Study of Electron Acceleration and Ion Acoustic Waves during Low-β Magnetic Reconnection using Laser-Powered Capacitor Coils

Hantao Ji

Department of Astrophysical Sciences, Princeton University

Princeton Plasma Physics Laboratory

Acknowledgement: L. Gao, G. Pomraning, K. Sakai (*NIFS*), A. Stanier and F. Guo (*LANL*), Xiaocan Li (*Dartmouth*), A. Milder (*Rochester*), A. Chien, S. Zhang, O. French, K. Hill (*Princeton*); E. Blackman, R. Follet, D. Froula, J. Katz, P. Nilson (*Rochester*); W. Daughton, A. Le, K. Flippo, A. Rasmus (*LANL*); G. Fiksel, S. Klein, C. Kuranz (*Michigan*); C. Li, A. Birkel and R. Petrasso (*MIT*), H. Chen, J. Moody, R. Cauble (*LLNL*); A. Fazzini, J. Fuchs (*LULI*); S. Chen, G. Bleotu (*ELI-NP*); S. Fujioka, R. Takizawa, Y. Sakawa (*ILE*)

The 16th Interrelationship Between Plasma Experiments in the Lab and Space (IPELS)

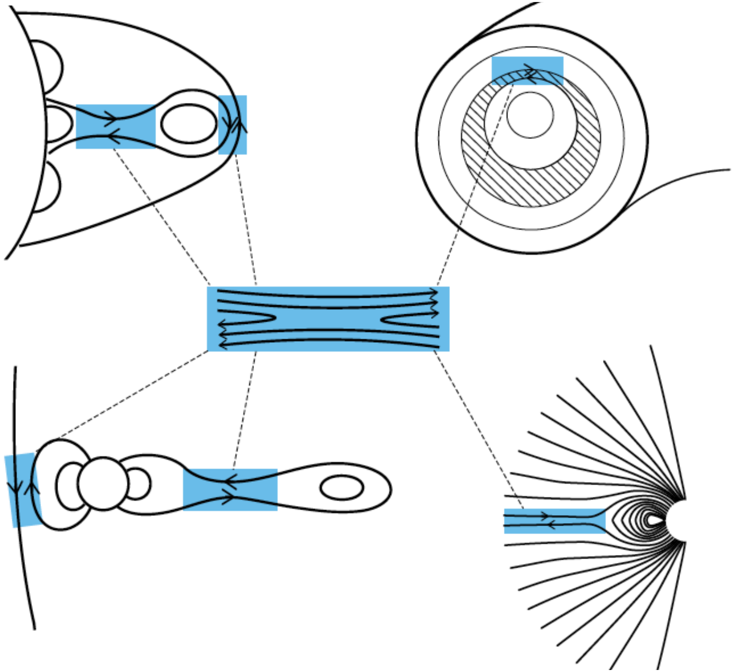
Munich, Germany, August 5-9, 2024

Outline

- Introduction: what motivates this work?
- Laser-powered capacitor coils* to magnetically drive reconnection at low upstream β (micro-MRX)
  - Electron acceleration directly by reconnection electric field**
  - Ion and electron acoustic bursts driven by electric current***
- Summary**** and future work

*Gao et al., “Ultrafast Proton Radiography of the Magnetic Fields Generated by Laser-Driven Coil Currents”, *Phys. Plasmas* **23**, 043106 (2016)
*Chien et al., “Study of a magnetically driven reconnection platform using ultrafast proton radiography”, *Phys. Plasmas* **26**, 062113 (2019)
*Chien et al. “Pulse width dependence of magnetic field generation using laser-powered capacitor coils”, *Phys. Plasmas* **28**, 052105 (2021)
Chien et al., “Non-thermal electron acceleration from magnetically driven reconnection in a laboratory plasma,” *Nature Physics* **19, 254 (2023)
***Zhang et al., “Ion and Electron Acoustic Bursts during Anti-Parallel Reconnection Driving by Lasers,” *Nature Physics* **19**, 909 (2023).
****Ji et al., “Study of magnetic reconnection at low-beta using laser-powered capacitor coils”, submitted to *Phys. Plasmas* (2024).

Magnetic Reconnection Occurs throughout the Universe and in Fusion Plasmas*



- Nearly collisionless*

$$\text{Lundquist number } S \equiv \frac{\mu_0 L V_{\rm A}}{\eta} \sim 10^6 - 10^{30}$$

- Plasma is large*

$$\text{effective size } \lambda \equiv \frac{L}{\rho_{\rm sound}} \sim 10^2 - 10^{14}$$

- Occurs impulsively and energetically, often at low upstream β, favoring
  - Particle energization

$$\text{average energy increase } \frac{\Delta E}{E_0} = \frac{1}{\beta} \gg 1$$

  - Current-driven micro-instabilities, such as ion acoustic wave(IAW) instability

$$\text{relative drift } \frac{V_{\rm drift}}{V_{\rm sound}} = \sqrt{\frac{2}{\beta}} \gg 1$$

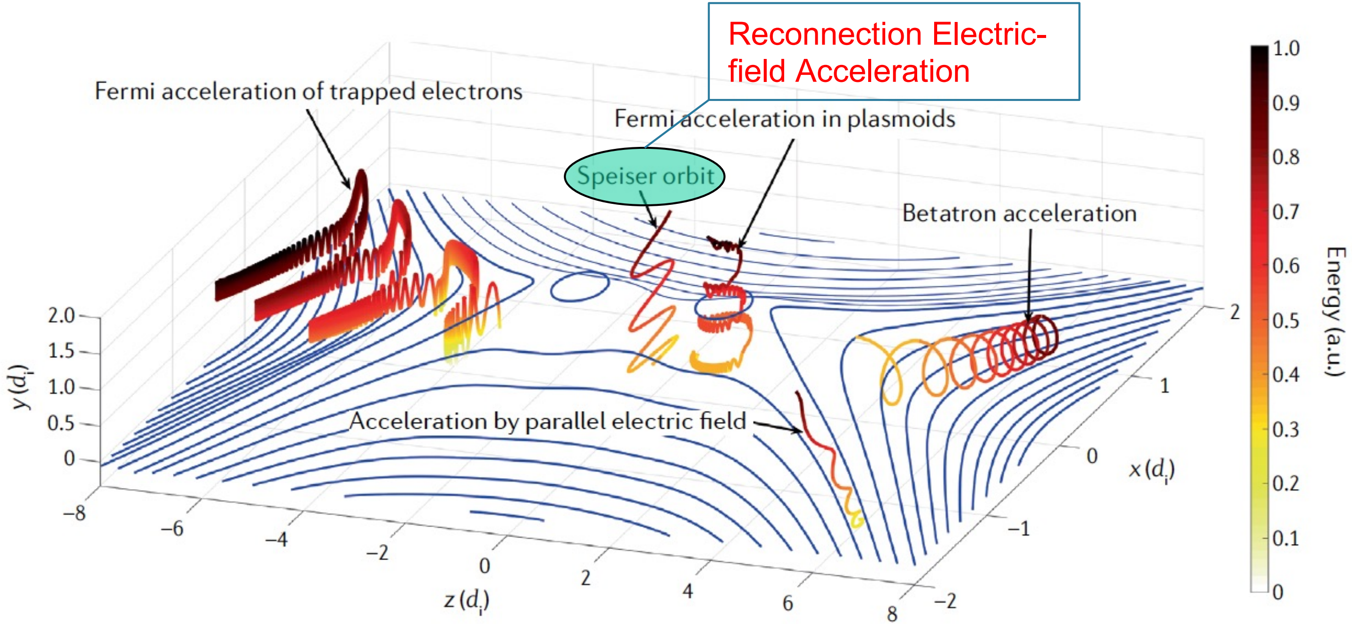
*H. Ji & W. Daughton, *Phys. Plasmas* **18**, 111207 (2011)
*H. Ji, W. Daughton, J. Jara-Almonte, A. Le, A. Stanier, and J. Yoo, *Nature Rev. Phys.* **4**, 263 (2022)

Various Particle Acceleration Mechanisms by Magnetic Reconnection Have Been Proposed

parallel E betatron Fermi polarization drift

$$\frac{d\varepsilon}{dt} = qE_{||}v_{||} + \mu\frac{dB}{dt} + q\mathbf{E}\cdot\mathbf{u}_c + \frac{1}{2}m\frac{d}{dt}|\mathbf{u}_E|^2$$

Ji+ Nat. Rev. Physics 2022



Reconnection Electric-field Acceleration

A large body of recent theory and numerical work on this subject (M. Hoshino, S. Zenitani, J. Drake, J. Dahlin, F. Guo, L. Sironi, D. Uzdensky, L. Comisso…)

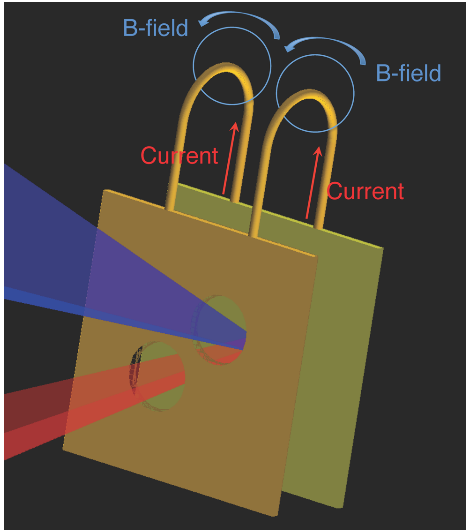
Laser-powered Capacitor Coils Provide a Unique Platform to Study Magnetically-driven Reconnection at Low Upstream Plasma β

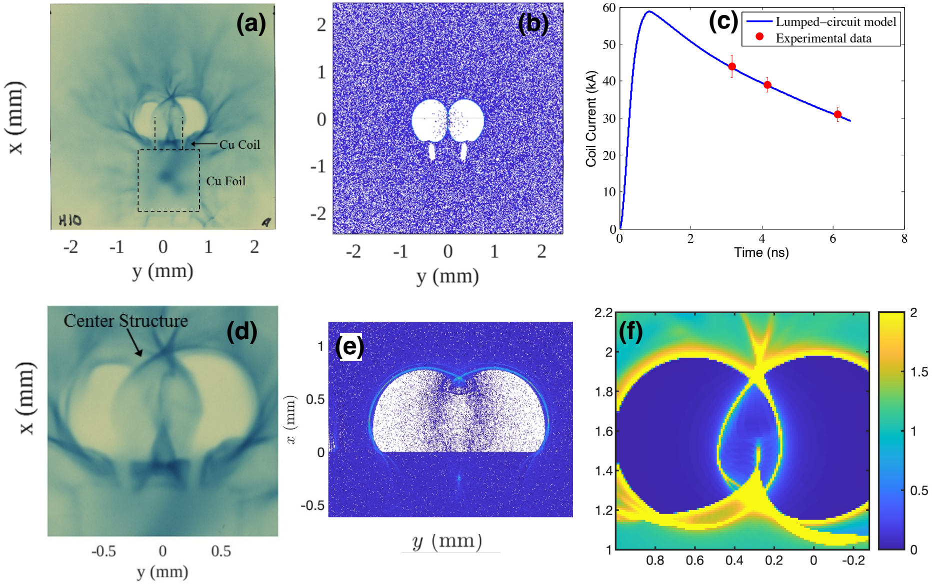
	RHESSI (solar)	**MMS (space)**	**MRX / FLARE**	**Laser-Powered Capacitor Coils**
Magnetic Field (B)	0.02 T	20-100 nT	0.02 T / 0.1 T	100 T
System Size (L)	10^4 km	10^4 km	0.4 m / 1.6 m	1 mm
Ion skin depth (d_i)	1-10 m	10 km	0.04 m	few 10^{-4} m
Lundquist number	10^{13}	10^{14}	10^3 / 10^5	10^{3-4}
Normalized Size (L/d_i)	10^{6-7}	10^3	10^1 / 10^2	2-20
Electron MFP ($\lambda_{MFP,\,e}$)	100 km	10^{4-5} km	5 cm	2-15 mm
Debye Length (λ_D)	2 mm	2-4 km	1 mm	2-40 µm
In-situ Detector Size $L_{in\text{-}situ}$	---	1 m	5 mm	---
Ion charge, Z	1	1	1	18
Electron Temperature T_e	100 eV	100-1000 eV	10 eV	200-400 eV
Ion Temperature T_i	100 eV?	100-5000 eV	10 eV	300- 1500 eV
Upstream plasma β	0.01	0.04-6	0.1	0.003-0.1
Control	No	No	Yes	Yes
In-situ measurements	No	Yes	Difficult	No
Ex-situ measurements	Yes (photon)	No	No	Yes (e,i)

$$V_{\text{sound}} \equiv \sqrt{\frac{ZT_e + T_i}{M}}$$

- $T_i < ZT_e$ favors IAW
- low upstream β favors particle energization and IAW
- Controllable
- Detecting accelerated particles

Magnetically Driven Reconnection Experiments Performed on a Variety of Laser Facilities at Low-β*





proton-radiography

prediction by PIC simulation

prediction by FLASH simulation

- Developed on OMEGA, OMEGA-EP, Titan and GEKKO XII facilities since 2015
- ns-long UV lasers used as the main drive

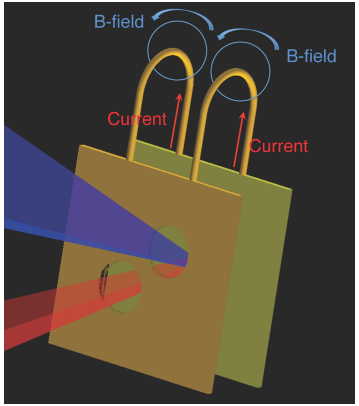
*Chien et al. *Phys. Plasmas* **26**, 062113 (2019)

*Chien et al. *Phys. Plasmas* **28**, 052105 (2021)

*Zhang et al., *Nature Physics* **19**, 909 (2023).

Our Platform Is Named Micro-MRX*

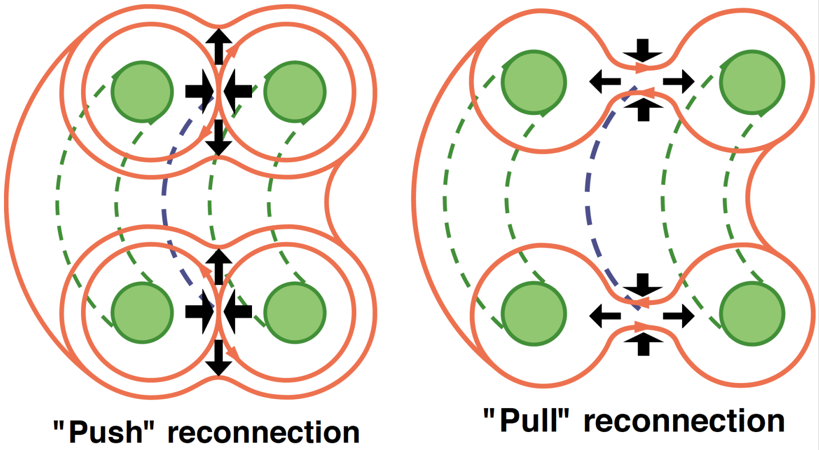
Micro-MRX



Similar to MRX:
- Magnetically-driven
- Low-β

In contrast to flow-driven and high-β experiments by Nilson, Li, Willingale, Zhong, Raymond, Dong, Fiksel, Kuramitsu, Law, Fox, Ping, Fucks,…

Magnetic Reconnection Experiment (MRX)*



Disadvantageous than MRX:
- No *in-situ* measurements

Advantageous than MRX:
- *ex-situ* detection of accelerated particles
- Accessibility of different parameter regimes (e.g. $T_i < ZT_e$)

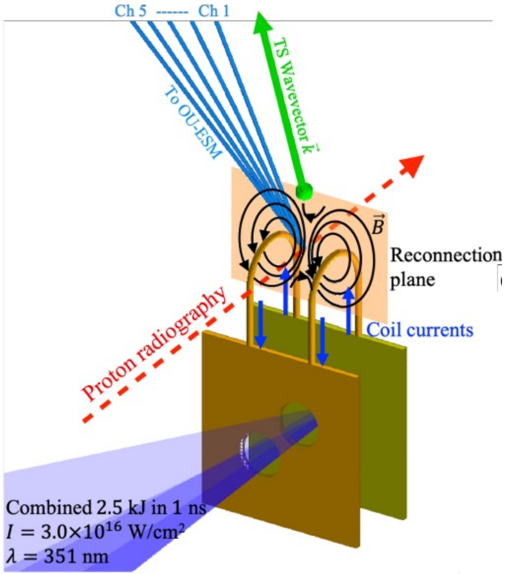
*M. Yamada, H. Ji, S. Hsu, T. Carter, R. Kulsrud, N. Bretz, F. Jobes, Y. Ono, F. Perkins, *Phys. Plasmas* **4**, 1936 (1997)

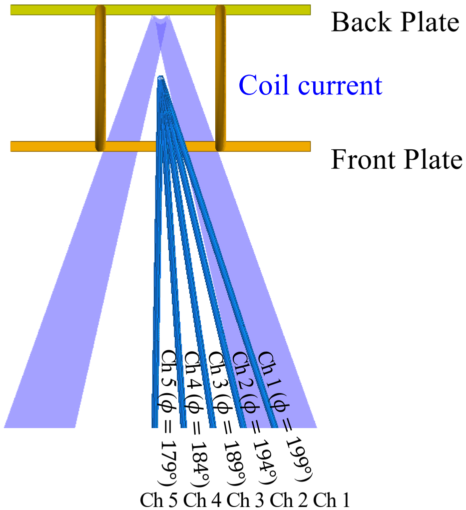
Experiment 1:

Electron Acceleration by Magnetic Reconnection at Low Upstream β

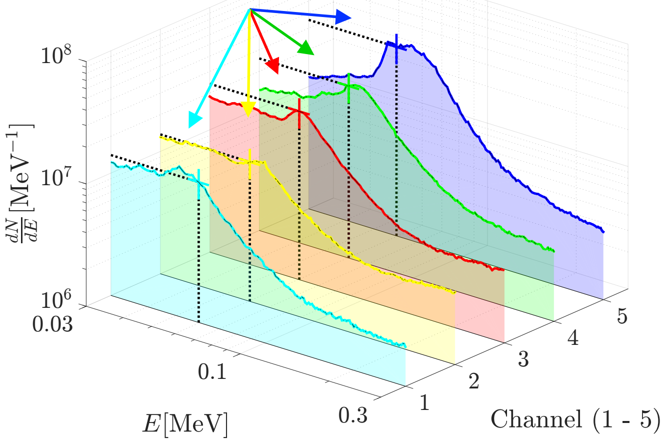
A. Chien, L. Gao, S. Zhang, H. Ji, E. Blackman, W. Daughton, A. Stanier, A. Le, F. Guo, R. Follett, H. Chen, G. Fiksel, G. Bleotu, R. Cauble, S. Chen, A. Fazzini, K. Flippo, O. French, D. Froula, J. Fuchs, S. Fujioka, K. Hill, S. Klein, C. Kuranz, P. Nilson, A. Rasmus, R. Takizawa, *Nat. Phys.* **19**, 254-262 (2023).

Angular Dependence of Detected Bumps in Electron Energy Spectra Suggests Reconnection Electric Field Acceleration

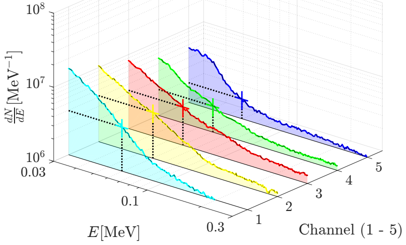




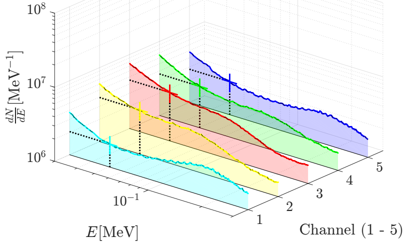
Reconnection bumps



One-Coil



No-Coil



Angular Dependance Reproduced by 2D Simulation Using VPIC Code* under Experimentally Relevant Conditions

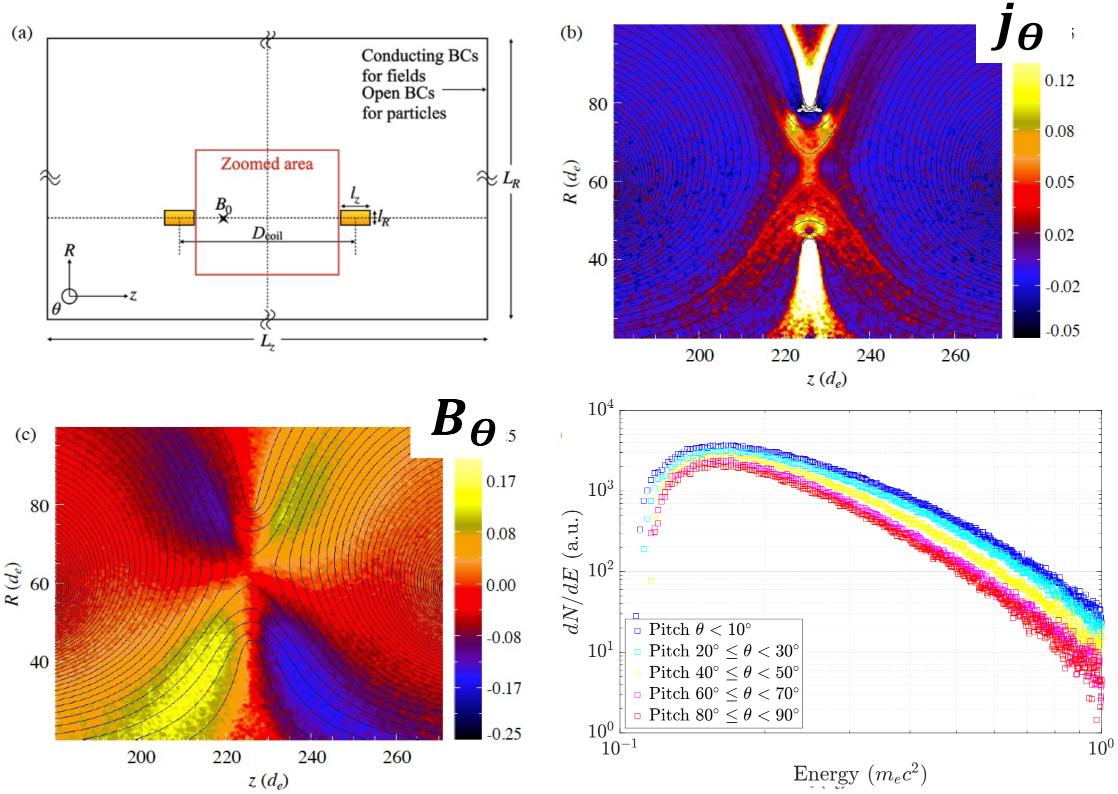
$t = 1.55\ t_{\text{rise}}$

$n_e = 10^{18}\ cm^{-3}$
$T_e = T_i = 400\ eV$
$B_0 = 50.7\ T$ (for initial current I_0 = 57 kA)
$\beta = 0.063$
$Z = 18$
$m_i/m_e = 1.16 * 10^5$

$t_{rise} = 1\ ns, \qquad \tau = 8.6\ ns$

$$I(t) = \begin{cases} \dfrac{I_0 t}{t_{rise}}, & t \leq t_{rise} \\ I_0 \exp\left(-\dfrac{t - t_{rise}}{\tau}\right), & t > t_{rise} \end{cases}$$

Conducting boundary condition for fields
Open boundary condition for particles



* Bowers et al. PoP (2008)

reconnection electric field: ~0.6 - 0.7 E_{rec}/V_AB_0; $\Delta E = qE_{rec}d$ ~ 30 keV

Estimated Energy from Direct Acceleration by Reconnection Electric Field Is Within a Factor of 2 of Measurements

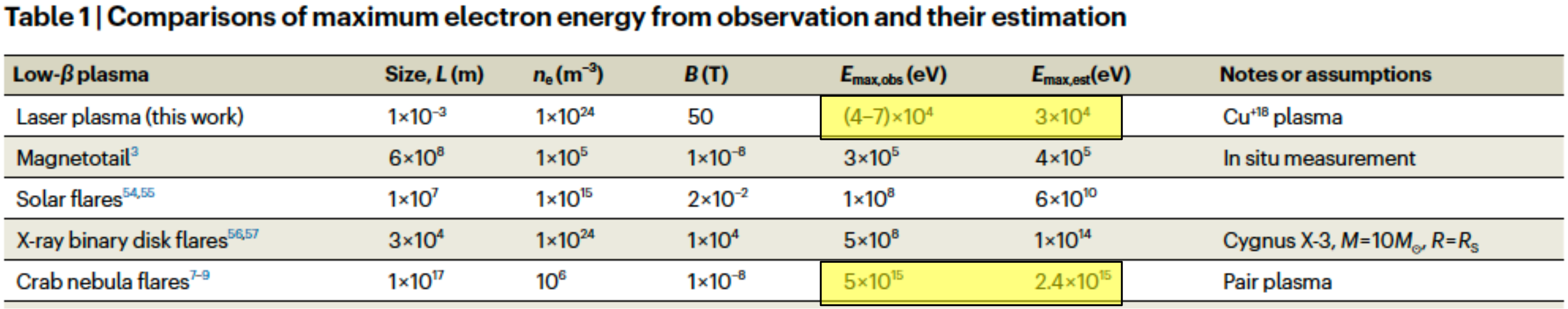
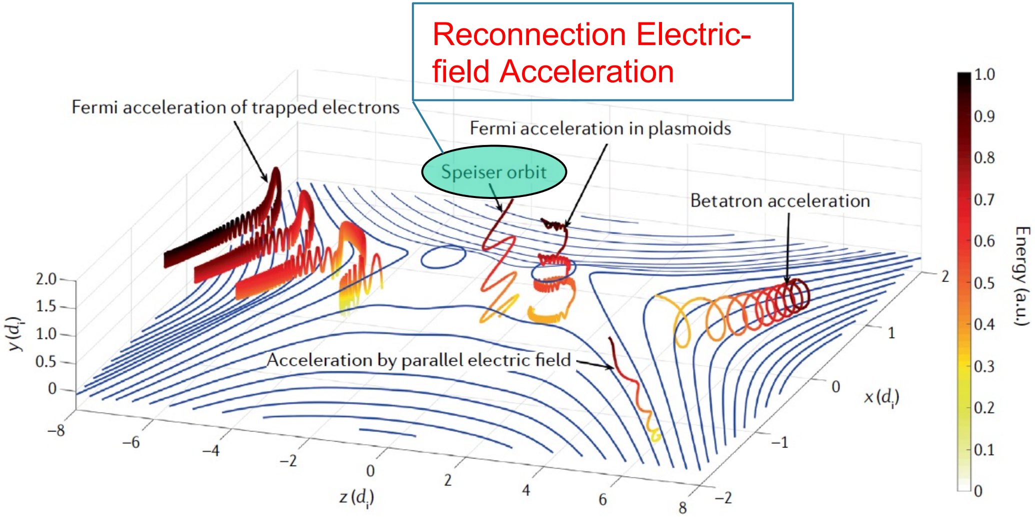
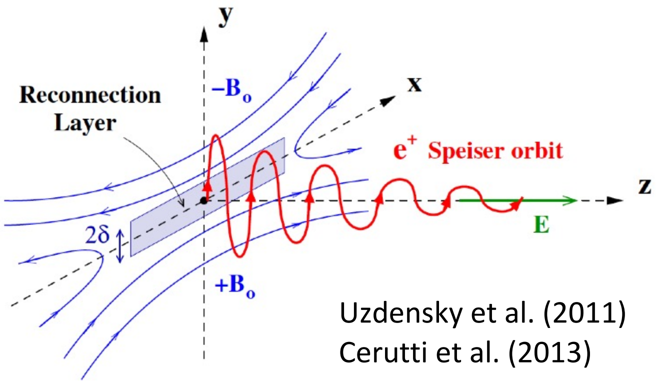


Table 1 | Comparisons of maximum electron energy from observation and their estimation

Low-β plasma	Size, L (m)	n_e (m^{-3})	B (T)	$E_{max,obs}$ (eV)	$E_{max,est}$ (eV)	Notes or assumptions
Laser plasma (this work)	1×10^{-3}	1×10^{24}	50	$(4–7)\times10^{4}$	3×10^{4}	Cu^{+18} plasma
Magnetotail[3]	6×10^{8}	1×10^{5}	1×10^{-8}	3×10^{5}	4×10^{5}	In situ measurement
Solar flares[54,55]	1×10^{7}	1×10^{15}	2×10^{-2}	1×10^{8}	6×10^{10}	
X-ray binary disk flares[56,57]	3×10^{4}	1×10^{24}	1×10^{4}	5×10^{8}	1×10^{14}	Cygnus X-3, $M=10M_{\odot}$, $R=R_S$
Crab nebula flares[7–9]	1×10^{17}	10^{6}	1×10^{-8}	5×10^{15}	2.4×10^{15}	Pair plasma



Reconnection Electric-field Acceleration



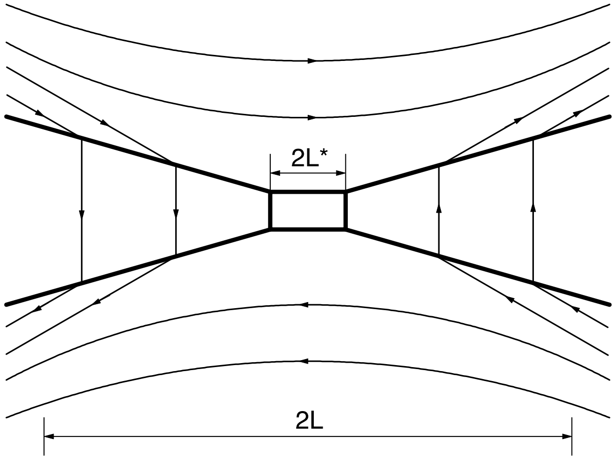
Uzdensky et al. (2011)
Cerutti et al. (2013)

Experiment 2:

Ion and Electron Acoustic Waves during Anti-parallel Reconnection at Low Upstream β

S. Zhang, A. Chien, L. Gao, H. Ji, E. Blackman, R. Follett, D. Froula, J. Katz, C. Li, A. Birkel, R. Petrasso, J. Moody, H. Chen, *Nat. Phys.* **19**, 909-916 (2023).

Ion Acoustic-type Waves Considered Important for Localized Anomalous Resistivity for Petschek Model of Fast Reconnection in Large Plasmas



Petschek model (1964)

- However, the current driven IAW rarely observed due to ion Landau damping when $T_i \sim ZT_e$
  - Observed recently by MMS when cold ions exist (Ergun 2016, Steinvall 2021)
- Other plasma waves often observed or proposed, but it is unclear if they are important:
  - Kinetic Alfven waves (Shay+ 2011…)
  - Lower-Hybrid Drift Waves (LHDW, Cater+ 2002, Ji+ 2004, Yoo+ 2020, Graham+ 2022, Yoo+ 2024…)
  - Whistler waves (Goldman+ 2014…)
  - Buneman instability (Che+ 2009…)

Micro-MRX provides unique opportunity to study IAW due to $T_i < ZT_e$ condition

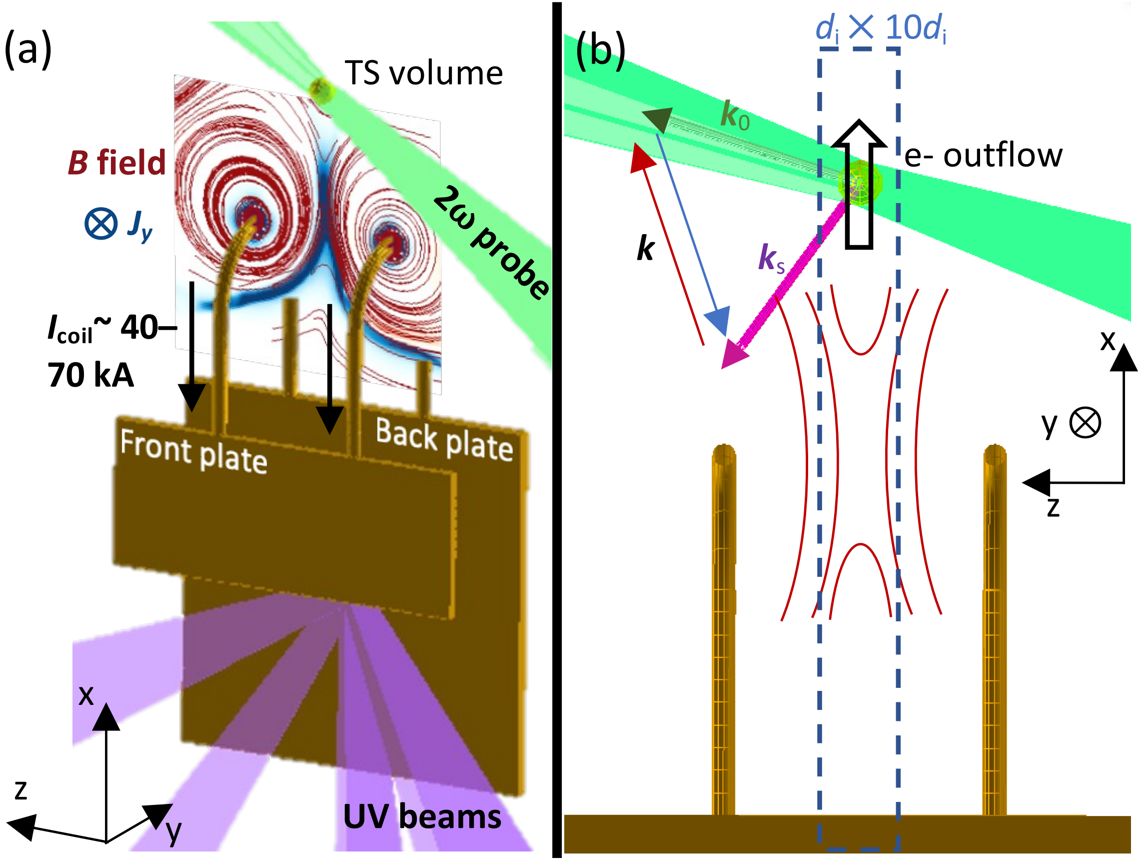
Experimental Setup

Collective Thomson Scattering:

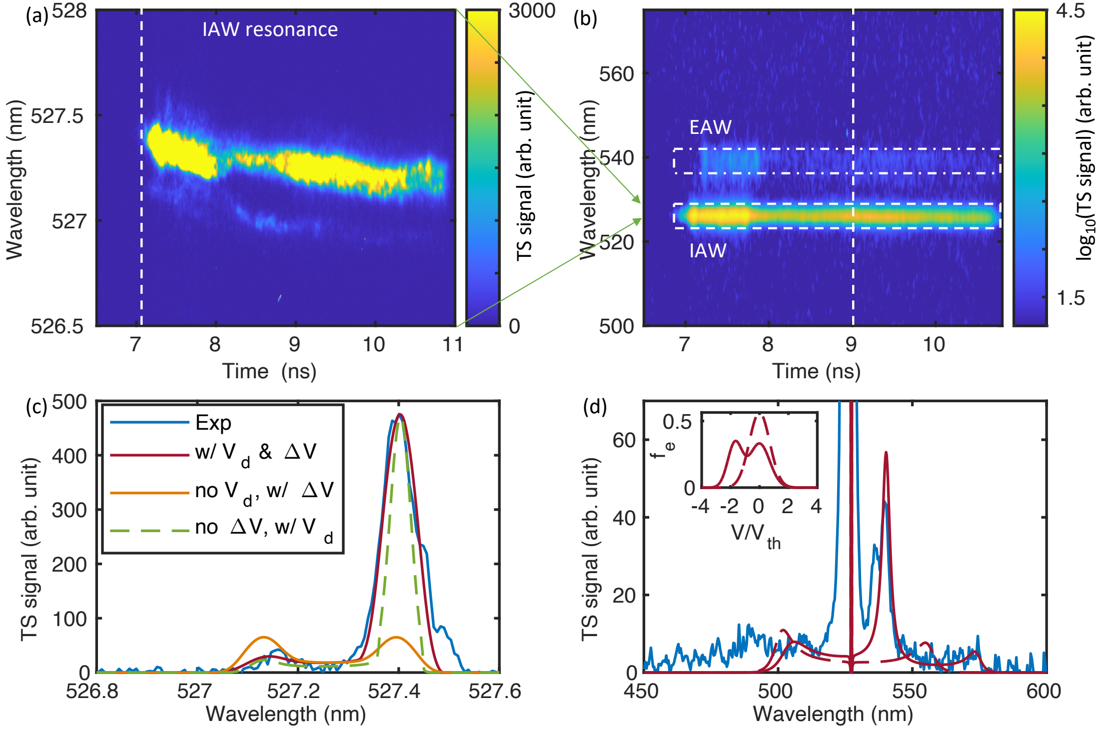
2ω @ 527 nm

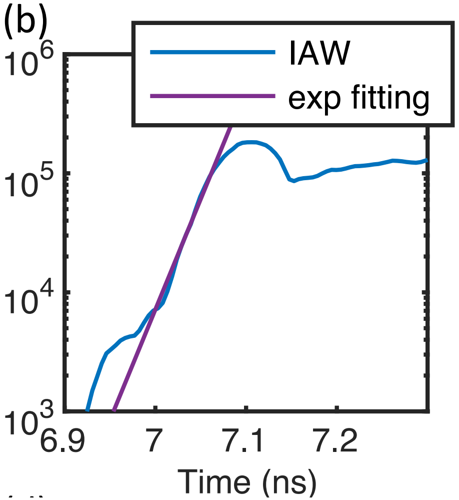
150 J, $60 \times 60 \times 50\ \mu m^3$

f/10 reflective



Direct Measurement of IAW and EAW During Reconnection

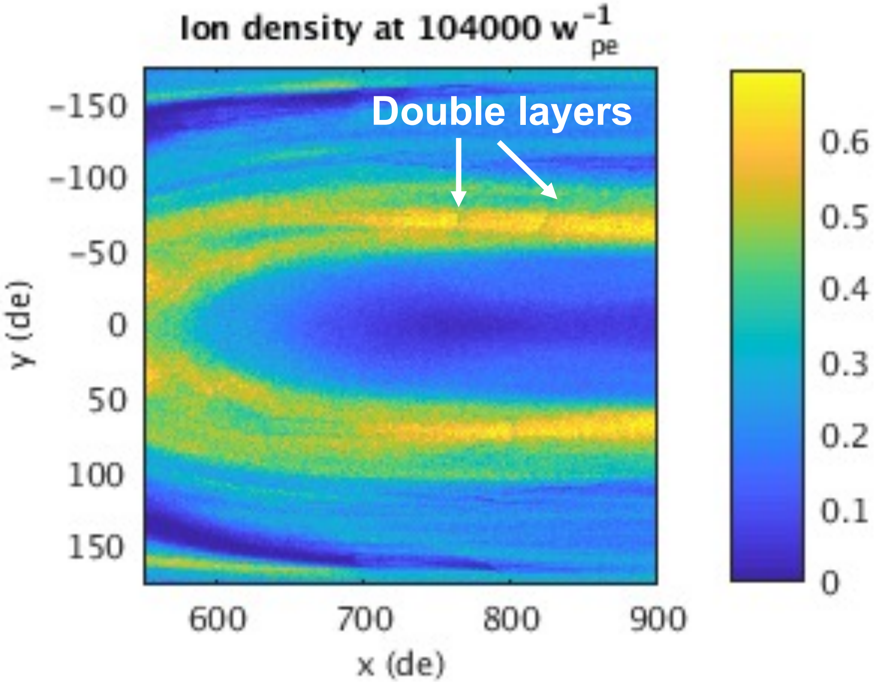


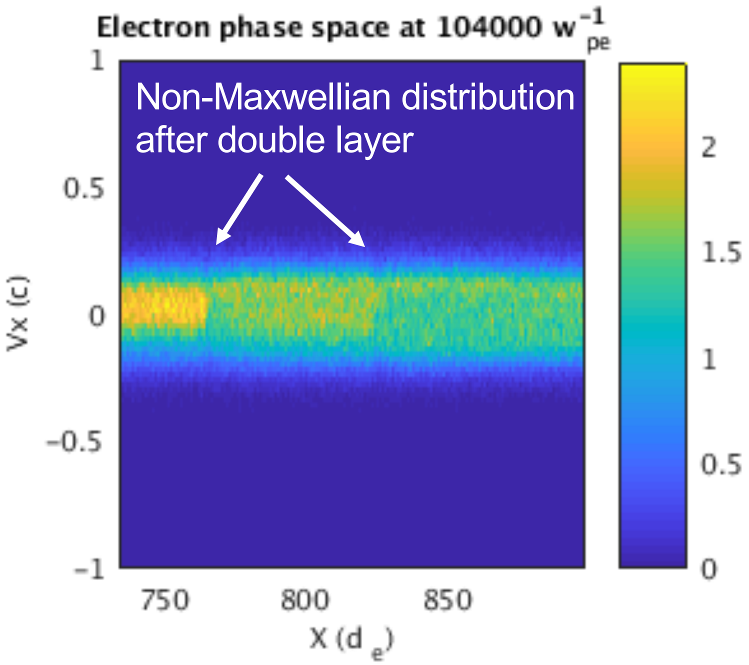


Large drifting electrons relative to ions are needed to reproduce the asymmetric IAW peaks, and two-stream electrons to reproduce the asymmetric EAW peaks

Reconnection with a Cold Background by 2D OSIRIS Code*, reproducing IAW and Double Layers in the Outflow

*Fonseca+, Computational Science – ICCS 2002





- Harris current sheet: balanced magnetic field pressure with thermal pressure
- For IAW to grow: cold background plasma: $T_e=T_i = 1/25\ T_{e,harris}$, $n_e=0.3n_0$
- Effective dissipation of magnetic energy needs to be further studied.

Summary and Future Work

- **The micro-MRX platform based on capacitor coils powered by kJ lasers can magnetically drive reconnection at low upstream β, favorable for studies of**
  - Particle acceleration due to *ex-situ* detection capabilities
    - Angular distribution of electron energy spectra and the resulting energies, supported by VPIC simulations, show that reconnection electric field acceleration is at work
  - Ion acoustic waves due to high Z ions
    - Burst IAW and EAW have been observed in the reconnection outflow and reproduced in OSIRIS PIC simulations demonstrating the importance of electrostatic double layers
- **Current and future research focuses on particle acceleration by different mechanisms (such as Fermi acceleration) and in different regimes, and IAW/EAW in the out-of-reconnection plane direction for possible anomalous resistivity.**

Chien et al., *Nature Physics* **19**, 254 (2023).
Zhang et al., *Nature Physics* **19**, 909 (2023).
Ji et al., submitted to *Phys. Plasmas* (2024).