What can we learn about magnetic reconnection using laser-induced High Energy Density Plasmas ?

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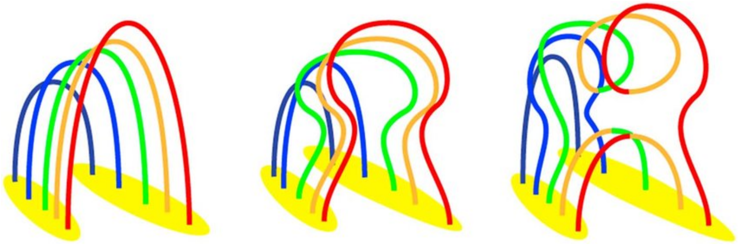
Magnetic reconnection in solar arches

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

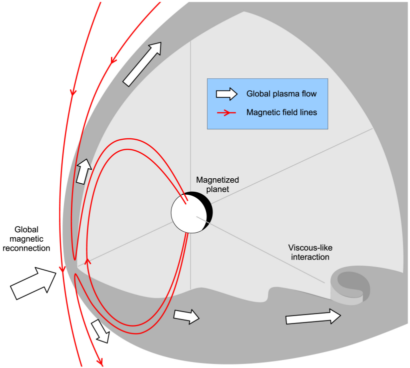
- Magnetic field lines emerge in cold sun spots



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

Magnetic reconnection in planetary magnetosphere

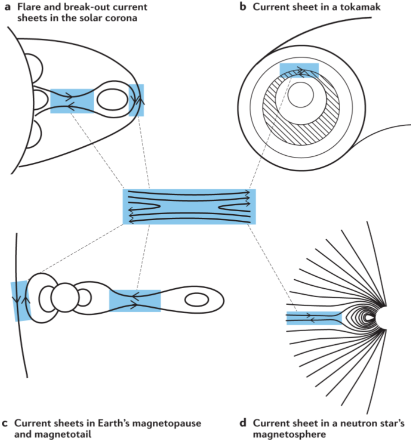
- Solar wind drives magnetosphere dynamics [*Masters* 2018, GRL] :



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

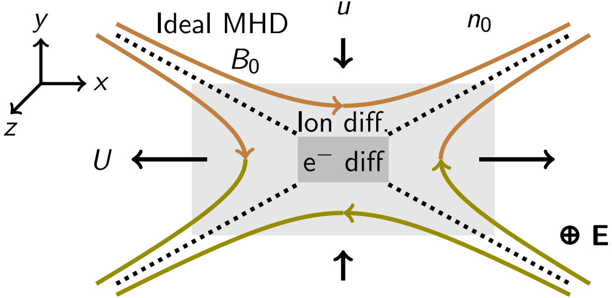
Current sheets in plasma physics

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



$\rightarrow$ could be a PeVatron for cosmic rays, black-hole jets...

Big picture of 2D magnetic reconnection



- Ohm's law :

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

- Efficiency of reconnection measured by $E' = E/B_0 v_A$

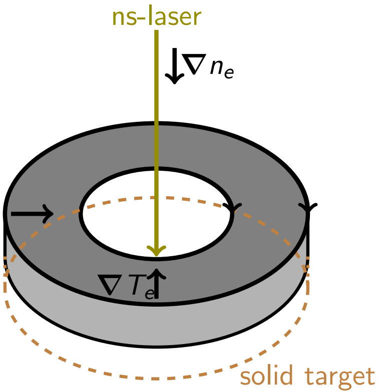
→ Ideal term in the MHD region
→ Hall term in the Ion diffusion region (control E')
→ Agyrotropic pressure term in the electron region (control J_z)

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

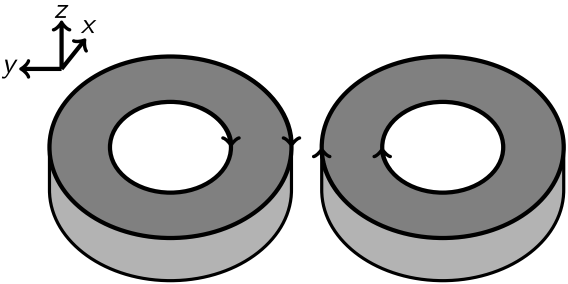


$\Rightarrow$ The B-field produced on front face is clock-wise oriented :

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

Reconnection between 2 magnetized plasma loops

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



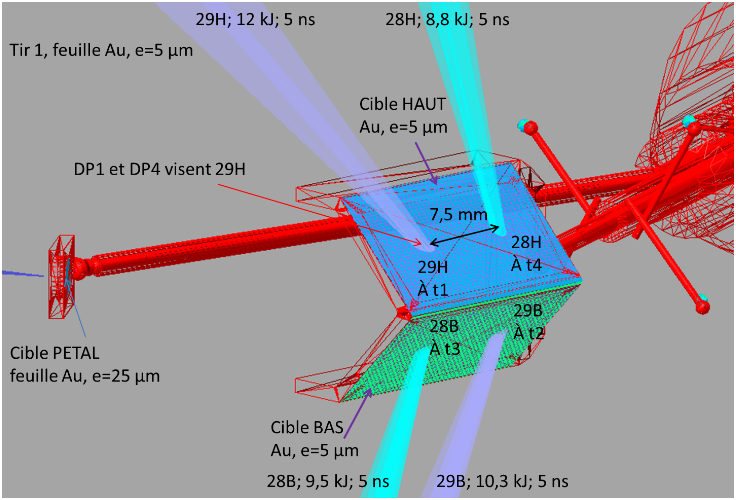
- The current sheet is building up during the irradiation
- Lundqvist number $S \sim 10^3$ (with Spitzer-Harm resistivity)

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

$\rightarrow$ 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 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	$\sim$ 600 nT	
Electron density	$\sim 4 \times 10^{27}$ m^{-3}	
Mean flow	$\sim 2 \times 10^5$ m.s^{-1}	$\sim c$
Kinetic energy	$\sim$ 100 eV	$\sim$ 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	$\sim$ 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

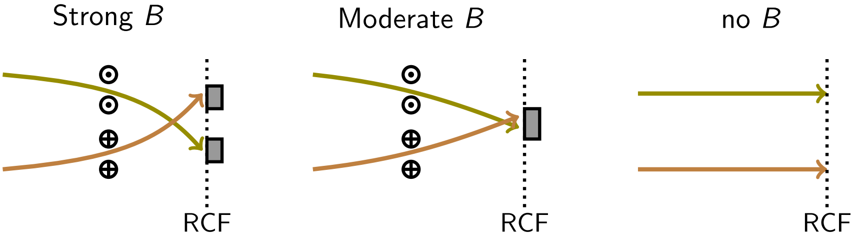
- DP1 & DP4

$\rightarrow$ provides an image of the focal spot

B-field pictured by proton-radiography

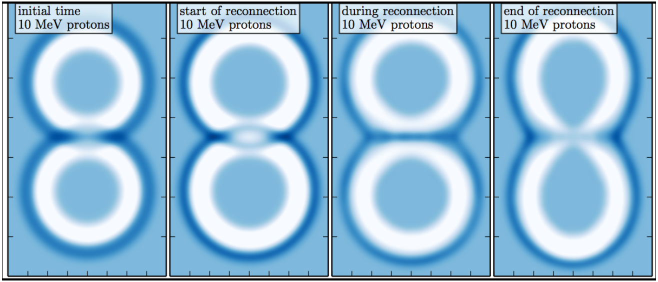
- Proton beam (42 MeV max. energy) produced by TNSA

→ 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 !

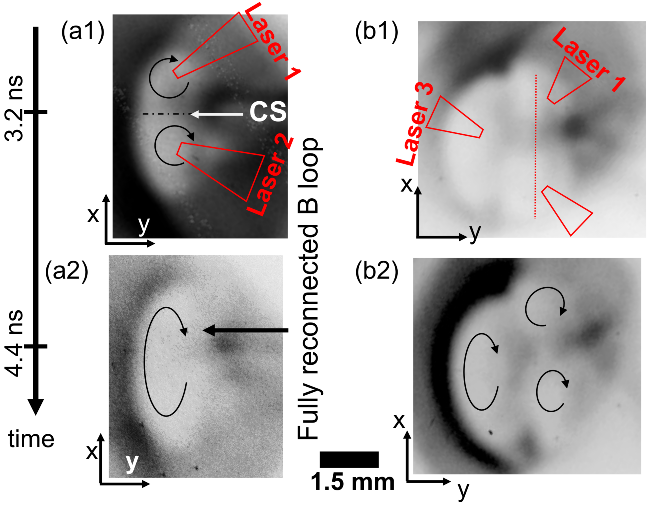
Synthetic RCF for 10 MeV proton beam



→ a "mouth" open when B field is compressed

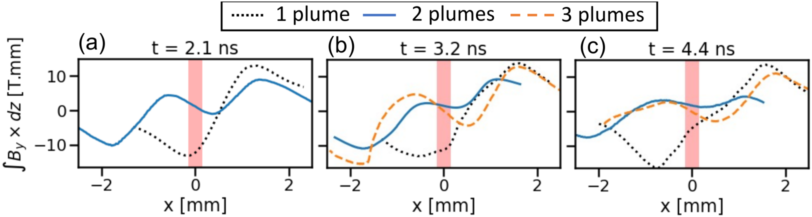
→ but closes when reconnection operates (and decrease B)

Proton radiographies from LMJ 2019 experiment



B-field reconstruction using `problem` solver

- 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}

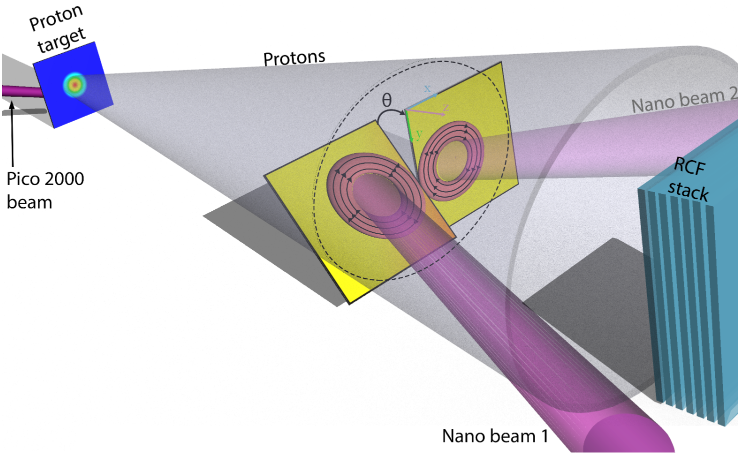
$\rightarrow$ frow Faraday law, $\partial_t \phi = \int E \mathrm{d}z \sim \lambda E$

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

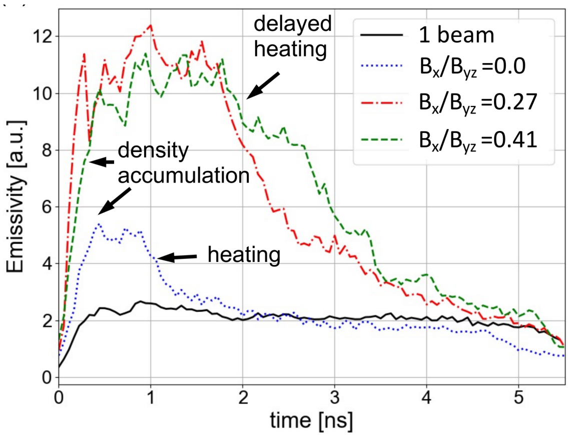
- reconnection rate $E' = 0.48^{+0.40}_{-0.20}$ (2-plumes case)

$\rightarrow$ Fast reconnection (even very fast...)

Lasers configurations (2017) at LULI2000



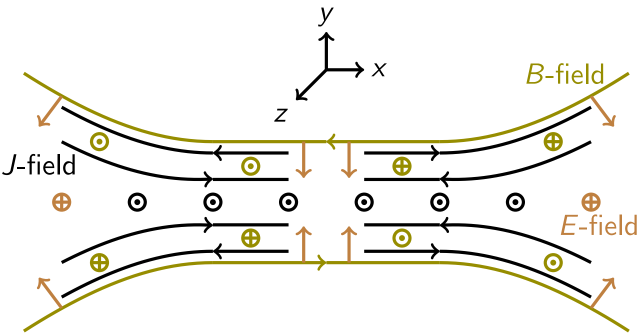
Streaked Optical Pyrometry



→ 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
→ 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

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

- One can play with target geometry for guide-field

$\rightarrow$ larger magnetic compression
$\rightarrow$ larger electron density, smaller electron temperature

- One can play with target geometry for Quadrupolar B-field

$\rightarrow$ investigated in 2015... to be published !