Generation of Laser-Driven, High-Mach-Number Magnetized Collisionless Shocks

Derek Schaeffer

Princeton University

HEDLA

Kurashiki, Japan

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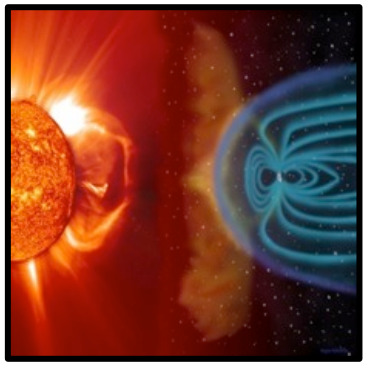
Collaborators

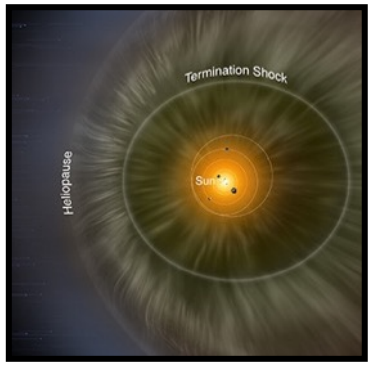
- Will Fox (PPPL)
- Amitava Bhattacharjee (PU/PPPL)
- Gennady Fiksel (U. Michigan)
- Dan Haberberger (LLE)
- Daniel Barnak (LLE)
- Suxing Hu (LLE)
- Russ Follett (LLE)
- Kai Germaschewski (U. NH)

Collisionless Shocks are Prevalent in Many Space and Astrophysical Systems

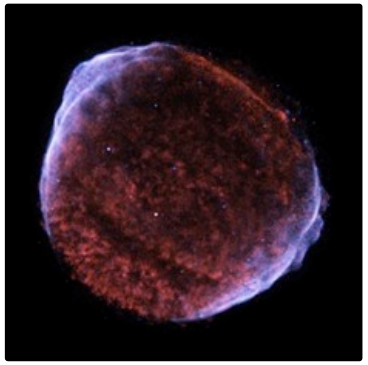
Solar Wind



Heliopause



Supernovae Remnants



Active Galactic Nuclei

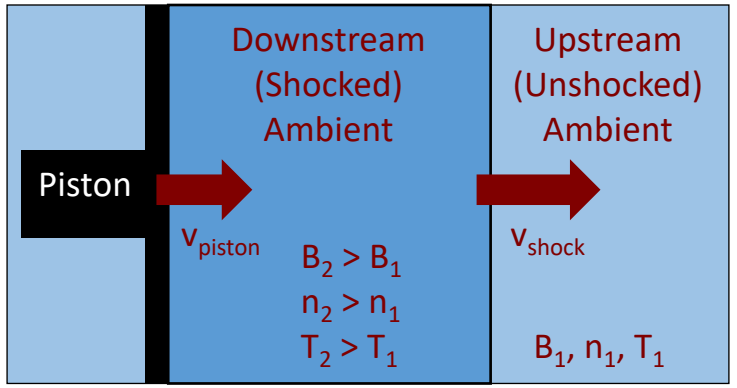
- Collisionless shocks convert the ram pressure of incoming supersonic flows to thermal pressure over length scales much shorter than the collisional mean free path
- Known to be the source of very high-energy particle acceleration, including cosmic rays
- Currently, most shock data limited to ~1-D spacecraft trajectories.

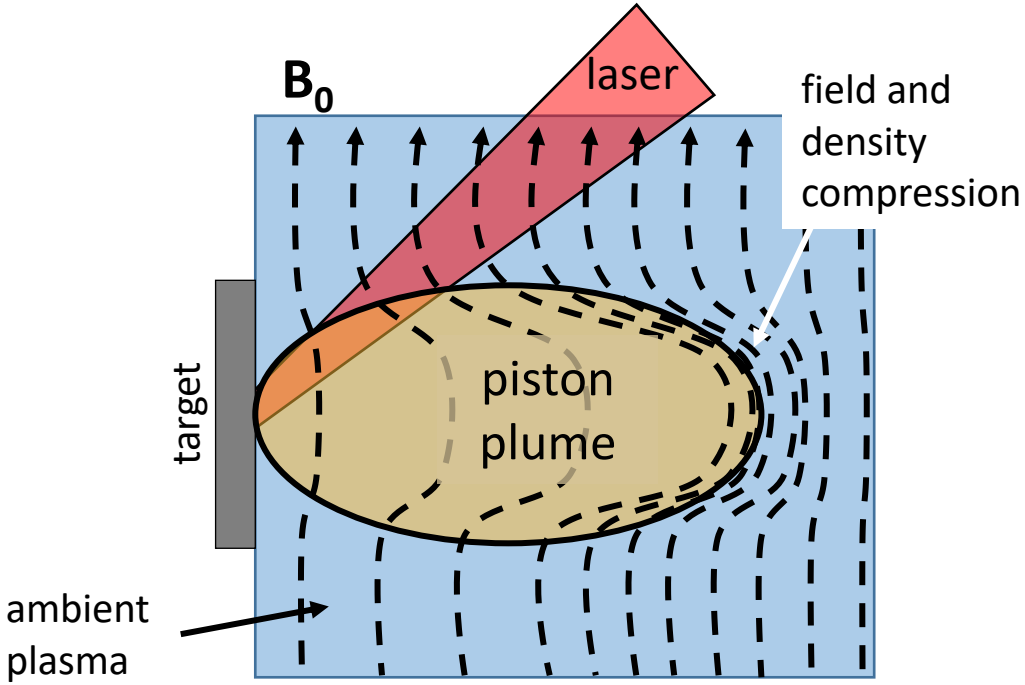
Through appropriate scaling, these systems can be studied in the laboratory.

Laboratory Experiments can Reproduce the Physics of Space and Astrophysical Collisionless Shocks in a Controlled Setting

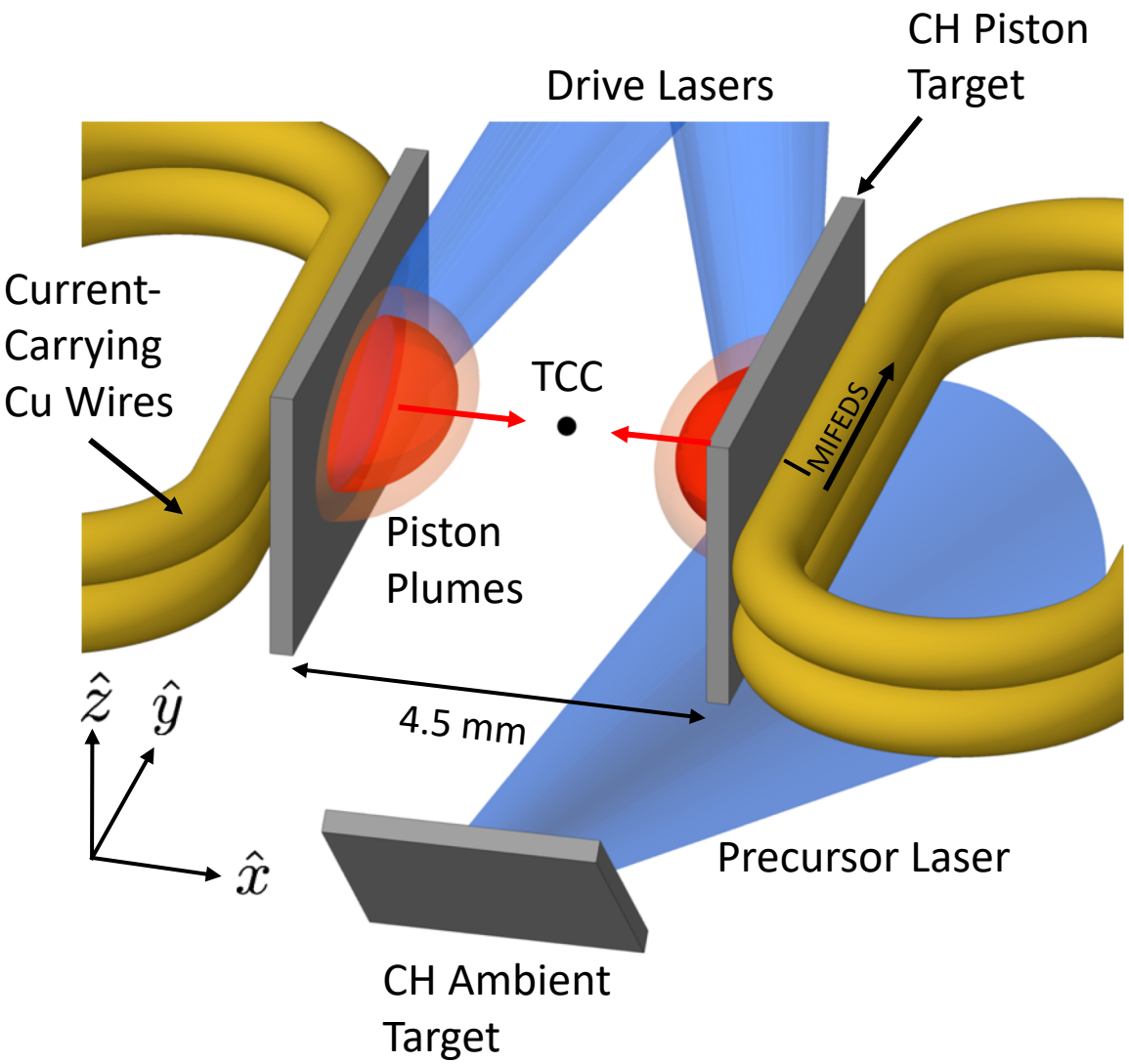
- Laboratory experiments can complement spacecraft and remote sensing measurements
  - Wide range of Mach numbers (M_A<40)
  - 2D and 3D datasets
  - Quasi-perpendicular and quasi-parallel magnetic geometries
- Criteria for high-Mach-number, piston-driven shocks
  - $M_A > 4$
  - Collisionless ambient-ambient interaction
  - B/B_0 and $n/n_0 > 2$
  - Shock width $\lesssim 1\ d_{i0}$
  - Separation of shock from piston

Model for Piston-Driven Shock Formation



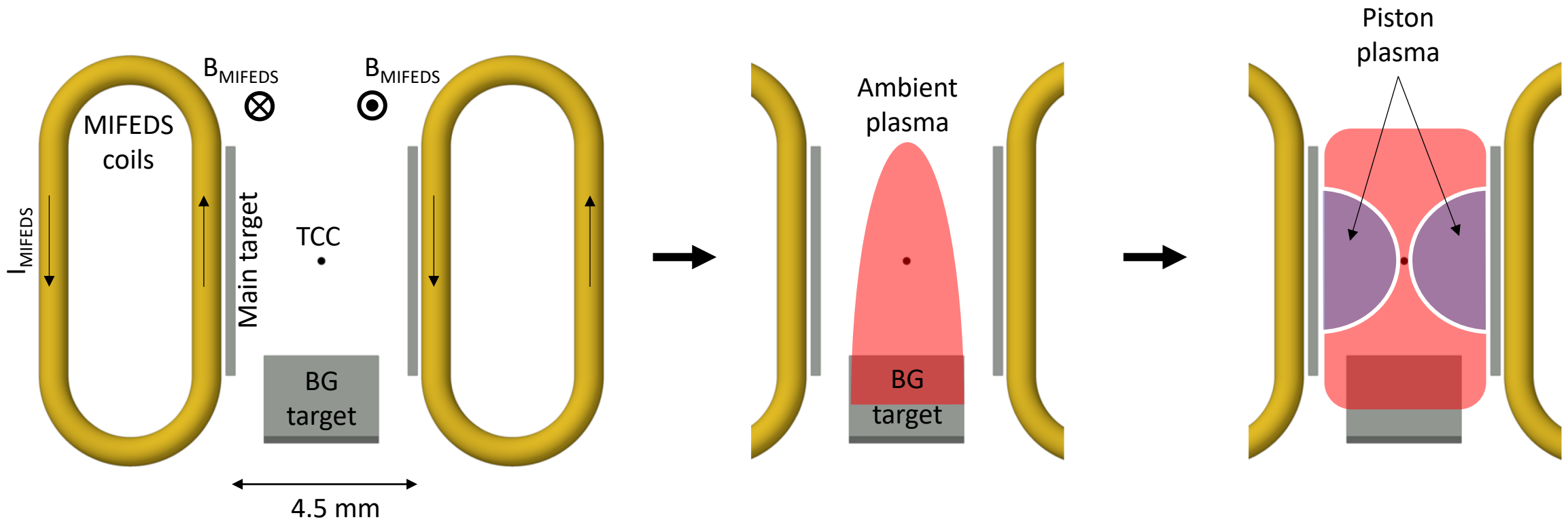


Experimental Setup for High-M_A Shocks on Omega EP



- Diagnostics:
  - Angular Filter Refractometry (AFR)
  - Shadowgraphy
  - Proton radiography
  - Thomson scattering (on Omega 60)

Experimental Setup for High-M_A Shocks on Omega EP

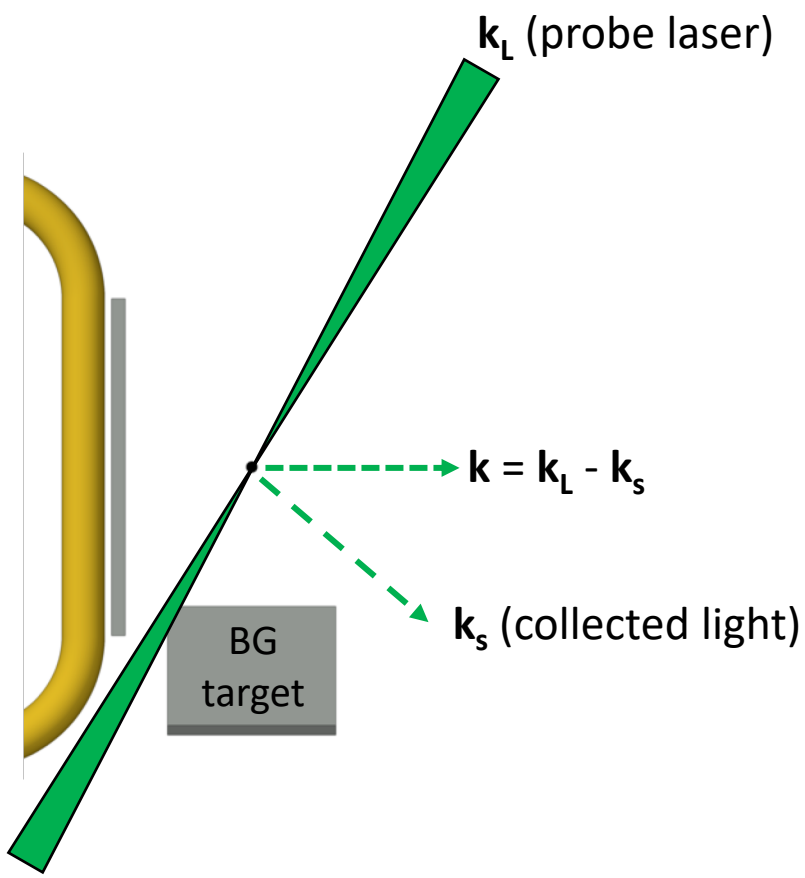


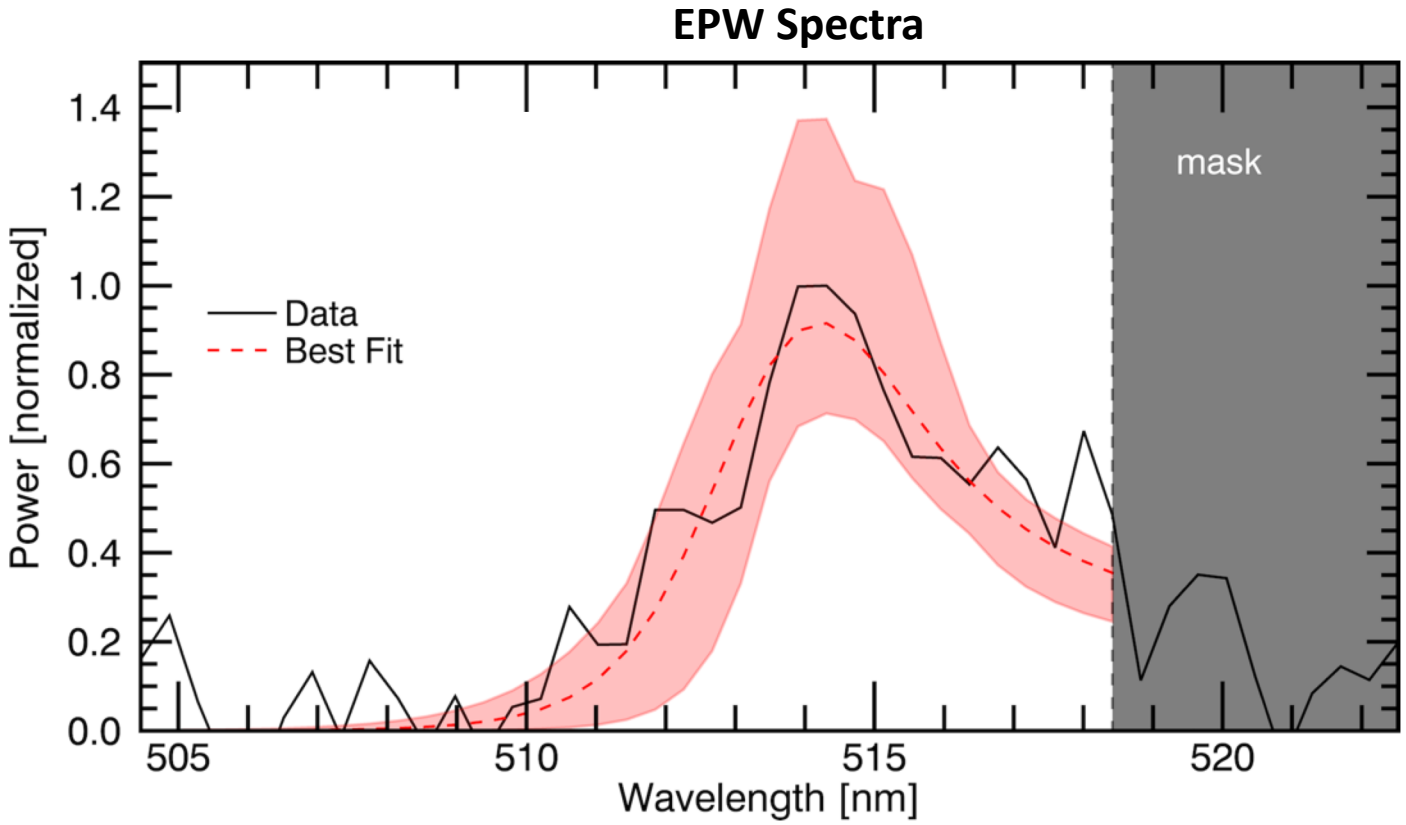
MIFEDS coils provide background magnetic field ~ 8T

Precursor beam ablates ambient plasma 12 ns before drive beams

Drive beams create supersonic piston plumes that expand into ambient plasma

Ambient (Upstream) Plasma Characterized with Thomson Scattering

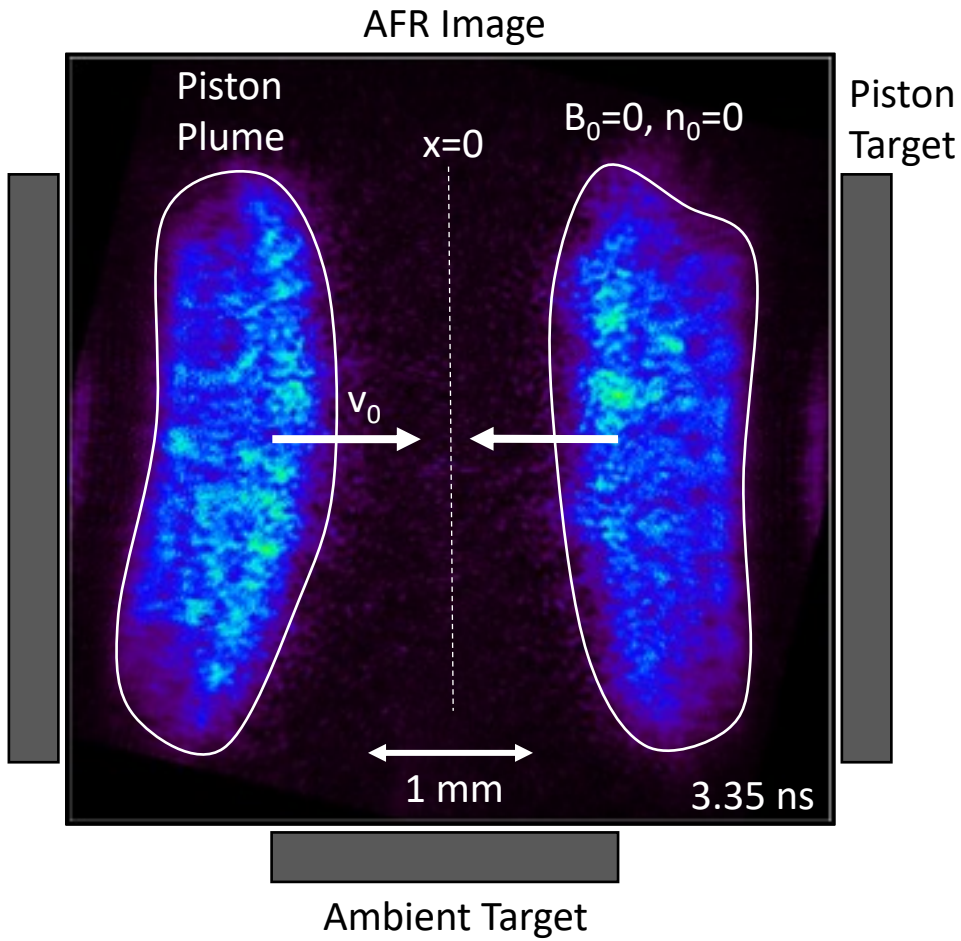


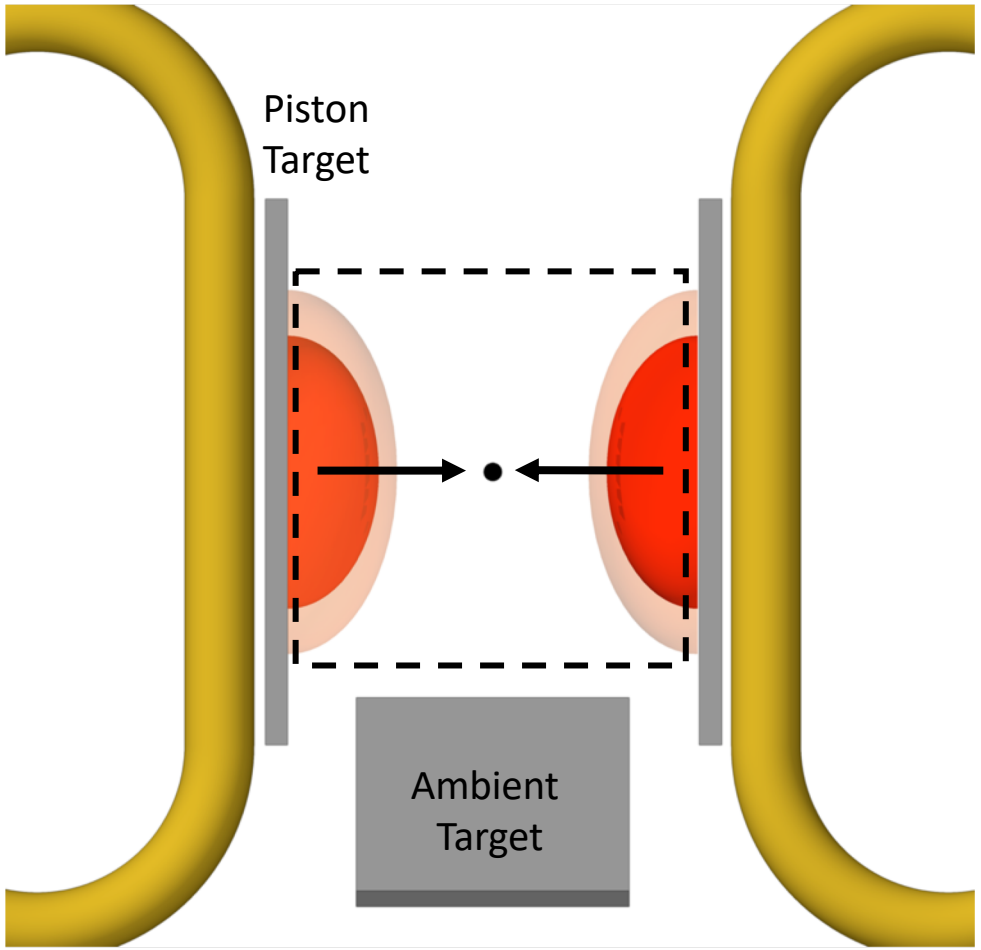


Electron density $\mathbf{n_{e0}} = 2\text{x}10^{18}$ cm^{-3}

Electron temperature $\mathbf{T_{e0}} = 30$ eV

Density Evolution Measured with AFR

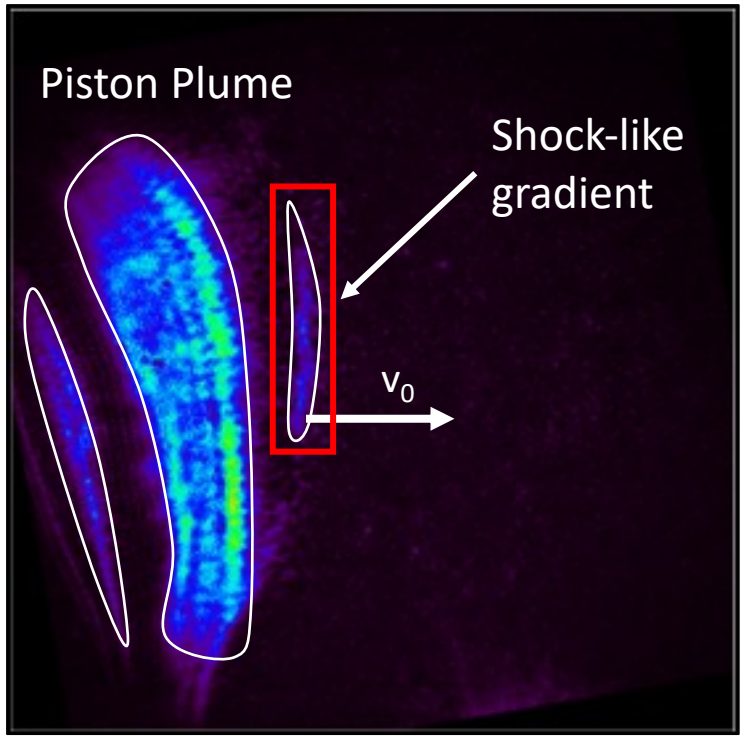




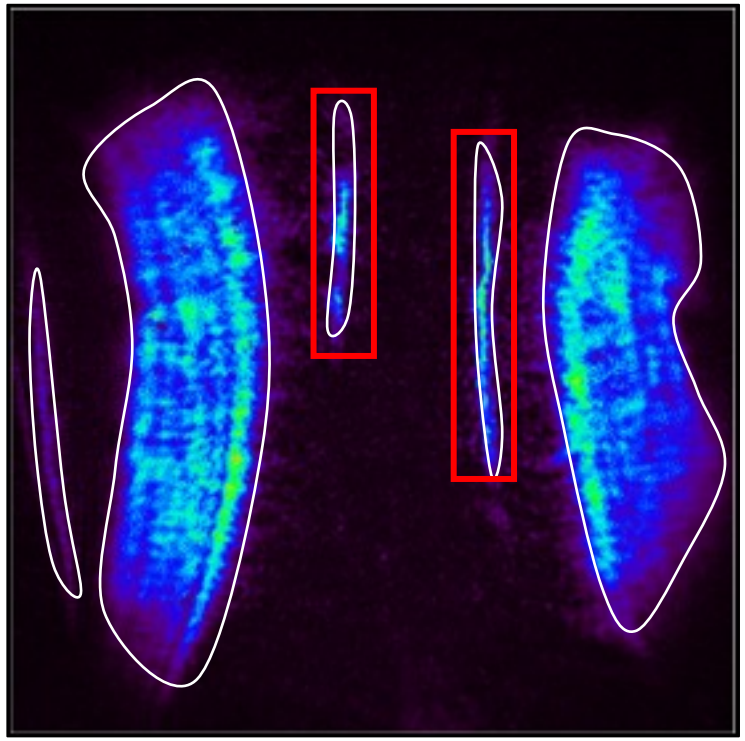
Without background magnetic field or ambient plasma, only piston plumes observed.

Shock-Like Gradients Observed with $B_0>0$ and $n_0>0$

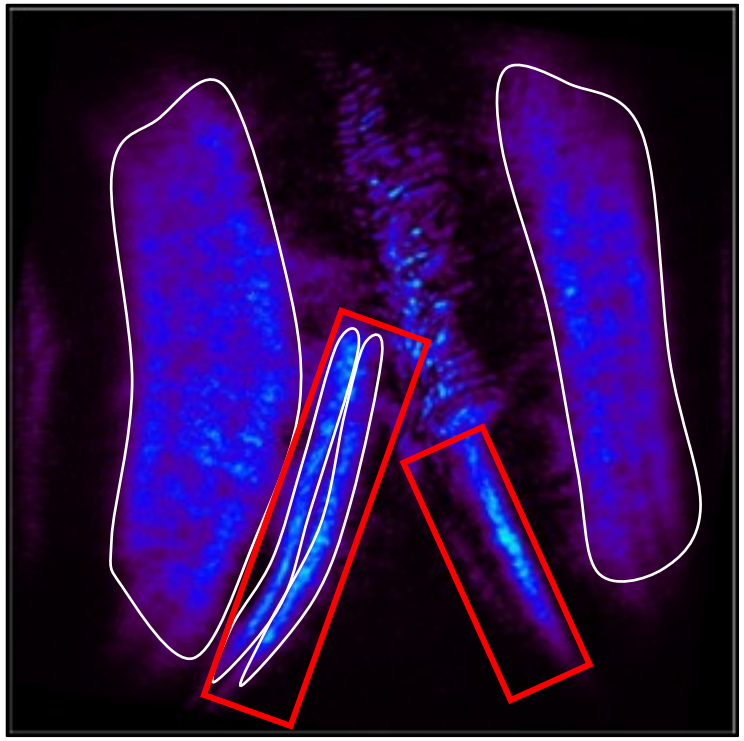
T0 + 2.35 ns



T0 + 2.85 ns



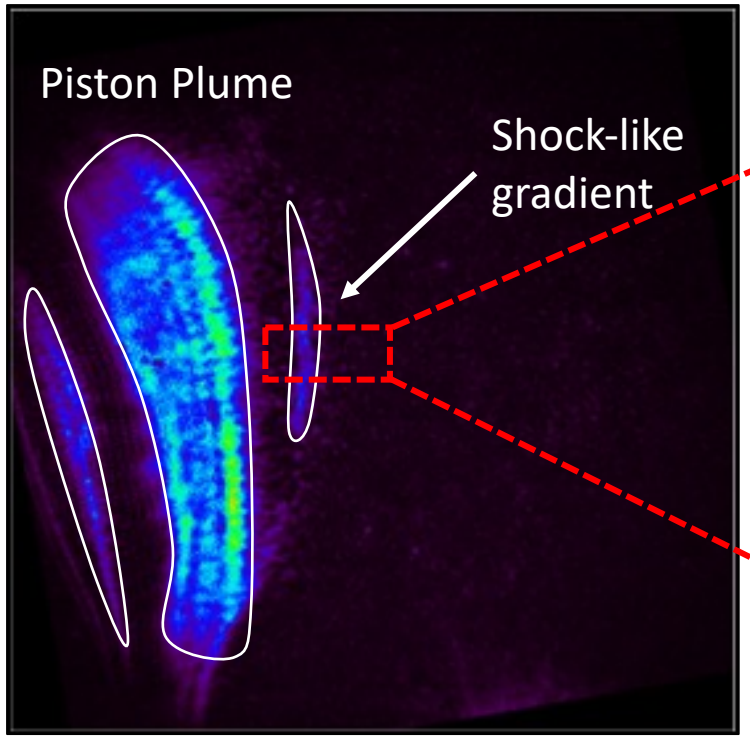
T0 + 3.85 ns



$\mathbf{v_0} \approx 700$ km/s ($\mathbf{M_A} \approx 15$)

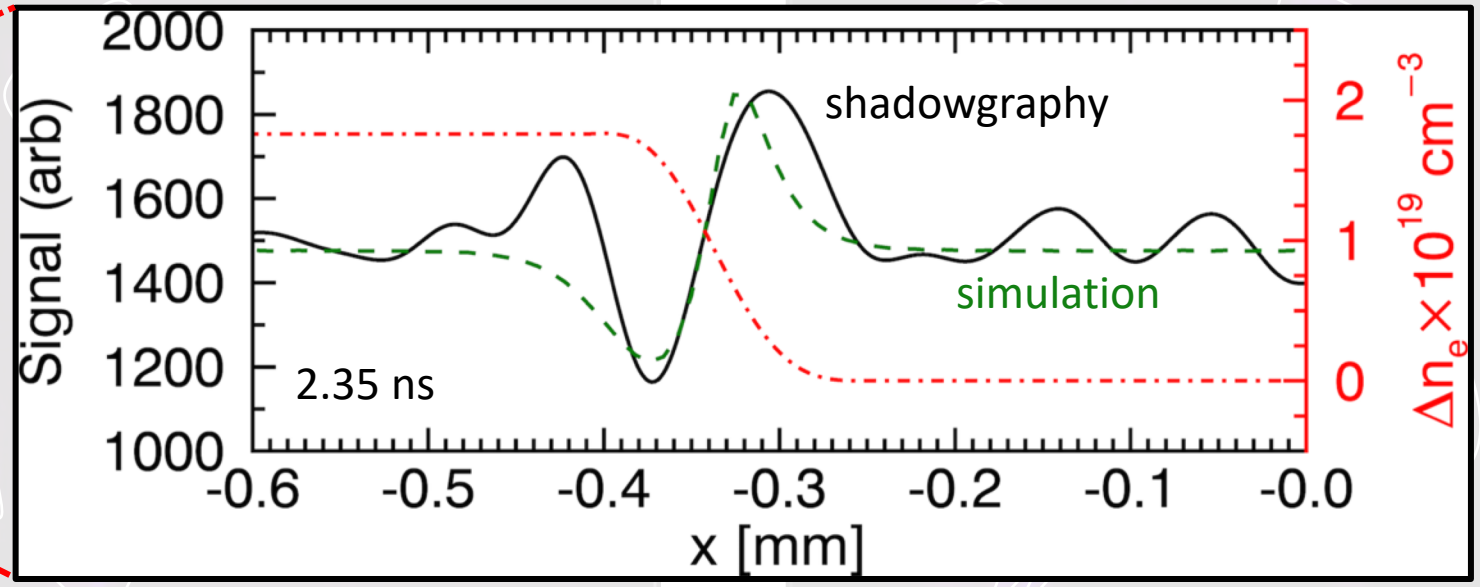
Shock-Like Gradients Observed with $B_0>0$ and $n_0>0$

T0 + 2.35 ns



T0 + 2.85 ns

T0 + 3.85 ns



Compression width $\boldsymbol{\Delta} \sim 0.5\ \mathbf{c}/\boldsymbol{\omega}_{\mathbf{pi}}$

Shock-Like Gradients Observed with $B_0>0$ and $n_0>0$

T0 + 2.35 ns

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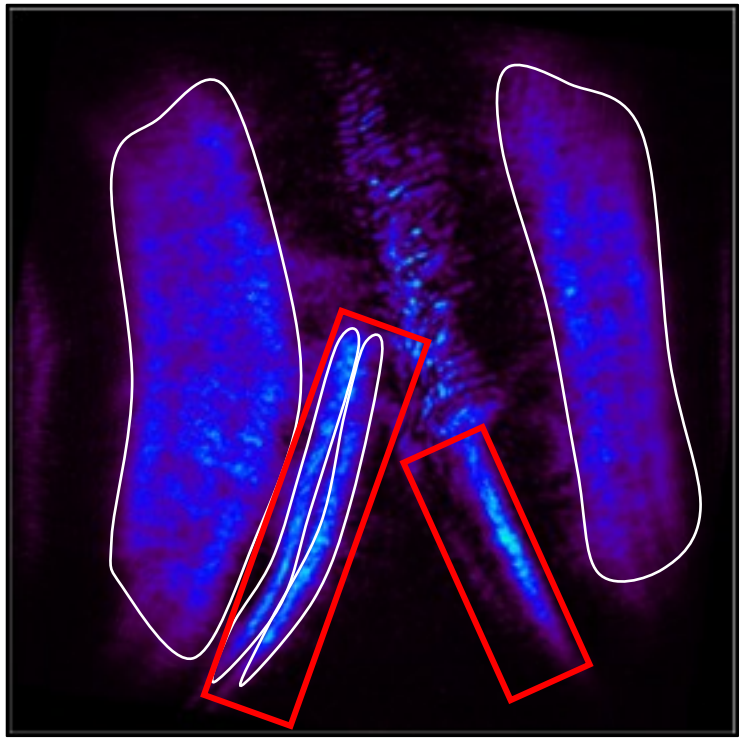
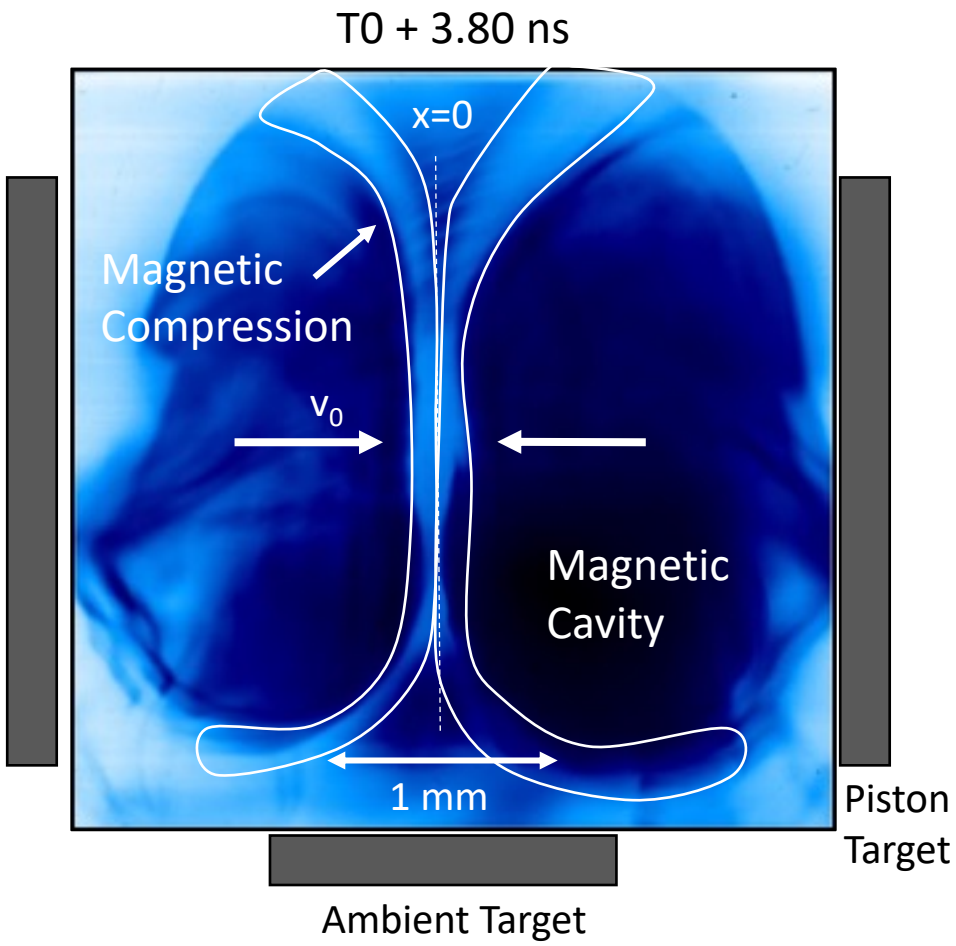
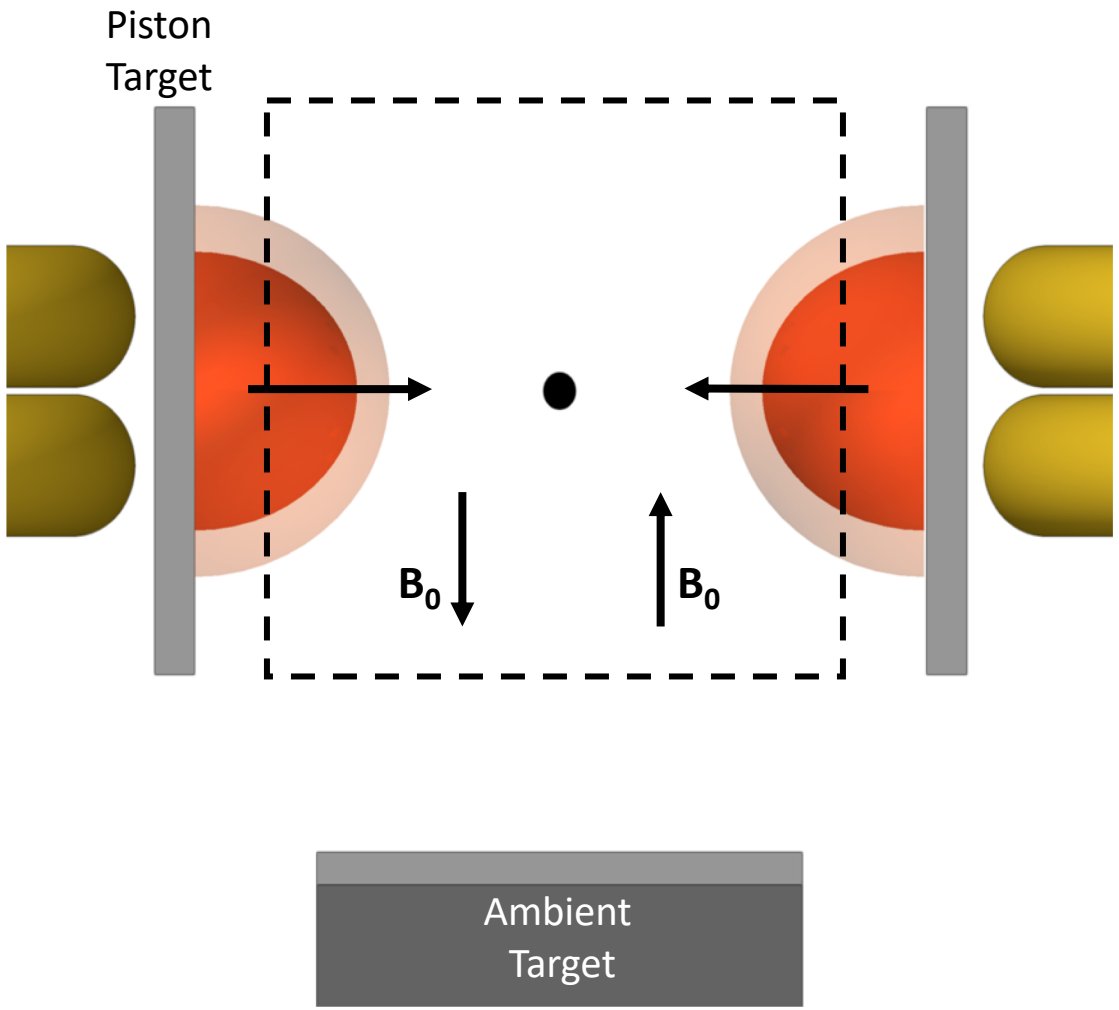


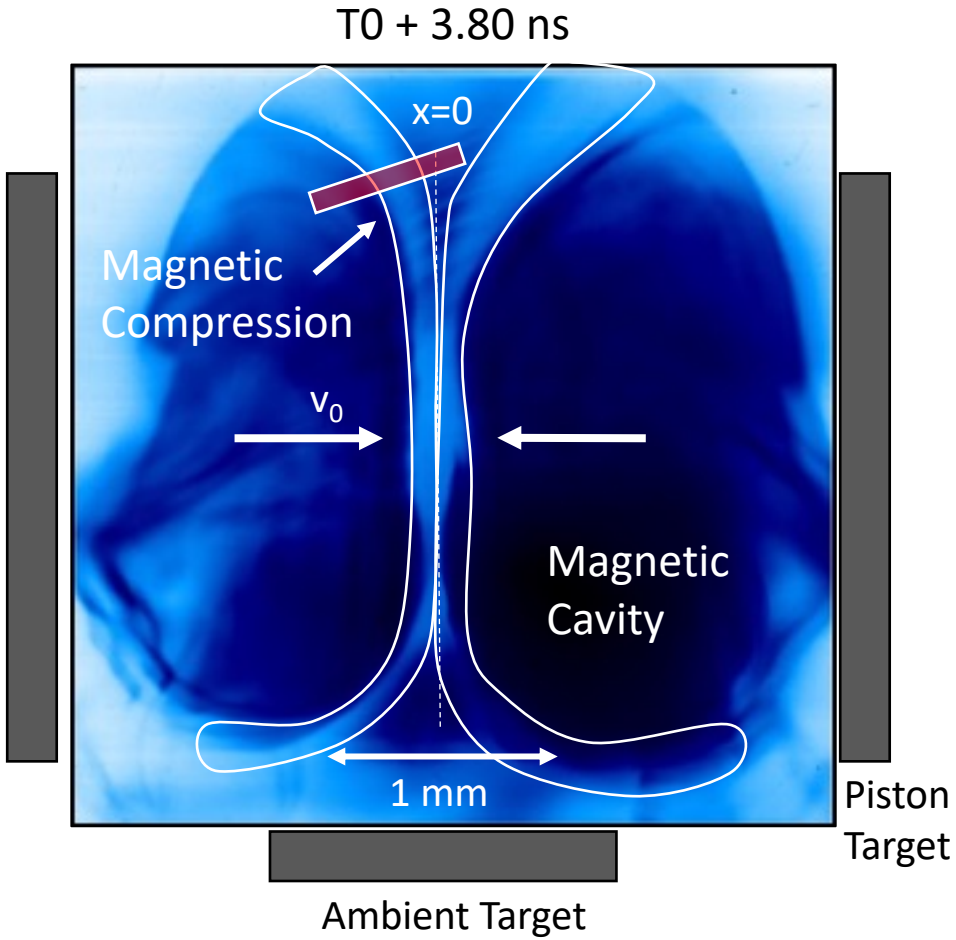
Density compression $\mathbf{n/n_0} \approx 7$

Magnetic Compressions Observed with Proton Radiography

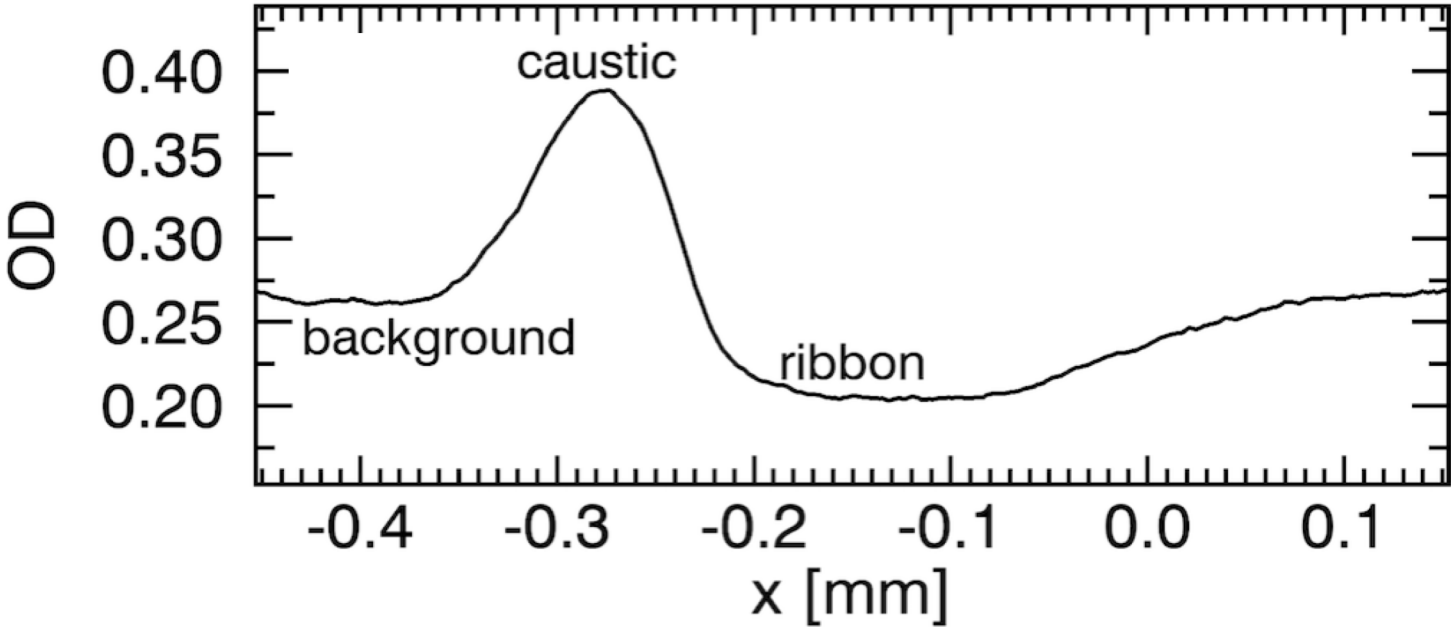




Magnetic Compressions Observed with Proton Radiography

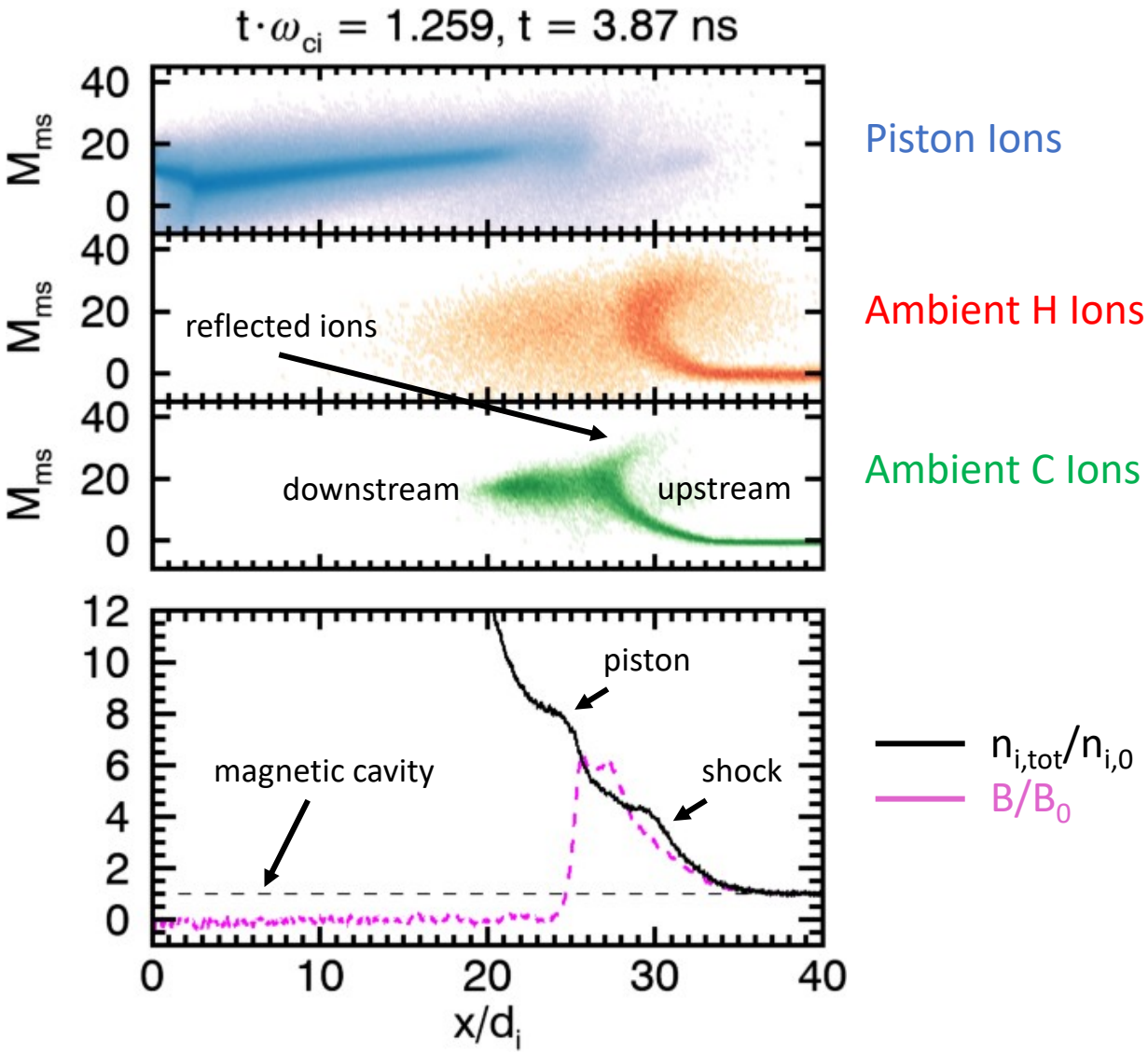


$$B\frac{L_y}{L_x} \approx 70\left(\frac{OD_{bg}}{OD_r} - 1\right)\,[\mathrm{T}]$$



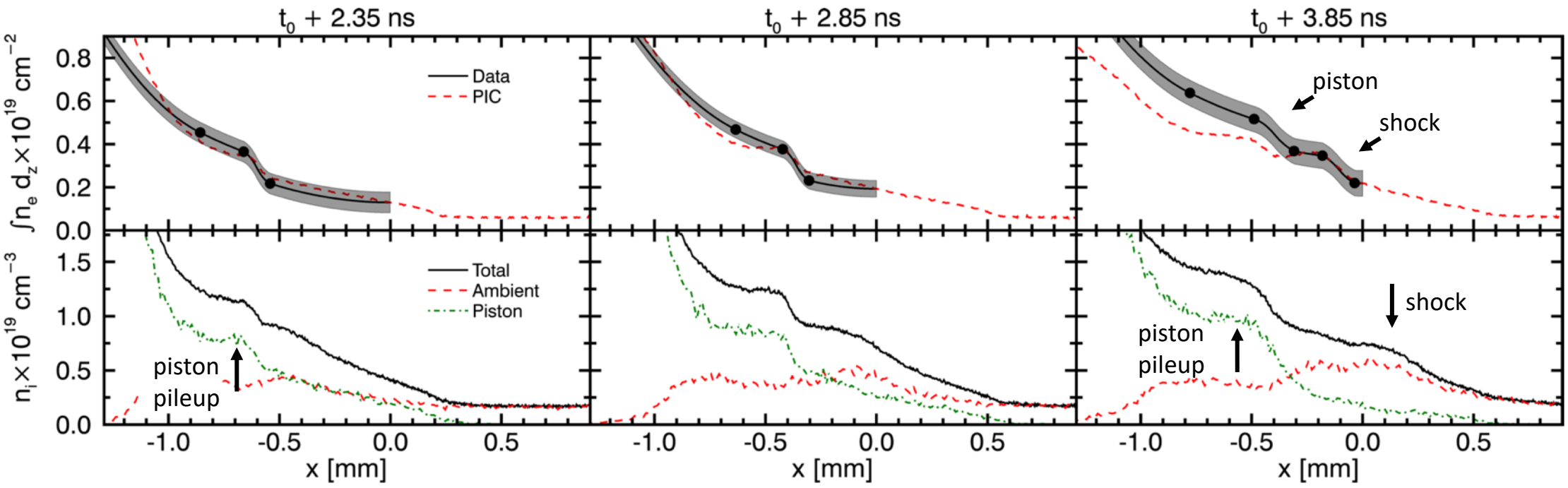
Magnetic compression $\mathbf{B/B_0} \approx 3$

PIC Simulations Indicate Formation of High-M_A Shock



- Magnetic cavity formed as magnetic flux is swept out by piston into thin, compressed region
- Piston ions get trapped behind this magnetic compression
- Ambient ions are reflected off magnetic compression, a hallmark of high-M_A shocks
- A double "bump" in the density profile develops, corresponding to the separation of the shock from the trapped piston ions

Data Profiles Show Density Evolution that is Consistent with High-M_A Shock Formation



Early time density compression mostly associated with pile-up of piston ions

At late time clear double bump feature associated with shock and trapped piston ions

$M_A \sim 15$ magnetized collisionless shock observed!

Schaeffer, *et al.*, PRL, POP, 2017

Summary and Outlook

- We have observed for the first time the formation and evolution of a laser-driven, high-M_A magnetized collisionless shock. The results agree well with PIC simulations.
- The development of this platform allows key questions of high-M_A shocks to be addressed:
  - Spatial and temporal scales of shock formation and reformation
  - Shock heating and energy partitioning
  - Particle injection and acceleration
  - Interplay between shocks, reconnection, and turbulence