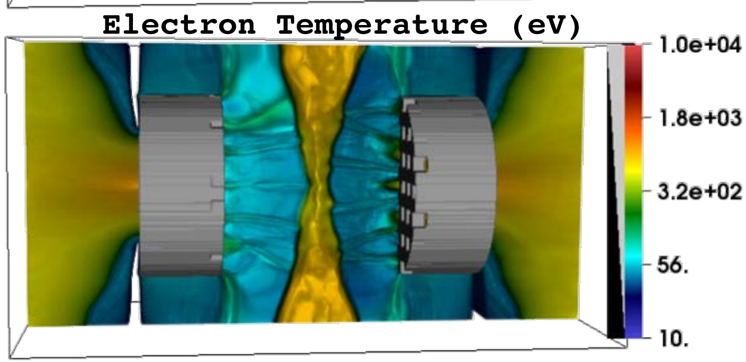
Meinecke+ arXiv:2105.08461

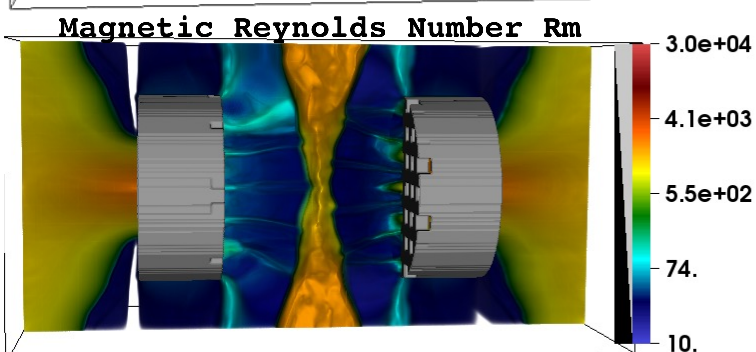
NIF Turbulent dynamo laser-target design

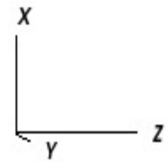


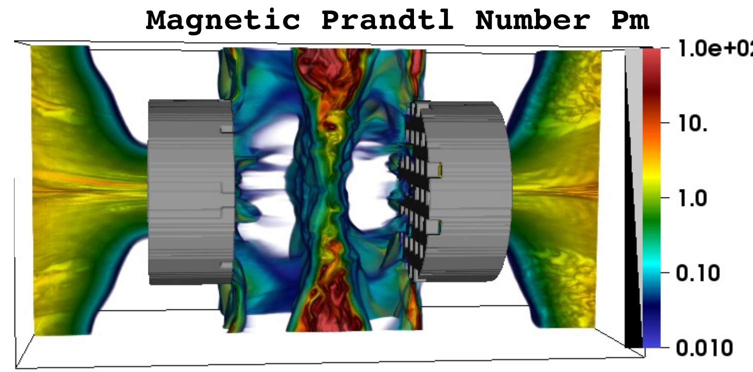
FLASH simulations predicts interaction region condition for fluctuation dynamo to operate





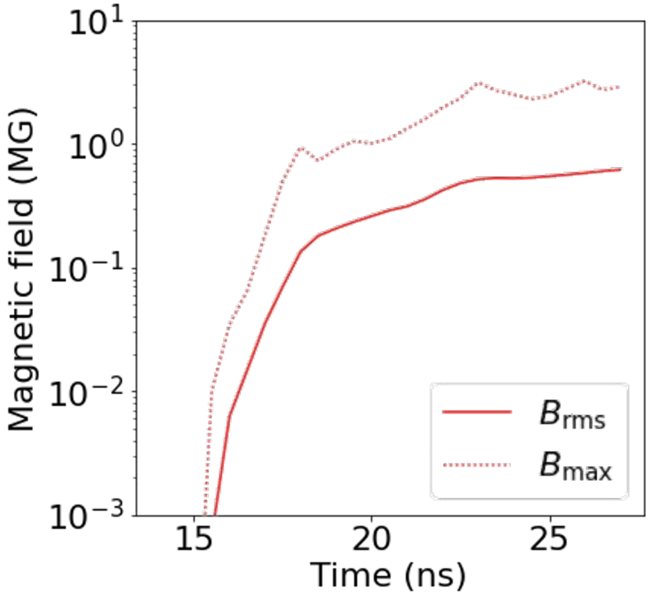


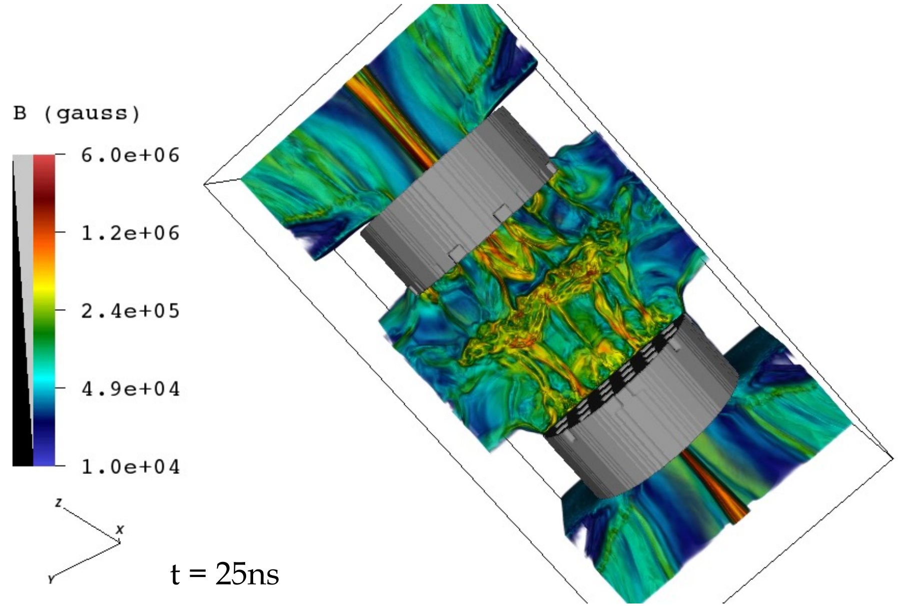




- ❑ The Interaction region turbulent plasma at 23ns has reached the following condition:
  $u_{rms} \sim 2\times10^7$ cm/s,
  $n_e \sim 2.3\times10^{20}$ cm^{-3}, $T_e \sim 710$ eV
  $Rm \sim 1.8\times10^3$, $Pm \sim 4$.
- ❑ Some locations in the interaction region can have higher Rm and Pm.
- ❑ We reach the condition for fluctuation dynamo to amplify the seed magnetic field.

Magnetic field amplified by turbulent dynamo and suppresses electron thermal conduction

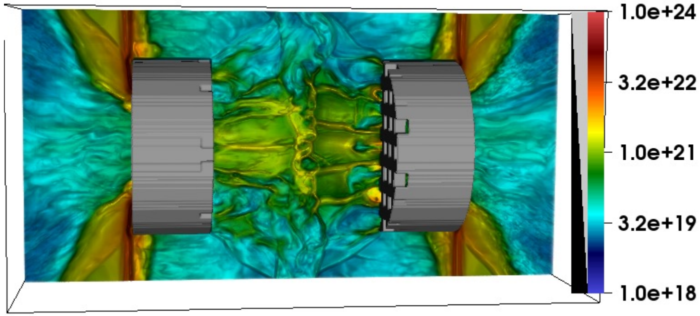




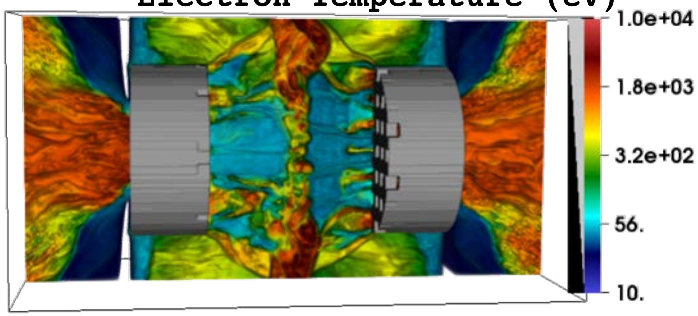
- Turbulent amplification of magnetic field results in B_{rms} ~ 0.5 MG and B_{max}~ 2.4 MG.
- The plasma is in magnetized regime (electron Larmor radius r_g < mean free path λ_e) with $r_g = 1.3x10^{-4}$ cm and $\lambda_e = 1.1x10^{-3}$ cm.
- Electron heat conduction is suppressed due to magnetization or other sources (e.g., kinetic instabilities, turbulence, non-local effects). We incorporate the suppression by switching off the electron thermal conductivity in FLASH.

Predicted plasma properties in conduction-off runs

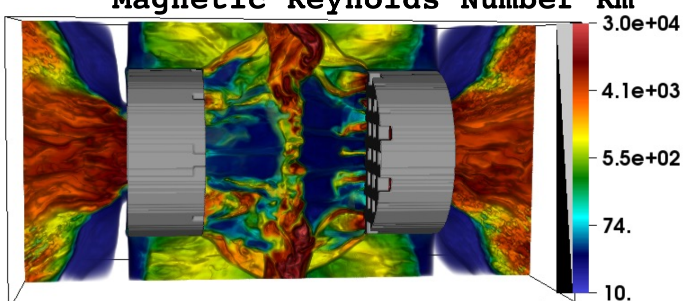
Electron Density (cm^{-3})

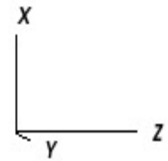


Electron Temperature (eV)



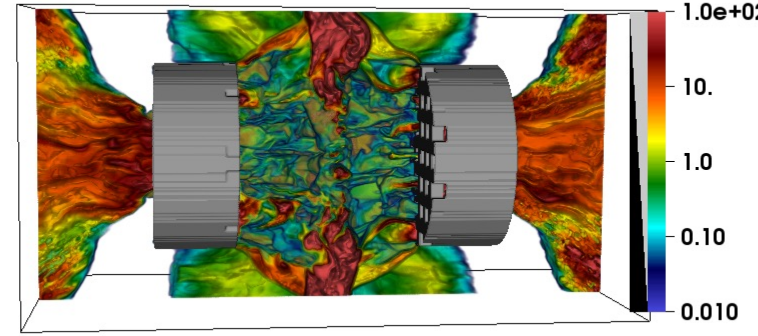
Magnetic Reynolds Number Rm





t = 23ns

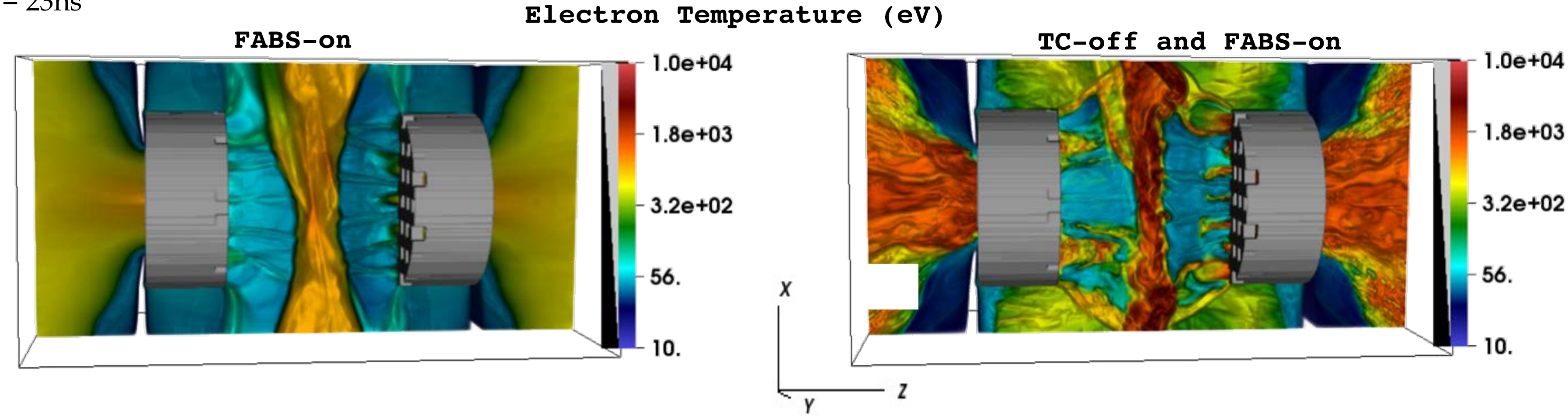
Magnetic Prandtl Number Pm



- For conduction off run:
  - The Interaction region at 23ns reaches $n_e \sim 4\times10^{20}$ cm^{-3}, $T_e \sim 1.2\times10^3$ eV $Rm \sim 3.9\times10^3$, $Pm \sim 20$
  - We also see that high Rm and above-unity Pm condition last longer
  - Electron temperature profile is highly structured due to the suppression of electron thermal conduction

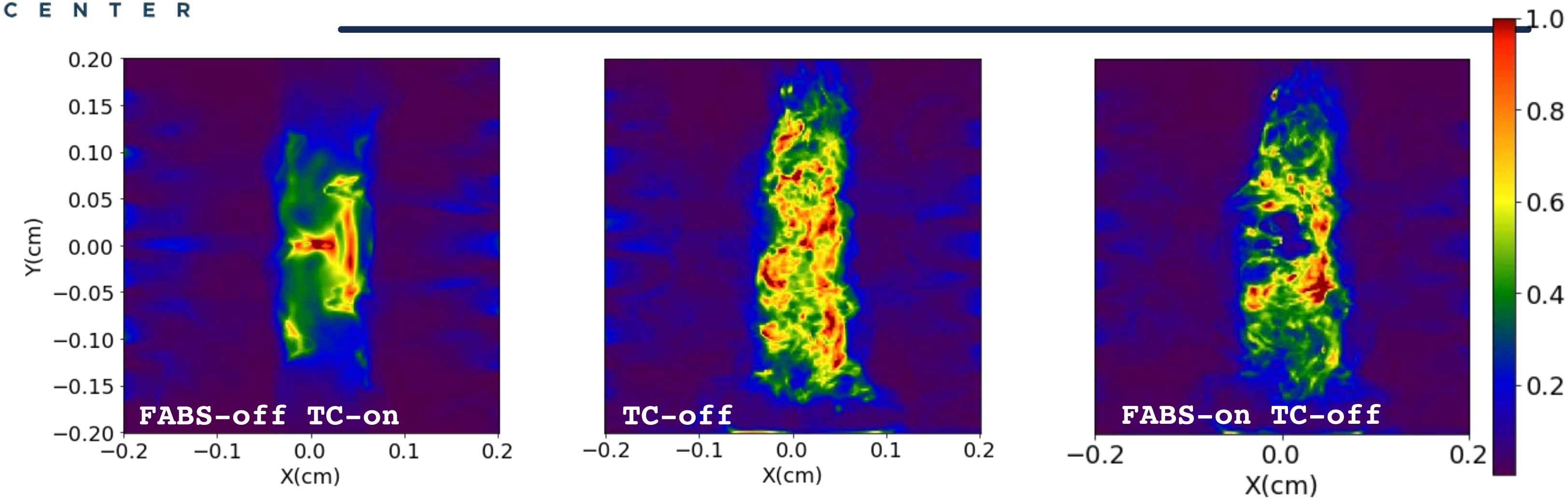
Electron temperature in conduction-off and FABS-on cases

t = 23ns



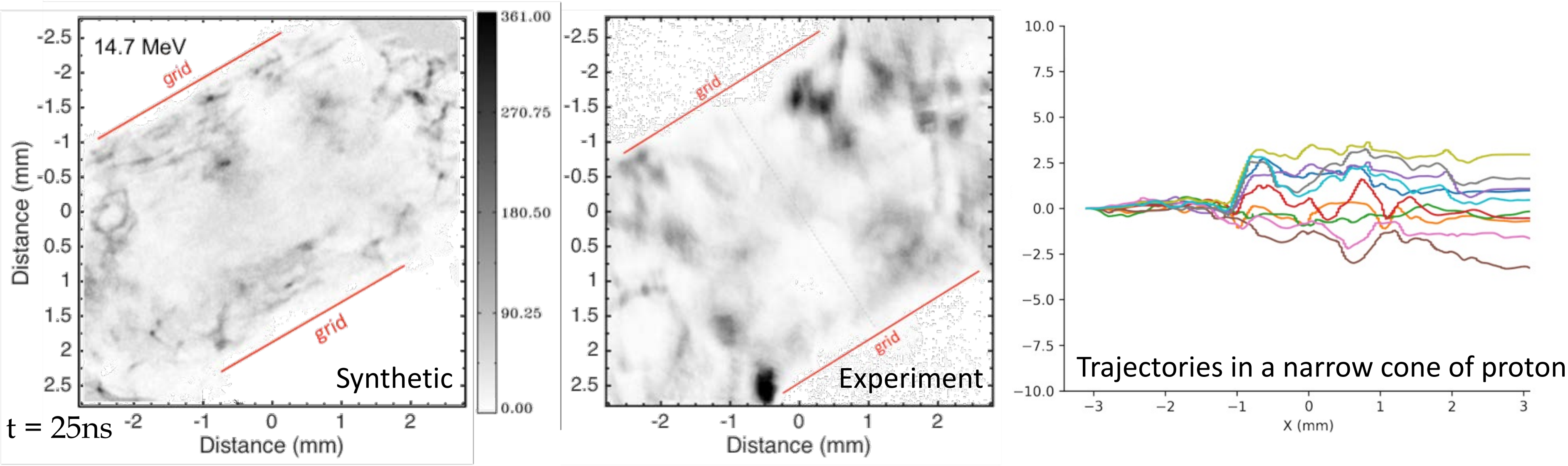
- Full-aperture backscatter system (FABS) being used to measure the turbulent velocity in the plasma can heat the plasma and affect the physical process. We compute the heating from FABS.
- In TC-on (conduction-on) case, we find moderate increase of temperature to $T_e \sim 750$ eV due to FABS.
- In TC-off, We have $T_e \sim 1.2\times10^3$ eV. FABS does not have a significant effect because we have thermal conduction turned off, and any heating is localized in the plane of FABS.

Synthetic X-ray self-emission images



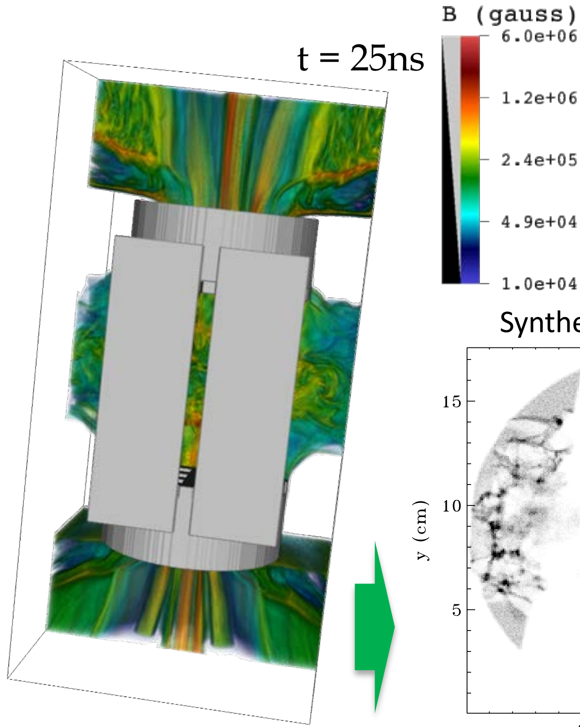
- For TC-off, electron temperature profile is highly structured for the conduction-off runs, resulting in highly structured X-ray self-emission intensity.
- Synthetic X-ray images enable quantitative comparison with the experimental data.
- The suppression of electron thermal conduction has been demonstrated in the experiment (Meinecke+ arXiv:2105.08461, also see the talk by Petros Tzeferacos in this session)

Proton images and trajectories show image contrast in the diffusive regime

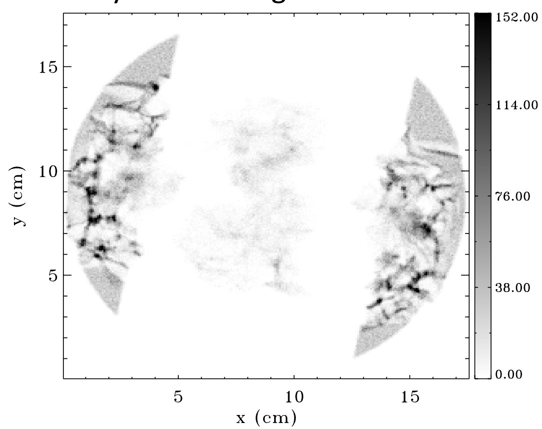


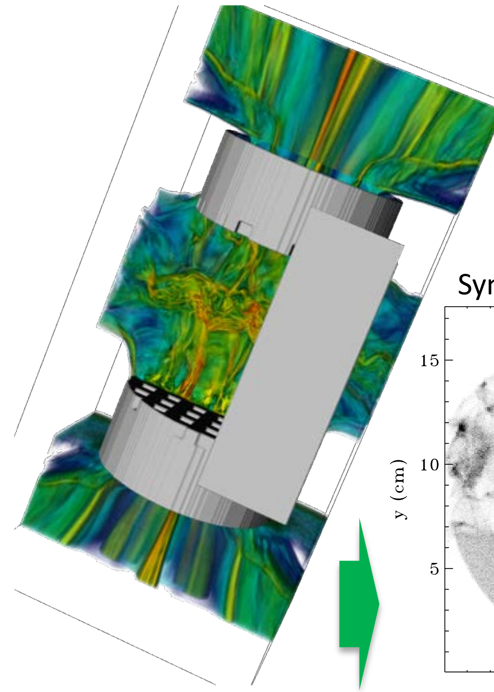
- ❑ Both the synthetic and experimental proton images are in the diffusive regime (Bott+ 2017) characterized as following:
  - ❑ Synthetic proton trajectories from a narrow cone source have crossings before they leave the plasma
  - ❑ The correlation length of the magnetic field is $l_B = 0.0036\mathrm{cm}$, which is less than the RMS perpendicular displacement of protons going through the interaction regime plasma due to magnetic deflections $l_z\delta\theta = 0.014\mathrm{cm}$.

Using obstacles to measure magnetic fields for proton images in diffusive regime

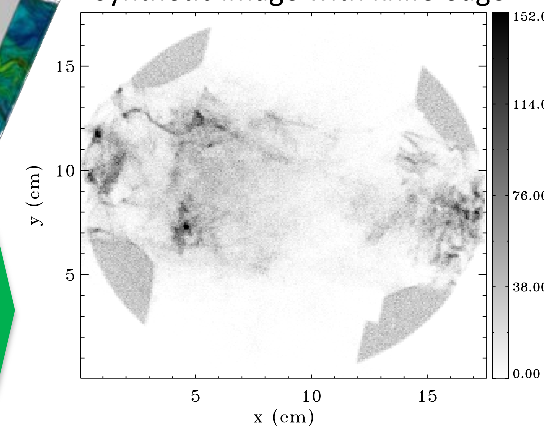


Synthetic image with slit





Synthetic image with knife edge



- Using the image with slit or knife edge, we can measure the velocity diffusion coefficient and infer the range of RMS magnetic field strength.

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