

Experimental mitigation of fast magnetic reconnection in multiple interacting laser-produced plasmas

S. Bolanos¹, J. Fuchs¹, C. Courtois² , A. Grisolet²,
R. SMETS³, et al.

¹LULI, ²CEA, ³LPP...

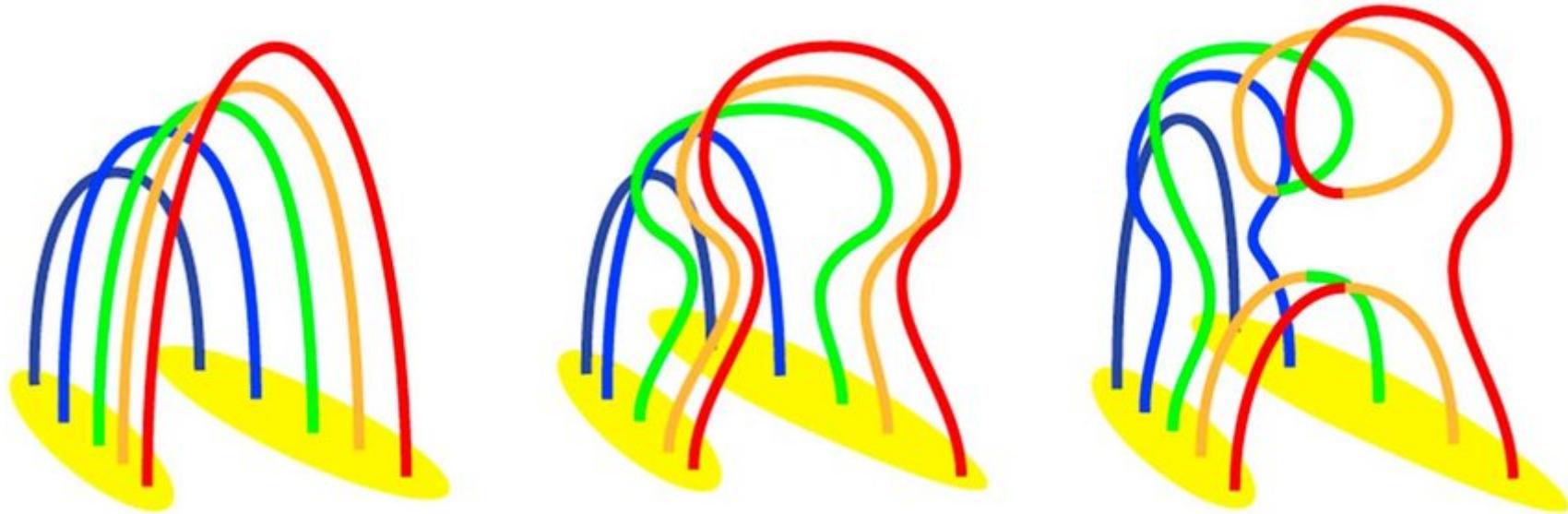
This study is submitted to PRL.

"LMJ user meeting", 8-9 june 2023

Magnetic reconnection in solar arches

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

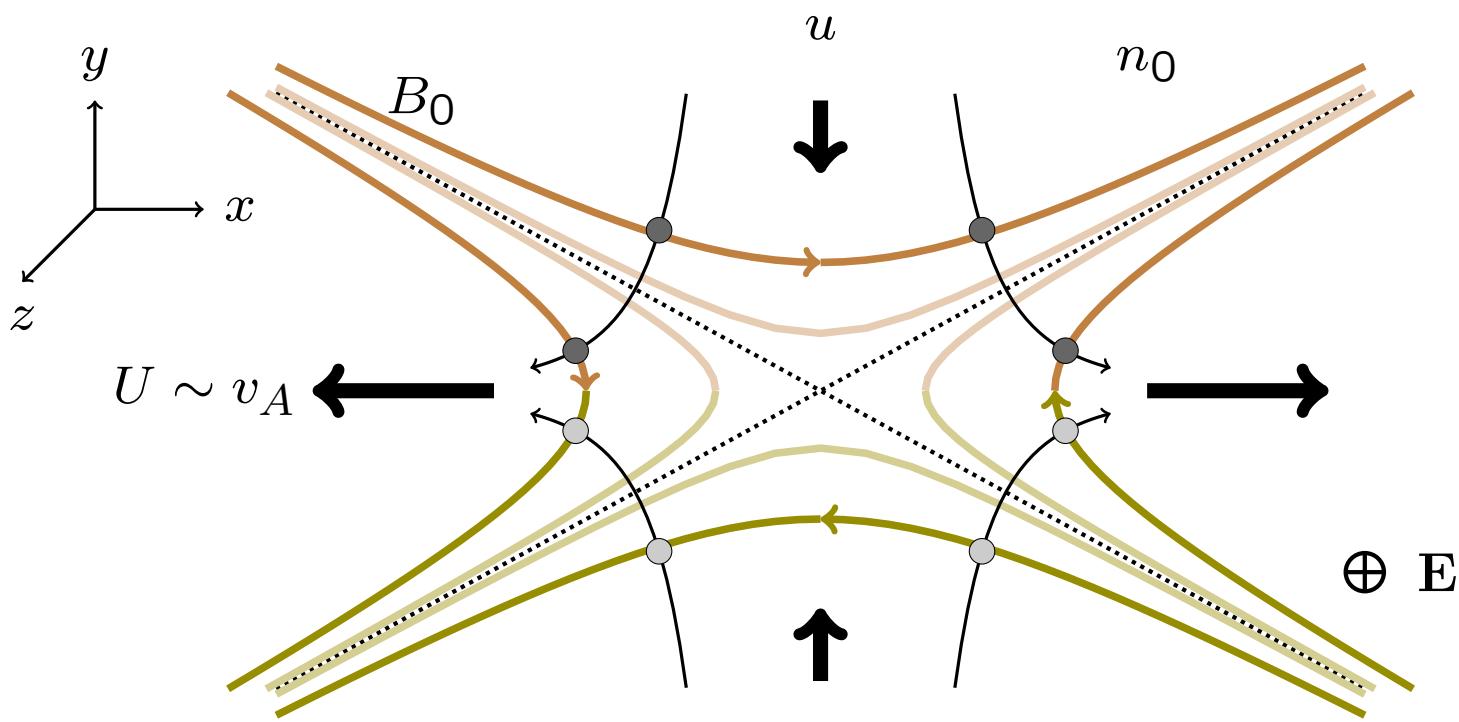
- Magnetic field lines emerge in cold "sun" spots



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

⇒ Can this 3D phenomenon be reduced to a simpler 2D problem ?
What is the origin of the dissipation ? How fast it goes ?

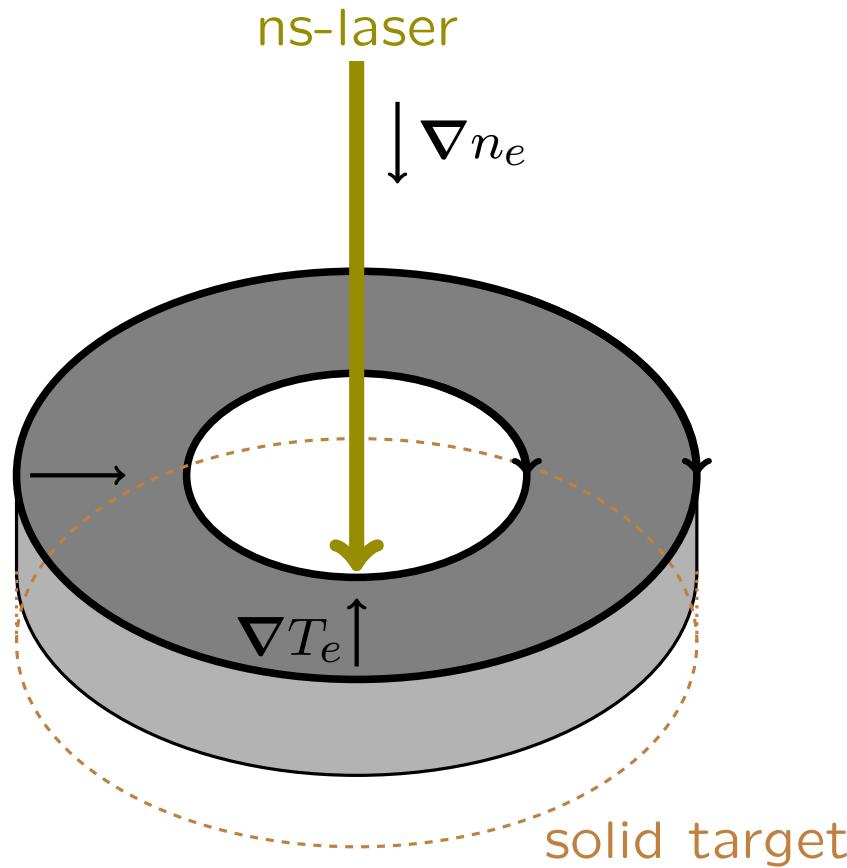
Magnetic reconnection in 2D



- Ohm's law : $\mathbf{E} = -\mathbf{V} \times \mathbf{B} - \frac{1}{en}[\mathbf{j} \times \mathbf{B} - \nabla \cdot \mathbf{p}_e] + \eta \mathbf{j} - \eta' \Delta \mathbf{j} + m_e d_t \mathbf{j}$
- Efficiency of reconnection measured by $E' = E/B_0 v_A$
 - Dissipation \equiv plasma resistivity : "slow reconnection" $E' \leq 0.01$
 - Dissipation $\equiv e^-$ agyrotropy : "fast reconnection" $E' \sim 0.1$

Magnetized plasma loop using a ns-laser

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



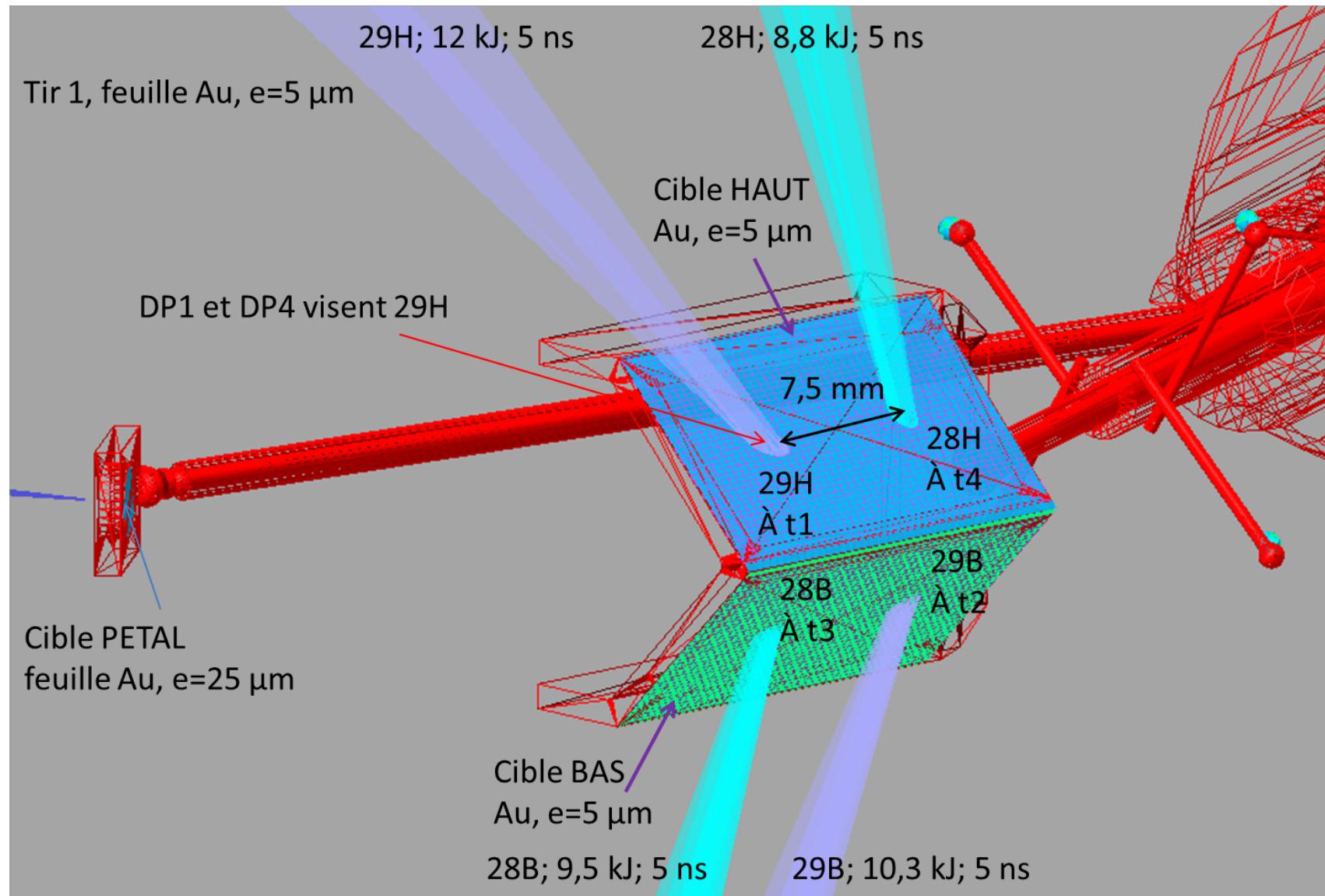
⇒ The B-field produced on front face is clock-wise oriented :

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

Diagnostics

- 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) for depending on time
- DP1 & DP4
 - provides an image of the focal spot

Lasers configurations (first shot)



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 and energy is then modulated
- energy depends on the angle... 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

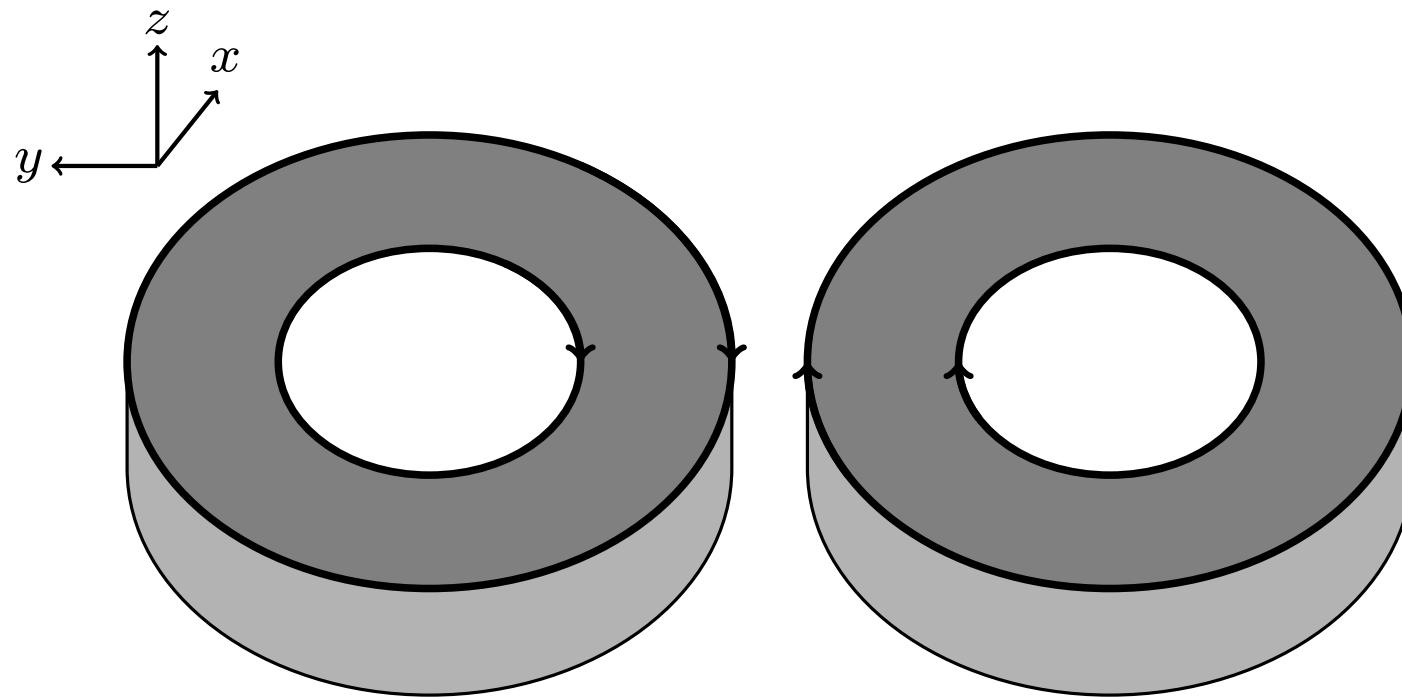
Plasmas parameters

- From fci2 simulation for the plasma plume :

	Plasma plume	Proton beam
Magnetic field	$\sim 600 \text{ nT}$	
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	$\sim 2 \times 10^5 \text{ m.s}^{-1}$	

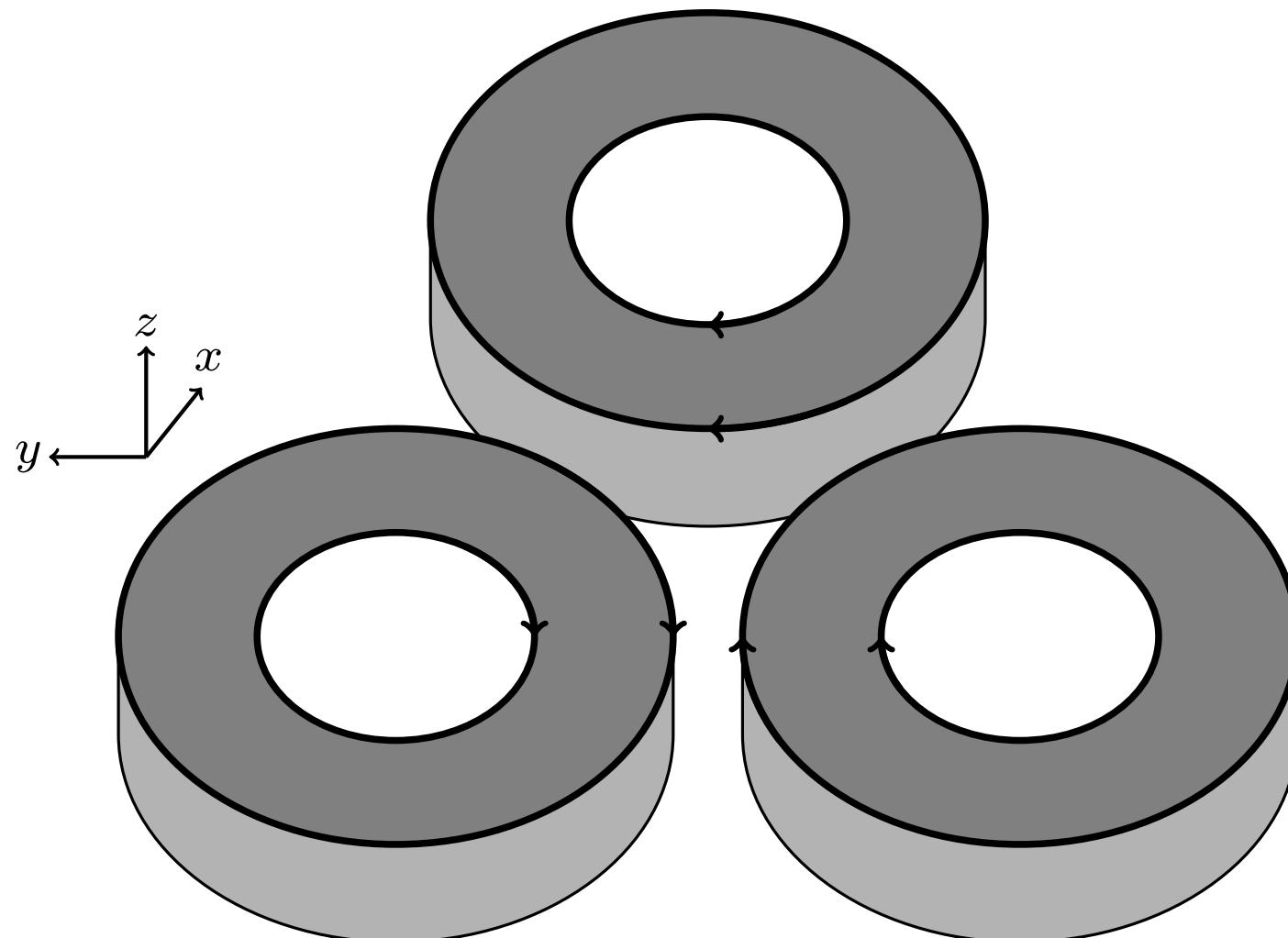
- close to the $\beta \sim 1$ regime
- magnetization parameter $\sigma \ll 1$

Reconnection between 2 magnetized plasma loops



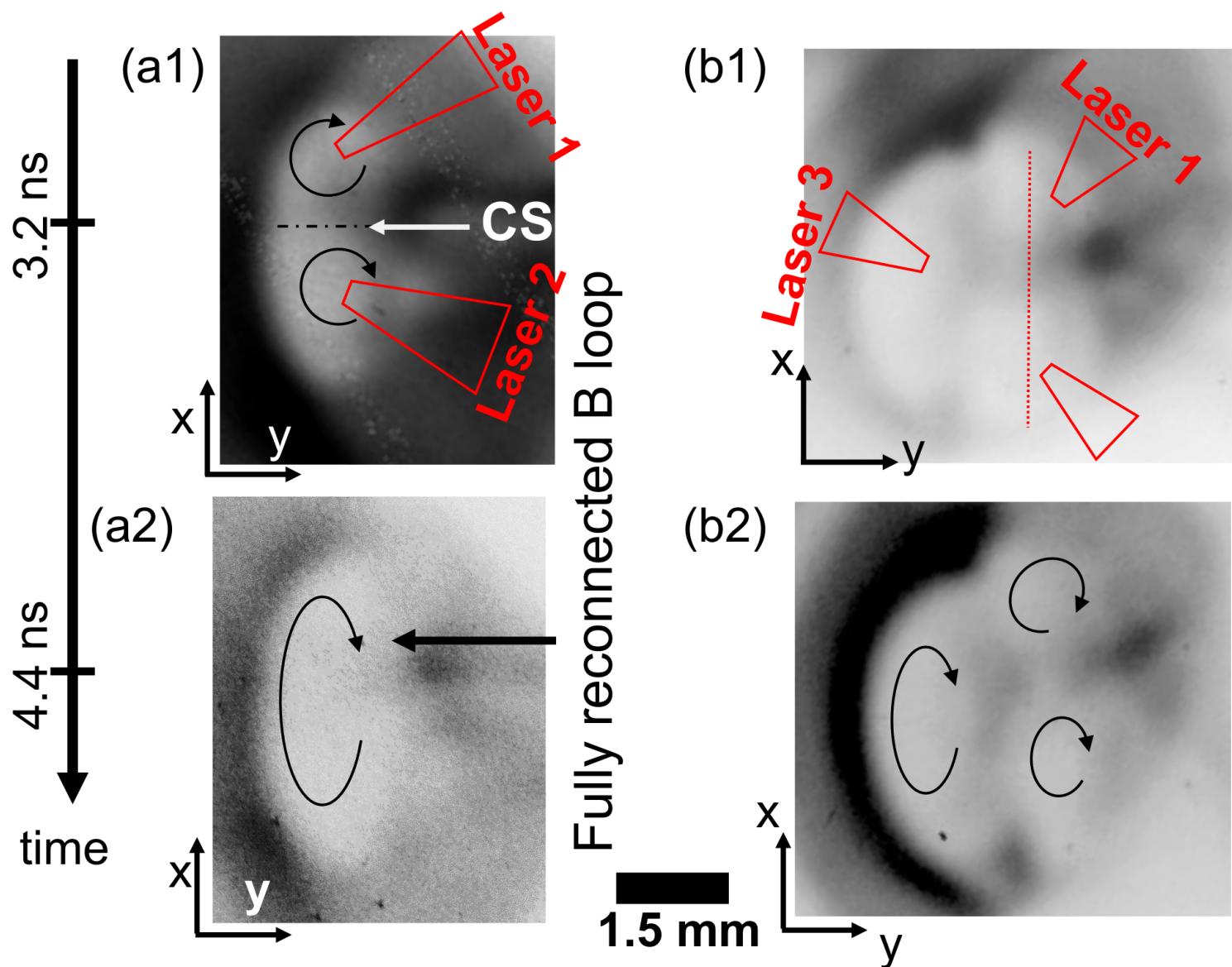
- the current sheet is building up with the irradiation
- Lundqvist number $S \sim 10^3$ (Spitzer-Harm) : somewhat collisionless
- aspect ratio of the current sheet < 50
- curvature of the B-field in favour of single X-type reconnection
- we consider the problem with a 2D (numerical) approach

Reconnection between 3 magnetized plasma loops



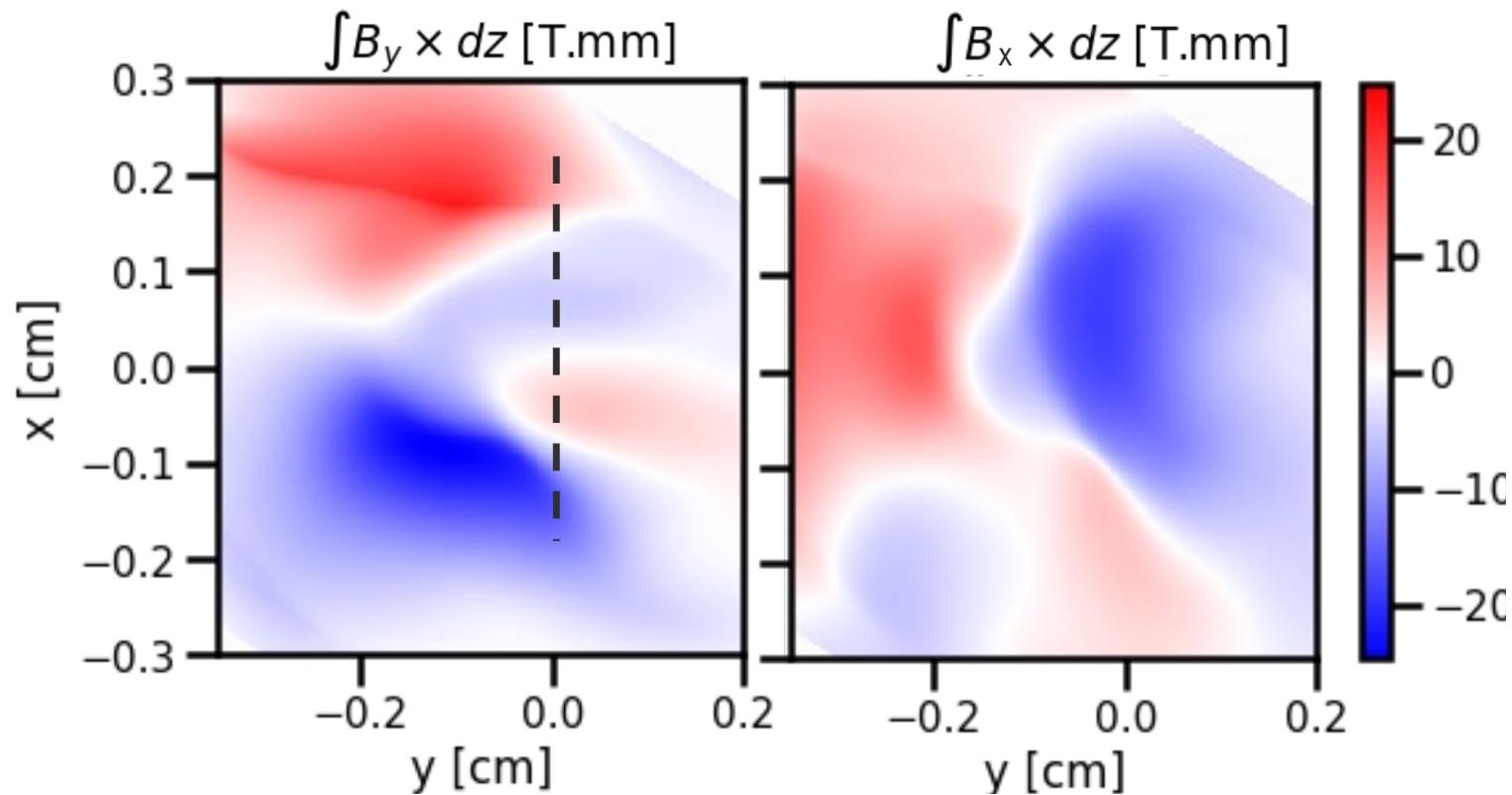
→ the plasma outflow is "trapped" in closed structures

Comparison between 2-plumes & 3-plumes



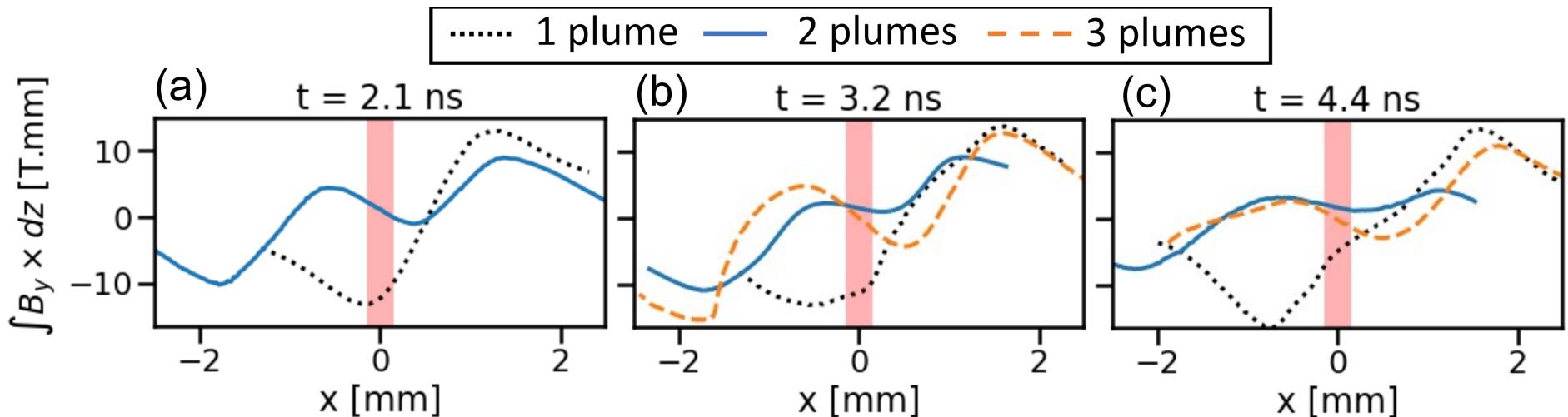
→ reconnection rate E' larger for 2-plumes

Path-integrated for B-field (3-plumes)



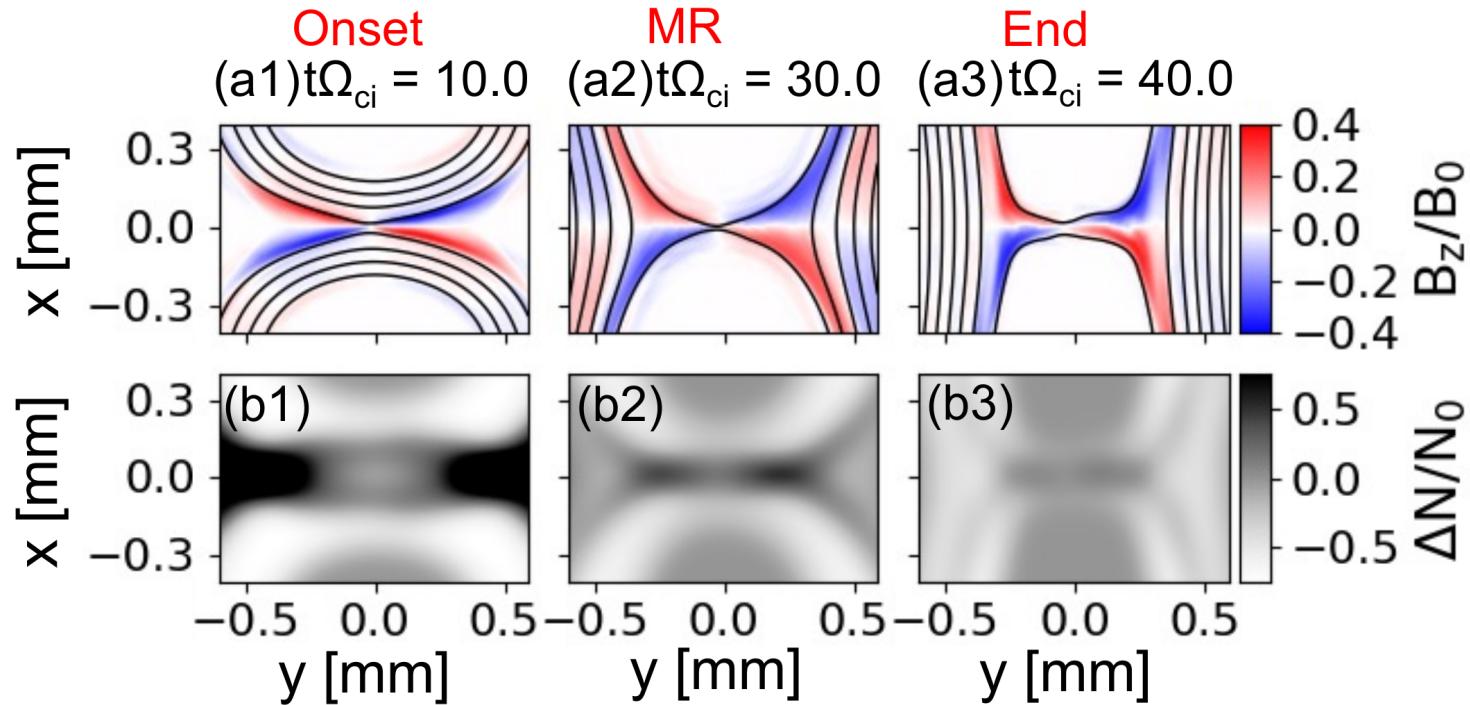
- using problem solver [*Bott et al. 2017, JPP*]
- we considered 30 MeV protons for this analysis

B-field reconstruction using problem



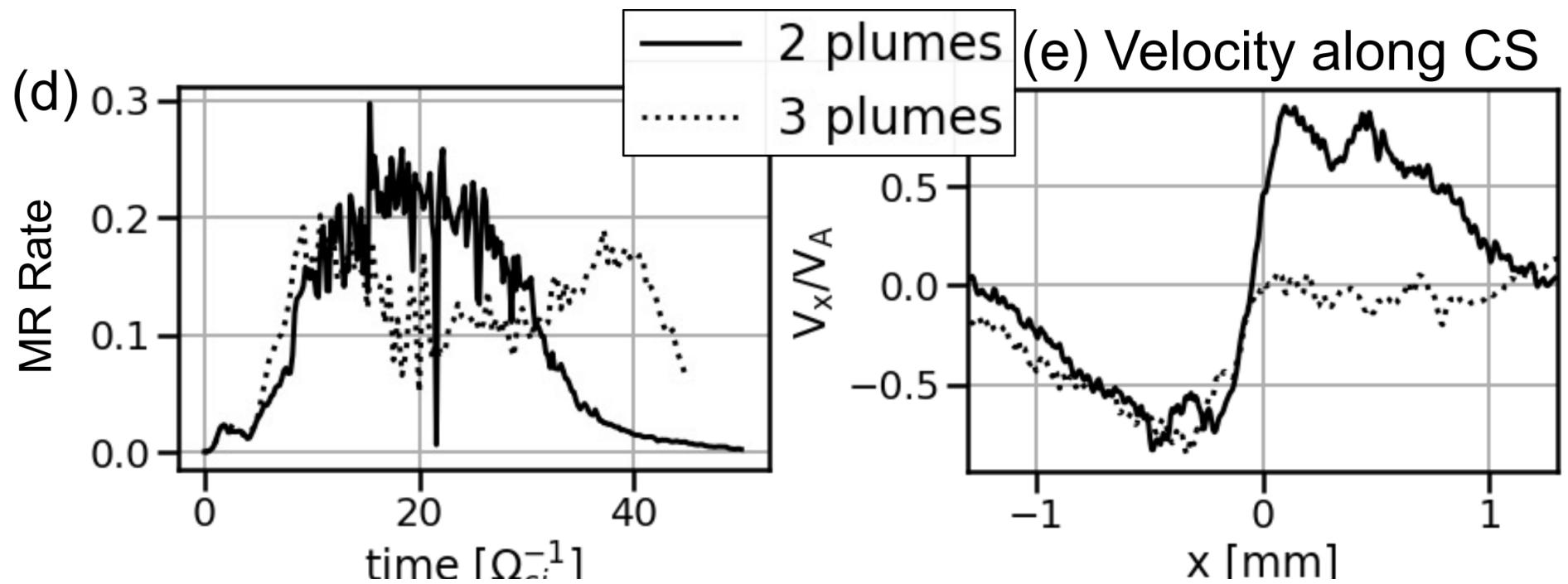
- weaker B-field in current sheet for 2-plumes
- we can then compute $\partial_t \phi = \partial_t \iint B_y dx dz = 2.5 \pm 0.6 \text{ T.mm}^2.\text{ns}^{-1}$
- from Faraday law, $\partial_t \phi = \lambda E$
- with $\int B_y dz = 13 \text{ T.mm}$ and $V_0 \sim v_A = 400 \pm 130 \times 10^3 \text{ m.s}^{-1}$
- then, the reconnection rate $E' = 0.48^{+0.40}_{-0.20}$

Hybrid-PIC simulation using heckle



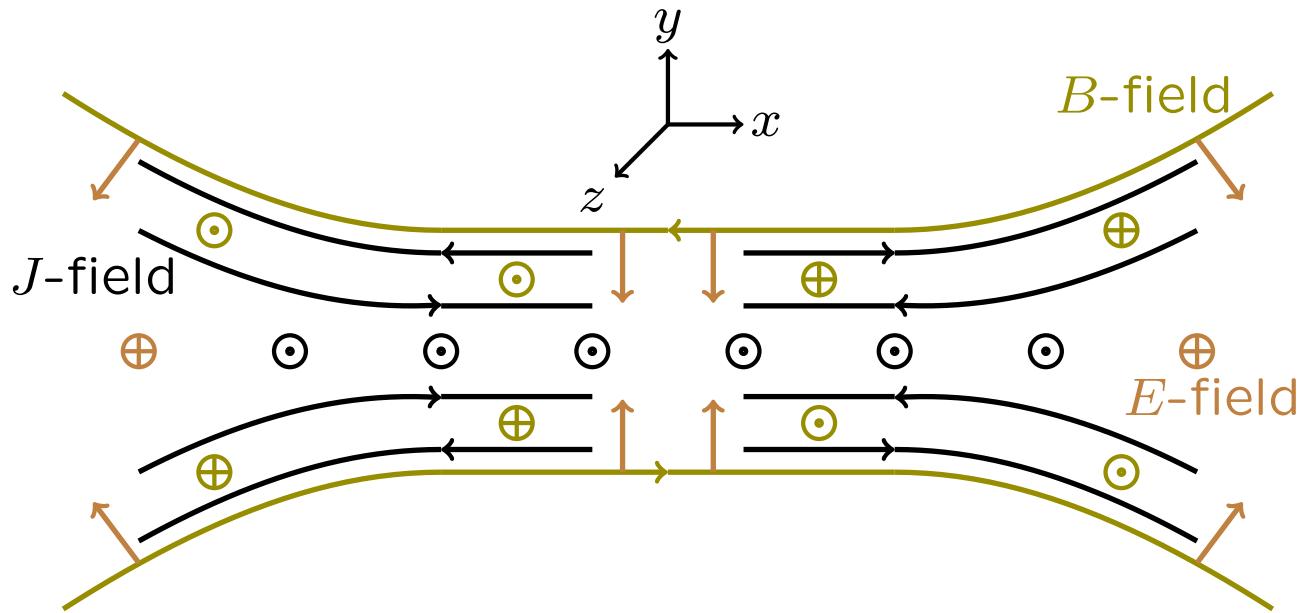
- the "mouth" opens just before the onset
- then closes during reconnection
- and disappears when there is no more B-field

Numerical reconnection rate with heckle



- smaller reconnection rate with 2 plumes
- the outflow velocity is clearly inhibited by the closed structure

Importance of the Hall effect for fast reconnection

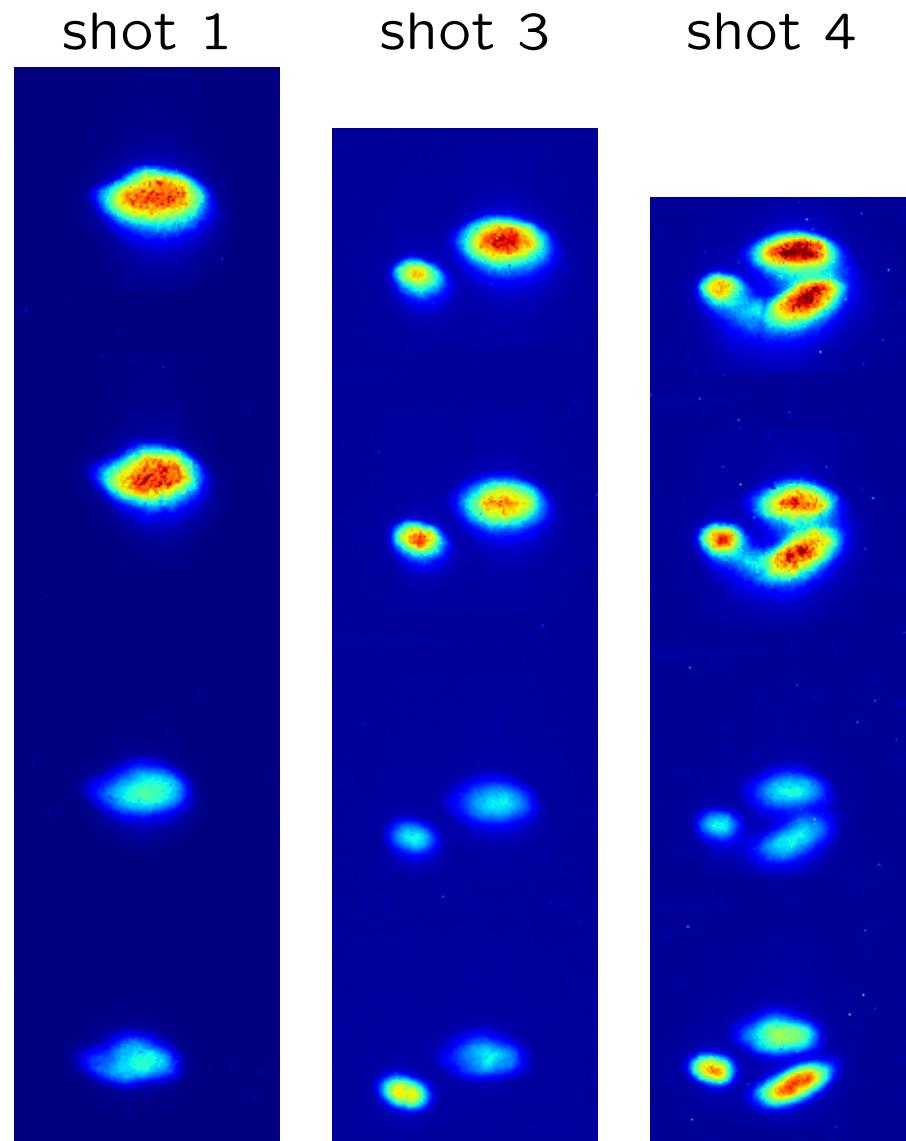


- (Hall) E_{XY} electric field associated to J_Z and B_{XY}
- J_Z grows at the tip of each loops when colliding
→ quadrupolar B_Z grows because E_{XY} is no more curl-free
- J_{XY} associated to this out-of-plane magnetic field
→ carried by electrons because protons are demagnetized

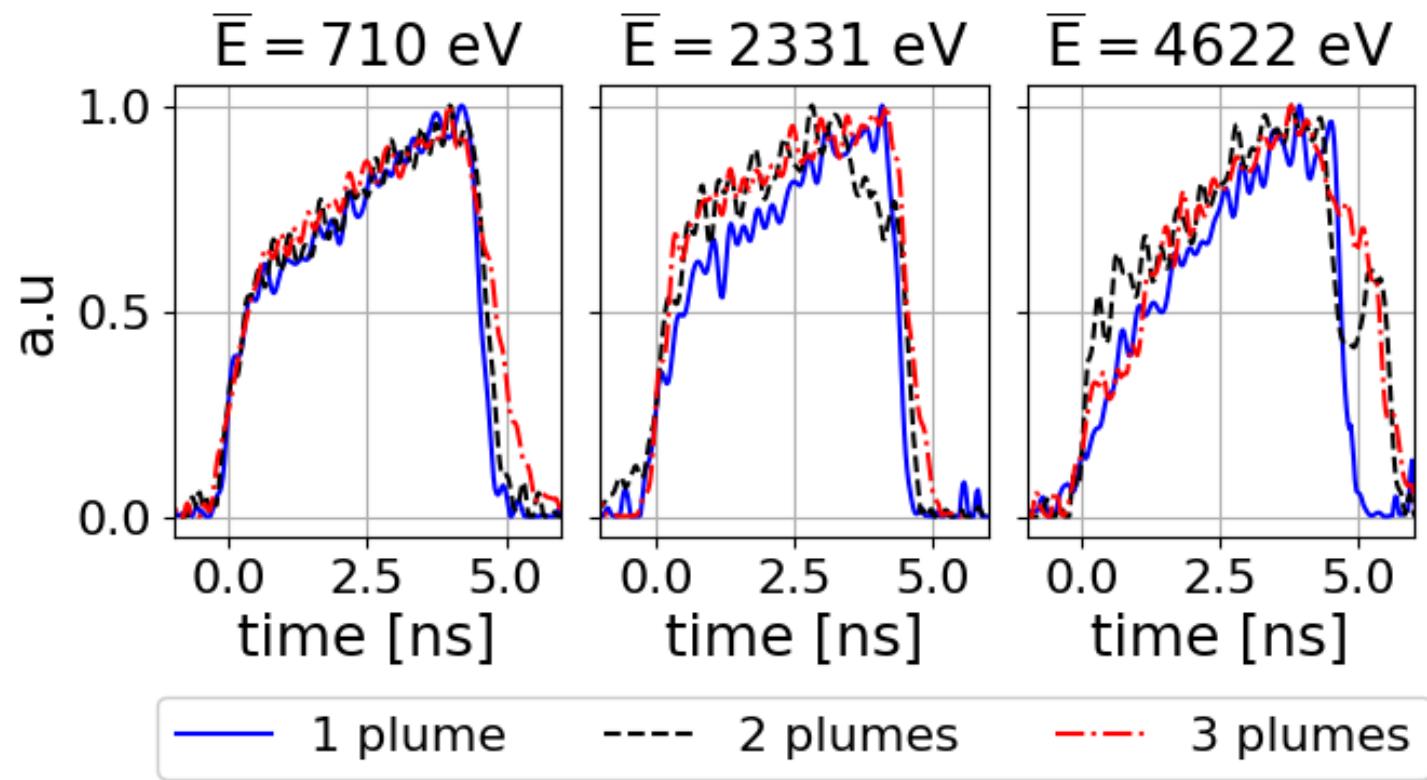
Concluding remarks

- Magnetic reconnection operates in both 2-plumes & 3-plumes cases
- In the 2-plumes case, $E' > 0.48$
 - first measure (of a lower value) of a reconnection rate
 - balance between creation & loss rate is coherent with fci2 results
- "Fast reconnection" is slowed down in the 3-plumes case
 - magnetic reconnection is hampered as the outflow is trapped
 - magnetic reconnection is hampered as the Hall B-field is lowered

DP1 images



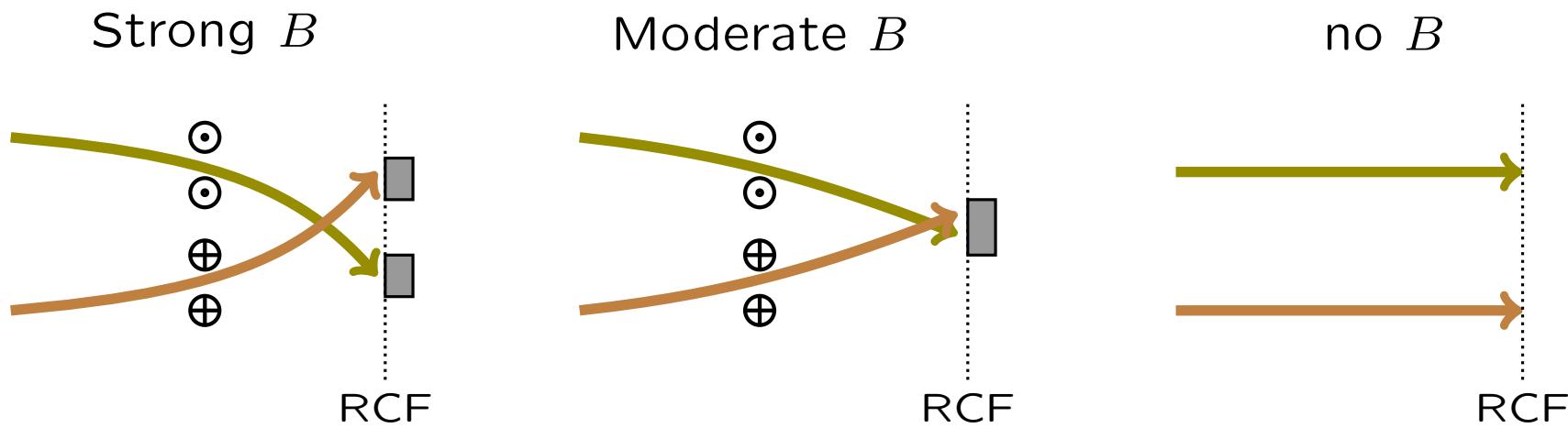
DMX spectra



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

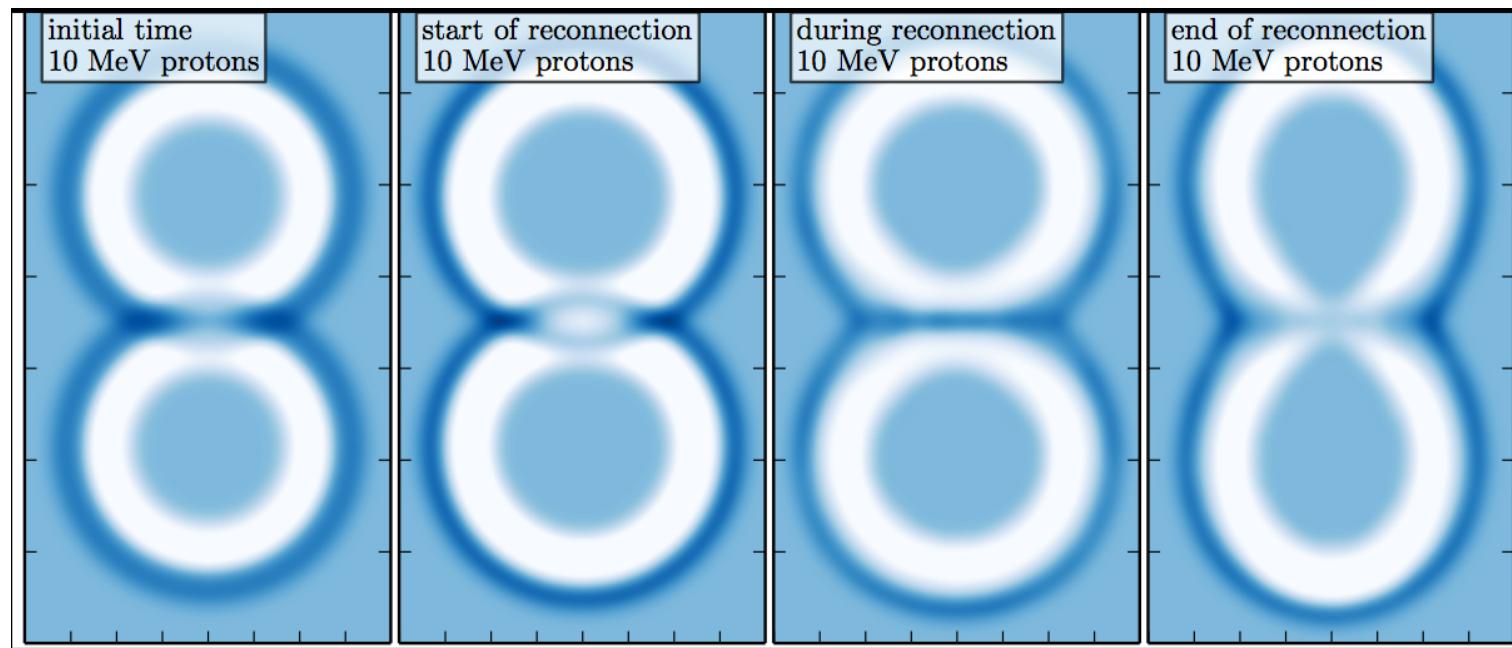
B-field pictured by proton-radiography

- 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)