Magnetized Collisionless Shock Formation Mediated by the Modified Two-Stream Instability

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A laboratory achievable perpendicular magnetized collisionless shock is mediated by a modified two-stream instability

- Supercritical perpendicular magnetized collisionless shock can be readily formed on TeraWatt laser systems (e.g. OMEGA-EP)
- Mode analysis in the shock transition region indicates a modified two-stream instability (MTSI) provides the main dissipation for shock formation
- The growth rate of MTSI ($\gamma_{MTSI}$) is much larger than (>10x) the ion gyro-frequency ($\Omega_{ci}$); realistic ion/electron mass ratio substantially separates the shock formation time from $T_{ci} (=2\pi/\Omega_{ci})$
- Shock reflected ions gyrate in the upstream and participate in shock front reformation

Zhang et al., Phys. Plasmas 28, 072111 (2021)
Collaborators

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High-power lasers and computational advances enable study of collisionless shocks in the laboratory

Studies on magnetized collisionless shock

- Telescopes*
- *In situ* spacecraft missions**
- Laser experiments†
- Simulations‡

Bow shock near galactic center* (Gemini North, Oct. 17, 2000)

International Sun-Earth Explorer (ISEE) Program**

OMEGA-EP counterpropagating plasma plumes experiment†

Quasi-1D particle-in-cell simulation‡

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‡ Matsukiyo et al., J. Geophys. Res. 108, 1459 (2003); Matsukiyo et al., ApJ 742 47 (2011);
A collisionless shock can be launched by a laser-driven super-magnetosonic piston on TeraWatt laser systems.

\[ \mathbf{v}_{[\text{sim./wall/piston}]} = \mathbf{v}_{[\text{lab}]} + V_d \mathbf{e}_x \]
Modified two-stream instability provides dissipation for the collisionless shocks

- Dispersion relation* (Maxwellian unmagnetized ion and magnetized electron)

\[ 1 + \frac{\omega_{pe}^2}{k^2 v_{th}^2} \left[ 1 - \exp \left( -\lambda_e \right) \sum_{n=-\infty}^{\infty} I_m (\lambda_e, \frac{\omega}{\omega + m\Omega_{ce}}) - \sum_{s=m,ce} \frac{\omega_{ps}^2}{2k^2v_{th}^2} Z'(\xi_s) = 0 \]

\[ \frac{\gamma_{MTSI}}{B} - \frac{\omega_{le}}{B} = e \sqrt{\frac{Z}{m_i \gamma_e}} \]

\[ \frac{\gamma_{MTSI}}{\Omega_{ci}} \gg \Omega_{ci} \]

The shock can form within an ion gyro-period \( T_{ci} (=2\pi/\Omega_{ci}) \), or, a few tenths of a nanosecond under \( B \sim 50 \) T.

** McBride et al., Phys. Fluids 15, 2368 (1972)

\[ \frac{M_{s1}}{m_i} \]

Reduced \( m_i/m_e \), unrealistically high \( B \), and/or reduced \( c \), may alter the relative importance of different instabilities.
A supercritical hydrogen shock forms within $0.1 \ T_{ci}$

- The signature of a supercritical shock: reflected ions

Shock compression ratio: $r \sim 2.35$

Mach #: $M_s \sim 5.62, \ M_A \sim 2.06$

Weibel instability is suppressed by the strong external magnetic field
Ions are reflected by self-generated $E$-field, resulting in MTSI

- Low-energy tail of incoming ion is reflected to $v_{xi} \sim 2V_{\text{shock}}$ by an electrostatic $E_x$ field

Mode analysis indicates MTSI is the operating instability

- Fourier spectrum
  - $E_x$ fluctuation
  - Dispersion relation
  - Phase space
  - Piston distribution
Motional electric field also accelerates reflected ions in the shock tangential direction

- Reflected ion is co-accelerated by the motional $E_z$ field to 6.5-9.7 keV (average ~8 keV)

Accelerated ions will participate in shock front reformation at later times
Longer time 1D simulations shows shock front reformation as shock evolves

- Shock front reformation happens on length scale of $\sim \rho_{i1}$, with a period of $\sim 0.55 T_{ci1}$
- Rankine–Hugoniot jump conditions are satisfied for a portion of the duration in each reformation period (white dashed line)
Summary

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