Study of Magnetized Collisionless Shocks in Laser-produced Plasmas

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Physics of Collisionless Shocks

Shock: sudden change in density, temperate, pressure that decelerates supersonic flow. On earth: most of shocks are mediated by collision.

Collisionless: Shocks must be mediated without direct collision, but through interaction with collective fields. Collisionless shocks are common in Astrophysics. Sources of particle acceleration, non-thermal emission, and magnetic fields amplification.
How Collisionless Shocks Work

For low initial B field, particles are deflected by self-generated magnetic fields (filamentation/Weibel instability)

Experiment by laser: Fox et. al 2013, Huntington et. al 2015

For large initial B field, particles are deflected by compressed pre-existing fields

measurement of density compression through shadowgraphy (Schaeffer et. al 2017)
<table>
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<th>B field</th>
<th>Density</th>
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We study magnetized shock formation by driving a fast ablated piston plasma into pre-magnetized background plasma.
Piston Driven Shock Experiment on Omega-EP Laser: Diagnostic View and Proton Radiography

Proton radiography is main diagnostic
Proton Radiography in Experiments

Features in radiography:

- Trapezoid Distortion
- Moving Proton deficit region followed by caustic
- Evolution of thickness of proton deficit region
- Tilted proton deficit region and caustic
Proton Radiography in Experiments

Features in radiography:

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Trapezoid distortion: estimation the external B Field

B-off: No Trapezoid Distortion

B-on: Trapezoid Distortion

Model trapezoid distortion and the distances of pegs:
External B (MIFEDS) is about 7~8T
Proton Radiography in Experiments

Features in radiography:
- Trapezoid Distortion
- Moving Proton deficit region followed by caustic
- Evolution of thickness of proton deficit region
- Tilted proton deficit region and caustic
The moving feature indicates a propagating compressed B field. The feature speed is $\sim 450$ km/s, $n_e = 10^{17} - 10^{18}$ cc, $M_A = 3\sim12$. $\lambda_{mfp} \approx 2cm >$ Diameter of Coil

Collisionless condition achieved!

Proton deficit region: 
**Increasing B (from right to left)**

Proton caustic enhancement: 
**Decreasing B**

Simulated Proton Radiography
w/o overshoot the proton deficit region is separated from the caustic.
With overshoot the caustic follows the proton deficit region.

Caustic always follows proton deficit region.
Magnetic overshoot in the experiment!
Proton Radiography in Experiments

Features in radiography:
- Trapezoid Distortion
- Moving Proton deficit region followed by caustic
- Evolution of thickness of proton deficit region
- Tilted proton deficit region and caustic
Simulated Proton Radiography

\[ M_A = 9 \]

\[ \frac{\tilde{B}}{B_0} \cdot \frac{\tilde{\rho}}{\rho_0} \cdot \left( \frac{u}{c \omega_m} \right)^2 \cdot \left( \frac{v_x}{c \omega_m} \right) \cdot \left( \frac{u}{c \omega_m} \right) \cdot \left( \frac{v_x}{c \omega_m} \right) \cdot \left( \frac{u}{c \omega_m} \right) \]
Signature of Strong Magnetized Shock: Magnetic Overshoot

- High Mach number shocks undergo periodic reformation in the first ion loop
- Reformation leads to periodic extra magnetic compression (overshoot), proportional to $M_A$
- Periodic enhancement of compression leads to narrowing of proton deficit region
- We observe thinning of the deficit region later in time — this constrains the Mach number to be $M_a > 8$

$M_A$ can be constrained with radiography only!
2-D PIC vs. Experiment

Formation of contact discontinuity

$\Omega_{i} t = 0.6 \ (t=2\text{ns})$

$\Omega_{i} t = 0.9 \ (t=3\text{ns})$

$\Omega_{i} t = 1.2 \ (t=4\text{ns})$

$\Omega_{i} t = 1.5 \ (t=5\text{ns})$

Ion 1st gyration

Shock feature and speed consistent with the experiment

Magnetic Overshoot

$B_x/B_{x0} \geq 6$

Simulated proton radiography

Experiment proton radiography

$M_A = 12, M_S = 10$
Features in radiography:
- Trapezoid Distortion
- Moving Proton deficit region followed by caustic
- Evolution of thickness of proton deficit region
- Tilted proton deficit region and caustic
The tilted proton caustic feature is caused by density gradient of background plasma and curvature of magnetic field.
Proton Radiography in Experiments

Features in radiography tell us:

- Trapezoid Distortion: External B field is 7~8 T.
- Moving Proton deficit region followed by caustic: Compressed magnetic field with magnetic overshoot
- Evolution of thickness of proton deficit region: A strong magnetic overshoot
- Tilted proton deficit region: Background density gradient and B-field curvature

The formation of a high Mach number magnetized shock!
Conclusion:

The experiment generates a piston-driven collisionless shock in a magnetized background plasma.

The proton radiography shows a moving compressed magnetic field with speed of 450km/s.

The proton-deficit-region narrowing indicates a strong magnetic overshoot and constrains the $M_A > 8$.

The 3-D PIC simulations explain well the tilted proton-deficit and caustic feature.

The experiment achieved the formation of a high Mach number ($M_A \approx 8 - 12$) magnetized collisionless shock.
Formation of contact discontinuity: B field is compressed by piston; background ions are reflected; piston electrons and background electrons are separated.
Shock in Ion first gyration:

Shock in Ion first gyration: magnetic overshoot; background ions are in the first gyration; piston ions and background ions are separated.
Fully formed shock:

\[ y(\frac{c}{\omega_{pe}}) \]

\[ x(\frac{c}{\omega_{me}}) \]

\[ \frac{B_x}{B_{x0}} \]

\[ \frac{\rho}{\rho_0} \]

ion \( v_x \)

electron \( v_x \)

Fully formed Shock: shock becomes thicker; background ions show several gyrations;