

Investigating magnetic reconnection in Laser-produced plasmas

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et al.

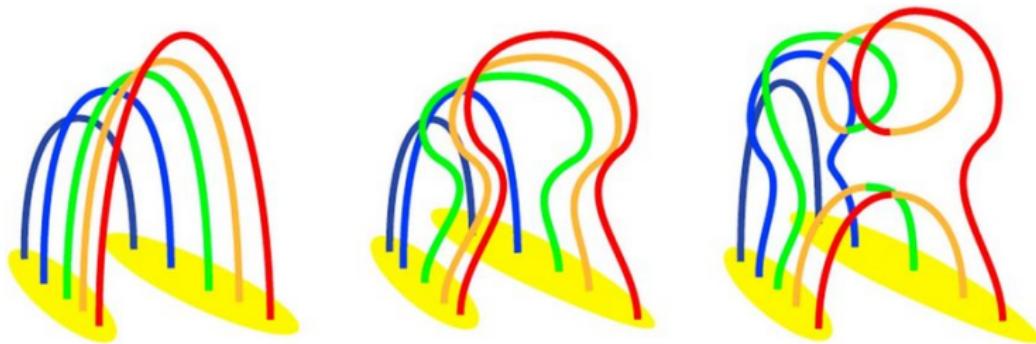
¹LULI, ²CEA, ³LPP...

MEC MatPla winter school : 5-9 february 2024

Magnetic reconnection in solar arches

3D (revised) standard model [*Holman 2016, JGR*] :

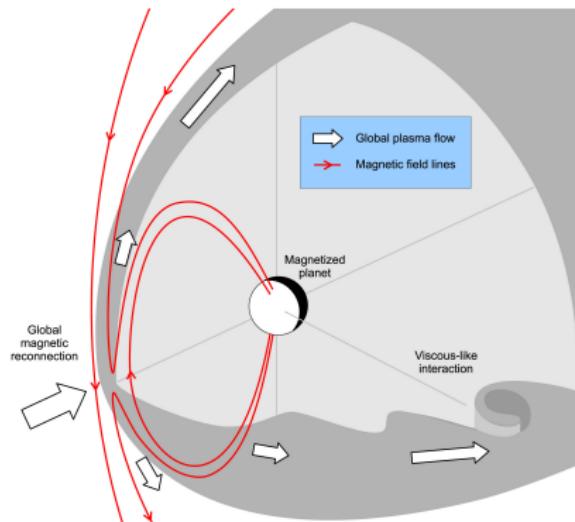
- Magnetic field lines emerge in cold sun spots



- asymmetric & unparallel ribbons (feet of B -lines)
- involve an inhomogeneous shear of the loops
- reconnection propagate along the arcade

Magnetic reconnection in planetary magnetosphere

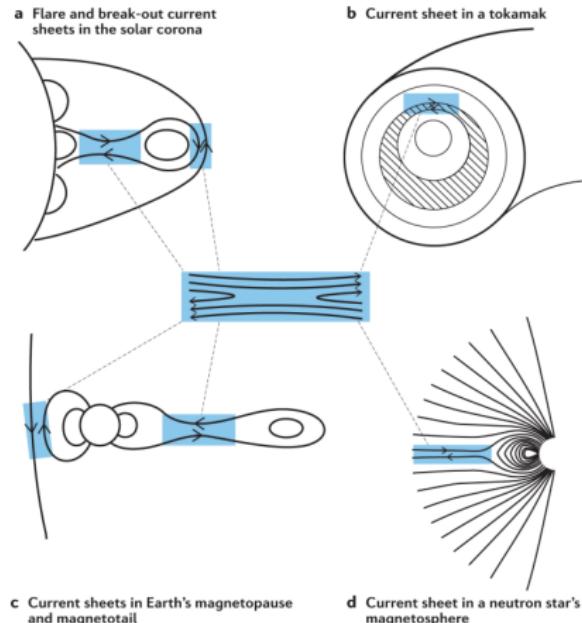
- Solar wind drives magnetosphere dynamics [Masters 2018, GRL] :



- magnetic reconnection spreads along a line
- thining of the current sheet driven by solar wind pressure
- viscous-like interaction (like KH instability) is secondary

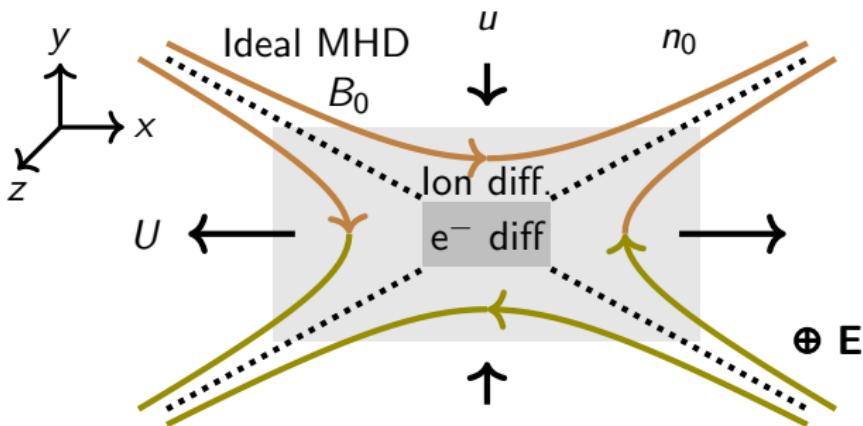
Current sheets in plasma physics

- Ubiquitous in the universe [Ji et al. 2022, Nat. Rev. Phys.] :



→ could be a PeVatron for cosmic rays, black-hole jets...

Big picture of 2D magnetic reconnection



- Ohm's law :

$$\mathbf{E} = -\mathbf{V}_i \times \mathbf{B} - \frac{1}{en} [\mathbf{j} \times \mathbf{B} - \nabla \cdot \mathbf{p}_e] + \eta \mathbf{j} - \eta' \Delta \mathbf{j} + m_e d_t \mathbf{j}$$

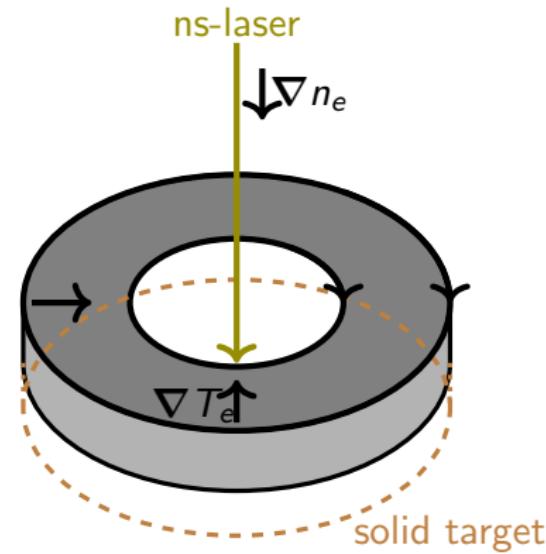
- Efficiency of reconnection measured by $E'_z = E_z / B_0 v_A$
 - Ideal term in the MHD region
 - Hall term in the Ion diffusion region
 - Agyrotropic pressure term in the electron diffusion region

Pending questions

- What is the origin of the local dissipation?
- What is the importance of the 3D geometry?
- How efficiently plasma and B -field are transported through the reconnection site?
- How and where do X lines form in the current sheet?
- X line formation: local spreading in a global context?
- What controls their length?
- How do they respond to the temporal variations of external conditions?
- What are the respective roles of large scale inhomogeneities and local kinetic effects?

Magnetized plasma loop using a ns-laser

- Plasma produced by a ns-laser on a solid target
- B -field produced by Biermann-battery effect

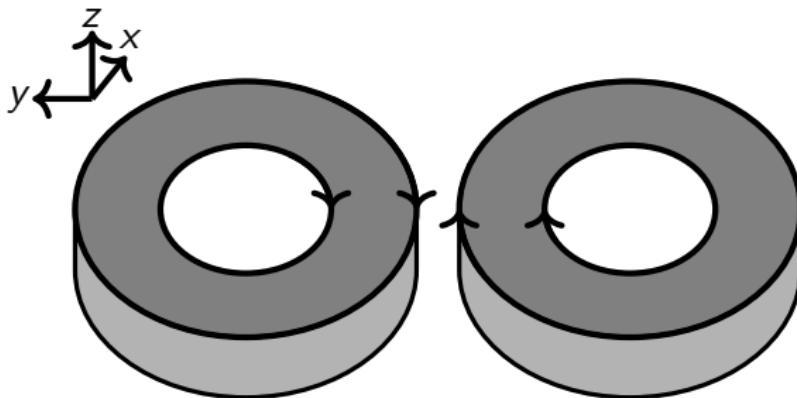


⇒ The B-field produced on front face is clock-wise oriented :

$$\partial_t \mathbf{B} = -\frac{1}{en_e} \nabla n_e \times \nabla T_e$$

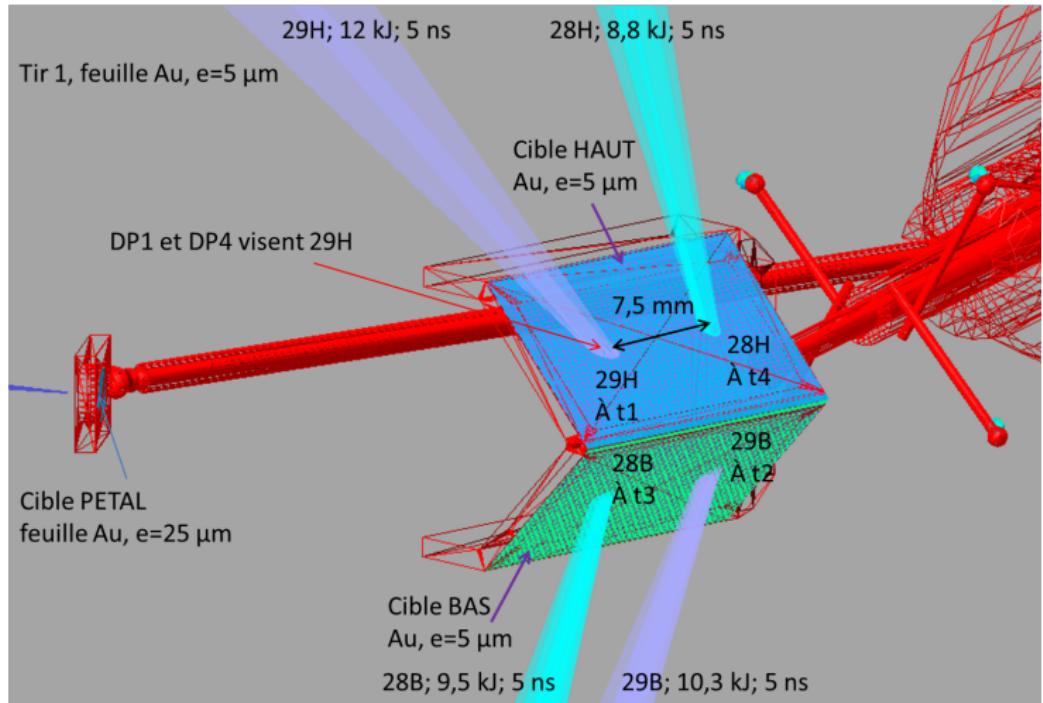
Reconnection between 2 magnetized plasma loops

- Distance between the 2 focal spots \geq twice the plume radii



- The current sheet is building up during the irradiation
- Lundqvist number $S \sim 10^3$ (with Spitzer-Harm resistivity)
 - aspect ratio of the current sheet $L/\delta < 50$
 - we then are not in the plasmoid regime
- Curvature of the B-field in favour of single X-type reconnection
- Numerical approach with a 2D Hybrid-PIC code

Lasers configurations (first shot - 2019) on LMJ



Lasers parameters

	LMJ	PETAL
Pulse duration	5 ns	0.7 ps
Energy	12 kJ	400 J
Solid target	Au - 5 μ m	Au - 25 μ m
Wave length	351 nm	1053 nm

- we used 6 quads : C28, C29, C10, both H & B
- laser incidence depends on the quad for experimental reasons
→ energy is then modulated for somewhat similar plasma loops
- proton probe incidence of 34°
- hot spots separation : 7.5 mm & 1.5 mm for reconnection
- a total of 7 shots (1 on Ti-foil)
- 3 times for 2-loops and 3-loops reconnection : 2.1, 3.2 & 4.3 ns

Plasmas parameters

- From fci2 simulation (for a 1-plume plasma) :

	Plasma plume	Proton beam
Magnetic field	$\sim 600 \text{ T}$	
Electron density	$\sim 4 \times 10^{27} \text{ m}^{-3}$	
Mean flow	$\sim 2 \times 10^5 \text{ m.s}^{-1}$	$\sim c$
Kinetic energy	$\sim 100 \text{ eV}$	$\sim 42 \text{ MeV}$
β parameter	$\beta_e = 0.5, \beta_i = 0.02$	
Loop radii	$\sim 300 \rightarrow 900 \mu\text{m}$	
Ion Inertial length	$\sim 4 \mu\text{m}$	
Ion Gyroperiod	$\sim 17 \text{ ps}$	
Alfvén velocity	$\sim 2 \times 10^5 \text{ m.s}^{-1}$	

→ close to the $\beta \sim 1$ regime

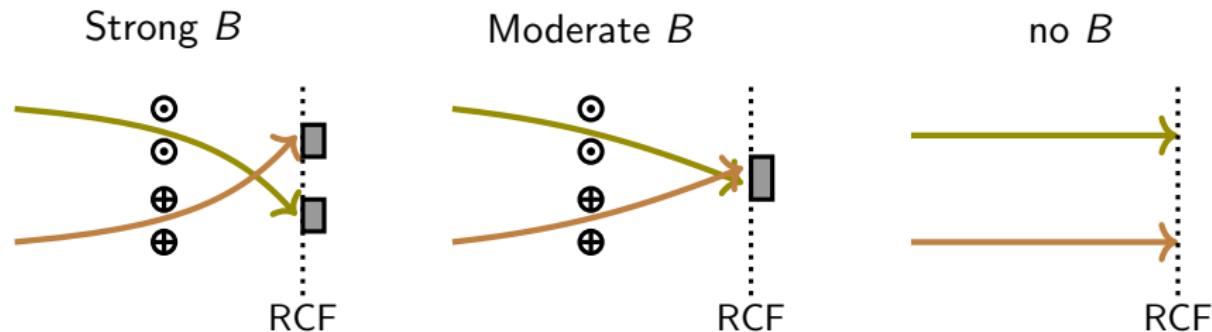
→ magnetization parameter $\sigma \ll 1$

Diagnostics (LMJ experiments in 2019)

- Proton radiography using PETAL on a solid target
 - a proton beam is created with ps-laser on solid target by TNSA
 - collected on a stack of Radio-Chromic-Films (resolved in energy)
 - the proton dose give insights on the path-integrated B -field
- DMX
 - integrated spectra (arbitrary units) depending on time
- DP1 & DP4
 - provides an image of the focal spot

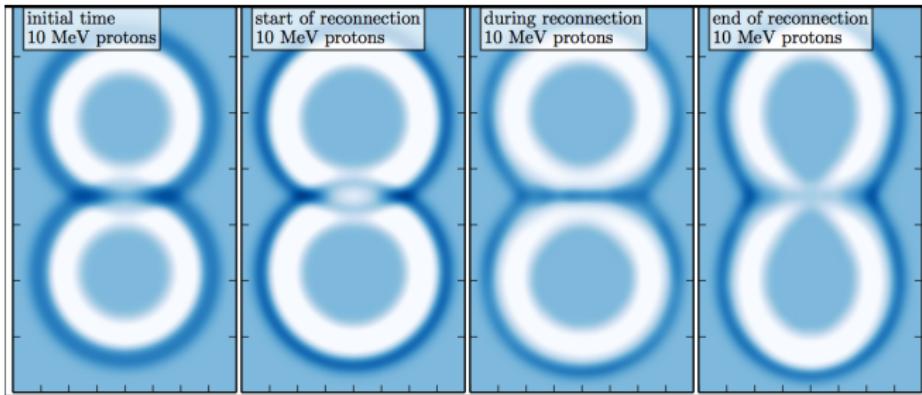
B-field pictured by proton-radiography

- Proton beam (42 MeV max. energy) produced by TNSA
→ using PETAL on a 25 μm gold foil



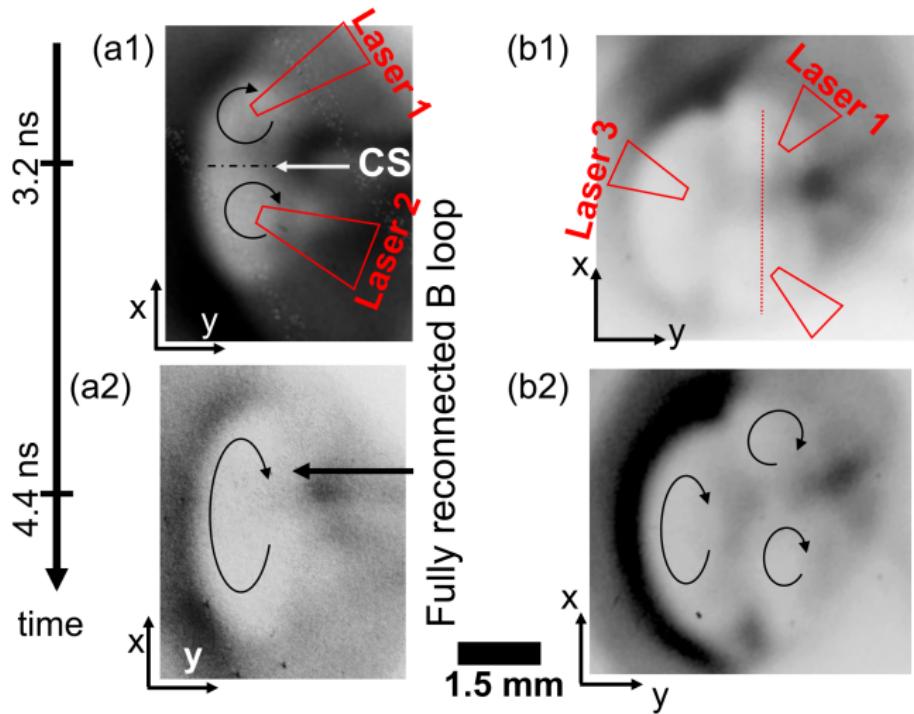
- Strong $B \Rightarrow$ before Reconnection : "open mouth"
- Moderate $B \Rightarrow$ during reconnection : "closed mouth"
- no $B \Rightarrow$ after reconnection : nothing !

Synthetic RCF for 10 MeV proton beam



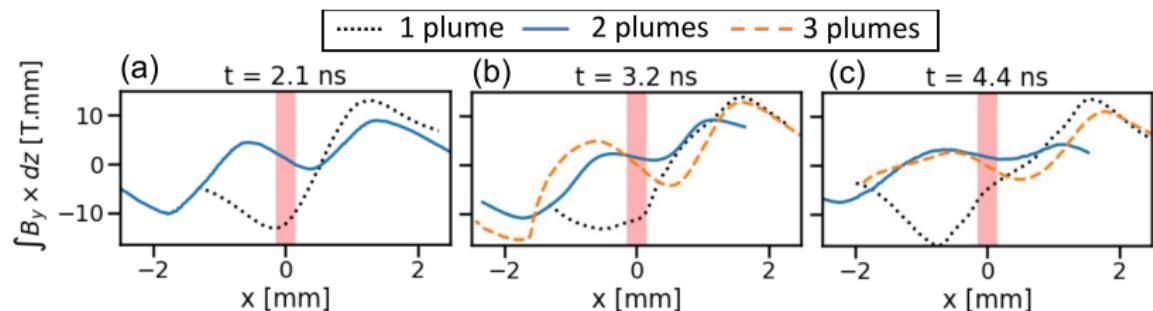
- a "mouth" open when B field is compressed
- but closes when reconnection operates (and decrease B)

Proton radiographies from LMJ 2019 experiment



B-field reconstruction using problem solver

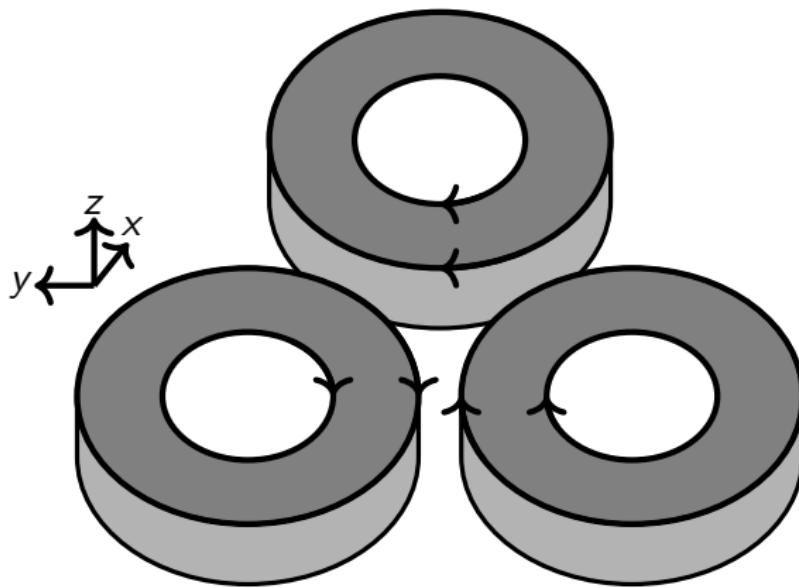
- Maxwell-Faraday : relation between magnetic flux $\partial_t \phi$ and E



- weaker B-field for 2-plumes & 3-plumes : reconnection operates !
 - $\partial_t \phi = \partial_t \iint B_y \, dx \, dz = 2.5 \pm 0.6 \text{ T.mm}^2 \cdot \text{ns}^{-1}$
 - from Faraday law, $\partial_t \phi = \int E \, dz \sim \lambda E$
 - $\int B_y \, dz = 13 \text{ T.mm}$ and $V_0 \sim v_A = 400 \pm 130 \times 10^3 \text{ m.s}^{-1}$
- reconnection rate $E' = 0.48_{-0.20}^{+0.40}$ (2-plumes case)
 - Fast reconnection (even very fast...)

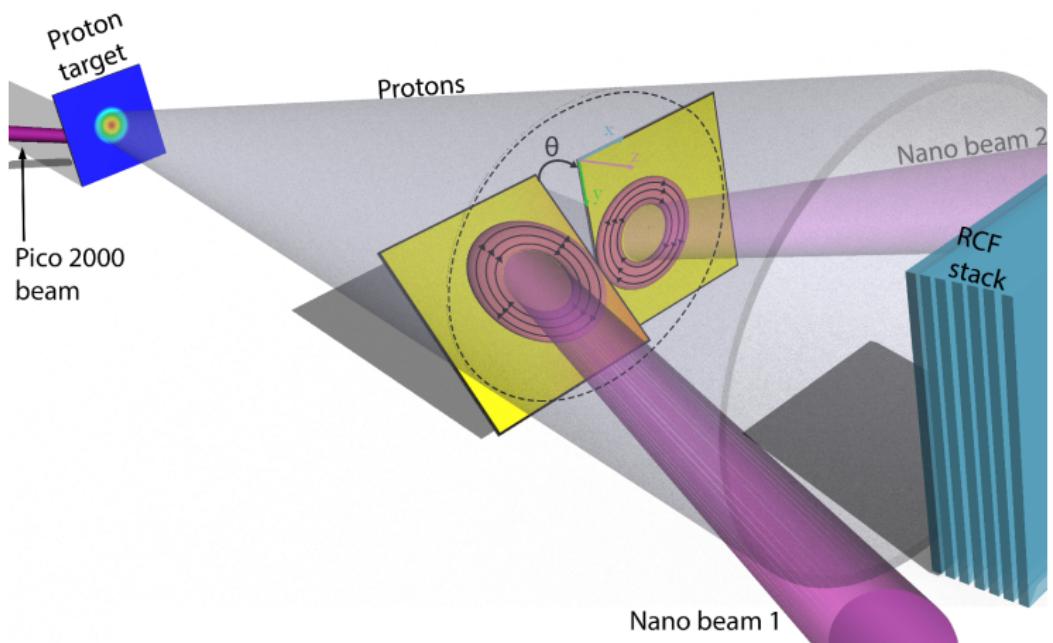
Reconnection between 3 magnetized plasma loops

- Why did we also used 3-plumes reconnection ?

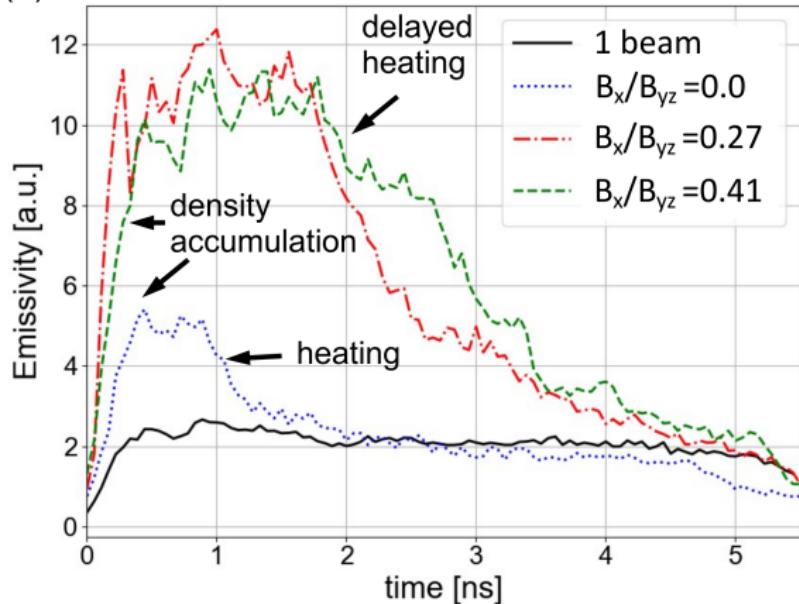


- The plasma outflow (ejecta) is "trapped" in closed structures
- With 2 plumes, creation rate < reconnection rate (small j_z)
→ with 3 Plumes, smaller reconnection rate which make j_z grows

Lasers configurations (2017) at LULI2000



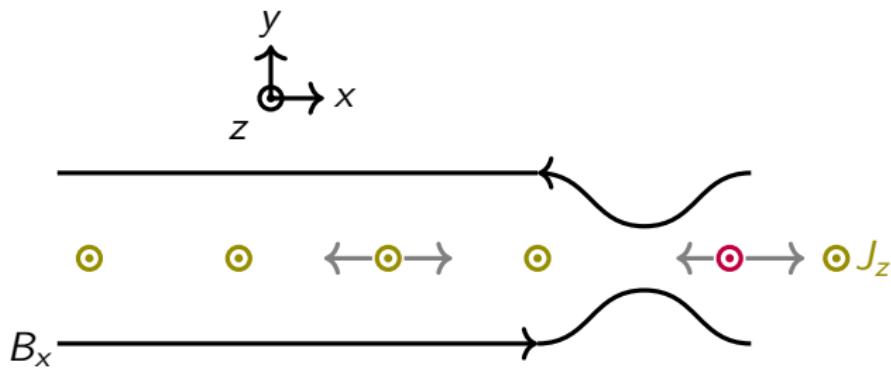
Streaked Optical Pyrometry



- Emissivity increases with density because of the pile-up
- Emissivity decreases for hot plasma

Collisional vs collisionless tearing

- A current sheet is intrinsically unstable to tearing

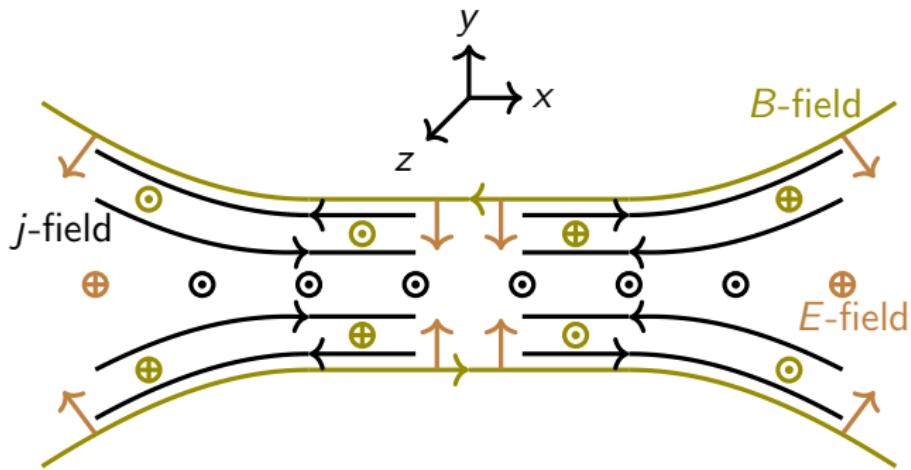


- Magnetic reconnection triggers with a dissipation mechanism:
 - Coulomb collisions [*Furth et al. 1963, Phys. Fluids*]
 - Particle-wave resonant process [*Coppi et al. 1966, PRL*]

Characteristic scales for magnetic reconnection

- Collisional tearing : $\gamma = \frac{(\Delta' L)^{4/5}}{\tau_R} S^{2/5}$
→ $S \gg 1$, $L \gg \lambda_{CS}$ collisional reconnection & $\tau_R \ll \tau_A$
→ $E' \lesssim 0.01$ for "fast" high- S reconnection
- Collisionless tearing : $\gamma = \frac{1}{\sqrt{\pi}} (1 - k^2 \lambda_{CS}^2) \frac{d_e^2}{\lambda_{CS}^2} \frac{v_{Te}}{\sqrt{\rho_e \lambda_{CS}}}$
→ $\lambda_{CS} \sim d_p$, $\rho_e \sim d_e$ so γ is a fraction of Ω_p
→ $E' \sim 0.1$ for fast reconnection mediated by Hall effect
- Hall-MHD, hybrid-PIC & full-PIC simulations
→ growth on $\Omega_p t \sim 20$ [Birn et al., 2001, J. Geophys. Res.]
- $\Omega_p \sim 10$ ps for $B = 10^3$ T and $d_p \sim 2\mu\text{m}$ for $n_e = 10^{28} \text{ m}^{-3}$

Hall term in the ion diffusion region



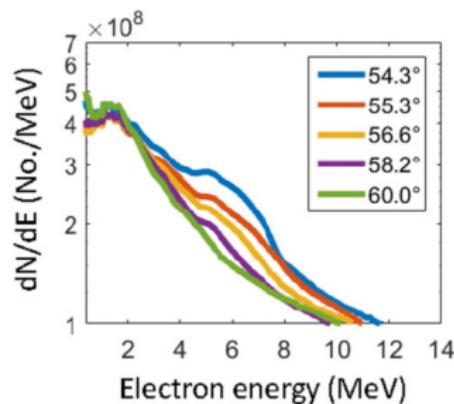
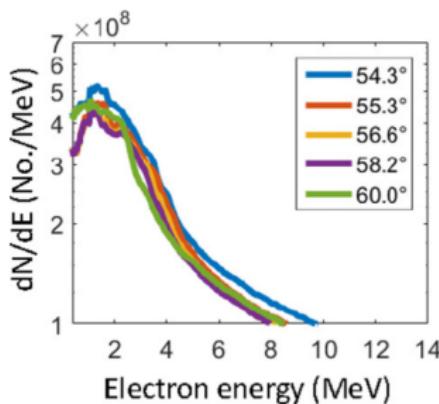
- (Hall) E_{XY} electric field associated to J_Z and B_{XY}
- j_Z grows at the tip of each loops when colliding
→ quadrupolar B_Z grows because E_{XY} is no more curl-free
- j_{XY} associated to this out-of-plane magnetic field
→ carried by electrons because protons are demagnetized

Relativistic magnetic reconnection ($\sigma > 1$)

Investigated by [Raymond et al., 2018, PRL]

- 2 J & 40 fs w. HERCULES & 500 J & 20 ps w. OMEGA-EP
- quadrupolar Hall-like B-field using OSIRIS 3D full-PIC code

- Create $B \sim 10^4$ T in a e^- coronae expanding at $\sim c$
- X-ray imaging of e^- current sheet (resolved in space and time)
- Multi-channel spectrometer : Non-thermal electron populations



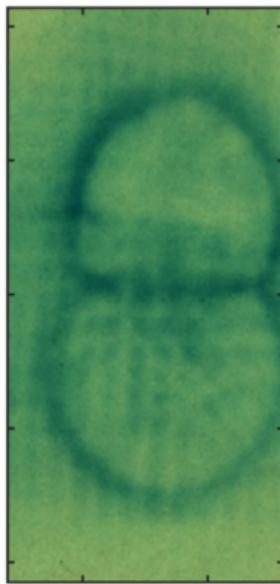
- Heating of the current-sheet e^- by reconnection

Relativistic magnetic reconnection ($\sigma > 1$)

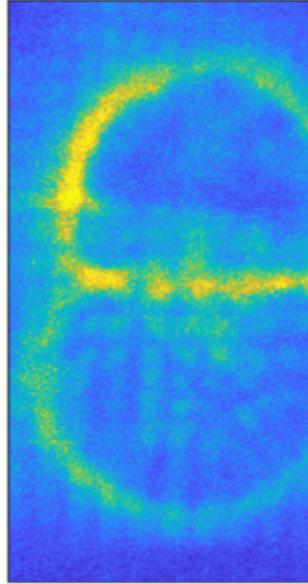
Also investigated by [Palmer et al., 2019, PoP]

→ using 220 J & 9.6 ps w. VULCAN & proton probing (by TNSA)

p^+ RCF



p^+ dose



B -field



→ In the frame of eMHD [Gordeev et al., 1994, Phys. Rep.] ?



Reconnection in electron-positron (pair) plasma

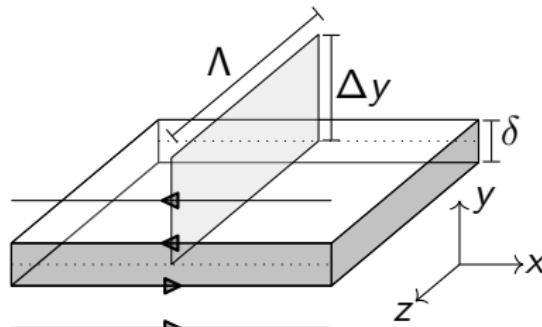
- Important in extra-galactic jets and pulsar (striped) winds
→ need to derive a relativistic Ohm's law to get E'
- No more Hall term in an electron-positron plasma
→ "single" diffusion region [*Bessho & Bhattacharjee* 2005, PRL]
→ the reconnection rate is still $E' \sim 0.1$
→ dynamics on the electron scales... well suited for ps lasers
- Produced in the Lab [*Greaves & Surko*, 1995 PRL] :
→ positron created by β -radiactive source (^{22}Na) & Penning traps
- May we envision such an experiment on Appollon ?

Concluding remarks

- Competiting effects of Biermann-battery and reconnection
 - B-field created by Biermann-battery : source term
 - B-field is then reconnected : loss term
- We already measured fast reconnection : $E' > 0.48$
 - first measure (of a lower value) of a reconnection rate
- For long pulse lasers, one can play with target geometry
 - guide-field, initial quadrupolar B-field
- For short-pulse lasers, scales need to lowered
 - enough time to trigger reconnection (strongly driven) ?
 - pair plasma of interest in compact objects...

Additional material,

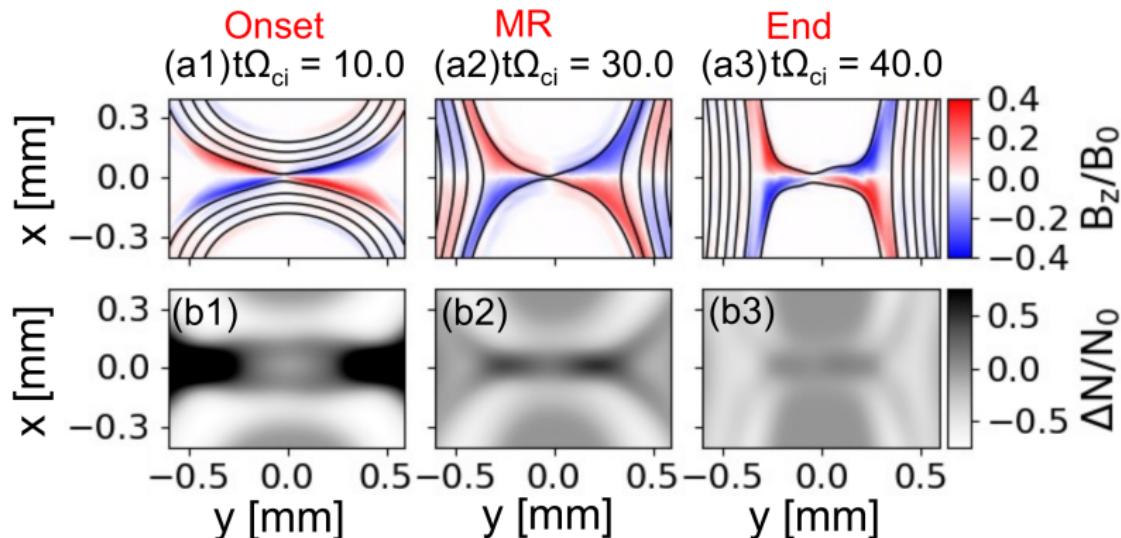
Hybrid-PIC simulation using heckle



- $d\Phi = \mathbf{B} \cdot d\mathbf{S}$: differential magnetic flux across the surface $d\mathbf{S}$
→ hence $\partial_t \Phi = B\Lambda\Delta y/\Delta t$
- $\partial_t \Phi$ is associated to the transport of B (along x) advected at the velocity U (along y) by the E field (along z)
- Maxwell-Faraday : $\partial_t \iint \mathbf{B} \cdot d\mathbf{S} = \iint (\nabla \times \mathbf{E}) \cdot d\mathbf{S} = \int \mathbf{E} \cdot d\mathbf{l} = E\Lambda$
- Same upward flow below the $y = 0$ plane, hence $E = 0$ at $y = 0$
→ $E = B\Delta y/\Delta t = BU$ where U is the fluid velocity
→ E can be normalized using B_0 and A_0 , ie
 $E' = E/(B_0 A_0) = U/A_0$
- This is a creation rate of flux upstream the current sheet
→ for stationary reconnection, creation rate \equiv reconnection rate

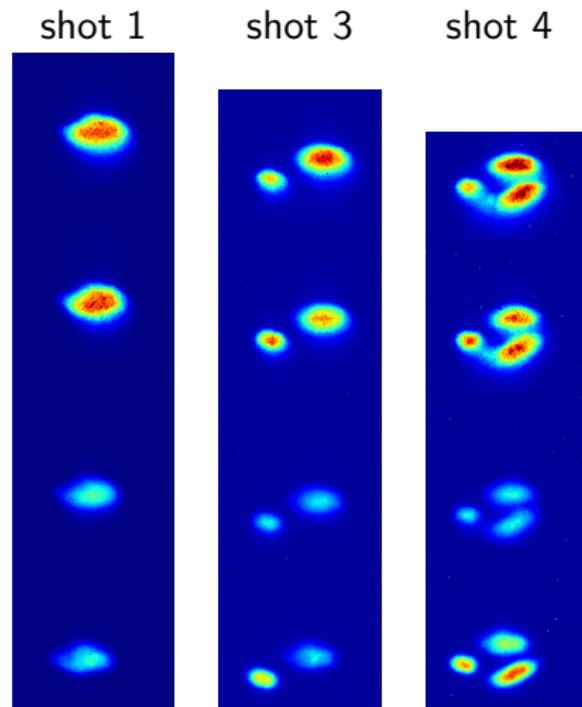
Hybrid-PIC simulation using heckle

- Creation of a "Hall" quadrupolar B-field

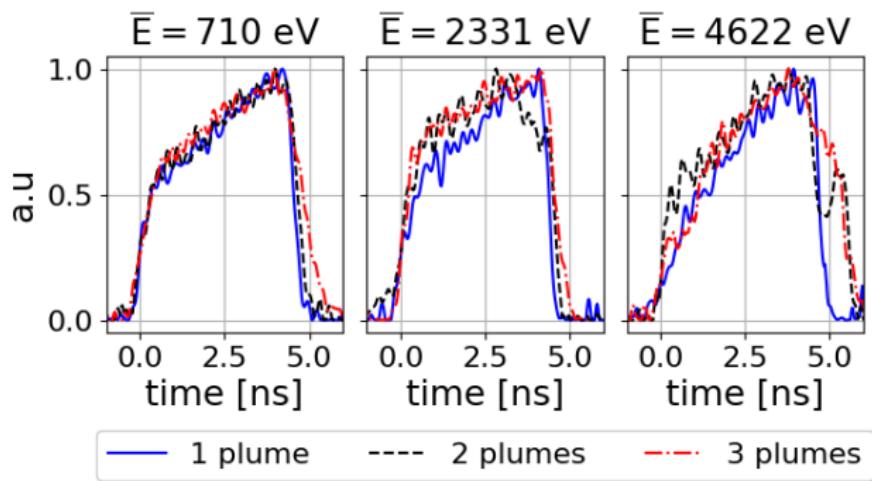


- the "mouth" opens just before the onset
- then closes during reconnection
- and disappears when there is no more B-field

DP1 images



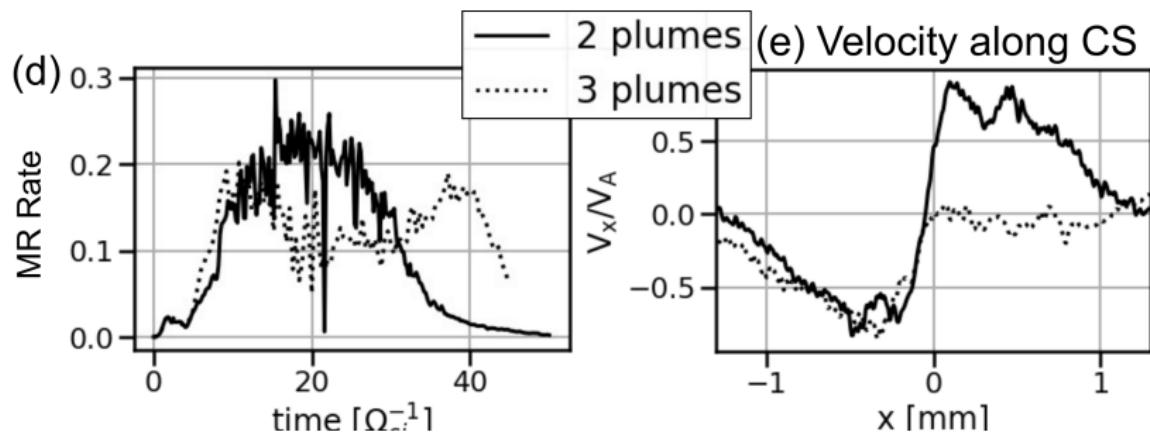
DMX spectra



→ unfortunately, no clear insights from these spectra...

Numerical reconnection rate with heckle

- We then "measured" E' at the saddle point & U_y



- The reconnection rate ($E' \sim 0.2$) is clearly fast
 - smaller reconnection rate with 2 plumes
 - the outflow velocity is clearly inhibited by the closed structure