Overview of the collaborative « Magnetism » program and HEDP magnetic reconnection study

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Outline

- « Magnetism » program
- Current status of research
- Experimental measurement of B-field produced by high-power laser
- Simulations of reconnexion in non-HEDP and HEDP configurations
- Next stages

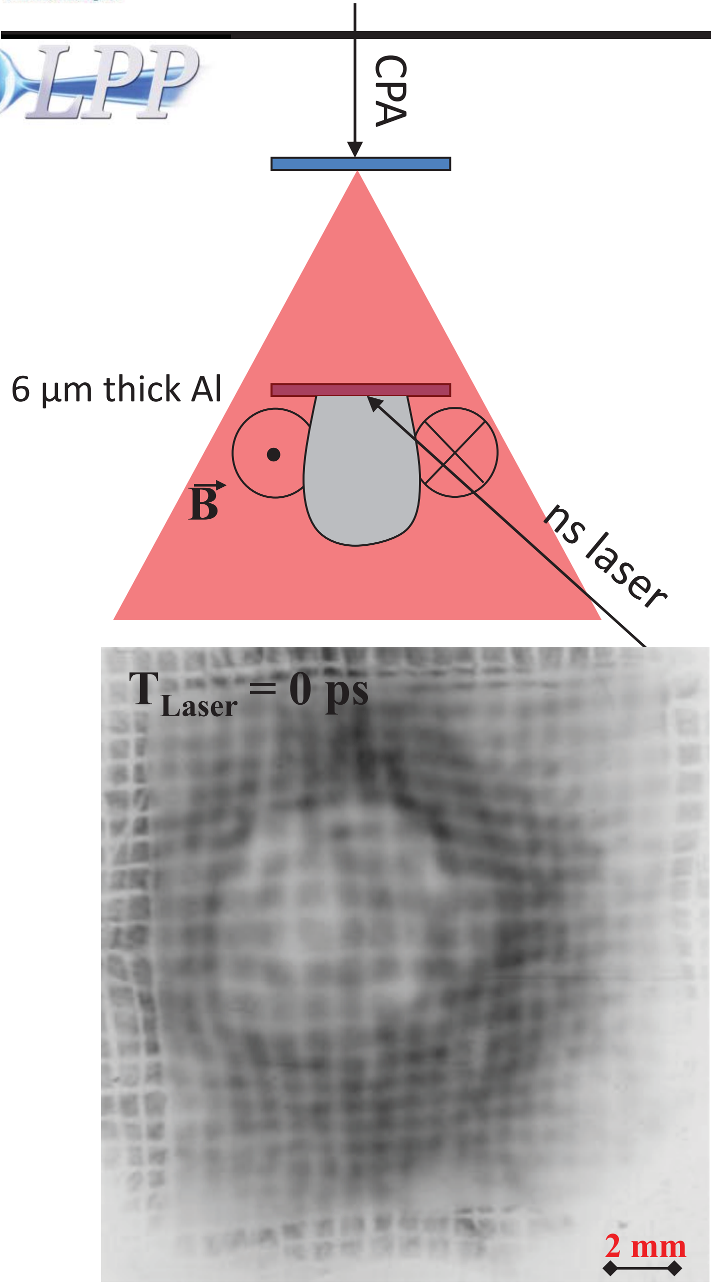
« Magnetism » program

- The program is aimed at improving the current understanding in B-field
  - generation, growth (in relation with heat flow)
  - reconnexion with applications in HEDP (ICF) and space physics
- Collaboration between HELP labs (INRS, LULI) and space physics labs (LPP, LESIA)
- Includes experimental (using lasers) and theoretical effort
- Open to collaborations!

Past and ongoing effort

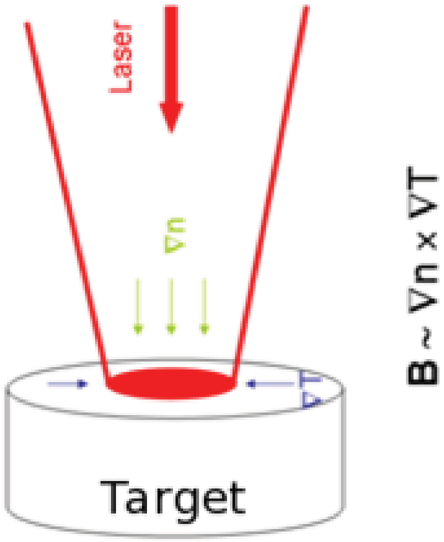
- Clarify the interplay between magnetic fields and heat flow in order to have **predictive capability regarding B field growth and evolution in HEDP**
    - B fields affect heat carrying electrons (gyration & heat flow bending through Righi-Leduc effect)
    - Heat flow & non-locality affect B fields through the Nernst effect
- Previous work (IC, MIT, LLE) have underlined the complexity of the topic & the ability of VFP simulations to model correctly such dynamics
- Our work: improve MHD modeling & B fields/heat flow measurements in various HEDP conditions
- Explore the applicability of HEDP experiments to space & solar physics issues, namely reconnexion in various configurations

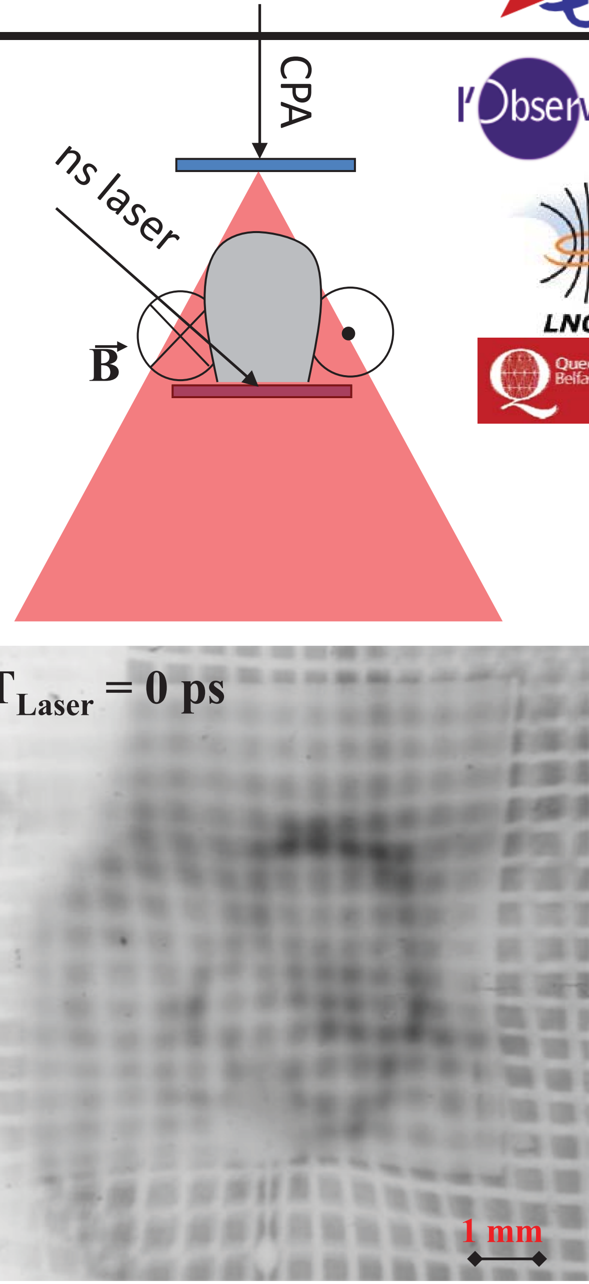
A first experiment conducted at RAL clearly showed the toroidal nature of the probed B-fields



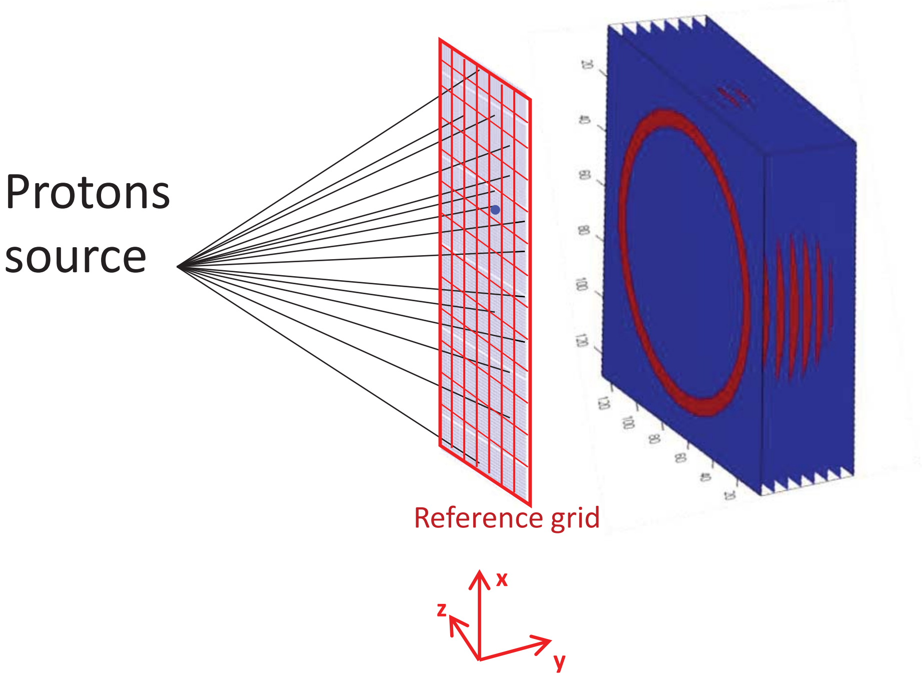
RAL Vulcan
C. Cecchetti et al., PoP 2009

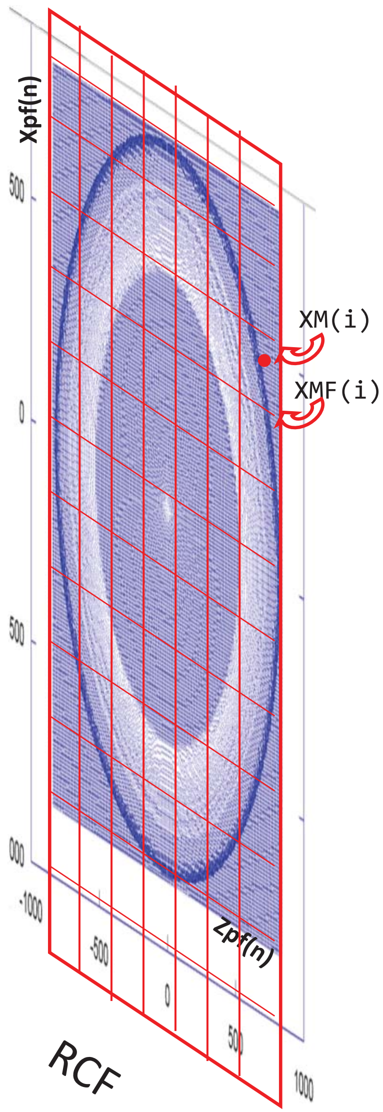
50 J, 1 ns at 1 µm
focal spot of 50 µm
I=3-6 x10^{14} W/cm^2



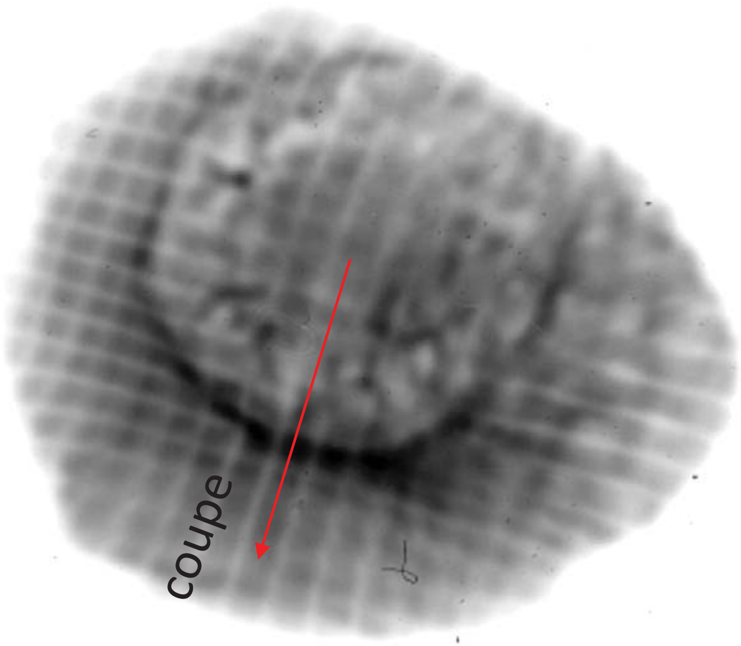


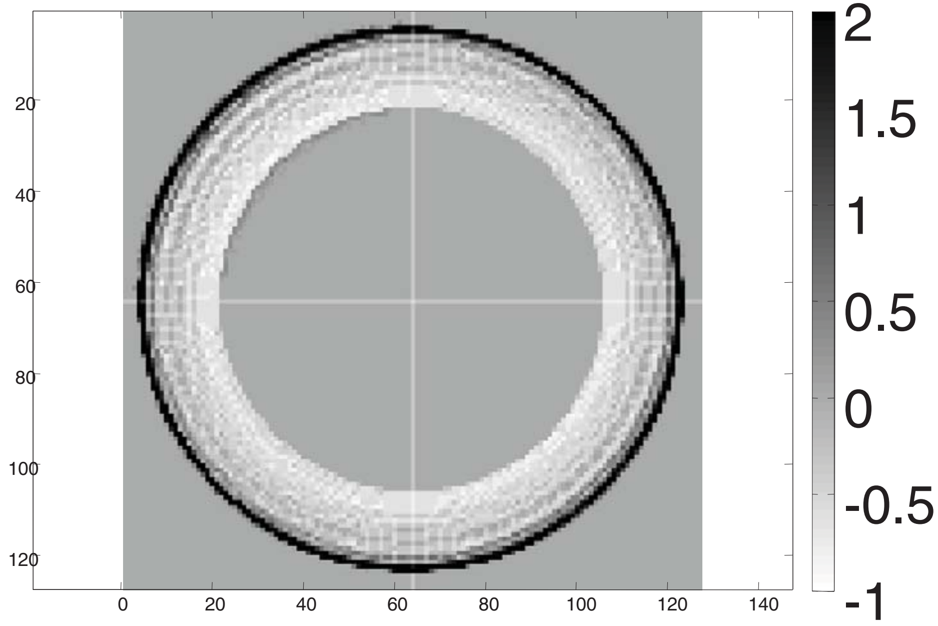
To allow comparison with hydro-rad simulations, we compute 3D proton trajectories in B-fields

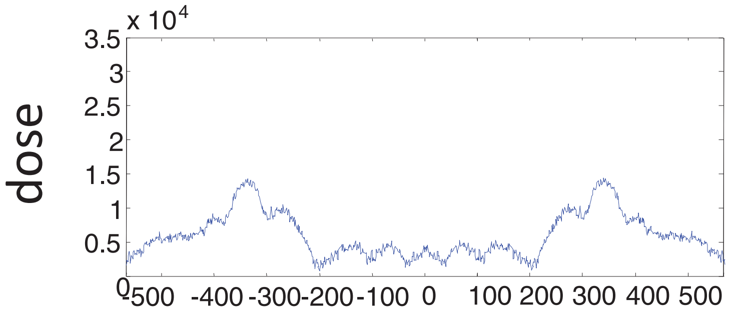


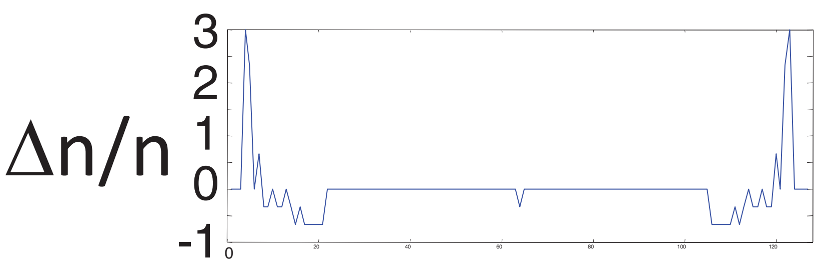


Both the dose modulation and the location of the deflexion are used to compare with the experiments



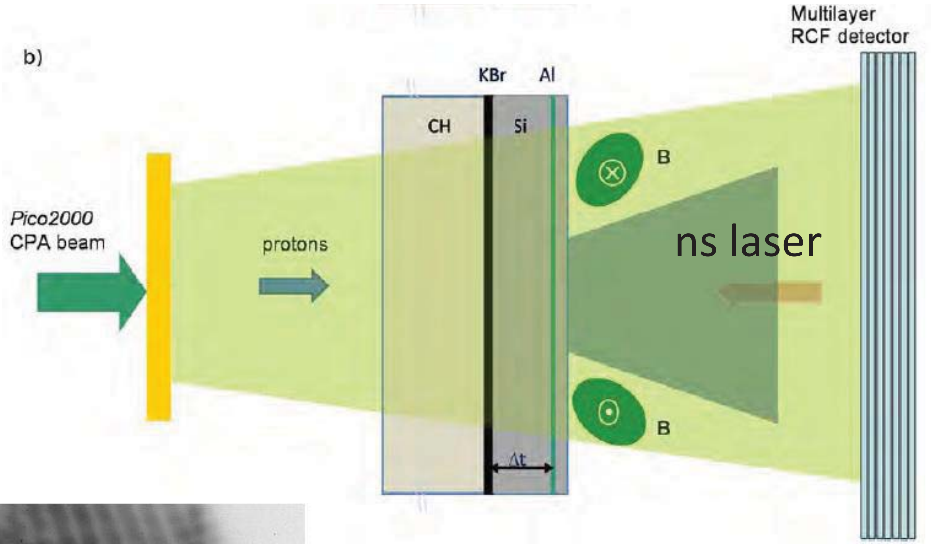


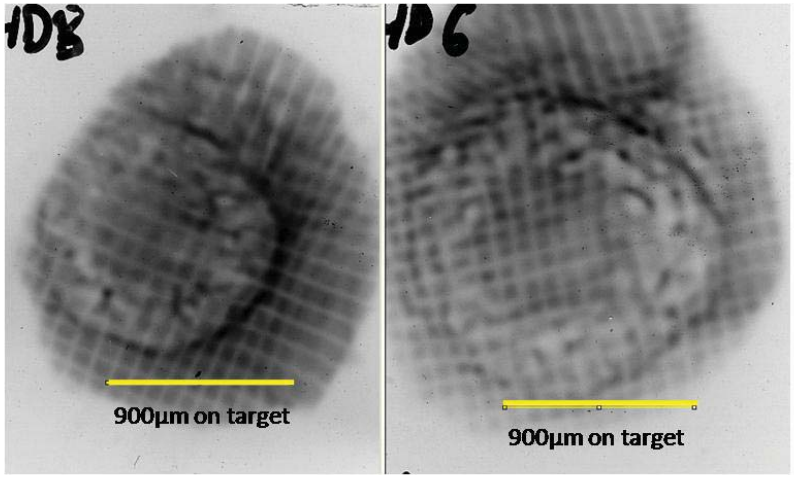




Transverse lineout

A second experiment was performed at LULI2000 using higher energy (200-400 J) and large focal spot



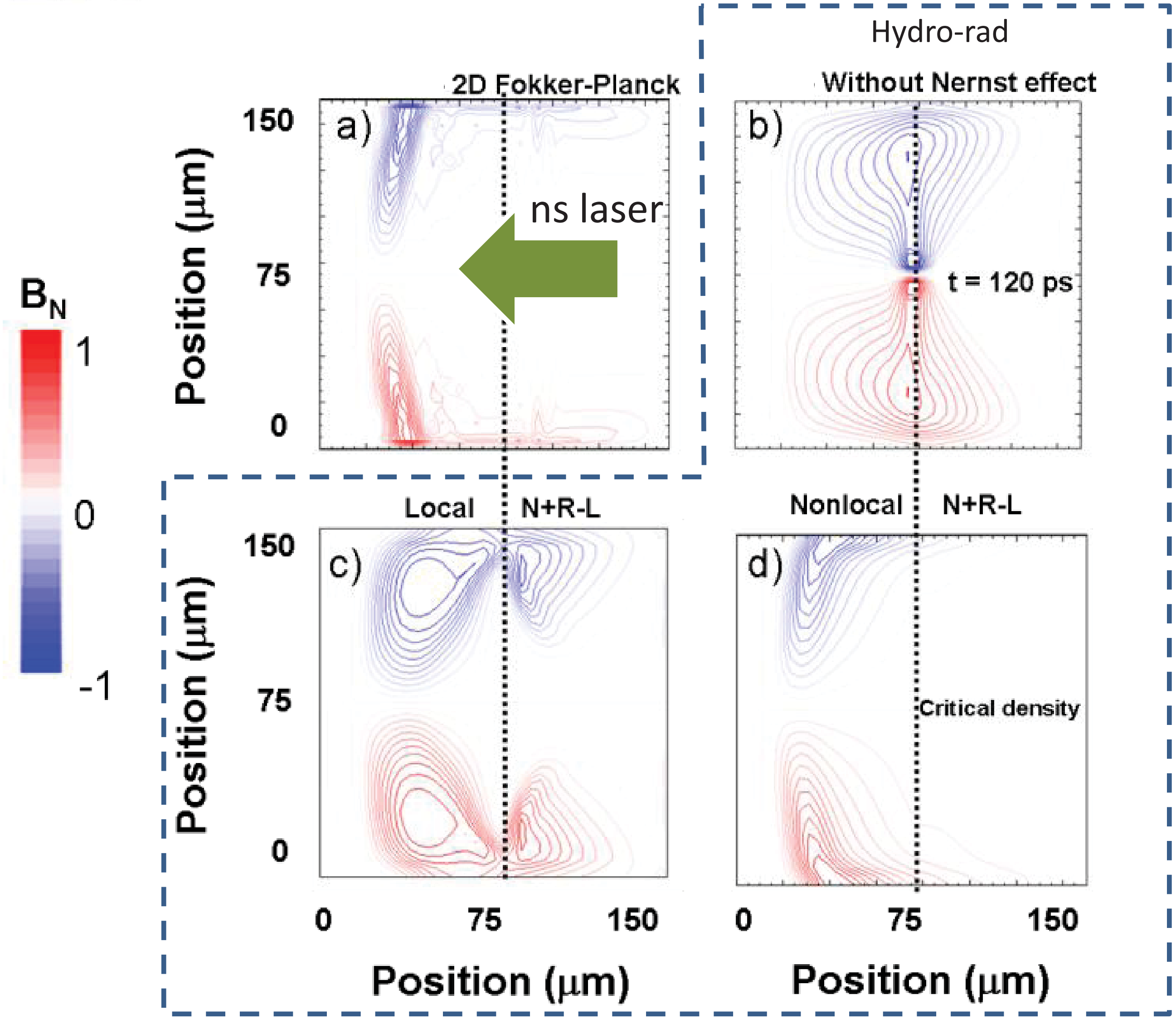


100µm Gaussian 200µm flat top
probed 0.6 ns after the onset of the ~2 10^{14} W/cm² / 2 ns beam

- Large deflections were observed
- The longitudinal heat flow measured through x-ray tracers was consistent with the simulations

L. Lancia et al., LPB 2013

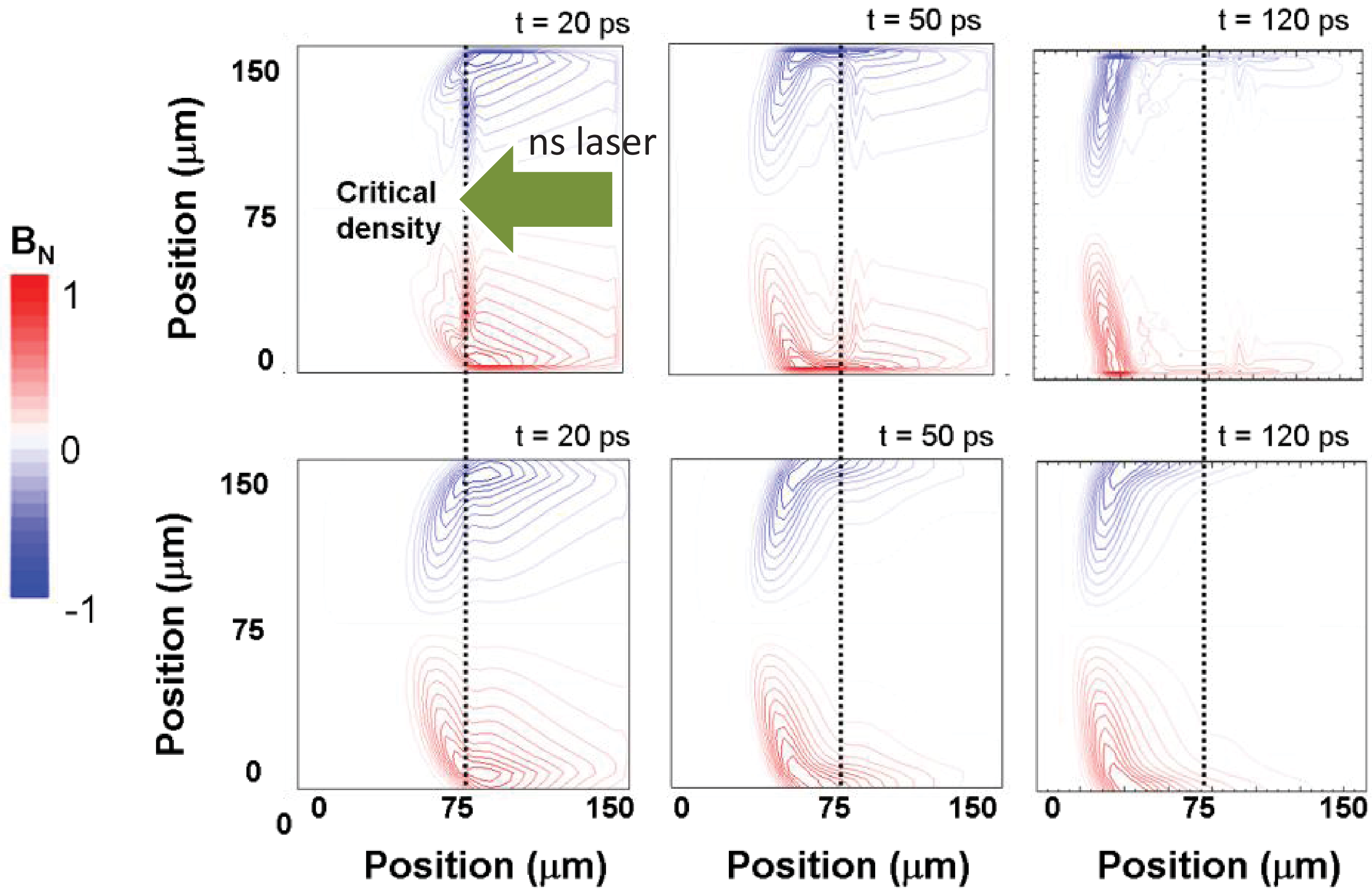
Significant efforts were made on the simulation side



Comparison between:
•kinetic code
•hydro-rad code with detailed MHD

(taking into account pressure driven source term, resistive diffusion of magnetic field and non local electron transport with magnetic inhibition)

Significant efforts were made on the simulation side



2D FP

Hydro-rad

We could observe that NL heat transport plays an essential role to correctly model the B field

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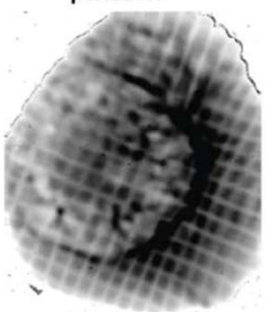
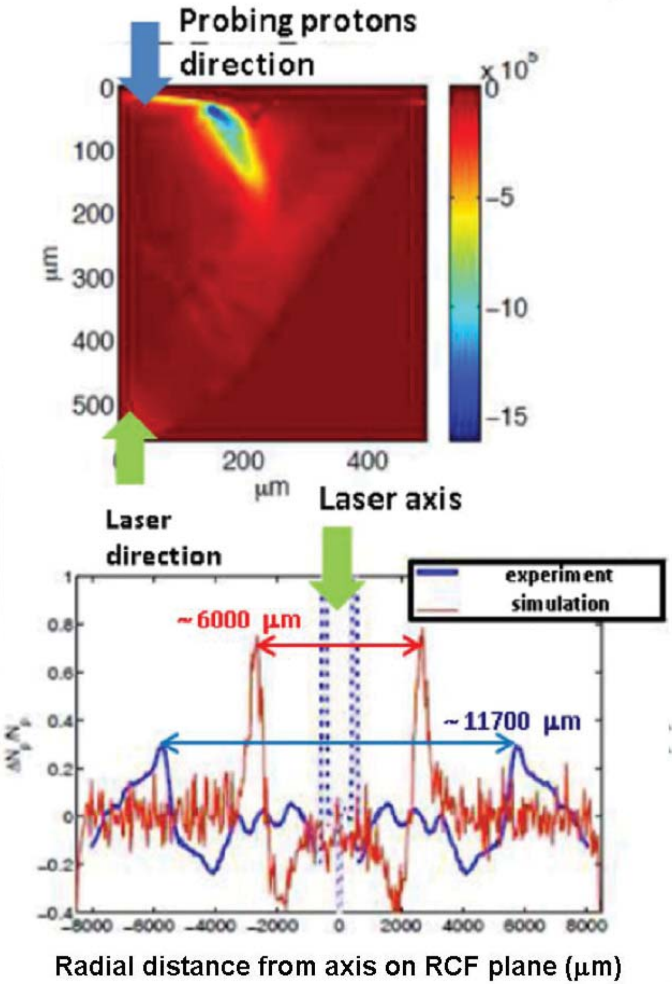
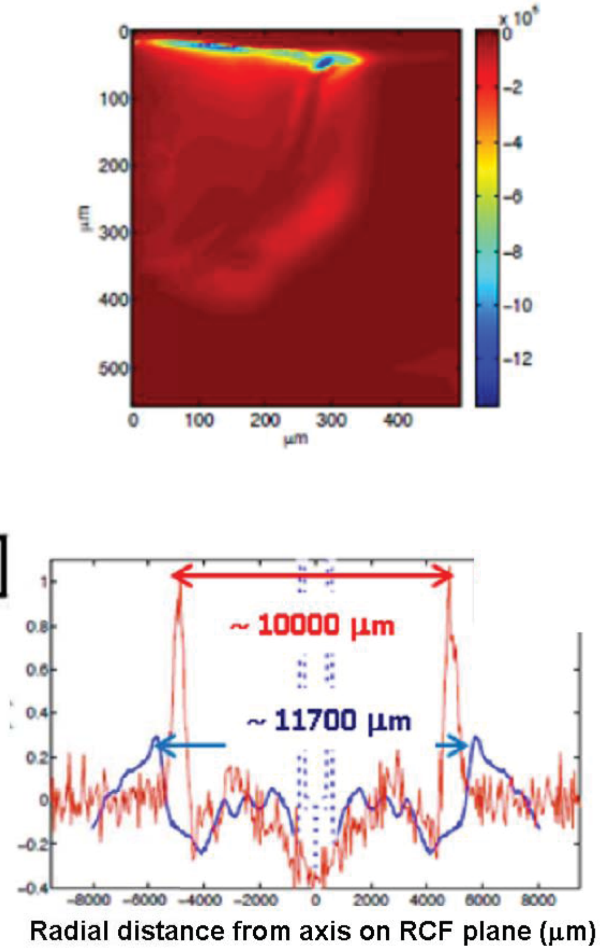
Local N+R-L

Nonlocal N+R-L

Experimental pattern







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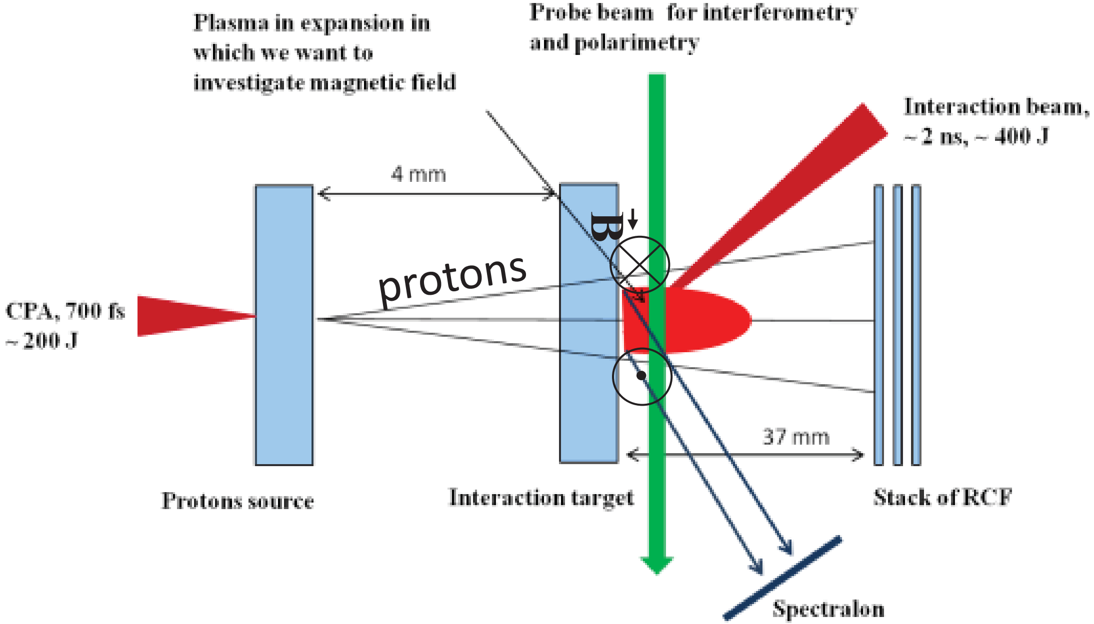
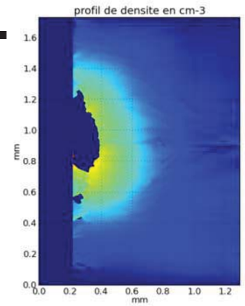
But the late evolution of the B field is still pending

- The LULI2000 campaign probed the plasma only at the beginning of the high-power laser irradiation
- MHD could reproduce well the B-fields, but was validated against the kinetic model only over short times
- Li et al. (07, 09) showed issues with Masnex modeling of late time evolution of B fields
- This motivated us to study the long-term B evolution



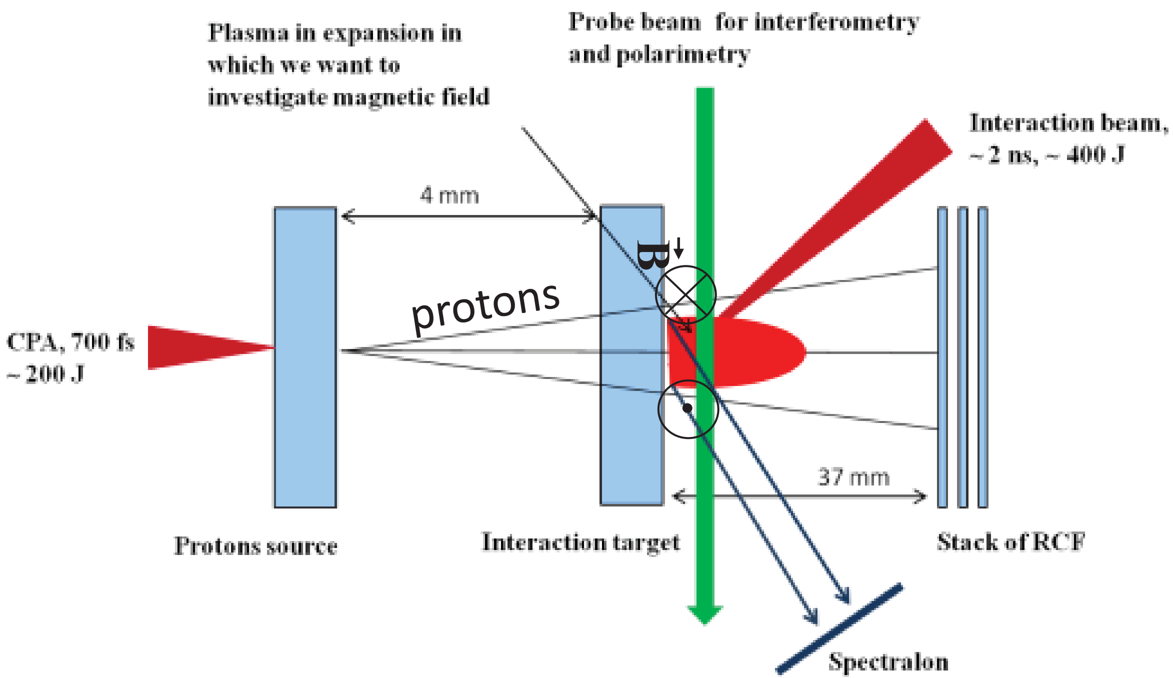
The experiment (@ Titan/LLNL) used many diagnostics to constrain the simulations



- Visible transverse interferometry (n_e)
- Visible transverse polarimetry (**B** in the corona)
- Proton probing (**B** in the dense plasmas)
- X-ray pinhole

  (time-integrated)
- Spectralon

  (scattered ns beam light)



Hybrid simulations

Can hybrid code handle magnetic reconnection in HEDP ?

Physical hypotheses :

- Quasi-neutrality : $n_e \sim n_i$ (but $\boldsymbol{\nabla}.\mathbf{E} \neq 0$)
- Electrons mobility $\rightarrow \infty$: $\mathbf{V}_e$ is such as $\mathbf{J} = ne(\mathbf{V}_i - \mathbf{V}_e) = \boldsymbol{\nabla} \times \mathbf{B}$
- Closure equation for electrons : isotherm or adiabatic
- Neglect transverse component of displacement current
- Hence, needs an Ohm's law :

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} + N^{-1}(\mathbf{J} \times \mathbf{B} - \boldsymbol{\nabla}.\mathbf{P}_e) + \eta \mathbf{J} - \eta' \Delta \mathbf{J}$$

$\Rightarrow$ Can solve $kd_i \lesssim 1$, $\omega/\Omega_i \gg 1$, but no electron scales (neither spatial, nor temporal), and no plasma frequencies. Well suited if $\omega_P/\Omega \gg 1$ (1000 in the solar wind).

What is needed for reconnection ?

To trigger a reconnecting instability, one needs an electric field such as $\nabla \times E_{||} \neq 0$

$\Rightarrow$ If we are not interested in the onset (at electron scales), small (numerical) resistivity can do the job.

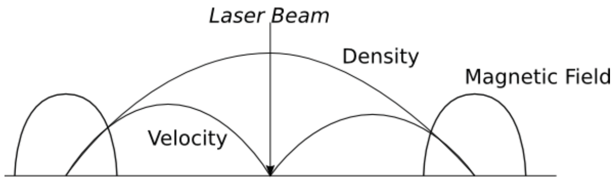
For collisionless & $\beta \sim 1$ plasmas, GEM challenge (Birn 2001) showed that when the Hall effect is considered, the reconnection rate does not depend on the formalism.

$\Rightarrow$ What about HEDP ?

Nernst and Righi-Leduc effects are not considered. Collisions can be included.

HECKLE is versatil, 3D & parallelized

Initial set up, very close to Fox et al. 2011 :



$\Rightarrow$ 2 bubbles initially (and not 2 halves) including a background :

- Can handle asymetries on $\mathbf{B}$, n, T, $\mathbf{V}$...
- Can handle non-coplanar configurations : set a given angle of rotation around the 2 directions of the target plane.

$\Rightarrow$ Plus few cautions to get $\nabla.\mathbf{B} = 0$ and periodic boundary conditions.

Initial conditions

Old standing problem : if the initial set-up is not a kinetic equilibrium, energy has to be redistributed... generally in a wave.

This is the case if one uses a Maxwellian with an initial fluid equilibrium.

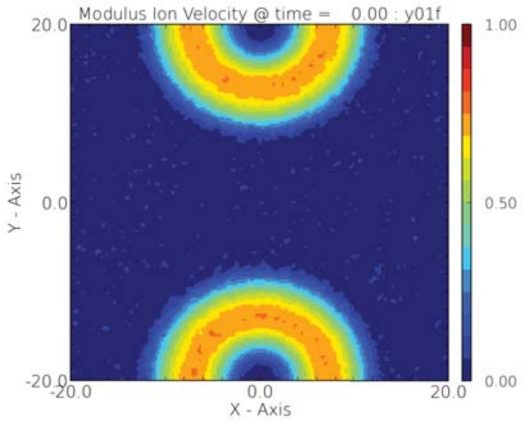
In our conditions, we are not even at an equilibrium... and of course we launch a $k_\perp$ (magnetosonic) mode at $t = 0$.

A kinetic equilibrium is generally very hard to find even in apparently simple topology : We do not think about it for laser configuration !

$\Rightarrow$ Is it a problem for the reconnection process ?

Initial wave

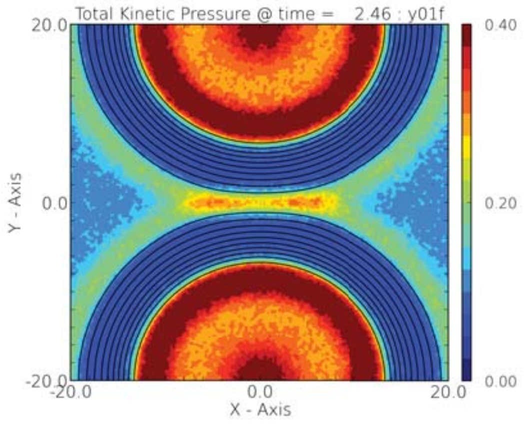
This wave is very clear on the modulus of total ion velocity :



⇒ This question the initial set-up... that nevertheless seems coherent with hydro-radiative simulations. The associated RAM pressure is small.

Initial Slow-down

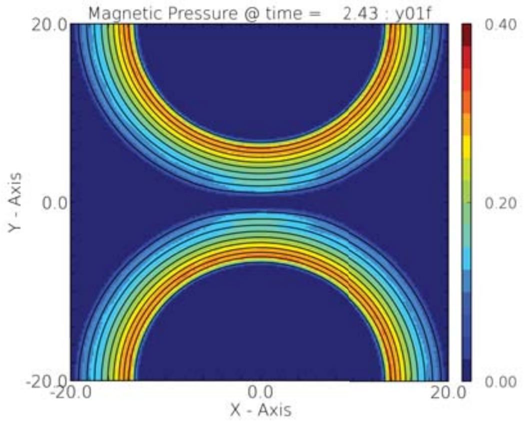
The initial ion velocity is also slowed-down prior reconnection :



⇒ Essentially because of the enhancement of electron density at the noze (snowplow problem). Mostly a consequence of the background...

Initial magnetic flux pile-up ?

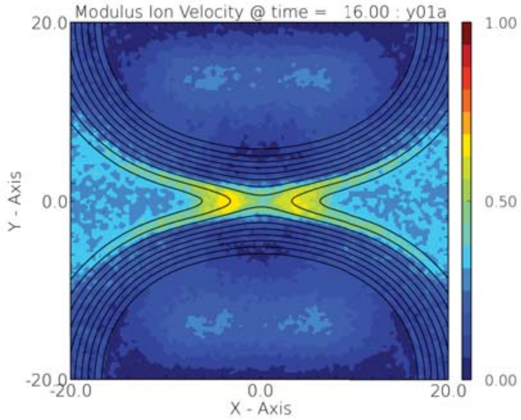
Redistribution of magnetic pressure in the flux tube :



⇒ The flux tube is pushed from inner side, and blocked in the outer side. The total magnetic flux to be reconnected is conserved...

First run

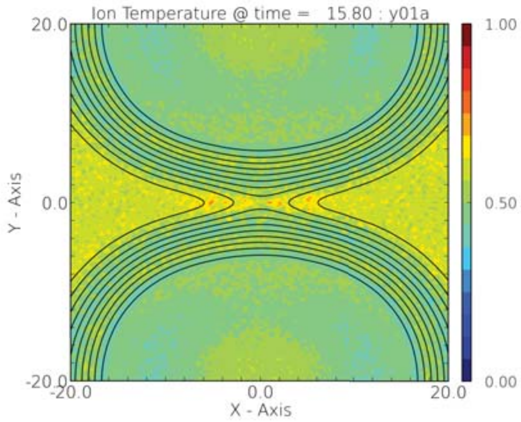
Let's have a look at reconnection...



⇒ Fast reconnection with an outward jet velocity bounded by the Alfvén speed... as in GEM challenge.

Energy budget

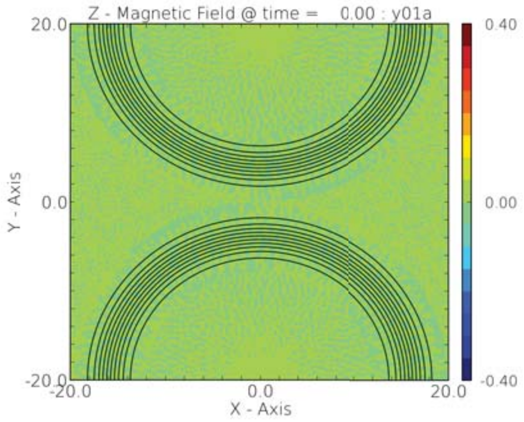
Is this accelerated flow associated to heating ?



⇒ Energy budget is debated (Birn et al. 2010, Aunai et al. 2011), and should be measured in experiments.

Fast reconnection ?

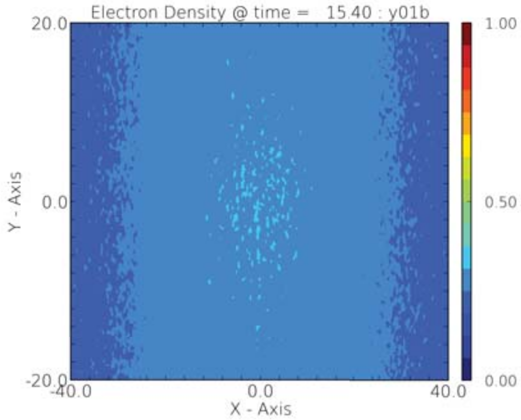
Are we talking about fast reconnection ?



⇒ Yes. Electron jets at the separatrix, results in a Hall electric field : the Hall component of the magnetic field (Mandt et al. 1994)... should also be measured in experiments.

Plasma dynamics with $B = 0$

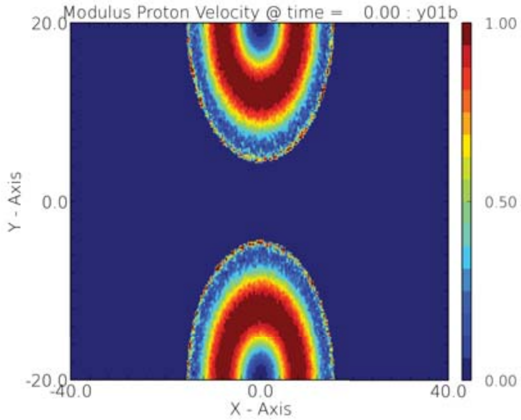
If one doubts about magnetic reconnection in HEDP :



$\Rightarrow$ Totally diferent picture,

Plasma dynamics with $B = 0$

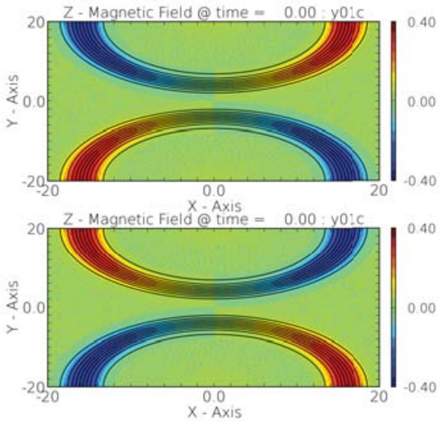
If one doubts about magnetic reconnection in HEDP :



$\Rightarrow$ Totally diferent picture,

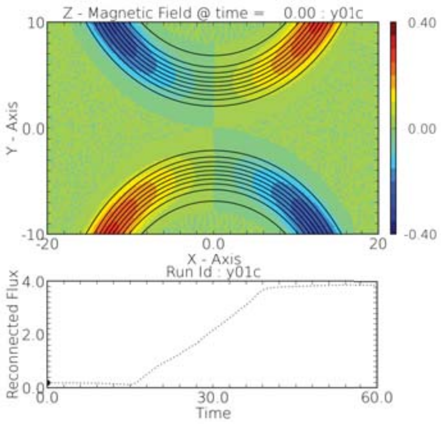
Non-coplanar reconnection

Depends on the angle : salient or reflex ?



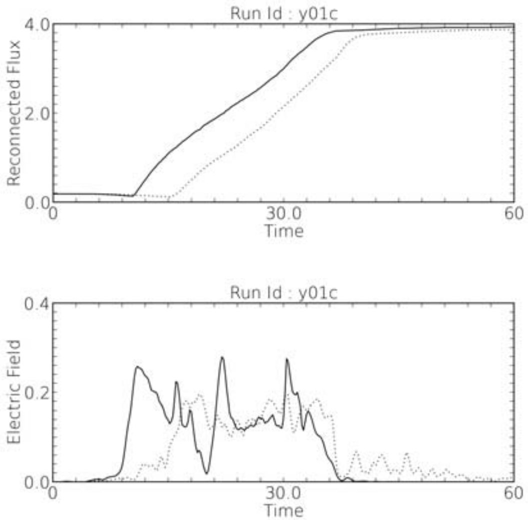
⇒ Is the Hall magnetic field a cause or a consequence of magnetic reconnection ?

Non-coplanar reconnection



$\Rightarrow$ No magnetic reconnection onset with the "wrong" B_Z.

Consequence for the reconnection rate

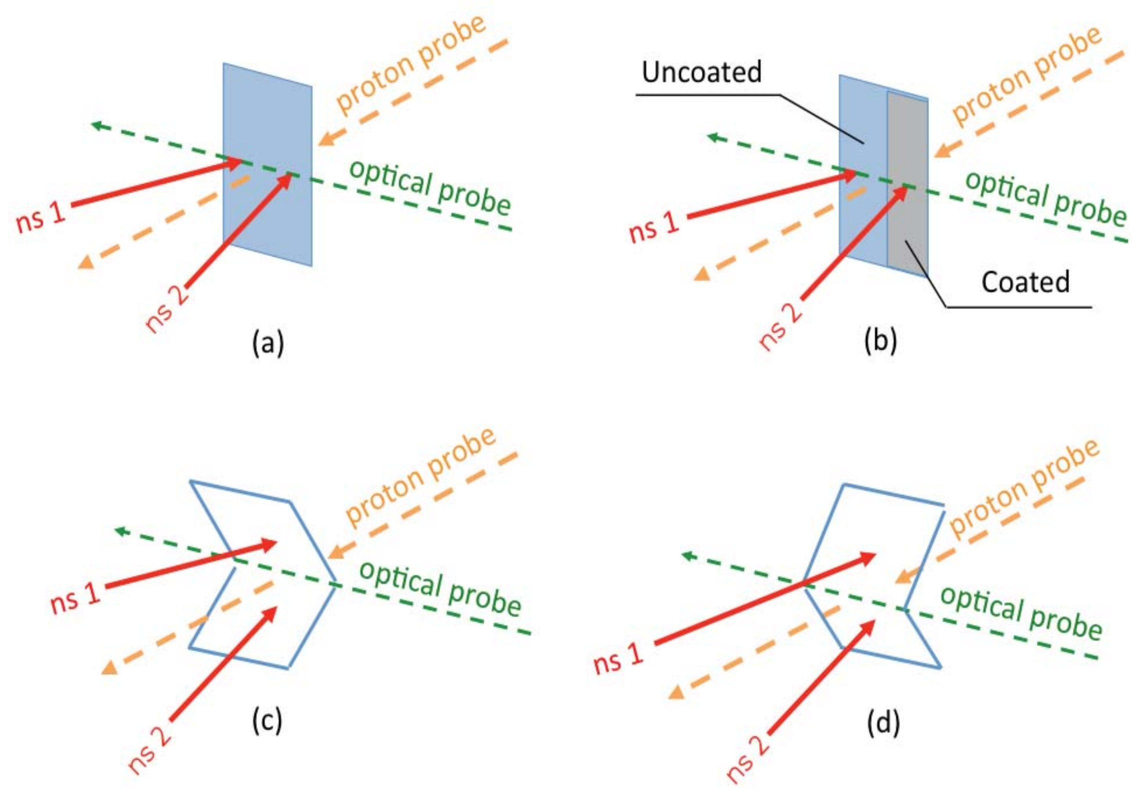


⇒ Reconnection is triggered later, but at a same rate.

Short-term program on B-field reconnexion experiments

- A beamtime is planned at GSI in 2014 using Phelix

- Aim: to study symmetric (a) and non-symmetric (b)(c) and (d) reconnexion



Long-term program

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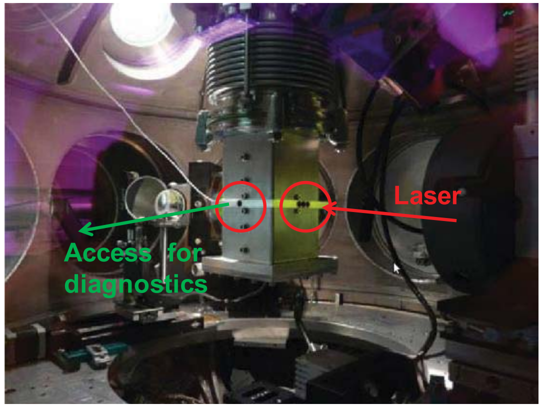
- Study macroscopic large-scale consequences of reconnection (solar corona)



- Aims:
  - Importance of so-called guide field (use of pulsed-power unit we developed coupled to the laser)
  - Identification of QSLs and study of energy release in slip-running reconnection (using the OHM code)