A tunable achromatic optics for focusing of kA laser generated ions beams using B-fields

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Outline

- State of the art in focusing laser-based ion beams

- Concept of exploiting laser-triggered B-fields

- Methodology

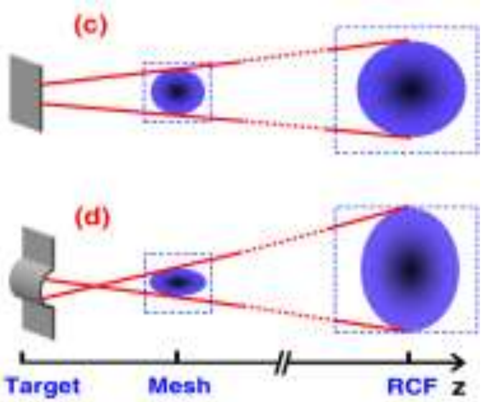
- Experiment and results

- Conclusions

Focusing laser-based ion beams: State of the art

Limitations of previous works

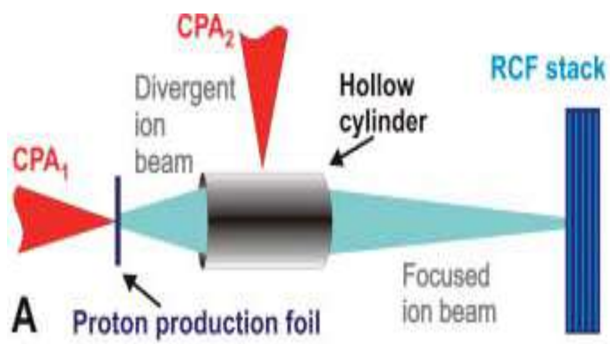
Using curved target[1,2]



Applications limited to small distance from the source 0.1-1 mm

[1] S. Kar et al., PRL, 106, 225003 (2011)
[2] S. N Chen et al., PRL, 108, 055001 (2012)

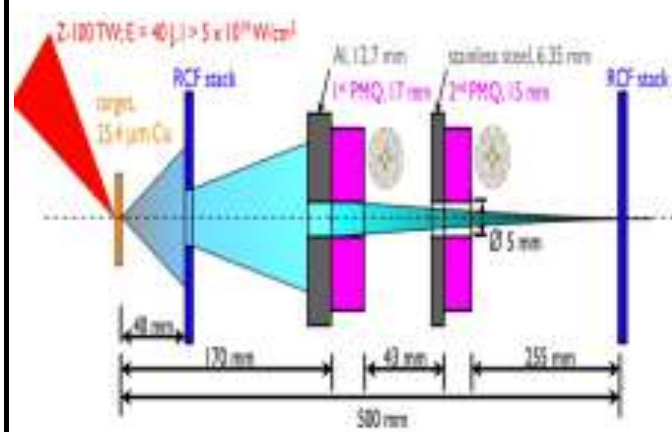
Using electric field [3]



Target assembly is not straightforward and chromatic

[3] T. Toncian et al., Science, 312 410-413 (2006)

Using permanent magnet[4]



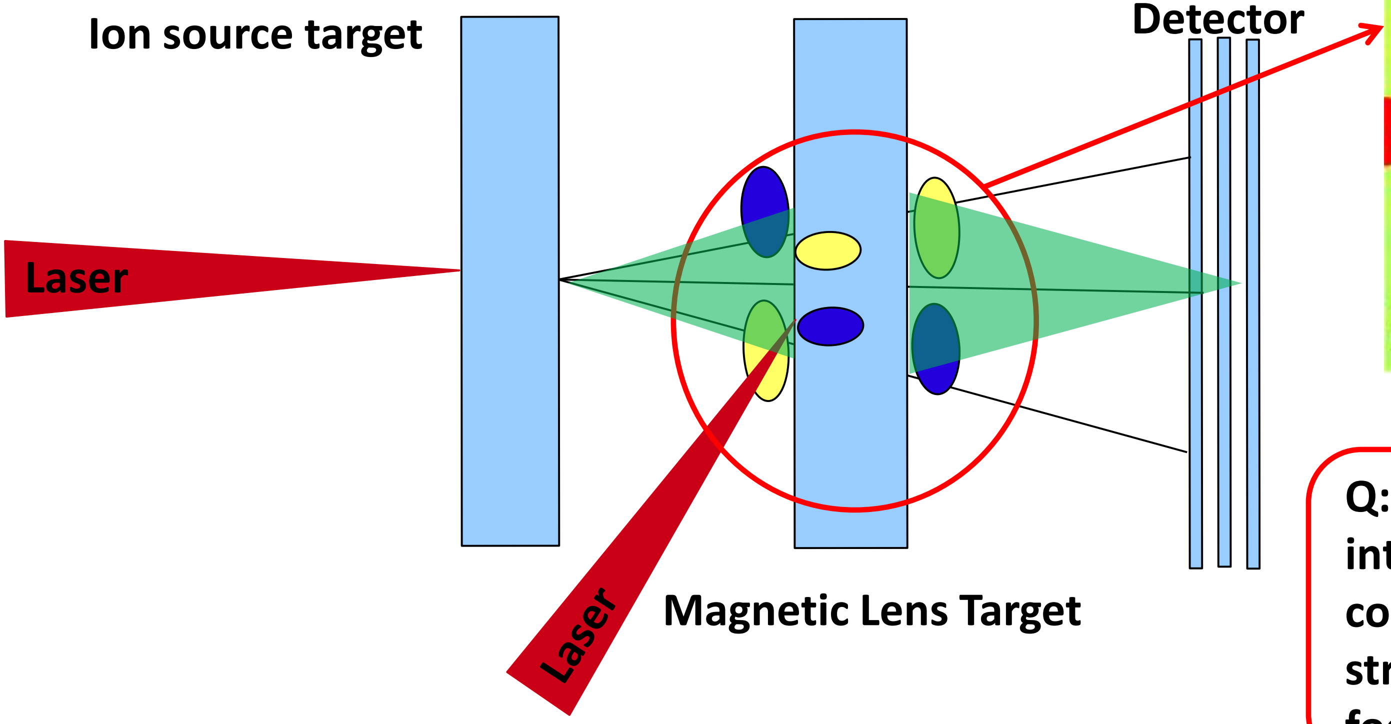
Low transmission of the number of generated proton through the magnet 0.1 %

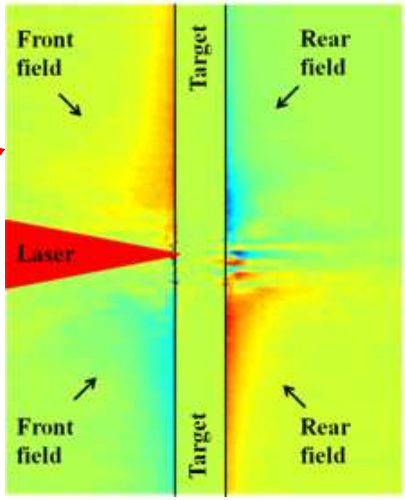
[4] M. Schollmeier et al., PRL 101, 055004 (2008)

Another possibility: exploit B-fields in a *plasma* optics

❑Particularly B fields produced by UHI pulses which are **tens of MG** (see G. Sarri, PRL 2012)

❑Concept:





Q: is there an interesting configuration for strong magnetic focusing?

Source of B-field

<u>Generation of Magnetic Field governed by :</u>

$$\frac{\partial B}{\partial t} = \underbrace{\nabla \times (v \times B)}_{\text{Convection}} - \underbrace{\nabla \times \left(J \times \frac{B}{n_e e}\right)}_{\text{Hot electrons (Short time scale)}} + \underbrace{\frac{1}{n_e e} \nabla T_e \times \nabla n_e}_{\text{Thermoelectric Effect (Long time scale)}} - \underbrace{\nabla \times (\eta J)}_{\text{Dissipative loss (Short time scale)}}$$

<u>Modelling:</u>

Analysis of the first times of the interaction : PIC code

Transition time between short & long time scales evaluated through 1D three temperatures model

Particle tracing code to see the influence of magnetic field on charged particles

How to *a priori* exploit at best such scheme?

<u>Experimental :</u>

Generation of proton beams through well-known TNSA mecanism

→ High particles number (10^{12}-10^{13}), Good Laminarity, High energies

Use of Plasma Mirror (PM)

→ to avoid pre plasma and optimize magnetic field due to thermoelectric effect by having steep density and temperature gradient

Use of thin target

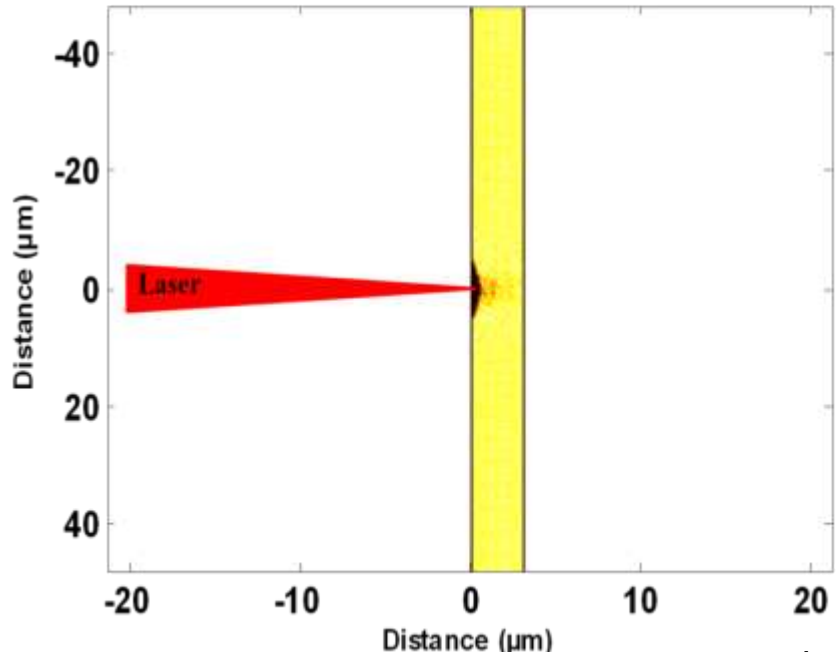
→ to minimize scattering of protons and avoid strong resistive magnetic field inside the target

BUT: can we have favourable field configuration? When is the right time to pass protons through? What is the time-scale of the acting B-field?

Evaluation of the first phase: Magnetic Field due to hot electrons current (1/2)

Simulations parameters :

- 5.10^{19} W/cm^2
- pulse duration: 700 fs
- S polarization
- Box simulation size 50*63 µm
- Targets: - Au 197 Mp, Z=79
  - Al 27 Mp, Z=13
- Ion density: 400 nc



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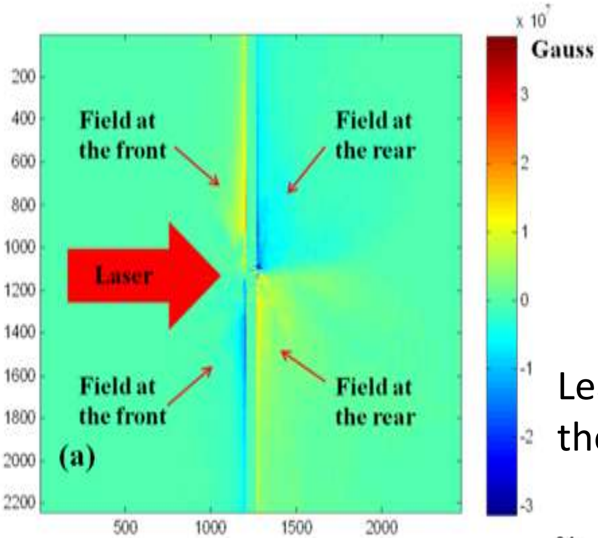
E.D'Humières

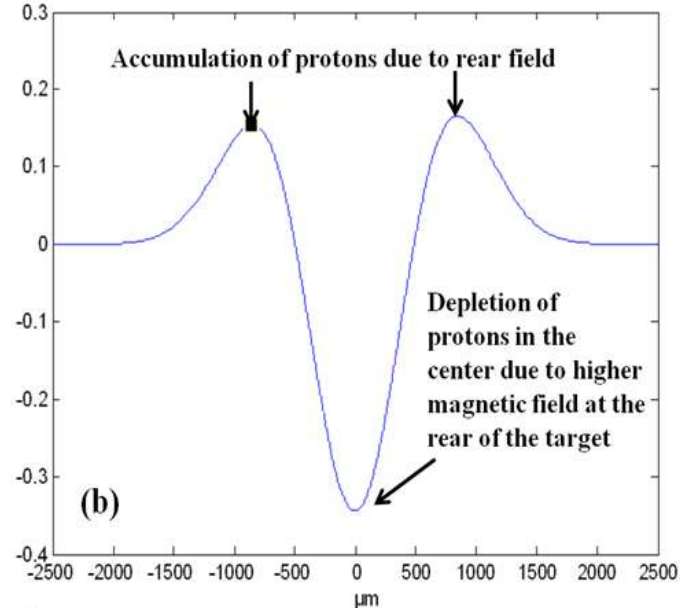
Particles in simulations: ~2 millions

Evaluation of the first phase: Magnetic Field due to hot electrons current (2/2)

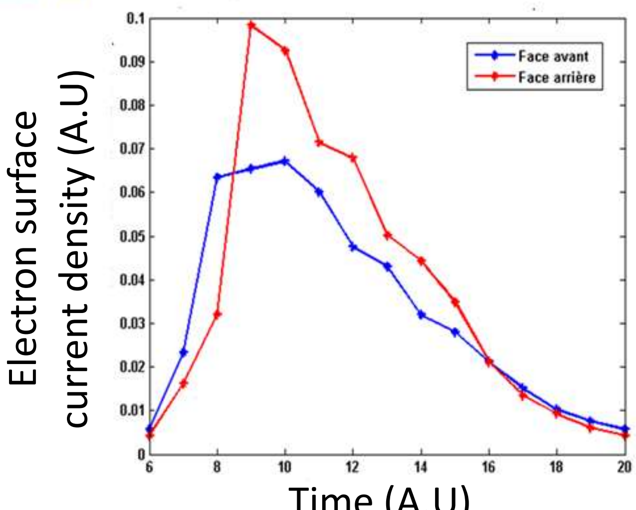
Normal incidence for Au 3 µm target :



Leads to a divergence of the passing proton beam



Divergence due to difference between rear surface current and front surface current (30 %)

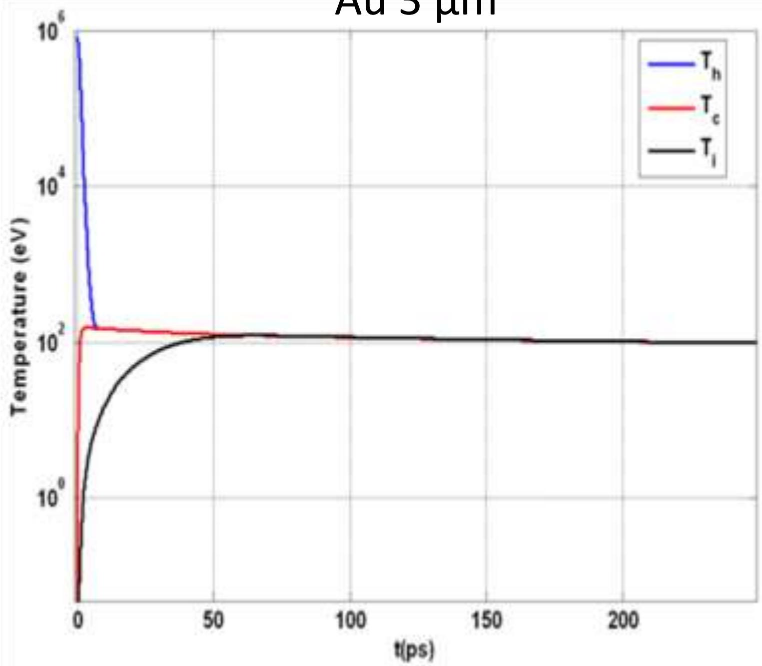


Configuration not interesting to collimate protons but to collimate negative y charged particles

Later: transition between the hot electrons phase and the phase of hydrodynamic plasma expansion

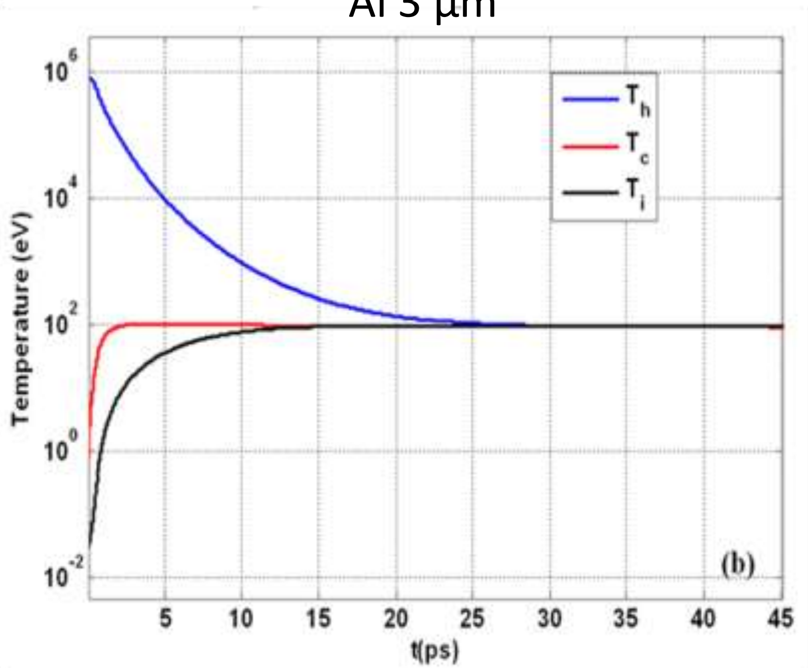
<u>Evaluated with a 1D, 3 temperatures models</u> when the hot electrons temperature is below ~100 eV (highly collisionnal), they don't contribute anymore to the generation of a MG magnetic field

Au 3 µm



Slow transition > 100 ps

Al 3 µm



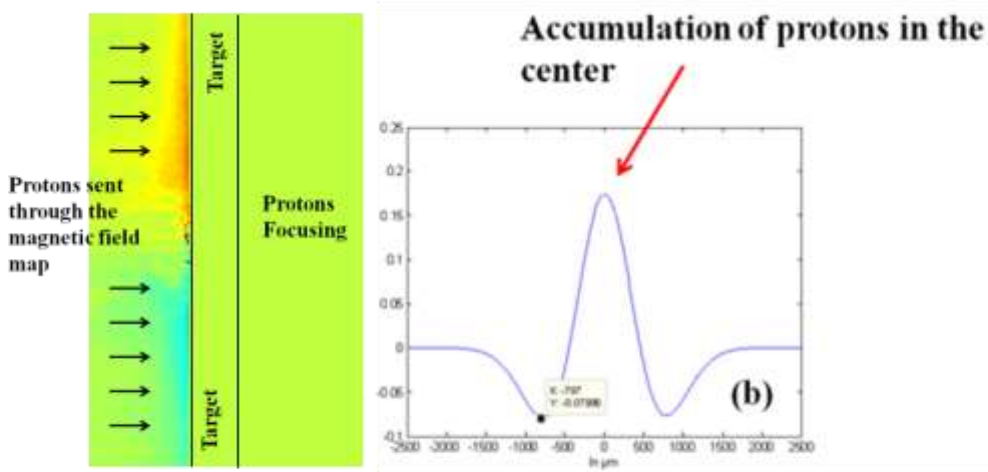
Fast transition ~ 25 ps

Even later: the hydrodynamic expansion of the plasma

Magnetic Field generated through thermoelectric effect : $$\frac{1}{n_e e}\nabla T_e \times \nabla n_e$$

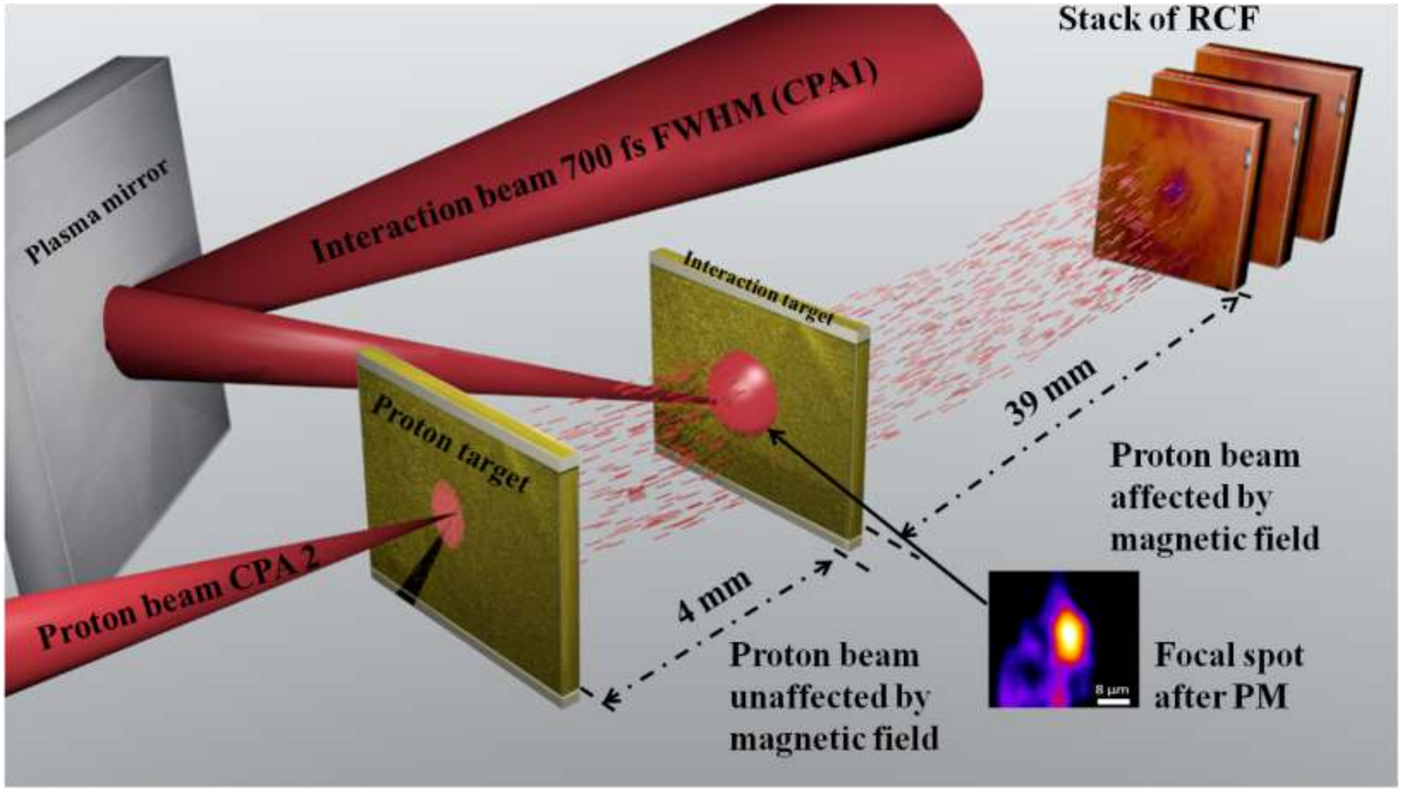
Likely **strong dissymetry** between front magnetic field and rear magnetic field due to absence of strong temperature gradient at the rear surface [P. Antici et al., Phys. Rev. Lett 101, 105004 (2008)]

A dissymetric field would lead to confinement of passing positive charged particles + long-lived (100s of ps)



Proof-of-principle experimental set-up

Experiment performed at LLNL on TITAN :



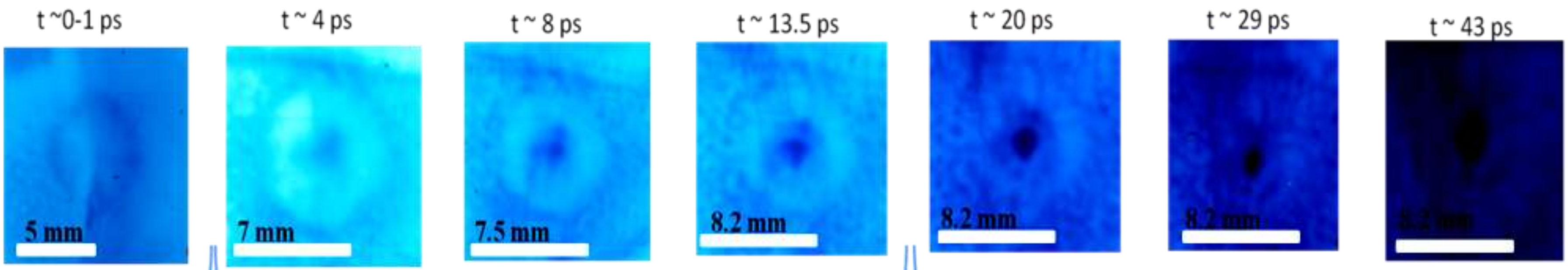
Laser parameter :

Pulse duration: 700 fs FWHM

Energy: ~ 55 J

Some experimental results:

Al 3 µm

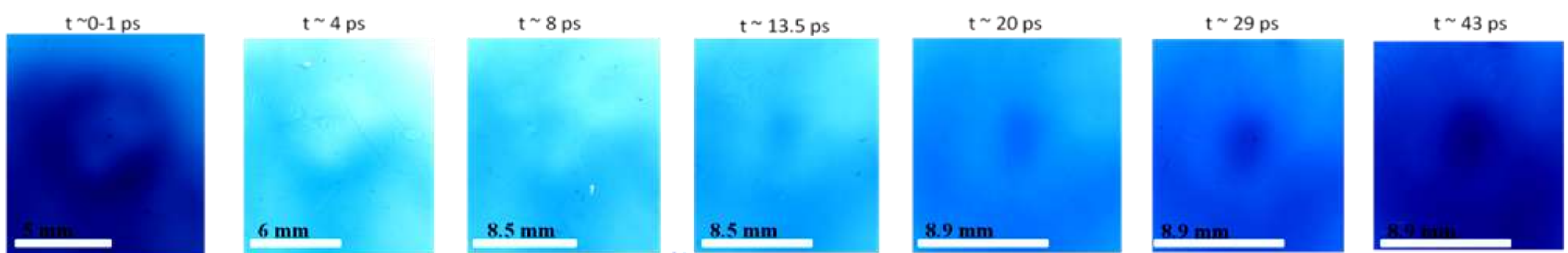


Hot electrons phase

Transition between the two phases

Hydrodynamic expansion phase

Au 3 µm



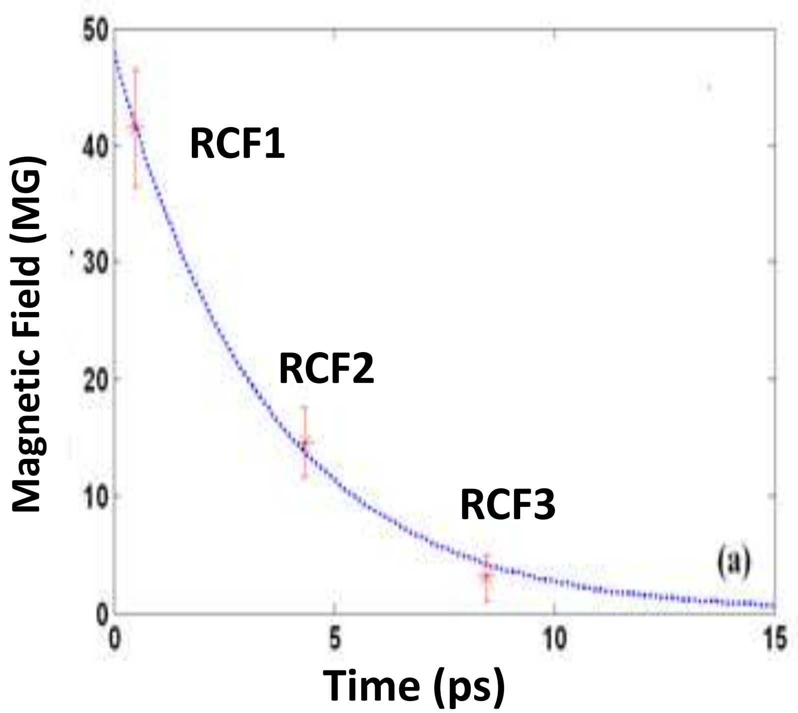
Hot electrons phase

Transition between the two phases

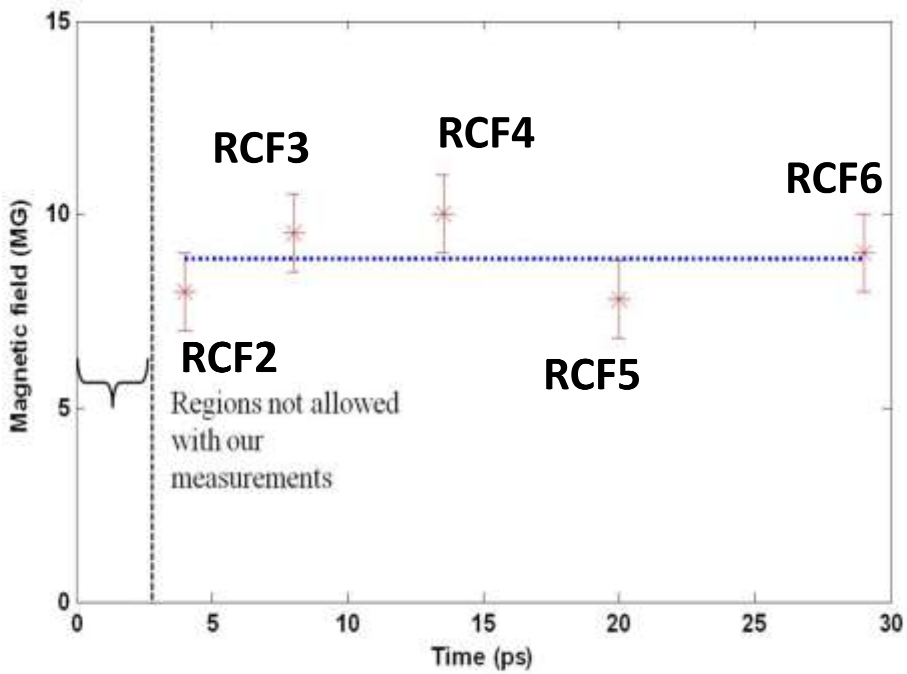
Measurement of magnetic field for Al confirms the late-time dissymetry between front and rear fields

Measurement of magnetic field through post-processing of observed deflections (see G. Sarri et al., Phys. Rev. Lett 109, 205002 (2012))

At the rear surface of the target :

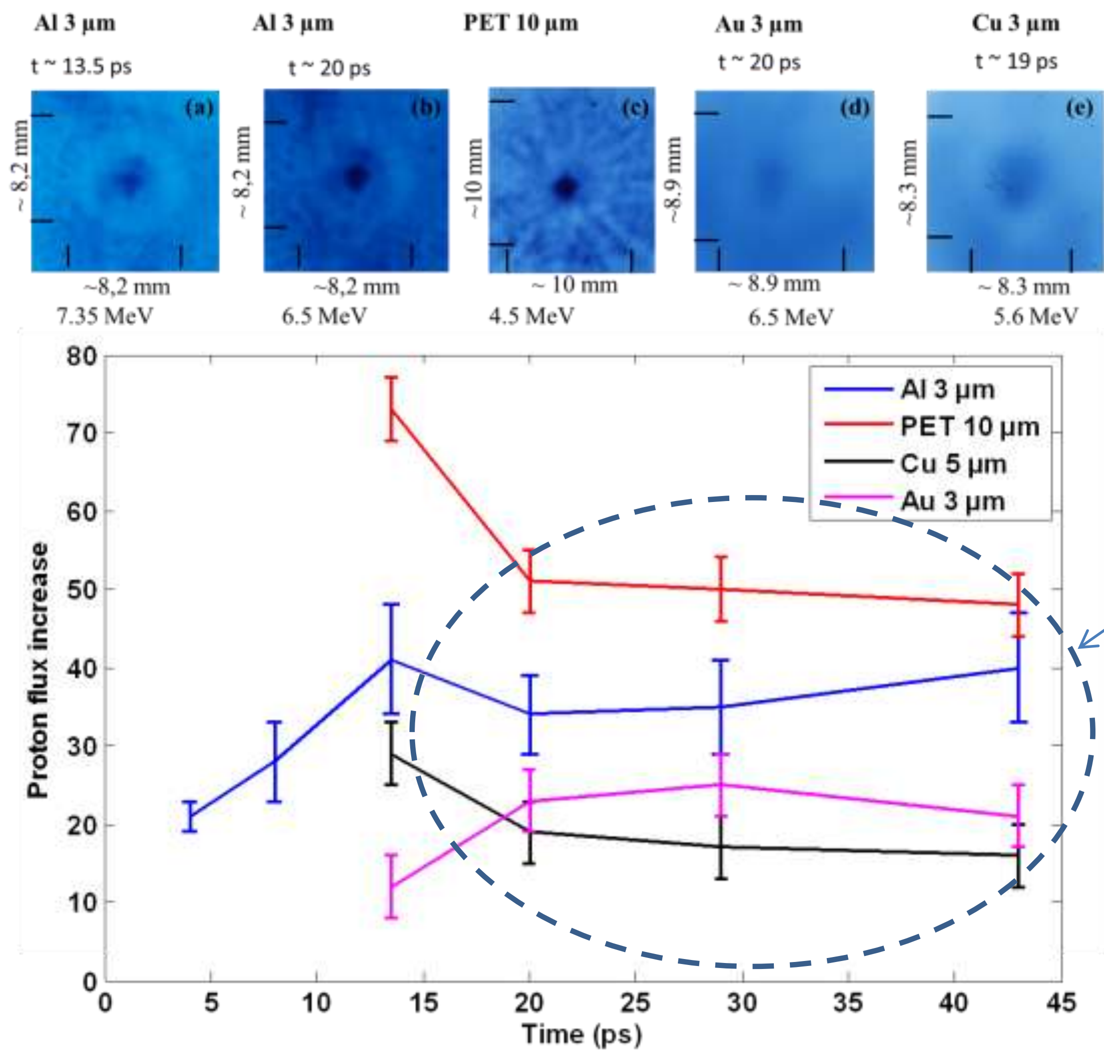


At the front surface of the target



Plateau of ~ 8.5 MG

Quantitative measurement of proton flux increase



Nicely achromatic!

Conclusion

- For normal laser incidence irradiation:

first phase can focus but only for short-times & toward the laser for positively charged particules

second phase can focus positive charged particles achromatically & efficiently

-Control of the collimation can be done easily in :

→ Varying the delay between the laser creating the magnetic field and the laser created the protons beams

→ Varying the target material

→ Varying the target thickness

Proton flux increase can be significant : ~50-100 & capturing the kA whole beam