How to study space plasma physics with Laboratory experiments

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Laboratory Experiments :

- MRX (Princeton Univ.) :
  driven/guided reconnection [Yamada et al, 1997]
- LAPD (UCLA) :
  3D reconnexion of flux ropes [Gekelman et al., 2012]
- Z-Pinch (Imperial College) :
  driven reconnection [Hare et al., 2018]
- VTF (Harvard Univ.) :
  new facility in Madison Univ.
- High-power Laser : Titan, Omega, LMJ, Osaka,...

→ We focus on laser facilities in this presentation

How lasers can be used ?

- Irradiation of a solid target : plasma plumes on few ns
- Irradiation of a gas : ionization inverse Bremsstrahlung
- External coils can create B fields (quasi-DC) of few T

$\rightarrow$ How scales compare ?

$\rightarrow$ Which range of parameters ?

$\rightarrow$ What can be measured (& how) ?

$\rightarrow$ Which topologies can be explored ?

Space plasmas vs HEDP

	HED Plasmas	Space Plasmas
Magnetic field	20 T	60 nT
density	10^{27} m^{-3}	10^{7} m^{-3}
Temperature	400 eV	200 eV
Resistivity (Spitzer)	10^{-7} Ωm	0
Lundqvist Numb.	200	∞
Beta parameter	100	1
Ion cyclotron time	0.5 ns	1 s
Ion skin depth	10 μm	30 km
Alfvén speed	20 km.s^{-1}	200 km.s^{-1}
Sound speed	200 km.s^{-1}	200 km.s^{-1}
Ion thermal speed	300 km.s^{-1}	200 km.s^{-1}

What can we observe ?

- RCF w. proton beam by TNSA & ps laser : EM fields
- Thomson parabola : energy spectra
- interferometry : (integrated) density
- imager : resolved in space but integrated in freq.

  $\rightarrow$ temperature w. assumption like black body...

- Integrated quantities :

  $\rightarrow$ need to be decifered w. post-treatment

Which consequences on the physics ?

- We need to consider the energy deposition on the plasma
- We need to evaluate the DC magnetic field
- We need to consider the collisions (magnetic diffusivity)
- Non-relativistic : Sonic/Alfvenic mach number ?
- Strong gradient : which transport phenomenons ?
- Are we close to the critical density ?

$\rightarrow$ Strong consequences on the kind of numerical simulations one can use

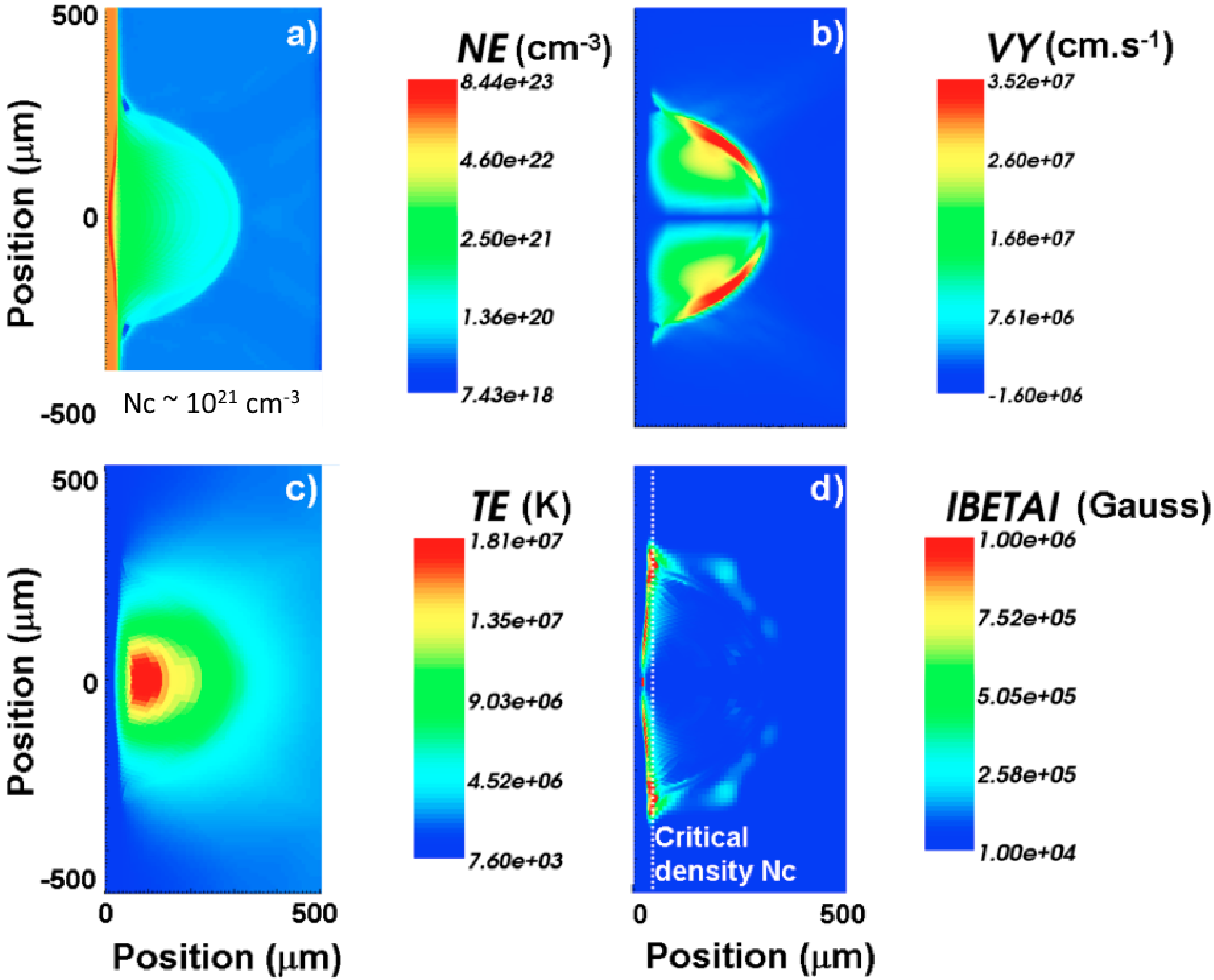
Energy deposition (photons)

The energy deposition mediated by the photons coming from the laser is very important :

- ionization rate
- density
- temperature

Classified research...
especially if Z value of the target is too large

Hydro-radiative codes (FCI2)



Biermann-battery effect

- Dynamo effect : growth of B field from a seed...
- Biermann-battery effect : birth of B field from 0...

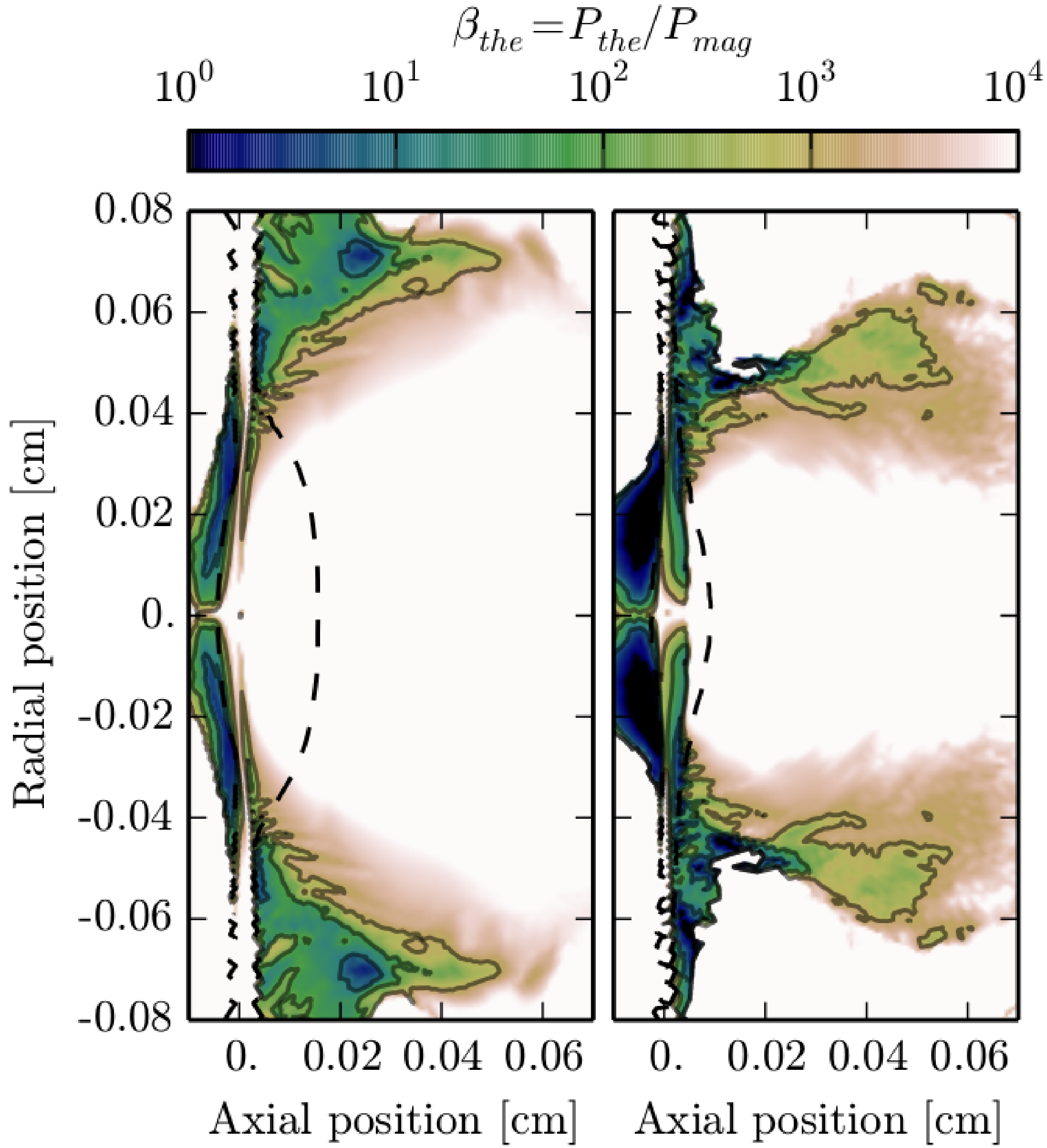
Irradiation with the laser normal to the target

$\rightarrow$ strong density gradient toward the hot spot

$\rightarrow$ strong radial electron temperature gradient

By Maxwell-Faraday, B appears in the $\boldsymbol{\nabla} n \times \boldsymbol{\nabla} T_e$ direction

What about the β value ?



Resistivity

Ohm's law from electron momentum conservation :

(neglecting electron inertia, i.e. $m_e = 0$)

$$\mathbf{E} = -\mathbf{V}_i \times \mathbf{B} + \frac{1}{en}(\mathbf{J} \times \mathbf{B} - \boldsymbol{\nabla}.\,\mathbf{P}_e) + \eta\mathbf{J}$$

η associated to electron-ion collisions (transport process)

$\rightarrow$ this is a dissipation process

$\rightarrow$ not pertinent in space plasmas, but oftenly at play in numerical simulations

Collisions

- ion-ion collisions : treated w. Monte-Carlo technique [Takizuka & Abe, 1977], [Nanbu, 1997]

- ion-electron collisions : same technique, w. fluid electrons [Sherlock, 2008]

- ion-neutral collisions : important for low ionization rate [Lipatov, 2002]

$\rightarrow$ Important dissipative process

Hyper-resistivity

Ohm's law from electron momentum conservation :

(neglecting electron inertia, i.e. $m_e = 0$)

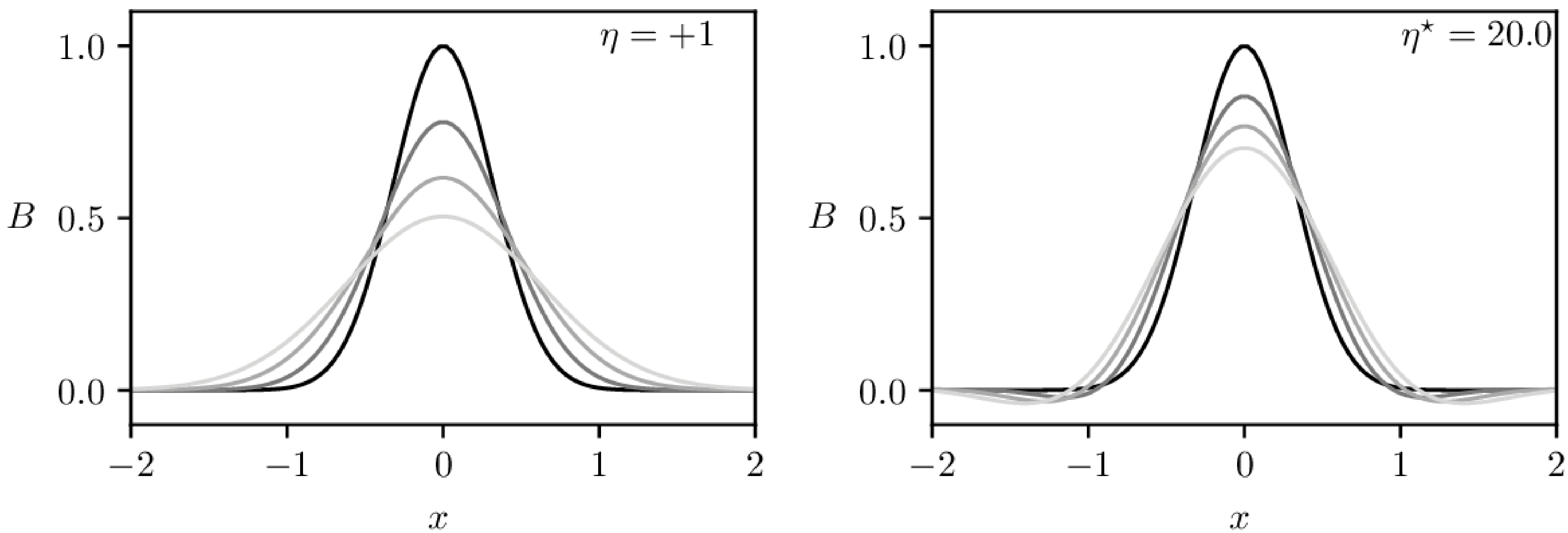
$$\mathbf{E} = -\mathbf{V}_i \times \mathbf{B} + \frac{1}{en}(\mathbf{J} \times \mathbf{B} - \mathbf{\nabla} . \mathbf{P}_e) - \eta^\star \mathbf{\Delta J}$$

Associated to electron viscosity (transport process)

Dissipative process that depends on the scale (through Δ)

Magnetic diffusivity

Magnetic diffusivity from η and $\eta^\star$: $\partial_t \mathbf{B} = \frac{\eta}{\mu_0}\Delta\mathbf{B} - \frac{\eta^\star}{\mu_0}\Delta^2\mathbf{B}$



$\rightarrow$ Smooth out the magnetic field

Nernst effect

Because of the electron heat flux, Nernst velocity appears [Nishiguchi et al. 1984] :

$$\mathbf{V}_N = \frac{\mathbf{q}_e}{{}^5\!/_2\, p_e}$$

$\rightarrow$ This velocity has to be considered in the Ohm's law

As a consequence, the electron heat flux can modify the magnetic field transport [Joglekar et al., 2014]

Righi-Leduc effect

The electron heat flux is modified by the magnetic field [Braginskii, 1965]

$$\mathbf{q}_e = -\kappa_{\|}\boldsymbol{\nabla}_{\|}T_e - \kappa_{\perp}\boldsymbol{\nabla}_{\perp}T_e - \kappa_B\widehat{\mathbf{B}} \times \boldsymbol{\nabla}T_e$$

A more general evolution equation of $\mathbf{q}_e$ involves the Nernst velocity [Haines, 1986]

$\rightarrow$ This effect directly depends on the collisions,
$\rightarrow$ needs also an evolution equation for p_e or $\mathbf{P}_e$
(see poster of Sladkov et al.)

Non-locality

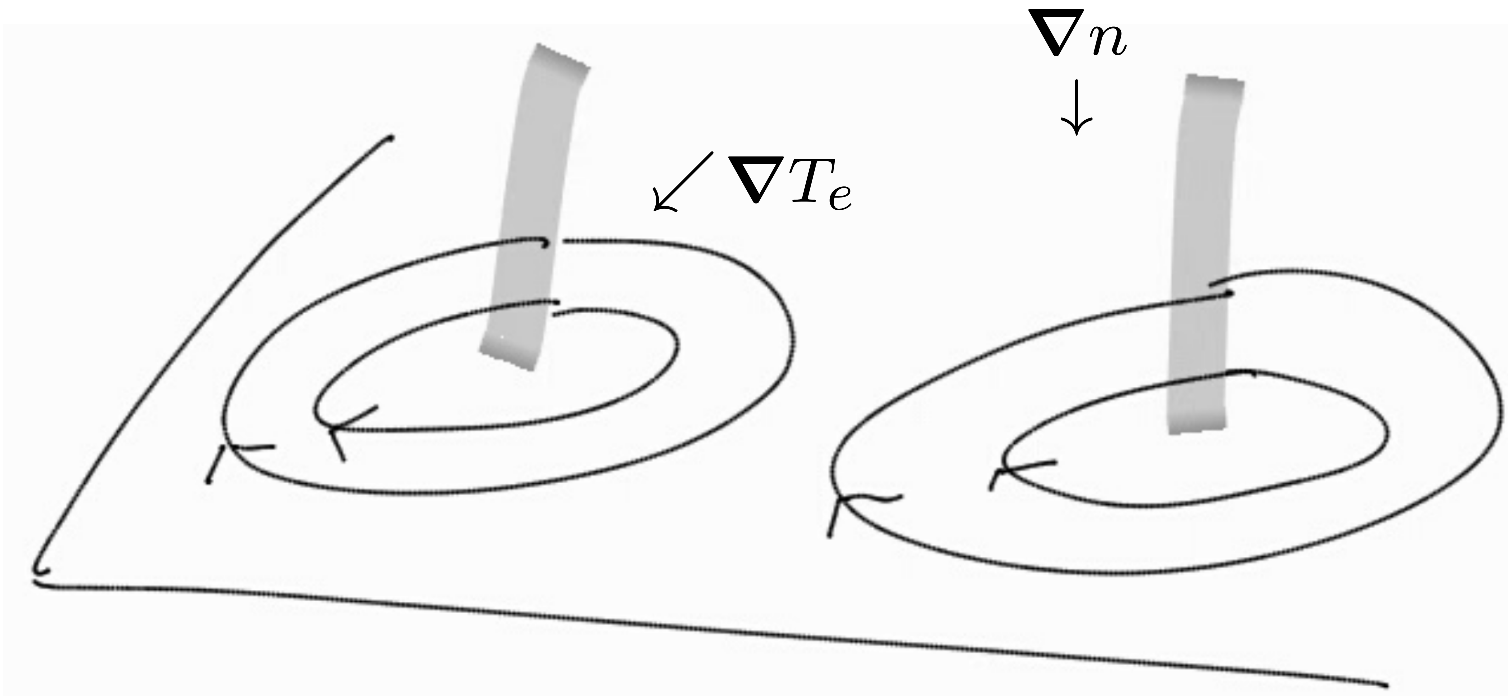
Because of the energy deposition by the laser, there is a very strong $\boldsymbol{\nabla} T_e$

$\rightarrow$ The associated heat flux is non-local in HEDP

Non-locality is already considered in hydro-radiative codes

This is pretty common in plasma : $\mathbf{D} = \varepsilon . \mathbf{E}$ only in (ω, k)

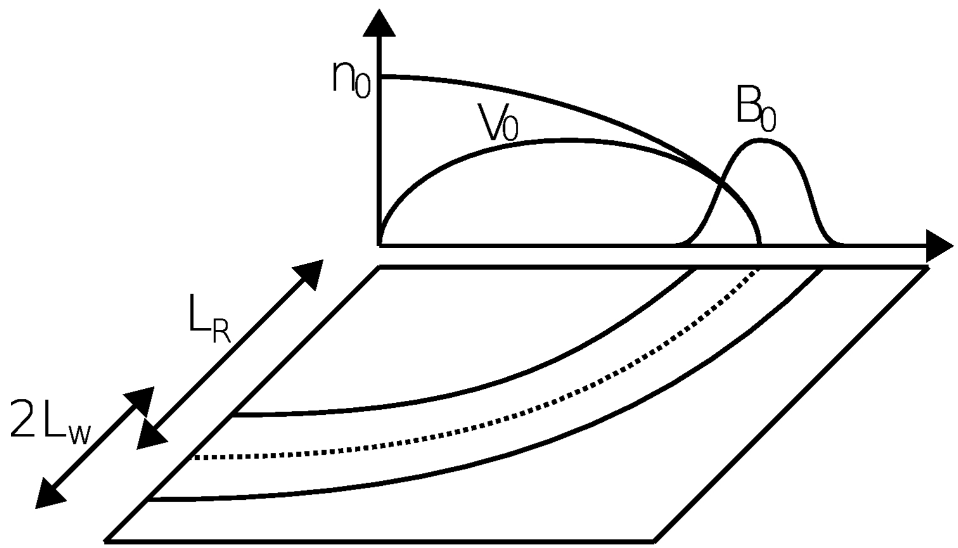
With high-intensity Lasers... [Nielson et al., 2006]



2 hotspots on solid target :

$\rightarrow$ 2 anti-parallel Magnetic loops (Biermann-battery effect)

Initial set-up, close to... [Fox et al., 2011]

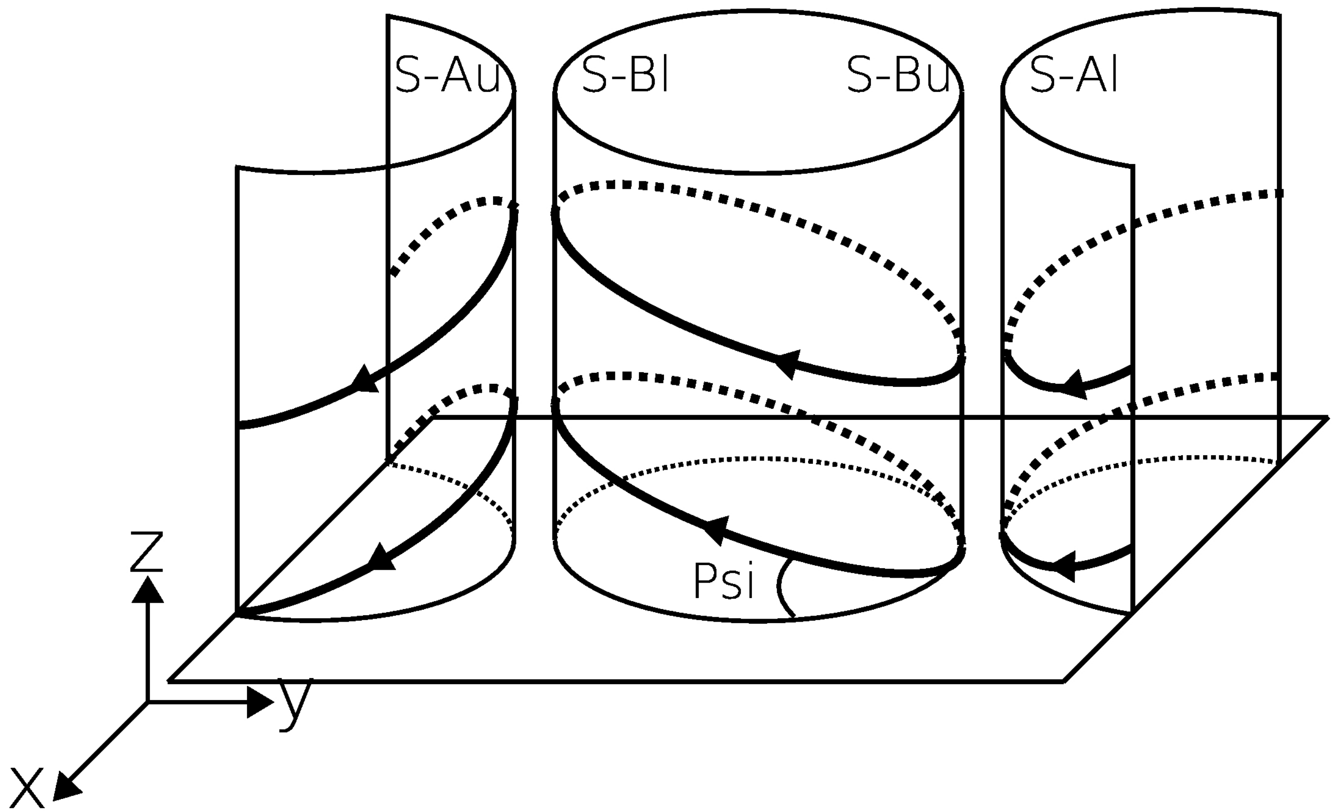


$\rightarrow$ Few cautions to get $\nabla.\mathbf{B} = 0$ and periodic BCs

$\rightarrow$ 2 bubbles plus a background to avoid vaccum problems :

- Can handle asymetries on $\mathbf{B}$, n, $\mathbf{V}$, T...
- Can handle non-coplanar configurations

When folding targets [Smets et al., 2014]

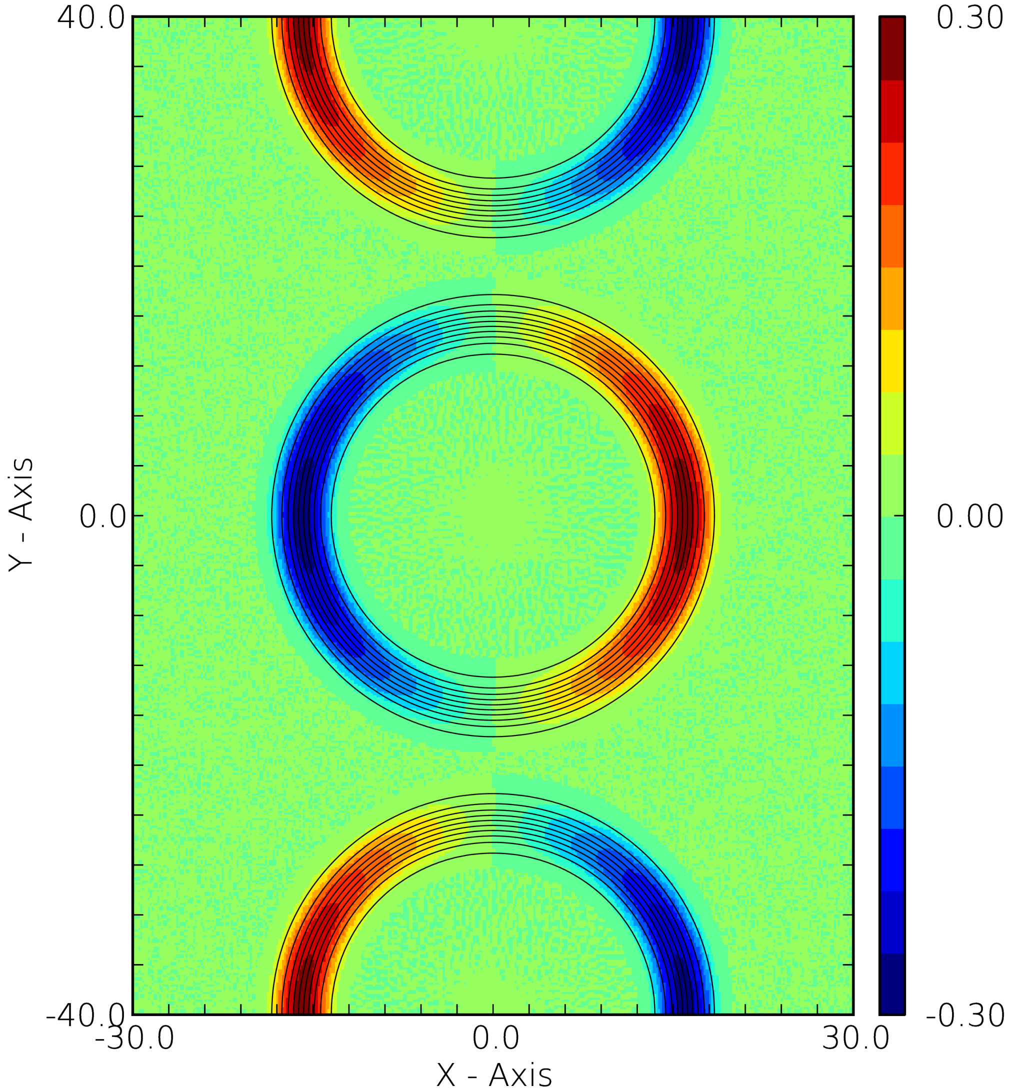


Initial out-of-plane magnetic field : Quadripolar structure

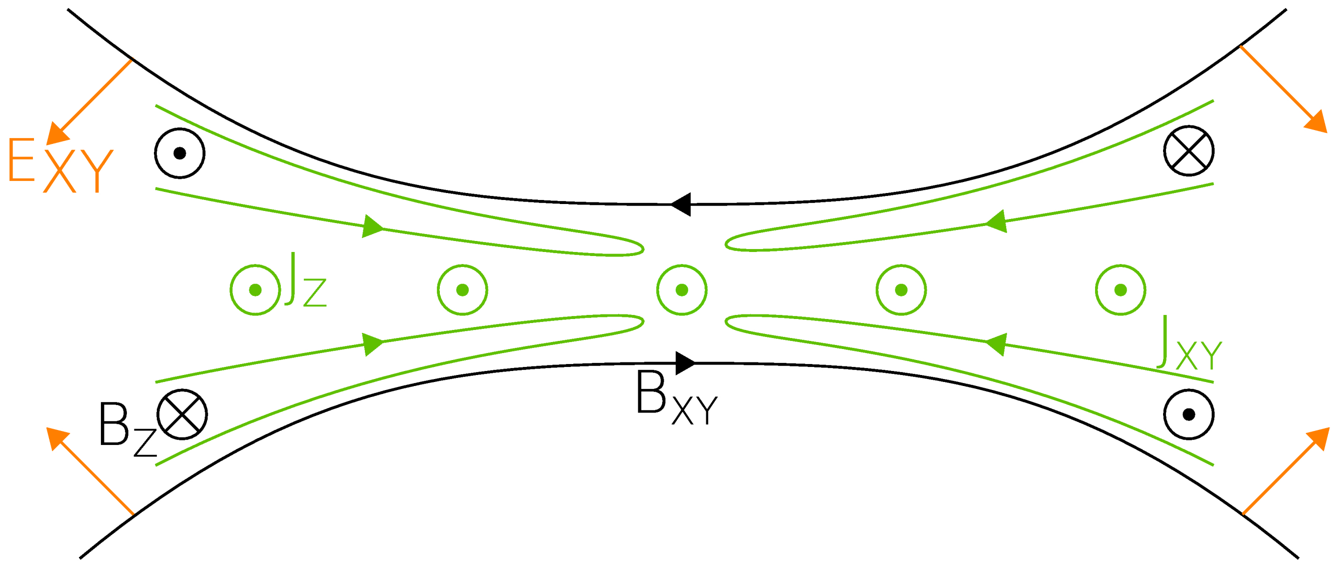
$\rightarrow$ Reconnection rate depends on sallient/reverse angle

$\rightarrow$ 6 shots scheduled on LMJ/PETAL : spring 2019

Non-Coplanar Hybrid simulation : t=0



About the Hall effects



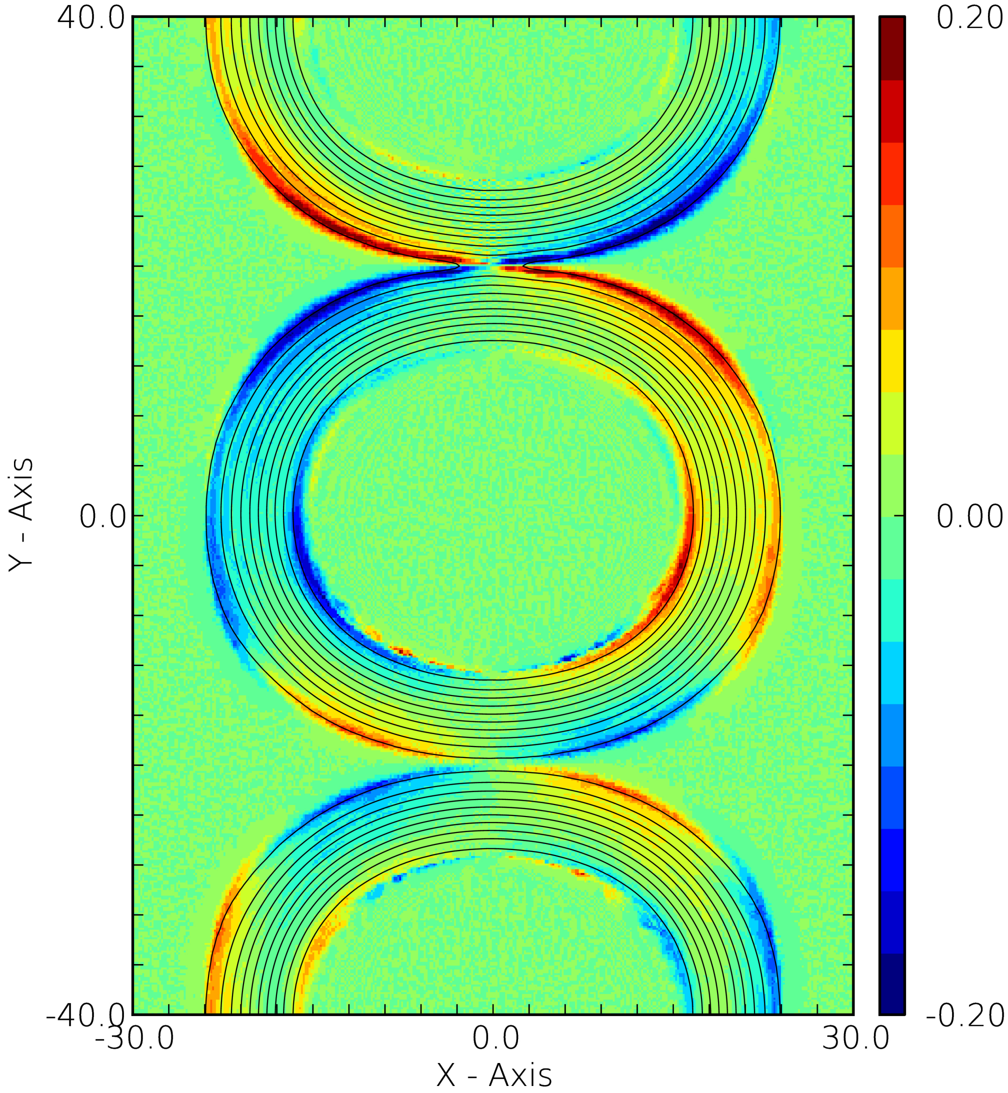
- (Hall) E_{XY} electric field associated to J_Z and B_{XY}
- J_Z grows at the tip of each loops when colliding

$\rightarrow$ quadrupolar B_Z grows because E_{XY} is no more curl-free

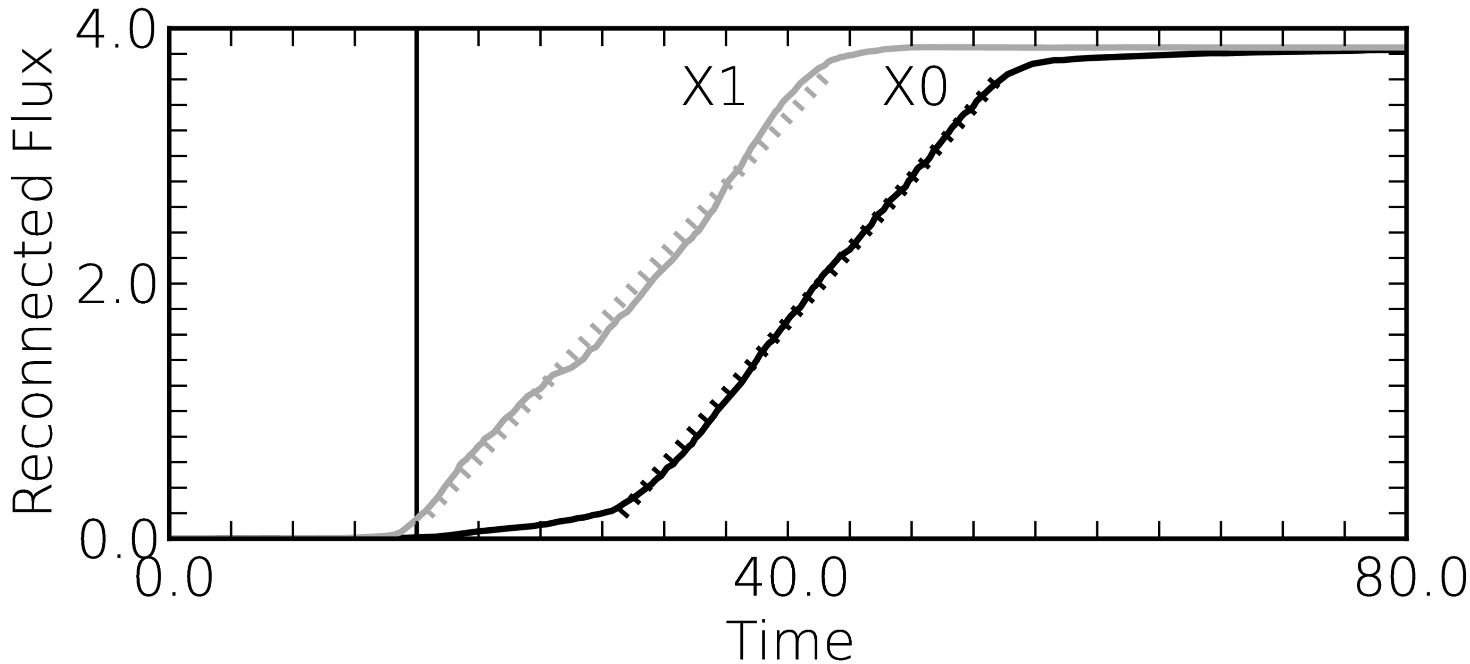
- J_{XY} associated to this out-of-plane magnetic field

$\rightarrow$ Carried by electrons (protons are demagnetized)

Non-Coplanar Hybrid simulation : t=16



Reconnected flux

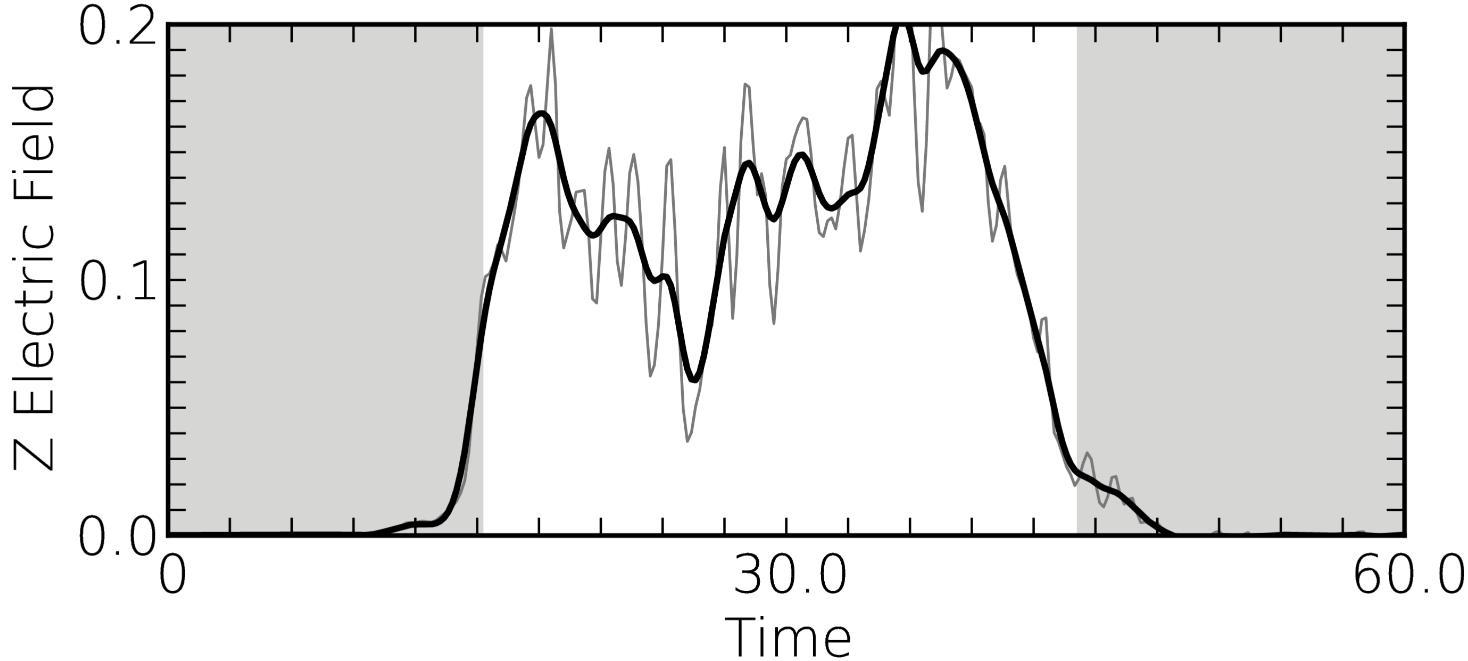


$\longrightarrow$ B_Z develops prior the reconnection onset (t=16)

$\longrightarrow$ Same reconnection rate at each loci (slope of A_Z)

$\longrightarrow$ Time lag between the 2 onsets of reconnection

Reconnection Rate

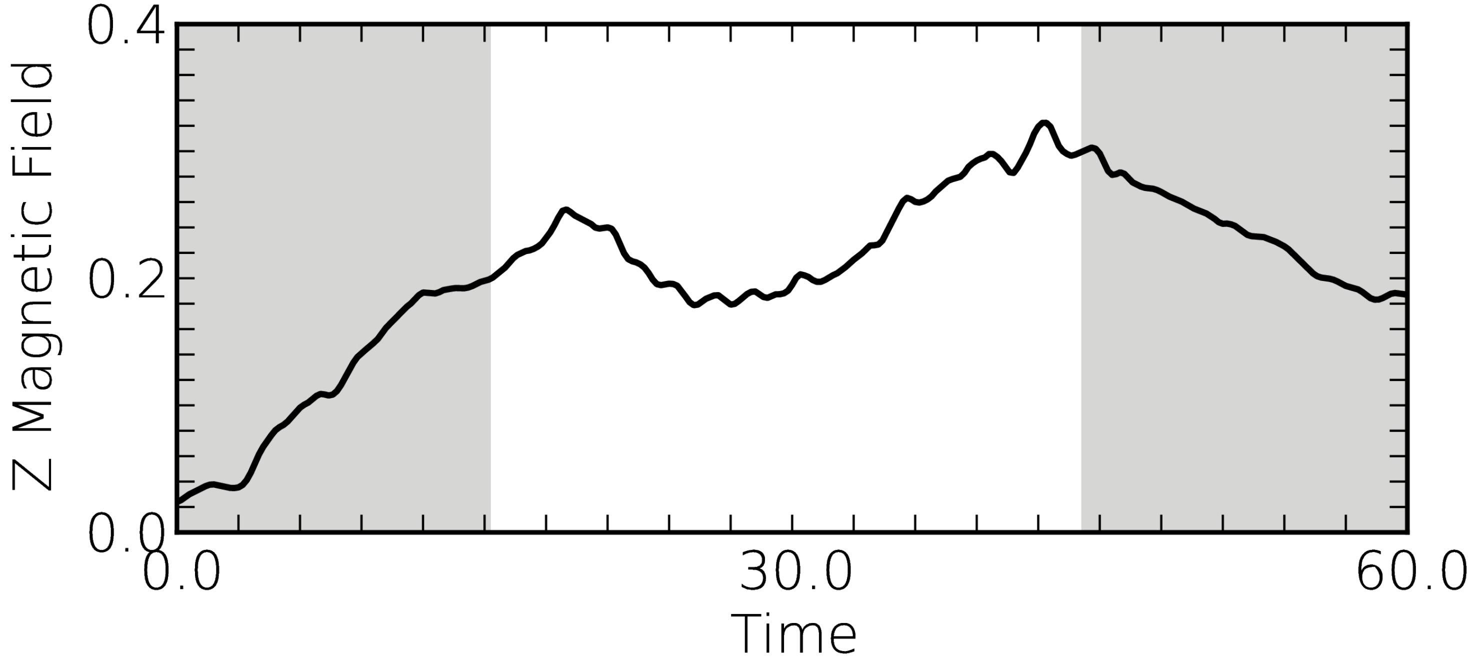


Slope of the reconnected flux : $E_Z = -\partial_t A_Z$

Reach the "holly" value of 0.2...

$\longrightarrow$ The outflow speed is aroud 0.2 times the (upstream) Alfvén speed (not yet normalized)

Out-of-plane quadrupolar (Hall) Magnetic Field



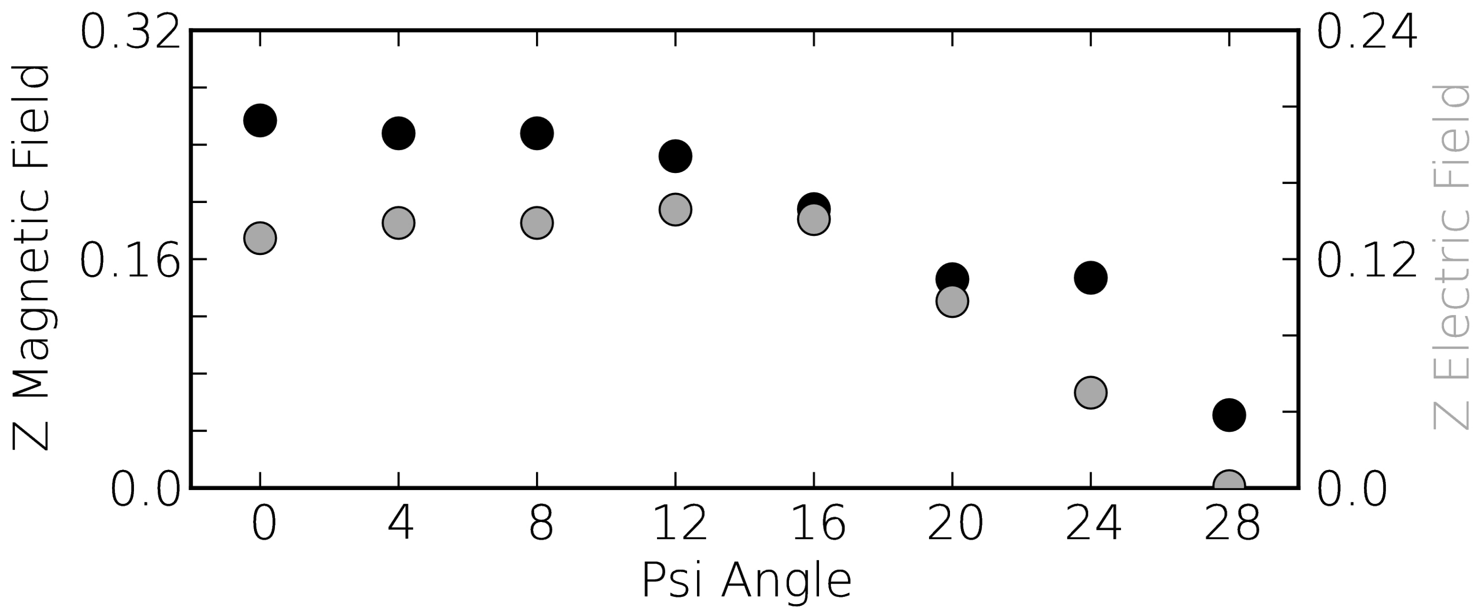
Its value clearly increases prior the reconnection onset

$\longrightarrow$ Can not be a consequence of the reconnection process

Double hump structure like the one of the E_Z component

$\longrightarrow$ Close connection between these two components

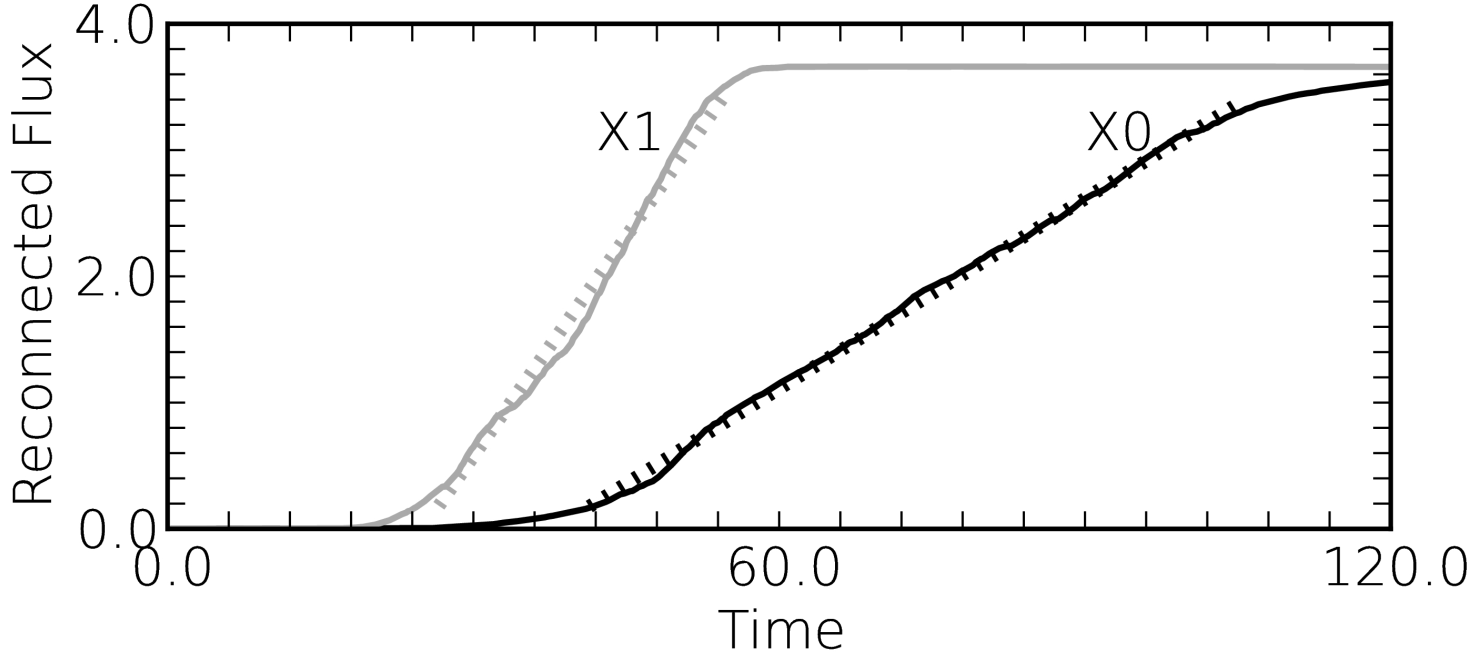
On the relation between E_Z and B_Z



Clear correlation between the Hall magnetic field and the reconnection rate

$\longrightarrow$ The organic link being the in-plane current associated to B_Z that drives the reconnection rate

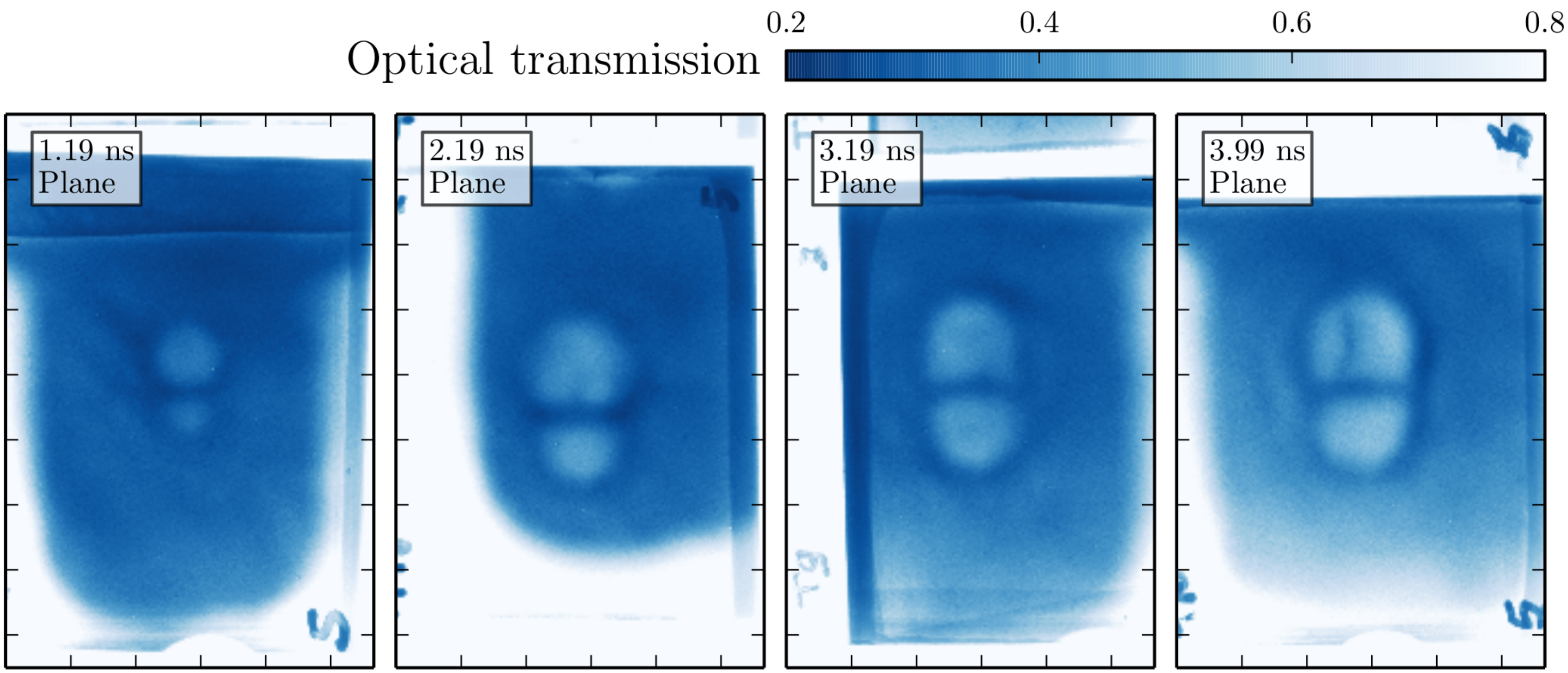
Reconnected flux for $\Psi = 24^o$



The reconnected rate is clearly decreasing for larger Ψ angles :

$\Rightarrow$ The initial "anti-Hall' magnetic field drives an electric field reverse to the reconnection one.

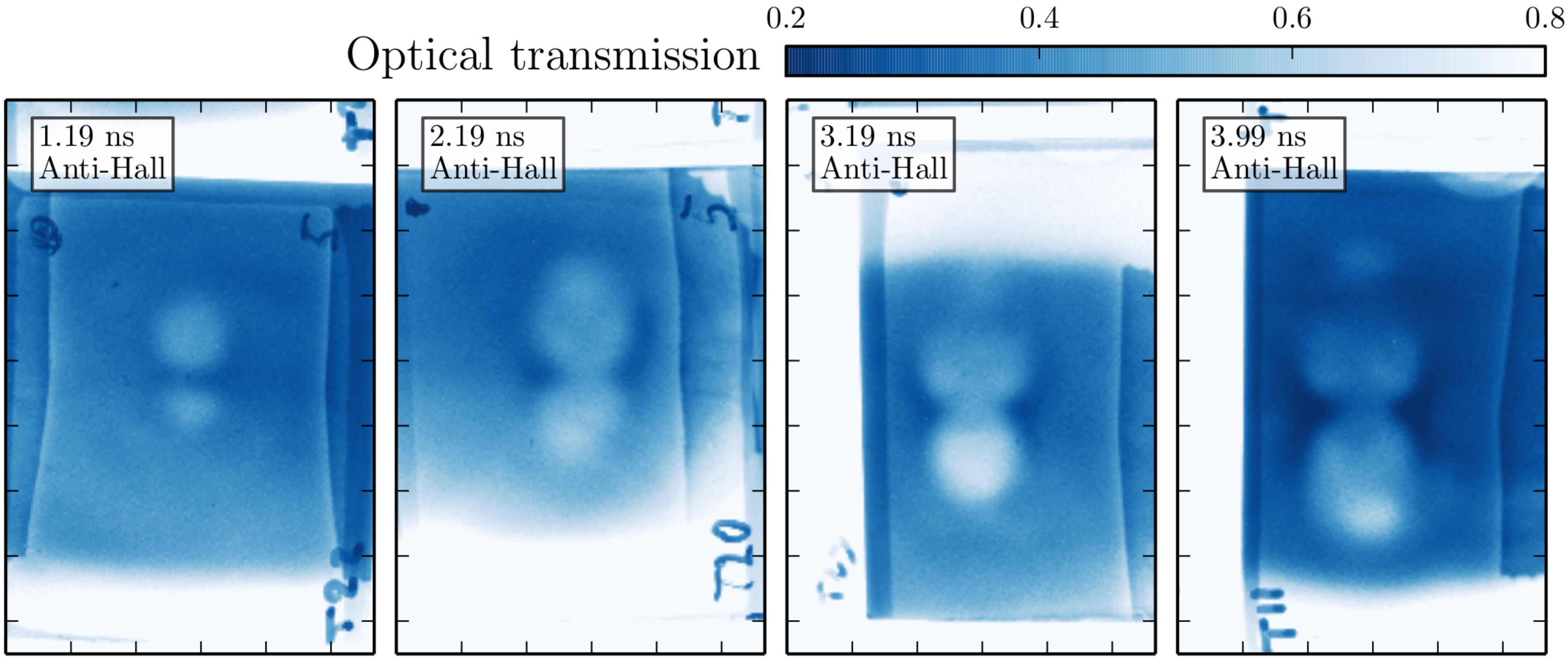
LULI 2000 : 2 beams with 200 J & 4.0 ns each



→ The 2 magnetic shells get compressed and get flat

→ On the reconnection sheet, protons are weakly scattered

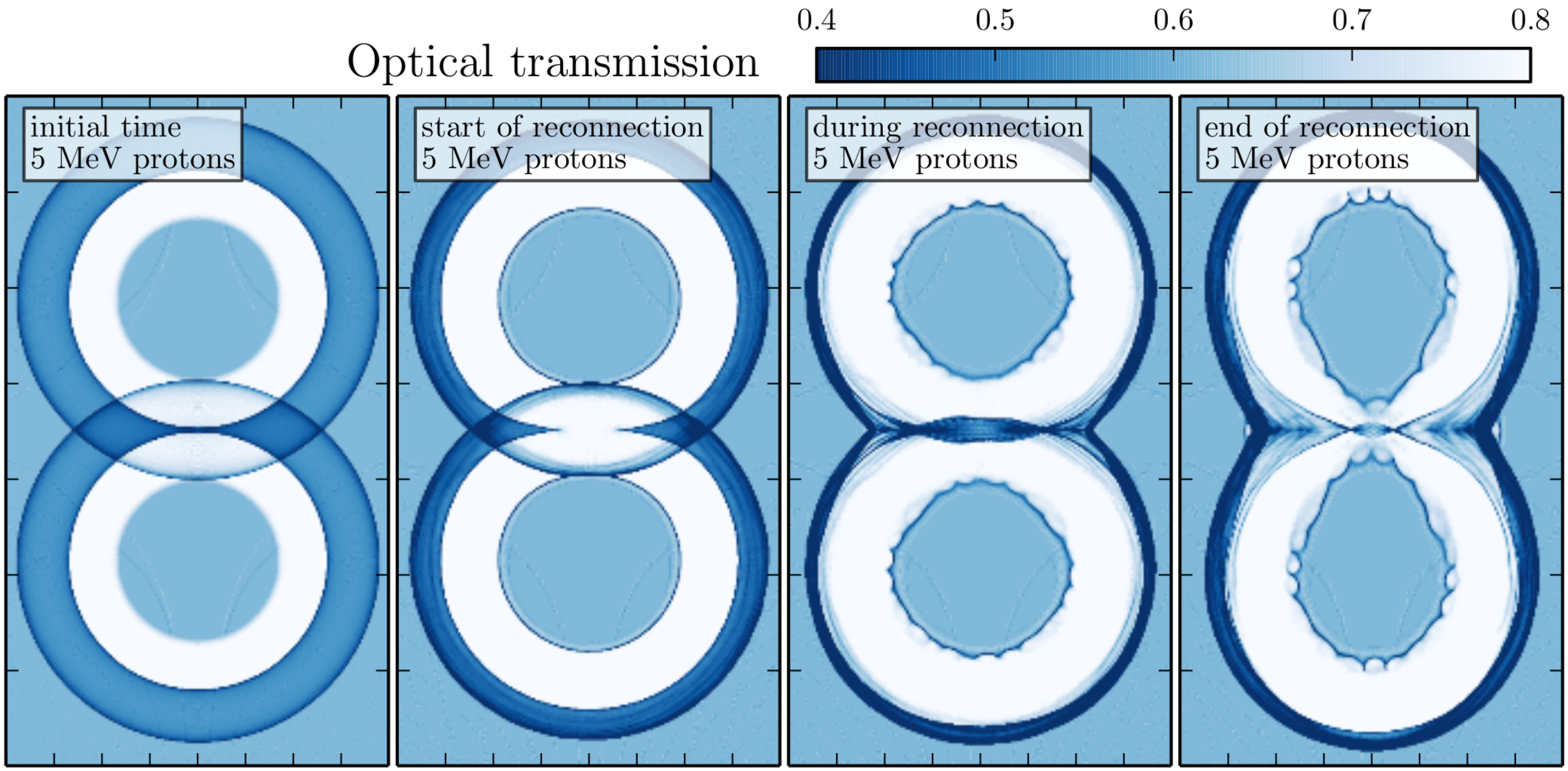
LULI 2000 : 2 beams with 200 J & 4.0 ns each



→ No more flat sheet betweens the 2 shells

→ Reconnection inhibited ?

Modelization of RCF diagnostics



→ Using 5 MeV protons in ILZ

LMJ/PETAL shots in spring 2019

- 8 kJ, 4 ns with 4 quads
- Increase magnetization & shorten reconnection process
- High Z target decreases the associated β value
- Proton radiography

$\rightarrow$ Get (integrated) E & B fields at different times

- DP1 X-ray imager : 12 images with resolution of 130 ps

$\rightarrow$ a sequence of 2D images

- DMX Spectrometer : X-rays spectra resolved in time

$\rightarrow$ measure the black-body spectrum of $T \sim 100$ eV plasma

Concluding remarks

The out-of-plane magnetic field is not a consequence of the magnetic reconnection process

The out-of-plane magnetic field and the reconnection process are both consequences of thin non-flat current sheet (for $kd_p \sim 1$)

This can be of interest for ICF with direct (Hall) or indirect (anti-Hall) attack for the stability of the confinement

Ion Streaming Instability

- Micro-Instability (kinetic process)
- Free energy : the beam energy
- Low ω (extended MHD modes)
- Threshold instability with $\omega_{\mathrm{max}}(k_{\mathrm{max}})$

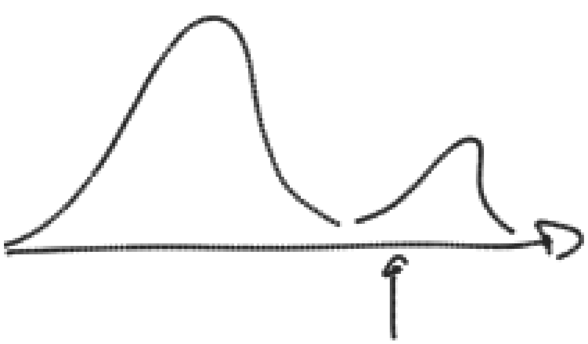
- Results in pitch-angle scattering (QL theory)
- Slowing down of the beam
- Heating of the main and/or beam
- Growth of temperature anisotropy

3 unstable modes (EM - circularly polarized) *Gary 1993*

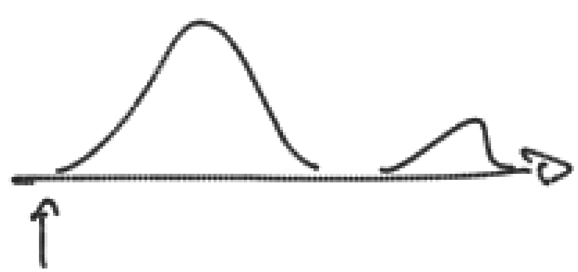
Linearized Vlasov equation with k along B_0 field :

- population 1 : “main” (solar wind plasma)
- population 2 : “beam” (back-scattered protons)

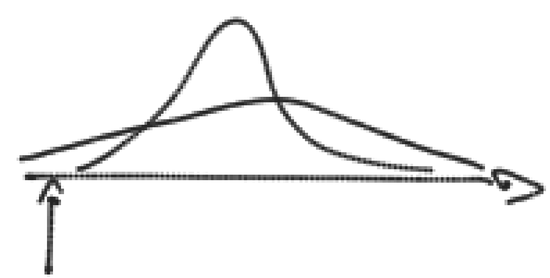
Right-resonant Non-resonant Left-resonant



$$\frac{\omega + \Omega_p}{k_{||}}$$



$$\frac{\omega - \Omega_p}{k_{||}}$$



$$\frac{\omega - \Omega_p}{k_{||}}$$

Right-resonant mode *Kulsrud & Pierce 1969*

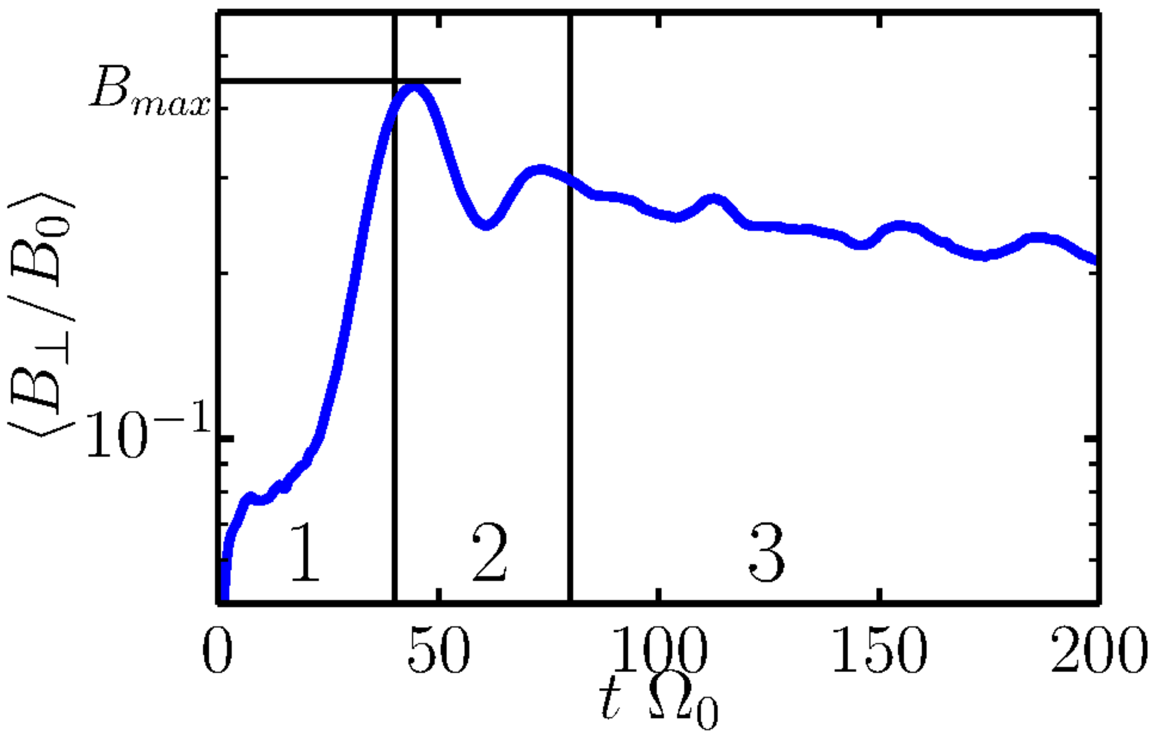
- mode with lowest thresold for cold proton beam
- Right-hand polarized (positive helicity) along $+\mathbf{V}_b$
- Most unstable mode with $\omega_r \sim \gamma$
- Growth rate in the cold limit

$$\frac{\gamma}{\Omega_p} = \left(\frac{n_b}{2n_T}\right)^{1/3}$$

- $k_{\text{max}} = o(c/\omega_p)^{-1}$: asymptotically goes to whistler mode
- Beam protons are resonating :
  - pitch-angle diffusion of beam protons (QL theory)
  - heating of protons from main & beam

Right-resonant mode

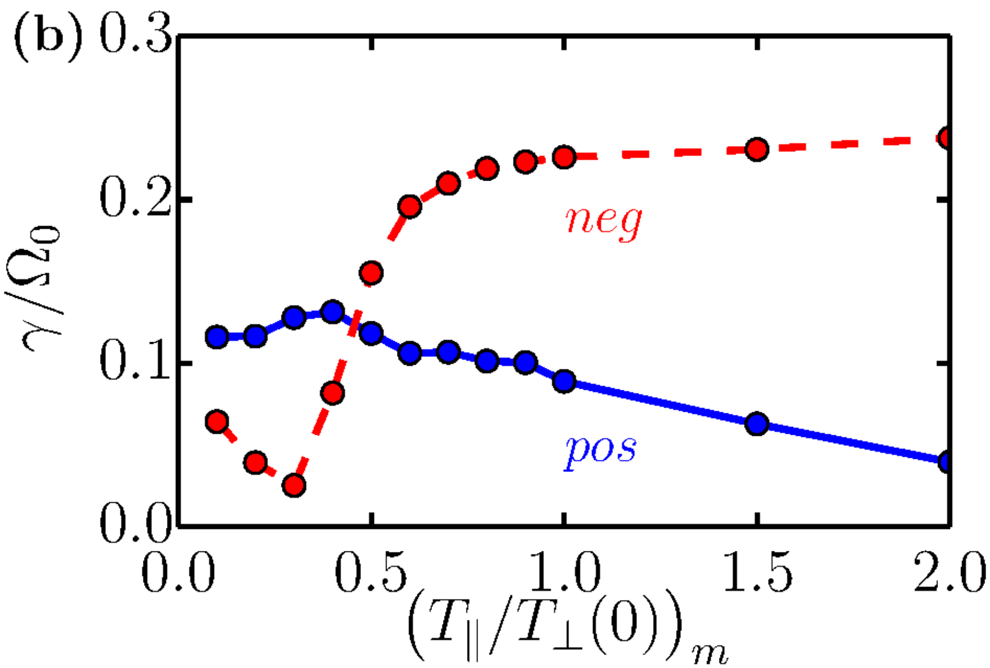
• 3 phases : growth, saturation (overshoot) & relaxation



$\longrightarrow$ Effects of magnetic fluctuations ?

Non-resonant mode *Bell 2003*

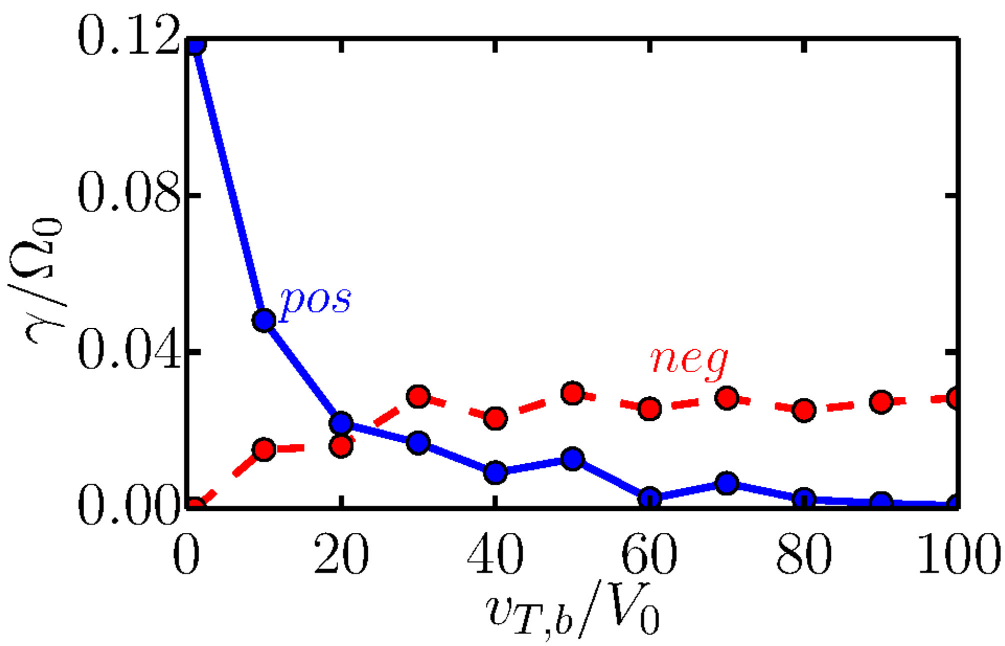
- This is a fluid-like mode (close to firehose mode)
- Needs a dense/fast beam



$\longrightarrow$ Can dominate the R-resonant mode : $\dfrac{\gamma}{\Omega_p} = \dfrac{n_b}{2n_T}\dfrac{v_b}{v_A}$

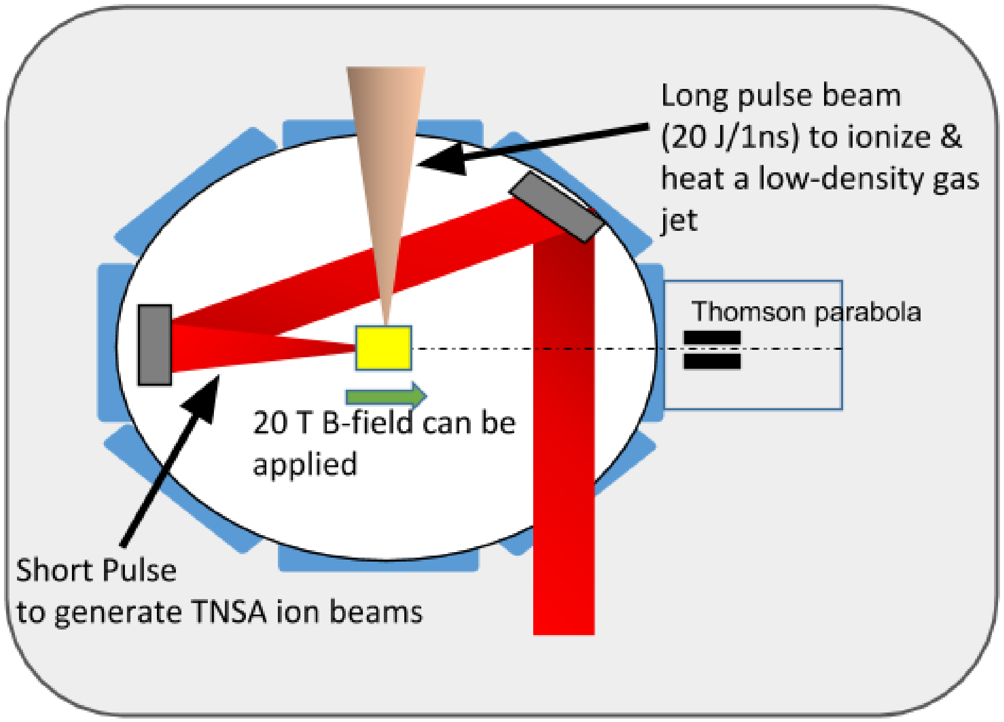
Left-resonant mode

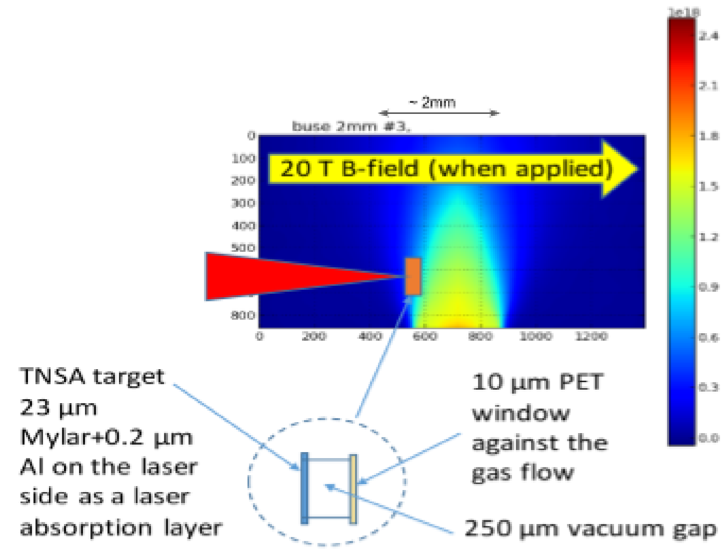
Needs a very hot beam...



- Negative helicity, along $+\mathbf{V}_b$
- Proton beam resonating

Experimental Set-up





- Magnetic field from external coils (LNCMI)
- Gas/plasma produced by the nano laser
- Beam produced by the pico laser (TNSA)

Experimental features

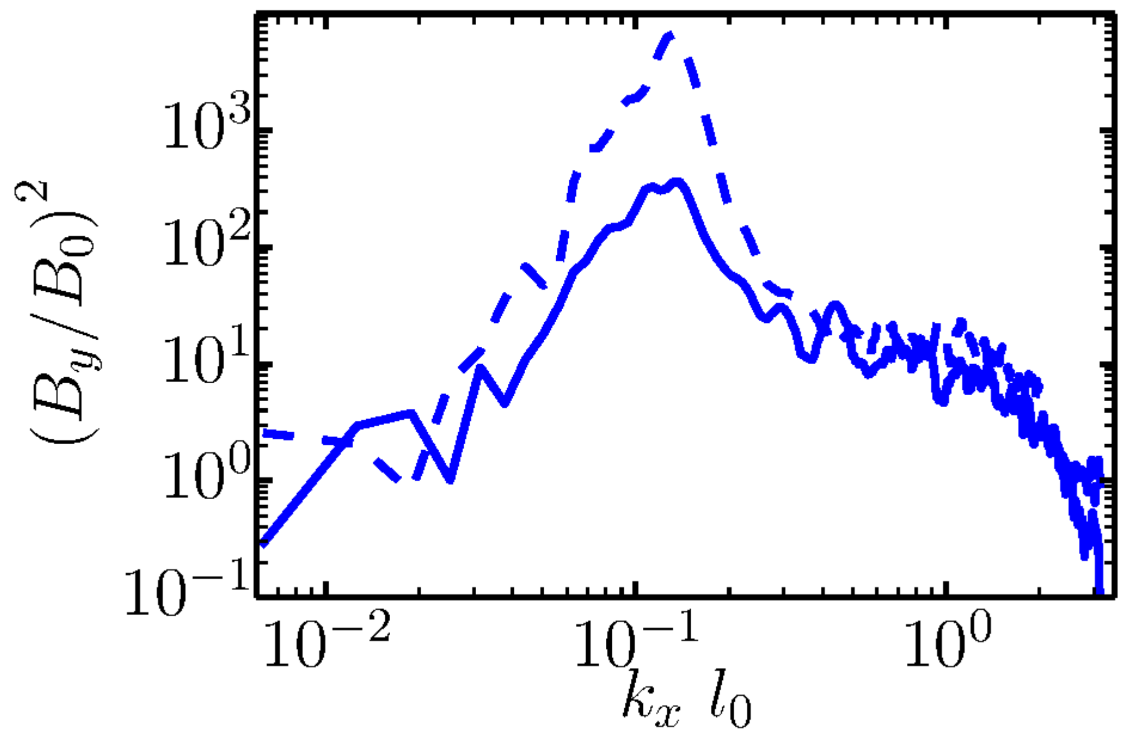
- Gas or Plasma of the “main” :
  - pre-ionized by the pico laser & e^- from the beam
  - ionization rate $\sim 10^{-2} - 10^{-3}$
  - can be ionized by the nano laser (inverse Bremsstrahlung)

- Proton beam by TNSA mechanism :
  - large energy dispersion
  - spectral shape can eventually be modified

$\rightarrow n_b/n_m$ vary with distance from beam to gas : 10^{-1} 10^{-4}

$\rightarrow v_b$ vary with the pico intensity (up to 10MeV)

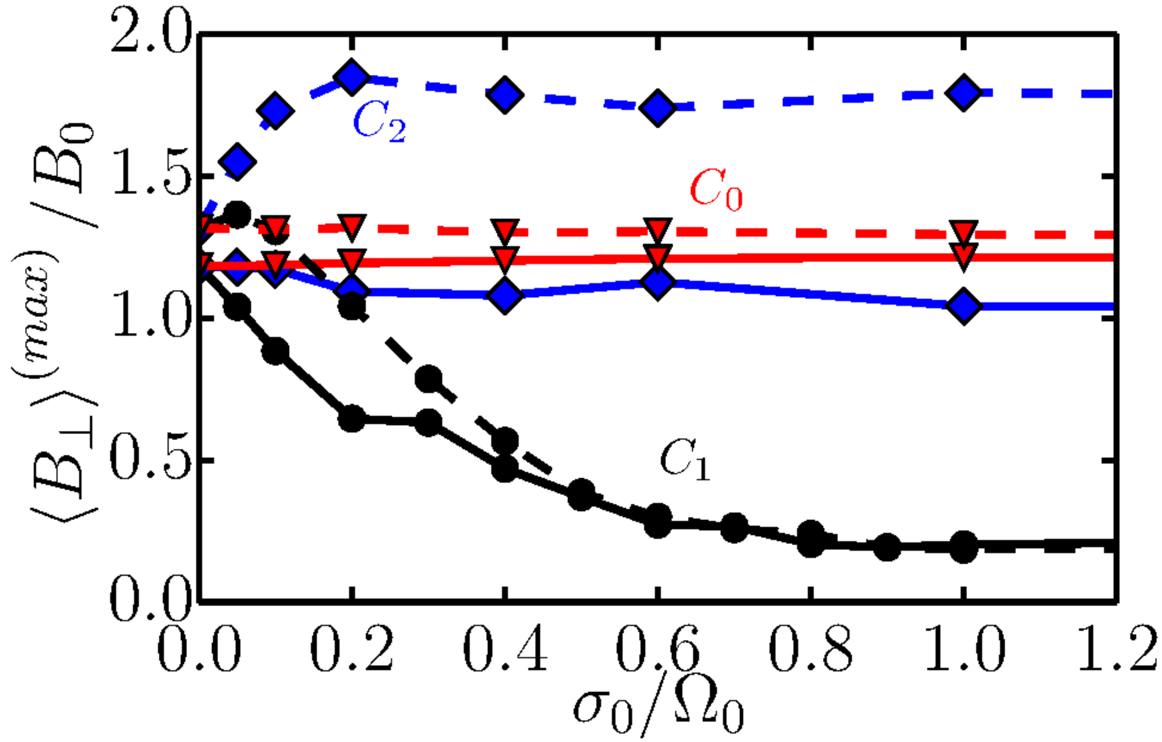
Effects of collisions



- Collisions do not modify the instability features
- Can slow down the beam and ease energy transfers

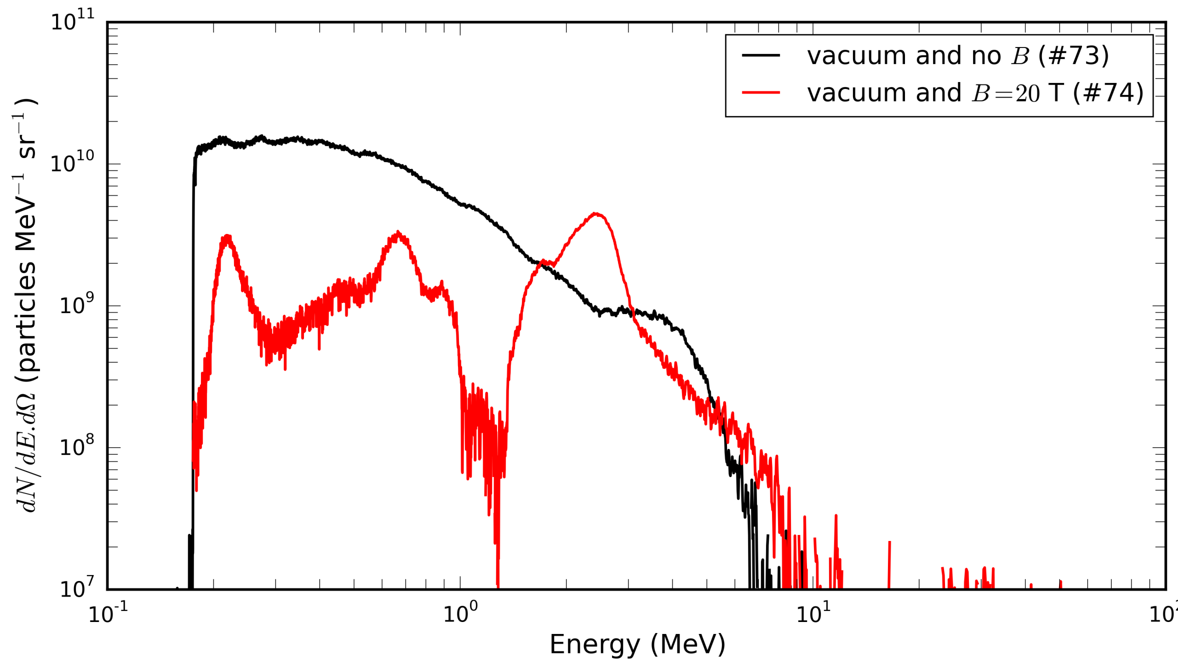
Effects of collisions

For a mixed case : R-resonant & non-resonant



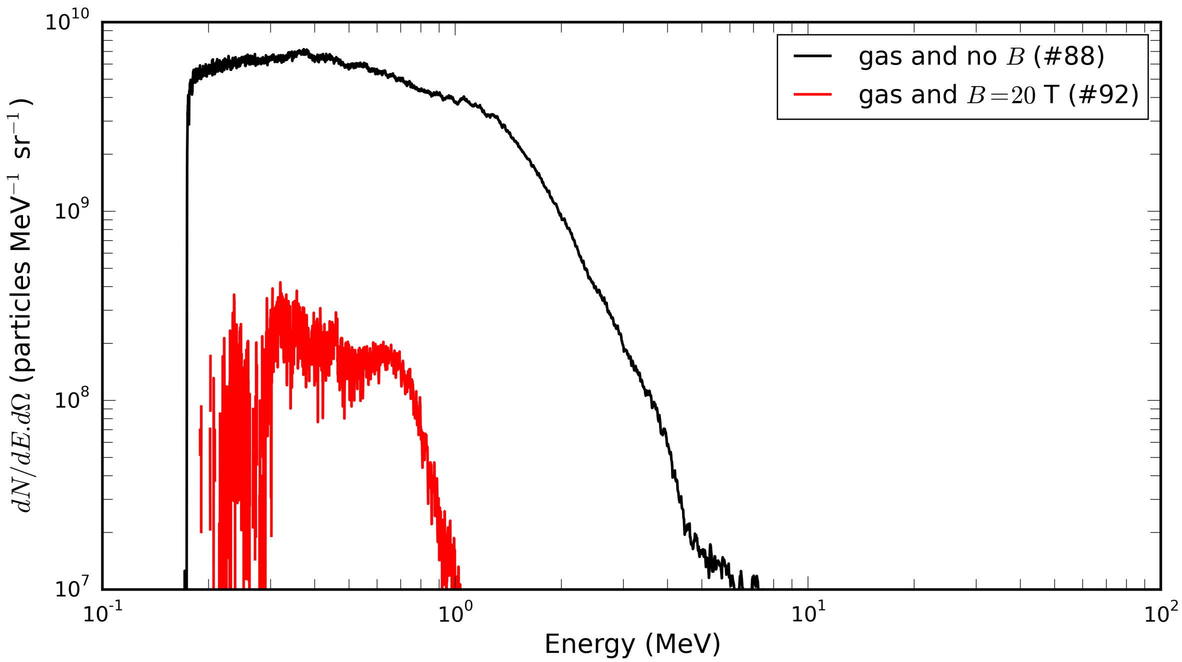
$\rightarrow$ Growth of δB depends on the colliding particles

Proton beam in magnetized vacuum



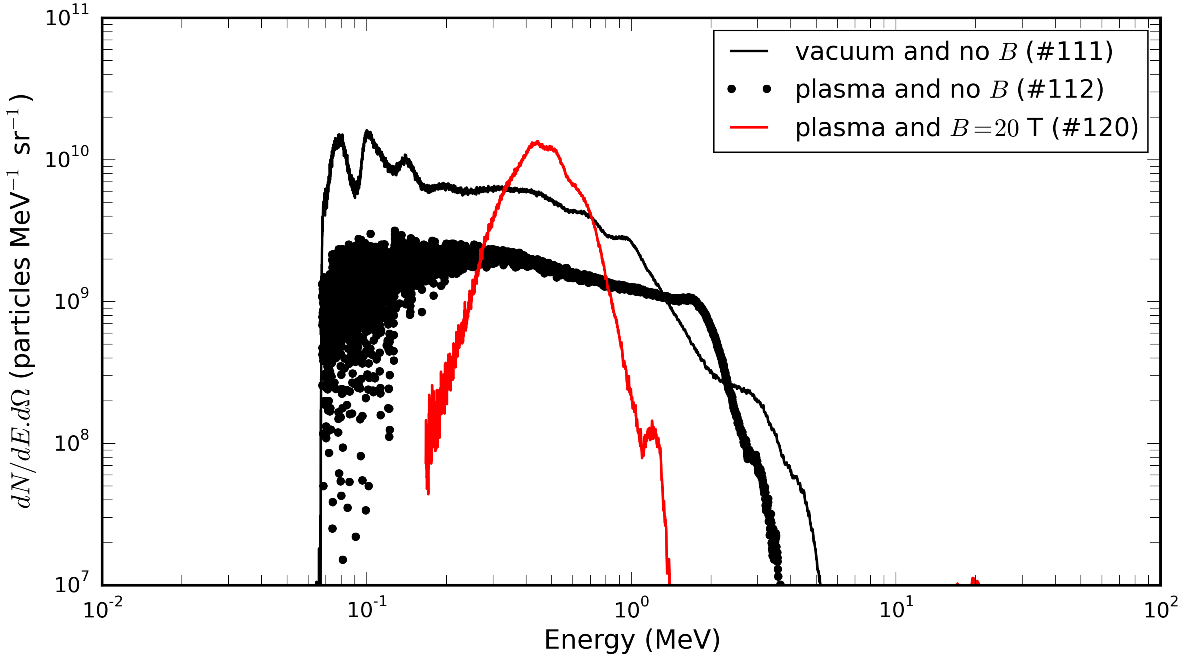
- Energy cutoffs : Thomson parabola & pico intensity
- With B : effects of hot magnetized e^-

Proton beam in magnetized gas



- Without B : no interraction with neutral gas
- With B : ionization of background for instability ?

Proton beam in magnetized plasma



- Without B : interraction with the plasma ?
- With B : same cutoff & clear bunching

Concluding remarks

- EM ion streaming instabilities : 3 modes
- Kinetic structure of ionized ISM & CR are to be clarified
- Effects of collisions are numerically importants
- Role in growing δB & slowing down/heating the beam
- Lab experiments are promizing (add diagnostics)
- Need simulations to decifer data from experiment

Comparison of parameters

Parameters	HEDP	ISM
Magnetic field (T)	20	3×10^{-10}
main density (m^{-3})	10^{22} - 10^{25}	10^{3} - 10^{4}
beam density (m^{-3})	10^{19} - 10^{21}	10^{-4}
main temperature (ev)	10 - 50	10^{4} - 10^{5}
beam temperature (MeV)	0.1 - 10	1 - 100
mean free path (m)	10^{-2}	
Beta parameter (main)	$10^{-3}-1$	1
Beta parameter (beam)	$10^{-2}-1$	1
Ion gyroperiod (s)	5×10^{-10}	3×10^{1}
Proton skin depth (m)	7×10^{-5}	7×10^{6}
Alfvén speed ($m.s^{-1}$)	2×10^{5}	2×10^{5}

Most unstable mode : non-resonant ?

In the cold limit :

$$\frac{\gamma_{RR}}{\gamma_{NR}} = 2\left(\frac{m_m}{m_b}\frac{n_m}{n_b}\right)^{2/3}\frac{v_A}{v_b} = 1 - 25$$

- mean free path $>$ system size
- $v_b \sim 3v_A$
- total time of experiment : up to 50 gyroperiods

Collisionality of the beam