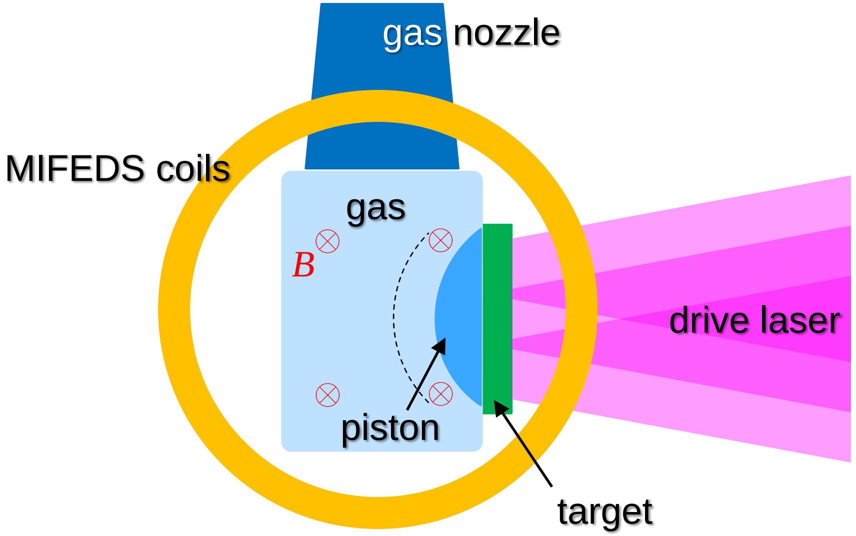
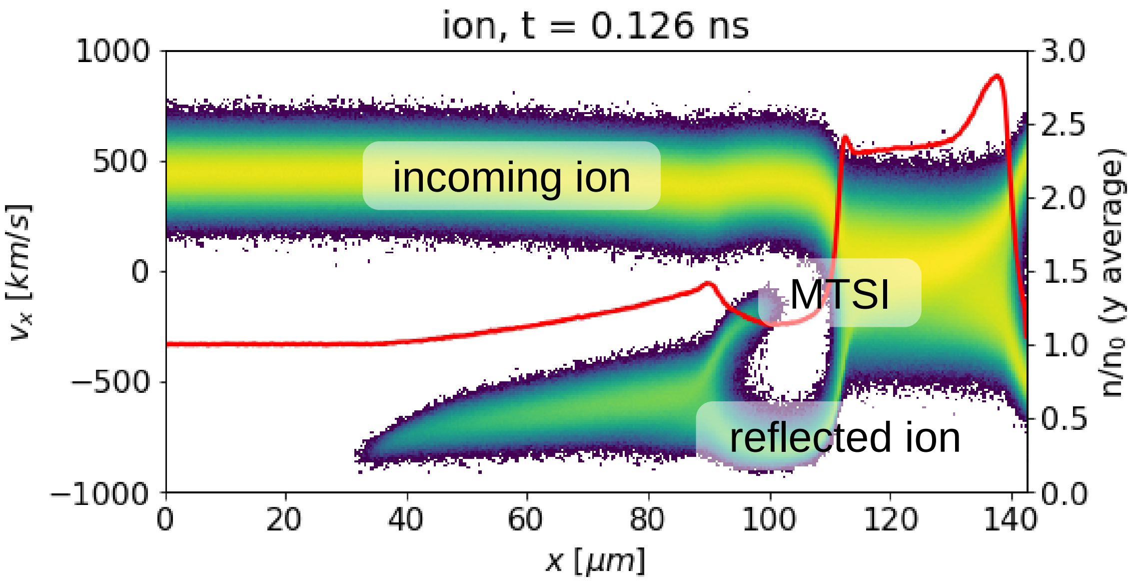
Kinetic Simulation Study of Magnetized Collisionless Shock Formation using OMEGA EP





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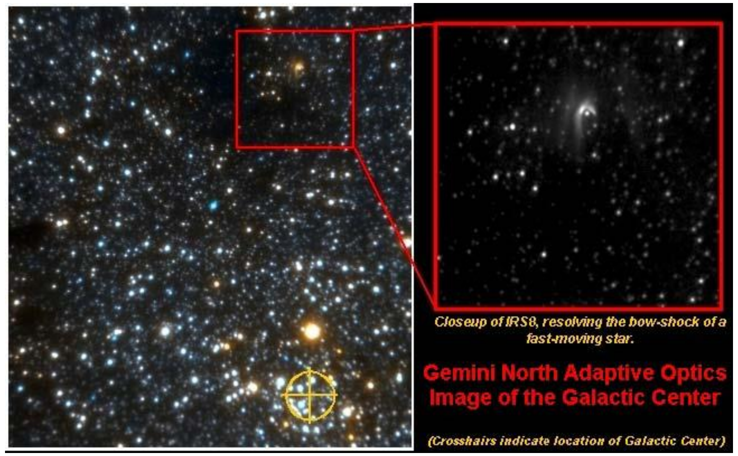
2D particle-in-cell simulations showed perpendicular magnetized collisionless shocks can be formed on the OMEGA-EP / MIFEDS platform

- **Modified two-stream instability (MTSI) provides the main dissipation for shock formation.**
- **The shocks can form within 1 ns, 100's μm in both H and Ne, with *B* = 50 T on OMEGA-EP.**
- **Particle acceleration and non-Maxwellian distribution are observed.**

High-power lasers enable study of collisionless shocks in laboratory

Magnetized collisionless shock

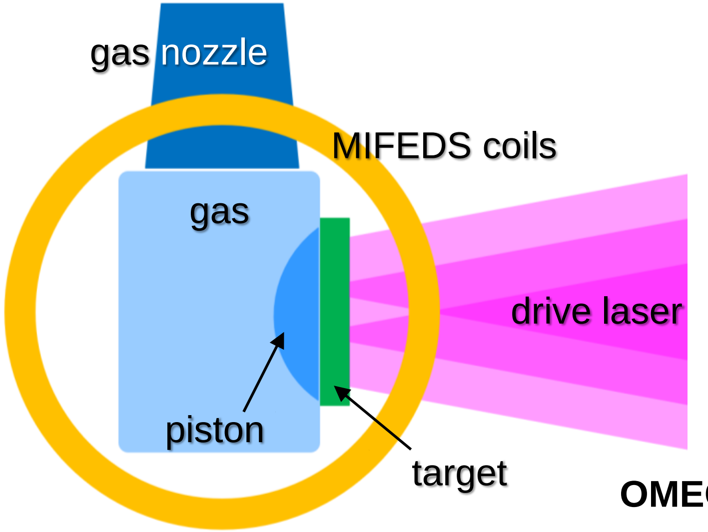
- Telescopes*
- *In situ* spacecraft missions**
- Laser experiments†
- Simulations‡

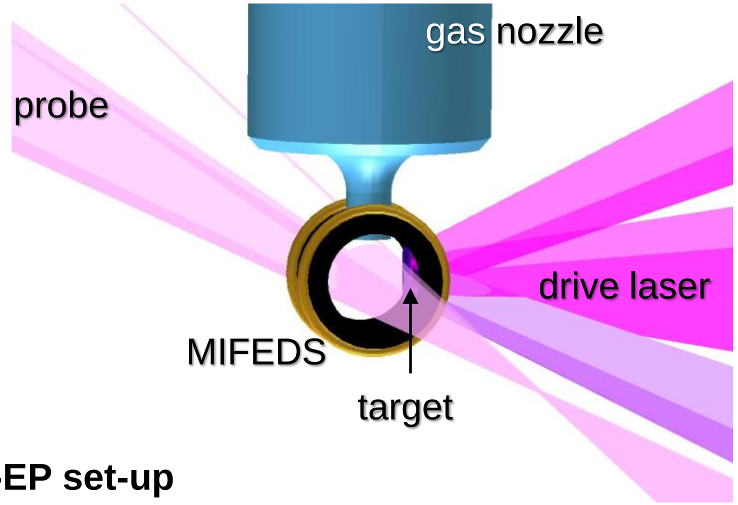


Bow shock near galactic center*
(Gemini North, Oct. 17, 2000)

OMEGA-EP experiments

- Gas jet species: hydrogen / neon
- Gas jet density: $10^{18} \sim 10^{20}$ cm^{-3}
- Gas jet temperature: 40 ~ 400 eV
- Laser-driven piston velocity: < 500 km/s
- MIFEDS magnetic field: < 50 T





OMEGA-EP set-up

* 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)

The plasma density is constrained by the collisionless and super-magneto-sonic requirements

- **Ion collisional mean free path***

$$\lambda_{ii} = \frac{2\pi\epsilon_0^2 m_i^2 V_p^4}{n_i Z_i^4 e^4 \ln\Lambda} \gg L \quad \rightarrow \quad n_{e\,[10^{19}\,\mathrm{cm}^{-3}]} \ll \frac{131}{\ln\Lambda}\left(\frac{m_i}{m_p}\right)^2 \frac{1}{Z_i^3}\left(\frac{L_{[\mu\mathrm{m}]}}{100}\right)^{-1}\left(\frac{V_{p\,[\mathrm{km/s}]}}{500}\right)^4$$

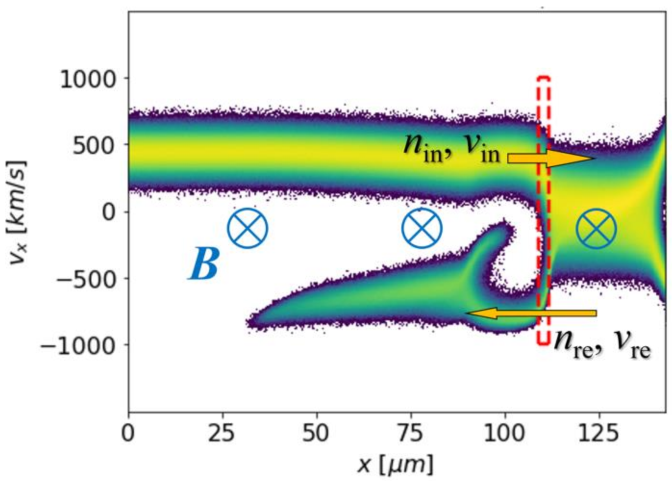
- **Super-magneto-sonic piston**

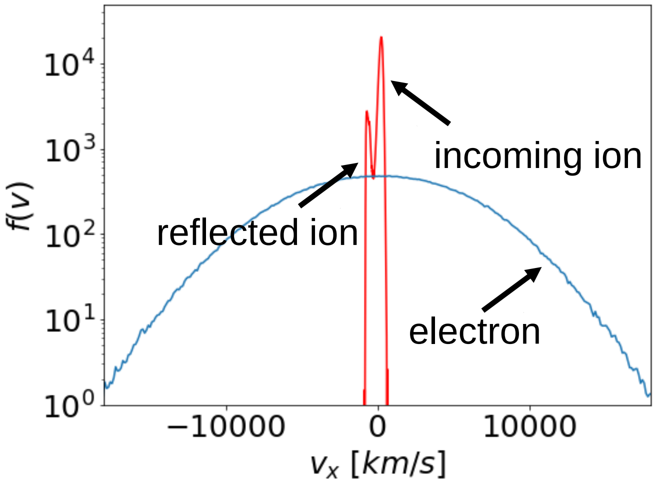
$$V_p > \sqrt{v_A^2 + c_s^2} \quad \rightarrow \quad n_{e\,[10^{19}\,\mathrm{cm}^{-3}]} > \frac{27 Z_i \left(\frac{B_{[\mathrm{T}]}}{50}\right)^2}{56\frac{m_i}{m_p}\left(\frac{V_{p\,[\mathrm{km/s}]}}{500}\right)^2 - Z_i \frac{T_{e\,[\mathrm{eV}]}}{50} - \frac{T_{i\,[\mathrm{eV}]}}{50}}$$

* Kuramitsu *et al.*, Phys. Rev. Lett. **106**, 175002 (2011); Spitzer, Physics of Fully Ionized Gases, Interscience (1962)

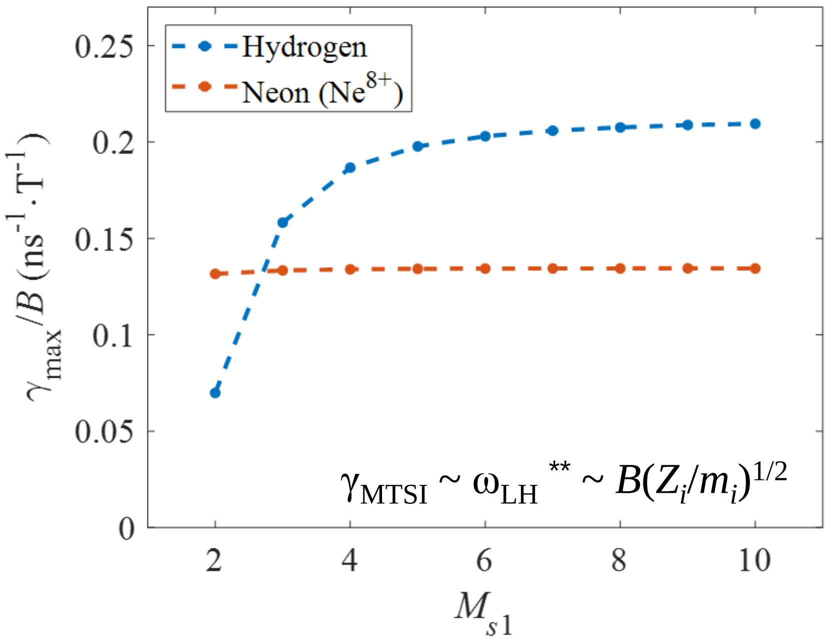
Modified two-stream instability provides dissipation for the collisionless shocks

- **Modified two-stream instability between incoming and reflected ion**





Growth rate of MTSI (w/ n_{in}/n_{re} = 3 and $T_i = T_e$)



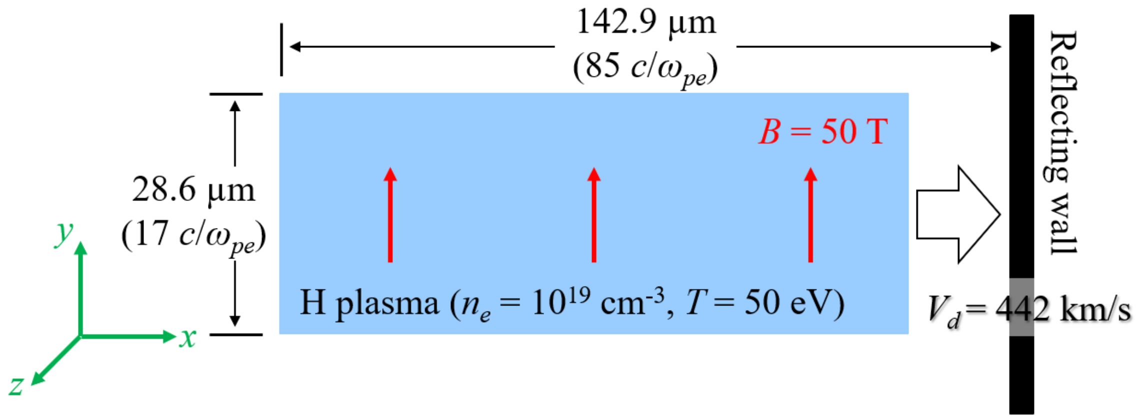
- **Dispersion relation***

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

* Gary, Theory of Space Plasma Microinstabilities, Cambridge University Press (1993); Park *et al*., Phys. Plasmas **19**, 062904 (2012)
** McBride *et al*., Phys. Fluids **15**, 2368 (1972)

PIC simulation setup

Piston frame simulation (Hydrogen)



Hydrogen

$m_i = 1836\ m_e$

$n_e = 10^{19}$ cm^{-3}

$T = 50$ eV

$V_d = 3.5\ M_s = 442$ km/s

$B = 50$ T

$\beta = 0.16$

Neon

$m_i = 20 \times 1836\ m_e$

$Z_i = 8$

$n_e = 0.6 \times 10^{19}$ cm^{-3}

$T = 160$ eV

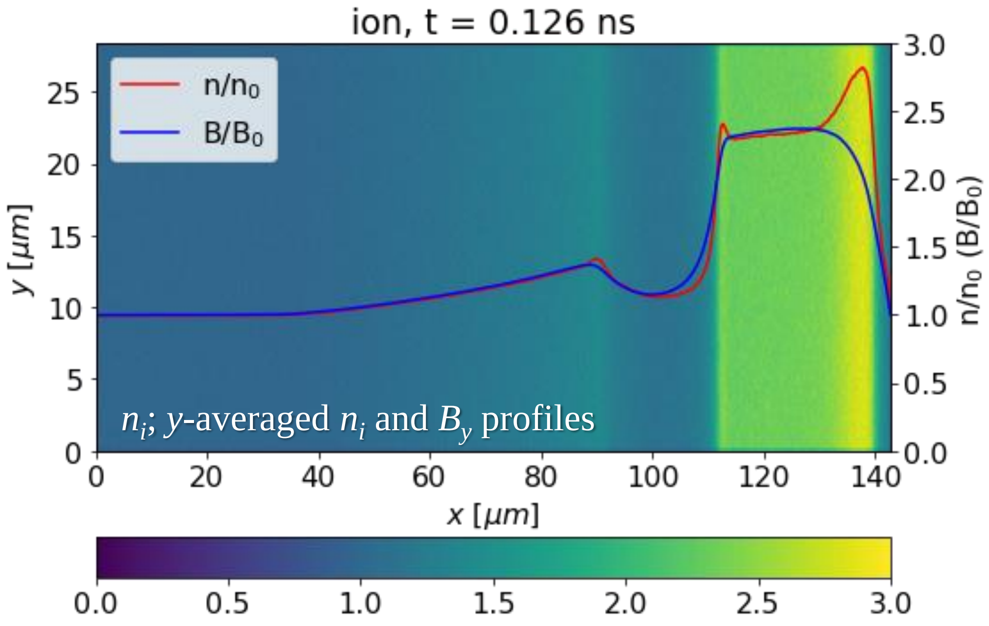
$V_d = 3.5\ M_s = 375$ km/s

$B = 50$ T

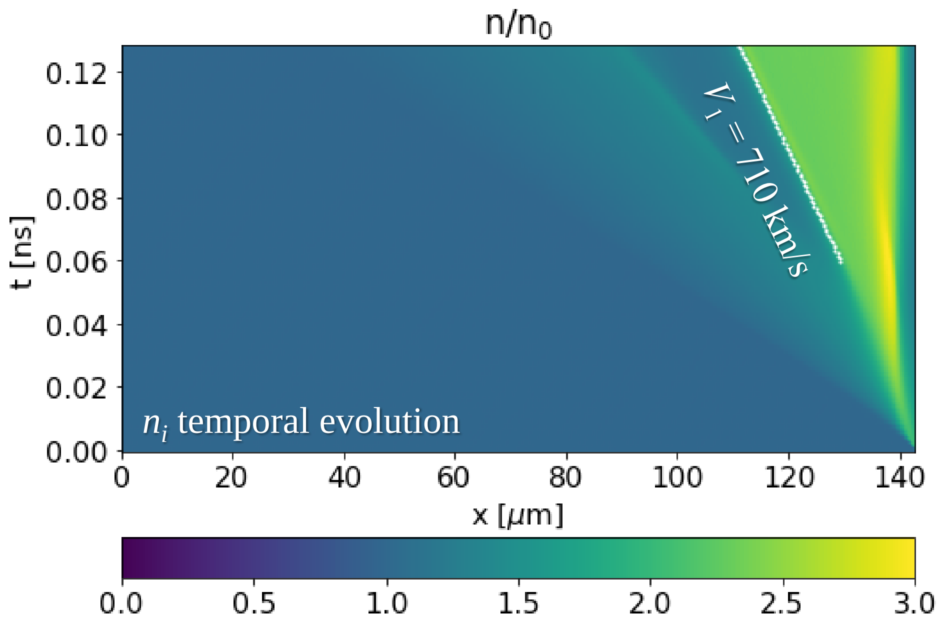
$\beta = 0.17$

A hydrogen shock forms in ~0.1 ns, traveling with a velocity over 700 km/s

Hydrogen shock



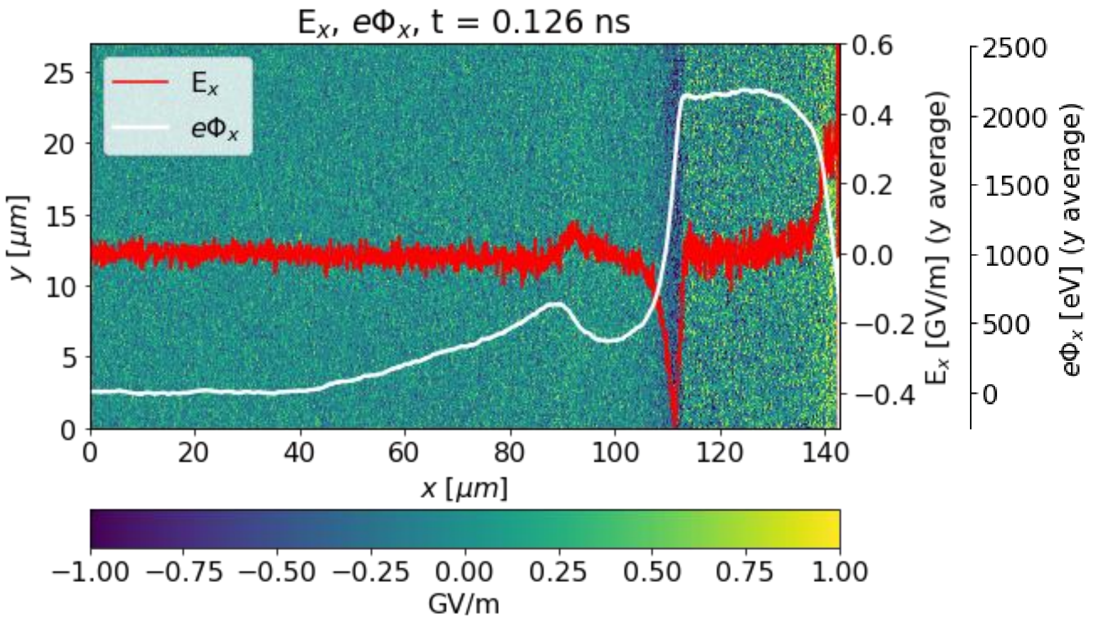
Shock compression ratio: $r \sim 2.35$

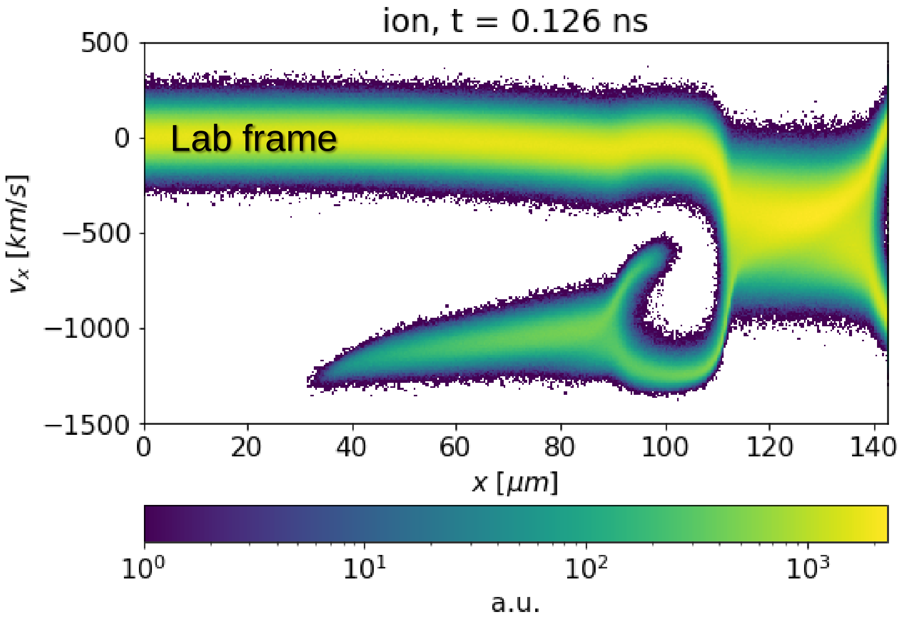


Mach #: $M_s \sim 5.62$, $M_A \sim 2.06$

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

- An electrostatic E_x field exists at the shock front*
- ~19% of incoming ion is reflected
- Ions can be reflected to $\lesssim 2V_{shock}$**

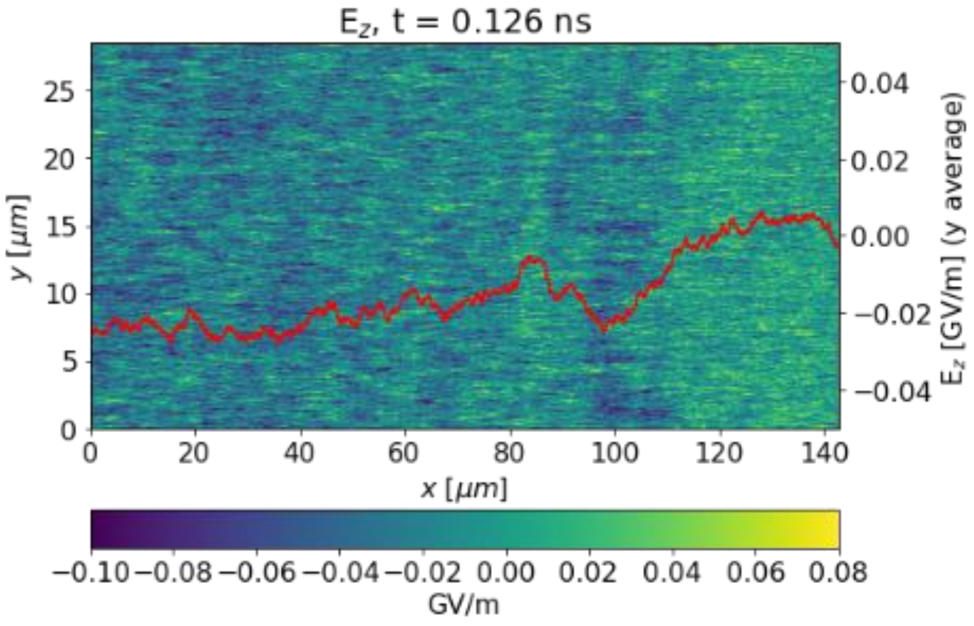


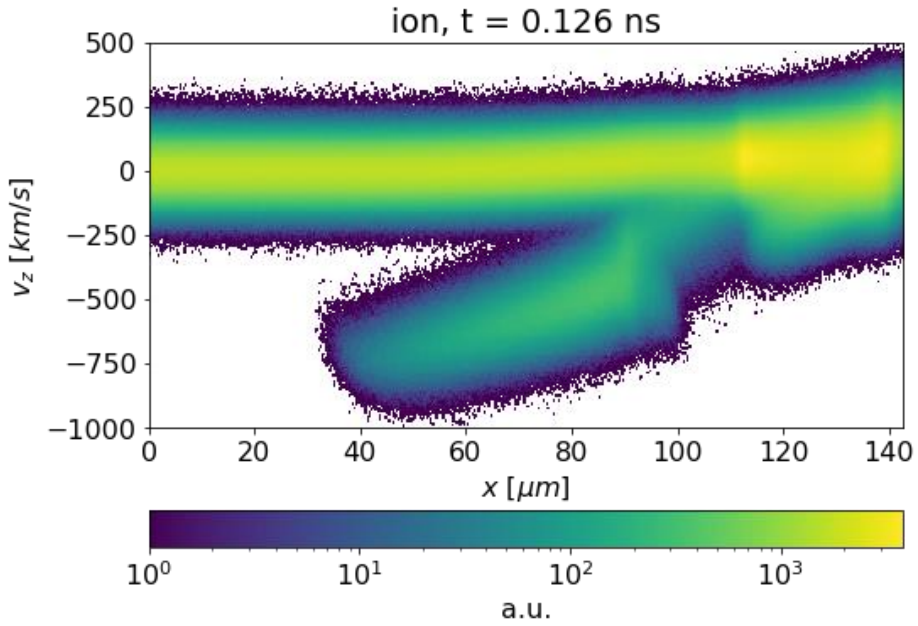


* Treumann, Astron. Astrophys. Rev. **17**, 409 (2009); Liu *et al.*, Phys. Plasmas **23**, 113103 (2016)
** Silva *et al.*, Phys. Rev. Lett. **92**, 015002 (2004)

Energetic ions can escape the shock front

- Reflected ion is also accelerated by E_z
- ~12% of the downstream ion population is accelerated to 6.5~9.7 keV





These energetic ions are potential experiment observables

The observed compression ratio is larger than that from the Rankine Hugoniot jump conditions

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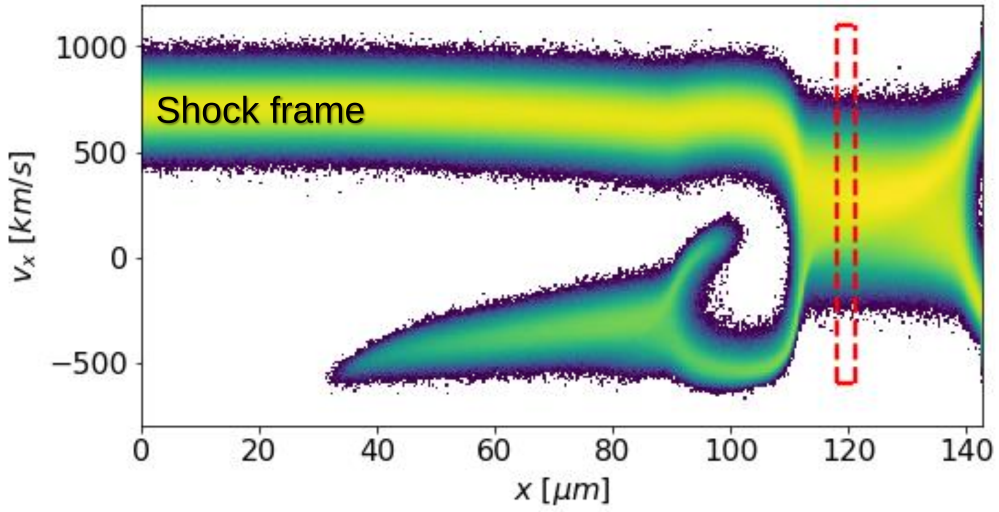


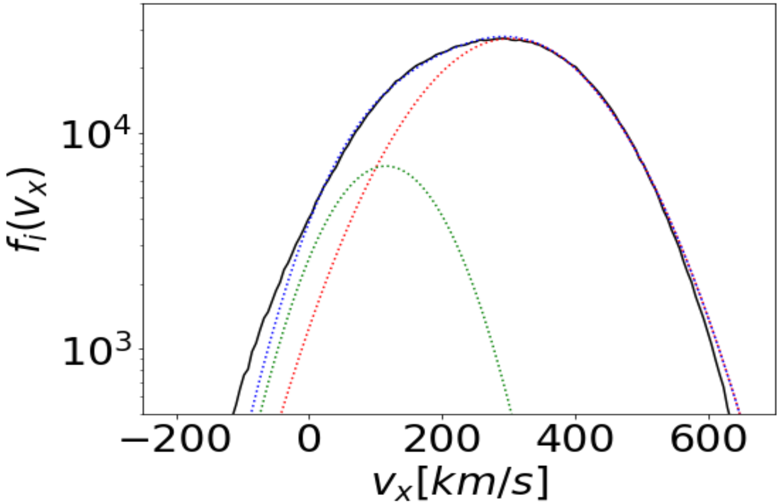
Classical Rankine Hugoniot jump conditions*

$$\frac{1}{r}=\frac{1}{8}\left\{\frac{5\beta_1}{2M_{A1}^2}+1+\frac{5}{2M_{A1}^2}+\left[\left(\frac{5\beta_1}{2M_{A1}^2}+1+\frac{5}{2M_{A1}^2}\right)^2+\frac{8}{M_{A1}^2}\right]^{1/2}\right\}$$

- However, the observed r = 2.35 > 2.07 ($\beta_1 = 0.16$, $M_{A1} = 2.06$)

Downstream ion v_x distribution is not a single Maxwellian

- This ion bi-Maxwellian distribution can be diagnosed by Thompson scattering**

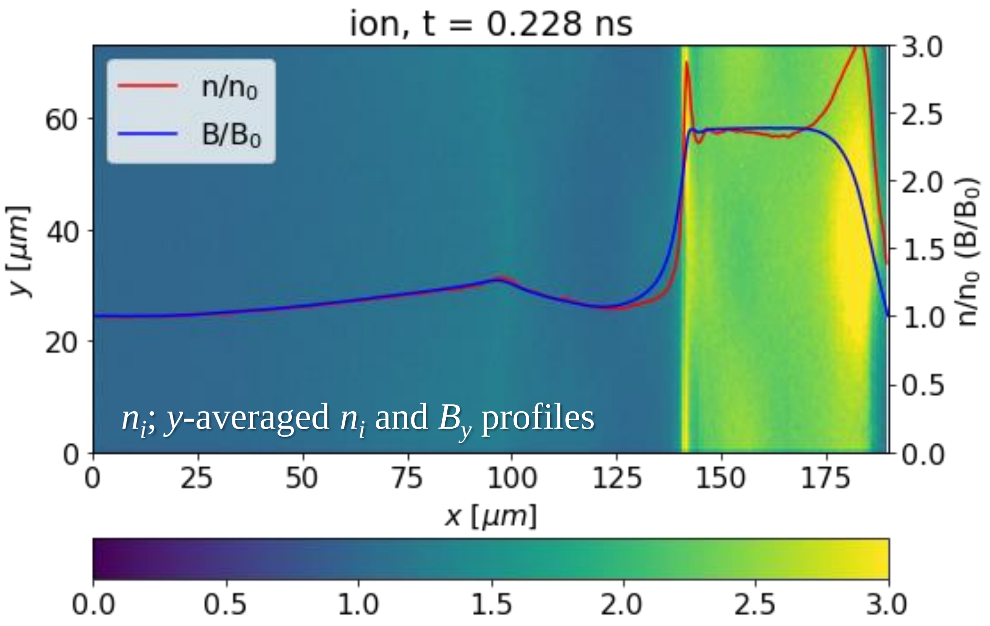


* Tidman *et al*., Shock Waves in Collisionless Plasmas, Wiley Interscience (1971); Gurnett *et al*., Introduction to Plasma Physics, Cambridge University Press (2005)
** Rinderknecht *et al*., Phys. Rev. Lett. **120**, 095001 (2018)

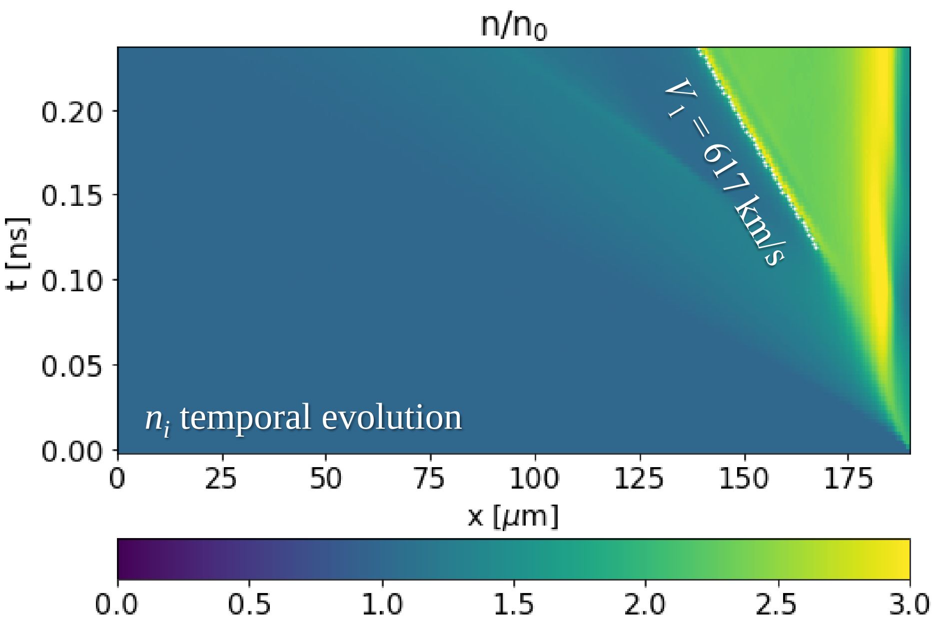
A neon gas jet potentially allows spectroscopy measurements

Neon shock

- $m_i = 20 \times 1836 m_e$, $Z_i = 8$
- $n_e = 0.6 \times 10^{19}$ cm^{-3} , T = 160 eV, $V_d = 3.5 M_s$ = 375 km/s, B = 50 T



Shock compression ratio: $r \sim 2.35$



Mach #: $M_s \sim 5.75$, $M_A \sim 2.19$

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