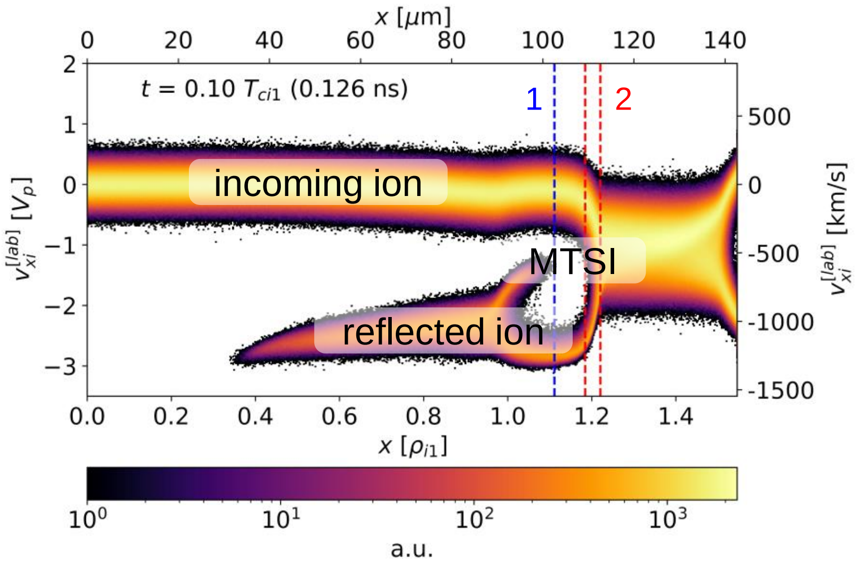
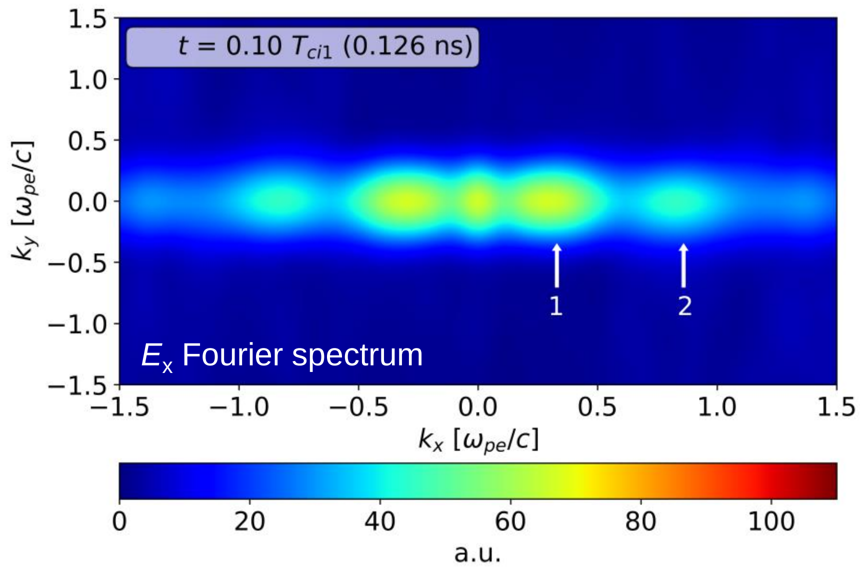
Magnetized Collisionless Shock Formation Mediated by the Modified Two-Stream Instability





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Summary

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 (γ_{MTSI}) is much larger than (>10x) the ion gyro-frequency (Ω_{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**

Collaborators

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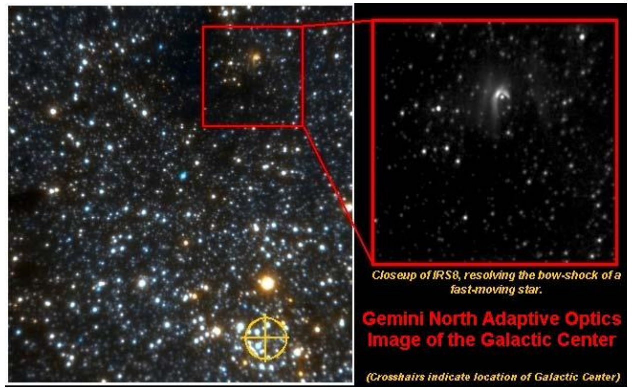
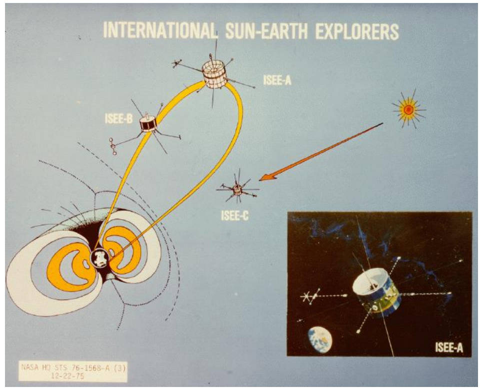
High-power lasers and computational advances enable study of collisionless shocks in the laboratory

Studies on magnetized collisionless shock

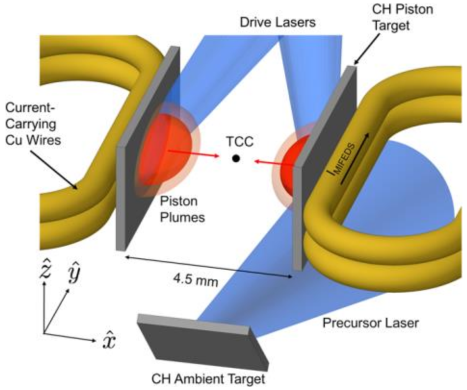
- Telescopes*
- *In situ* spacecraft missions**
- Laser experiments†
- Simulations‡



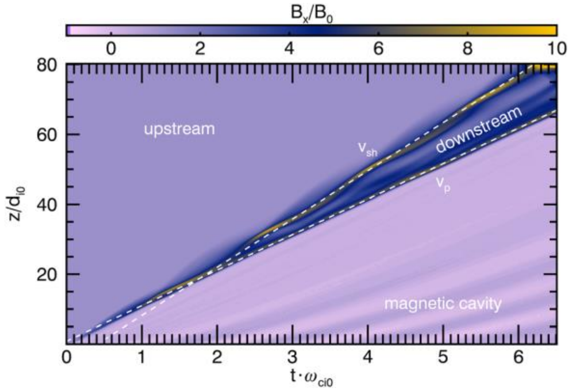
Bow shock near galactic center* (Gemini North, Oct. 17, 2000)



International Sun-Earth Explorer (ISEE) Program**



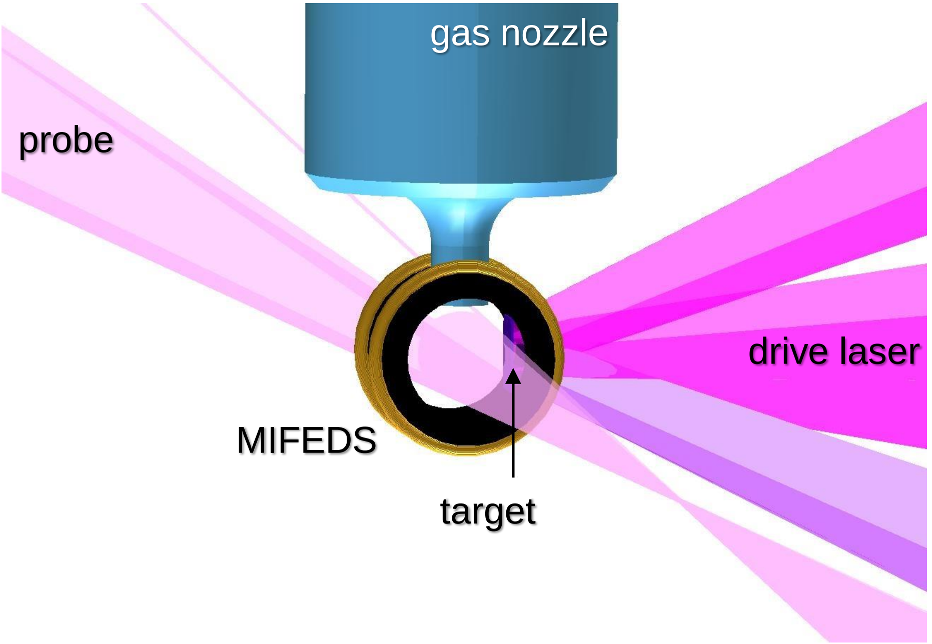
OMEGA-EP counterpropagating plasma plumes experiment†

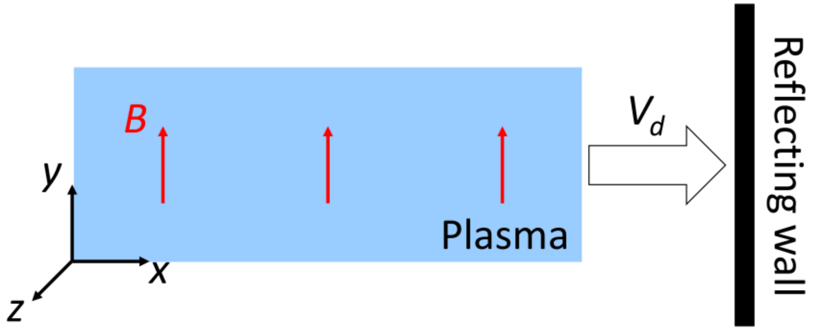


Quasi-1D particle-in-cell simulation‡

* NASA, https://apod.nasa.gov/apod/ap001017.html
** UCLA, http://www-ssc.igpp.ucla.edu/ssc/isee.html; Wang *et al.*, Geophys. Res. Lett. **46**, 562 (2019)
† Woolsey *et al.*, Phys. Plasmas **8**, 2439 (2001); Schaeffer *et al*., Phys. Plasmas **19**, 070702 (2012); Schaeffer *et al*., Phys. Plasmas **24**, 041405 (2017)
‡ Matsukiyo *et al.*, J. Geophys. Res. **108**, 1459 (2003); Matsukiyo *et al*., ApJ **742** 47 (2011); Park *et al*., Phys. Plasmas **19**, 062904 (2012); Park *et al.*, ApJ **765** 147 (2013); Schaeffer *et al.*, Phys. Plasmas **27**, 042901 (2020)

A collisionless shock can be launched by a laser-driven super-magnetosonic piston on TeraWatt laser systems





$$\mathbf{v}^{[\mathrm{sim./wall/piston}]} = \mathbf{v}^{[\mathrm{lab}]} + V_{\mathrm{d}}\mathbf{e}_x$$

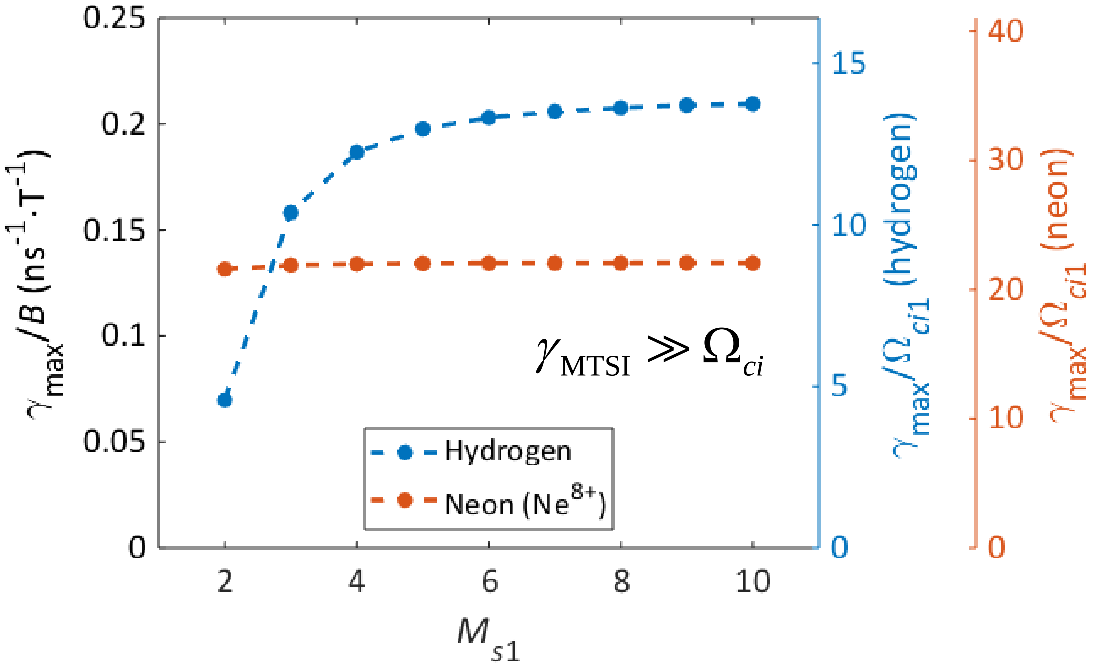
Zhang *et al.*, Phys. Plasmas **28**, 072111 (2021)

Modified two-stream instability provides dissipation for the collisionless shocks

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

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

$$\left(\frac{\gamma_{\mathrm{MTSI}}}{B}\sim\frac{\omega_{LH}}{B}^{**}=e\sqrt{\frac{Z_i}{m_i m_e}}\right)$$



$$\left(\frac{\gamma_{\mathrm{MTSI}}}{\Omega_{ci}}\sim\frac{\omega_{LH}}{\Omega_{ci}}^{**}=\sqrt{\frac{m_i}{Z_i m_e}}\right)$$

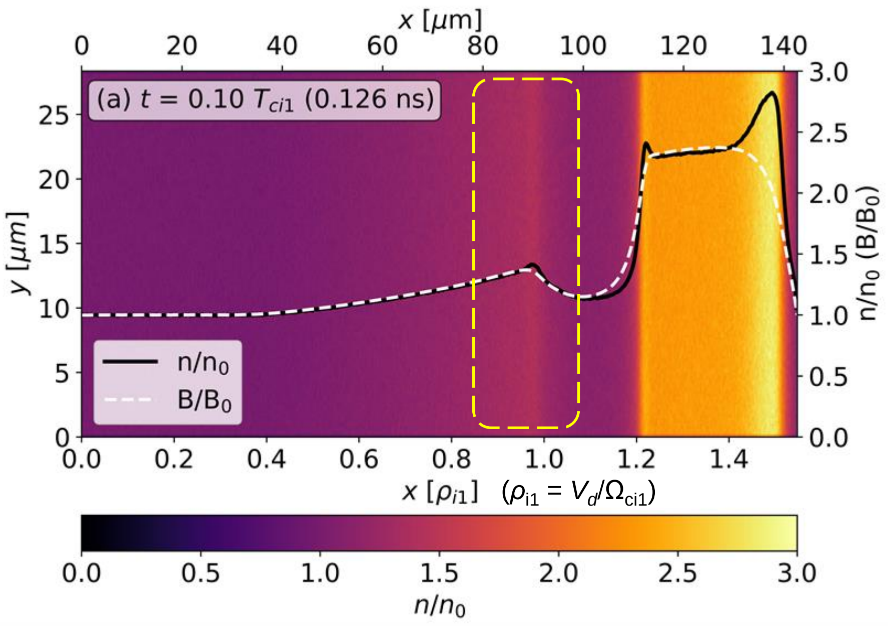
Reduced m_i/m_e, unrealistically high B, and/or reduced c, may alter the relative importance of different instabilities.

The shock can form within an ion gyro-period T_{ci} (=2π/Ω_{ci}), or, a few tenths of a nanosecond under B ~ 50 T

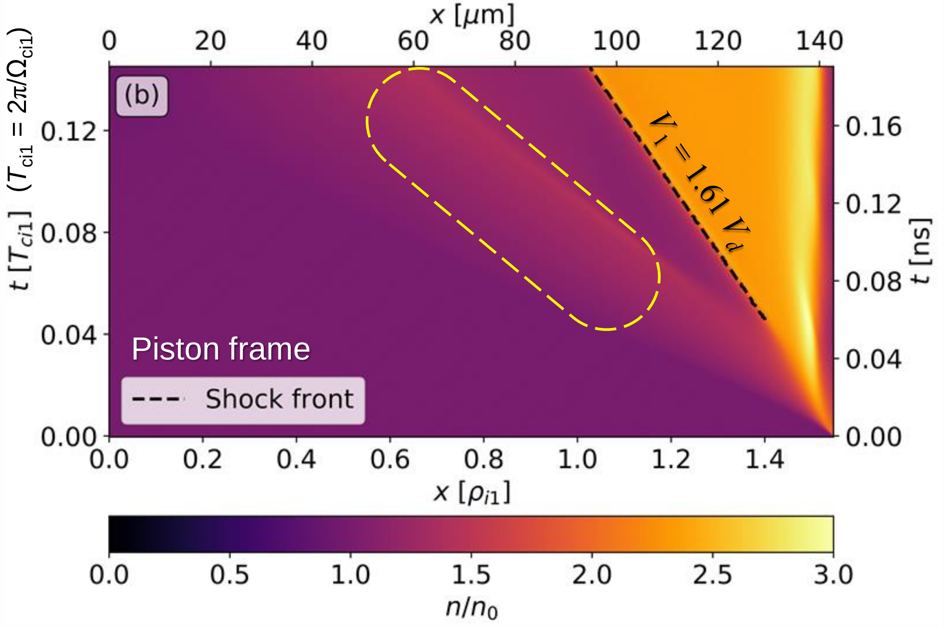
* Gary, Theory of Space Plasma Microinstabilities, Cambridge University Press (1993)
** McBride *et al.*, Phys. Fluids **15**, 2368 (1972)

A supercritical hydrogen shock forms within 0.1 T_{ci}

- **The signature of a supercritical shock: reflected ions**



Shock compression ratio: $r \sim 2.35$

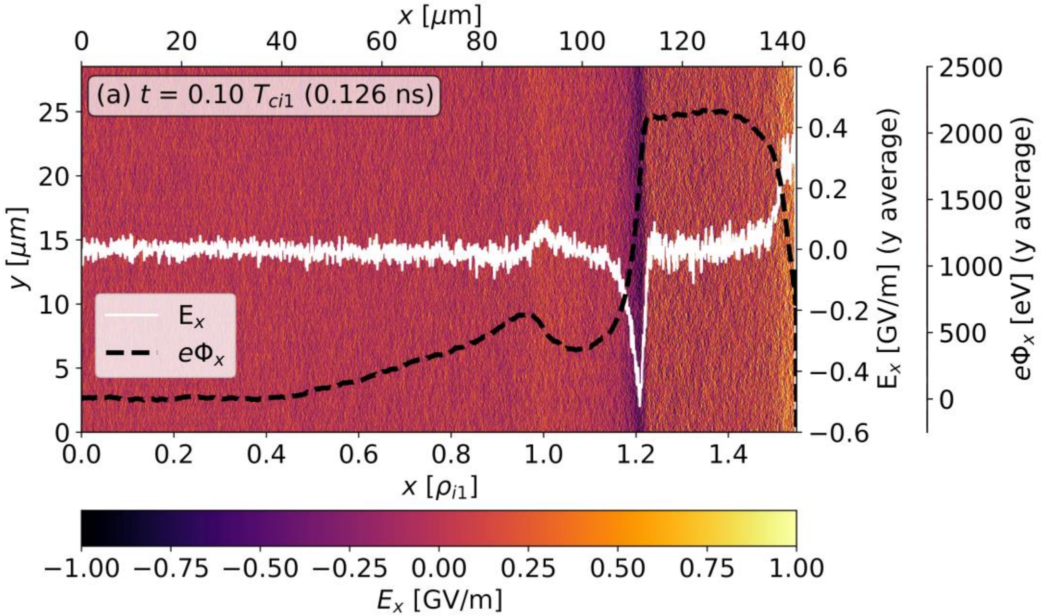


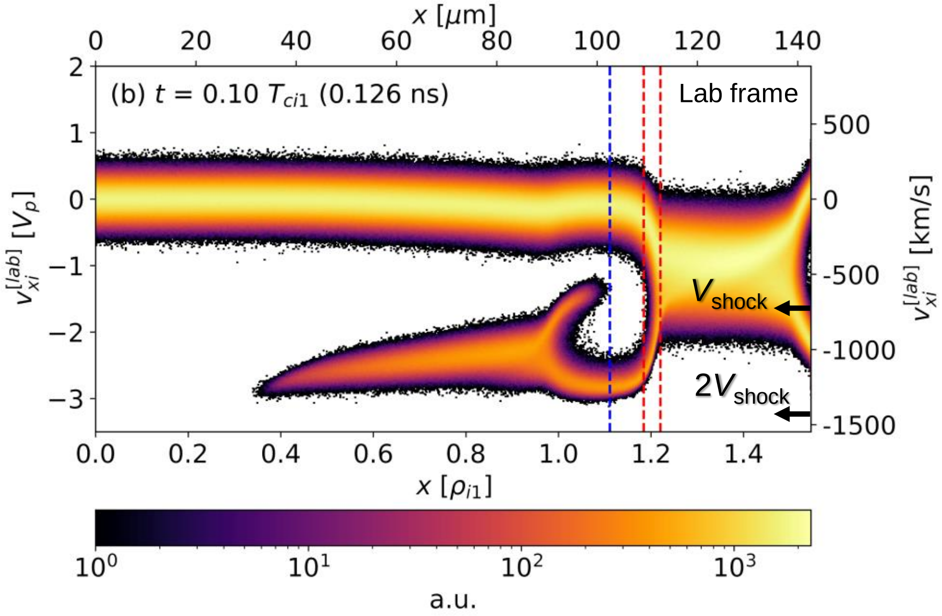
Mach #: $M_s \sim 5.62$, $M_A \sim 2.06$

Weibel instability is suppressed by the strong external magnetic field

Ions are reflected by self-generated *E*-field, resulting in MTSI

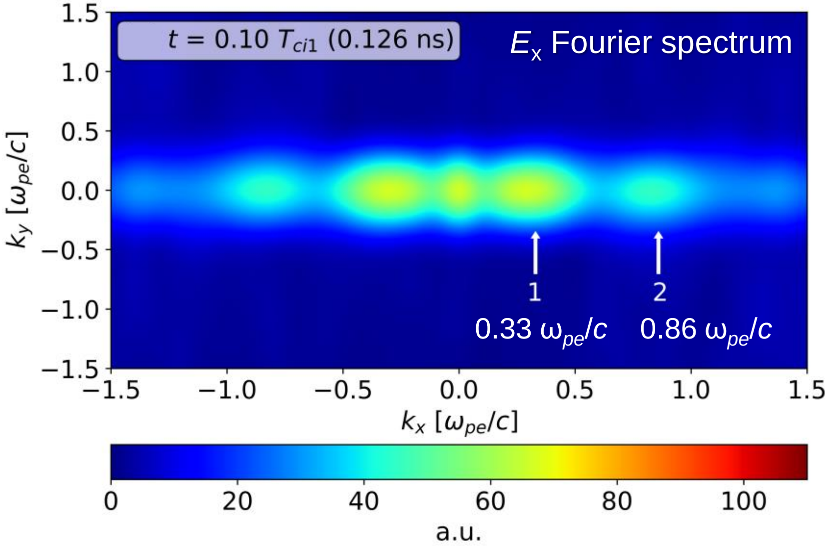
- **Low-energy tail of incoming ion is reflected to v_{xi}~$2V_{shock}$ by an electrostatic E_x field***

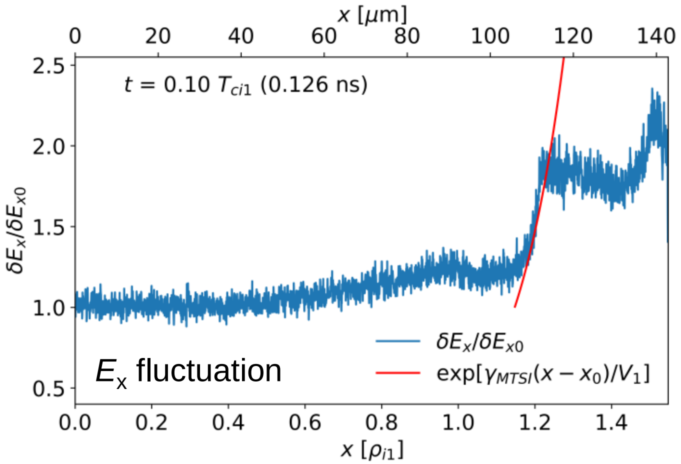


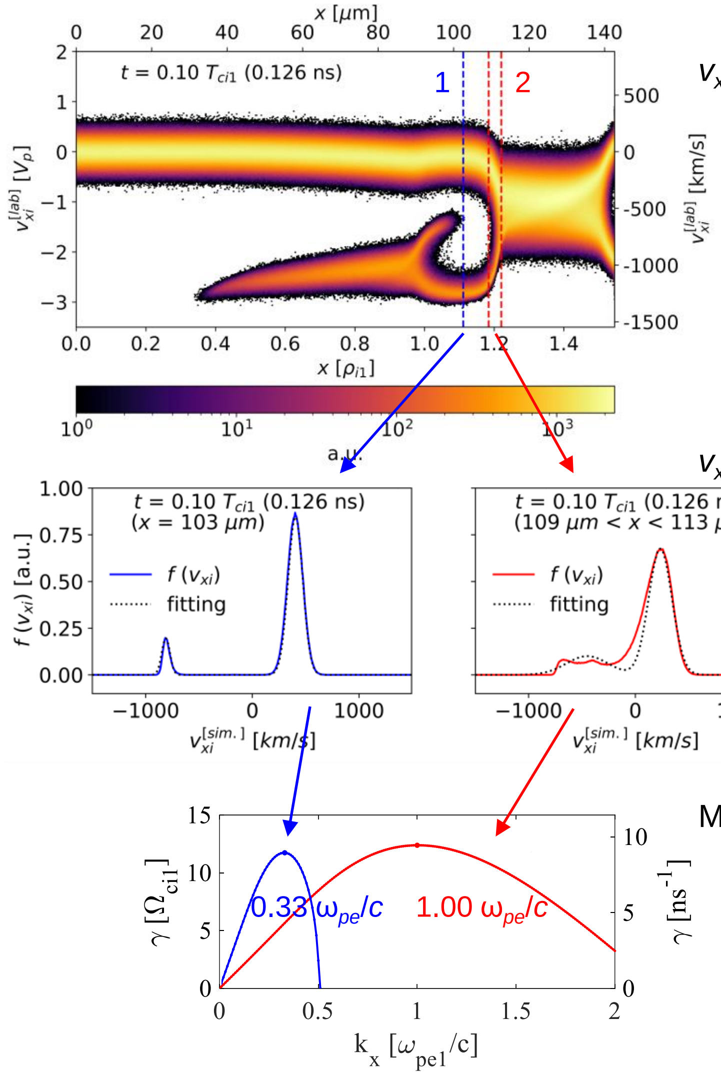


* Treumann, Astron. Astrophys. Rev. **17**, 409 (2009); Liu *et al.*, Phys. Plasmas **23**, 113103 (2016); Silva *et al.*, Phys. Rev. Lett. **92**, 015002 (2004)

Mode analysis indicates MTSI is the operating instability







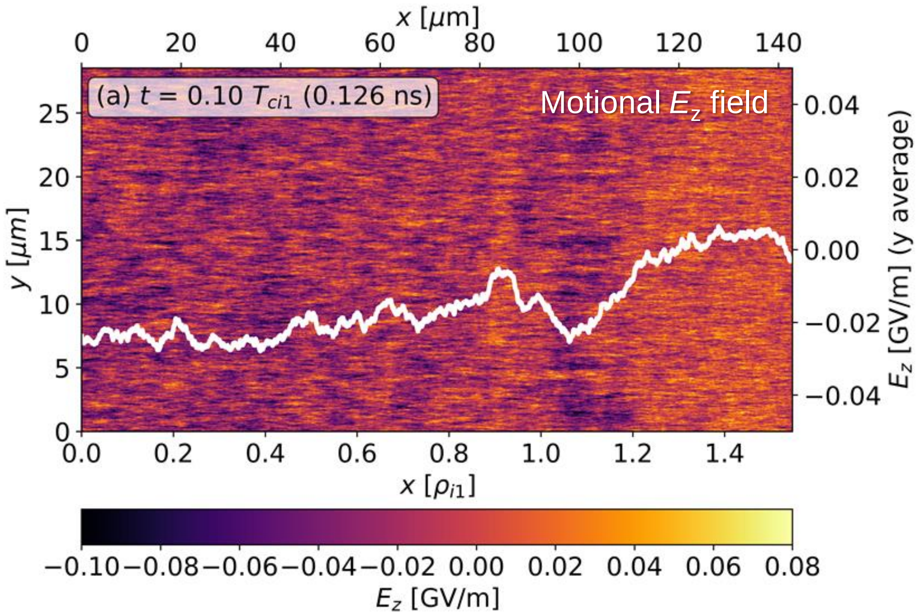
$v_{xi}^{[lab]}$ - x phase space

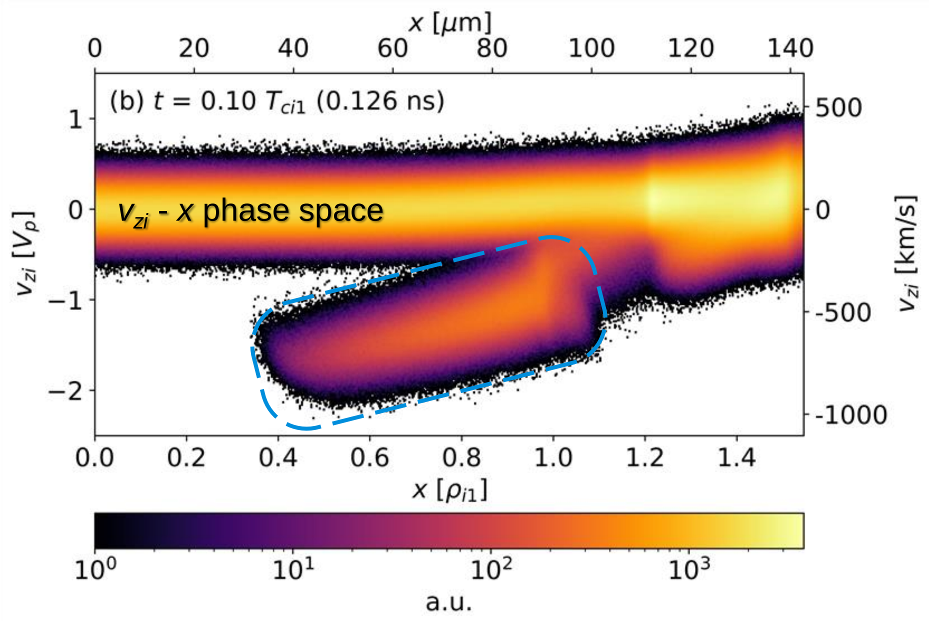
$v_{xi}^{[piston]}$ distribution

MTSI dispersion relation

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)**

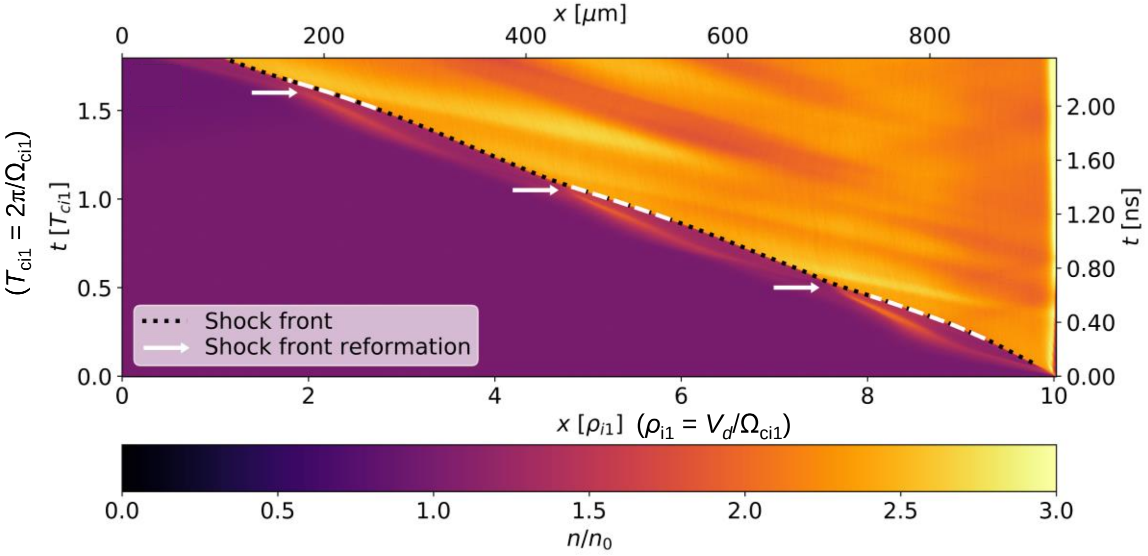




Accelerated ions will participate in shock front reformation at later times

Longer time 1D simulations shows shock front reformation as shock evolves

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



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