Studying fast plasma collisions in the laboratory using laser-accelerated ion beams

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Plan

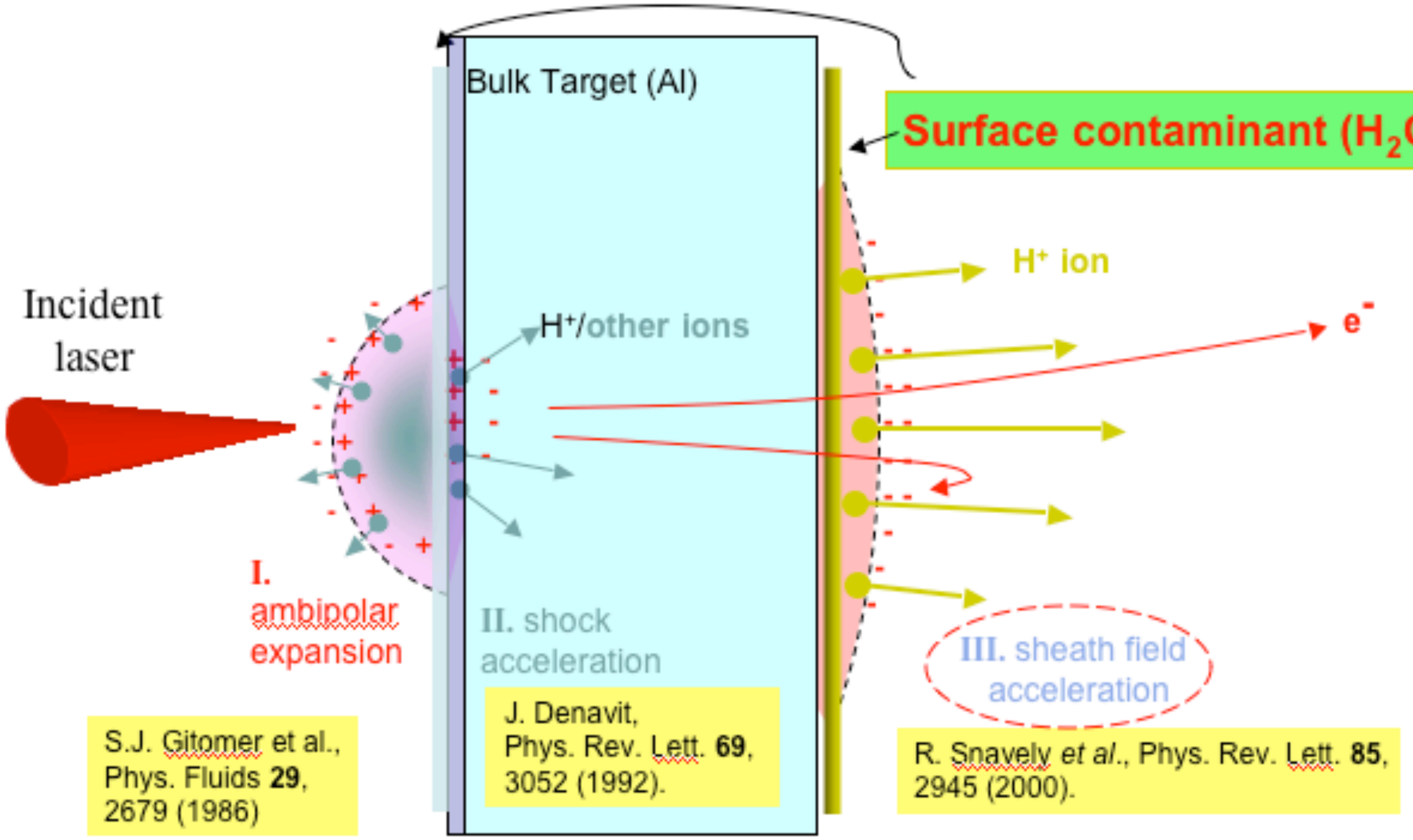
- Accélération d’ions par laser
- Etude de collisions de plasma en laboratoire avec des vitesses de quelques dizaines de % de c
- Méthode alternative pour la génération de champ magnétique externe
- Présentation de la partie de l’ANR SILAMPA sur les chocs sans-collision avec champ magnétique externe
- Expériences proposées sur Titan (Livermore)
- Conclusions

Context

- Knowledge in laser plasma interaction, laser particle acceleration and PIC simulations at CELIA.
- Will to use this knowledge to prepare laboratory astrophysics experiments.
- Astrophysical collisionless shocks and the subsequent particle acceleration is a natural choice as they constitute existing research topics in our group in the context of laser-plasma interaction.
- Increased collaboration with astrophysicists (ANR MACH).
- Possibility to use external magnetic fields (LULI, LNCMI)
- Colleagues studying collisionless shocks with lasers in experiments (M. Borghesi, L. Romagnani, theoretical support by M. Dieckmann...).

Laser ion acceleration tutorial

Proton acceleration mechanism in high intensity laser plasma interaction



Bulk Target (Al)

Surface contaminant (H_2O)

Incident laser

H^+/other ions

H^+ ion

e^-

I. ambipolar expansion

II. shock acceleration

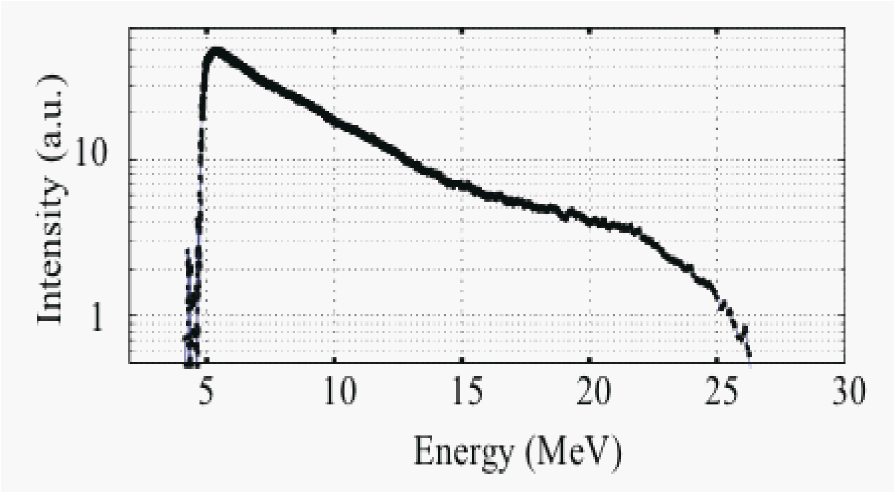
III. sheath field acceleration

S.J. Gitomer et al., Phys. Fluids **29**, 2679 (1986)

J. Denavit, Phys. Rev. Lett. **69**, 3052 (1992).

R. Snavely *et al*., Phys. Rev. Lett. **85**, 2945 (2000).

M. Allen et al., Phys. Rev. Lett. **93**, 265004 (2004); J. Fuchs et al., Phys. Rev. Lett. **94**, 045004 (2005).



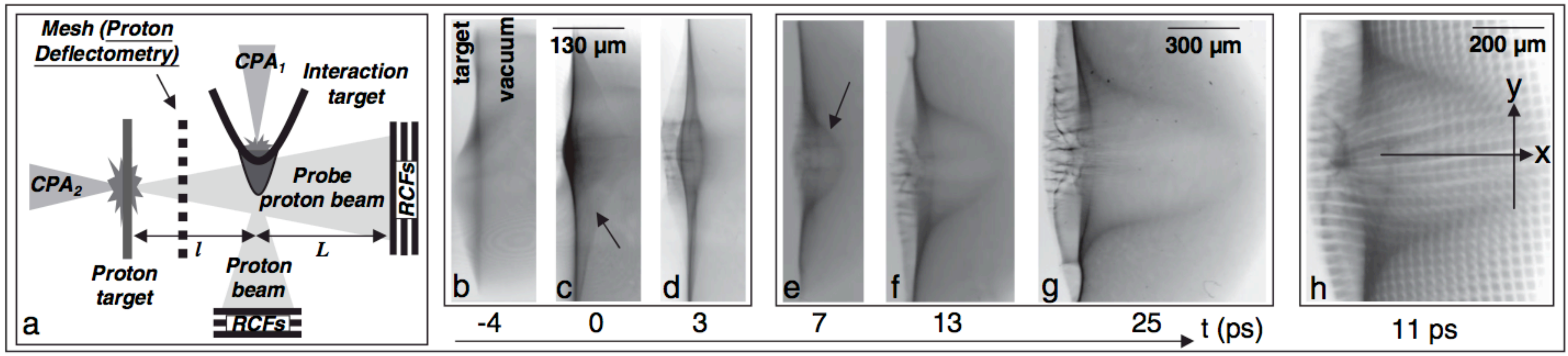
Typical proton spectrum obtained at LULI.

- Low emittance (<0.004 mm-mrad for the transverse emittance and $<10^{-4}$ eV-s for the longitudinal emittance)
- Short duration (ps at the source).
- High spectral cut-off
- TNSA: Maximum proton energy depends on hot electrons temperature and density.
- New regimes are now explored both theoretically and with experiments but the achievable maximum energy has only slightly increased in the last 10 years.

Applications of ion beams

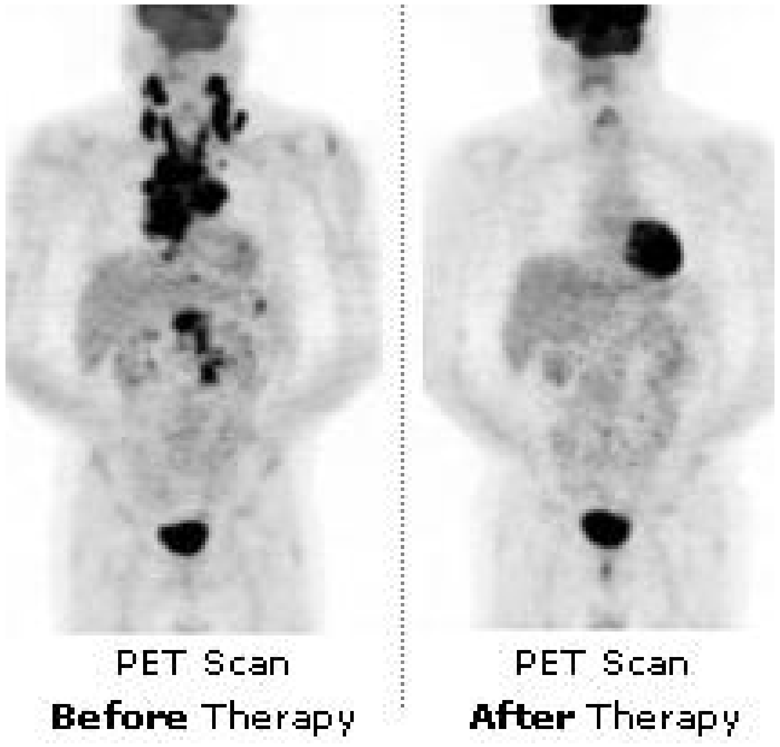
- new high-time resolution diagnostic techniques, since the short ion pulse duration;
- ion beam radiography / imaging and lithography;
- applications in energy research (ion “Fast Ignitor” in the inertial fusion energy context);
- medical treatment (proton therapy, transmutation of short lived radio-isotopes for positron emission tomography (PET) in hospitals);
- astrophysical phenomena in the Lab
- short neutron source.

L. Romagnani et al., Phys. Rev. Lett **95**, 195001 (2005)



Mechanisms of ion acceleration

1. Quasineutral plasma expansion
2. Collisionless shock (+trapping)
3. Target Normal Sheath Acceleration (Charge separation effect)
4. Coulomb explosion
2. Laser-piston regime $I \geq 10^{23}$ W/cm^2
6. Direct ion acceleration $I > 10^{24}$ W/cm^2



Laser ion acceleration optimization

Optimization of laser-target interaction for nowadays and future lasers

How to increase maximum proton energy ?
Finding of the optimal target (gas target/solid state target, thickness /density, transversal size)
Varying of the laser pulse parameters (duration/power, intensity /focal spot size, polarization, etc.)
Protons with energy of the order of 200 MeV (proton therapy) ?
Mono-energetic proton beams?
- Utilization of complex target composed from heavy and light ions
- Angular selection of protons

PIC code for simulation of laser-plasma interaction

$$\frac{\partial f_{i,e}}{\partial t}+\mathbf{v}\frac{\partial f_{i,e}}{\partial \mathbf{r}}+\mathbf{F}_{i,e}\frac{\partial f_{i,e}}{\partial \mathbf{p}}=0,$$

$$\mathbf{F}_{i,e}=q_{i,e}\left(\mathbf{E}+\frac{1}{c}[\mathbf{v},\,\mathbf{H}]\right),$$

$$\mathrm{rot}\mathbf{H}=\frac{4\pi}{c}\mathbf{j}+\frac{1}{c}\frac{\partial \mathbf{E}}{\partial t},\quad \mathrm{rot}\mathbf{E}=-\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t},$$

$$\mathrm{div}\mathbf{E}=4\pi\rho,\quad \mathrm{div}\mathbf{H}=0.$$

$$\mathbf{j}=\sum_{i,e}q_{i,e}\int f_{i,e}\mathbf{v}d\mathbf{v},\quad \rho=\sum_{i,e}q_{i,e}\int f_{i,e}d\mathbf{v}$$

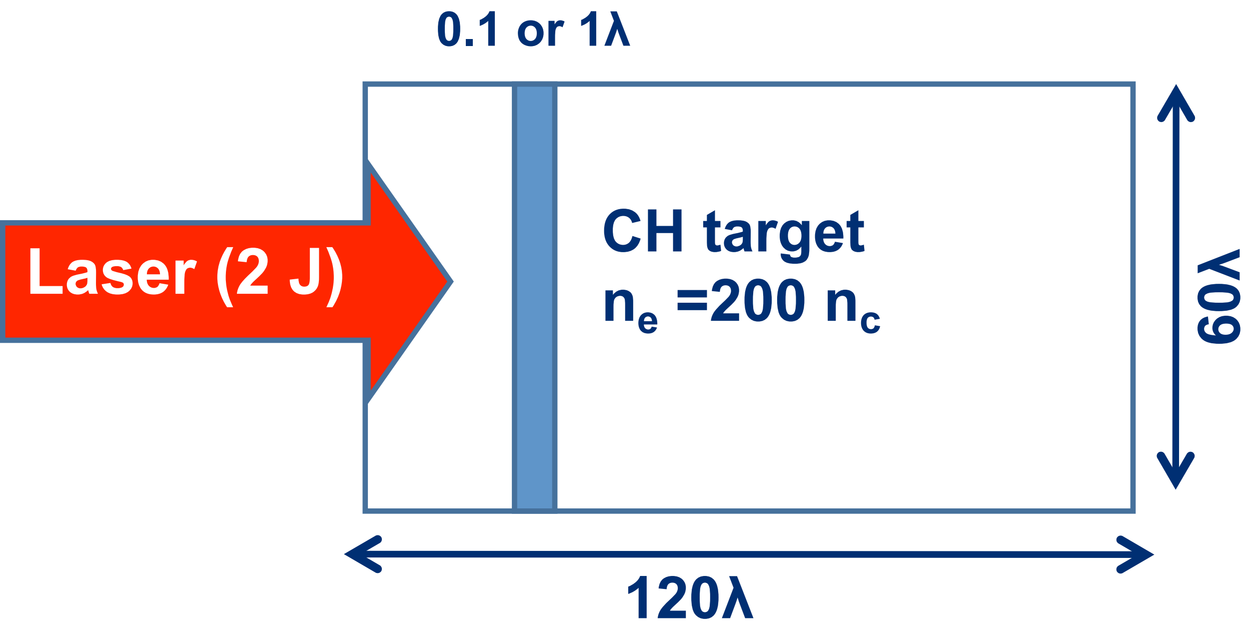
Kinetic equation – particle method
Maxwell equation – differential mesh scheme

Restriction
- ionization and particle collision do not take into account
- computational resources

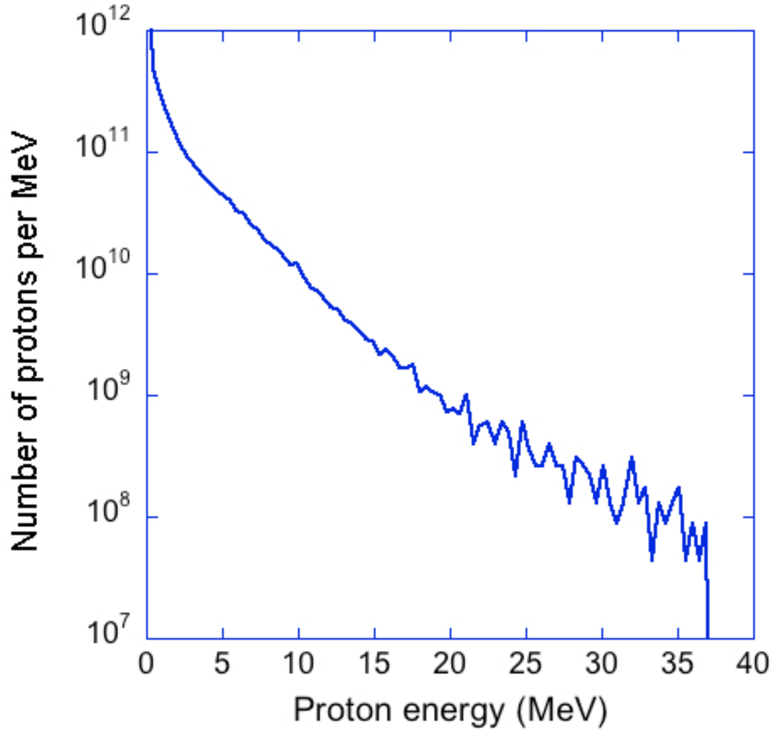
PICLS 2D parametric study of laser ion acceleration from foils

	Intensity ($\times 10^{18}$ W/cm^2)	Laser pulse duration (fs)	Laser FWHM (µm)	Maximum proton energy (max, MeV)	Number of protons within the spectral range /max=5% (a.u.)
0.1 µm target	100	45	6	25.5	9
	50	90	6	25.2	9
	225	20	6	15.9	5
	40	45	10	15.9	9
	225	45	4	**36.9**	13
1 µm target	100	45	6	9	7
	50	90	6	15.9	13
	225	20	6	3	3
	40	45	10	4.5	9
	225	45	4	15.3	13

Attention !
2D simulation.
Not optimal thickness.
For optimal thickness ~53 MeV

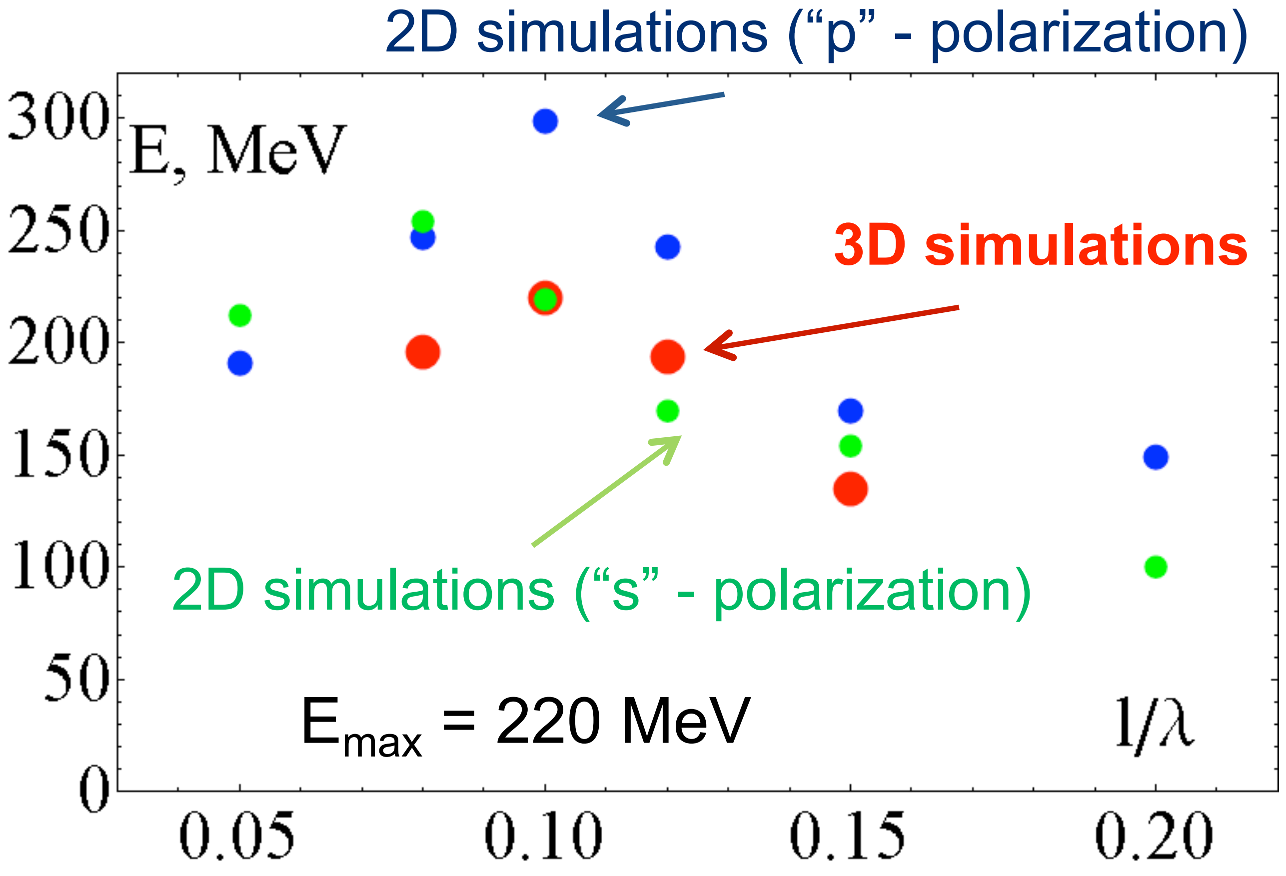


Optimum number of protons for 10-30 MeV regime: 4.25×10^{10} protons for the 20 J/50 fs laser pulse, we need at least 10^{13} protons → kJ/ps pulse



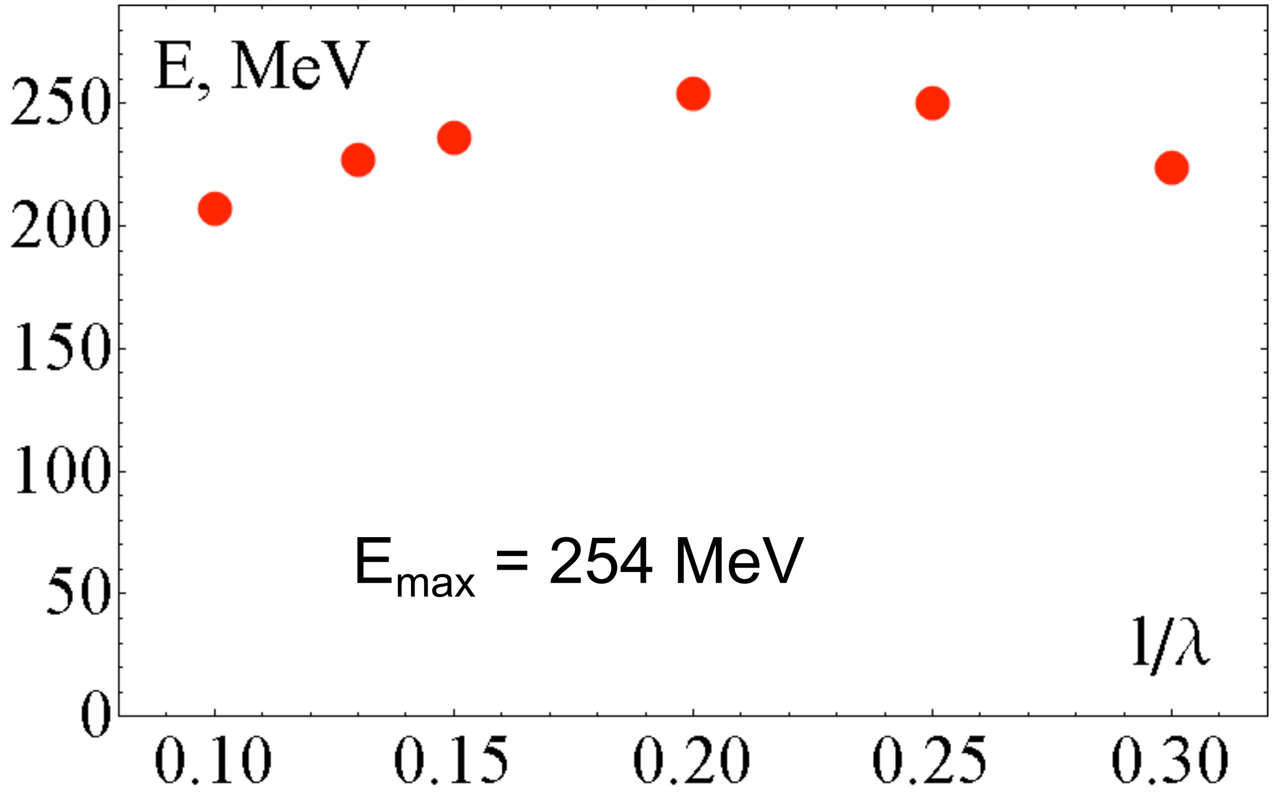
Optimal target thickness for powerful laser pulse (20 J)

I = 7.4 10^{21} W/cm^2 focused in 4 μm (FWHM) , 15 fsec



E_{max} = 220 MeV

I = 1.48 10^{22} W/cm^2 focused in 2 μm (FWHM) ($f_\#$ = 1.3), 30 fsec



E_{max} = 254 MeV

$\frac{n_e}{n_c}\frac{l}{\lambda}$ =78 a_0=73

Optimal condition $\frac{n_e}{n_c}\frac{l}{\lambda}$ =156 a_0=104

$a_0 = C\frac{n_e}{n_c}\frac{l}{\lambda}$ Increasing of laser pulse intensity results in decreasing of coefficient C ~0.7-1

Target – CH_2 foil with optimal thickness of 0.1 μm. It consists of heavy ions C^{+6} with n = 30 n_c, M =12 m_p and Z=6, light ions (protons) with n = 60 n_c and electrons with n_e =240 n_c

Going to oblique incidence or reduced target in the transverse directions does not lead to higher proton energies in this regime.

Intermediate conclusion

- Using 2D and 3D simulations with the Particle-In-Cell codes PICLS and MANDOR, it is shown that using thin solid foils and high intensity short pulse lasers, one can succeed in production of proton beams with a wide energy spectrum and a maximum proton energy of around 65 MeV for a 2 J laser and around 250 MeV for a 20 J laser.

- The 3D simulations are crucial for these studies since 2D simulations overestimate maximum proton energy by a factor of around 1.5.

Plasma collision experiment preparation and simulations

Motivations

- Here: using astrophysical parameters, we evaluate instabilities for energy transfer in counterstreaming plasmas (Davis et al, ApJ, 2011: in preparation; Davis et al. IOP, 244 (2010))

- TNSA: laser accelerated, Energetic protons at sub-relativistic velocities. Overdense targets.

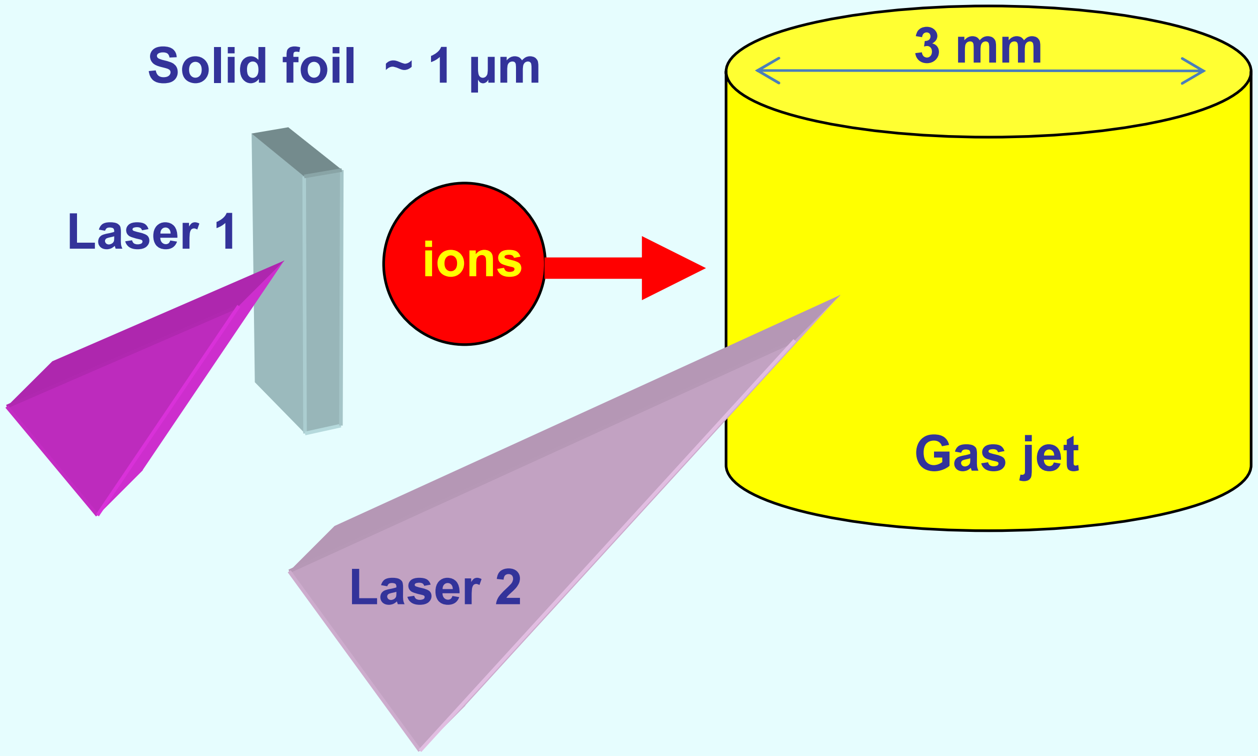
Previous Work:

Theoretical: T. Kato & H. Takabe ApJ, 681, 2008: Weibel mediated shocks may ocurr at low velocity; Y. Lyubarsky & D. Eichler, ApJ, 647, 2006: a fraction $\varepsilon_B \sim 10^{-4}$ of the total energy is converted into magnetic energy unless the electrons are heated greatly in the shock

Experimental: Kuramitsu, Y. et al., PRL 106, (2011): experiments on GEKKO XII (later on Omega): collision of two plasmas generated by ns high energy lasers. Failed to reach conditions highlighted by Kato et al. (10^{20} cm^{-3}, 1000 km/s). Obtained 10^{19} cm^{-3}, 1000 km/s. Electrostatic collisionless shock formation in very-high-velocity counterstreaming plasmas. Weibel filaments not seen – need much larger laser energy to excite a Weibel-mediated shock

- Our Experimental Scheme:
- interaction with secondary plasma jet target: instabilities
- proton bunches: provide directed kinetic energy collisionless transfer from protons to electrons, to magnetic and electric fields
- Demonstrate: Proton Weibel produces energy exchange [Davis et al., 2010 J. Phys.: Conf. Ser. 244]
- Energy Equipartition: ions => electrons => fields

Design of experiment on fast ion - plasma collision



Detection system:
- ion energy loss
- X-ray emission
- interferometer

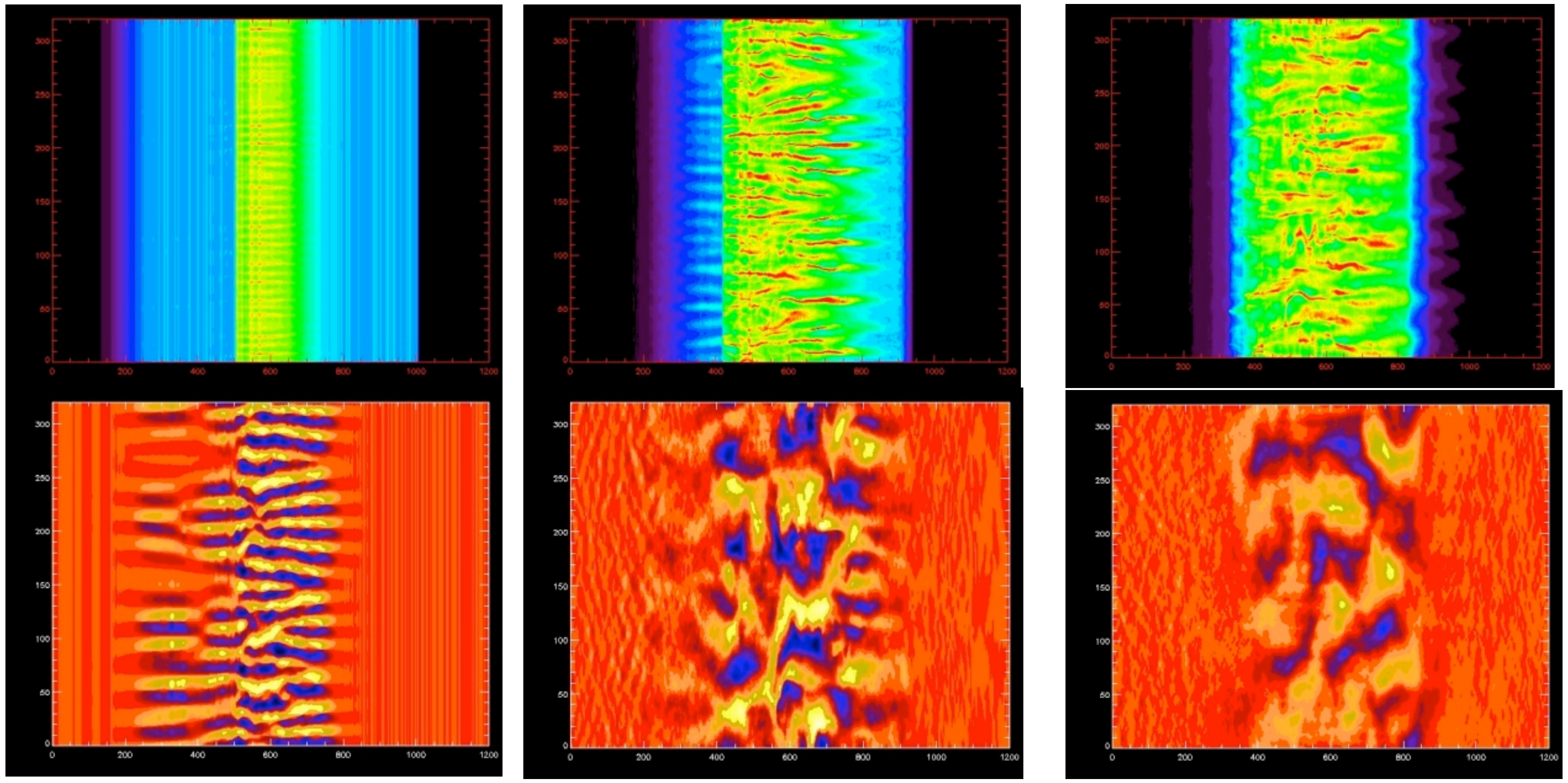
Principal stages of the interaction:
1. Ion acceleration at the rear side of a thin solid foil: 20 MeV, 10^{13} protons Ø 0.1 mm
2. Ion ballistic transport to the secondary target: 1 mm, 10^{18} cm^{-3} 1 mm
3. Formation of a secondary plasma with an auxiliary laser Ø 0.1 mm, length 3 mm
4. Plasma collision: measurements of the electron and ion heating, ion energy loss, x-ray emission, density and velocity profiles

PIC Simulation for Laboratory Experiment: Time Evolution of np and Bz: [0,5ps] (davis et al., IFSA 2009)

β = up /c = 0.2, $\varepsilon_p \approx$ 20 MeV; transverse Te = 10 KeV for incoming plasma and 100 eV for secondary plasma, $n_e = 10^{18}$ cm^{-3}, $\omega_{pe} = 5.6 \times 10^{13}$ s^{-1}, $\lambda_{sp} = c/\omega_{pi}$ = 220 μm, protons and electrons

proton density : top

B-Field: Bottom



L_y=320 µm

L_x=1200 µm

Time 1: 1ps   Time 2: 2ps   Time 3: 3ps

Maximum field generated by Weibel instability ~ 4 to 5 MG

Growth of B field and then dissipation is correlated with filaments

Intermediate conclusions

•Efficiency of "thermalization" of the directed proton energy and the level of magnetic field saturation are crucial issues for GRB physics

• Existent theoretical estimates and numerical simulations are contradictory and incomplete. More work is necessary: magnetic field dynamics, energy spectra, asymptotic behavior

• Numerical simulations in the scale of 100 c/ω_{pi} are possible at the present hardware at least in 2D.

• Laboratory experiments are possible at the laser level of a few kJ and a PW power – ion energies ~ 20 – 40 MeV. Possibility to rescaling on the relativistic conditions via numerical simulations with the same physical model

• Importance of electron temperature:

• Several instabilities develop one after the other.
• See talk by Vladimir Tikhonchuk.

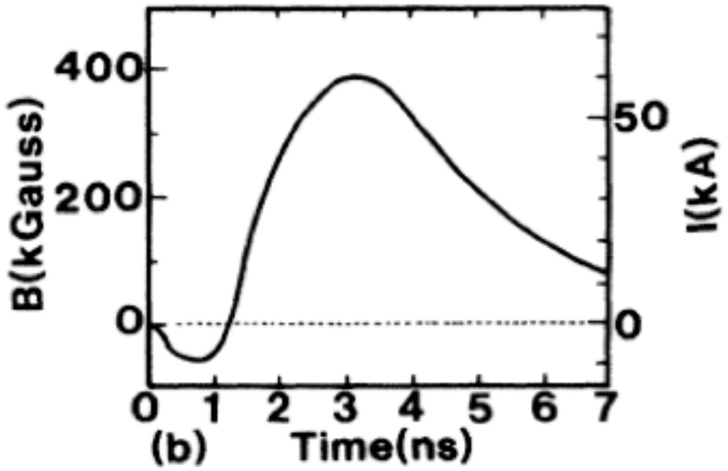
Astrophysics: *in situ* Laboratory collisionless shock creation yields insight on interactions involving an external jet and the ISM (e.g., gamma-ray burst afterglows, SNRs)

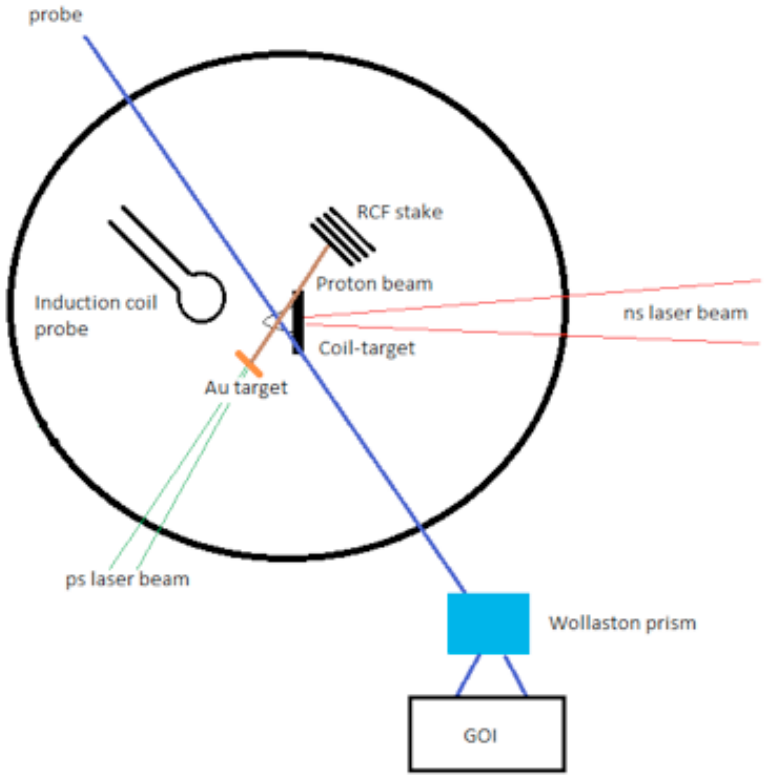
Possibility to do experiments with faster flows using higher energy lasers (and also to change flow densities).

Autre méthode pour créer le champs magnétique externe en laboratoire

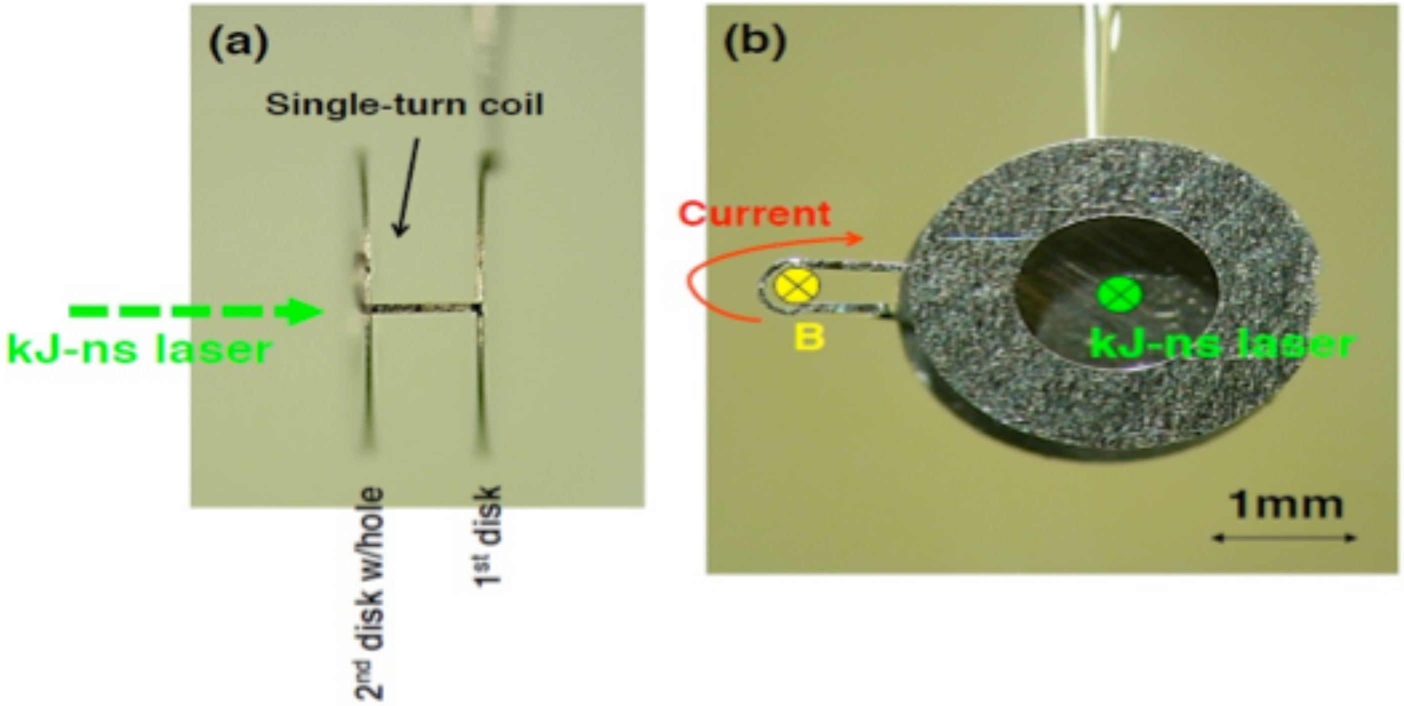
- In 1986 Daido et al. [17] generated magnetic fields by using targets composed of two parallel Cu disks, 50 μm thickness and 2 mm diameter separated by a 500 μm distance. The discs were connected with a 2 mm diameter one-turn coil made of 80 μm diameter Cu wire. The front disk had a 1 mm diameter hole at the center of the laser injection. The diagnostic for the magnetic field is composed by an induction coil connected to an oscilloscope.

- They reached 40 T.





Experimental setup for the first part of the experiment

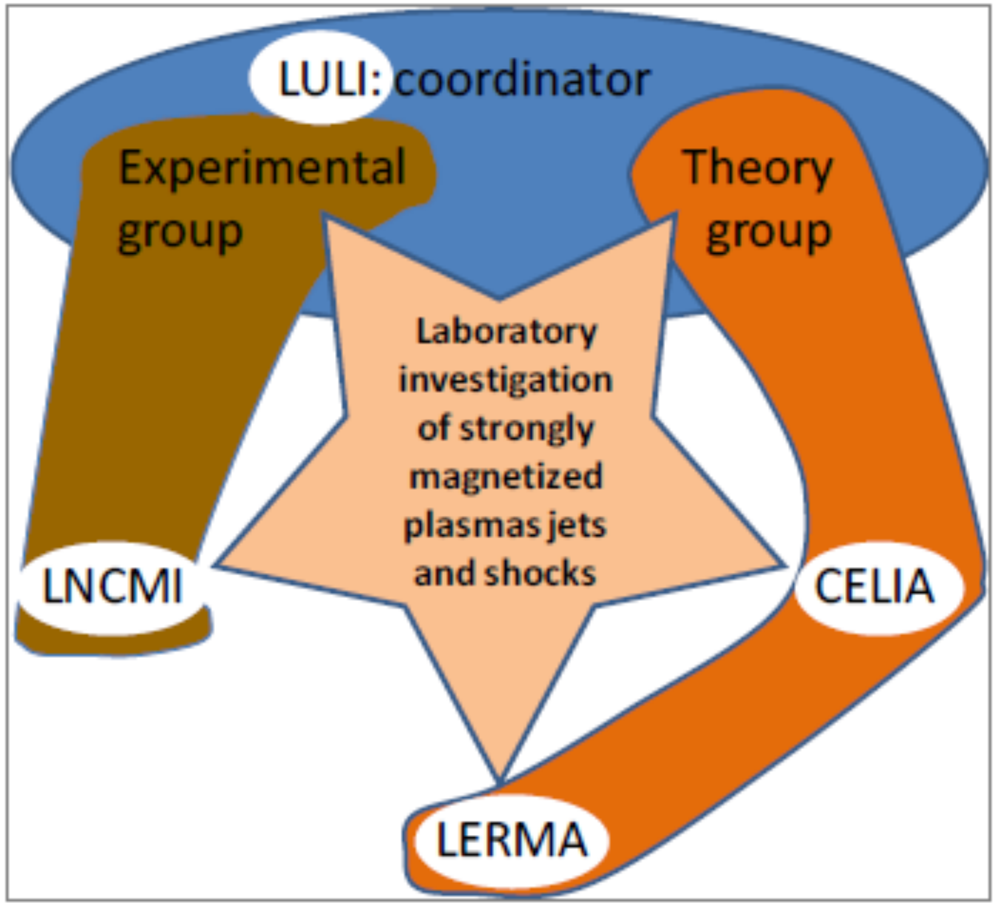


Photographs of a capacitor-coil target from (a) its side and (b) its front. The two nickel disks are connected by a nickel single-turn coil. [S. Fujioka et al.]

Présentation de la partie sur les chocs sans-collision avec champ magnétique externe

SCIENTIFIC PROGRAM, PROJECT STRUCTURE of the ANR SILAMPA

- ❑ Task 1 – Project coordination
- ❑ Task 2 – Generation of 40 T magnetic fields in a laser experiment-compatible fashion
- ❑ Task 3 – Study of plasma outflow collimation
- ❑ Task 4 – Study of particle acceleration and radiation generation in collisionless shock



LULI: coordinator

Experimental group

Theory group

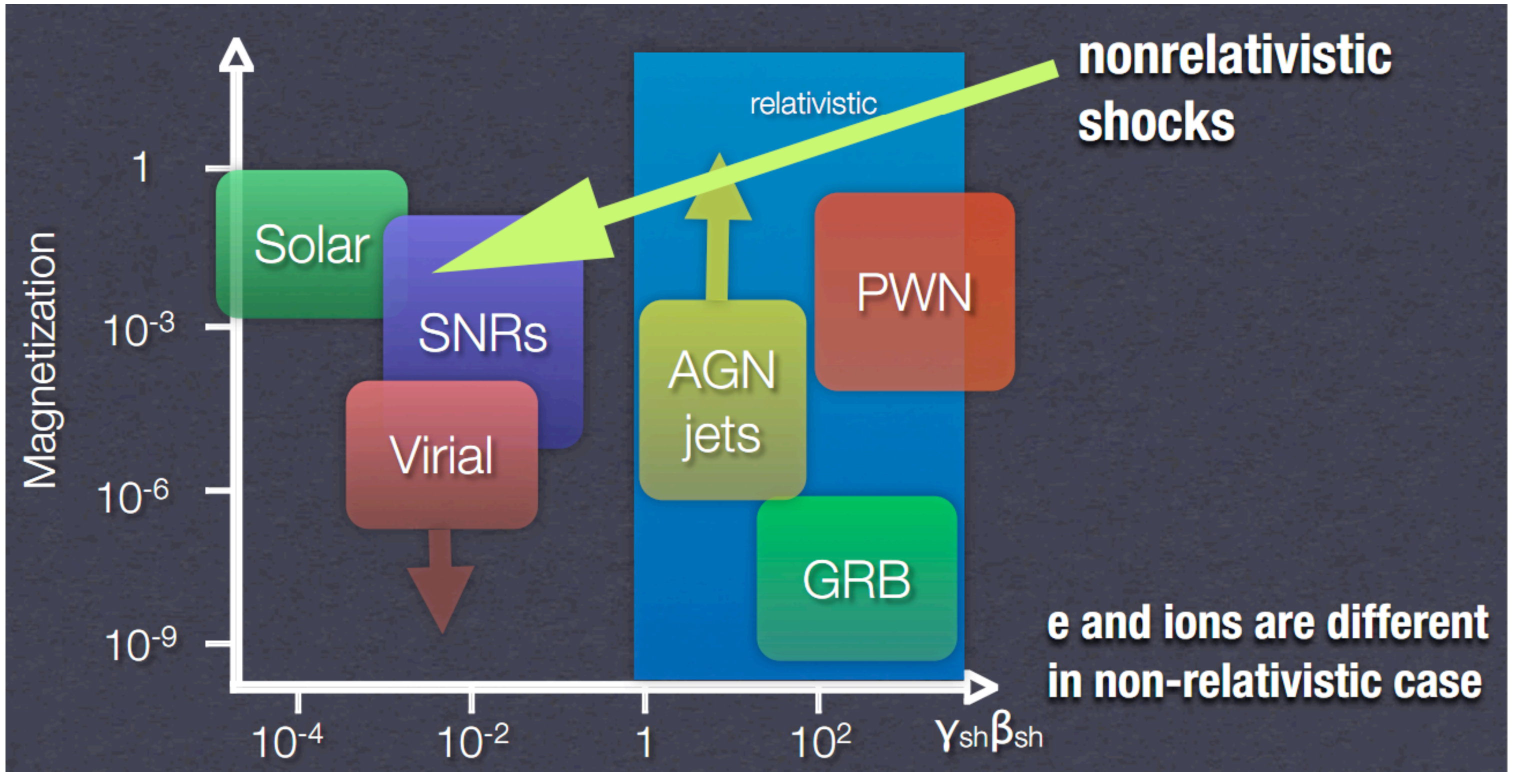
Laboratory investigation of strongly magnetized plasmas jets and shocks

LNCMI

CELIA

LERMA

Context



PRODUCTION OF COLLISIONLESS SHOCKS IN THE LABORATORY

- **The systematic study of collisionless shocks with velocities smaller than a few 1000 km/s**, excited by long-pulse lasers (~ns) having an increasing energy of 100's J to 10's kJ, **is in progress** in several laser facilities worldwide.

- **First experiments of collisionless shock production with an external magnetic field** have been performed at Omega (University of Rochester), but were limited to low plasma velocities (few 1000 km/s) and low magnetic fields (~T).

- However, as mentioned above, there have been **no experiments up to date in the regime of velocities of a few tenth of the velocity of light and in the moderate magnetization regime, i.e. experiments of relevance for SNR**.

- **Our strategy will be to have two high velocity (0.1-0.2 c) counter-propagating plasmas with a plasma density (before collision) of $n_0 = 10^{18}$ cm^{-3} embedded in a magnetic field** that will be used not only to provide magnetization, but also to reduce the required lengths of plasma inter-penetration to form such a shock.

Context (2)

- Regarding shocks, we also need the same level of magnetic field for the plasma parameters to be relevant to astrophysics.
- In the hot and low density region of the shock, the plasma will be collisionless. The magnetization parameter **$\sigma=(\omega_c/\omega_p)^2(c/v)^2$ has to be in the range 10^{-5} to 10^{-1} to cover the parameter range of SNRs (v is here the shock velocity), with v/c in the range of 0.01 to 0.5**.
- With the LULI laser parameters, the plasma produced will allow exploring v/c between 0.01 and 0.25, and σ between 10^{-5} and 2.5 (40 T, $ne=10^{17}$ cm^{-3}, v=0.25c). Hence, high magnetic fields are again needed to ensure that σ will be tunable over the whole shock parameter space.
- **Additional benefit from magnetizing the outflow inter-penetration: allows to reduce the required lengths to form such a shock and thus to study these collisionless shocks in the laboratory.**
- Experiments in the regime of velocities of a few tenth of the velocity of light and in the moderate magnetization regime of relevance for SNR have up to now never been accomplished in the laboratory, because without an external magnetic field, one needs to produce long and fast plasma flows to fully develop the shock, i.e. achieve ion reflection.
- **Dynamics of charged particles in the external magnetic field can reinforce instabilities leading to the shock for perpendicular shocks and increase the electron energy density in the shock region for parallel shocks**, hence making such experiments possible with nowadays lasers.
- In summary, with a 40 T magnetic field coupled to a laser- produced plasma jet, we should be in a very favourable position **to realize first astrophysically-relevant experiments of magnetized shocks**.

Presentation

General objective

By having two high-energy outflows colliding, we aim at clarifying, in a regime relevant for SNRs, the microphysics behind the production of energetic particle and radiation by collisionless shocks resulting from the outflow interpenetration.

Expected results

The key points that are sought after by astrophysicists to verify models, and on which we will concentrate to obtain quantitative measurements are the following:
(i) **Analysis of the shock structure and measurement of particle acceleration in non-relativistic shocks**,
(ii) **Measurement of ion acceleration as a function of Mach number in quasiparallel shocks**,
(iii) **Measurement of electron acceleration in quasiperpendicular shocks**.

We will use our experimental setup to study quasi-parallel and quasi-perpendicular configurations (this will be achieved by simply changing the direction of the magnetic field from parallel to perpendicular, with respect to the outflows interpenetration axis).

Experiments

We will exploit a scheme where we will have two high-velocity plasma outflow counter-streaming.

For the magnetic field, we will first exploit coils at 20 T, then at 40 T, allowing to increase the plasma magnetization. The collisionless shock will be produced at the convergence point between these outflows. We will make use of the following configurations:

-**Possibility to explore the shock parameter space** (magnetization vs shock velocity) by changing the laser-target interaction parameters to control the shock velocity (from 0.01c to 0.25c) and by changing the density (from 1017 cm-3 to a few 1019 cm-3) in the shock region by varying the distance between the targets (from a few hundreds of microns to a few mm) or the external magnetic field to control the magnetization.

- **Explore parallel shocks and perpendicular shocks**. In the first case, as illustrated in Figure 8, the lasers will irradiate the targets from the longitudinal holes of the coil. In the second case, the lasers irradiating will irradiate them from the transverse holes of the coil (the two holes of the coil are similar in design, i.e. have the same aperture).

-**Possibility to produce quasi parallel shocks of various angles** (lasers going through the longitudinal holes and various angles of the targets vs the laser axis) and **perpendicular shocks of various angles** (lasers going through the transverse holes and various angles of the targets vs the laser axis).

Diagnostics

We will measure:

* **The density increase** associated to the shock in the collision region using interferometry (applicable for plasma densities from 10^{17} cm^{-3} to a few 10^{19} cm^{-3}). This will use the standard optical probe beam.

* **Electric and magnetic fields.** For this, we will use proton radiography.

* **Plasma heating.** For this, we will use Thomson scattering in task 3 to measure the plasma temperature resolved in time and space

* **Emitted radiation** (UV to XUV domains and spatially resolved). This will be done using XUV spectrometers that are in-house at LULI.

* **Emitted particles:** we will use a fast time-of-flight technique (scintillator + photomultiplier tube + oscilloscope).

Simulations

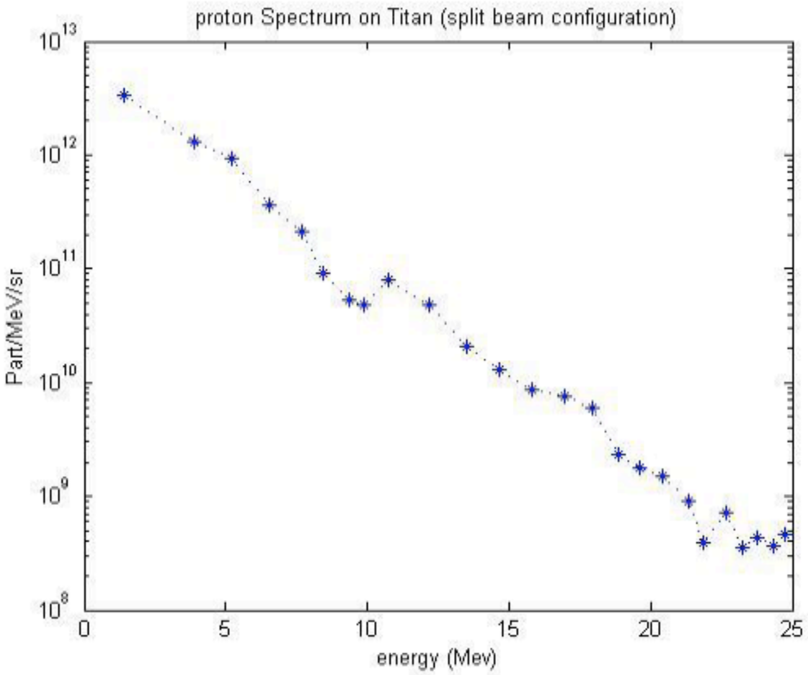
We will focus on:
- **Design of two laser pulses magnetized experiment to produce fast plasma expansions from two targets in order to prepare experiments.** For the latest point, more laser energy and power will indeed allow to get to faster shocks to explore a larger region of the shock parameter space or to study shocks with similar velocities but on longer time scales, allowing to study lower magnetizations.
- **Modeling of experimental results** and
- **Comparisons with existing astrophysical models**.

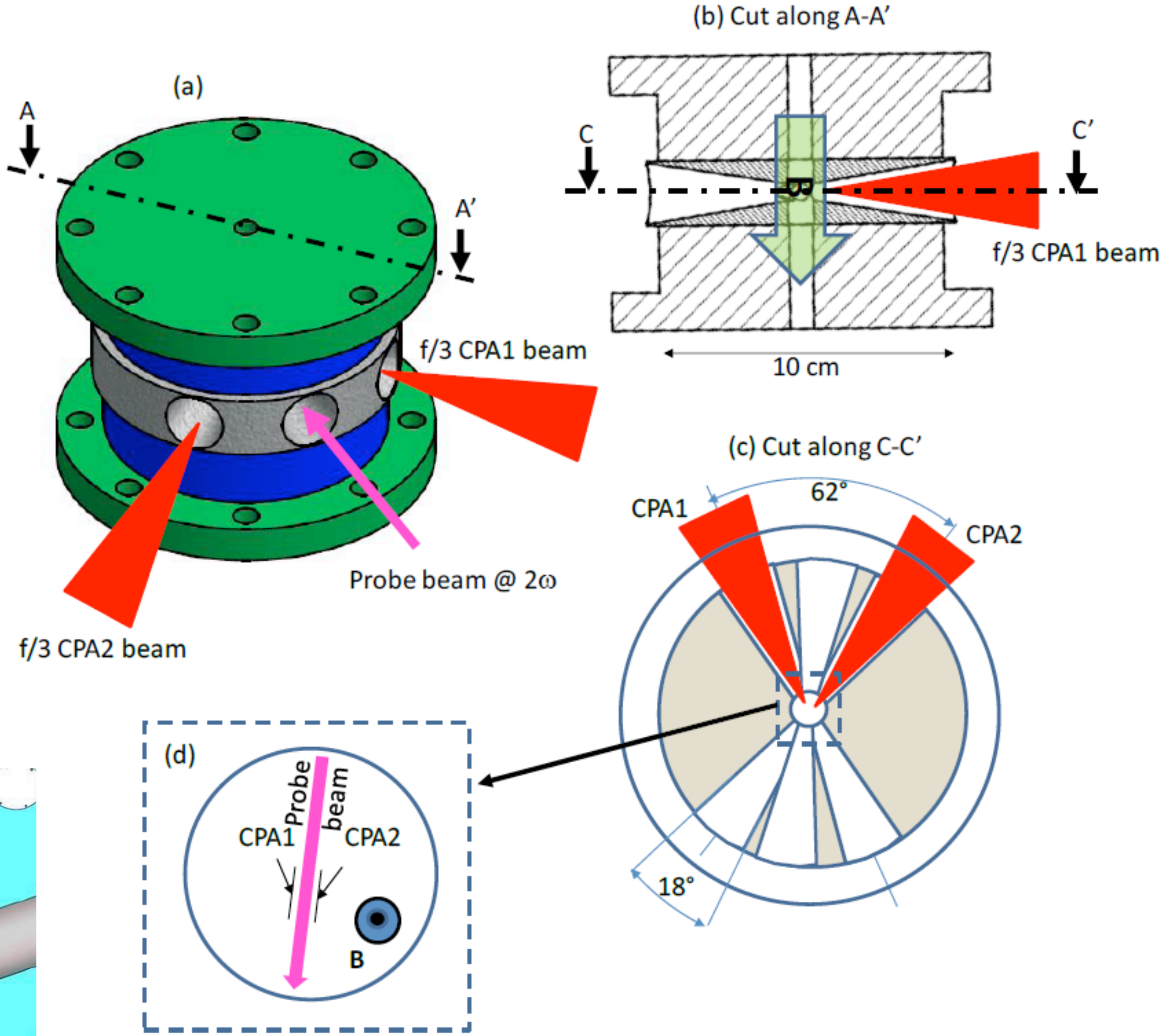
The design phase will concentrate on answering the **following key questions pertaining to the study of the instabilities leading to strong electron heating in collisionless shocks and the study of the deceleration of colliding plasma flows** depending on the magnetic field amplitude and orientation versus the plasma flows direction:
- **what are the instabilities leading to the strong electron heating? How is the growth of this instability affected by the plasma and external magnetic field parameters?**
- **what velocities can be reached with more laser energy? What are the effects of this higher velocity on the instabilities driving the shock?**
- **what are the characteristic spectra measured during the buildup of the shock depending on the key experimental parameters**? **What are the consequences on astrophysical observations?**

An important simulation and modeling work is also expected after the experiments to link the experimental measurements to astrophysical models of magnetized collisionless shocks.
The numerical work will be done with **several numerical codes of CELIA, LULI and LERMA** and will be supported by the important calculation time available to CELIA on large French clusters. The codes we will use are the fully parallel, relativistic 1D-2D-3D PIC code PICLS and the hydrodynamic codes CHIC, DUED and GORGON.

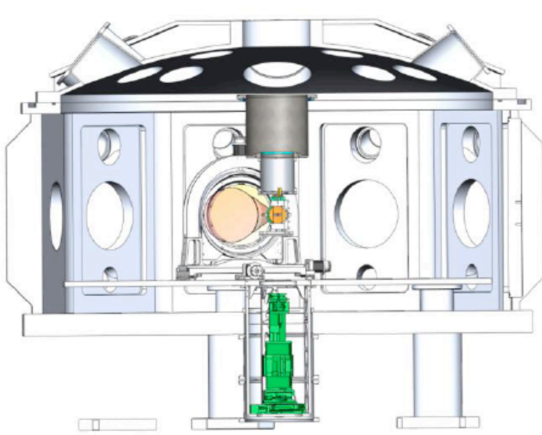
Proposition d’expériences sur Titan (Livermore) pour 2013

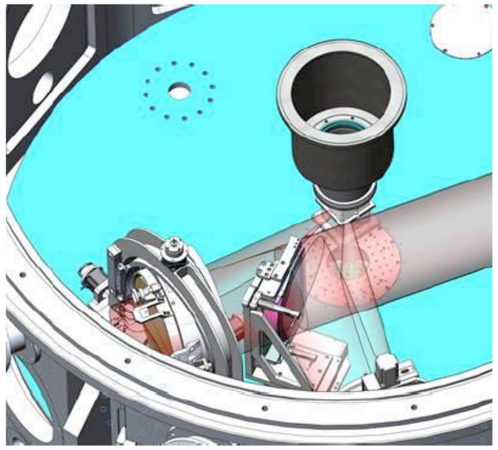
Titan experiment



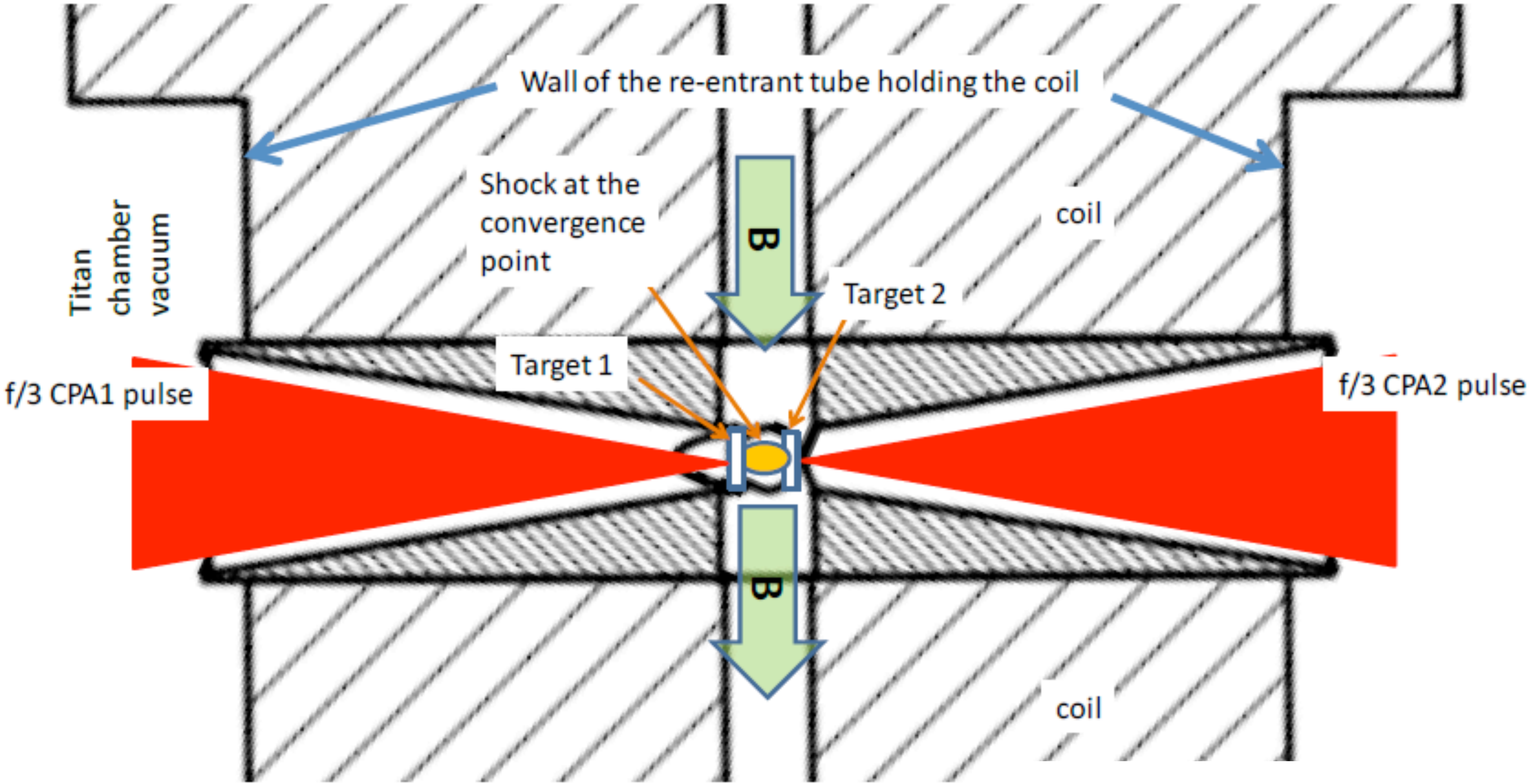


Possibility to get flows with velocities up to more than 0.3c and fields up to 40 T

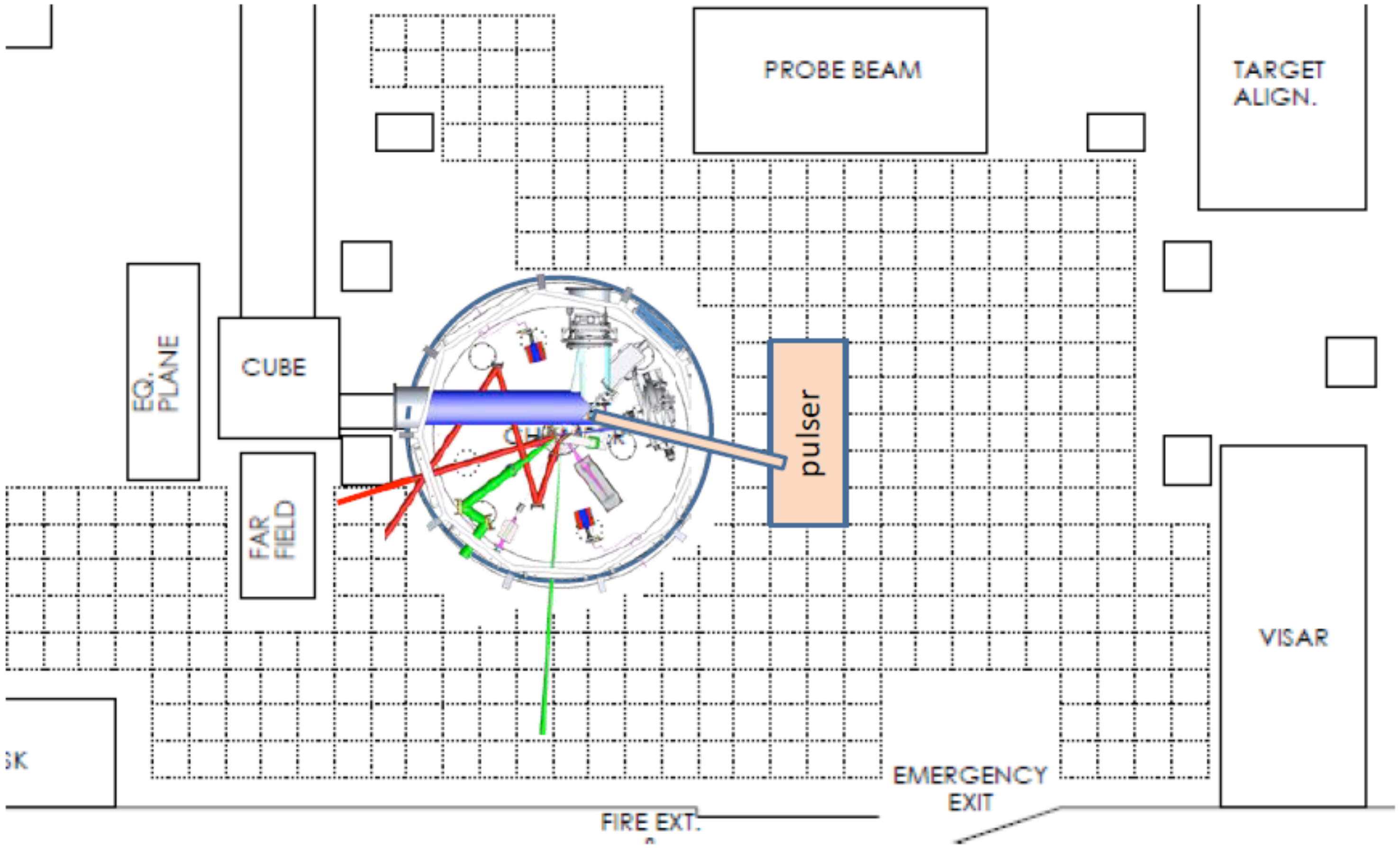




Titan experiment (2)



Possibility to do these experiments in mid-2013.
We will diagnose fields, particle emission, plasma density and temperature to **analyze the development of plasma instabilities and analyze the shock formation for various magnetization**.



Conclusions

- Possibility to generate couter-propagating plasma flows with high velocities and to add an external magnetic field.
- The parameters of these collisions are of interest for SNR studies.
- Modeling of these setups are already underway (see talk by V.T. Tikhonchuk without external magnetic field).
- Post-doc (18 mois avec possibilité d’extension) pour le CELIA (modélisation et simulation de chocs non collisionnels magnétisés).

Merci pour votre attention !