Investigating magnetic reconnection in Laser-produced plasmas

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Magnetic reconnection : definition & properties

• Magnetic reconnection (MR) occurs in electrically conducting plasma where :

— magnetic topology of the magnetic field lines is rearranged
— magnetic energy is converted in particle energy (both thermal and flow energy)

→ MR can disconnect formerly connected magnetic fields like in the solar photosphere (GIOVANELLI1947)

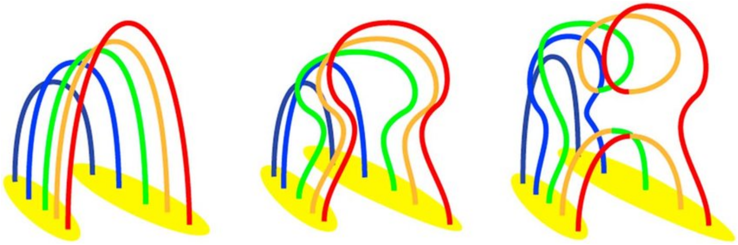
→ MR can connect formerly disconnected magnetic fields like in stellar wind-magnetosphere interaction (DUNGEY1961)

• MR important for transport across magnetic boundaries & energetization

Magnetic reconnection in solar arches

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

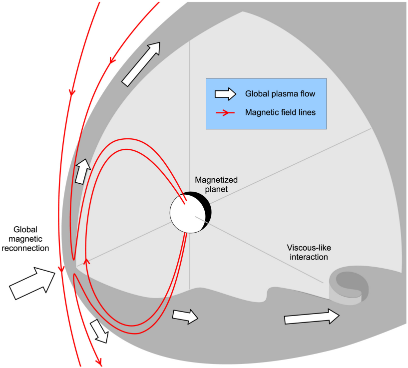
- Magnetic field lines emerge in cold sun spots



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

Magnetic reconnection in planetary magnetosphere

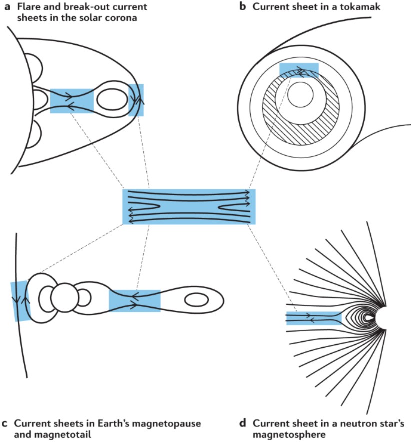
- Solar wind drives magnetosphere dynamics [*Masters* 2018, GRL] :



→ 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.] :

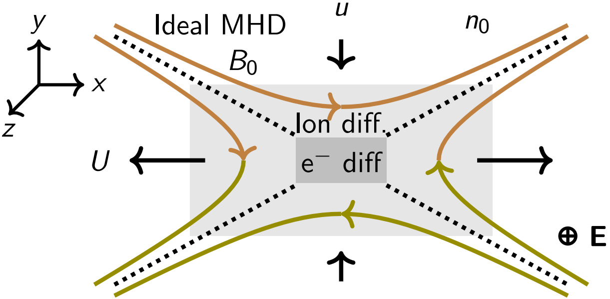


→ could be a PeVatron for cosmic rays, black-hole jets...

Big picture of 2D magnetic reconnection

- Ohm's law :

$$\mathbf{E} = -\mathbf{V}_i \times \mathbf{B} - \frac{1}{en}[\mathbf{j} \times \mathbf{B} - \nabla . \, \mathbf{p}_e] + \eta \mathbf{j} - \eta' \Delta \mathbf{j} + m_e \mathrm{d}_t \mathbf{j}$$



- 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

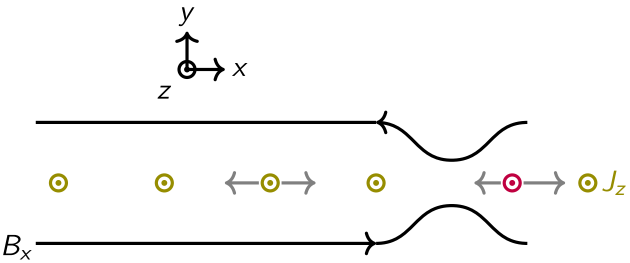
→ Agyrotropic pressure term in the electron diffusion region

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?

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 : $\gamma = \frac{(\Delta' L)^{4/5}}{\tau_R} S^{2/5}$ with $S = \frac{L v_A}{\eta}$

$\rightarrow S \gg 1$, $L \gg \lambda_{CS}$ collisional reconnection & $\tau_R \ll \tau_A$

$\rightarrow E' = S^{-1/2} \lesssim 0.01$ for "fast" high-S reconnection

- Collisionless tearing : $\gamma = \frac{1}{\sqrt{\pi}}(1 - k^2 \lambda_{CS}^2) \frac{d_e^2}{\lambda_{CS}^2} \frac{v_{Te}}{\sqrt{\rho_e \lambda_{CS}}}$

$\rightarrow \lambda_{CS} \sim d_p$, $\rho_e \sim d_e$ so γ is a fraction of Ω_p

$\rightarrow E' \sim 0.1$ for fast reconnection mediated by Hall effect

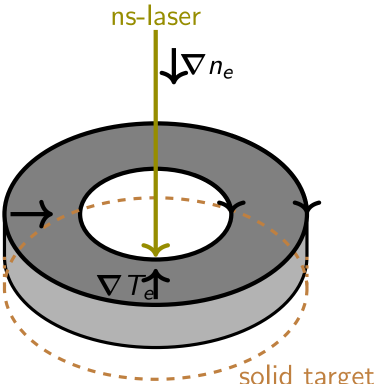
- Hall-MHD, hybrid-PIC & full-PIC simulations

$\rightarrow$ 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 $d_p \sim 2\mu$m for $n_e = 10^{28}$ m^{-3}

Magnetized plasma loop using a ns-laser

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

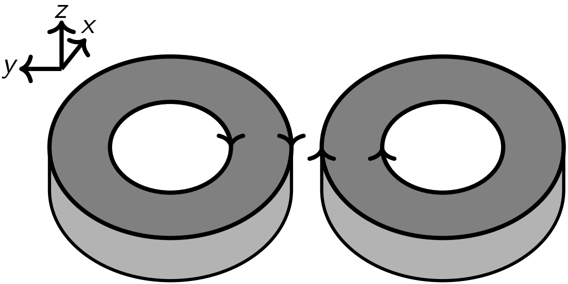


$\Rightarrow$ The B-field produced on front face is clock-wise oriented :

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

Reconnection between 2 magnetized plasma loops

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



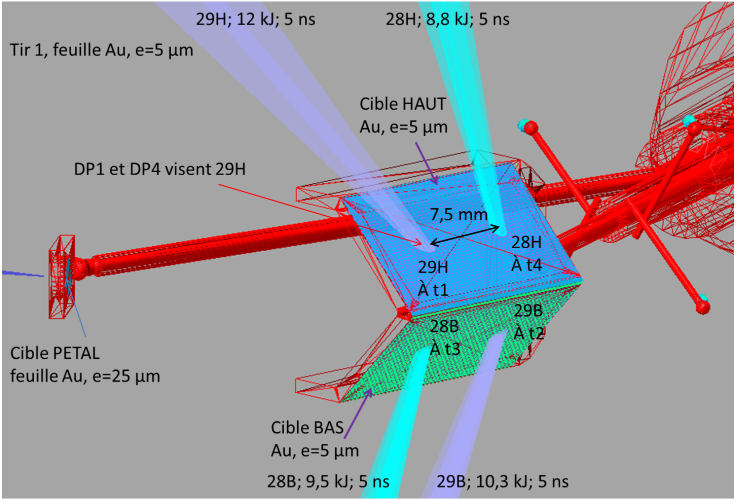
- The current sheet is building up during the irradiation
- Lundqvist number $S \sim 10^3$ (with Spitzer-Härm resistivity)

$\rightarrow$ aspect ratio of the current sheet $L/\delta < 50$

$\rightarrow$ we then are <u>not in the plasmoid regime</u>

- 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 μm	Au - 25 μm
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

$\rightarrow$ energy is then modulated for somewhat similar plasma loops

- proton probe incidence of 34^o
- 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	~ 600 T	
Electron density	$\sim 4 \times 10^{27}$ m^{-3}	
Mean flow	$\sim 2 \times 10^5$ m.s^{-1}	$\sim c$
Kinetic energy	~ 100 eV	~ 42 MeV
β parameter	$\beta_e = 0.5$, $\beta_i = 0.02$	
Loop radii	$\sim 300 \rightarrow 900$ μm	
Ion Inertial length	~ 4 μm	
Ion Gyroperiod	~ 17 ps	
Alfvén velocity	$\sim 2 \times 10^5$ m.s^{-1}	

$\rightarrow$ close to the $\beta \sim 1$ regime

$\rightarrow$ magnetization parameter $\sigma \ll 1$

Diagnostics (LMJ experiments in 2019)

- Proton radiography using PETAL on a solid target

$\rightarrow$ a proton beam is created with ps-laser on solid target by TNSA
$\rightarrow$ collected on a stack of Radio-Chromic-Films (resolved in energy)
$\rightarrow$ the proton dose give insights on the path-integrated B-field

- DMX

$\rightarrow$ integrated spectra (arbitrary units) depending on time

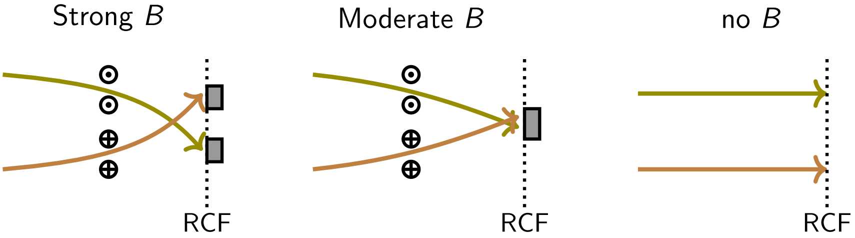
- DP1 & DP4

$\rightarrow$ provides an image of the focal spot

B-field pictured by proton-radiography

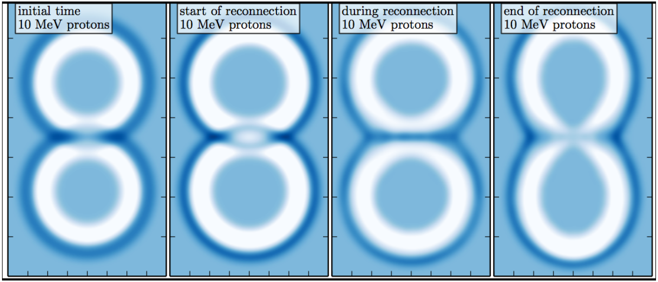
- Proton beam (42 MeV max. energy) produced by TNSA

→ using PETAL on a 25 μm gold foil



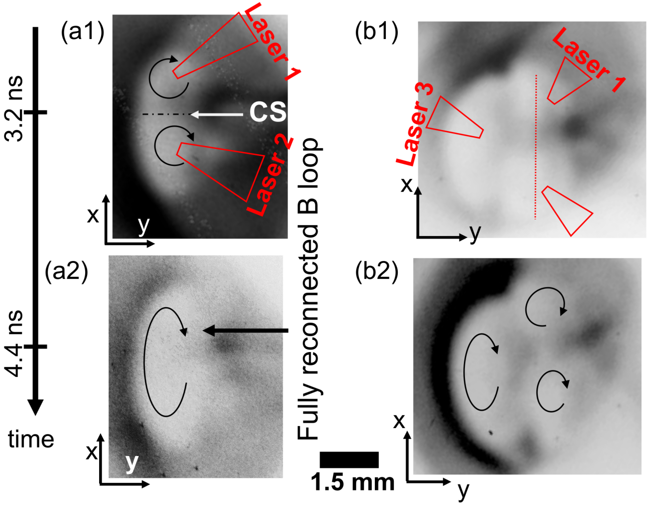
- Strong B ⇒ before Reconnection : "open mouth"
- Moderate B ⇒ during reconnection : "closed mouth"
- no B ⇒ after reconnection : nothing !

Synthetic RCF for 10 MeV proton beam



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

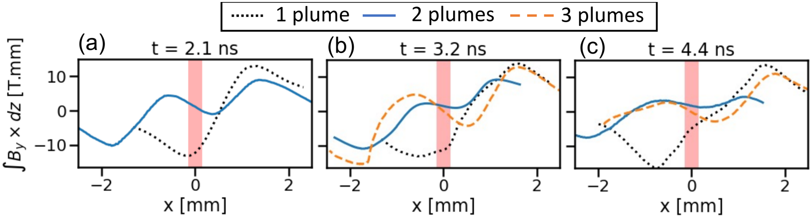
Proton radiographies from LMJ 2019 experiment



B-field reconstruction using `problem solver`

see [*Bott et al.*, 2017, J. Plasma Phys.] (open source on GitHub)

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



- weaker B-field for 2-plumes & 3-plumes : reconnection operates !

$\rightarrow$ $\partial_t \phi = \partial_t \iint B_y \, \mathrm{d}x\mathrm{d}z = 2.5 \pm 0.6$ T.mm^2.ns^{-1}

$\rightarrow$ frow Faraday law, $\partial_t \phi = \int E \mathrm{d}z \sim \lambda E$

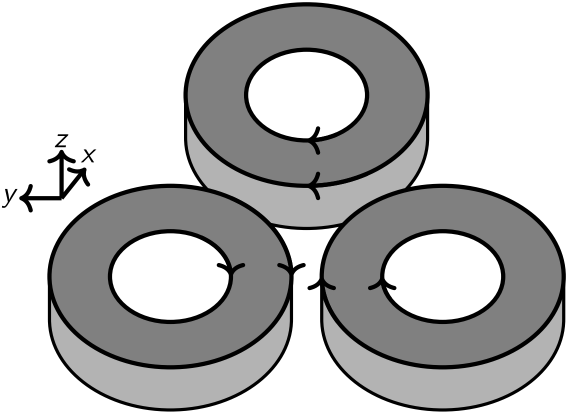
$\rightarrow$ $\int B_y \, \mathrm{d}z = 13$ T.mm and $V_0 \sim v_A = 400 \pm 130 \times 10^3$ m.s^{-1}

- reconnection rate $E' = 0.48^{+0.40}_{-0.20}$ (2-plumes case)

$\rightarrow$ <u>Fast reconnection</u> (even very fast...)

Reconnection between 3 magnetized plasma loops

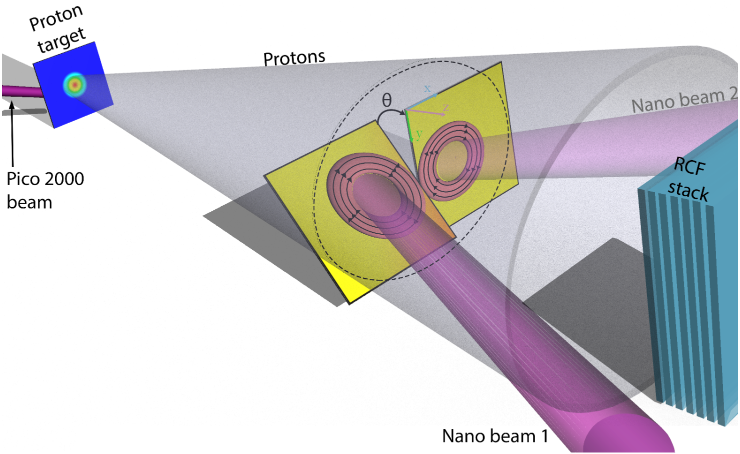
- Why did we also used 3-plumes reconnection ?



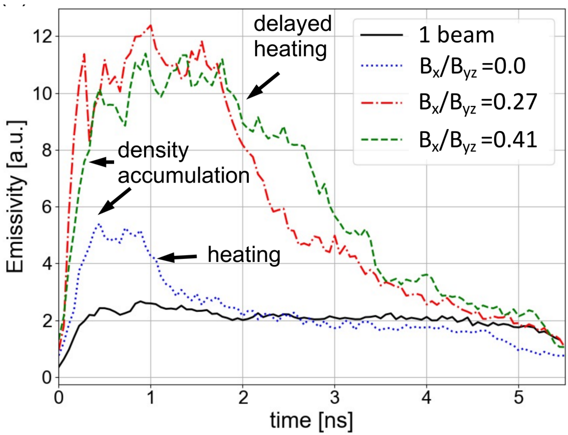
- The plasma outflow (ejecta) is "trapped" in closed structures
- With 2 plumes, creation rate < reconnection rate (small j_z)

$\rightarrow$ with 3 Plumes, smaller reconnection rate whcih make j_z grows

Lasers configurations (2017) at LULI2000



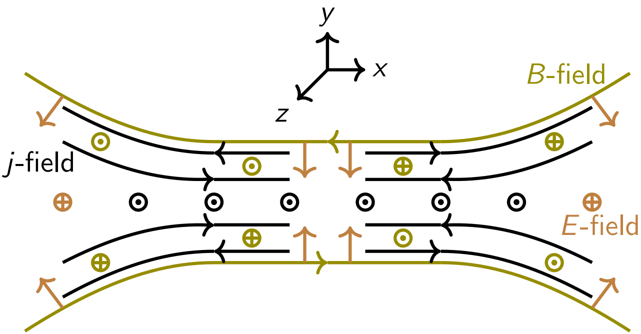
Streaked Optical Pyrometry



→ Emissivity increases with density because of the pile-up

→ Emissivity decreases for hot plasma

Hall term in the ion diffusion region

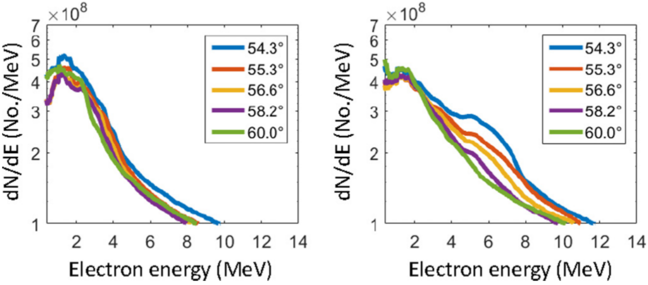


- (Hall) E_{XY} electric field associated to J_Z and B_{XY}
- j_Z grows at the tip of each loops when colliding
$\rightarrow$ quadrupolar B_Z grows because E_{XY} is no more curl-free
- j_{XY} associated to this out-of-plane magnetic field
$\rightarrow$ carried by electrons because protons are demagnetized

Relativistic magnetic reconnection ($\sigma > 1$)

Investigated by [*Raymond et al.*, 2018, PRL]
$\rightarrow$ 2 J & 40 fs w. HERCULES & 500 J & 20 ps w. OMEGA-EP
$\rightarrow$ quadrupolar Hall-like B-field using OSIRIS 3D full-PIC code

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

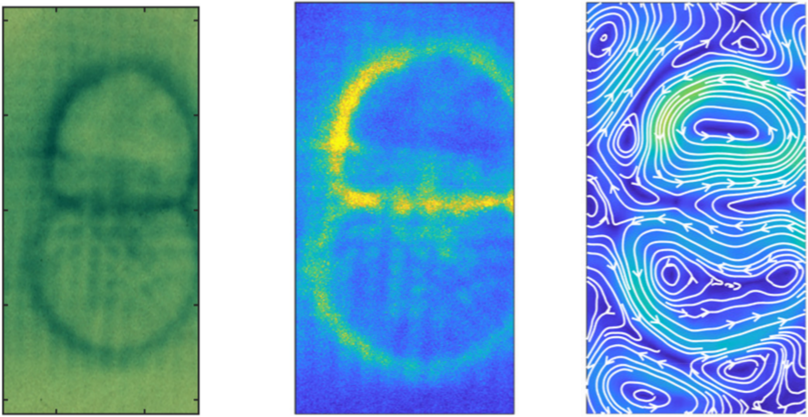


- Heating of the current-sheet e^- by reconnection

Relativistic magnetic reconnection ($\sigma > 1$)

Also investigated by [*Palmer et al.*, 2019, PoP]
$\rightarrow$ using 220 J & 9.6 ps w. VULCAN & proton probing (by TNSA)

p^+ RCF $\quad$ p^+ dose $\quad$ B-field



$\rightarrow$ 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

$\rightarrow$ need to derive a relativistic Ohm's law to get E'

- No more Hall term in an electron-positron plasma

$\rightarrow$ "single" diffusion region [*Bessho & Bhattacharjee* 2005, PRL]
$\rightarrow$ the reconnection rate is still $E' \sim 0.1$
$\rightarrow$ dynamics on the electron scales... well suited for ps lasers

- Produced in the Lab [*Greaves & Surko*, 1995 PRL] :

$\rightarrow$ 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

$\rightarrow$ B-field created by Biermann-battery : source term

$\rightarrow$ B-field is then reconnected : loss term

- We already measured fast reconnection : $E' > 0.48$

$\rightarrow$ first measure (of a lower value) of a reconnection rate

- For long pulse lasers, one can play with target geometry

$\rightarrow$ guide-field, initial quadrupolar B-field

- For short-pulse lasers, scales need to lowered

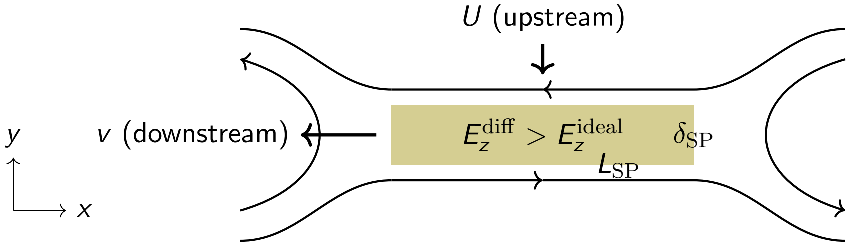
$\rightarrow$ enough time to trigger reconnection (strongly driven) ?

$\rightarrow$ pair plasma of interest in compact objects...

Additional material,

Sweet-Parker regime

- Upstream : frozen-in theorem $\rightarrow$ ideal Ohm's law $E_z = UB_0$
- Diffusion region (collisional) i$\rightarrow$ $J_z = \sigma E_z$

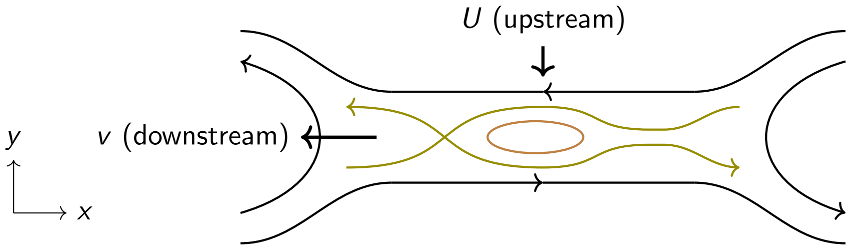


$L \ll \delta$: elongated current sheet & $E' = S^{1/2}$

$S \sim 10^8$ in solar flares... hence reconnection is very slow !

Plasmoid regime

- For $S > S_{\rm critical} \sim 10^4$, elongated SP layers are unstable to secondary magnetic islands (MATTHAEUS1985)



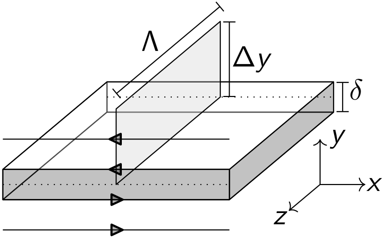
1 — linear collisional tearing (FURTH1963 + RUTHERFORD1973)

2 — X-point collapse in a SP elongated current sheet

3 — L grows until $L \gtrsim 50\delta$, that is $S \gtrsim S_{\rm crit} \equiv 10^4$

4 — collapse & creation of secondary islands (w. smaller δ)...

Hybrid-PIC simulation using `heckle`



- $\mathrm{d}\Phi = \mathbf{B}.\mathrm{d}\mathbf{S}$: differential magnetic flux across the surface $\mathrm{d}\mathbf{S}$

$\rightarrow$ 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 : $\partial_t \iint \mathbf{B}.\mathrm{d}\mathbf{S} = \iint (\boldsymbol{\nabla} \times \mathbf{E}).\mathrm{d}\mathbf{S} = \int \mathbf{E}.\mathrm{d}\mathbf{l} = E\Lambda$
- Same upward flow below the $y = 0$ plane, hence $E = 0$ at $y = 0$

$\rightarrow$ $E = B\Delta y/\Delta t = BU$ where U is the fluid velocity

$\rightarrow$ E can be normalized using B_0 and A_0, ie

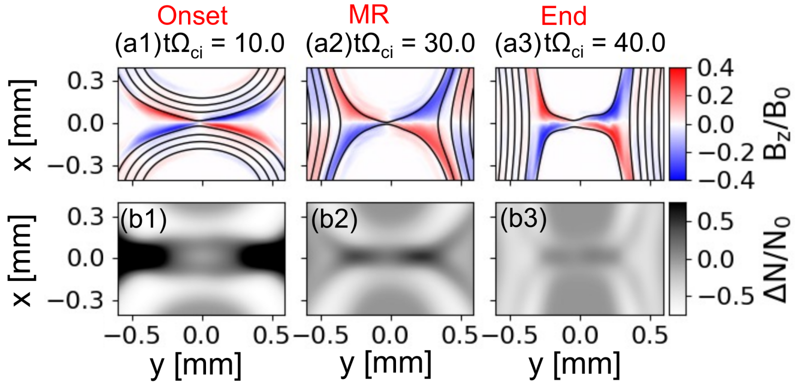
$E' = E/(B_0 A_0) = U/A_0$

- This is a creation rate of flux upstream the current sheet

$\rightarrow$ for stationary reconnection, creation rate $\equiv$ reconnection rate

Hybrid-PIC simulation using `heckle`

- Creation of a "Hall" quadrupolar B-field

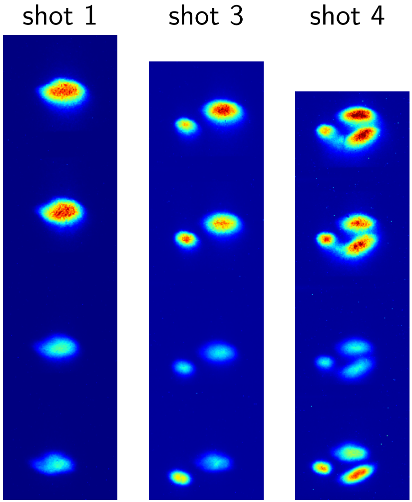


→ the "mouth" opens just before the onset

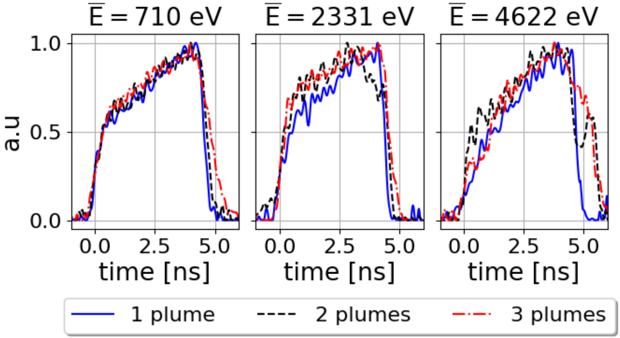
→ then closes during reconnection

→ and disappears when there is no more B-field

DP1 images



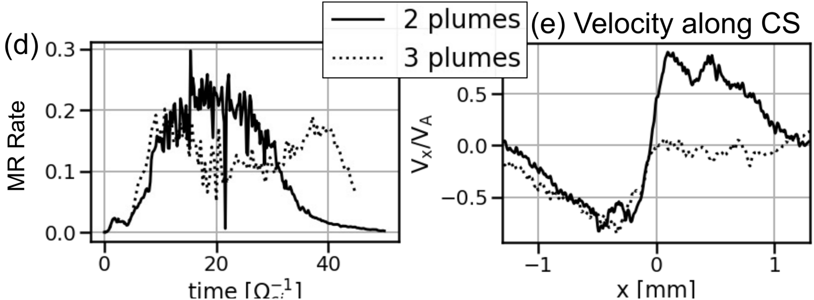
DMX spectra



→ 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

$\rightarrow$ smaller reconnection rate with 2 plumes

$\rightarrow$ the outflow velocity is clearly inhibited by the closed structure