# Laser-Driven Magnetized Collisionless Shocks

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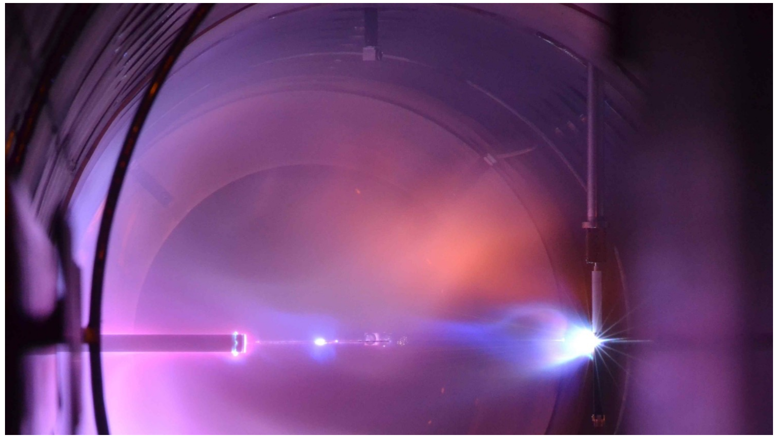
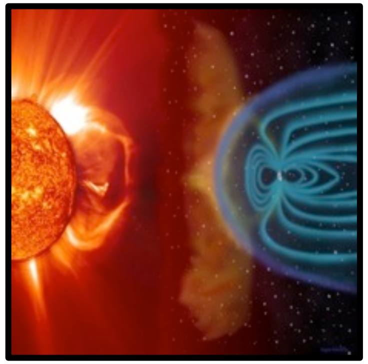
# Outline

- Brief introduction to laboratory research on collisionless shocks driven by magnetic pistons
- Recent measurements of the formation and evolution of a high-$M_A$ shock on the Omega EP laser facility
- Results on the formation and structure of low-$M_A$ shocks on the LAPD
- Dimensionless criteria that describe the conditions under which shocks driven by magnetic pistons form

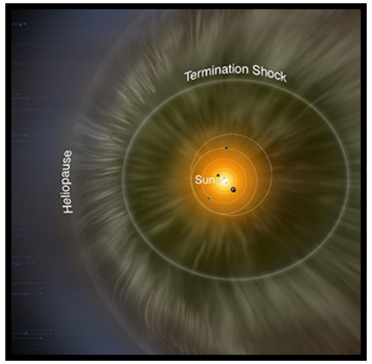


# Collisionless Shocks are Prevalent in Many Space and Astrophysical Systems

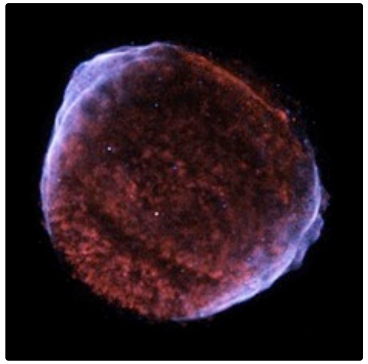
**Solar Wind**



**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
- Shocks are interesting!
  - Complex nonlinear and time-dependent systems
  - Rich phenomenology sensitive to ambient conditions
  - Associated with high energy particle acceleration
- Shocks classification:
  - Electrostatic
  - Turbulent (i.e. Weibel-mediated)
  - Magnetized

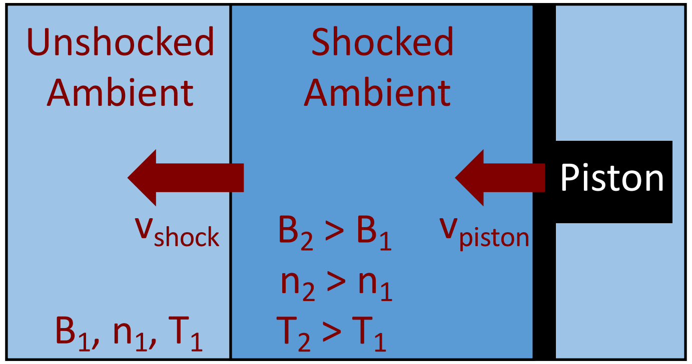
Romagnani, *et al.*, PRL, 2008
Kuramitsu, *et al.*, PRL, 2011
Haberberger, *et al.*, Nature, 2011
Fox, *et al.*, PRL, 2013
Huntington, *et al.*, Nature, 2015

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

- Spacecraft very successful but largely limited to 1D datasets and pre-formed shocks
- Early laboratory experiments also successful but of limited relevance to space shocks
  - The shocks were limited to M<6
  - The goal of the experiments was primarily shock heating (in particular electrons)
  - The experiments were limited to strictly perpendicular magnetic geometries
  - The available diagnostics were also limited to 1D datasets
- A new class of collisionless shocks experiments that utilize a laser-driven magnetic piston is now available
  - Wide range of Mach numbers (M<40)
  - 2D and 3D datasets
  - Quasi-perpendicular and quasi-parallel magnetic geometries

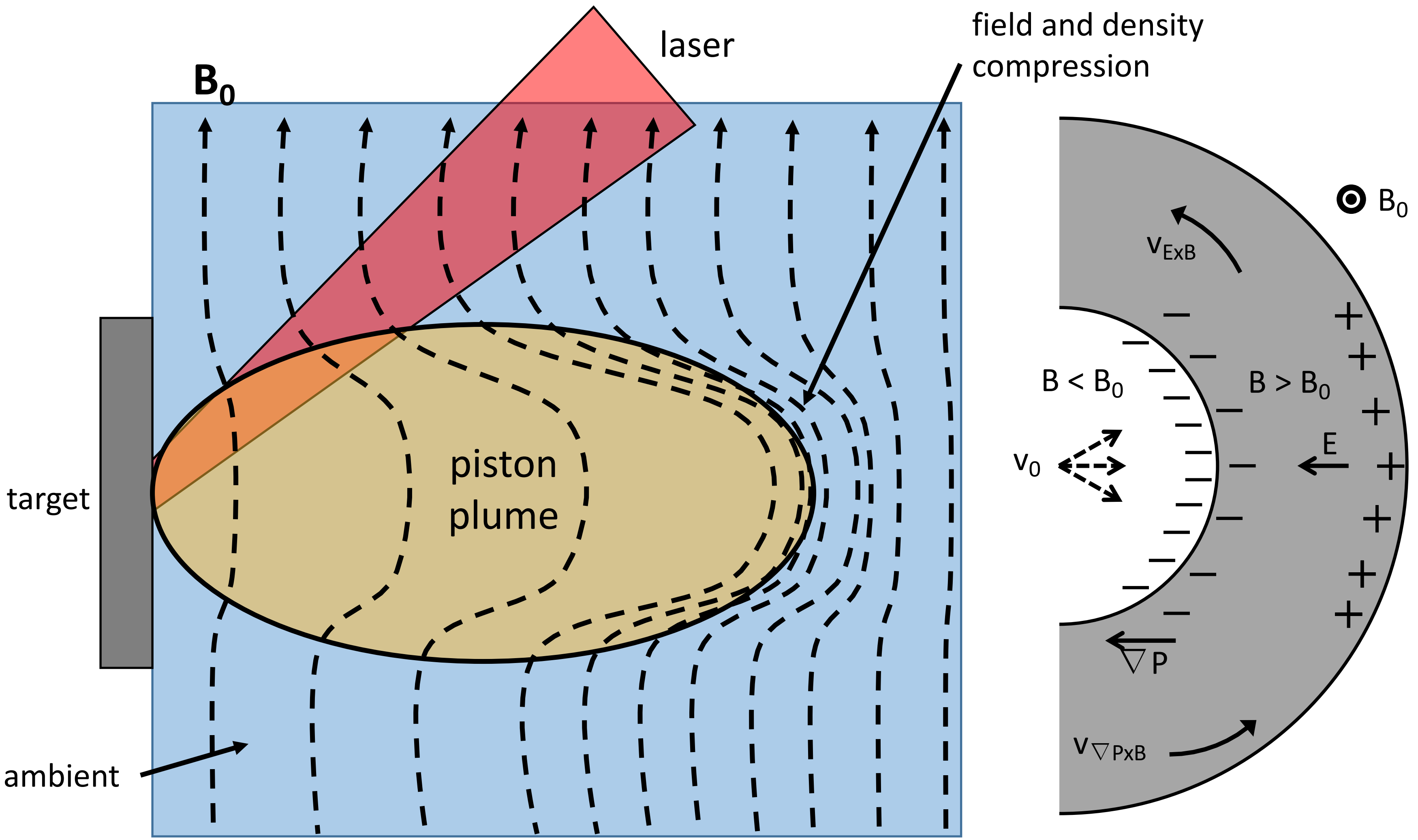
Russel, ASR, 1995

Paul, *et* al., Nature, 1965
Kurtmullaev, *et* al., J. App. Mech. Tech. Phys., 1965
Goldenbaum, *et al.*, PoF, 1967
Stamper, *et* al., PoF, 1969



Drake, PoP, 2000

# Laser-Driven Diamagnetic Cavity Acts as Piston, Launching Shocks in Ambient Plasma

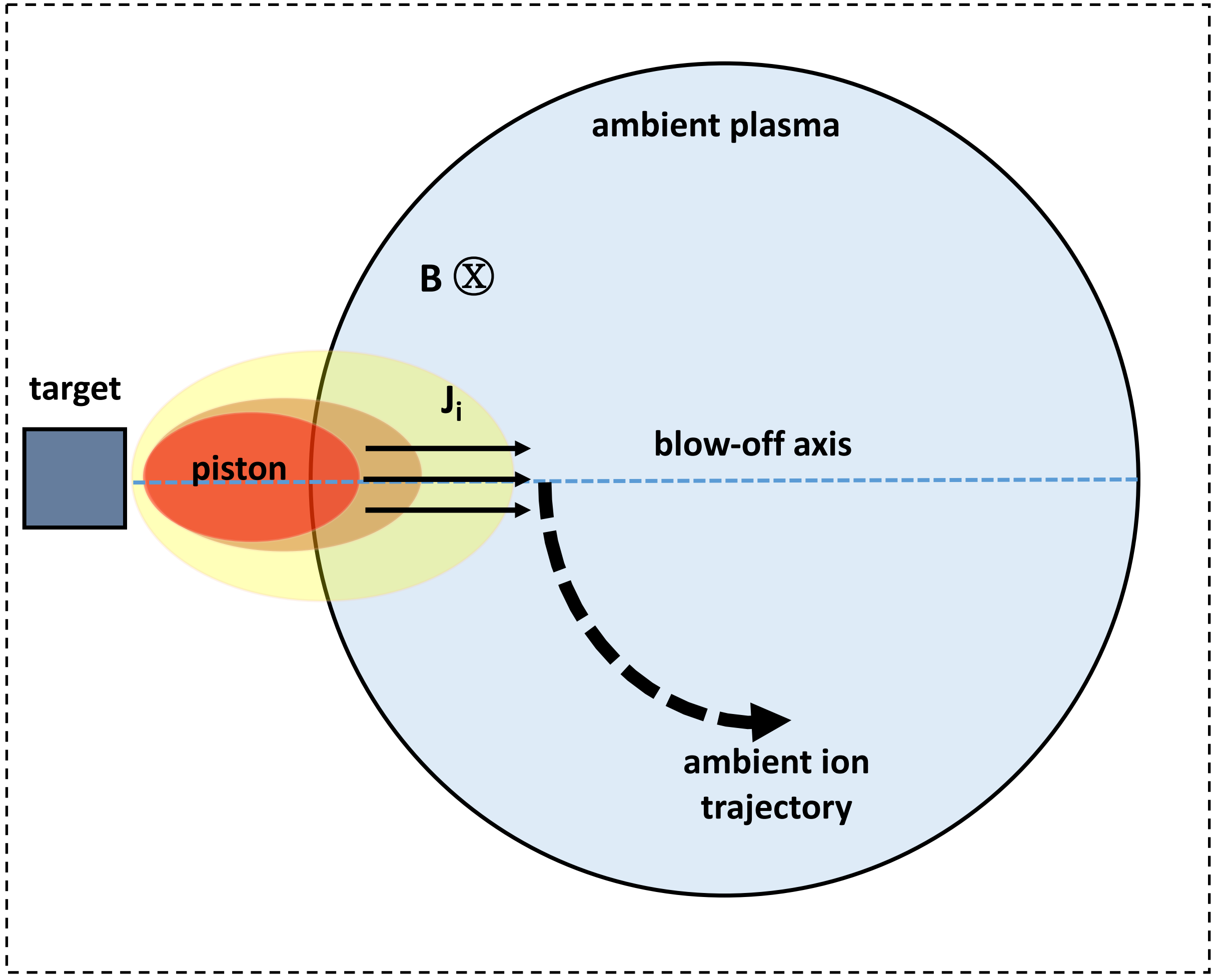


- Piston plume drives diamagnetic current, creating magnetic cavity and leading magnetic compression

Wright, PoF, 1971
Vanzeeland, *et al.*, PoP, 2004
Schaeffer, *et al.*, PoP, 2012

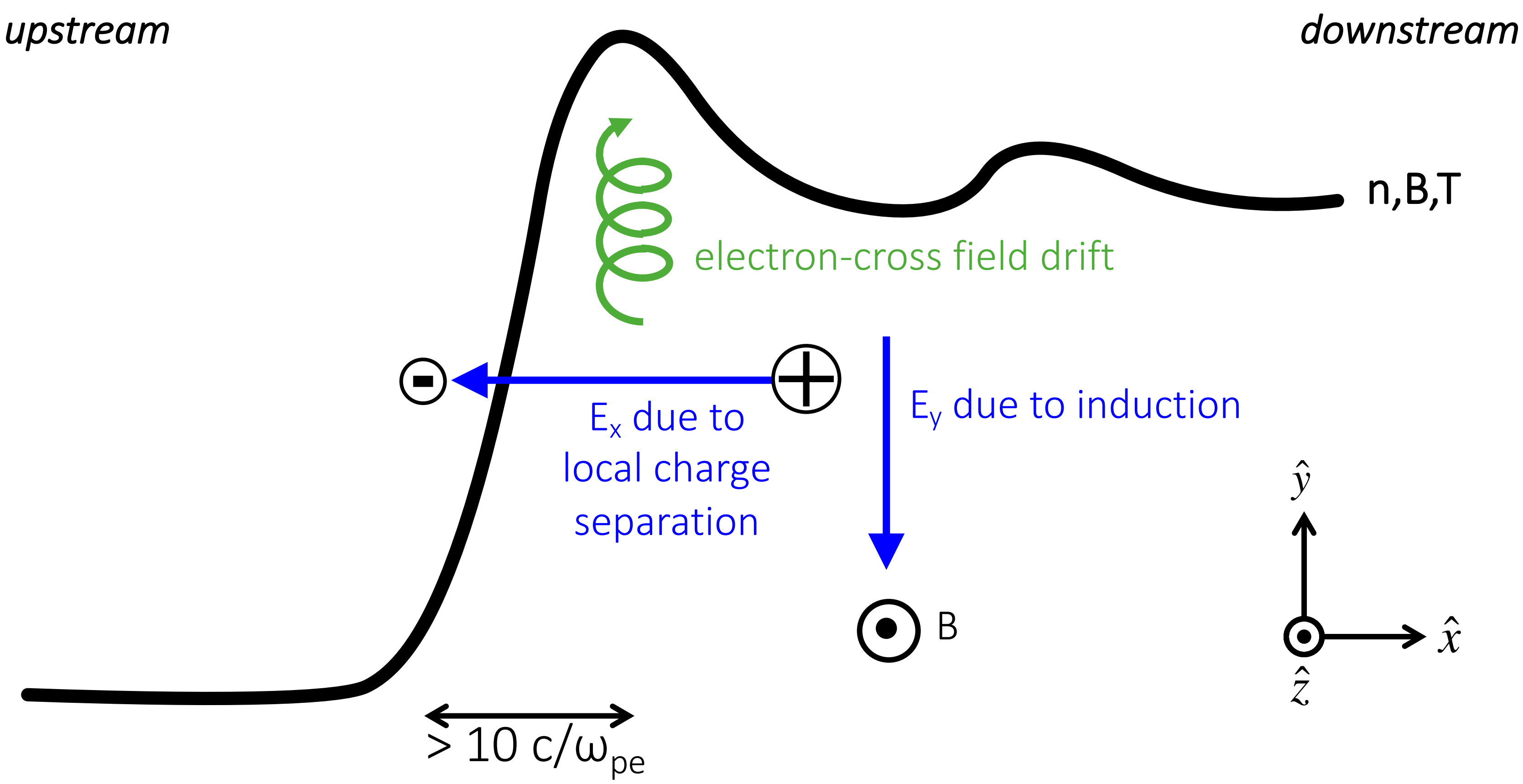
# Piston Energy and Momentum Transferred Collisionlessly to Ambient Plasma

$$\vec{E} = \underbrace{-\frac{\vec{\nabla} p_e}{e n_e}}_{\substack{\text{electron}\\ \text{pressure}\\ \text{gradient}\\ \text{(negligible)}}} \underbrace{-\frac{1}{4\pi e n_e}\vec{B}\times\left(\vec{\nabla}\times\vec{B}\right)}_{\substack{\text{magnetic}\\ \text{pressure}\\ \text{and curvature}\\ \text{(radial)}}} \underbrace{-\frac{\sum_i \vec{J}_i\times\vec{B}}{c e n_e}}_{\substack{\text{ion current}\\ \text{(Larmor term)}\\ \text{(azimuthal)}}}$$



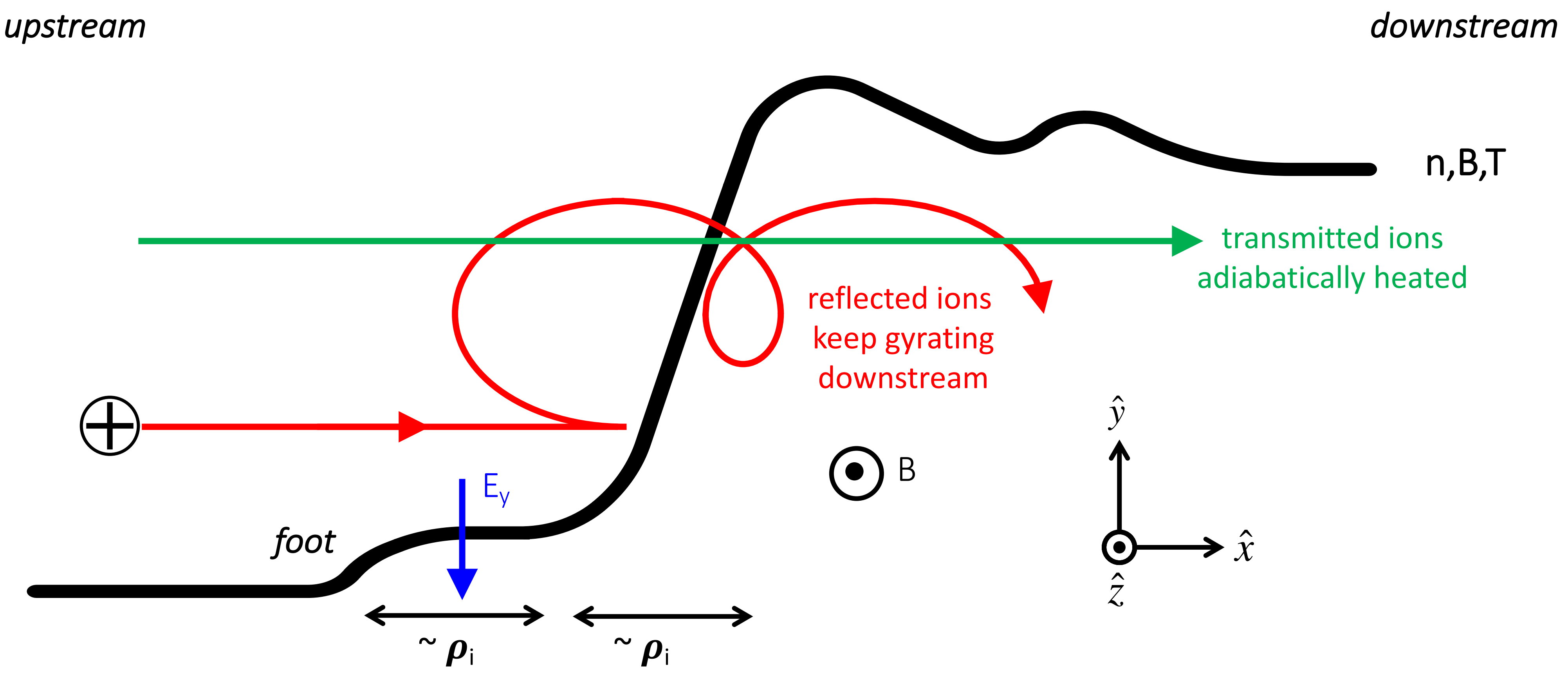
Berezin, *et al.*, Intl. J. Comp. Fluid Dyn., 1998
Hewett, *et al.*, JGR, 2011
Bondarenko, *et al.*, submitted, 2016

# Dissipation in Subcritical ($M_A$<3) Shocks Provided by Drift Instabilities



Treumann, AAR, 2009
Balogh and Treumann, *Physics of Collisionless Shocks*, 2013

# Dissipation in Supercritical ($M_A$>3) Shocks Provided by Ion Reflection

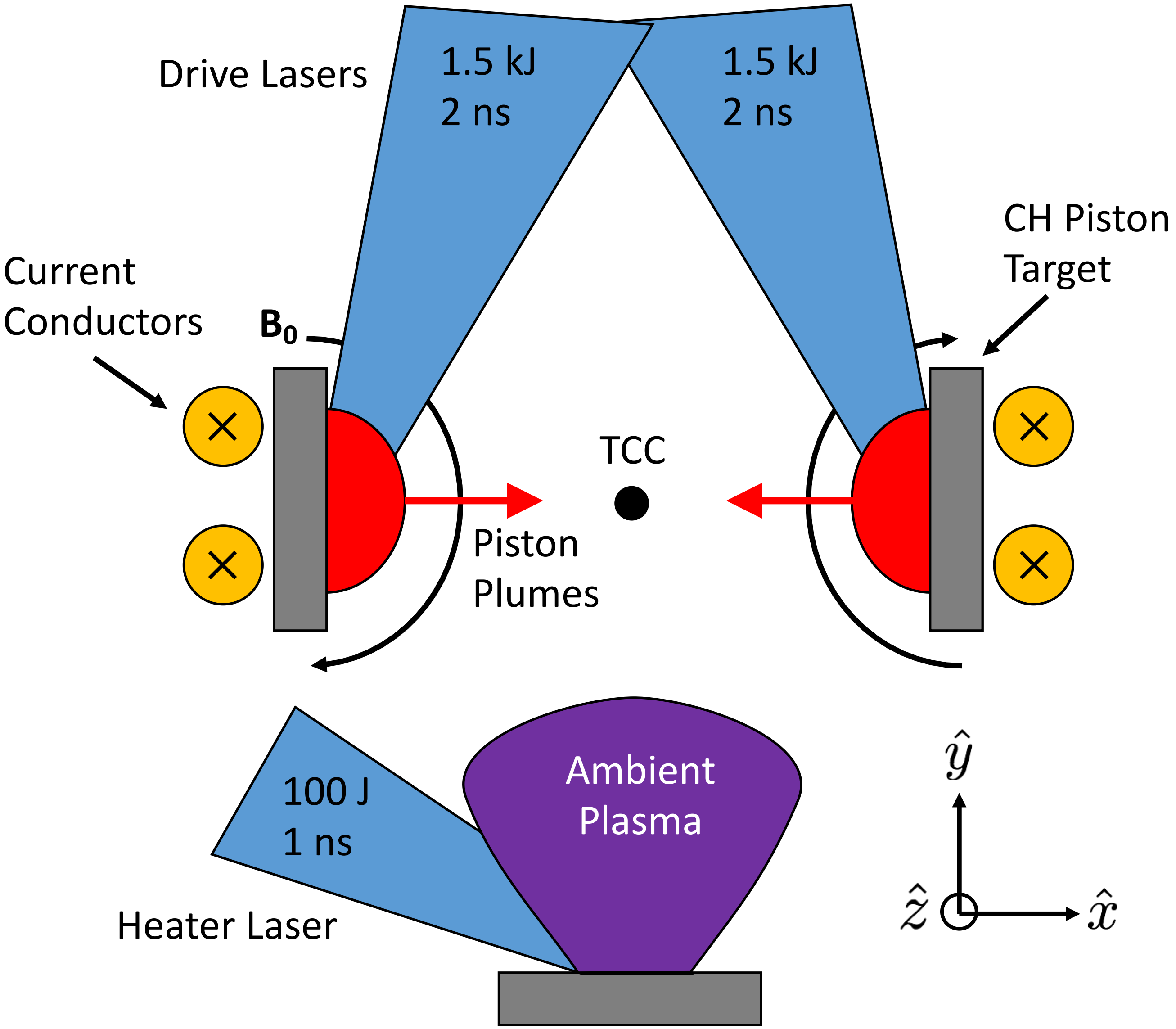


Treumann, AAR, 2009
Balogh and Treumann, *Physics of Collisionless Shocks*, 2013

# Shock Physics Indicates What Experimental Features Are Necessary

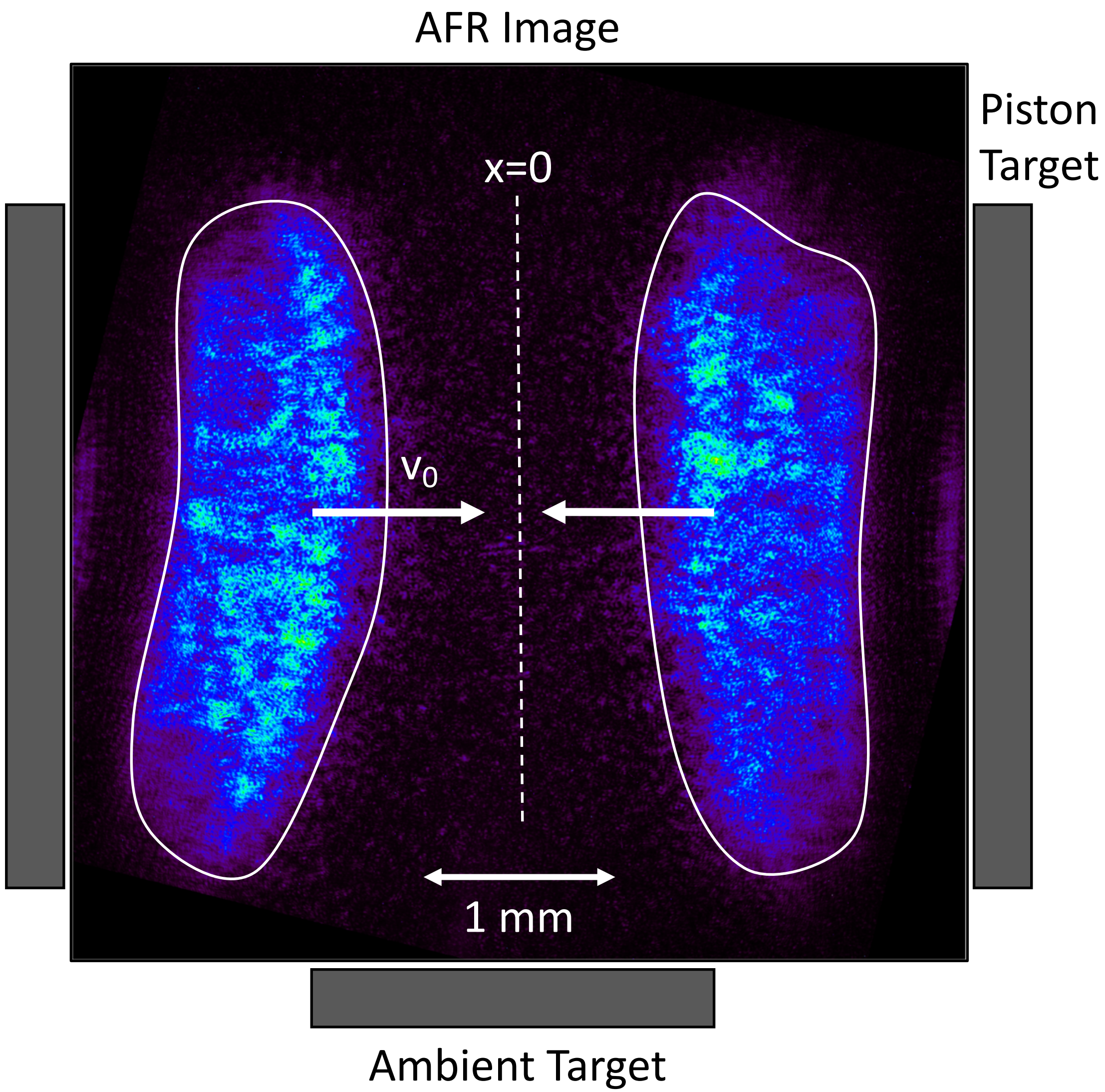
- Super-Alfvénic ($M_A > 1$)
  - Shock speed must be greater than upstream Alfvén speed
- Collisionless
  - Collisional mean free path > system size
- Large density and magnetic compressions
  - $n/n_0$ and $B/B_0 > 2$
- Steep compression widths
  - Density/magnetic jump $\gtrsim$ ion inertial length
- Shock separates from piston
  - Shock features should be distinct from piston

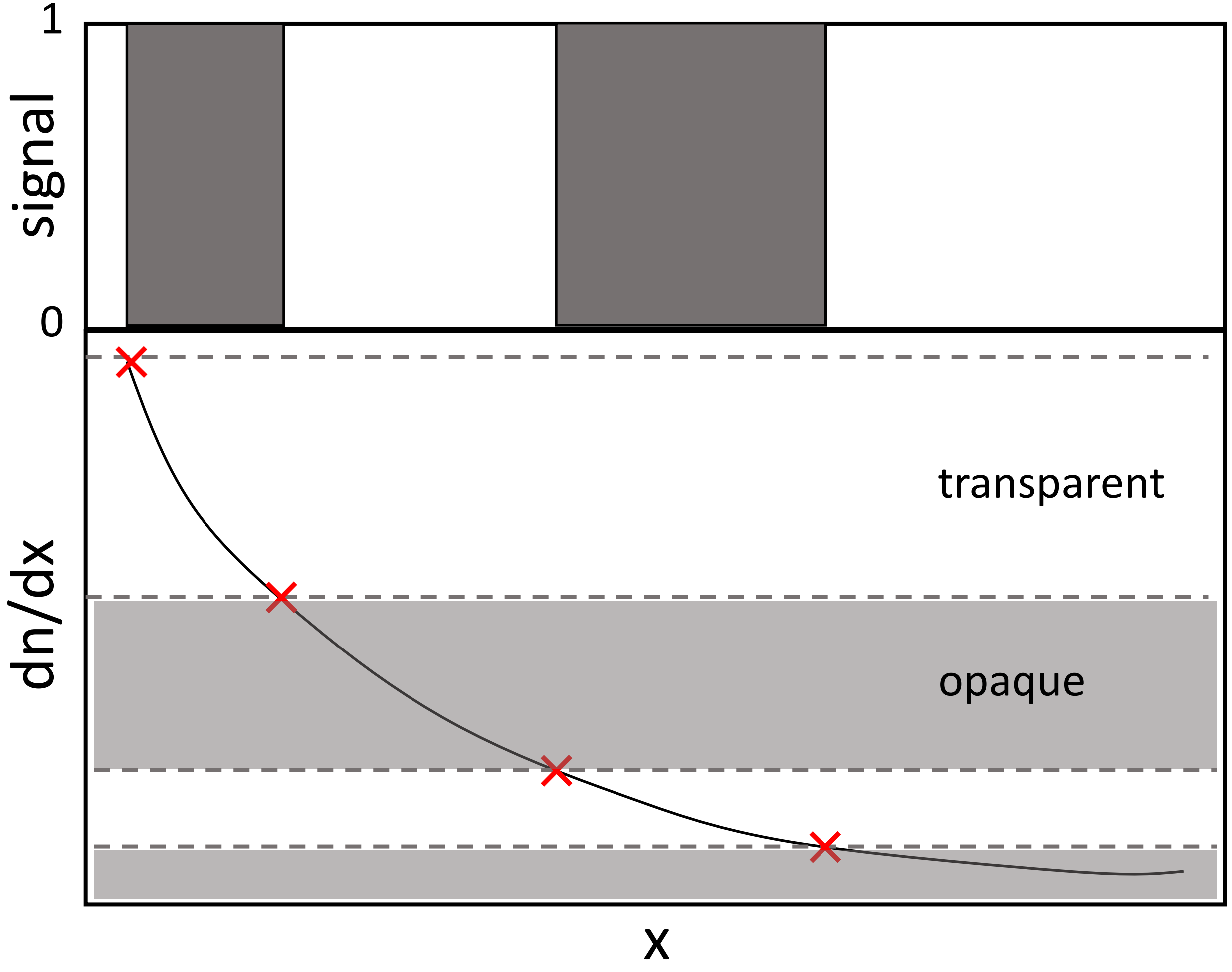
# Experimental Setup for Quasi-Perpendicular Shocks on Omega EP



- MIFEDS coils provide background magnetic field ~ 8T
- Heater beam ablates ambient plasma ($n_{i,0} \approx 10^{18}$) 12 ns before drive beams
- Drive beams create supersonic piston plumes that expand into ambient plasma
- Diagnostics:
  - Angular Filter Refractometry (AFR)
  - Shadowgraphy
  - Proton radiography

# AFR Diagnostic Measures Density Gradients

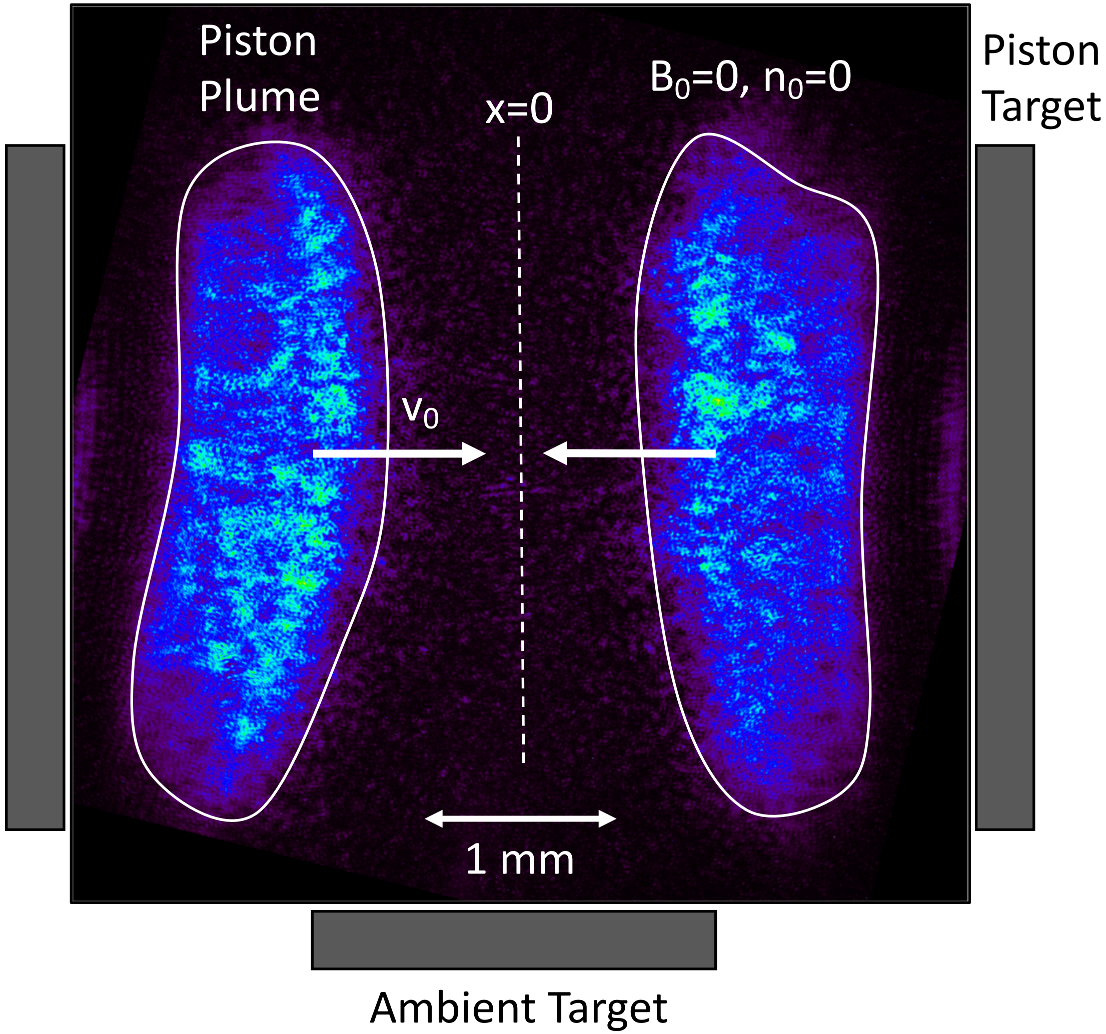




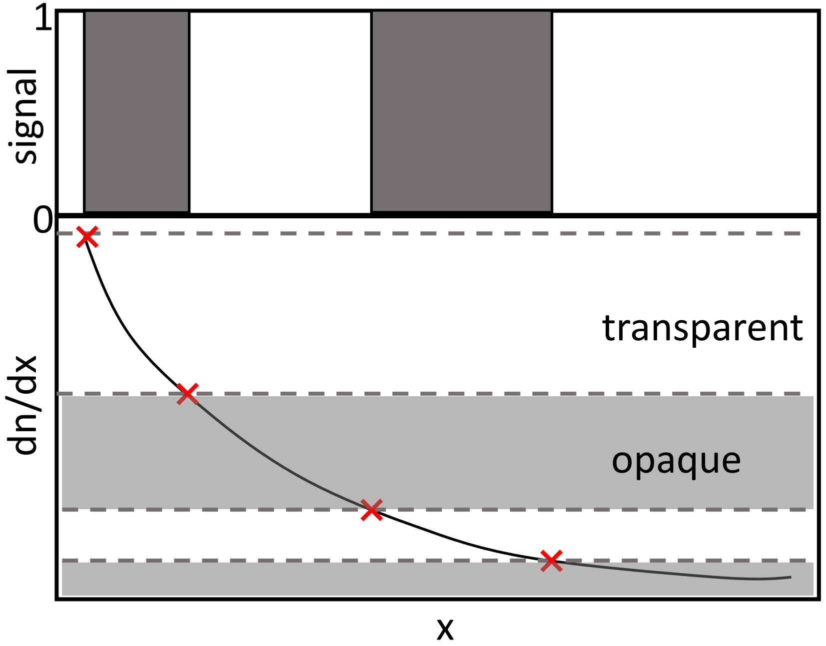
Haberberger, *et al.*, PoP, 2014

# Null Shots Show No Shock Features

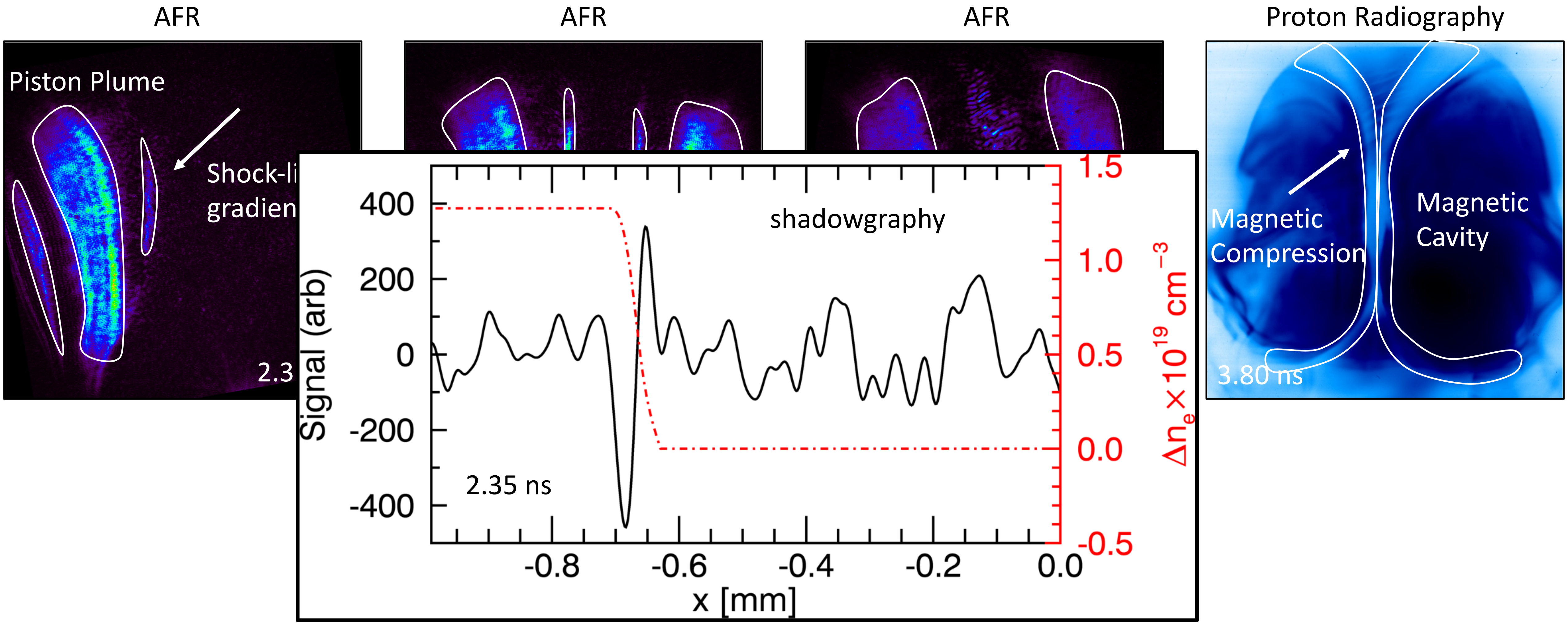
AFR Image



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

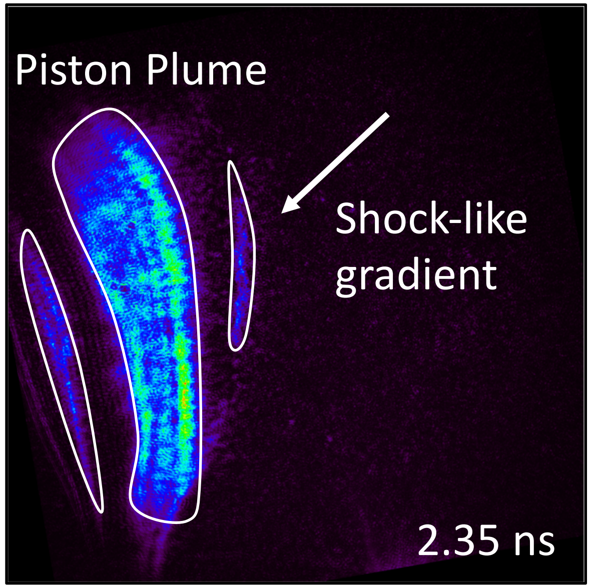


# Propagating Density and Magnetic Compressions Observed with $B_0 \neq 0$ and $n_0 \neq 0$

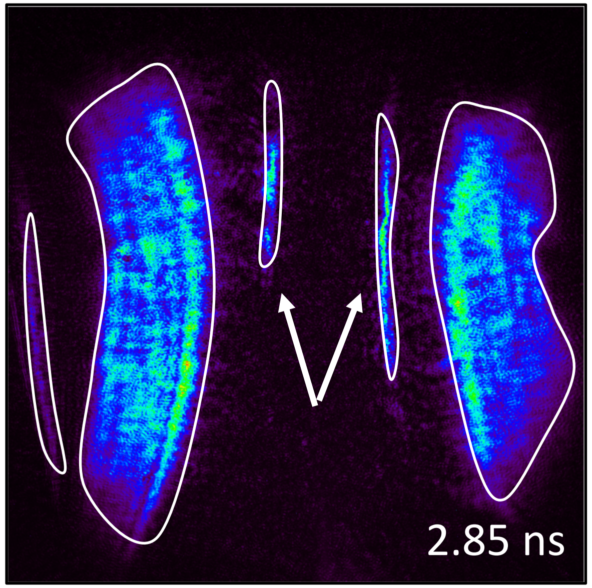


# Propagating Density and Magnetic Compressions Observed with $B_0 \neq 0$ and $n_0 \neq 0$

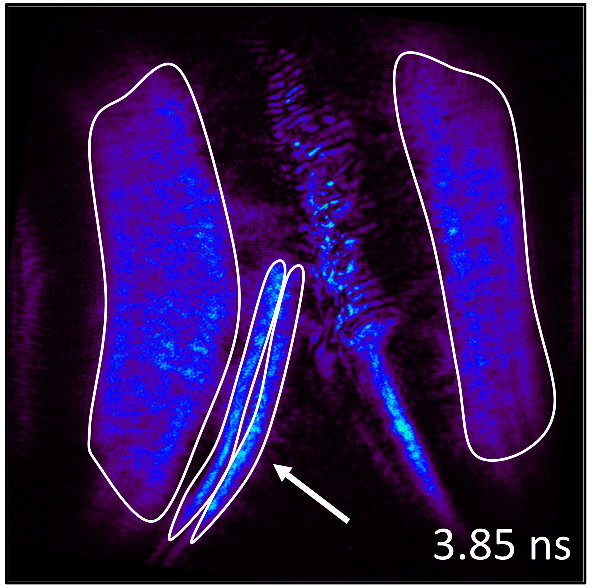
AFR



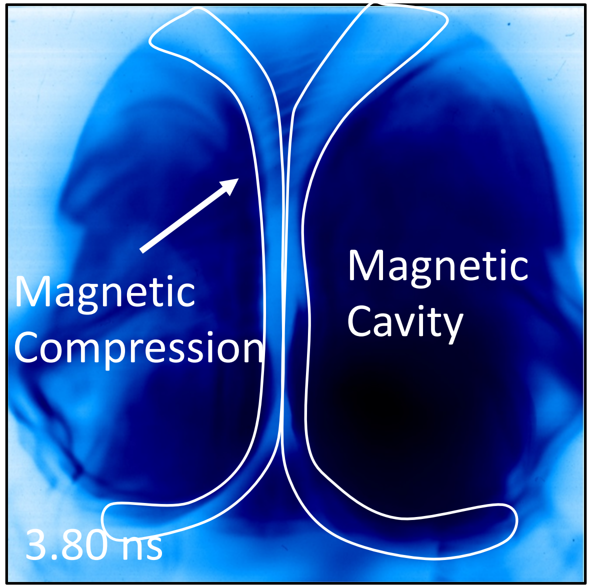
AFR



AFR

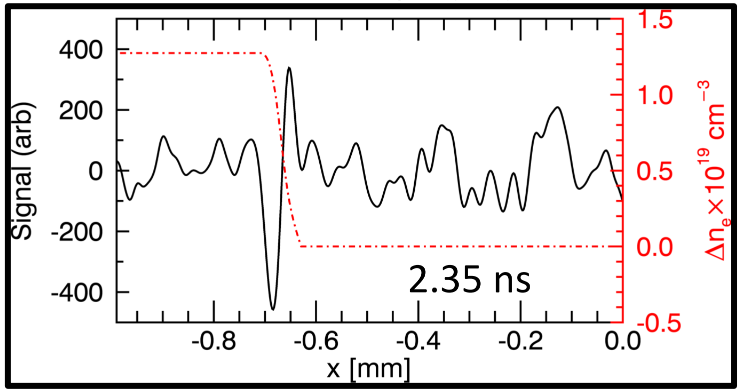


Proton Radiography

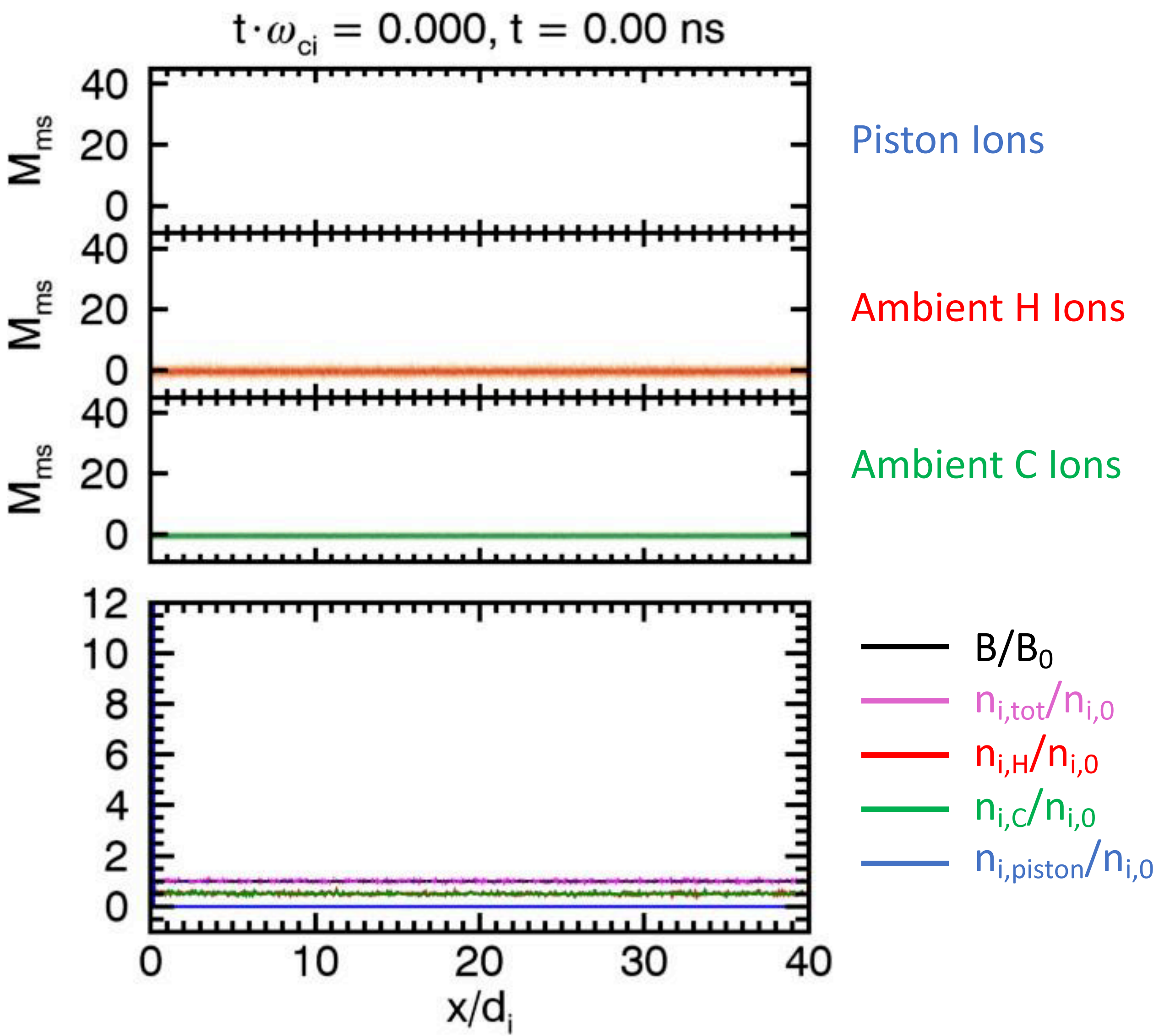


- Expanding at 700 km/s, yielding $\mathbf{M_{ms}} \approx 12$
- Density compression $\mathbf{n/n_0} \sim 3\text{-}4$
- Magnetic compression $\mathbf{B/B_0} \sim 2\text{-}4$
- Compression width $\boldsymbol{\Delta} > 1\ \mathbf{c/\omega_{pi}}$

shadowgraphy

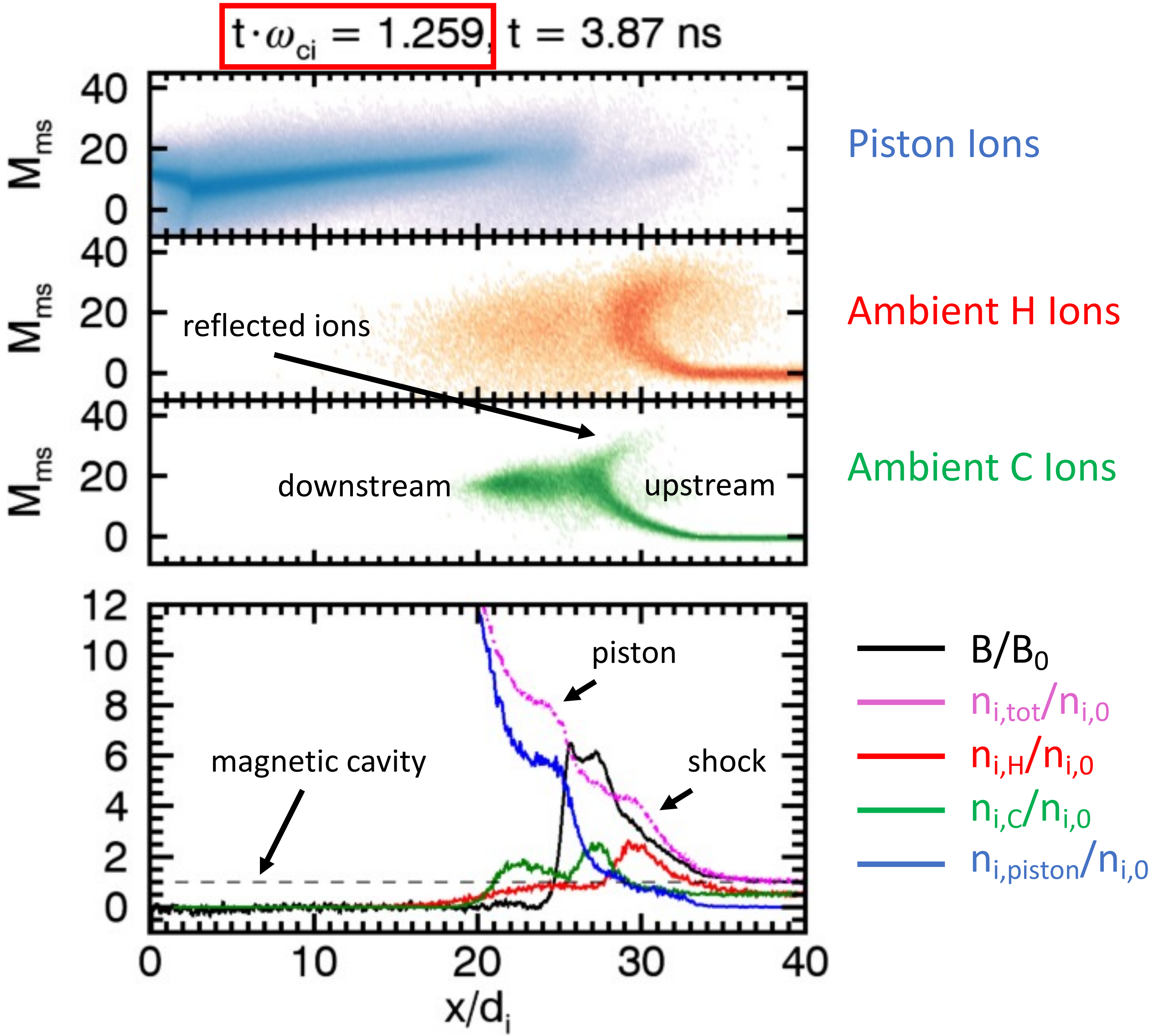


# 2D PIC Simulations Indicate Formation of High-$M_A$ Shock



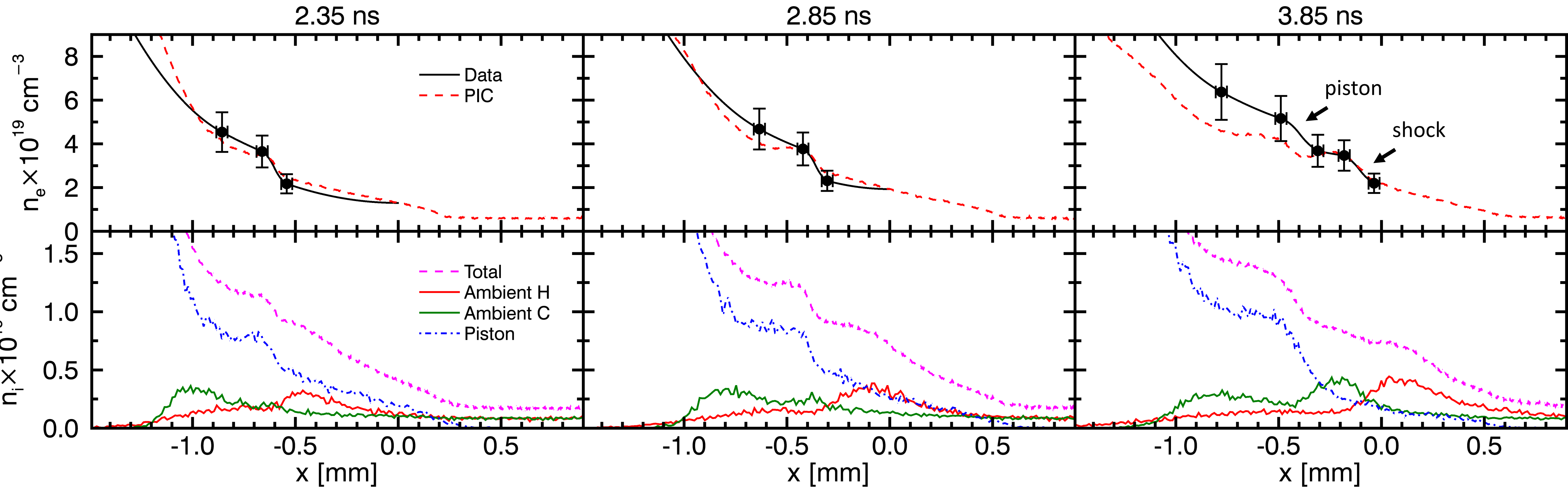
- CH piston plasma expanding into CH ambient plasma embedded in magnetic field
- Piston ions sweep out ambient ions and magnetic field
- At early times, this leads to the formation of a H shock, mixed with piston ions and the beginnings of a C shock
- At later times, a separate C shock forms behind the H shock, and the piston ions become trapped behind the C shock

# 2D PIC Simulations Indicate Formation of High-$M_A$ Shock



- The formation of a shock leads to a double "bump" density profile, corresponding to the leading shock and the trapped piston ions
- The density compression associated with the shock is $\mathbf{n/n_0 \sim 4}$
- The magnetic compression associated with the shock is $\mathbf{B/B_0 > 4}$
- The width of the density compression $\mathbf{\Delta \sim 1\, \rho_i}$

# 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

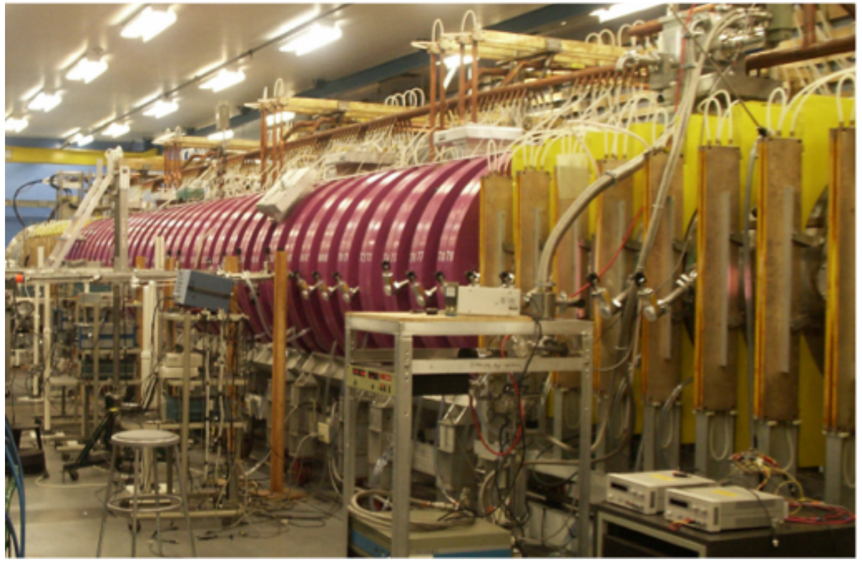
Schaeffer, *et al.*, submitted, 2016

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

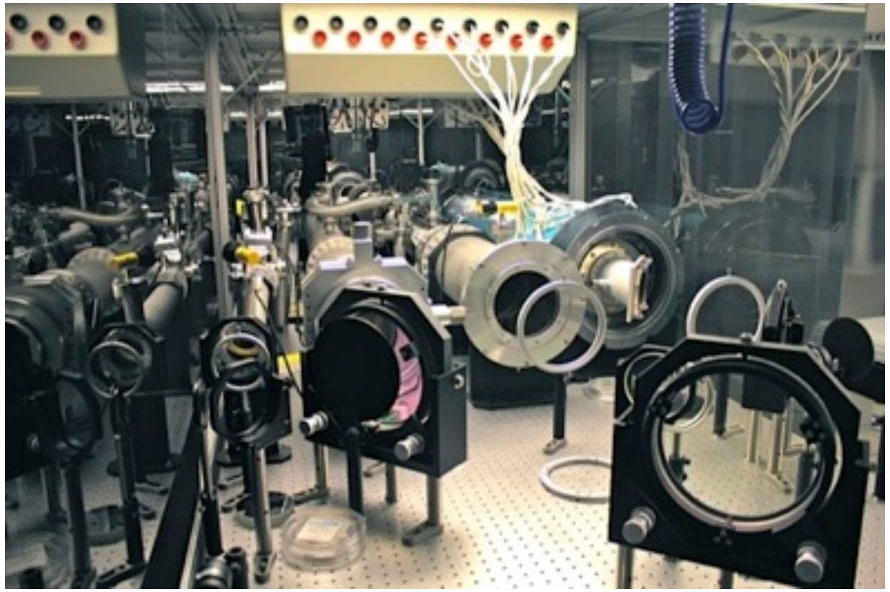
# The UCLA Facility Uniquely Combines a kJ-Laser and a Large Magnetized Plasma

| | |
|---|---|
| Plasma Length | **18 m** |
| Plasma Diameter | **60 cm** |
| Electron Density (Main) | **2x10$^{12}$ cm$^{-3}$** |
| Electron Density (LaB$_6$) | **2x10$^{13}$ cm$^{-3}$** |
| Electron Temp. | **5 eV** |
| Ion Temp. | **< 1 eV** |
| B Field | **0.2 – 1.8 kG** |
| Rep. Rate | **1 Hz** |

Large Plasma Device



Phoenix Laser Facility



Raptor Laser

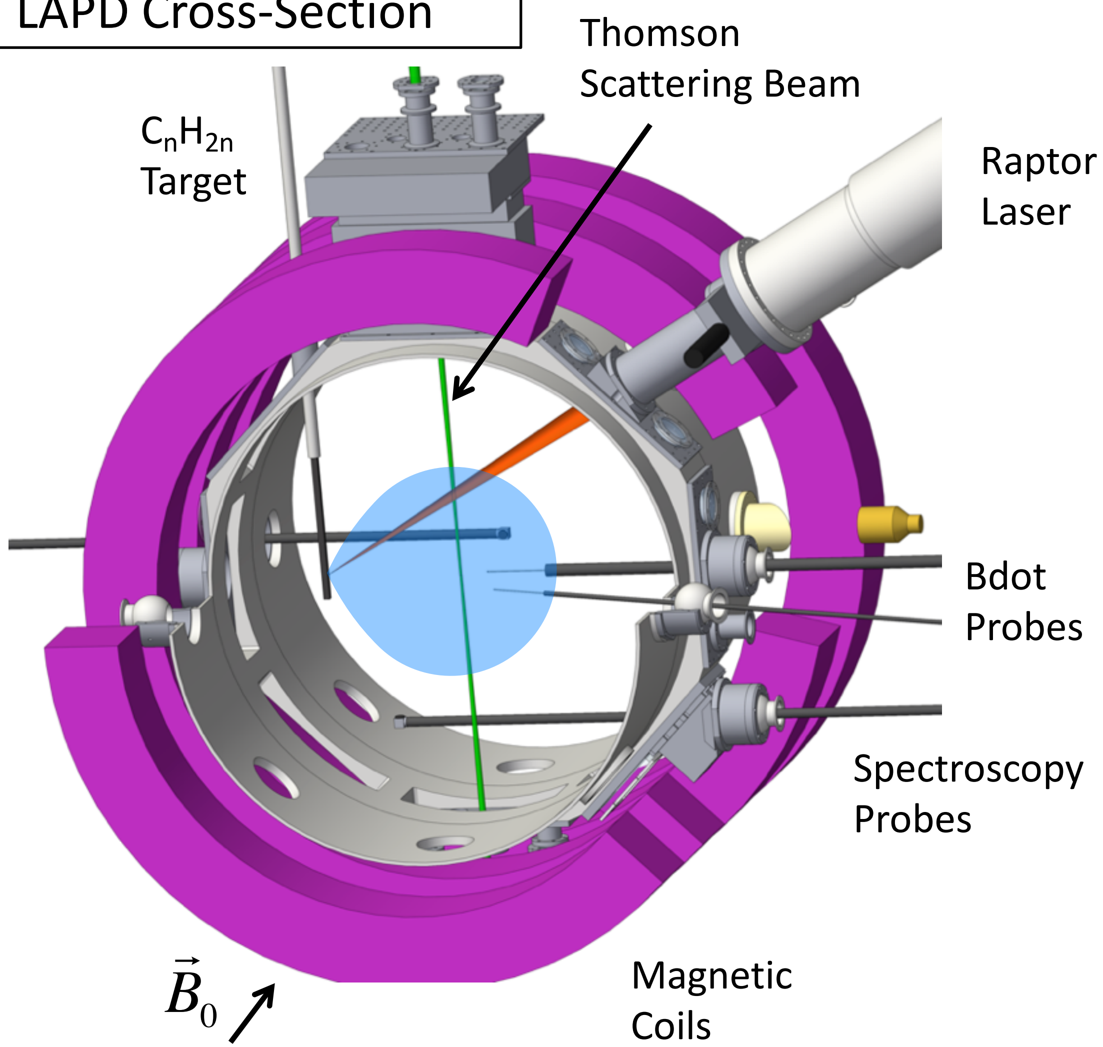
| | |
|---|---|
| Wavelength | **1053 nm** |
| Pulse Length (FWHM) | **25 ns** |
| Energy per Pulse | **300 J +** |
| Rep. Rate | **45 min** |

- Well-characterized ambient plasma
- Plasma large-enough for shock-piston separation → Shock physics decoupled from driver
- Flexible laser geometry: *quasi-perpendicular*, *oblique*, or *quasi-parallel*
- Large scale & low pressure ambient allows localized probe measurements

Goal: investigate shock formation, debris-ambient coupling, ion dynamics, etc.

# Experimental Setup for Quasi-Perpendicular Shocks in the LAPD

LAPD Cross-Section



Thomson Scattering Beam

$C_nH_{2n}$ Target

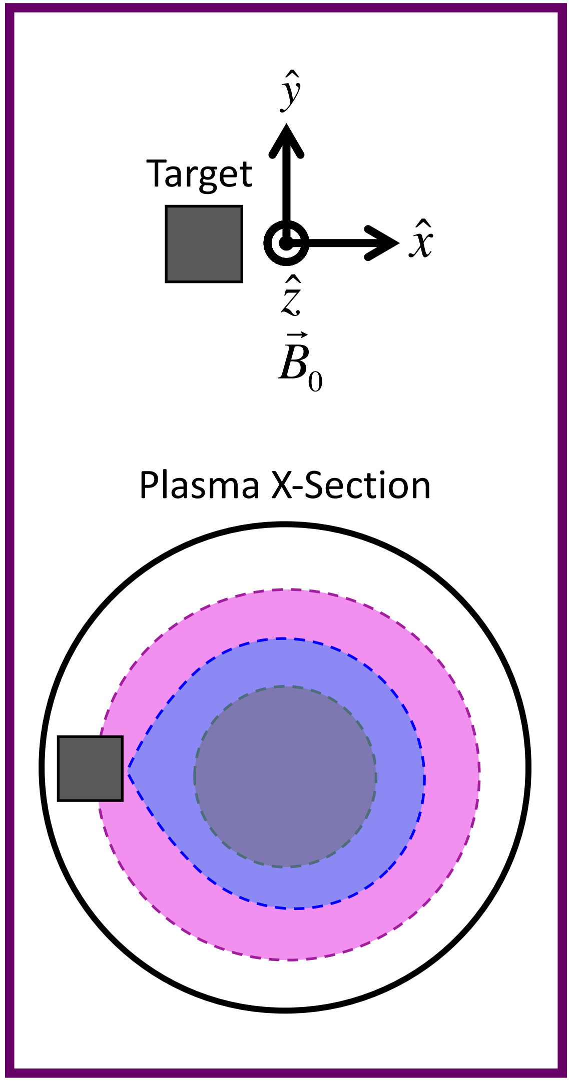
Raptor Laser

Bdot Probes

Spectroscopy Probes

Magnetic Coils

$\vec{B}_0$



Target

$\hat{y}$

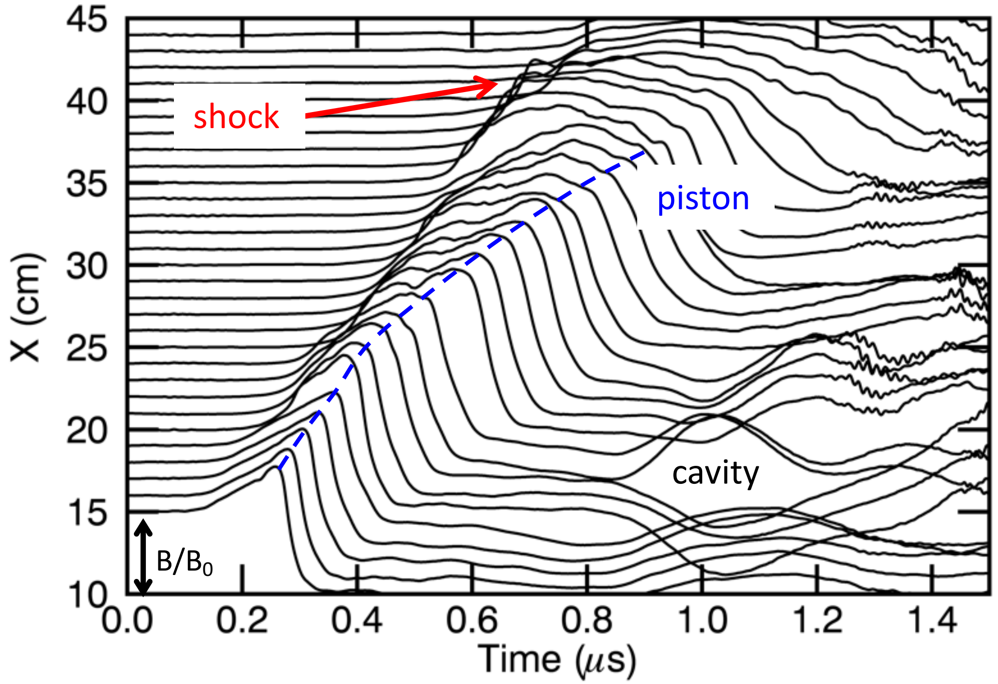
$\hat{x}$

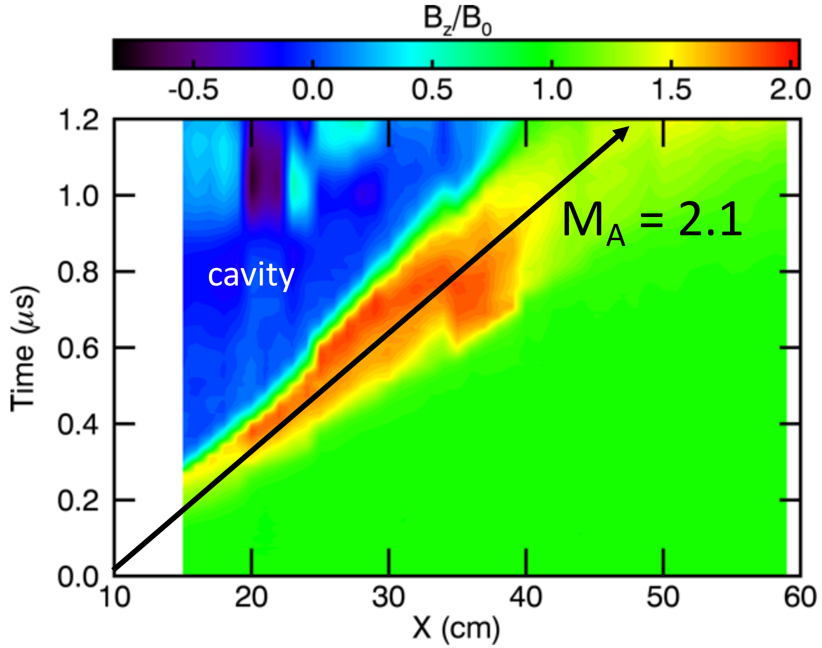
$\hat{z}$

$\vec{B}_0$

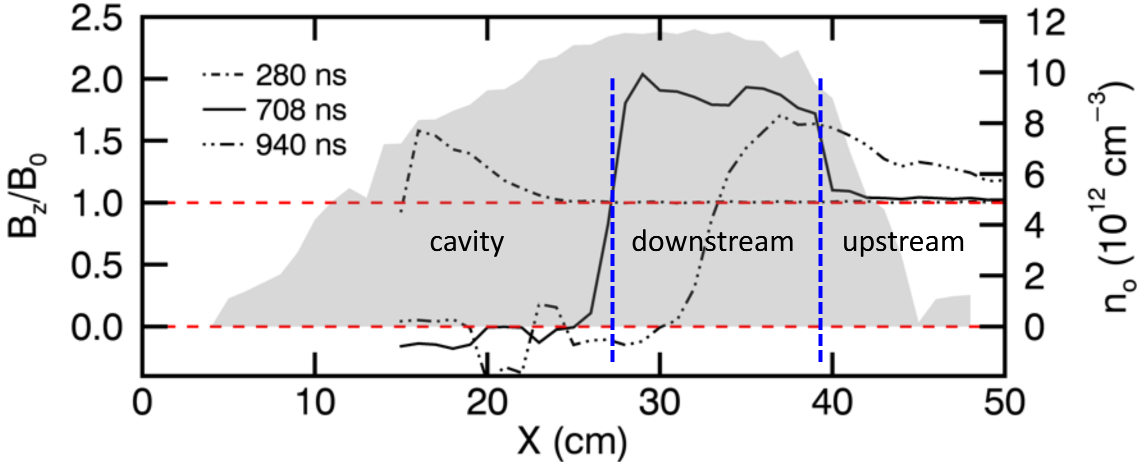
Plasma X-Section

# Mach ~2 Collisionless Shock Observed Separating from Piston



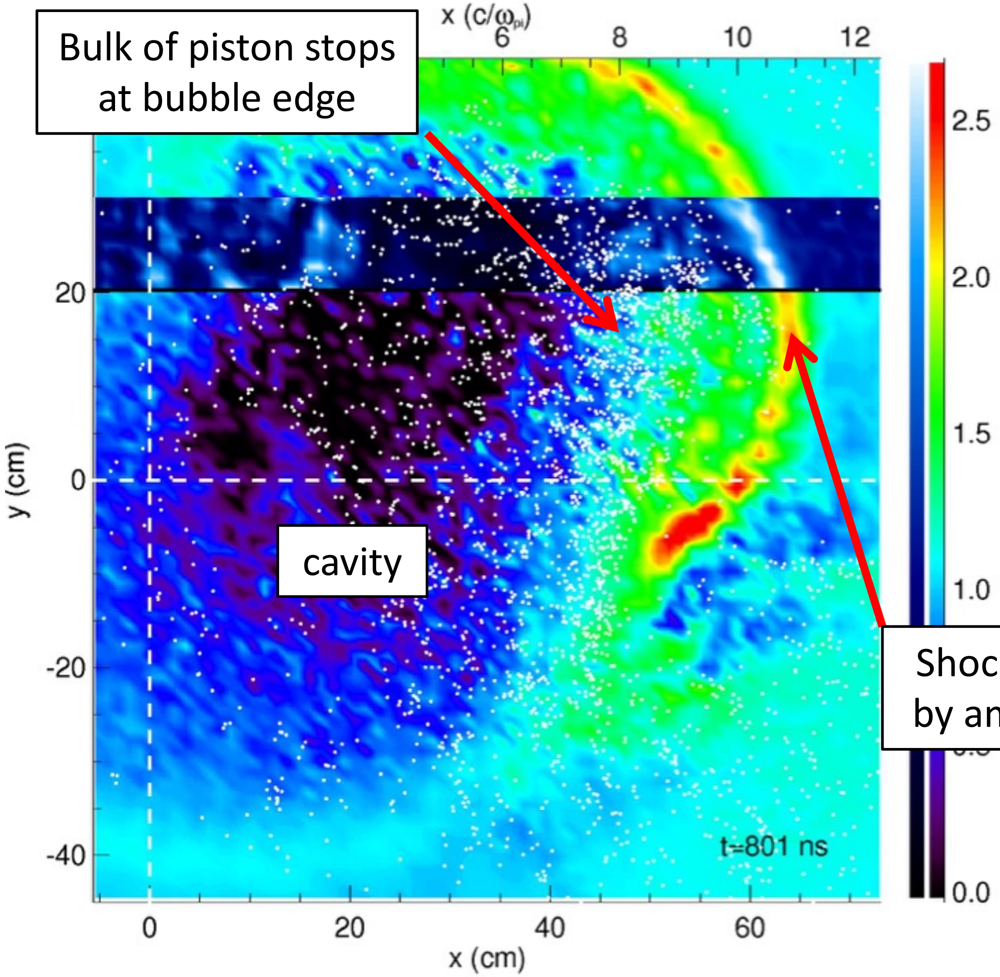


Niemann, *et al.*, GRL, 2014
Schaeffer, *et al.*, PoP, 2015



| | | | | | |
|---|---|---|---|---|---|
| **$B_0$** | 300 G | **$v_A$** | 190 km/s | **$v_0$** | 400 km/s |
| Plasma | $H^{+1}$ | **$c/\omega_{pi}$** | 6.6 cm | **$R_*$** | 18.8 cm |
| **$n_a$** | $1\text{x}10^{13}$ cm$^{-3}$ | **$\Omega_{ci}^{-1}$** | 2.2 μs | **ε** | 0.7 |
| **$E_{laser}$** | 190 J | **$\rho_d$** | 31.1 cm | **$\beta_k$** | 0.6 |
| **$I_{laser}$** | $1\text{x}10^{12}$ W cm$^{-2}$ | **$\rho_a$** | 14 cm | **$\lambda_{ii}$** | 400 m |

# Simulations Show Low-Mach Number Shock Formation

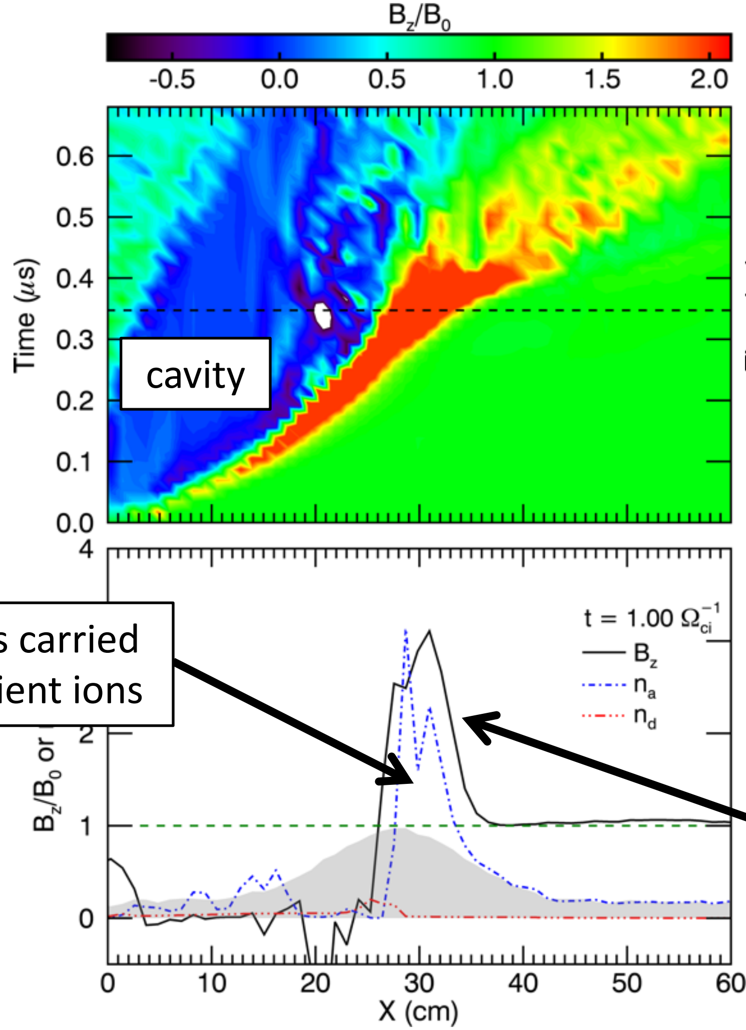


Bulk of piston stops at bubble edge

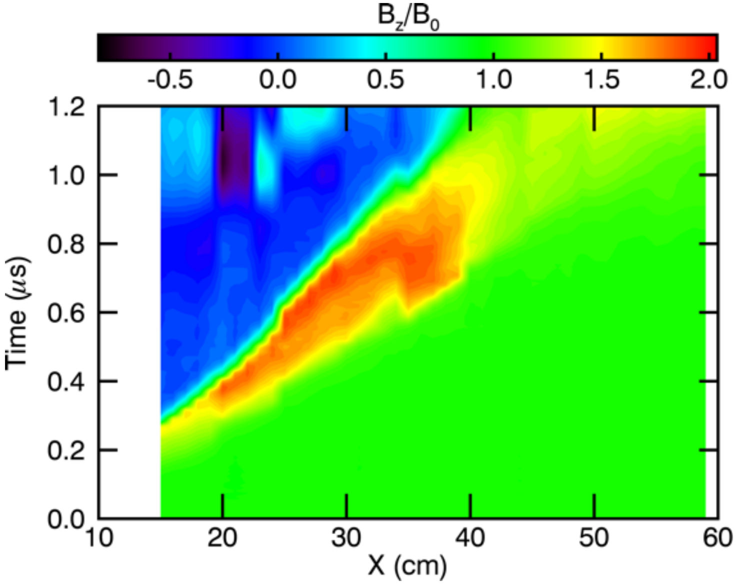
cavity

Shock is carried by ambient ions

Simulation



Experiment



Compression consistent
With jump conditions

# Criteria Necessary for Shock Formation

- Super-Alfvénic $(M_A > 1)$
  - Shock speed must be greater than upstream Alfvén speed
- Collisionless $(\lambda_{ii}/D_0 > 1)$
  - Collisional mean free path > system size
- Sufficient experimental size $(\rho/D_0 < 1)$
  - Ion gyro-orbits must fit within the experiment
- Sufficient piston magnetization $\left(\rho_p/R_m < \sqrt{2}\right)$
  - Piston ions must have enough energy to accelerate ambient ions
  - $R_m$ is the characteristic length scale for piston coupling
- Sufficient ambient magnetization $(\rho_a/R_* < 1)$
  - Ambient ions must be sufficiently accelerated
  - $R_*$ is the characteristic length scale for ambient coupling

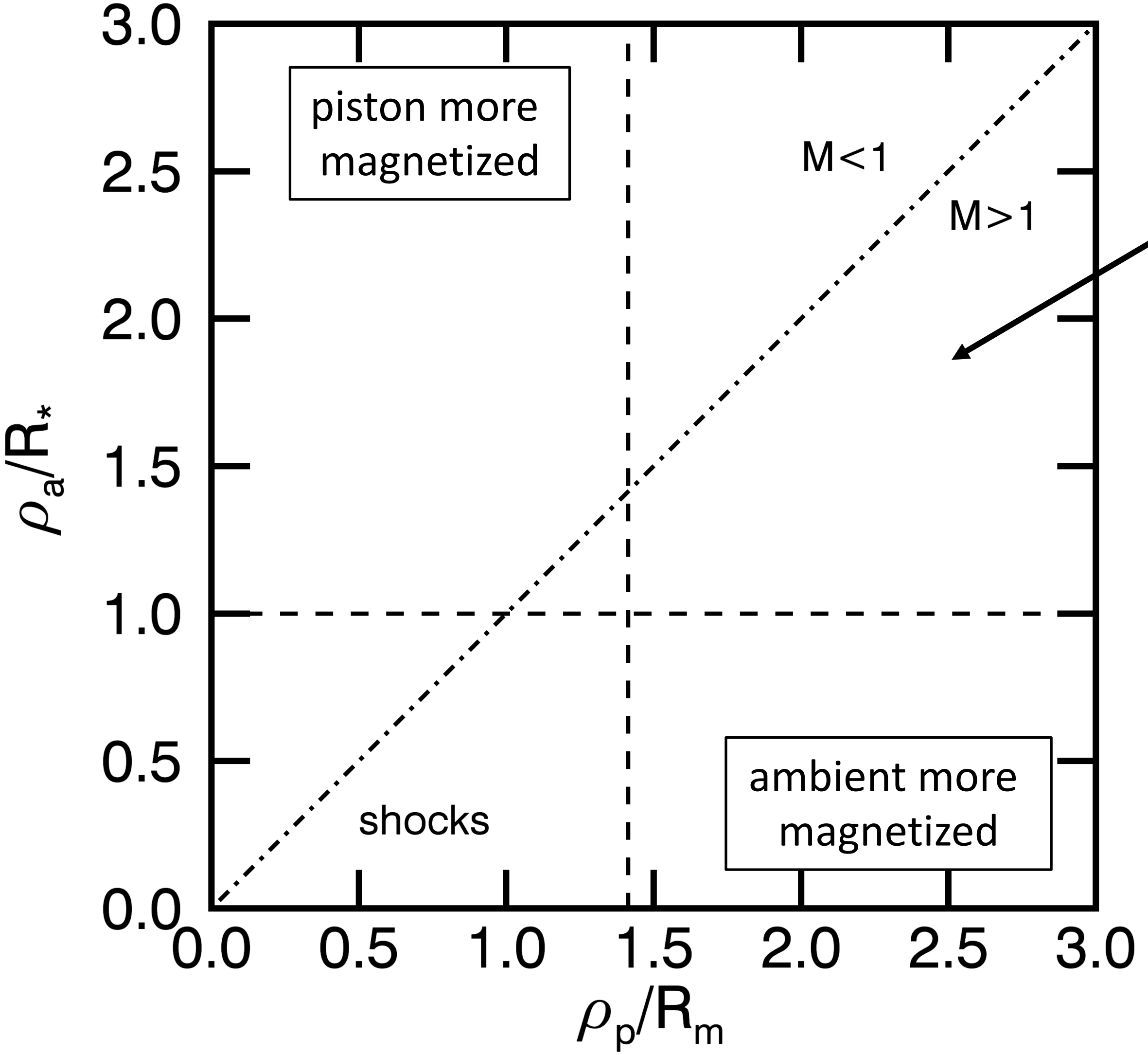
$$\boxed{R_m = (3N_0 m_p/4\pi m_a n_a)^{1/3}}$$

$$\boxed{R_* = (3N_0 Z_p/4\pi Z_a n_a)^{1/3}}$$

**Are these criteria valid?**

Bashurin, *et al.*, J. App. Mech. & Tech. Phys., 1983
Drake, PoP, 2000
Clark, *et al.*, PoP, 2013
Larson, *et al.*, JRERE, 2016

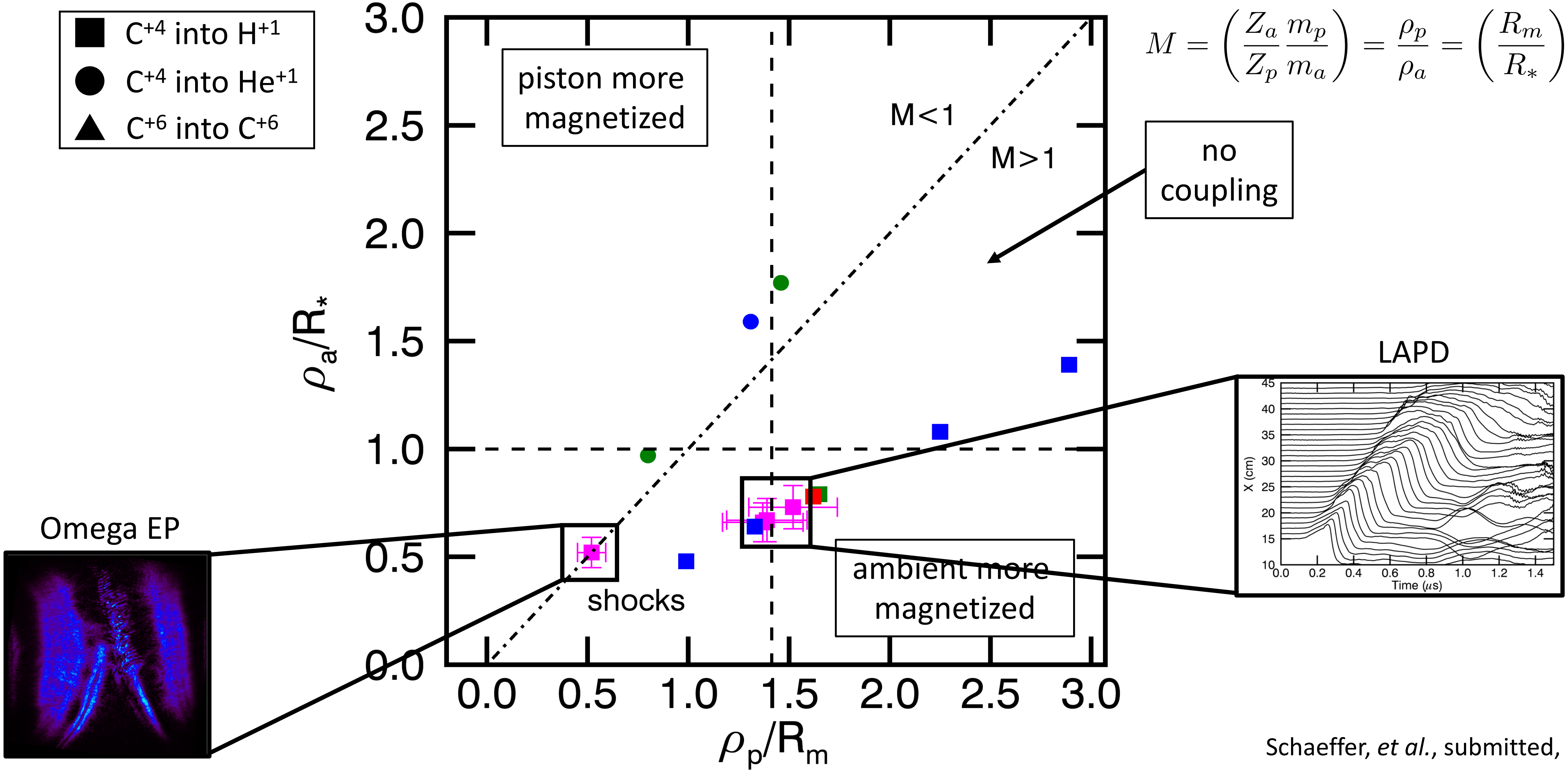
# Shock Experiments can be Predictively Organized by Formation Criteria



no coupling

$$M = \left(\frac{Z_a}{Z_p}\frac{m_p}{m_a}\right) = \frac{\rho_p}{\rho_a} = \left(\frac{R_m}{R_*}\right)^3$$

# Shock Experiments can be Predictively Organized by Formation Criteria



$$M = \left(\frac{Z_a}{Z_p}\frac{m_p}{m_a}\right) = \frac{\rho_p}{\rho_a} = \left(\frac{R_m}{R_*}\right)^3$$

Schaeffer, *et al.*, submitted, 2016

# Summary

- We have observed for the first time the formation and evolution of a laser-driven, high-$M_A$ (supercritical) collisionless shock. The results agree well with 2D PIC simulations.
- We have launched low-$M_A$ (subcritical) magnetized shocks and measured their formation and structure. Hybrid simulations reproduce the basic features observed in experiments.
- Shock experiments spanning large parameter ranges reveal that piston-driven shocks can be predictively organized by dimensionless formation criteria.

# Future Directions

- High-$M_A$ shocks and particle acceleration
  - How are particles injected into the shock acceleration process?
- Low-$M_A$ shocks and detailed shock structure
  - What dissipation mechanisms are at work in the shock layer?
- Varying magnetic geometry
  - Can quasi-parallel shocks be generated in the laboratory?
- Shocks and other highly-driven (i.e. lasers) systems
  - What, if any, interaction do shocks have with magnetic reconnection and turbulence, such as the Weibel instability?