UCLA

Laboratory study of lunar magnetic reconnection with laser-driven mini-magnetospheres

L. Rovige[1], F. D. Cruz[2], R. S. Dorst[1], J. J. Pilgram[1], T. Van Hoomissen[1] , C. G. Constantin[1], S. Vincena[1], F. Cruz[2], L. O. Silva[2], C. Niemann[1], D. B. Schaeffer[1]

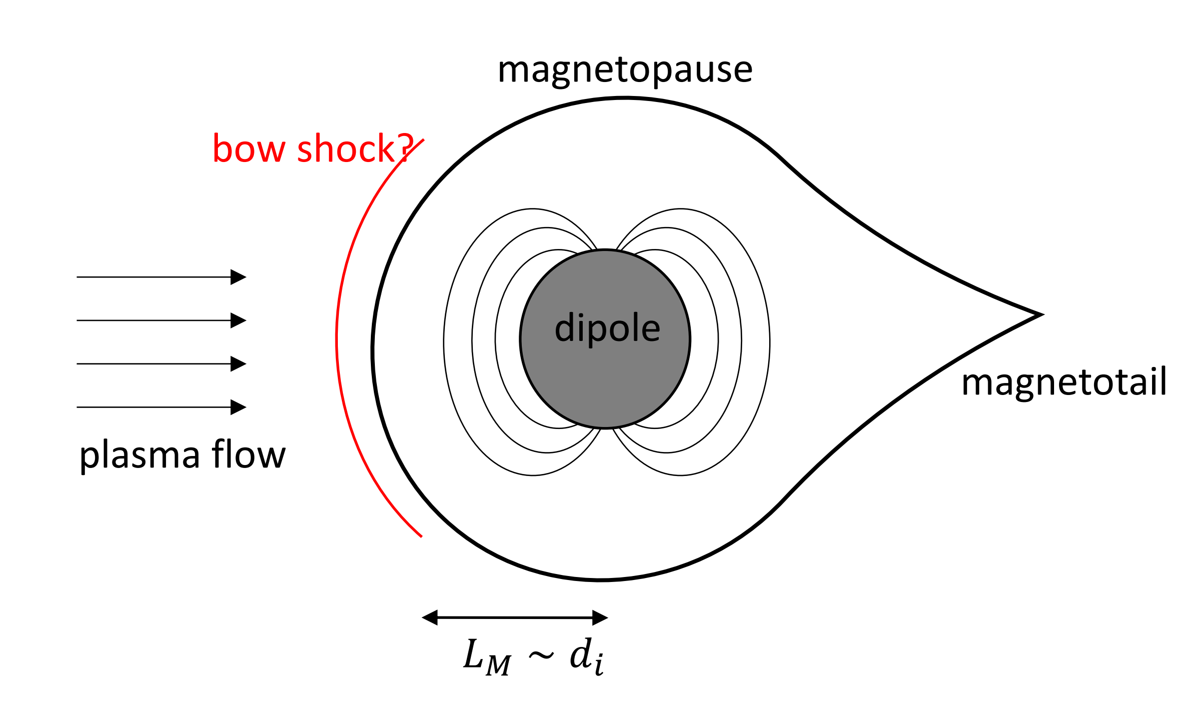
[1] University of California - Los Angeles
[2] Instituto Superior Técnico, Universidade de Lisboa

IPELS - 16

BaPSF NSF U.S. DEPARTMENT OF ENERGY | Office of Science LaserNetUS

Mini-magnetospheres form on ion scales

Mini-Magnetospheres



- Defined for standoff distances on the order of the ion inertial length

$$D = \frac{L_M}{d_i} \approx 1$$

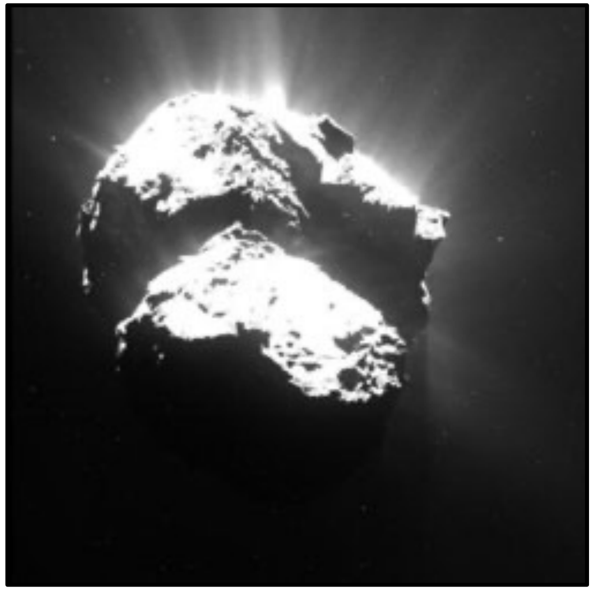
- Sensitive to kinetic effects and exhibit a range of behaviors as a function of D
- Can be used to study kinetic scale physics and bridge local and global simulations

Mini-magnetospheres well-suited for study with laboratory experiments

Mini-magnetospheres observed in many systems

Comets/Asteroids

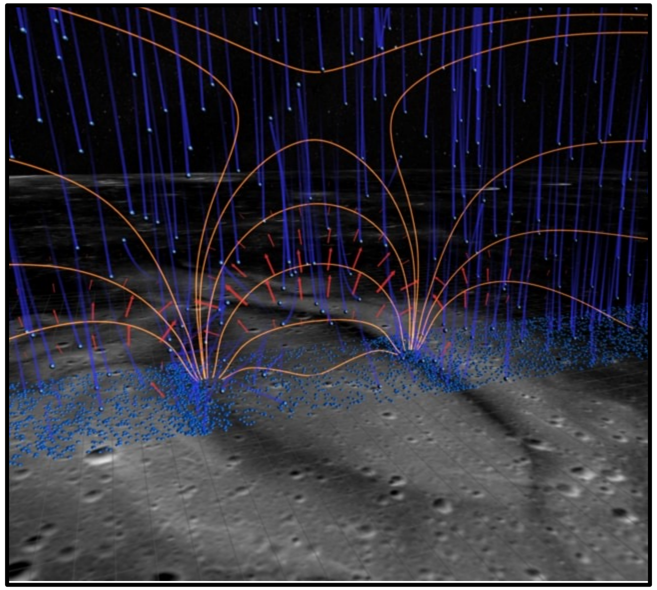
[Image Credit: ESA]



[Nilsson+ Science 2015]

Lunar Regions

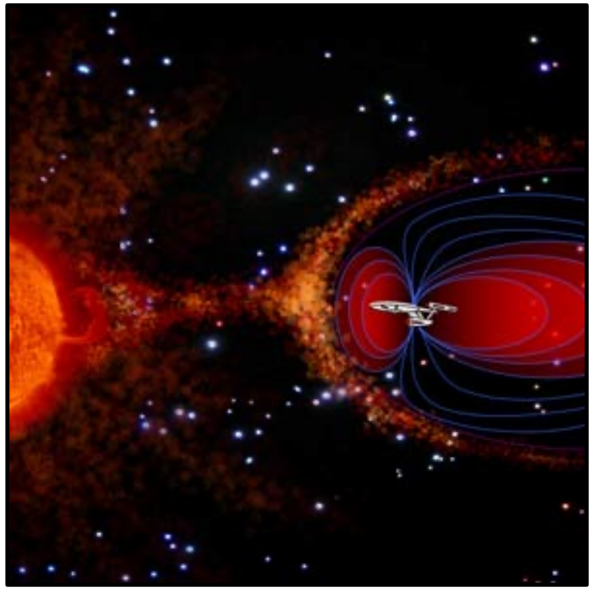
[Image Credit: NASA]



[Bamford+ PRL 2012]

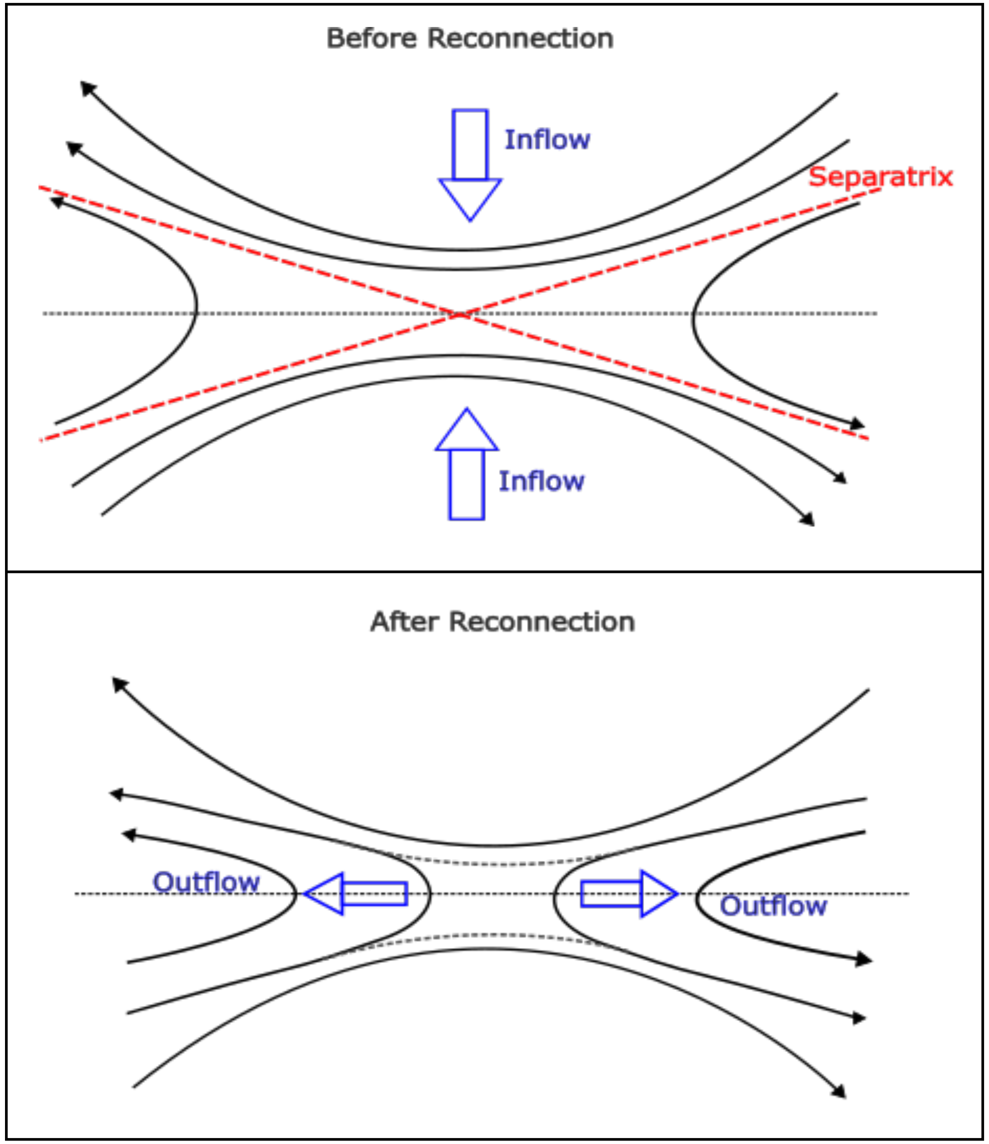
Spacecraft Propulsion/Protection

[Image Credit: RAL Space]



[Moritaka+ PoP 2012]

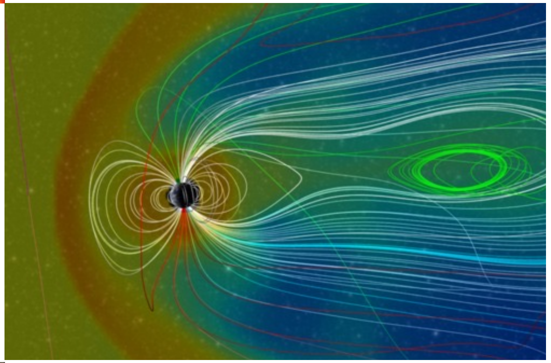
Magnetic reconnection reorganizes the field topology



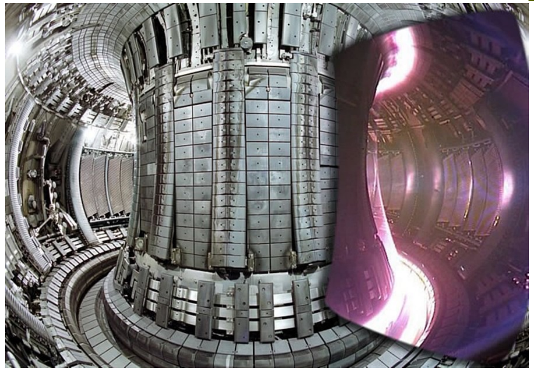
Solar flares

[*Image Credit: NASA*]

Planetary magnetospheres



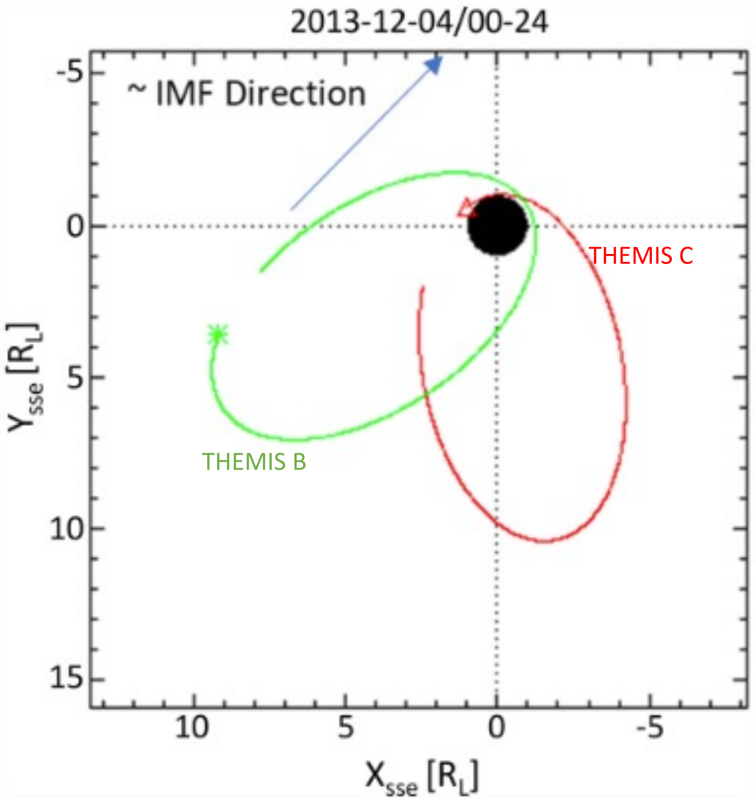
[*Image Credit: NASA*]



Laboratory plasmas, Tokamaks

[*Image Credit: CCFE, JET*]

Magnetic reconnection on the moon?

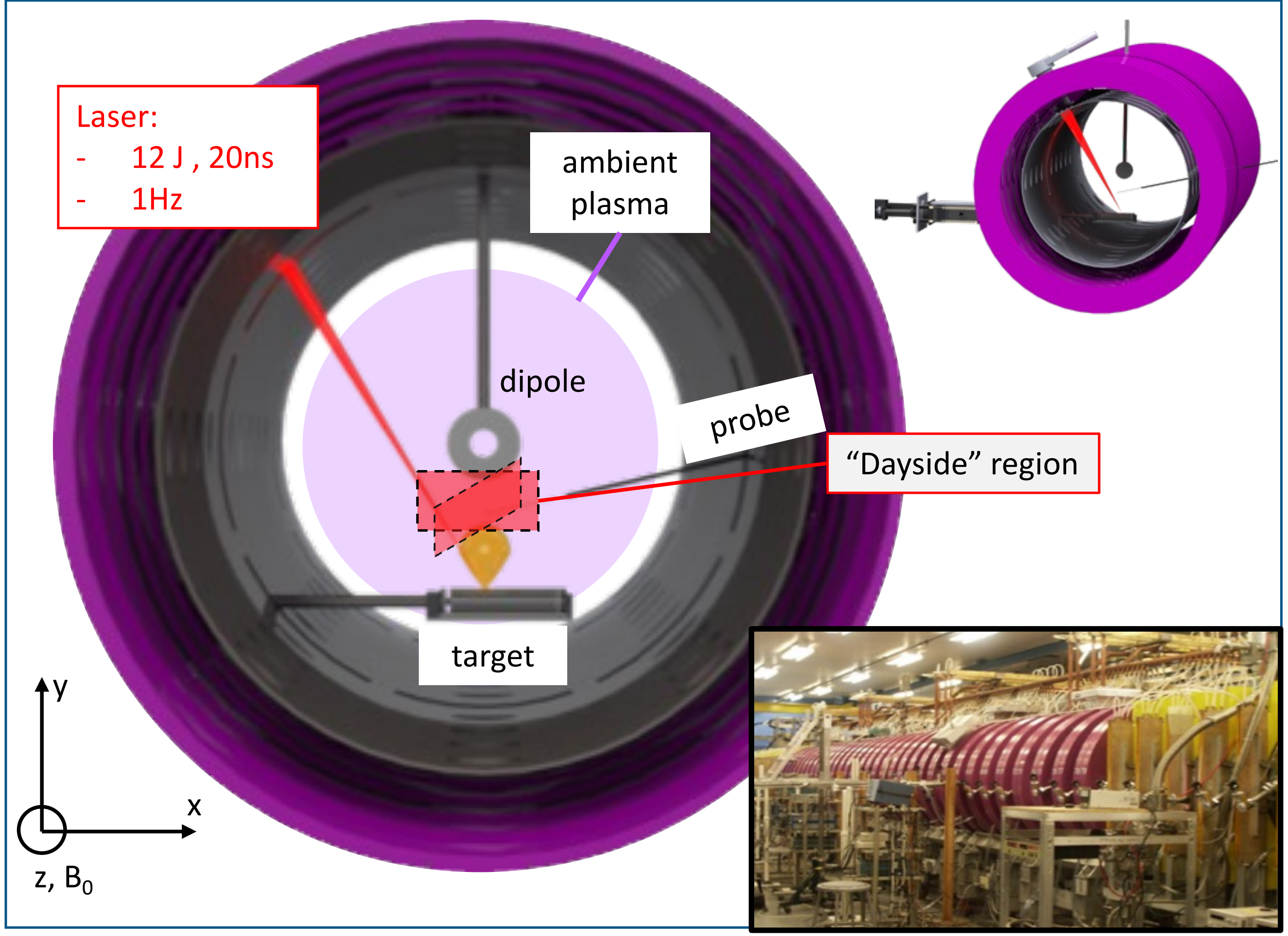


[Sawyer et al. , GRL, 50, e2023GL104733 (2023)]

- Recent evidence of magnetic reconnection on the moon *[Sawyer et al. GRL, 50 (2023)] from THEMIS/ARTEMIS* mission
- Observed Hall electric field and solar wind electrons on closed magnetic field lines
- Low altitude crossings are extremely rare, lab experiments can help understand the nature of this reconnection

“Dayside” experimental setup on the LAPD

LAPD Cross Section

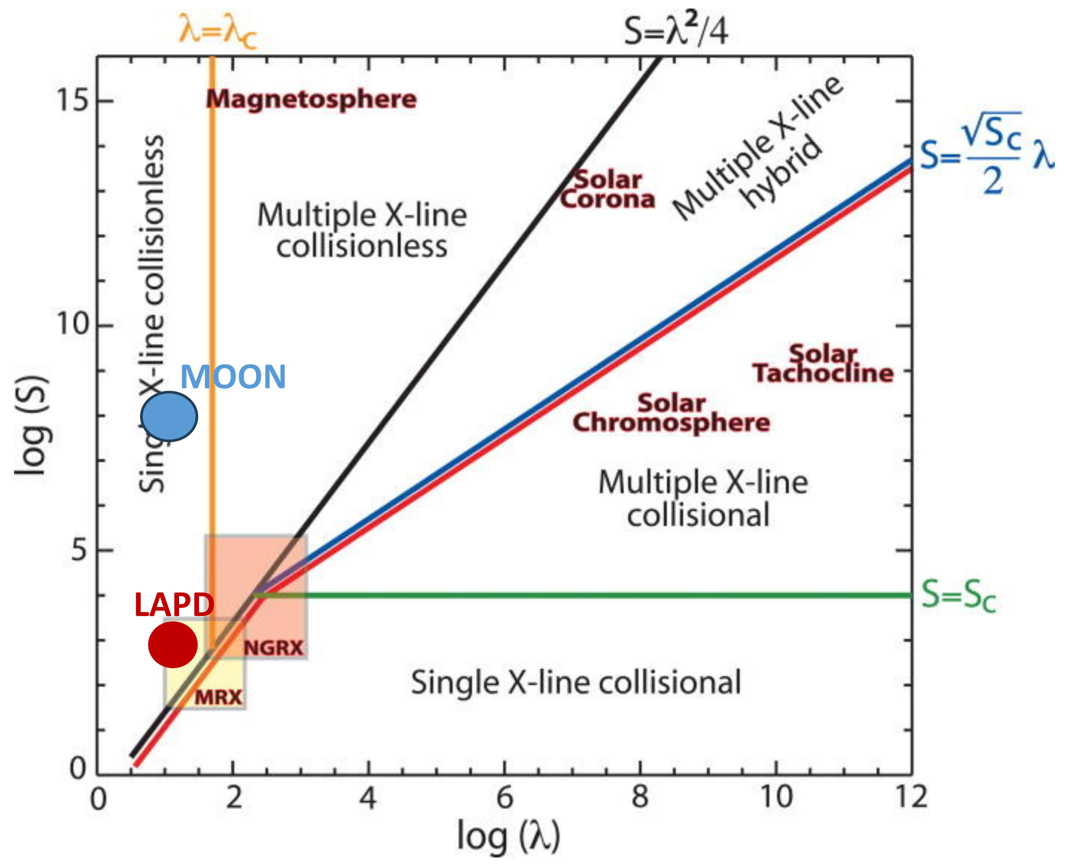


Typical Parameters

Background	H^{+1}
Ambient density n_0	1e13 cm^{-3}
Background field B_0	300 G
Flow speed v_0	150 km/s
Background ele. temperature T_e	~5 eV
Background ion temperature T_i	~1 eV
Electron inertial length d_e	0.2 cm
Ion inertial length d_i	7.2 cm
Ion gyroperiod ω_{ci}^{-1}	348 ns
Ion gyroradius $\rho_i = v_0/\omega_{ci}$	5.2 cm
Magnetic moment M	425 Am^2
Standoff distance L_M	9 cm
Hall parameter $D = L_M/d_i$	1.25

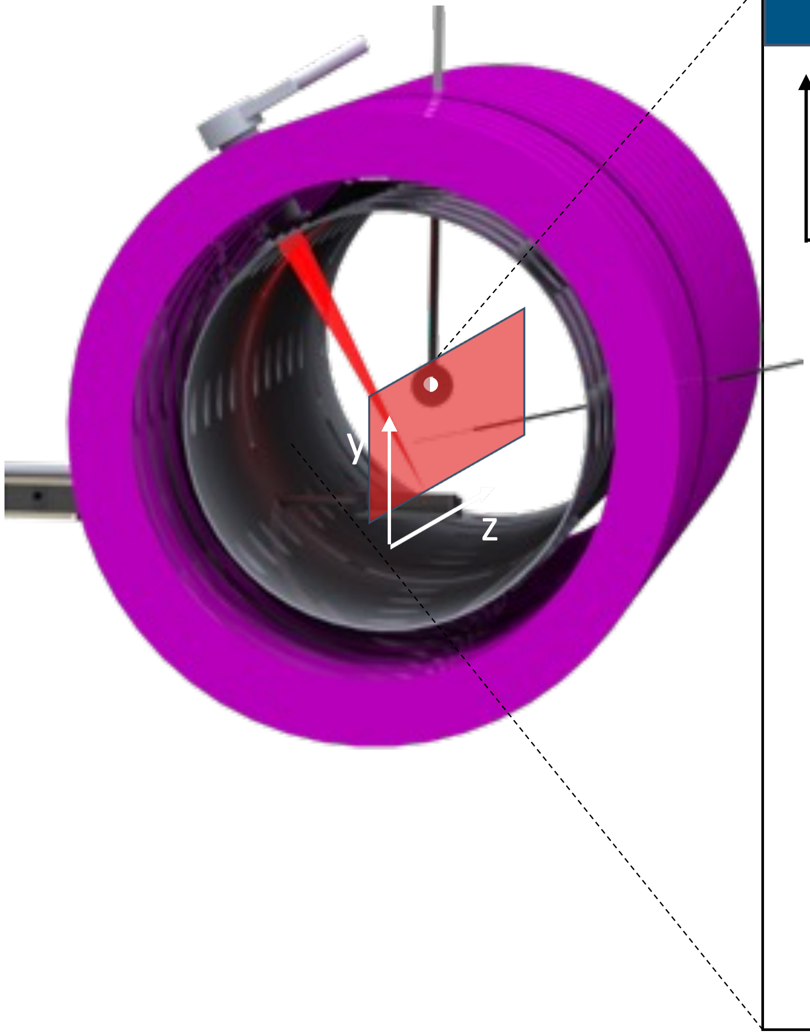
Comparison Moon - LAPD

Parameter	Lunar minimag / Solar wind	LAPD experiment
$D = L_M / d_i$	0.5 – 5 (0.7 in [Sawyer et al])	1.25
$G = L_M / \rho_i$	0.1	1.7
M_A	4-8	0.75
L_M/λ_{ii}	<<1	0.02
L_M/λ_{ee}	<<1	2
S (Lundquist)	>>1 (10^8)	550
beta	0.4	0.02

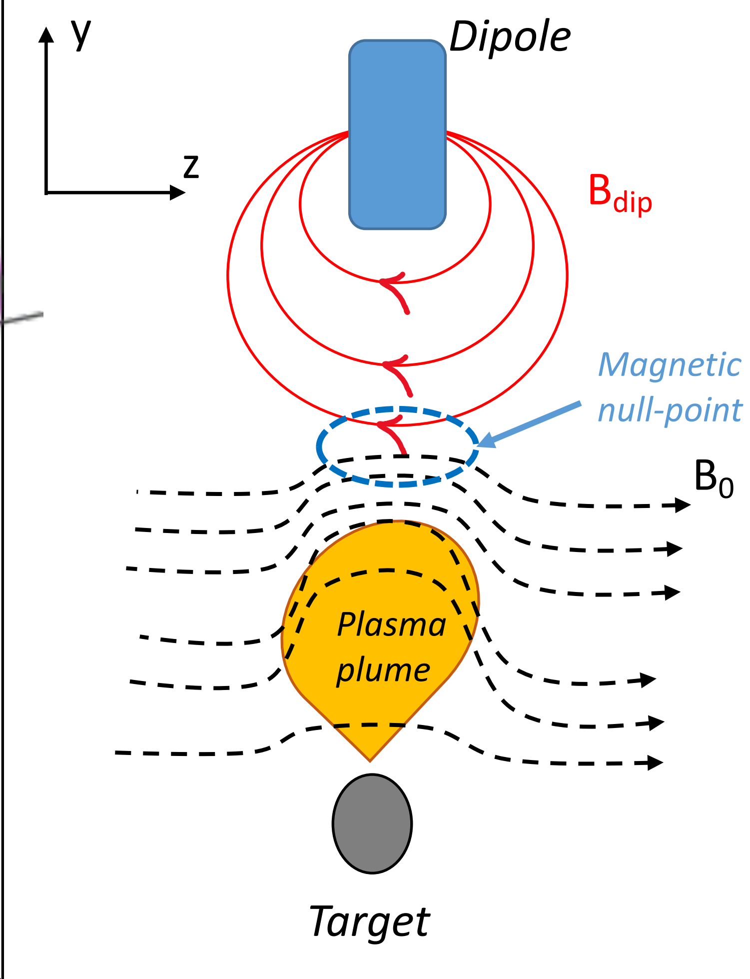


[Phys. Plasmas. 2011;18(11). doi:10.1063/1.3647505]

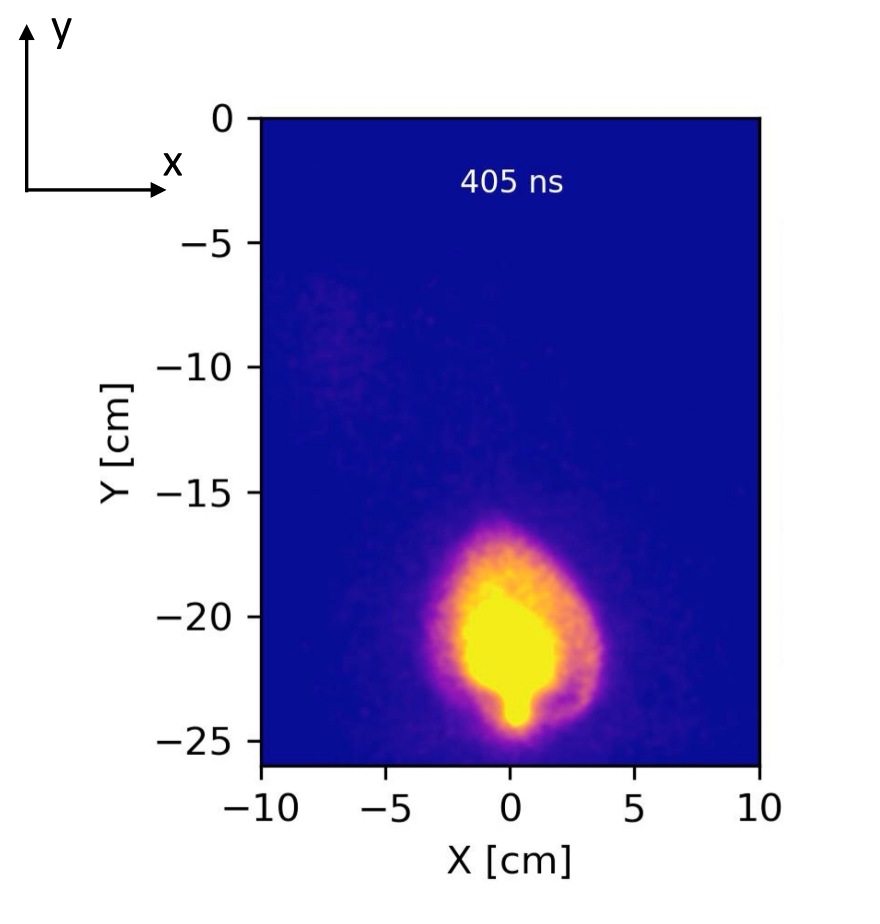
Field geometries to model antiparallel reconnection



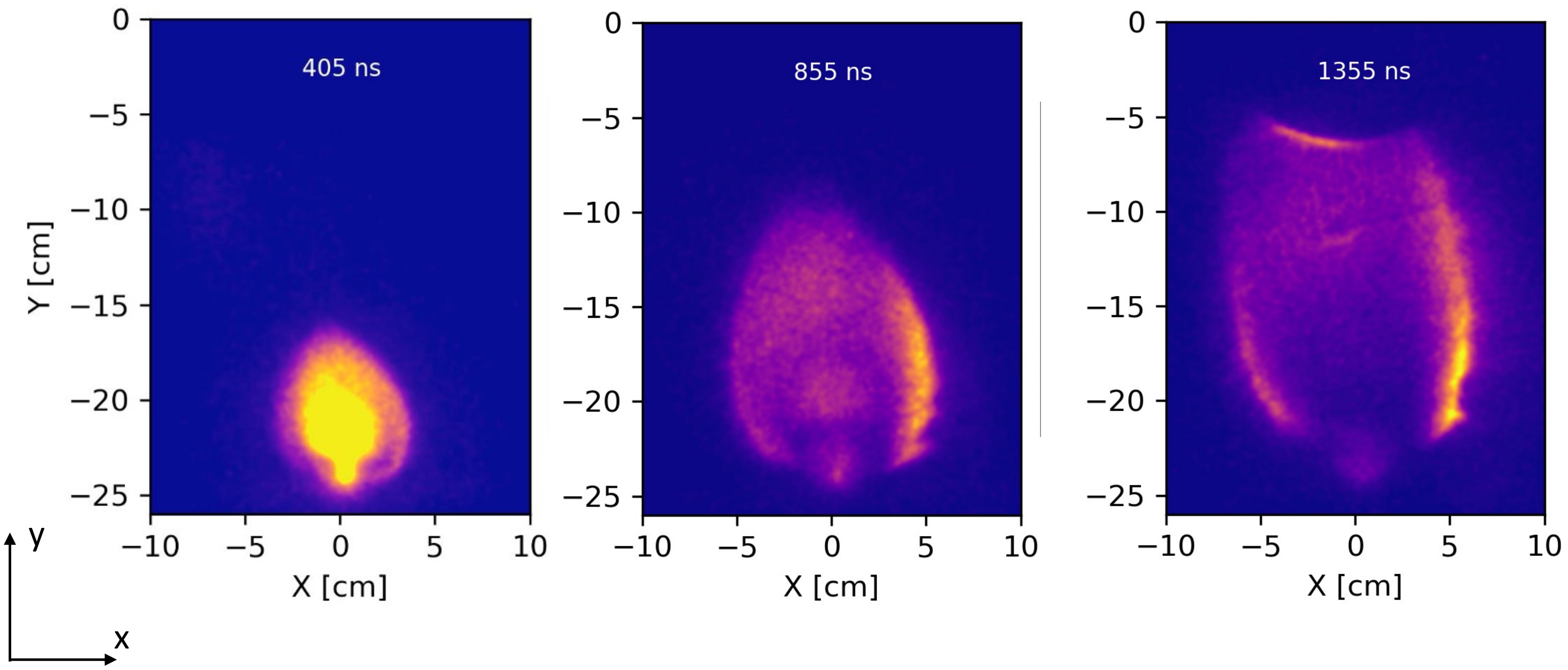
Field geometry: antiparallel



Fast-gate UV imaging of C4+ ions dynamics



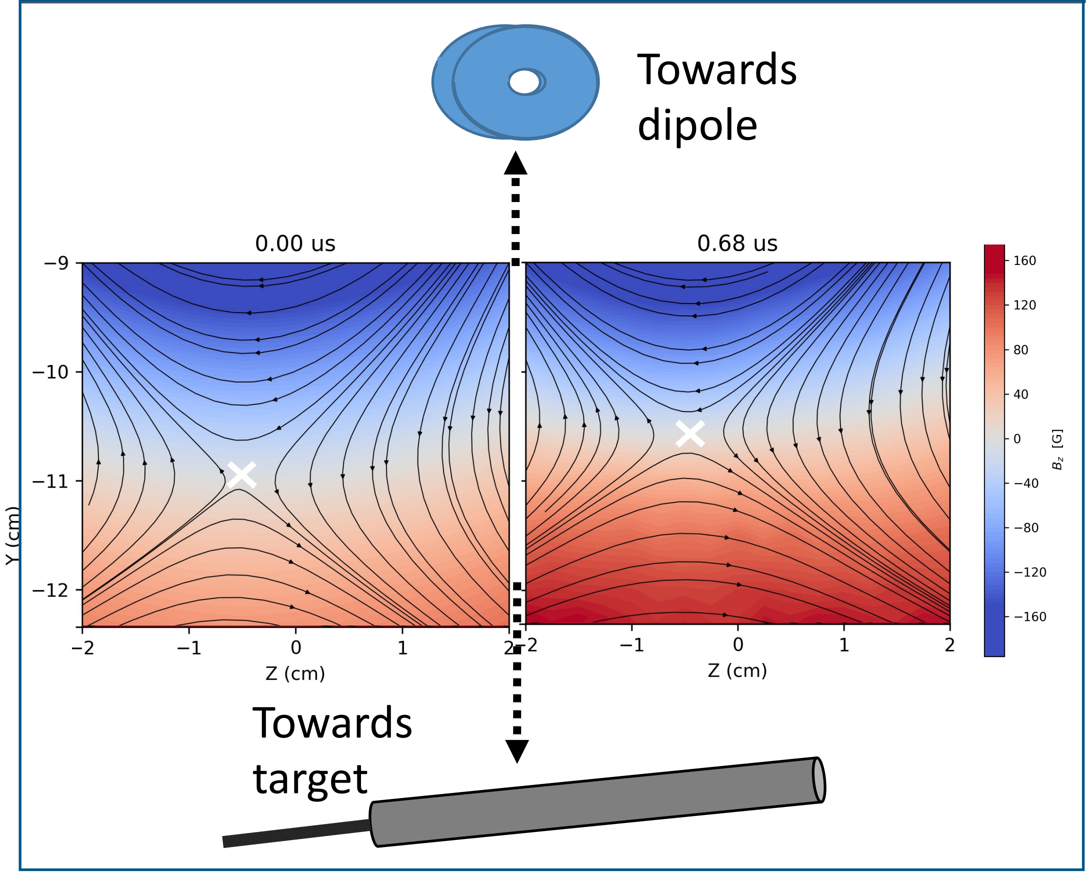
Fast-gate UV imaging of C4+ ions dynamics



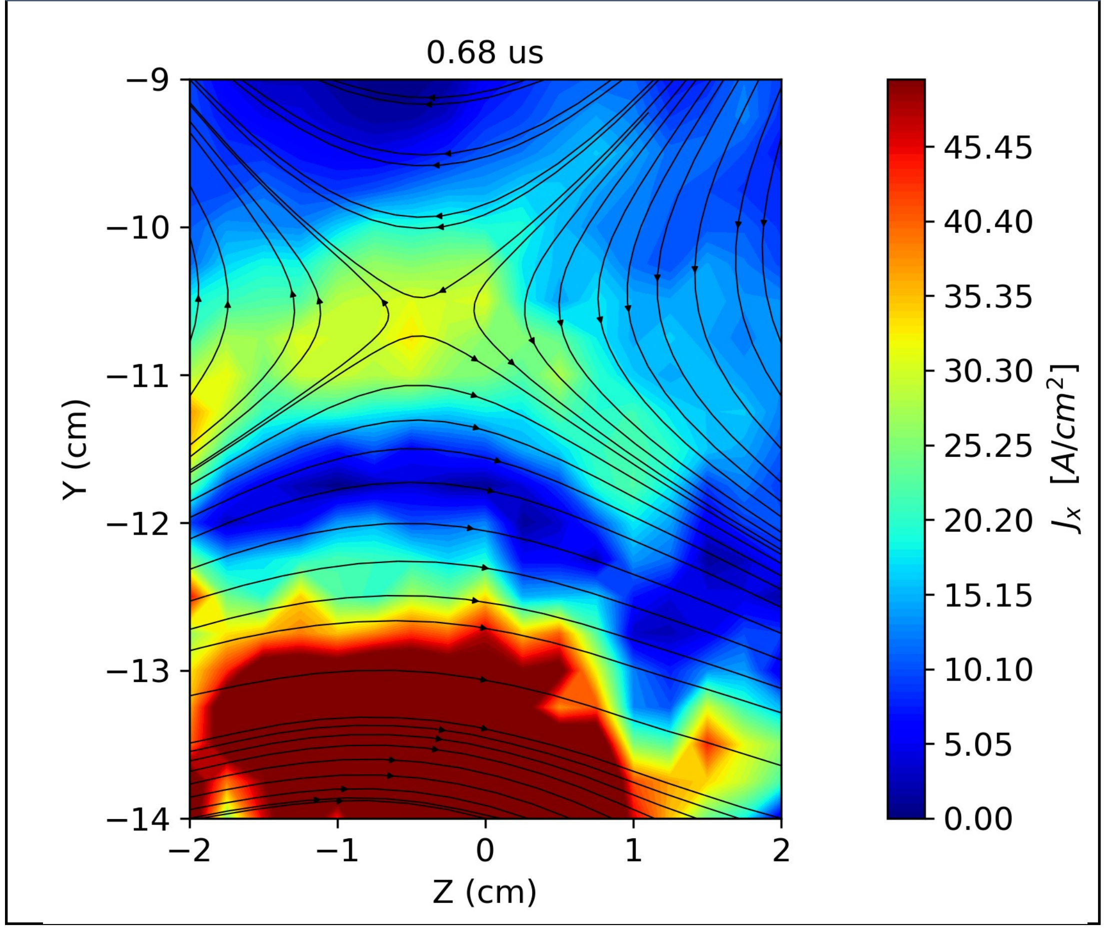
B-field compression pushes the null point and drives reconnection

UCLA

$Bz\ (Y, Z)$



$J_x\ (Y, Z)$ @ x = -0.25cm

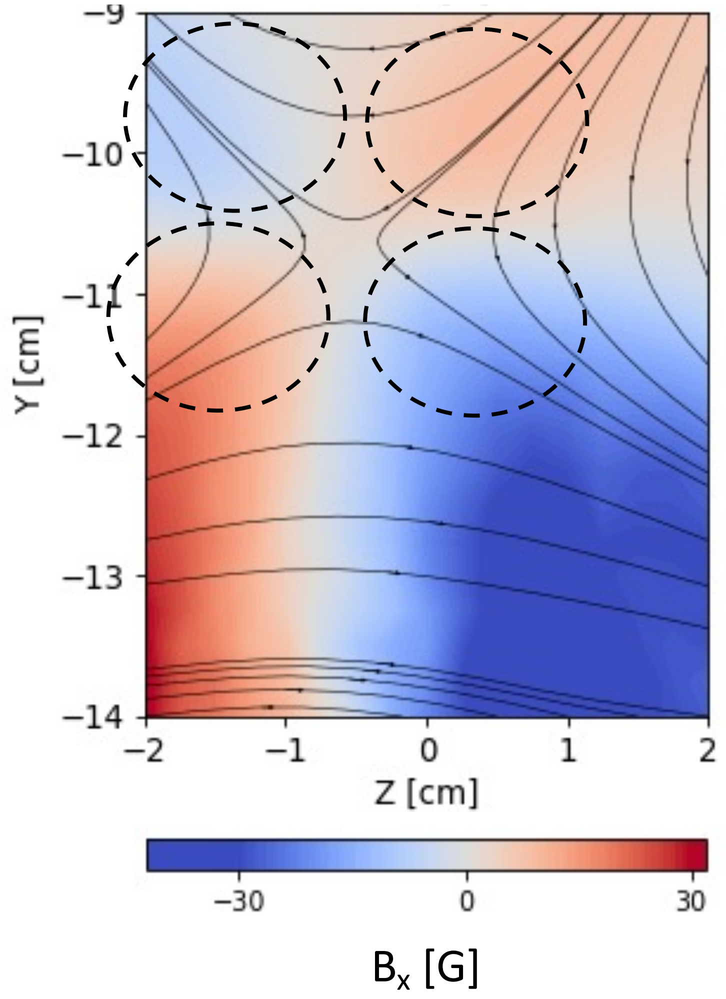


- The field compression pushes the null-point forward: favorable to reconnection

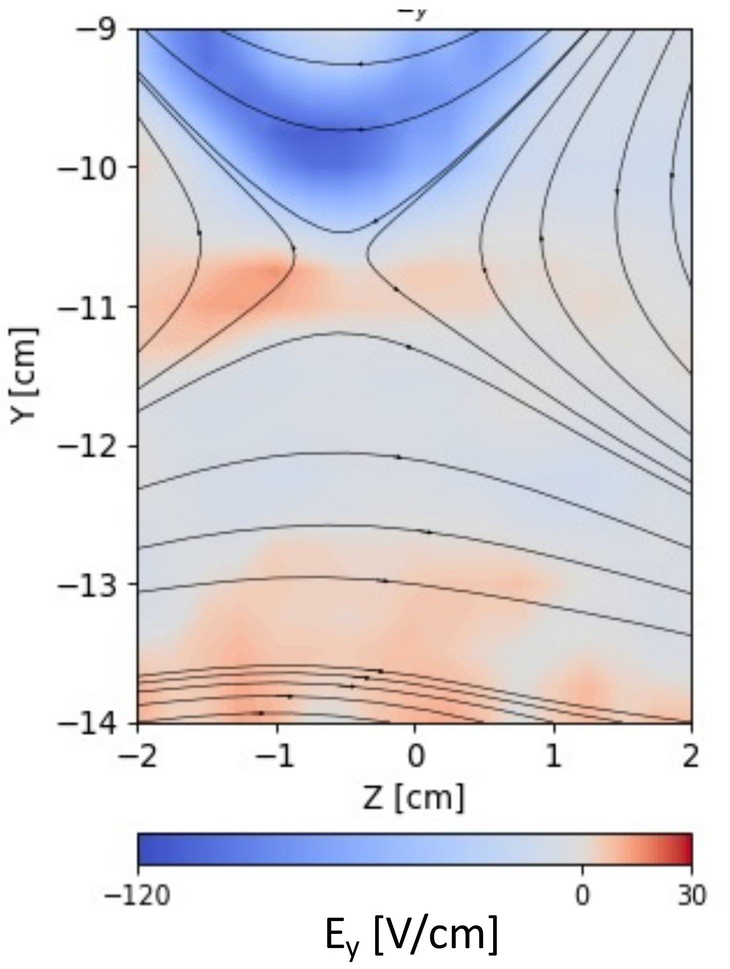
Current calculated from Ampere's Law: $J = (\nabla \times \Delta B)/\mu_0$

Hall fields are generated and indicate kinetic-scale reconnection

$\Delta Bx\ (Y, Z)$



Electrostatic field $Ey = -\nabla\Phi$



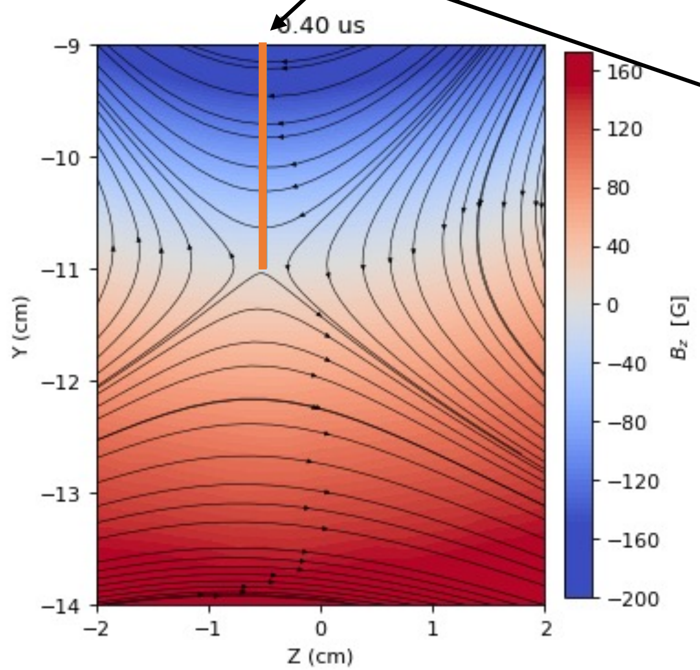
Generation of out of plane *Bx* in a quadrupole shape & dipolar *Ey* :

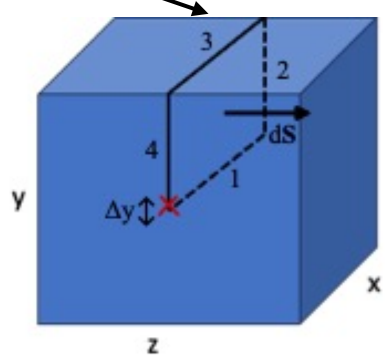
Signature of Hall reconnection

[Rovige et al. *The Astrophysical Journal, 969(2), 124. (2024)]*

We measure a reconnection rate of 0.04

We compute the reconnection rate by calculating the annihilated magnetic flux on a centered section one side of the X-line:



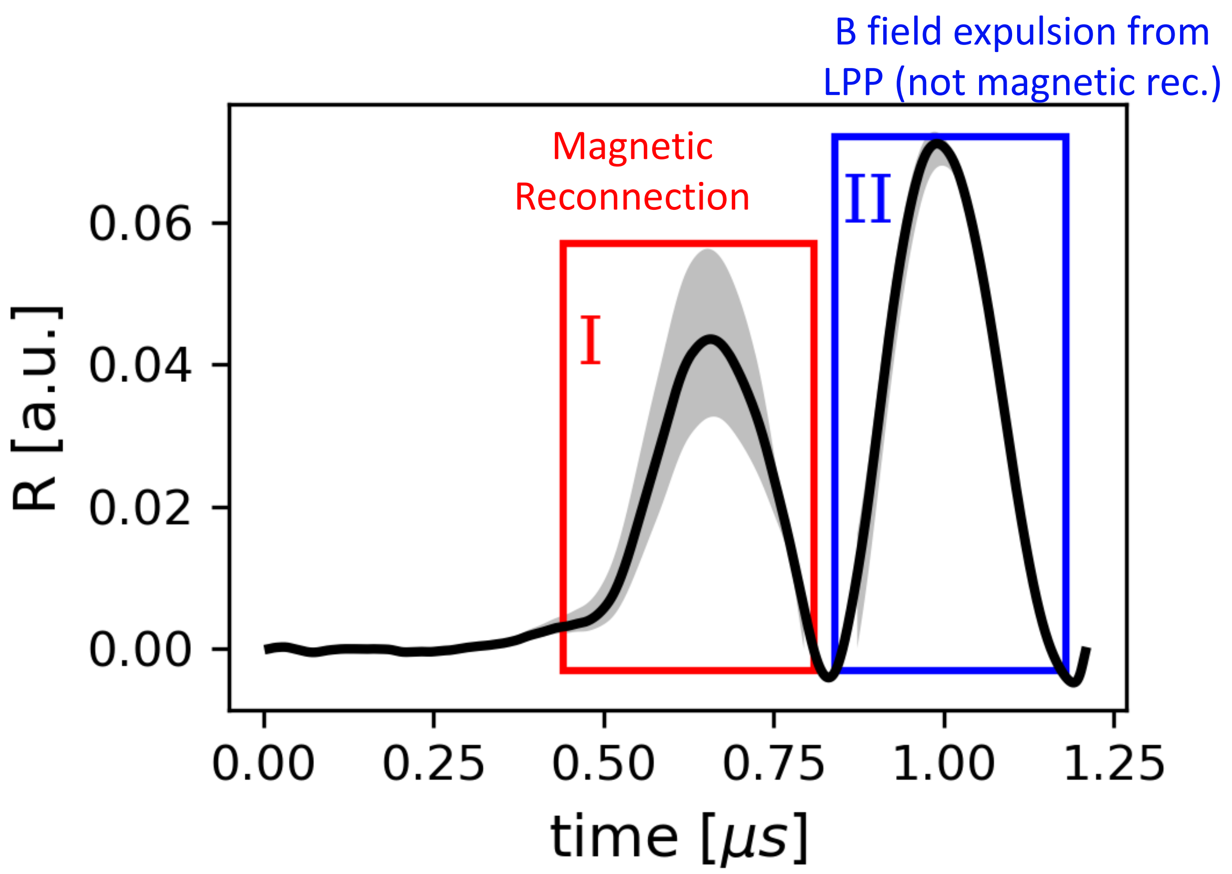


Faraday's Law

$$-\frac{d\phi_B}{dt} = \iint B \,.\, dS = \oint E \,.\, dl$$

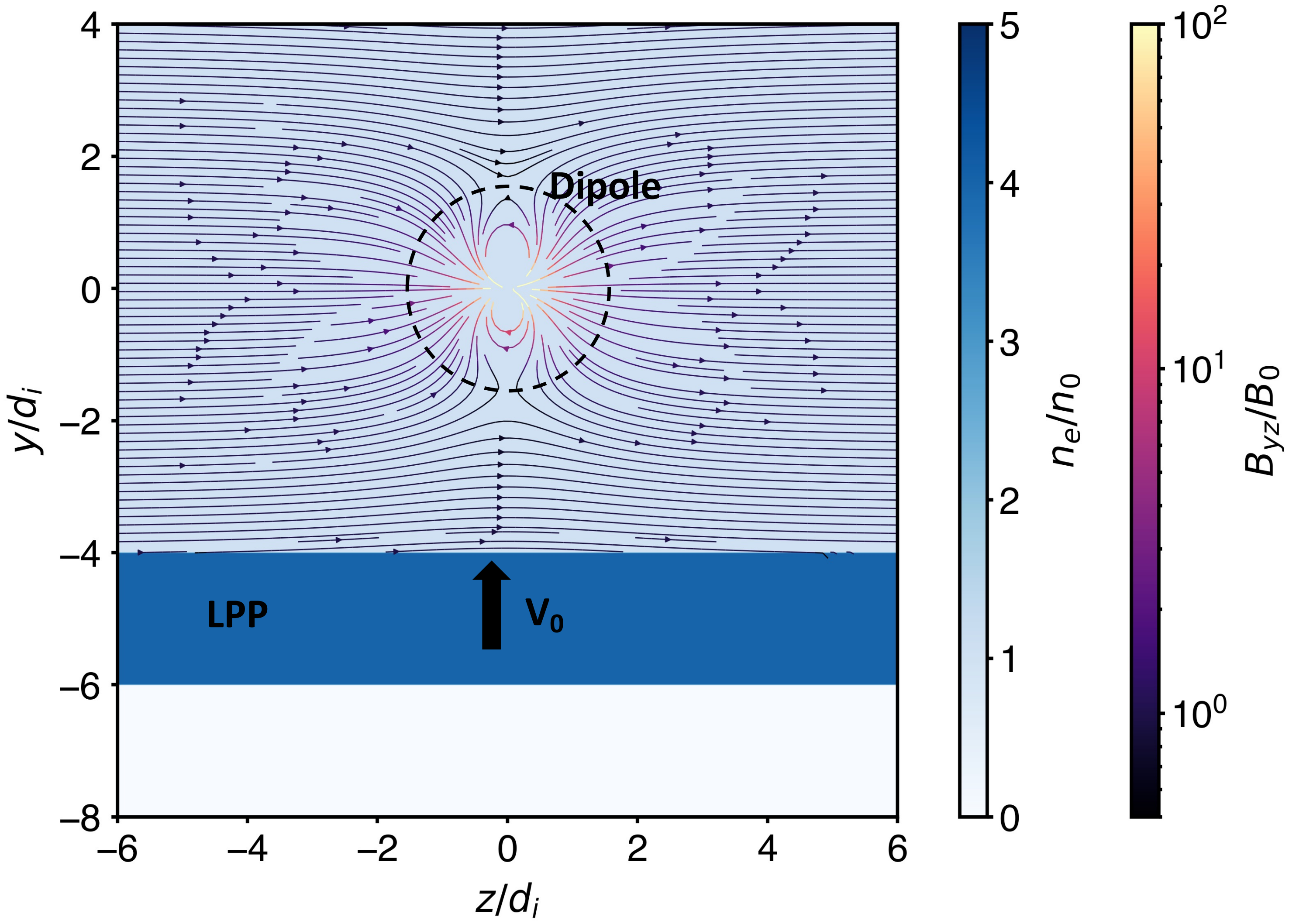
$$E_{rec} \approx -\frac{d\phi_B}{dt}\frac{1}{\Delta x}$$

Normalized reconnection rate : R = E_{rec} / $V_A B_0$



PIC Simulations

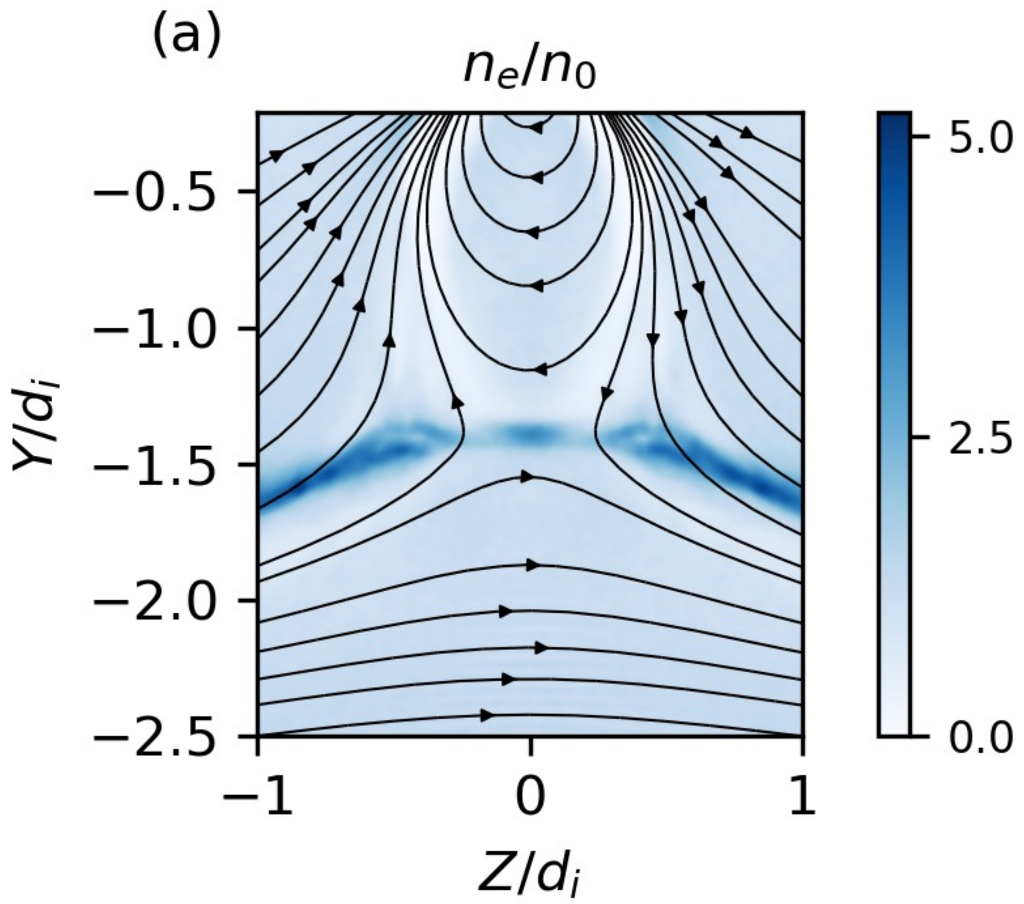
Simulations carried out by Filipe Cruz from *IST, Lisbon*



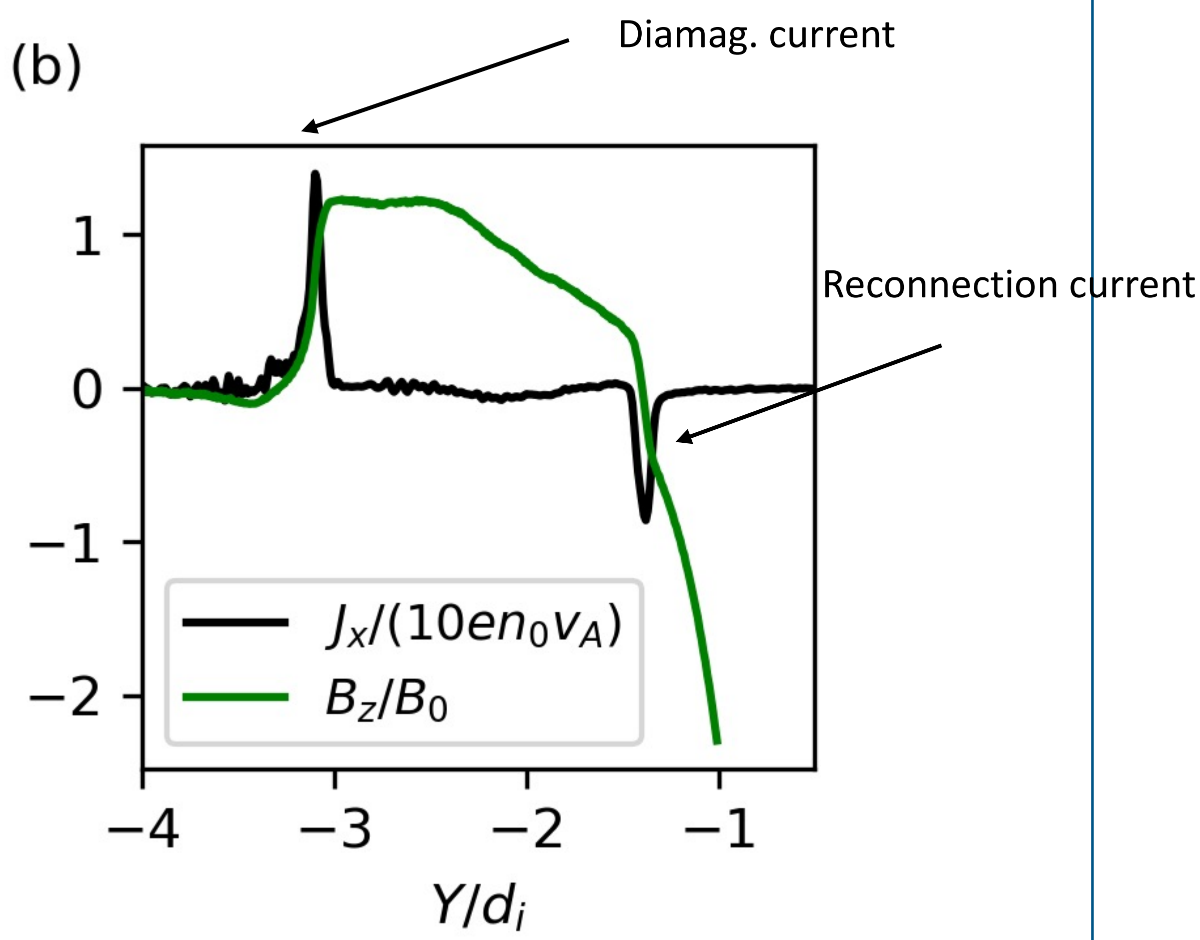
- Dense carbon (Z=+4) driver moving at V_0
- $M_A = 0.5$
- Background hydrogen (Z=+1) plasma immersed in background B field and dipole field
- Mass ratio: $m_i/m_e = 100$
- Standoff distance ~ 1di
- No collisions

PIC Simulations

Electron density and B-field lines



Reconnection current Jx



Evaluating the generalized Ohm's law terms contribution

Red: terms accessible experimentally

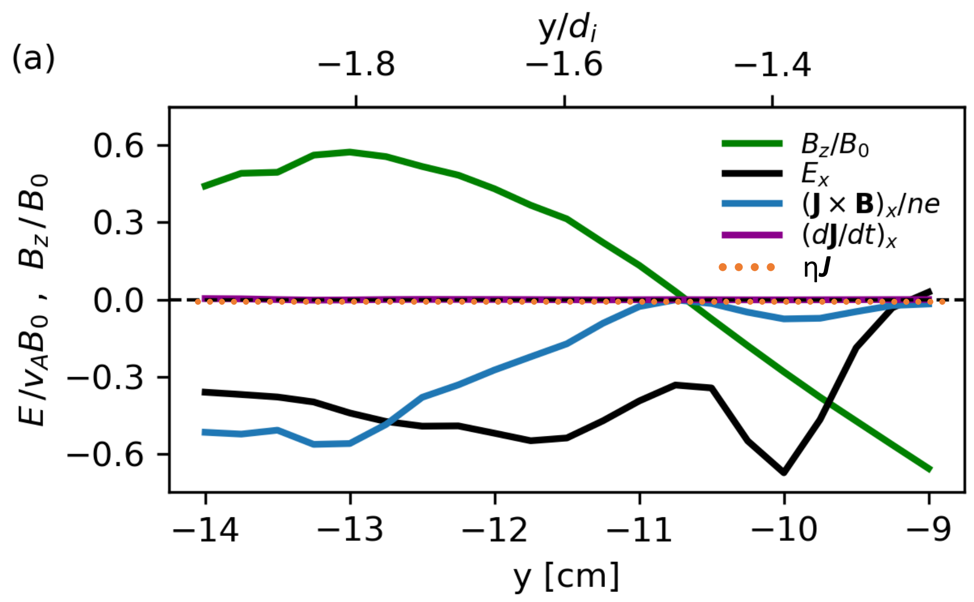
$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{J} + \frac{\boldsymbol{J} \times \boldsymbol{B}}{n_e e} - \frac{\nabla p_e}{n_e e} - \frac{\nabla \cdot \boldsymbol{\Pi_e}}{n_e e} + \frac{m_e}{n_e e^2}\frac{\mathrm{d}\boldsymbol{J}}{\mathrm{dt}}$$

Electric field; resistive term; Hall term; e- pressure (scalar); Anisotropic pressure (tensor); Electron inertia

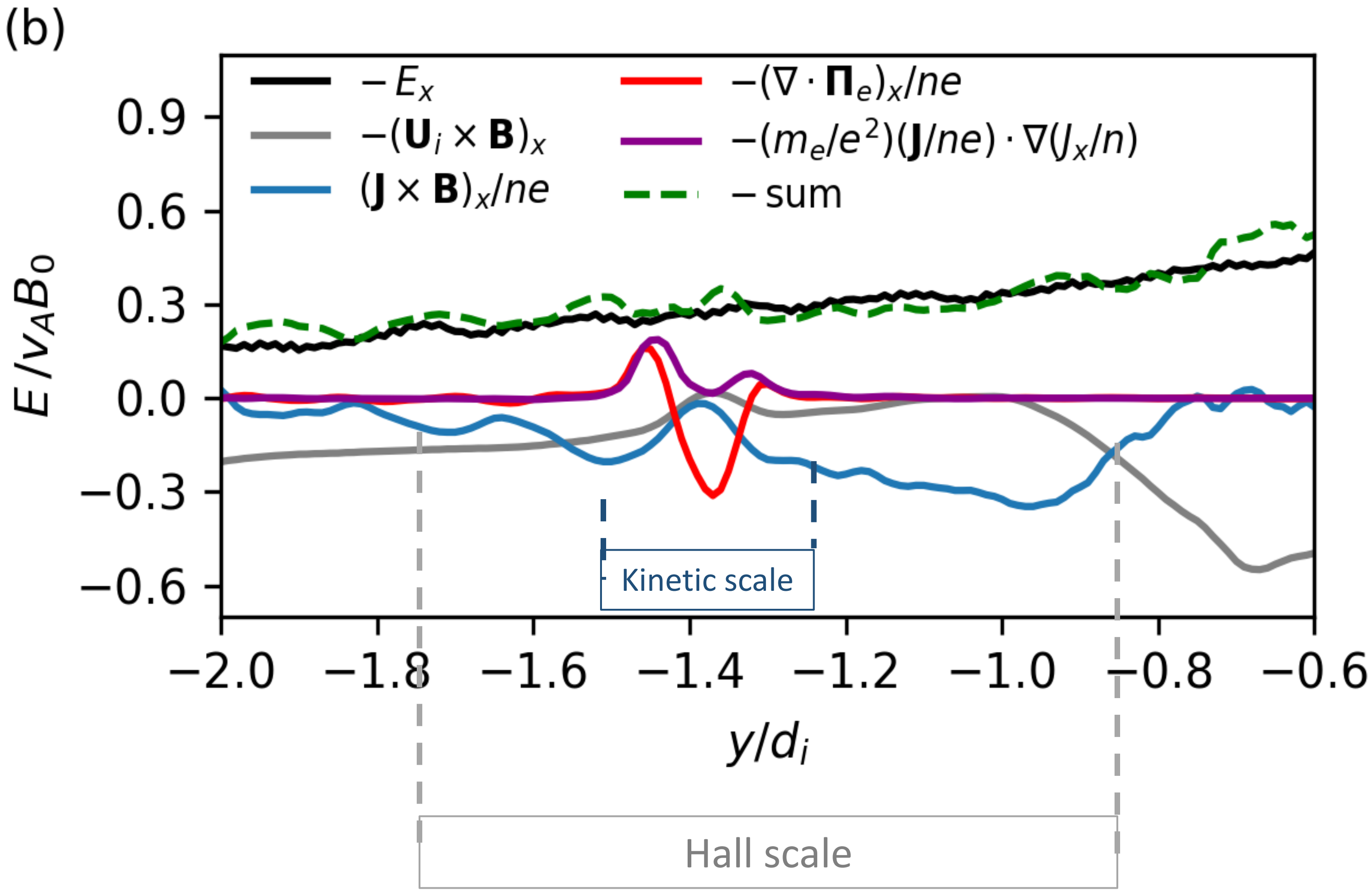
Evaluating the contribution of each terms: determine what phenomena are driving reconnection:

- No resistive contribution (collisionless)
- No e- inertia effect
- Significant Hall term
- What about electron pressure (kinetic effects) ?

Ohm's law terms (experimental)



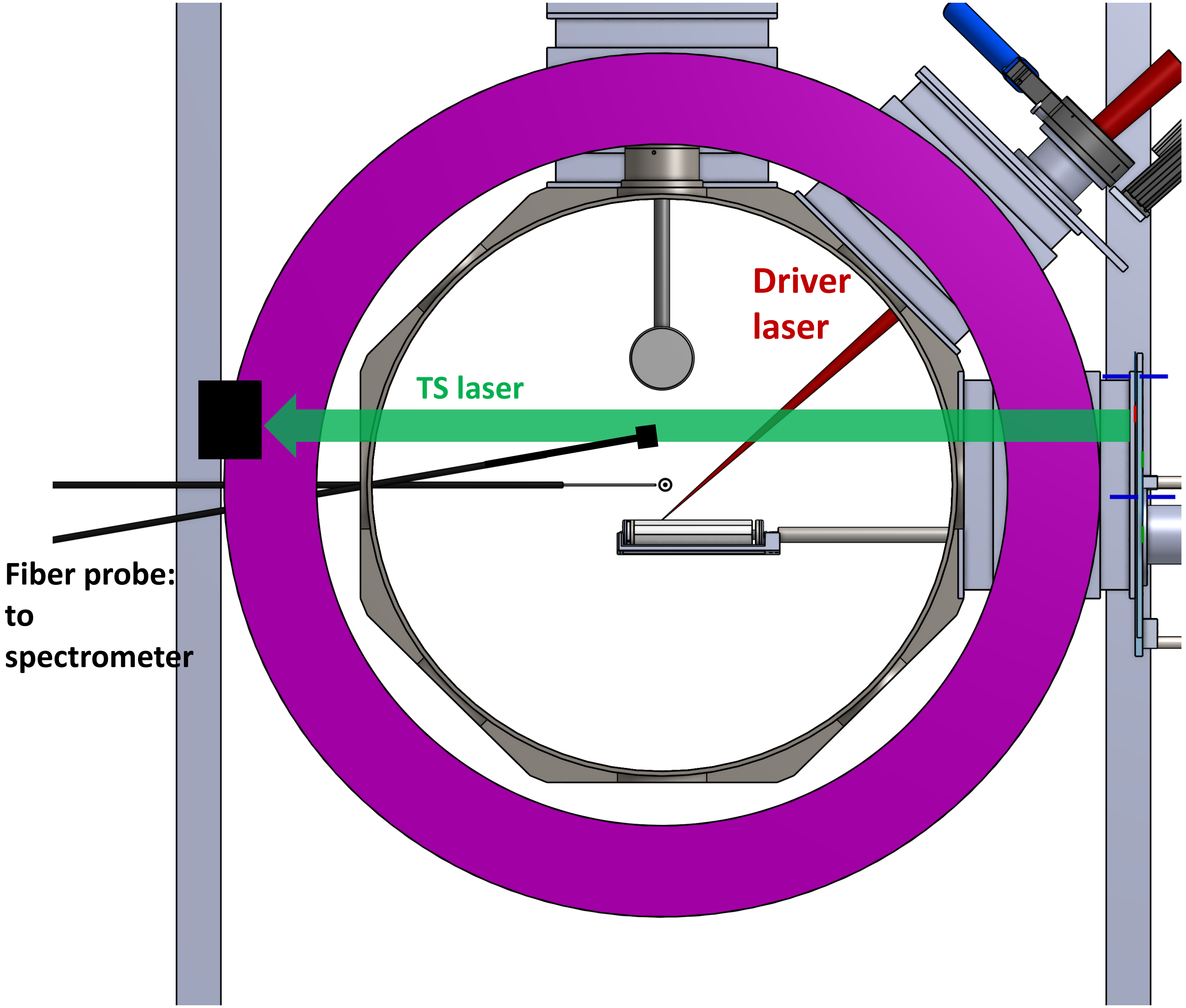
PIC simulations modeling the experiment indicate electron-scale reconnection



- Hall term dominates on the d_i scale
- Closer to the Xline: hall term goes to zero and reconnection is driven by the anisotropic pressure tensor (kinetic)
- On this small kinetic scale, electron stop being magnetized: breaking the frozen-in condition

Thomson scattering diagnostics

UCLA



- The Thomson beam can move in a 2in by 2in zone around the reconnection point, and the collection (fiber probe) follows it: enable 2D (2.5D) TS data acquisition!
- Scattered light collected by a fiber array collecting light in a 1mm X 2cm zone and sent to spectrometer
- Caveat: density is very low: needs a lot of shots for one spectrum (200-500)

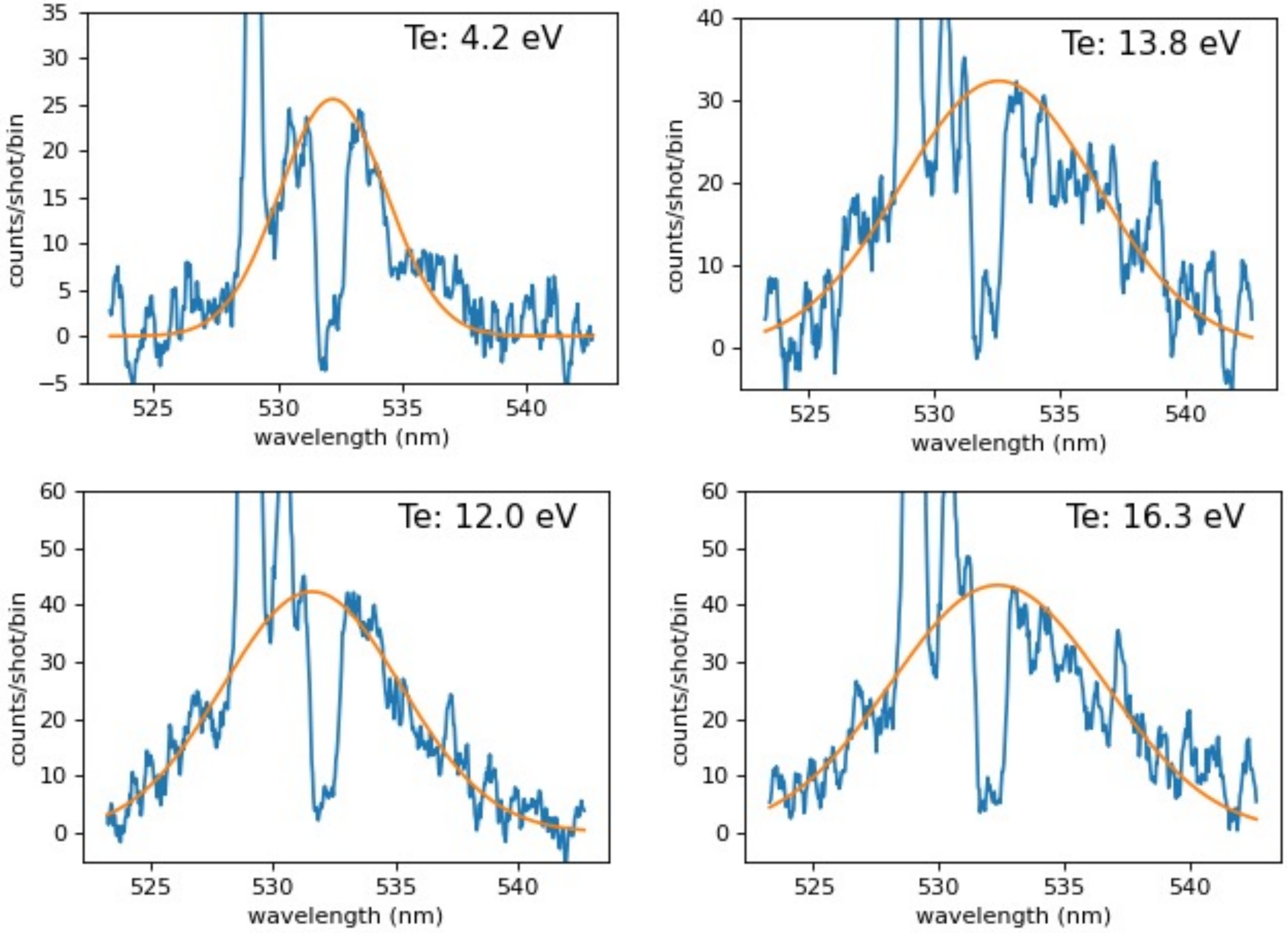
Preliminary data shows enhanced heating with dipole

UCLA

Dipole OFF — Dipole ON

t = 675us

t = 750us



- Data taken at X-point
- Increased heating when dipole is ON: is this due to reconnection?
- Large peaks are neutral carbon lines from C4+ hitting dipole
- Spatially/temporally data acquired: needs analysis

Conclusions & outlook

UCLA

- We developed a platform to study ion-scale magnetospheres
- This allowed us to gain new insight on the nature of reconnection on the moon
- We observe a significant impact of Hall physics on a global scale, and PIC indicates local, electron-only kinetic effects drive reconnection

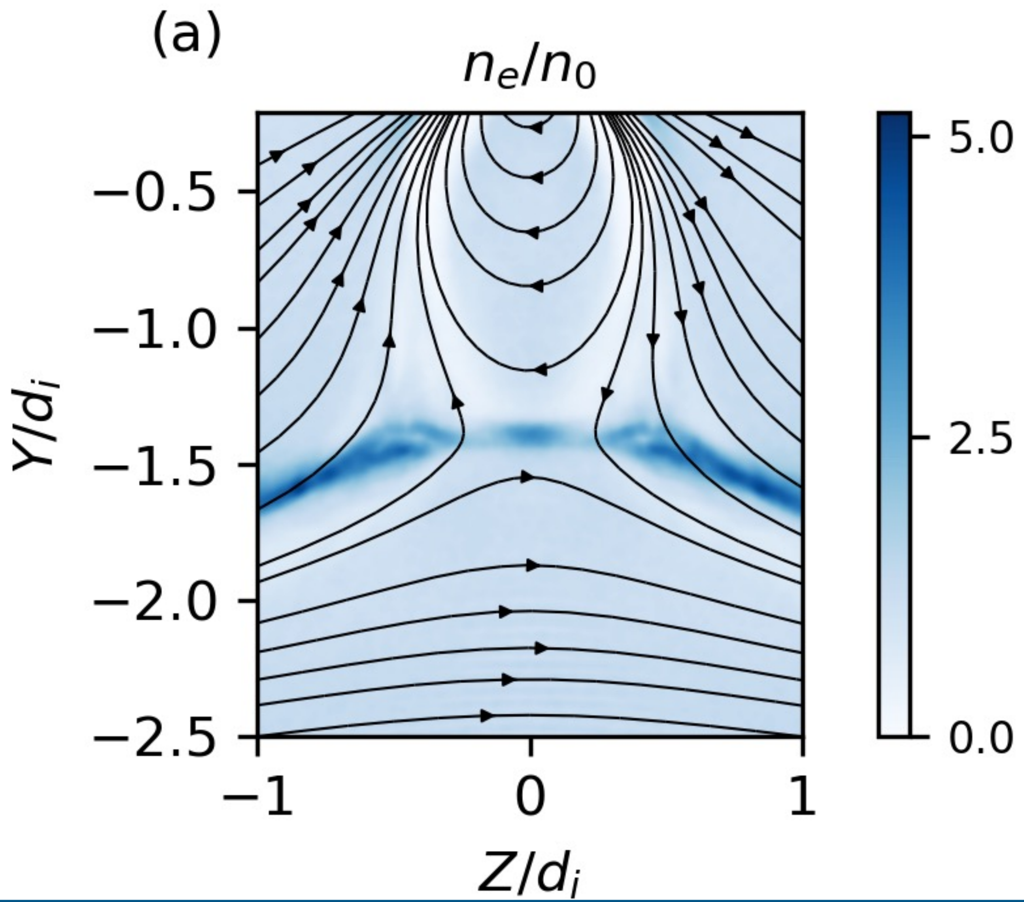
Future experiments will:

- Enhance Thomson scattering: measure kinetic effects
- Exploration of nightside reconnection

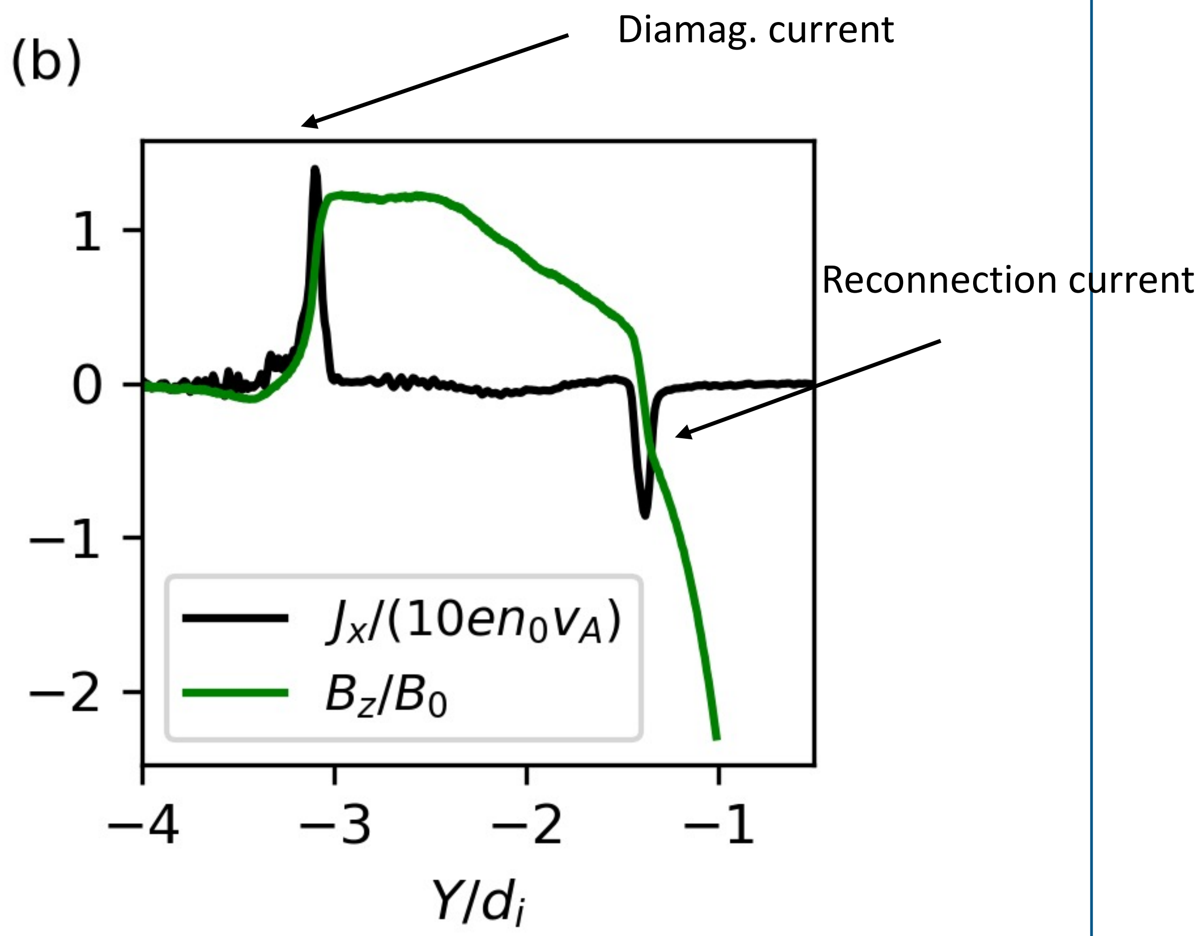
Thank You!

PIC Simulations

Electron density and B-field lines

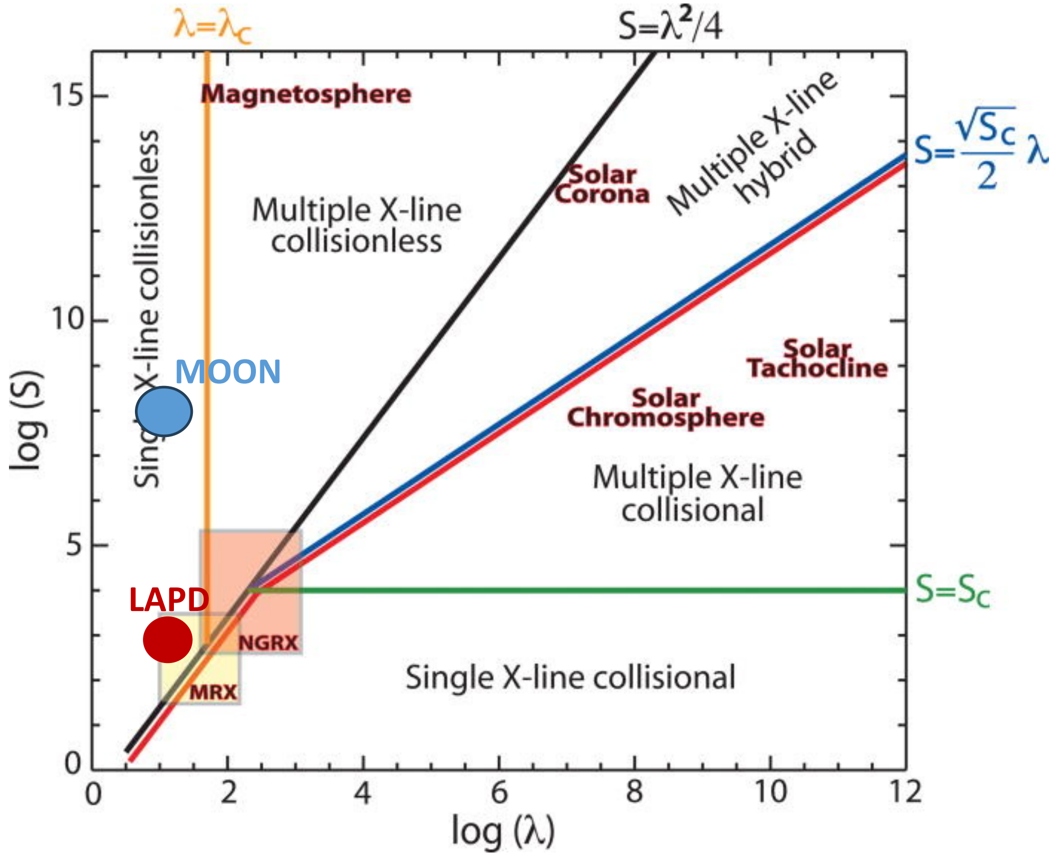


Reconnection current Jx



Comparison Moon - LAPD

Parameter	Lunar minimag / Solar wind	LAPD experiment
$D = L_M / d_i$	0.5 – 5 (0.7 in [Sawyer et al])	1.25
$G = L_M / \rho_i$	0.1	1.7
M_A	4-8	0.75
L_M/λ_{ii}	<<1	0.02
L_M/λ_{ee}	<<1	2
S (Lundquist)	>>1 (10^8)	550
beta	0.4	0.02

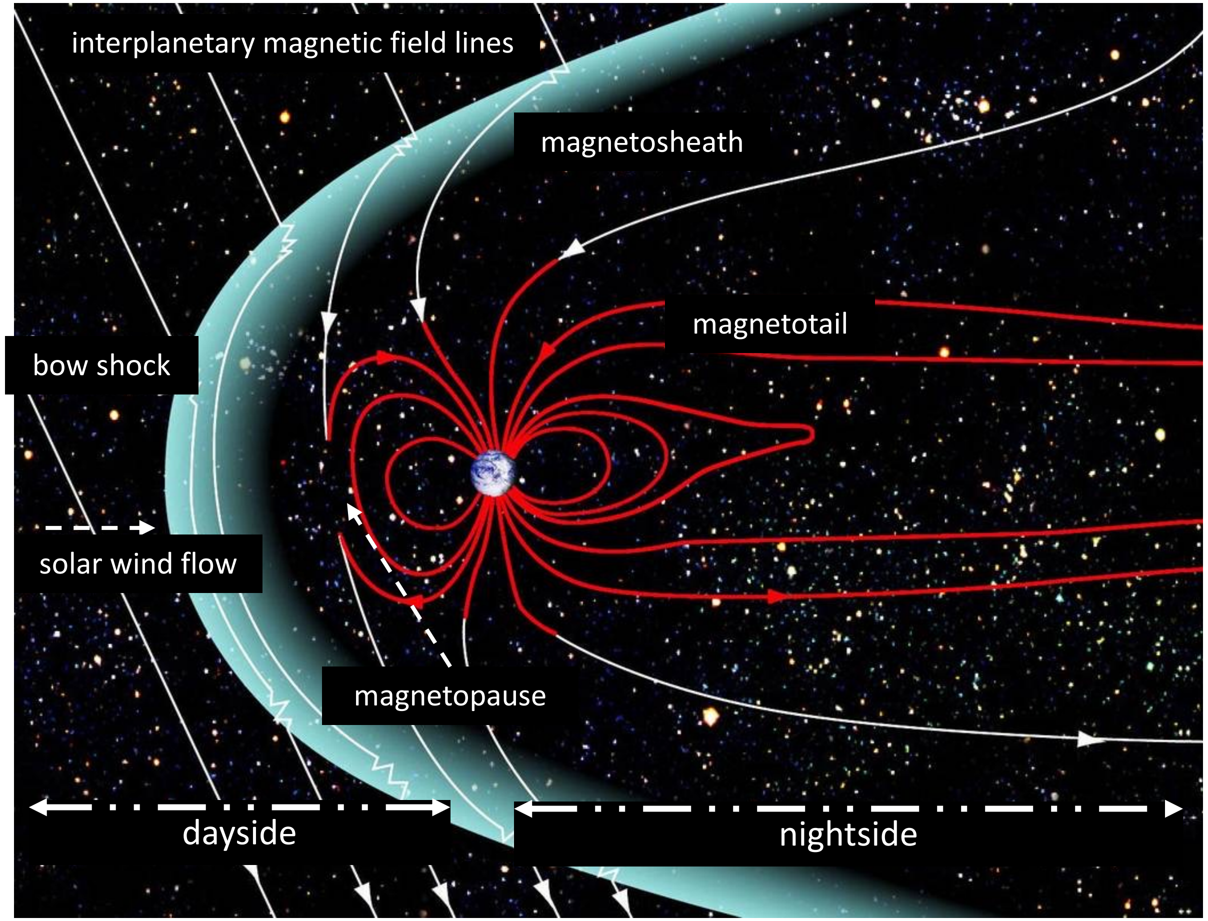


Phys. Plasmas. 2011;18(11). doi:10.1063/1.3647505

Planetary magnetospheres are highly dynamic and span global to kinetic scales

UCLA

Earth's Magnetosphere



[Image Credit: NASA]

Structure Dictated by Pressure Balance

- Magnetospheres form when flowing plasma impacts a magnetic obstacle
- A **magnetopause** develops where the ram and magnetic pressure balance
- Standoff distance L_M set by

$$n\, m\, v^2 = B_{dipole}^2/8\pi$$

$$B_{dipole} = M/L_M^3$$

plasma density
ion mass
fluid velocity
magnetic moment

- Magnetospheres characterized by parameter

$$D = L_M/d_i$$

ion inertial length

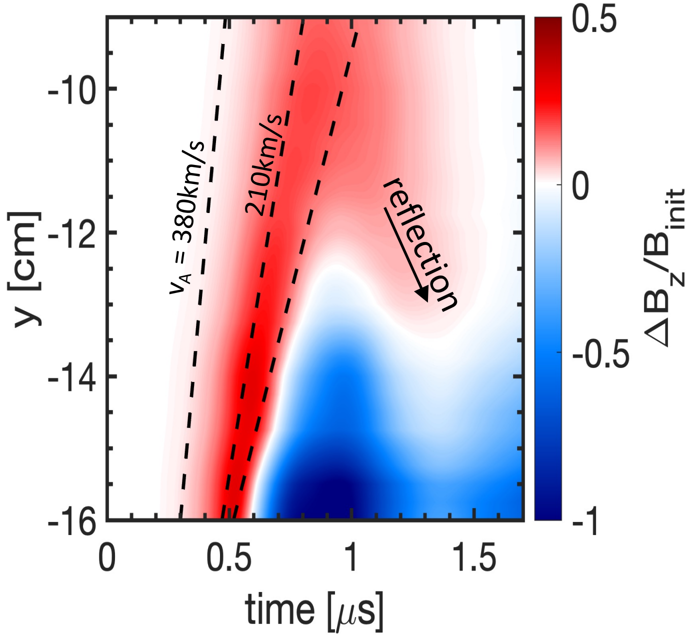
- For Earth, $D \approx 600$

Key questions remain, including the nature of dayside reconnection and kinetic-scale physics

Previous experiment observed the formation of ion-scale magnetosphere

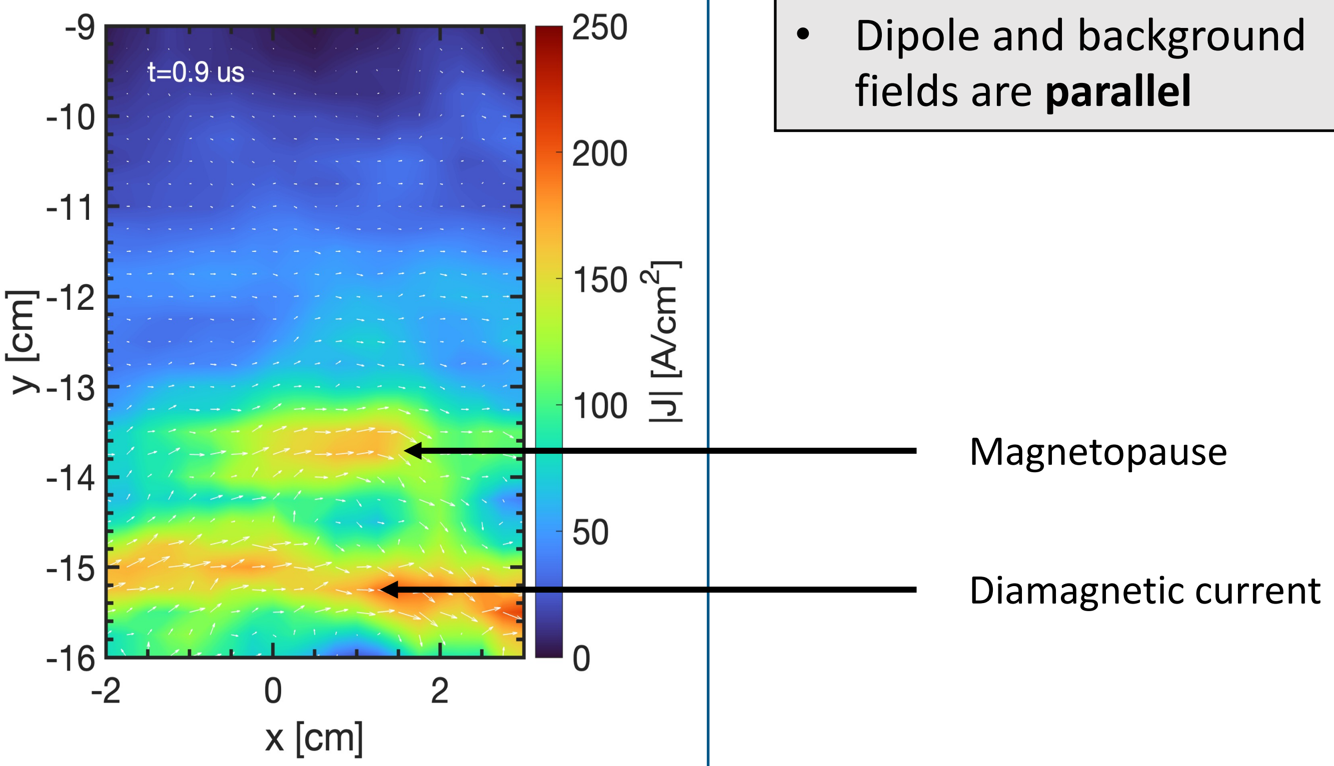
UCLA

$\Delta Bz\ (\mathrm{Y, t})$



- Laser-driven plasma creates magnetic cavity and leading compression
- Magnetic pressure balances driver ram pressure
- Compression reflected by dipole field

$J\ (x, y)$



- Dual current structure observed at moderate dipole moment

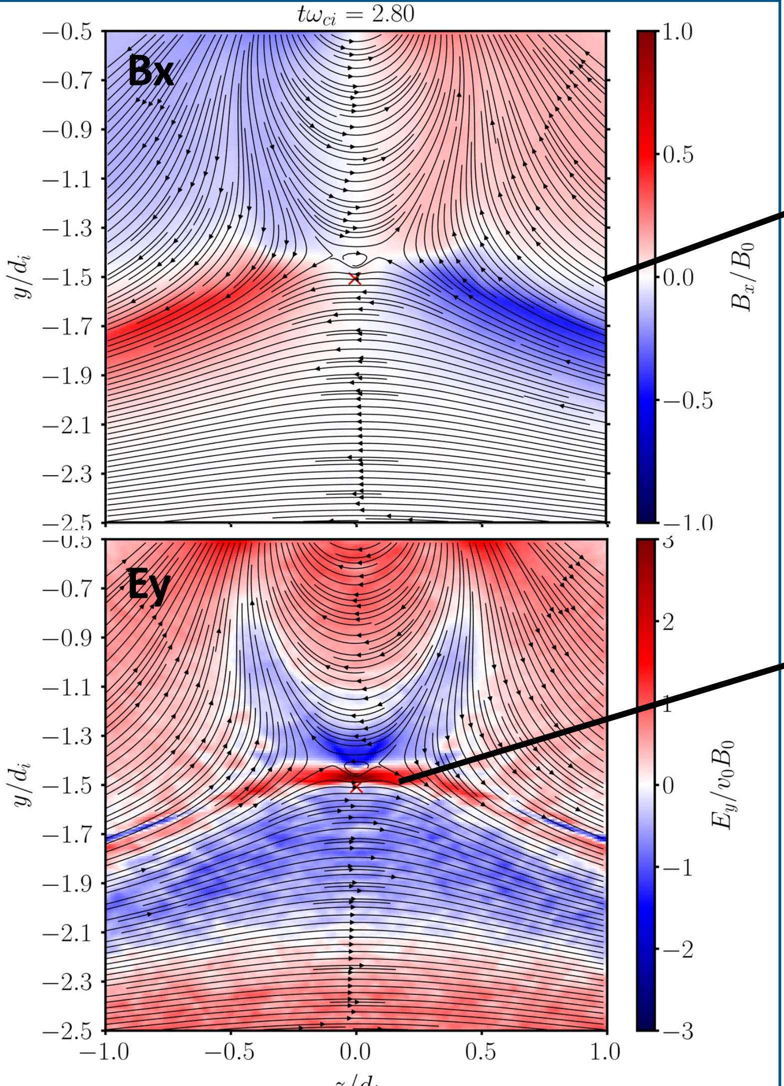
- Dipole and background fields are **parallel**

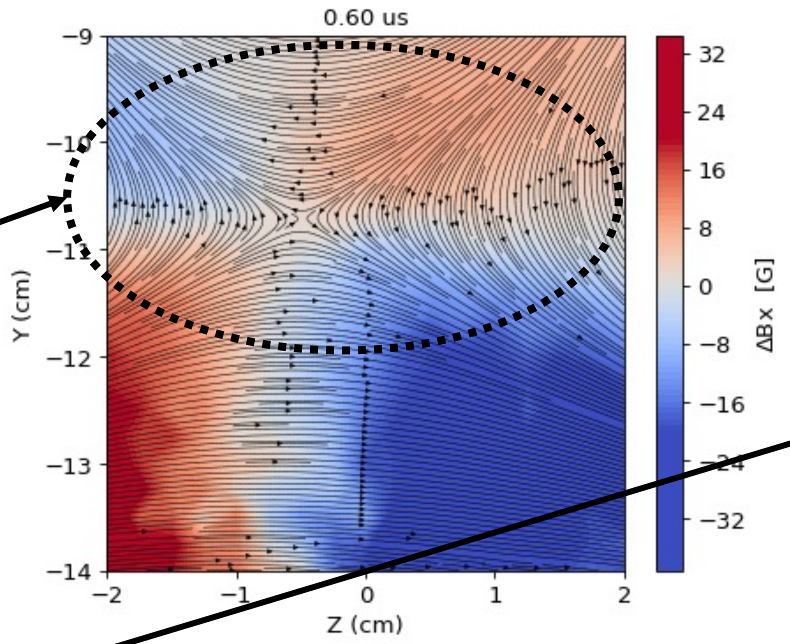
[Schaeffer et al. Physics of Plasmas, ***29*** *042901 (2022)]*
[Cruz et al. Physics of Plasmas, ***29*** 032902 (2022)]

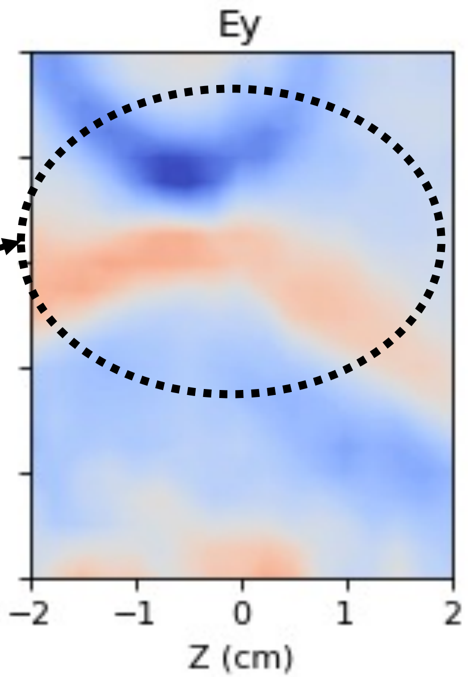
3D PIC Simulations

UCLA

Hall fields structure





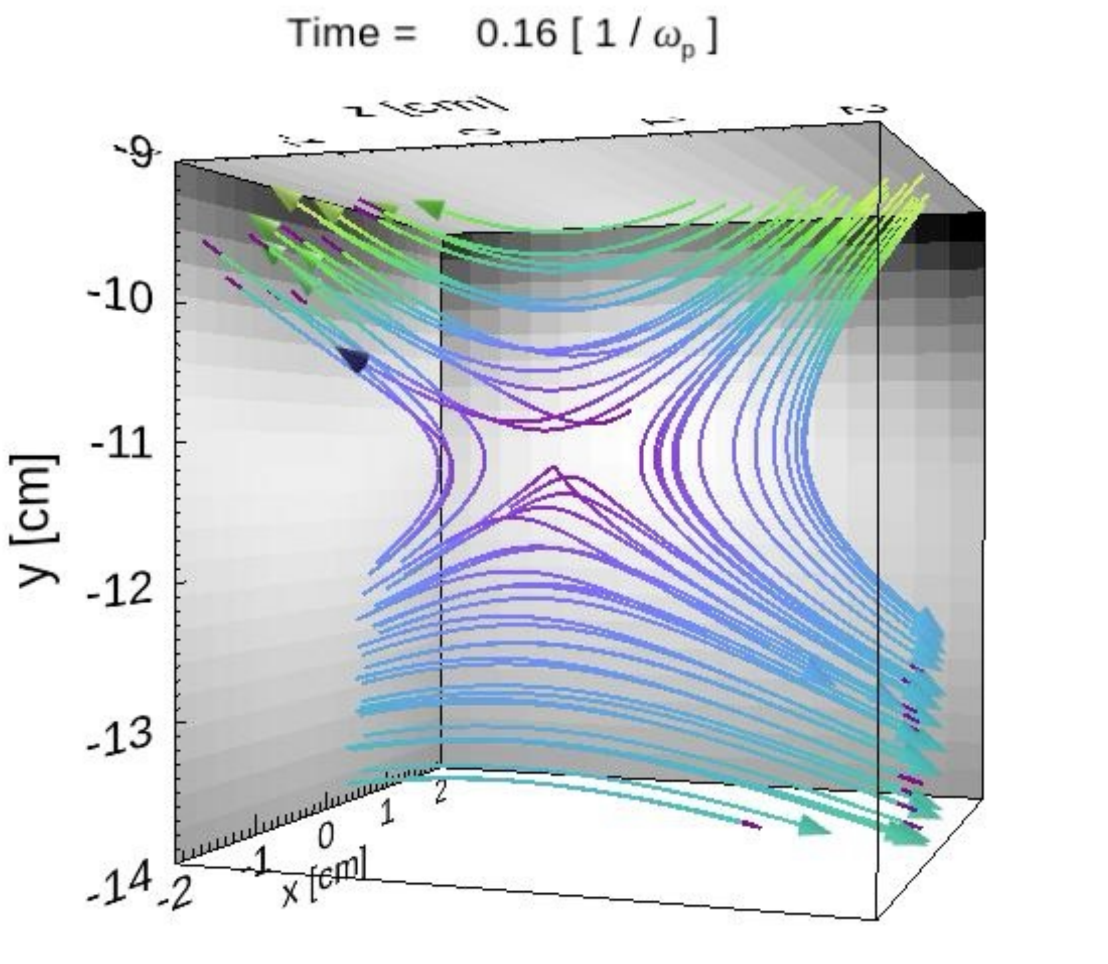


<u>Similar fields obtained</u>:

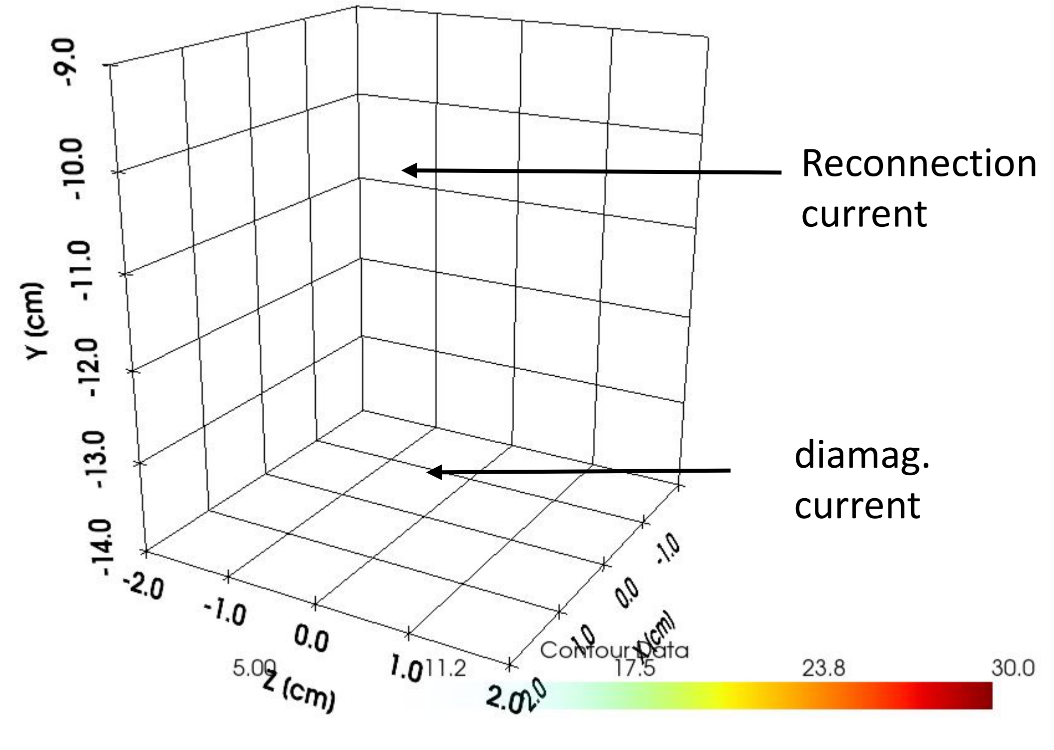
- Quadrupole Bx generation
- Dipolar Ey
- Reconnection current

High-rep. rate enables acquiring field data in 3D

Magnetic field lines in 3D



Jx (x,y,z,t)



- High rep-rate: we were able to obtain for the first time, volumetric (3D) field data for the B, J and E !
- 36000 laser shots for magnetic and electrostatic field data in a 5x4x4 cm^3 volume

Jz

Outflow associated with Jz but of peak amplitude after the identified reconnection period