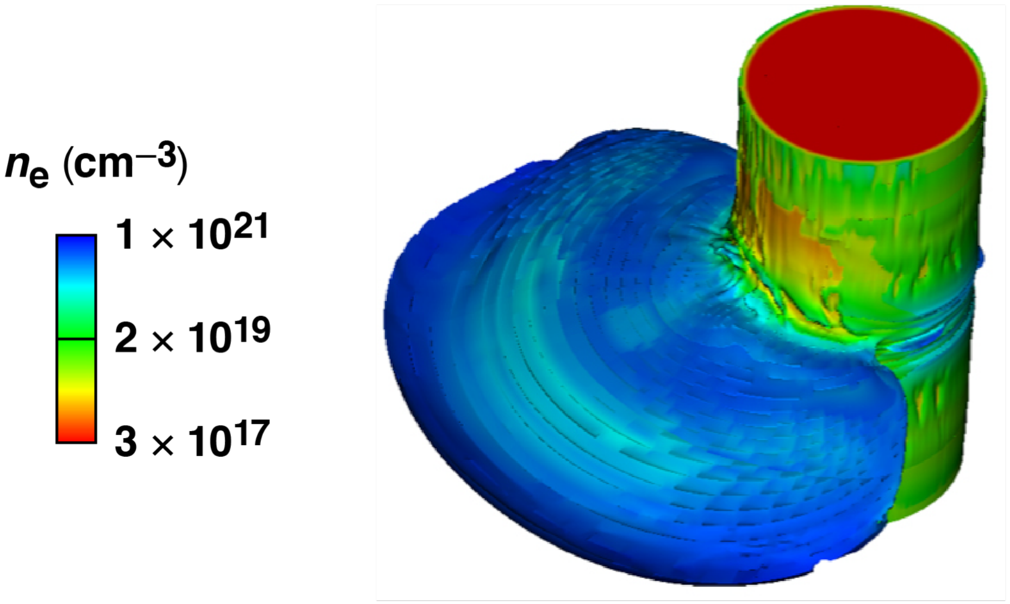
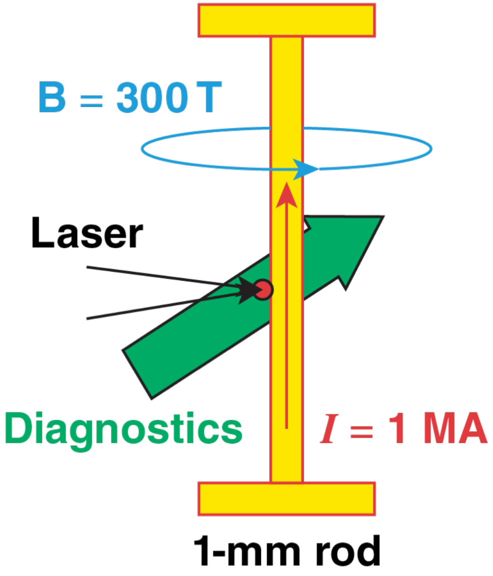
Three-Dimensional Modeling of Laser–Plasma Confinement in a Strong Magnetic field





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Division of Plasma Physics
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Summary

Extended MHD is needed to simulate plasma disc formation and magnetic confinement observed in laser-wire interaction experiments on Zebra

- The plasma disc is pinched and magnetically confined by the azimuthal magnetic field from the wire
- These simulations are in general agreement with the experiments at the Zebra facility using λ = 1.06-μm light and 1 MA of current
- A simulation using an extended magnetohydrodynamic (MHD) model captures the azimuthal plasma expansion and the evolution of plasma perturbations seen in experiments

M. Marinak, *et al.*, Physics of Plasmas 8, 2275-2280 (2001).
V. V. Ivanov *et al.*, Plasma Phys. Control. Fusion 59, 085008 (2017).

Collaborators

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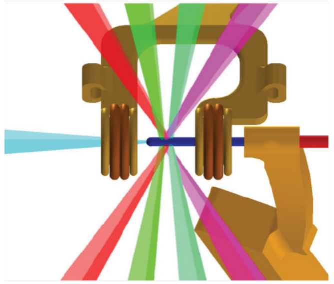
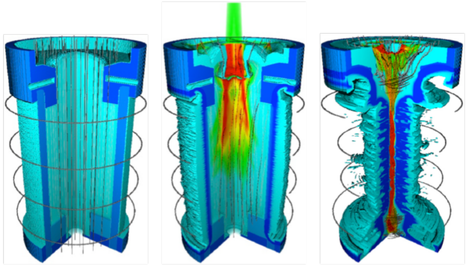
Studies of laser-generated magnetized plasmas have an important impact on magnetized inertial confinement fusion (ICF) and laboratory astrophysics

- **Multiple magneto-inertial fusion concepts involve the interaction of magnetic fields and laser plasmas**
- **The coupling of laser-ablated plasmas in strong magnetic fields is also similar to magnetized astrophysical phenomena with the plasma β parameter changing from $\beta < 1$ to $\beta \gg 1$**

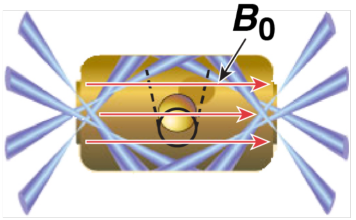
$$\beta = \frac{nkT}{B^2/2\mu}$$



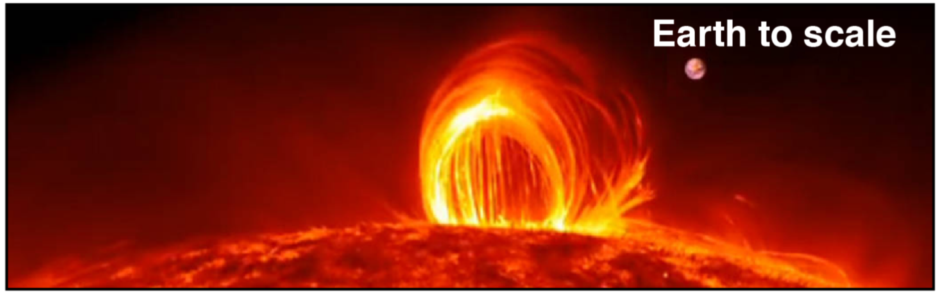
MIFEDS (LLE)
β 4 to 60



MagLIF (SNL)
β 5 to 80



Magnetic NIF (LLNL)
β ~190

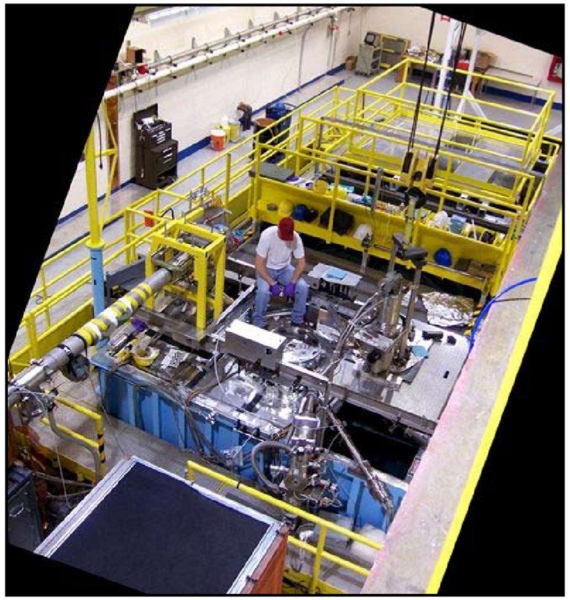


TC15107

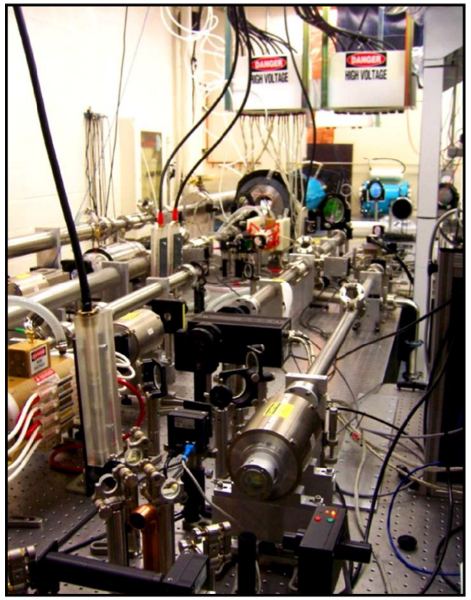
NASA/SDO/Goddard Scientific Visualization Studio
D. J. Strozzi, *et al.*, No. LLNL-CONF-672979. Lawrence Livermore National Lab. (LLNL), Livermore, CA (United States), 2015
M. R. Gomez, *et al.*, Physical review letters 113.15, 155003 (2014).
J. R. Davies, *et al.*, Physics of Plasmas 26.6, 062701 (2017).

MIFEDS: magneto-inertial fusion electrical discharge system
MagLIF: magnetized liner inertial fusion
NIF: National Ignition Facility
LLNL: Lawrence Livermore National Laboratory

The Zebra pulsed-power generator at UNR can be coupled with the Leopard laser for magnetized laser-plasma studies



- **Zebra generator**
  - load current 1 MA with LCM 1.7 MA*
  - current rise time 80 ns
  - storage energy 150 kJ
  - impedance 1.9 Ω



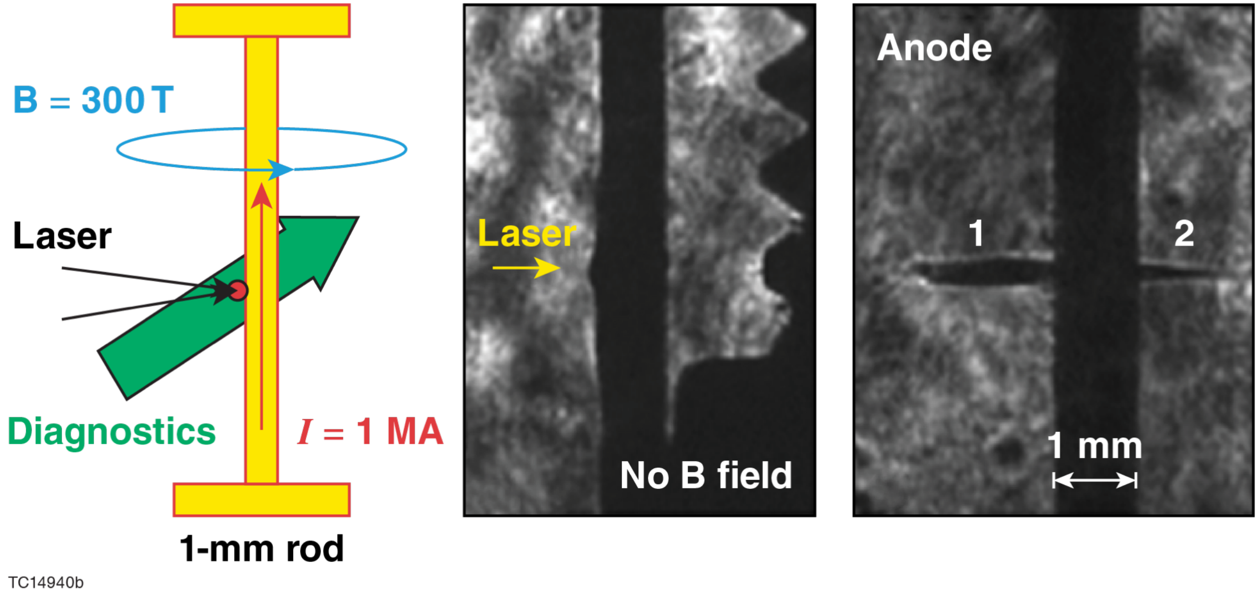
- **Leopard laser**
  - short pulse: 15 J, 0.35 ps
  - $I \sim 10^{19}$ W/cm^2, $K = 106$
  - long pulse: 35 J, 0.8 ns
  - $I \sim 6 \times 10^{15}$ W/cm^2

TC15112

*V. V. Ivanov *et al.*, Plasma Phys. Control. Fusion 59, 085008 (2017).
LCM: liquid-crystal modulator
UNR: University of Nevada, Reno

Disc-type plasma structures have been observed in recent experiments in megagauss magnetic fields

- The laser was focused to a spot of 30 μm with an intensity of ~3 $\times$ 10^{15} W/cm^2 for ~ 1 ns
- UV shadowgraphs show no disc plasma without the current
- laser probing and x-ray spectroscopy
  - measured electron density $n_e \sim 10^{19}$ cm^{-3}
  - density in the rings of 7 $\times$ 10^{18} cm^{-3}
  - electron temperature T_e = (200 to 400) eV



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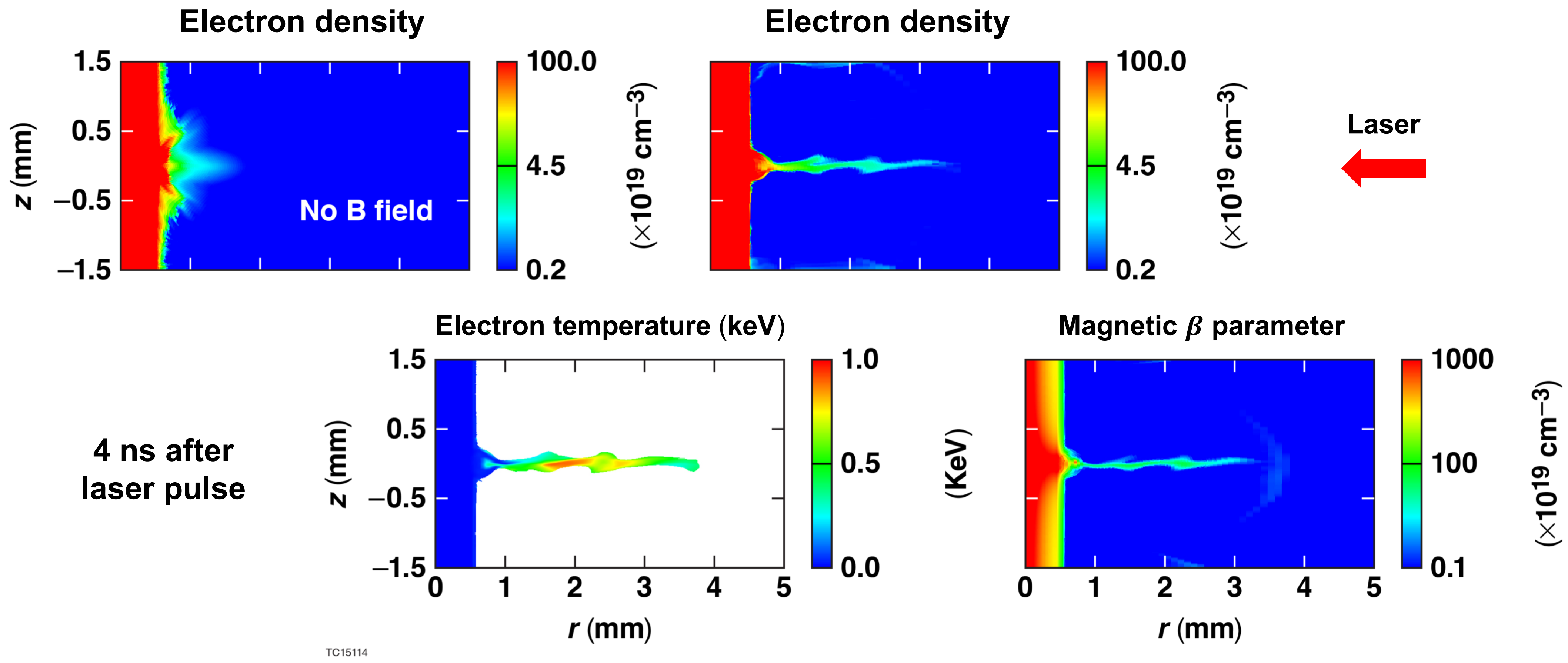
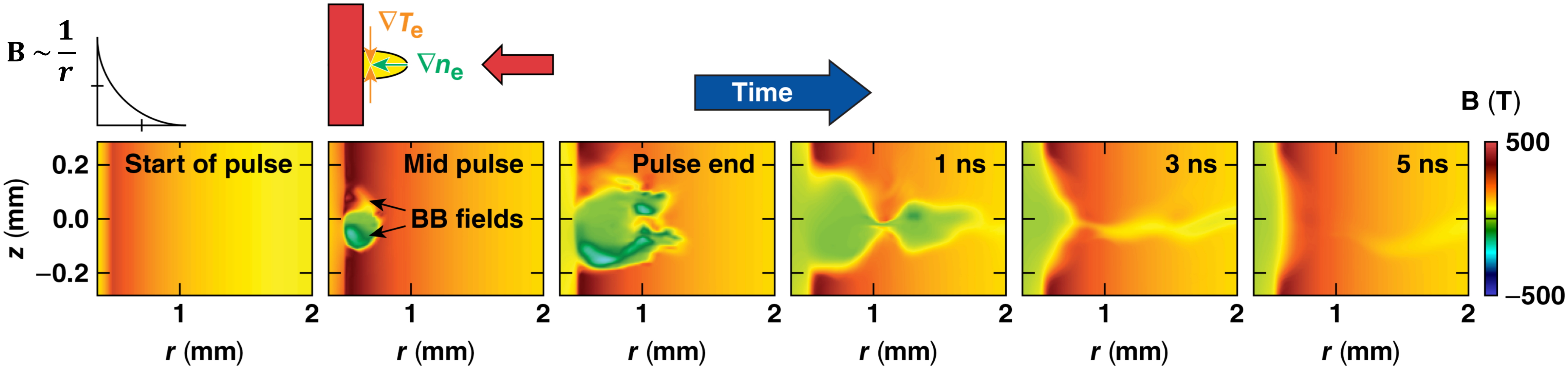
Cylindrical ($r-z$) simulations with azimuthal symmetry show axial collimation in the external magnetic field not seen without the magnetic field



The magnetic-field evolution over time shows a pinching effect that leads to disc formation



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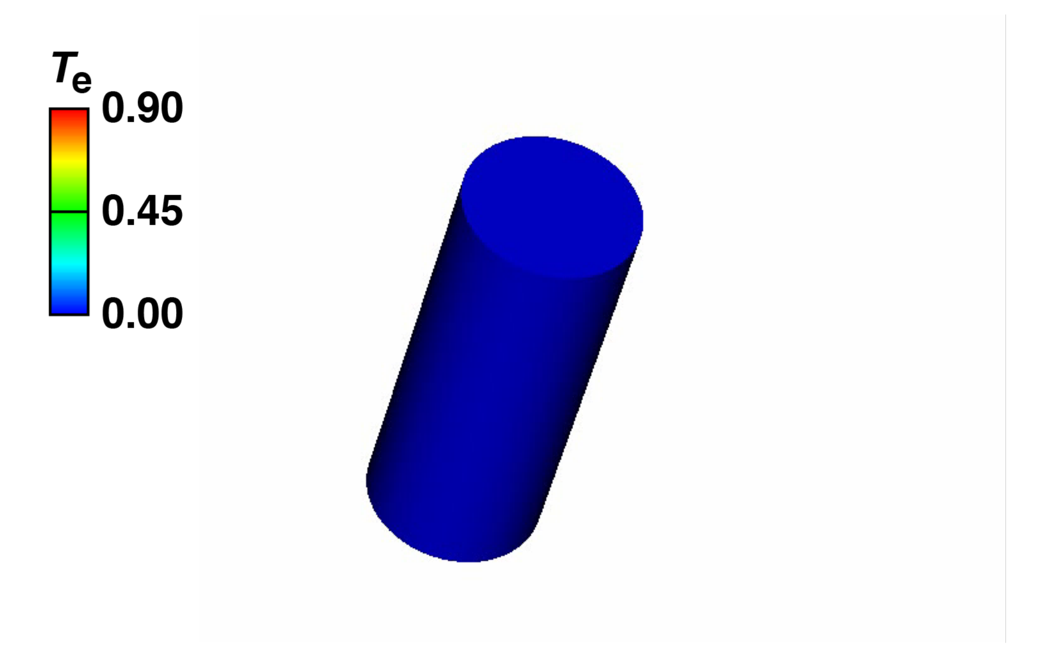
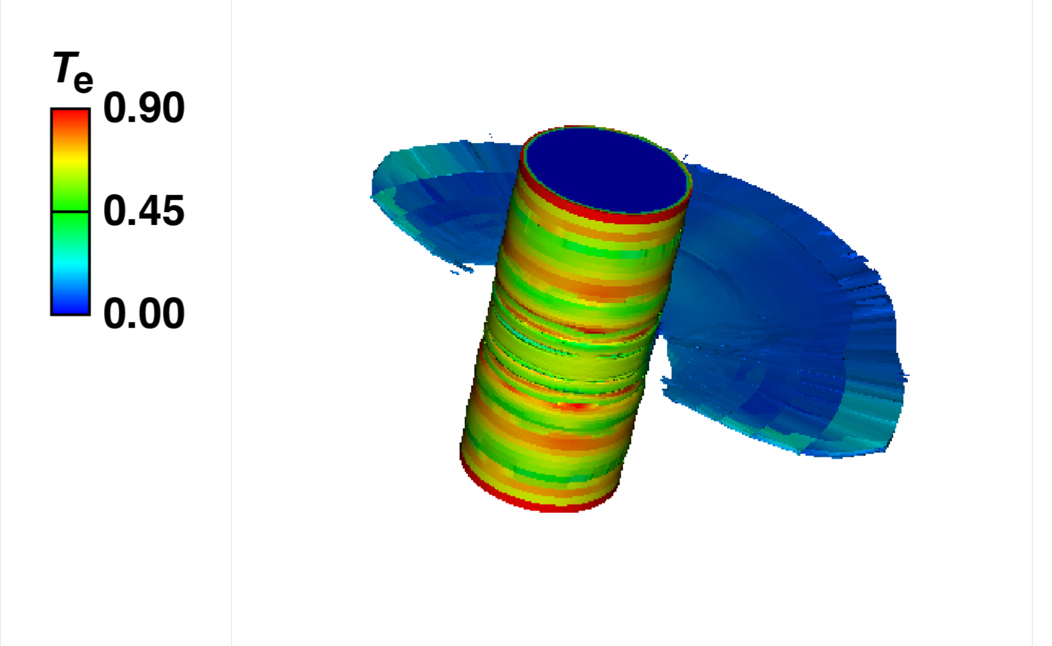
- The laser pulse ablates the plasma, pushing the external field and generating Biermann battery (BB) magnetic fields $B_{BB} \sim \nabla n_e \times \nabla T_e$
- BB fields introduce asymmetry to the disc
- The magnetic field pinches down on the plasma
- As the plasma expands, the temperature drops, and magnetic fields diffuse into the disc

The extended MHD model leads to faster disc structure formation compared to the resistive MHD model

Extended MHD



Resistive MHD



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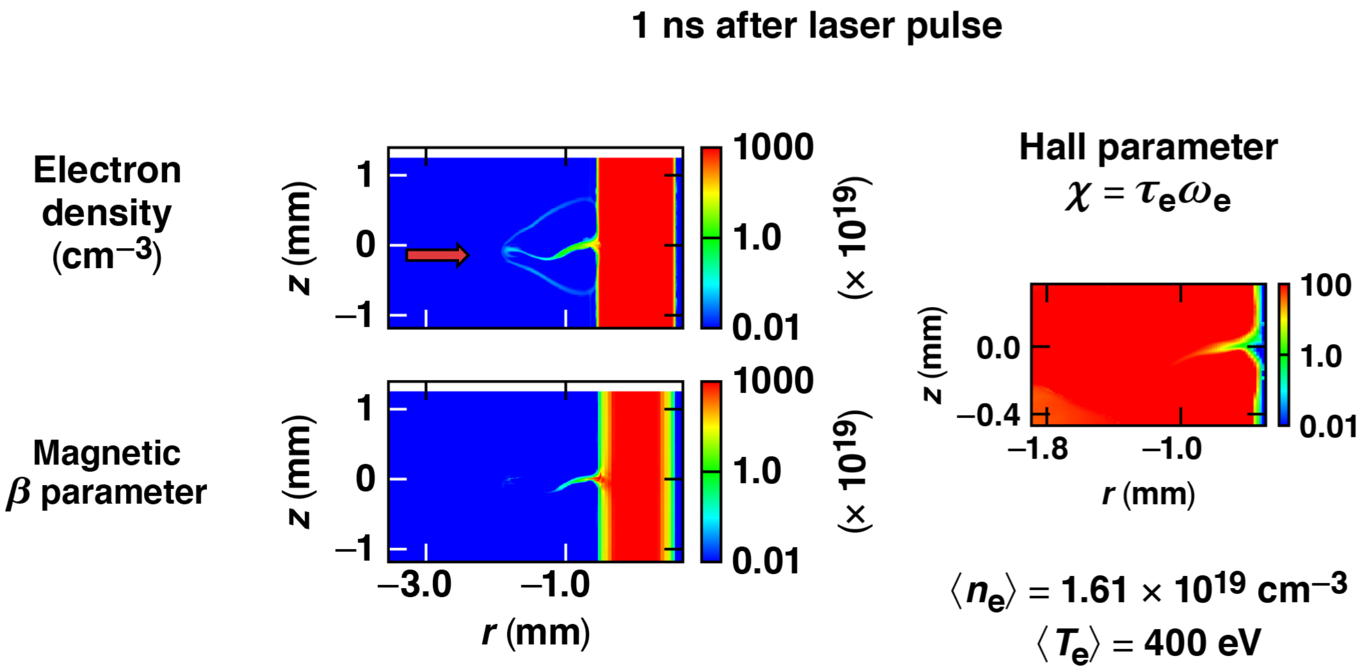
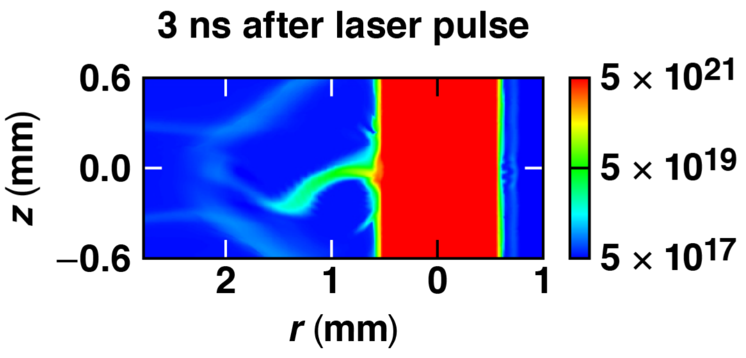
Ohm's Law

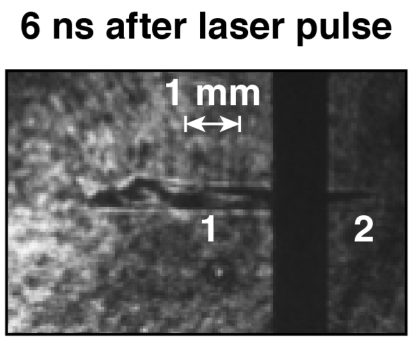
$$\vec{E} = -\frac{1}{c}\vec{U}\times\vec{B} + \overleftrightarrow{\eta}\times\vec{J} + \frac{\vec{J}\times\vec{B}}{cen_{\mathrm{e}}} - \frac{\nabla\overleftrightarrow{P_{\mathrm{e}}}}{en_{\mathrm{e}}} - \frac{k}{\mathrm{e}}\overleftrightarrow{\beta}\times\nabla T_{\mathrm{e}}$$

$$\vec{E} = -\frac{1}{c}\vec{U}\times\vec{B} + \overleftrightarrow{\eta}\times\vec{J}$$

Plasma structures are similar in simulations and experiments and measured parameters are in general agreement







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Extended MHD is needed to simulate plasma disc formation and magnetic confinement observed in laser-wire interaction experiments on Zebra

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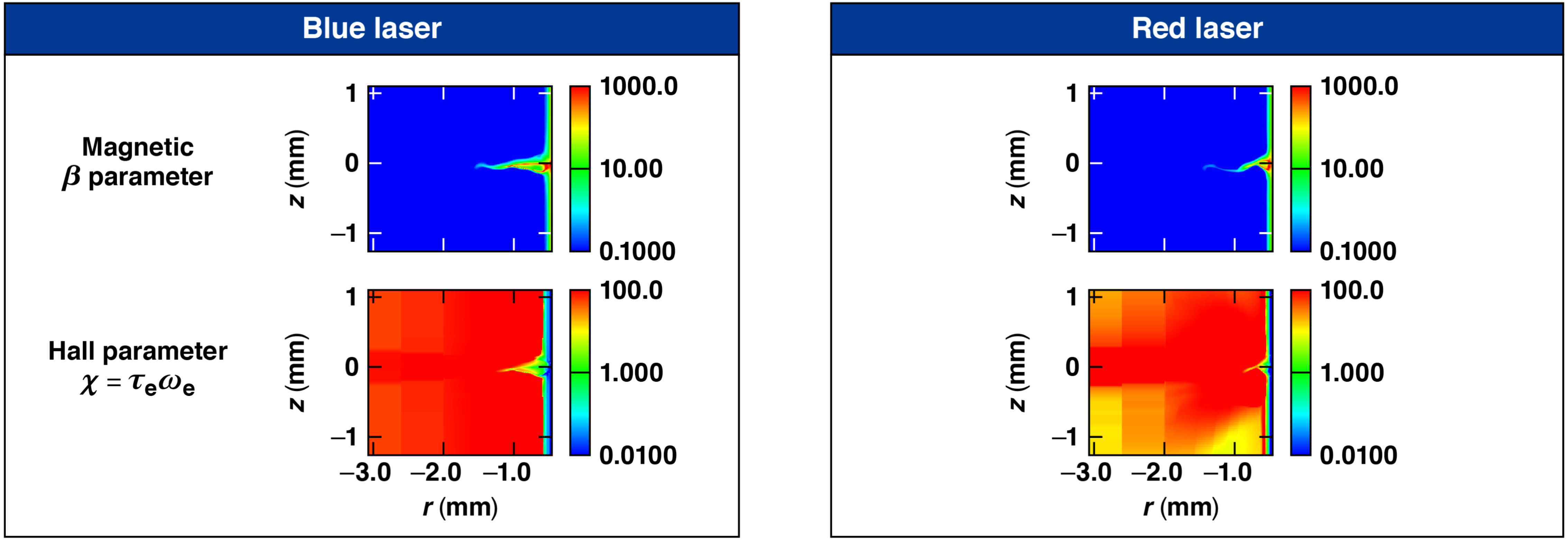
Backup

The plasma β parameter transitions from larger than unity to less than unity around the disc, and the Hall parameter changes from small to large



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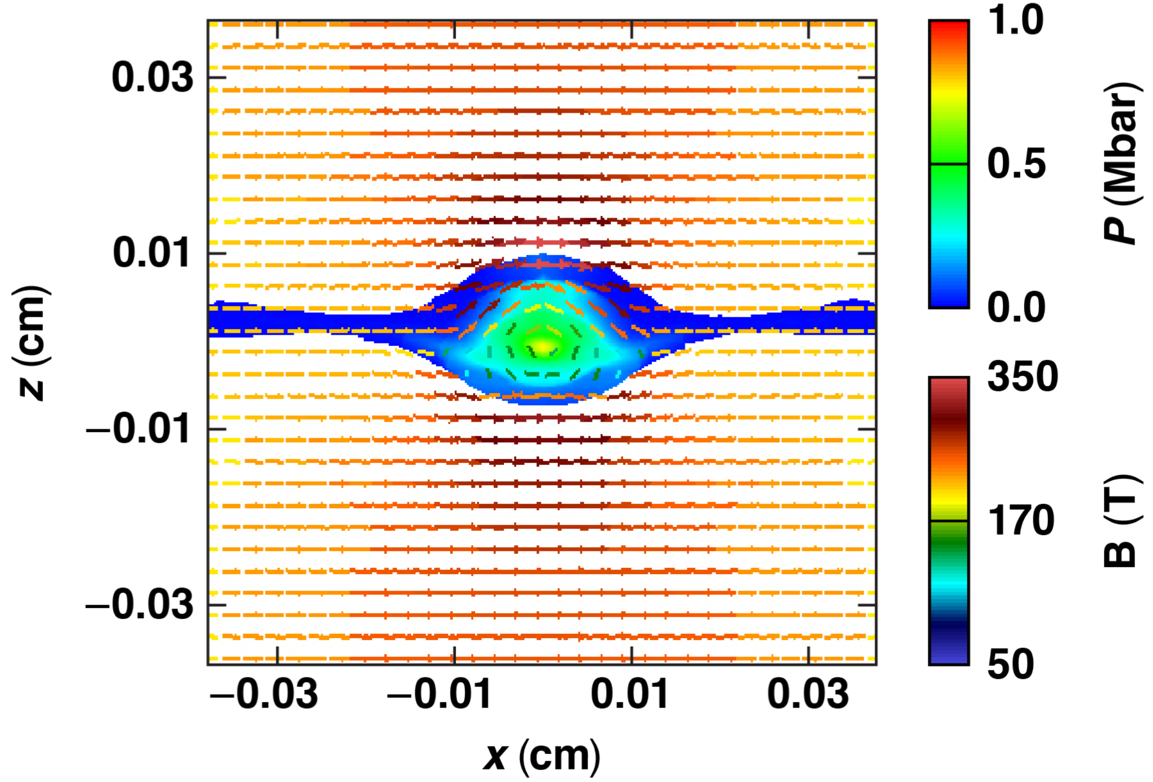
The field curvature of the disc and pressure gradient suggest the possibility of interchange instability

Midpoint of laser pulse



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$\kappa \times \nabla p > 0$ allowing for possible interchange instability