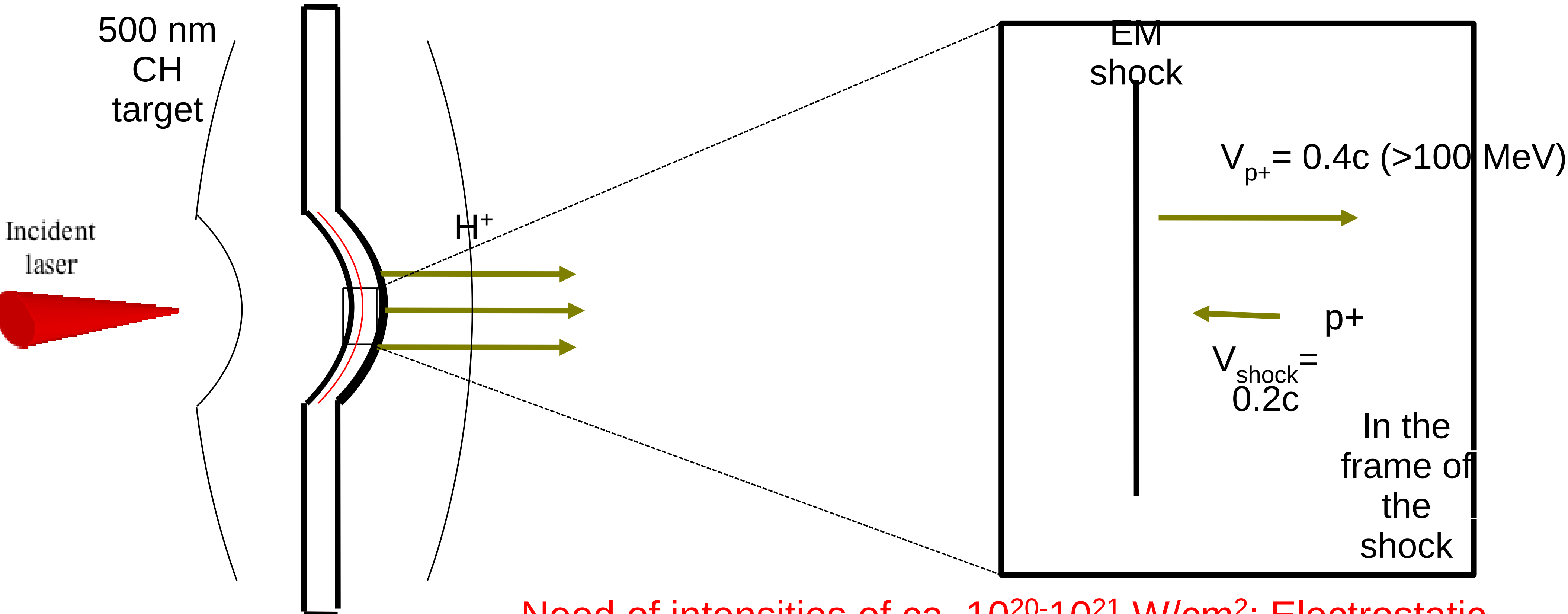
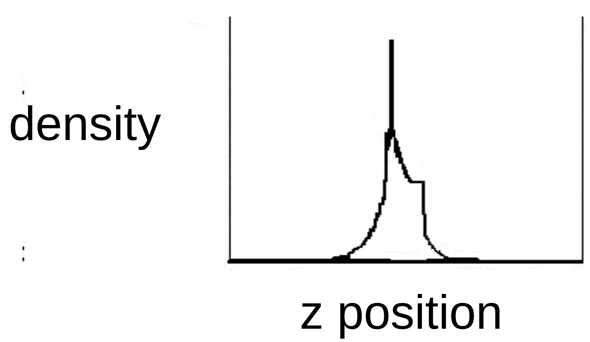
Laser ion acceleration with low density targets: a new path towards high intensity, high energy ion beams

P. Antici[1,2,3], J.Boeker[4], F. Cardelli[1],S. Chen[2],J.L. Feugeas[5], F. Filippi[1], M. Glesser[2,3], E. d'Humières[5], P. Nicolaï[5], H. Pépin[3], L. Romagnani[2], M. Scisciò[1], V.T. Tikhonchuk[5], O. Willi[4], J.C. Kieffer[3] and J. Fuchs[2]

[1]*Dipartimento SBAI, Università di Roma "La Sapienza" and INFN, Roma, Italy*
[2]*LULI, École Polytechnique, CNRS, CEA, UPMC, 91128 Palaiseau, France*
[3]*INRS-EMT, Varennes, Québec, Canada*
[4]*Institut für Laser- und Plasmaphysik Heinrich Heine Universität Düsseldorf*
[5]*Université de Bordeaux, CNRS, CEA, CELIA, 33400, Talence, France*

New path toward high energy proton acceleration: shock wave acceleration (predicted 2004)





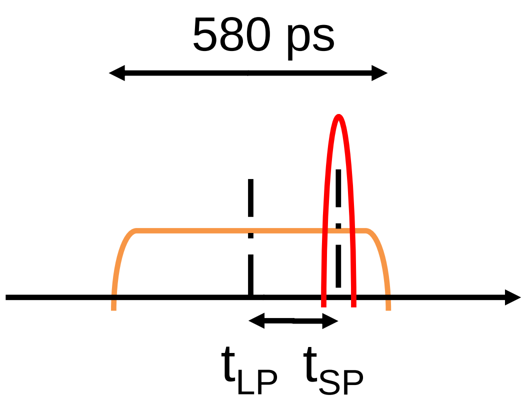
Need of intensities of ca. 10^{20}-10^{21} W/cm^2: Electrostatic wave travels faster than sound speed and generates shock: protons rebounce on surface

Silva et al., Physical Rewiev Letters, 92, 1 (2004)
E. d'Humières et al. Journal of Physics, Conference Series 244, 042023 (2010)
Palmer et al., Phys. Rev. Lett. 106, 014801 (2011)
Haberberger et al., Nature Physics, 8, 95–99 (2012)

Motivation for going beyond TNSA – What is the state of the art ?

- Goal: use Gas Targets instead of solids advantages: no debris, high rep. rate, volumetric energy absorption
- ISSUE 1: TNSA-like mechanism requires a very sharp plasma gradient with small thickness, difficult with gas targets (nozzle of <100 μm ?)
- ISSUE 2: Simulations show the possibility to efficiently accelerate protons by way of collisionless shocks with sub and near-critical density short-length plasmas (gas able to achieve near-critical densities ?)
- ISSUE 3: Contrary to other low density acceleration mechanisms, shock acceleration requires a smooth density gradient
- State of the art: JAEA (exploded foil), IC (gaseous target), BNL+UCLA (gaseous target + CO_2 laser)
- Our aim: explore this mechanism using high-energy, high-intensity laser pulses, and its transition from TNSA, laser wavelength 1 micron (not CO_2)

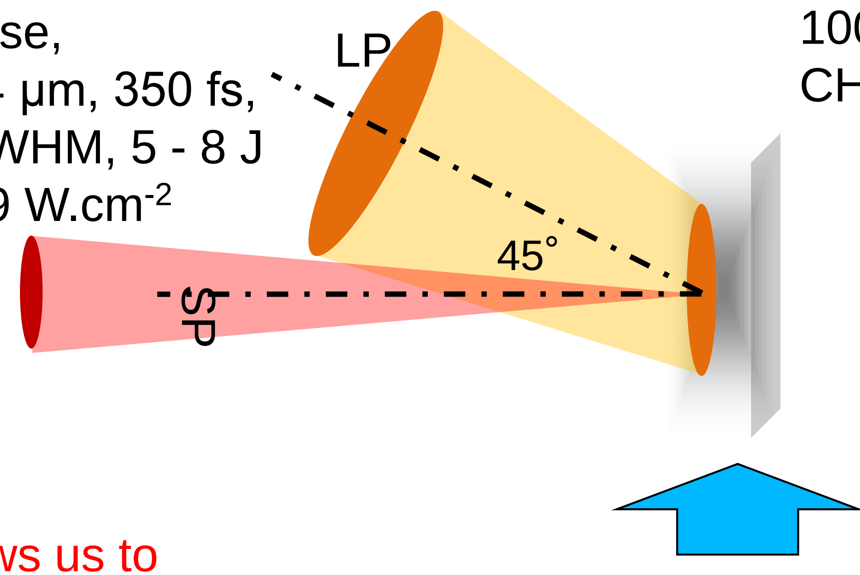
Experimental Setup for exploring shock acceleration @ LULI (low laser energy regime)



$\Delta t = t_{LP} - t_{SP}$

Long pulse,
580 ps, λ = 1.054 µm,
20 µm FWHM, 30 - 40 J, (OD 1 or 2 added)

Short pulse,
λ = 1.054 µm, 350 fs,
10 µm FWHM, 5 - 8 J
$I = 1\text{-}2e19\ W.cm^{-2}$



100 nm or 500 nm
CH foils

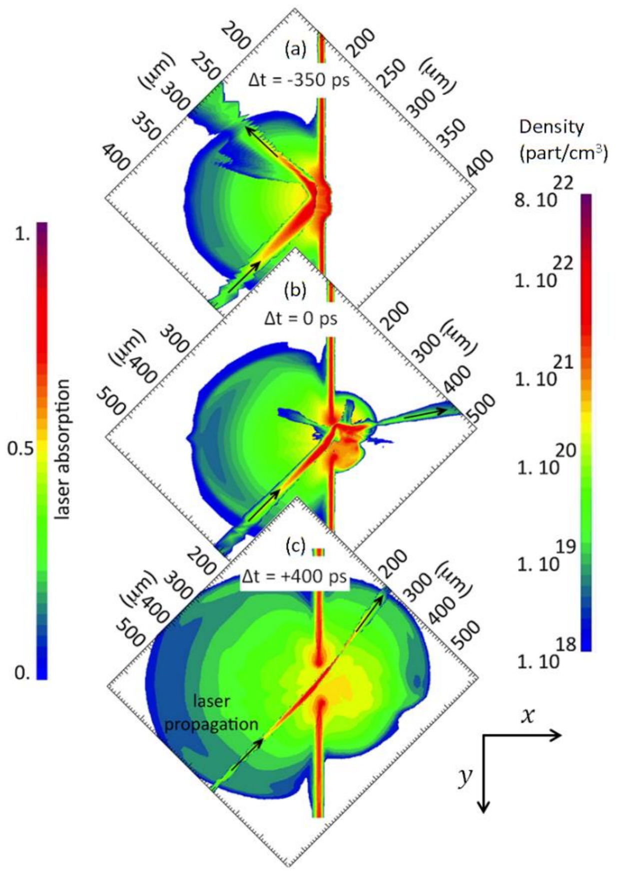
2 Thomson Parabolas at 0° and 15°

Interferometry measurements of the exploded foil density profile

The expansion of the thin foil allows us to explore various types of gradients by changing Δt and t_{LP}.

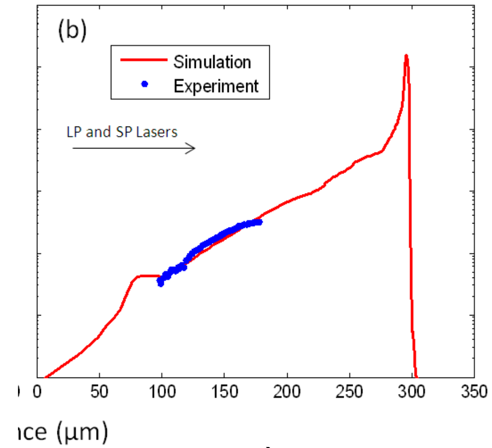
Experimental plasma profiles show good agreement with 2-D hydro simulation (CHIC) results

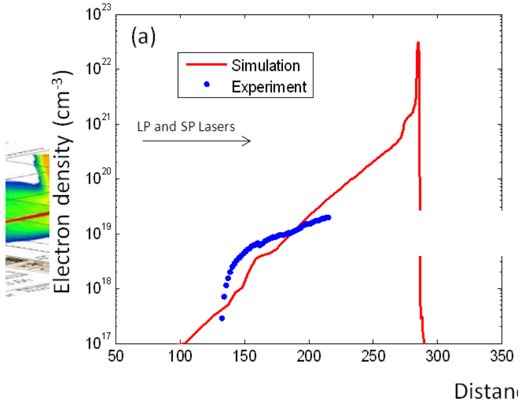
- 2-D hydrocode with experimental parameters : 500 nm foil, I_{LP} = ~10^{13} -10^{14} W/cm²
- 45° incidence yields asymmetric profiles.



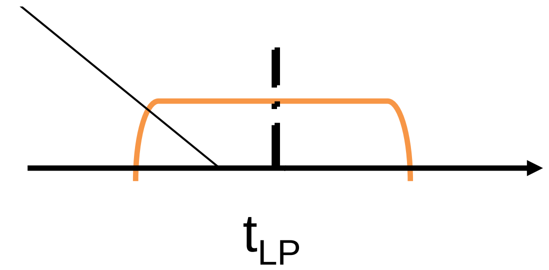
Interferometry

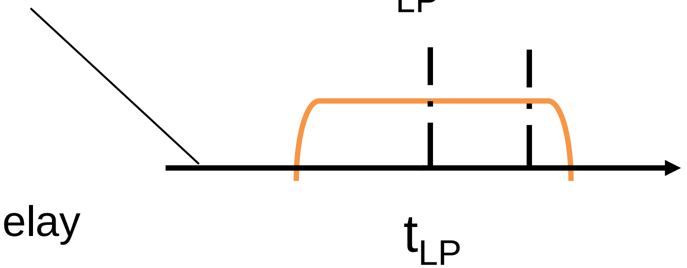
Exp.: 3 10^{13} W/cm², 0 ps delay





Exp.: 3 10^{14} W/cm², -400 ps delay





CHIC : J. Breil, P. Maire, Ph. Nicolai, and G. Schurtz, J. Phys.: Conference Series 112, 022035 (2008)

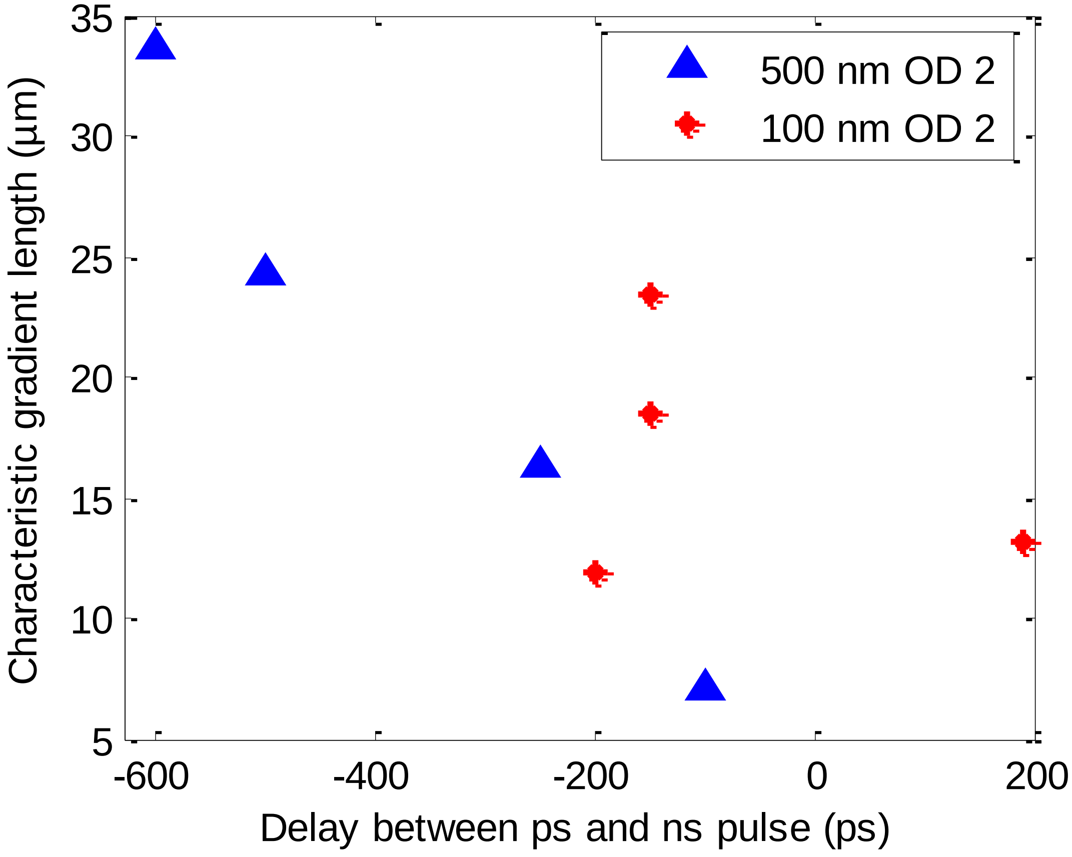
Using exploded targets, we can vary the density gradients in a predictable way (for 500 nm)

- Good relationship between the delay and the length of the density gradient for 500 nm CH foils

- Thinner CH foils (100 nm) are more sensitive to the laser intensity fluctuations from shot to shot

- When the LP laser beam intensity on target is high (10^{14} W/cm²), one sees less fluctuations on the profile shape, but longer gradients (~ 55 - 65 µm)

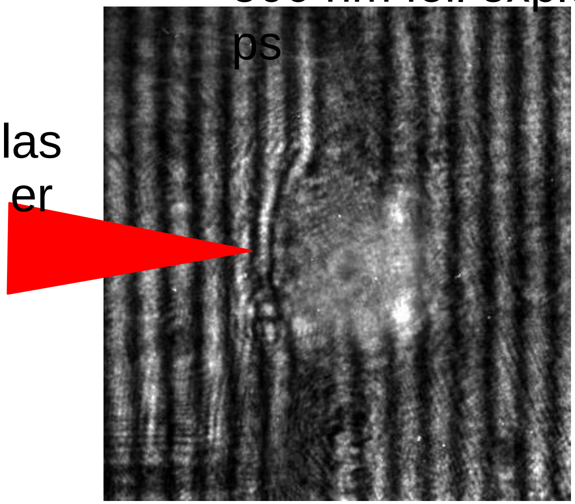
$I_{LP} = 10^{13}$ W/cm²

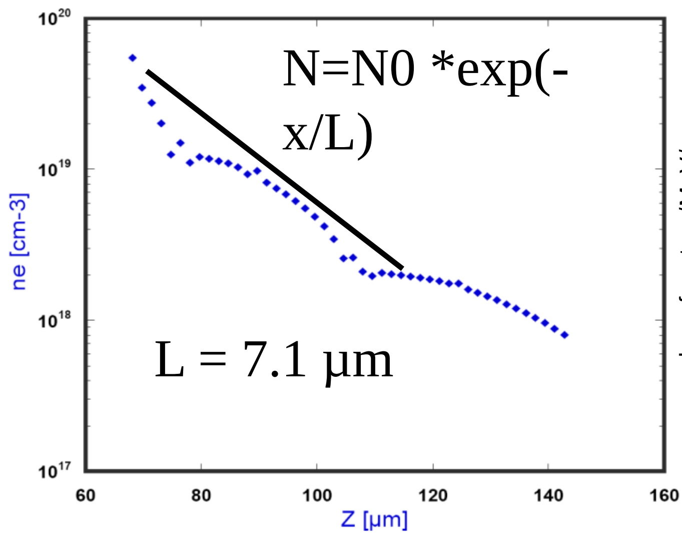


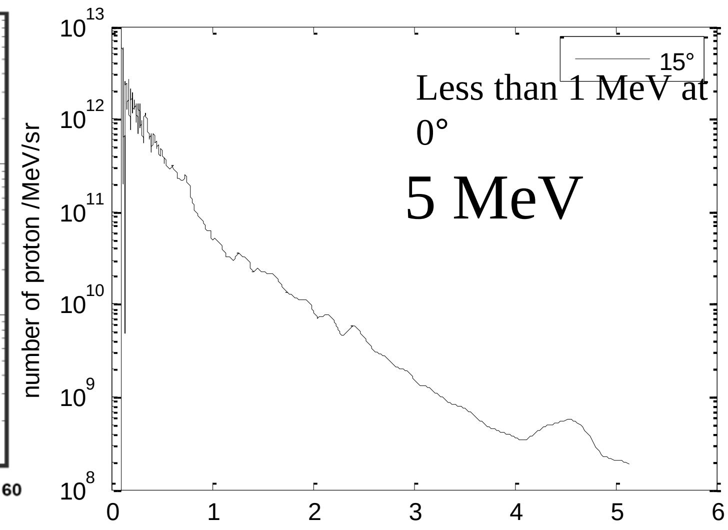
Experimental results @ LULI show that exploded targets can reach similar energy than T..A

Solid target Ref ca 7 MeV

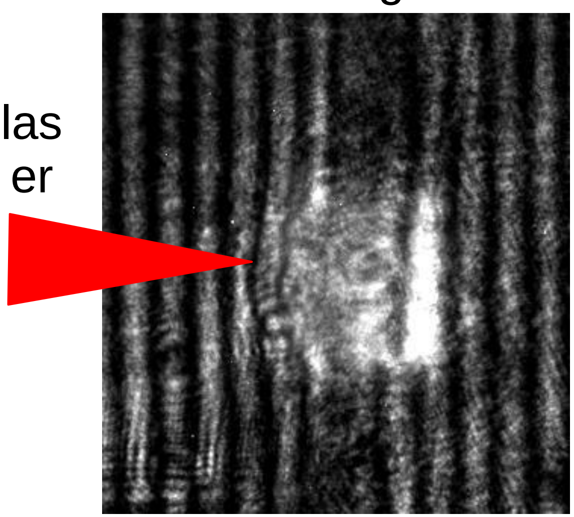
500 nm foil exploded by the long pulse (10^{13} W/cm²) 100 ps prior to the peak of the ps

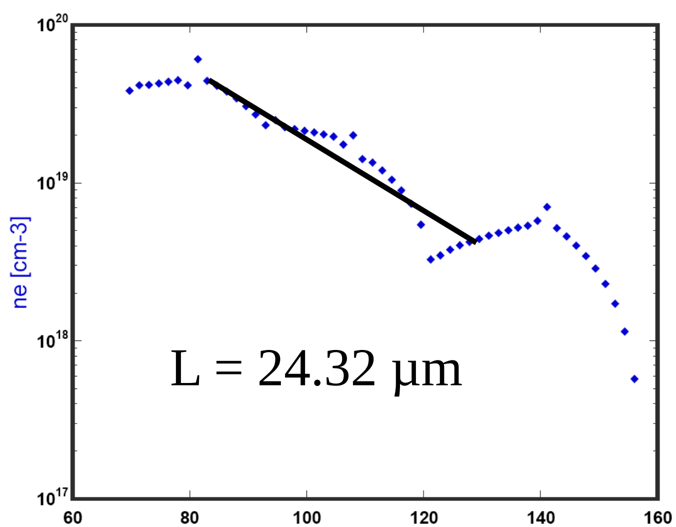


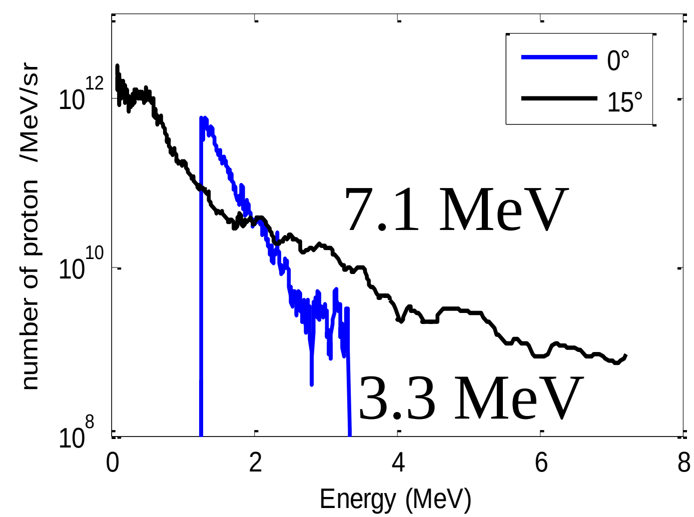




500 nm foil exploded by the long pulse (10^{13} W/cm²) 500 ps prior to the peak of the ps , similar to TNSA on gold 10 micron.







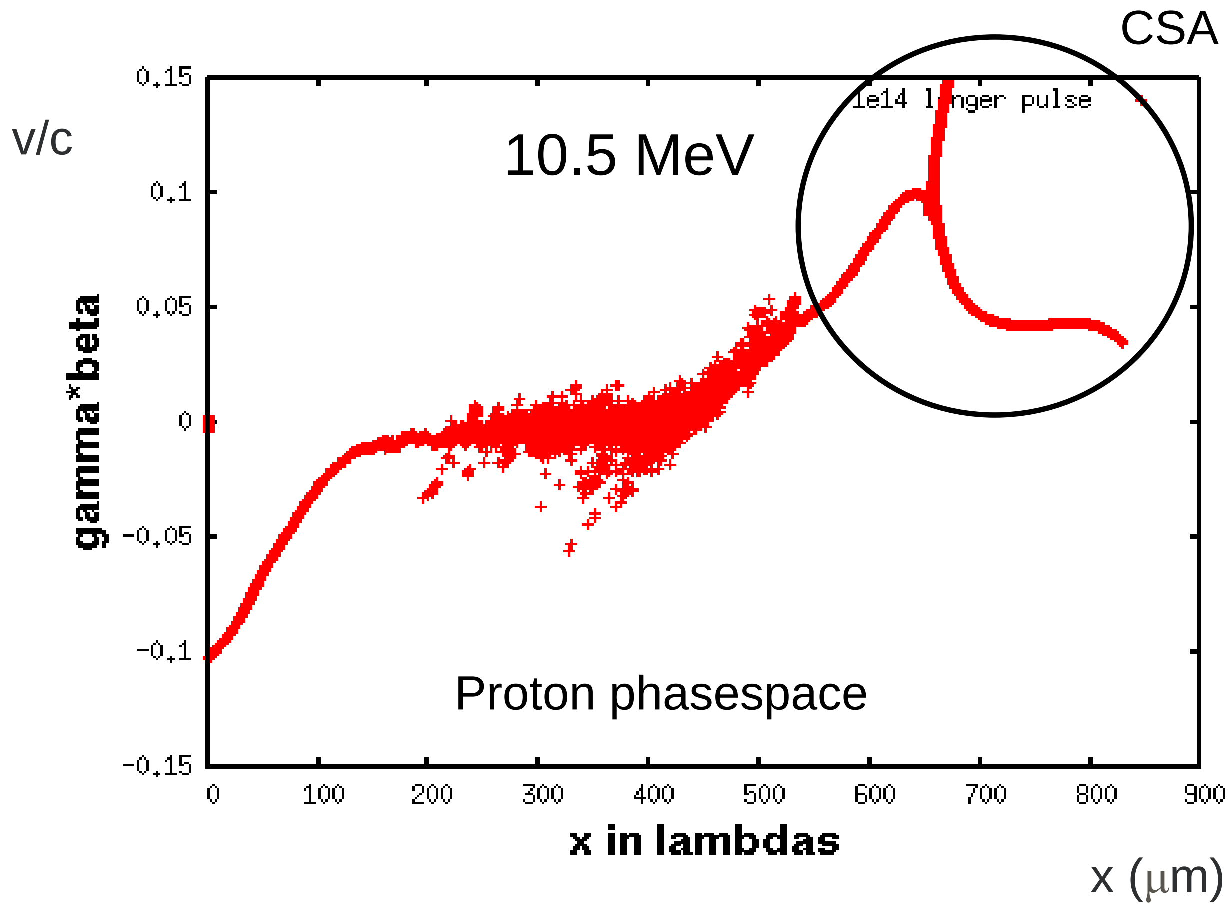
Low energy, 2D PILCS results using CHIC profiles show that we approach the shock acceleration

Two regimes can be investigated :

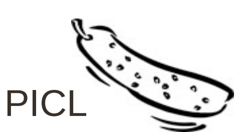
•TNSA and relativistic transparency when the back side of the target is not much affected by the long pulse laser. This is not the case in our experiments.

•Shock acceleration when a long density gradient is present at the back of the target.

E_{laser}~J



10^{14} W/cm^2 delay of +100 ps +8x10^{18} W/cm^2 350fs laser



PILCS : Y. Sentoku, A.J. Kemp, J. Comp. Phys. 15, 056709 (2008).

Simulations show that shock acceleration becomes much more interesting in the high laser energy, high-intensity regime -> we repeat experiment on TITAN

Target FWHM: 80 microns. Laser intensity: 5×10^{20} W/cm^2, pulse duration: 700fs FWHM, focal spot width: 6 microns FWHM.

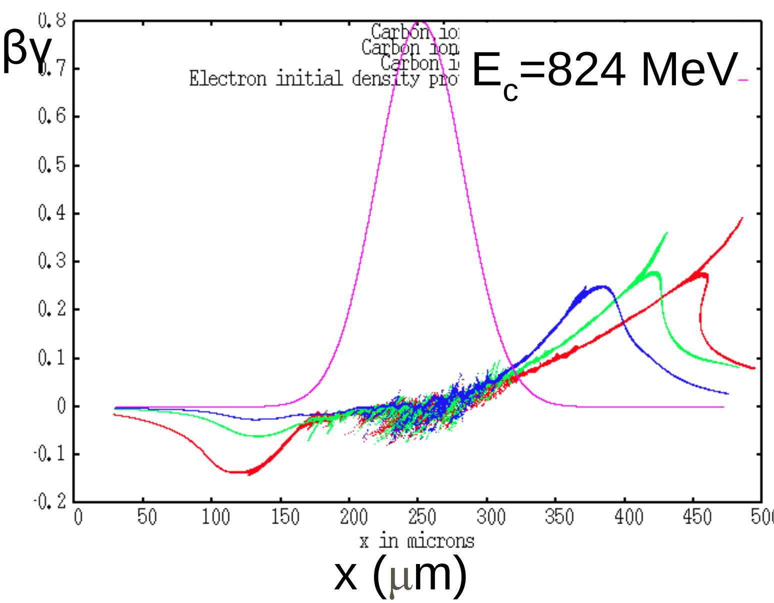
High laser energy and intensity allow to explore high density/thickness couples to maximise laser energy absorption.

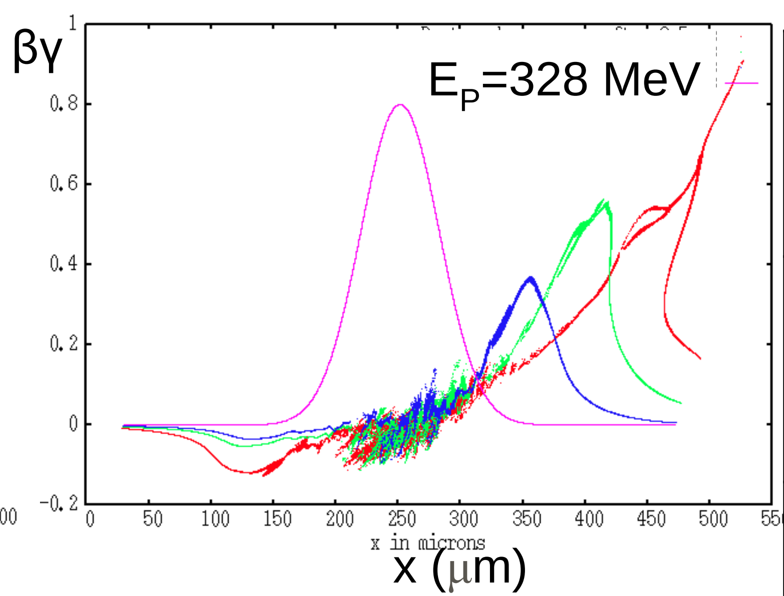
E_{laser}~600J

low laser energy (~J), process not optimized.
high energy, high intensity regime
shock regime
very high ion energies.

Influence of the target thickness

Plasma FWHM	35 microns	50 microns	80 microns
Max H energy	280 MeV	296 MeV	328 MeV
Max C energy	803 MeV	889 MeV	824 MeV



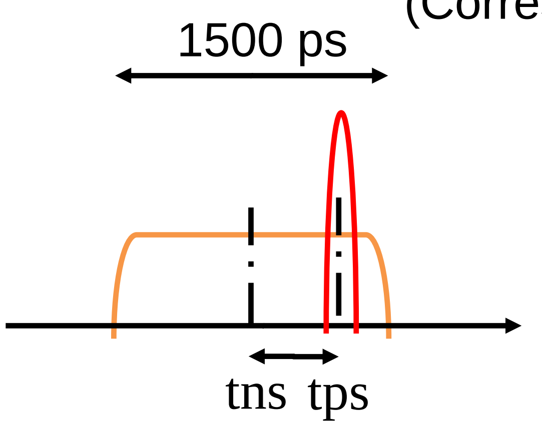


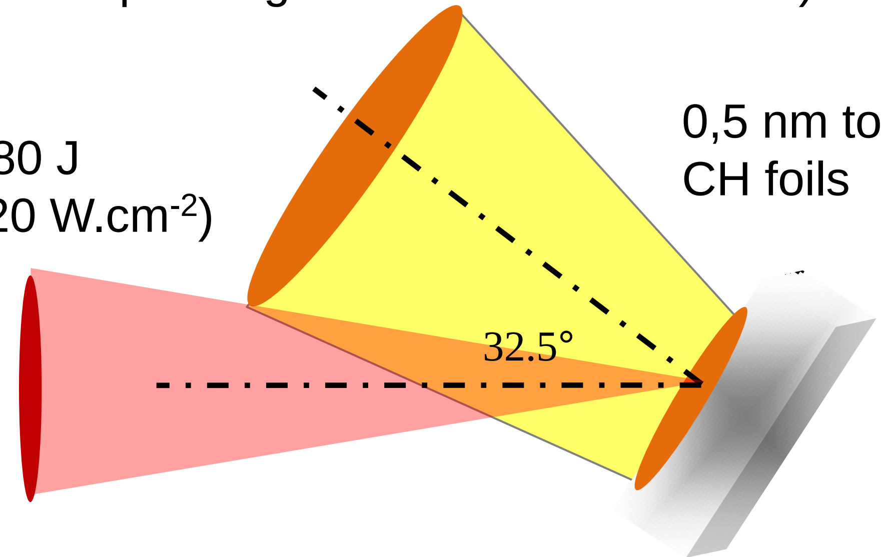
Exploded foil regime

Experimental Setup for exploring shock acceleration @ TITAN

Long pulse,
1,7 ns, λ = 530 nm,
1,20 mm FWHM, E from 0,2 to 390 J
(Corresponding to 1e10 to 1e13 $W.cm^{-2}$)

Short pulse,
λ = 1.054 μm, 400 fs,
26 μm FWHM, 50 – 180 J
(Corresponding to 1e20 $W.cm^{-2}$)





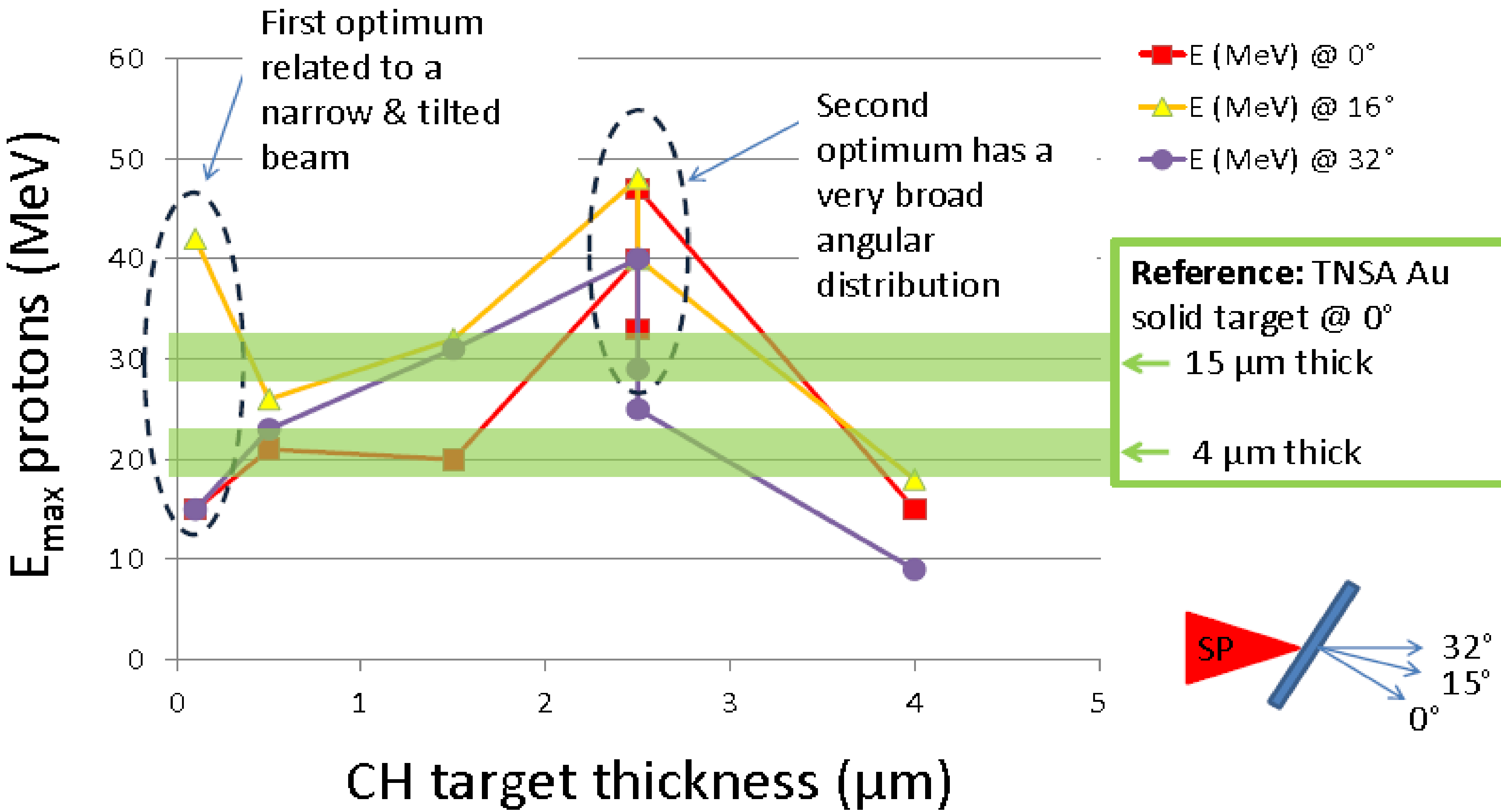
0,5 nm to 4 micron
CH foils

2 Thomson Parabolas
@ 32.5° and 0°
Proton spectrometer
RCF Stack

$\Delta t = t_{SP} - t_{LP}$

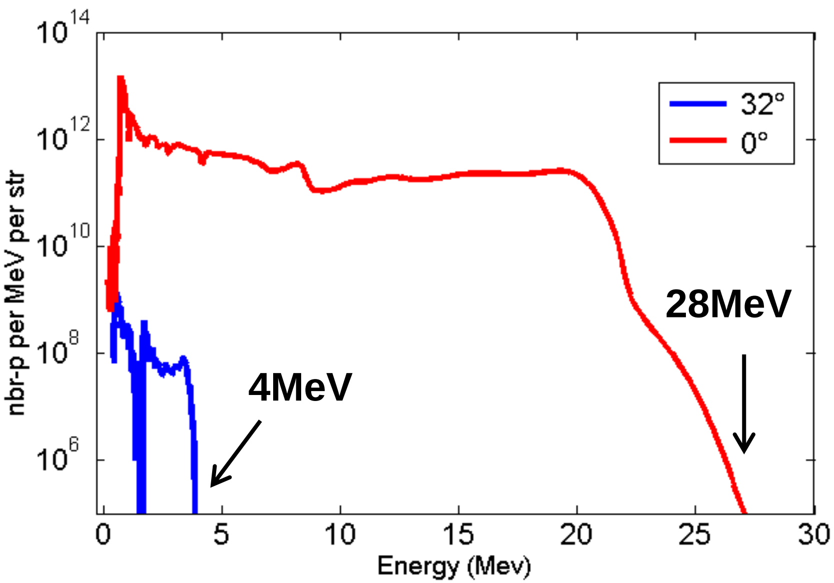
The expansion of the thin foil allows us to explore various types of gradients by changing Δt and t_{LP}.

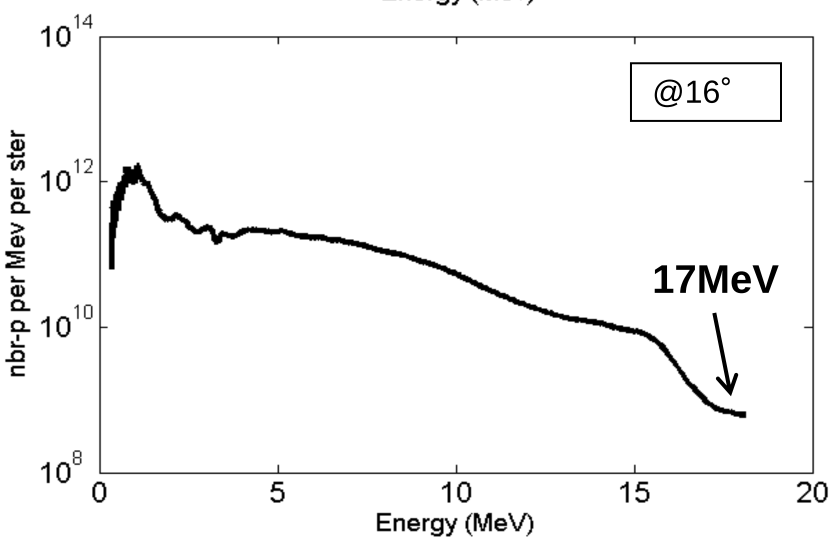
For thin CH targets exploded by the short-pulse ASE, very high proton energies are recorded, well above standard TNSA in the same conditons



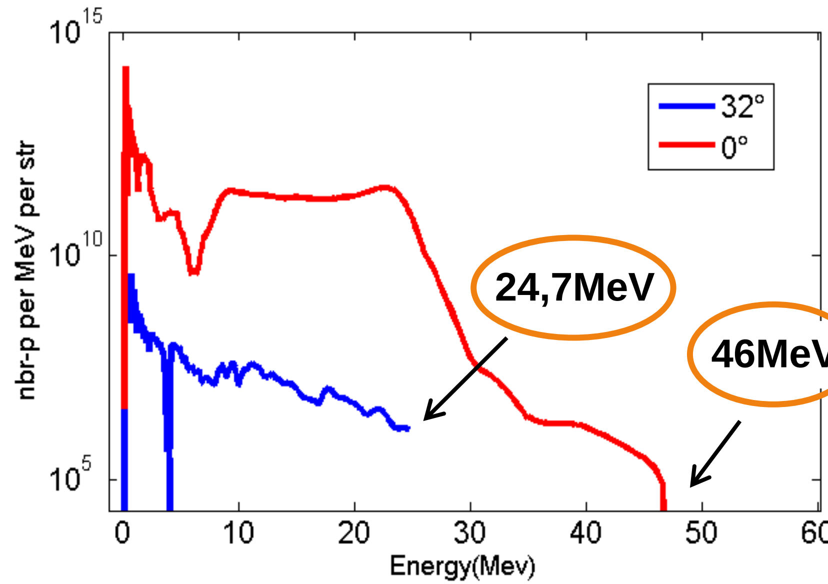
Exploded foils show similar spectral shape than TNSA but with higher maximum proton energy

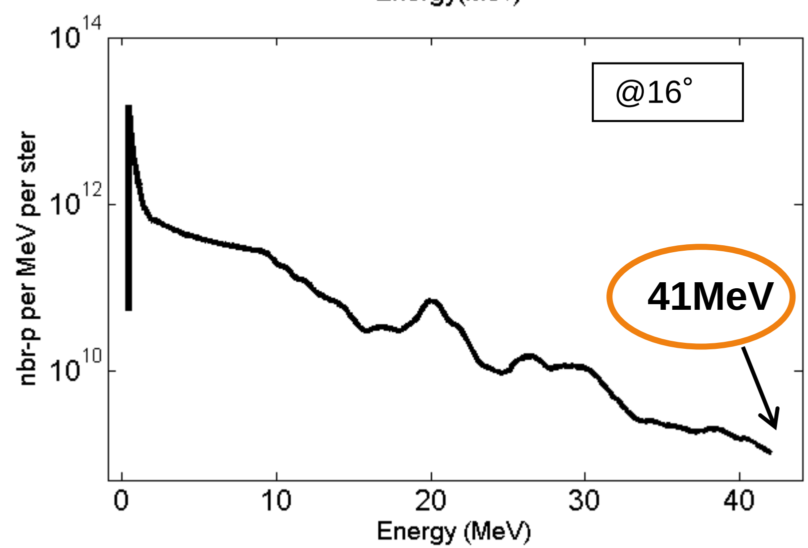
Shot 14: 15um Au foil (ref TNSA)

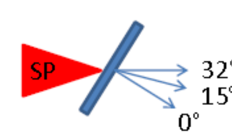




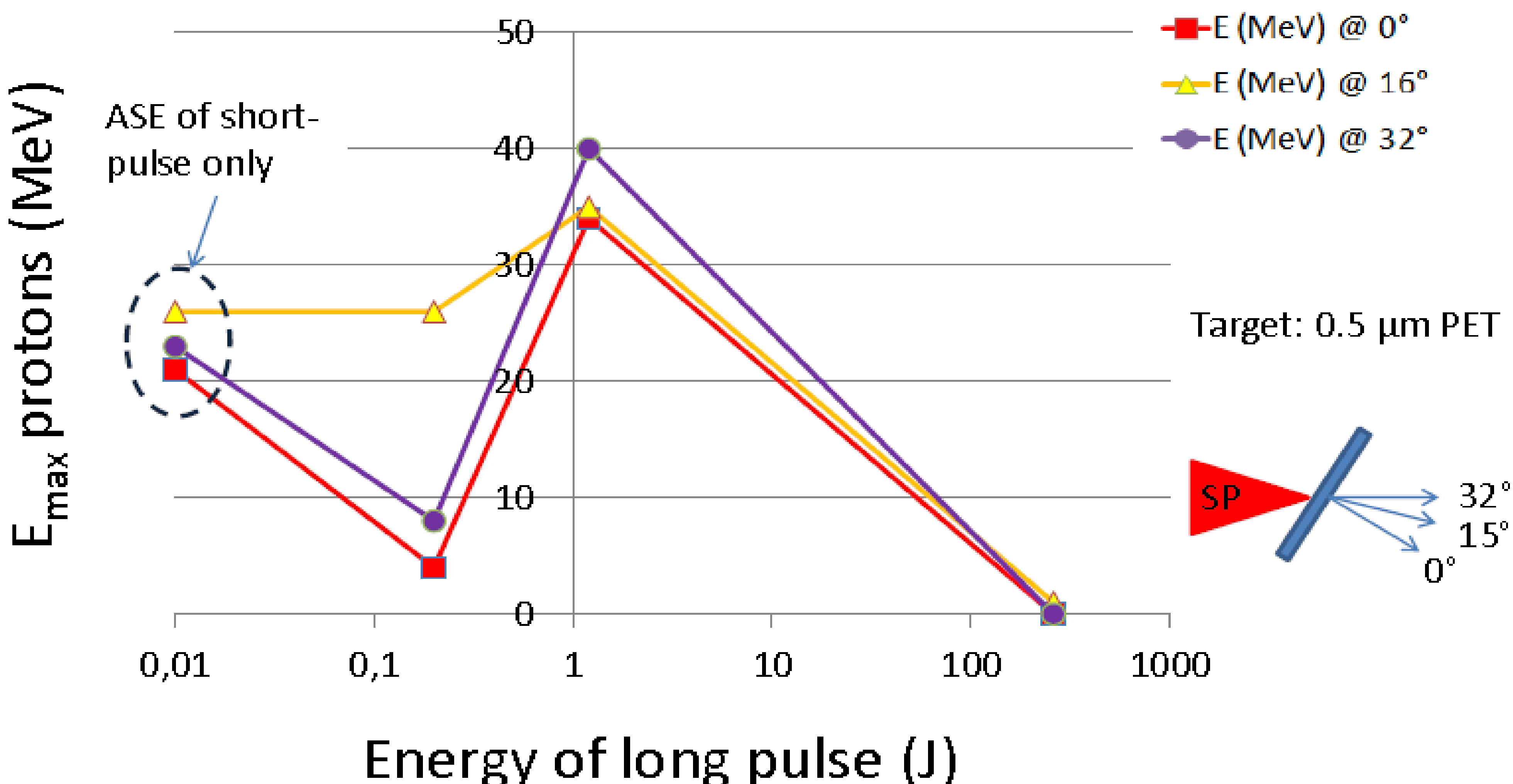
Shot 31: **2,5um PET foil exploded**





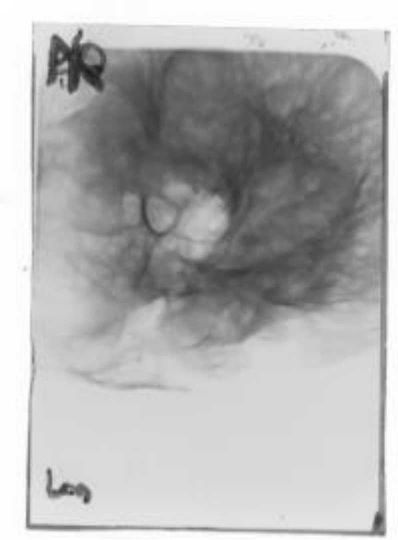


We can tune the proton energy by varying the level of the long-pulse energy prior to the short-pulse

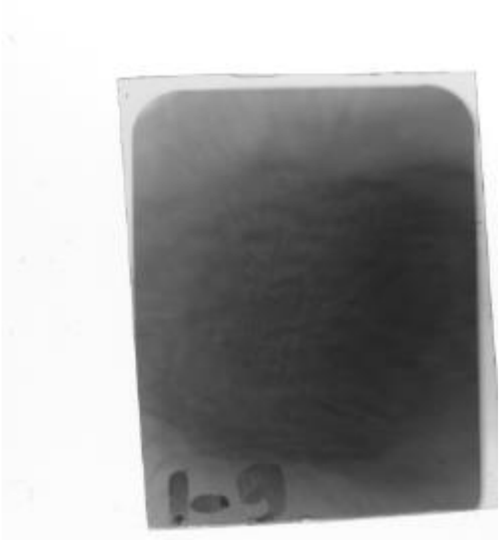


We observe interesting angular features and similar filamentation in RCFs

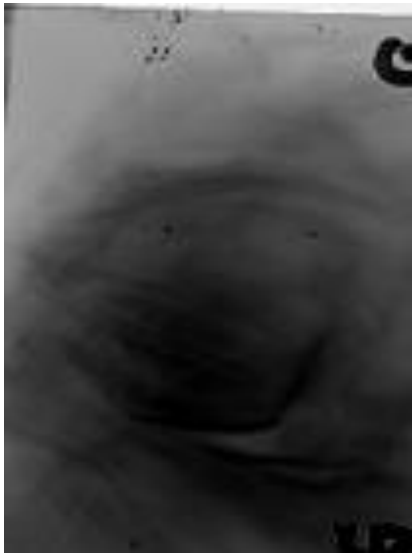
RCF Images



Ref shot
10 micron gold
Emax=28 MeV



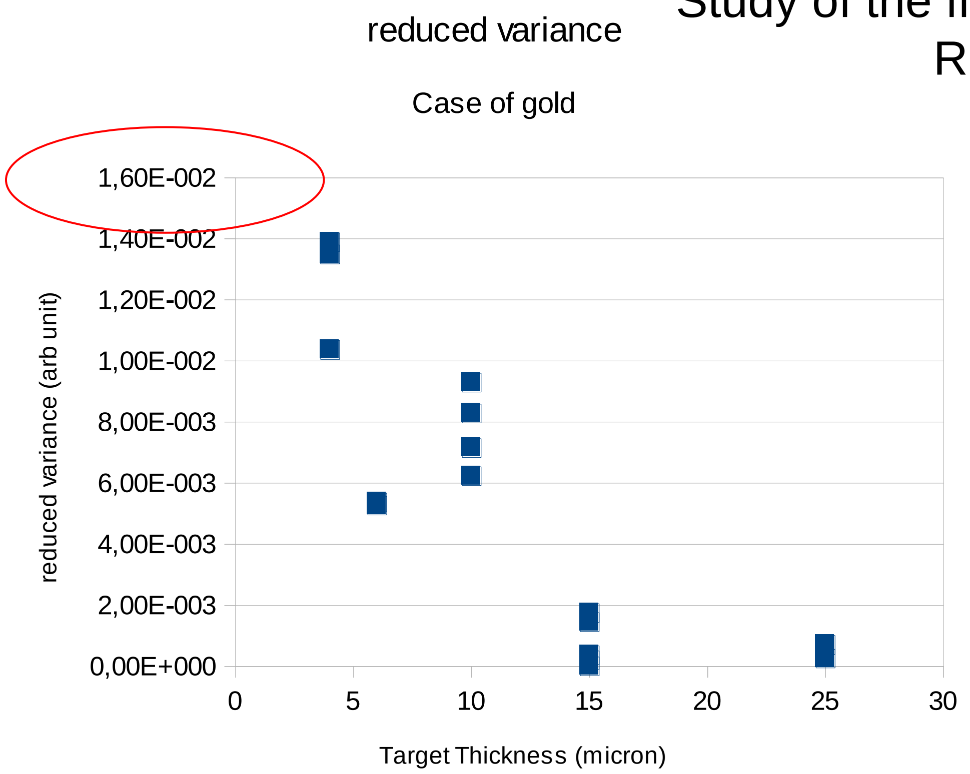
Ref shot
25 micron gold
Emax=20 MeV

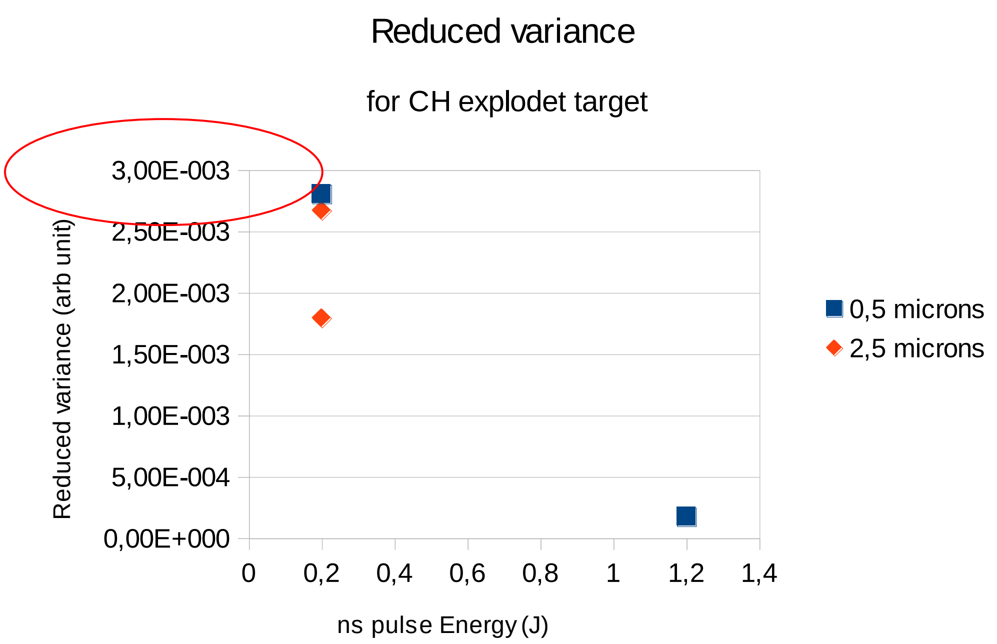


500 nm foil
exploded by 1.2J ns laser
Emax=40 Mev

Quantitative measurement of variance shows that shock produced protons are as unperturbed as thick-target TNSA

Study of the filamentation of the beam
RCF variance





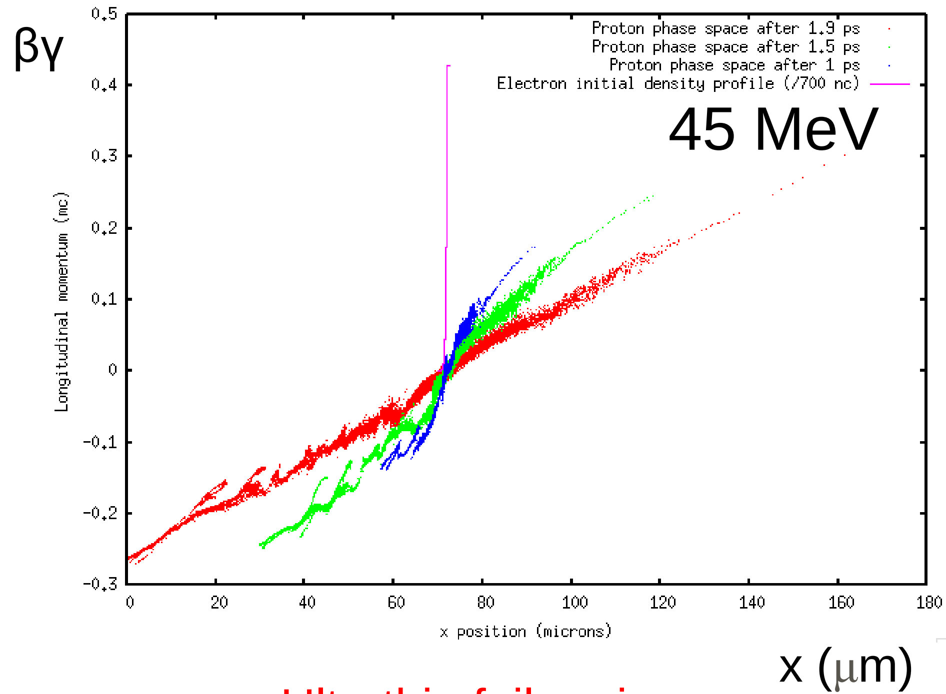
Reference filamentation for gold target of different thickness.

The variance is ten time lower in the case of CH exploded foil

Very low resistivity of the cold electrons = plasma
Beam is little perturbated as in thick gold target, no filamentation

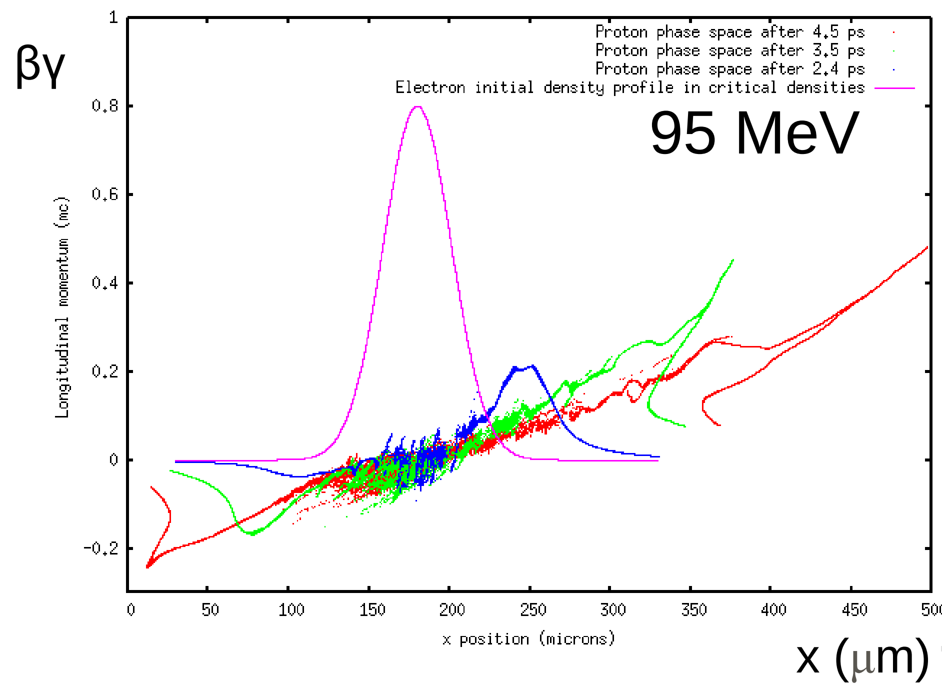
Preliminary 2D simulation results using Titan laser parameters (classical density profiles) confirm experimental trend

Titan parameters: Laser intensity: 7×10^{19} W/cm^2, pulse duration: 700 fs FWHM, focal spot width: 8 microns FWHM.



Ultrathin foil regime

Target thickness: 500 nm with small exponential preplasma.

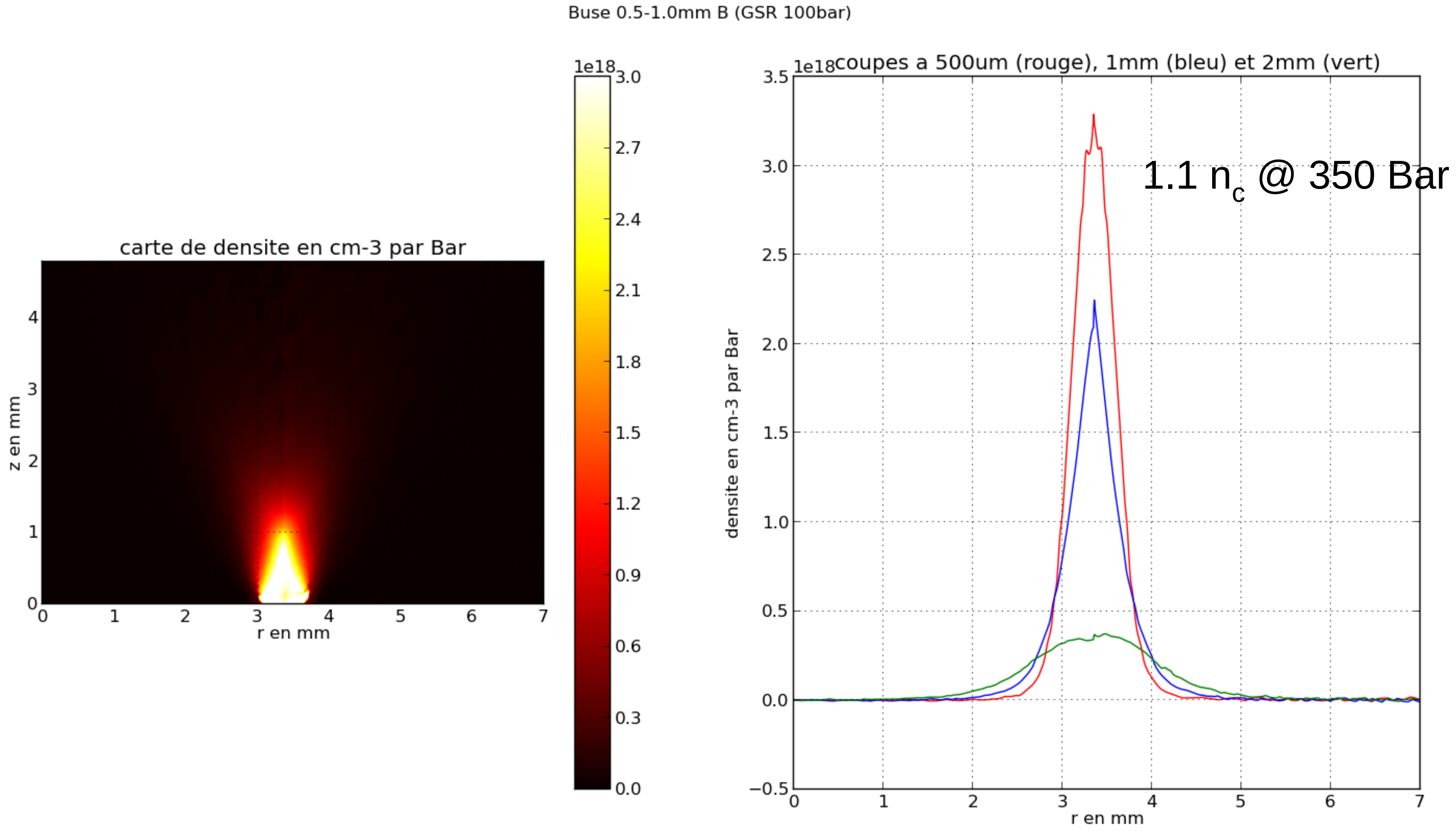


Exploded foil regime

Target FWHM (Gaussian): 35 microns.

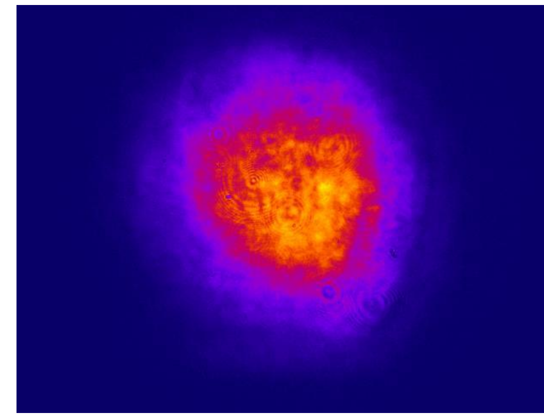
Next step: use CHIC hydro simulations to study the explosion of the target using the long pulse beam and new PIC simulations starting from the CHIC density profiles.

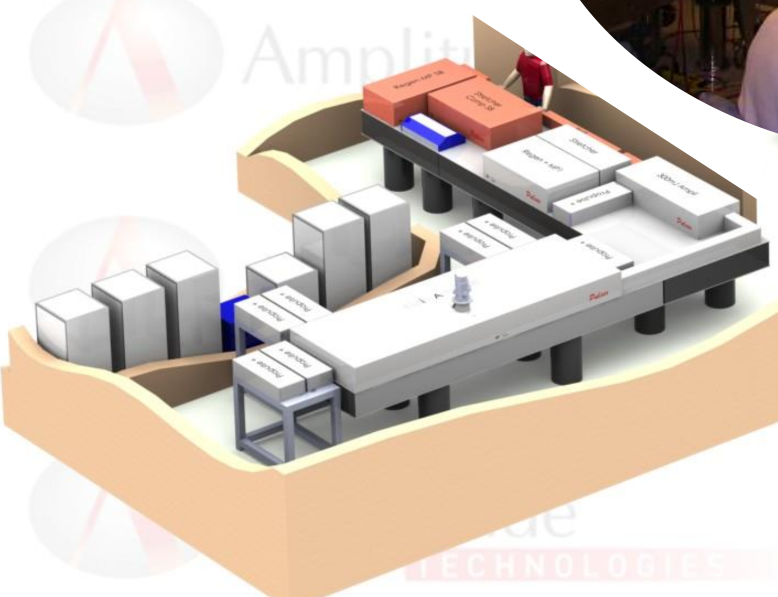
Perspective: we have developed a high-density gas jet which will allow exploring shock acceleration @ 10 Hz

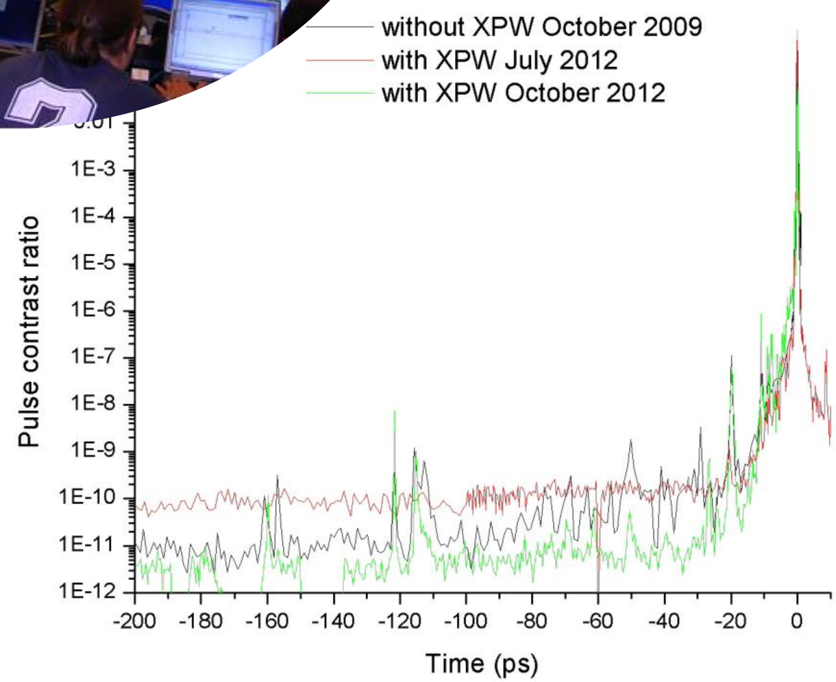


Possible facility:
The 200 TW ALLS system at INRS-EMT

4J after compression,
27fs, 10^{-12}:1 contrast
Deformable mirror
Plasma mirror
10Hz

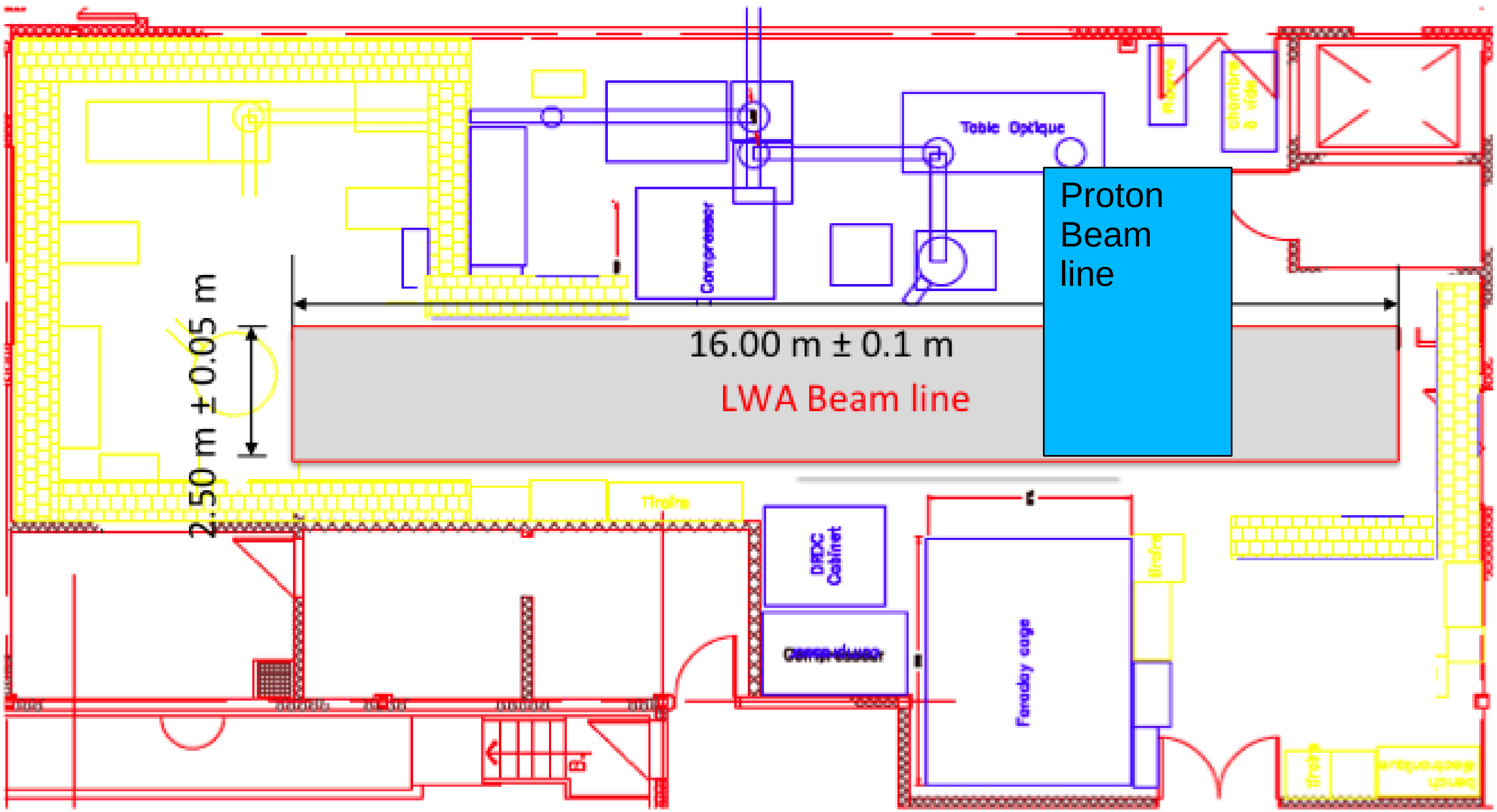




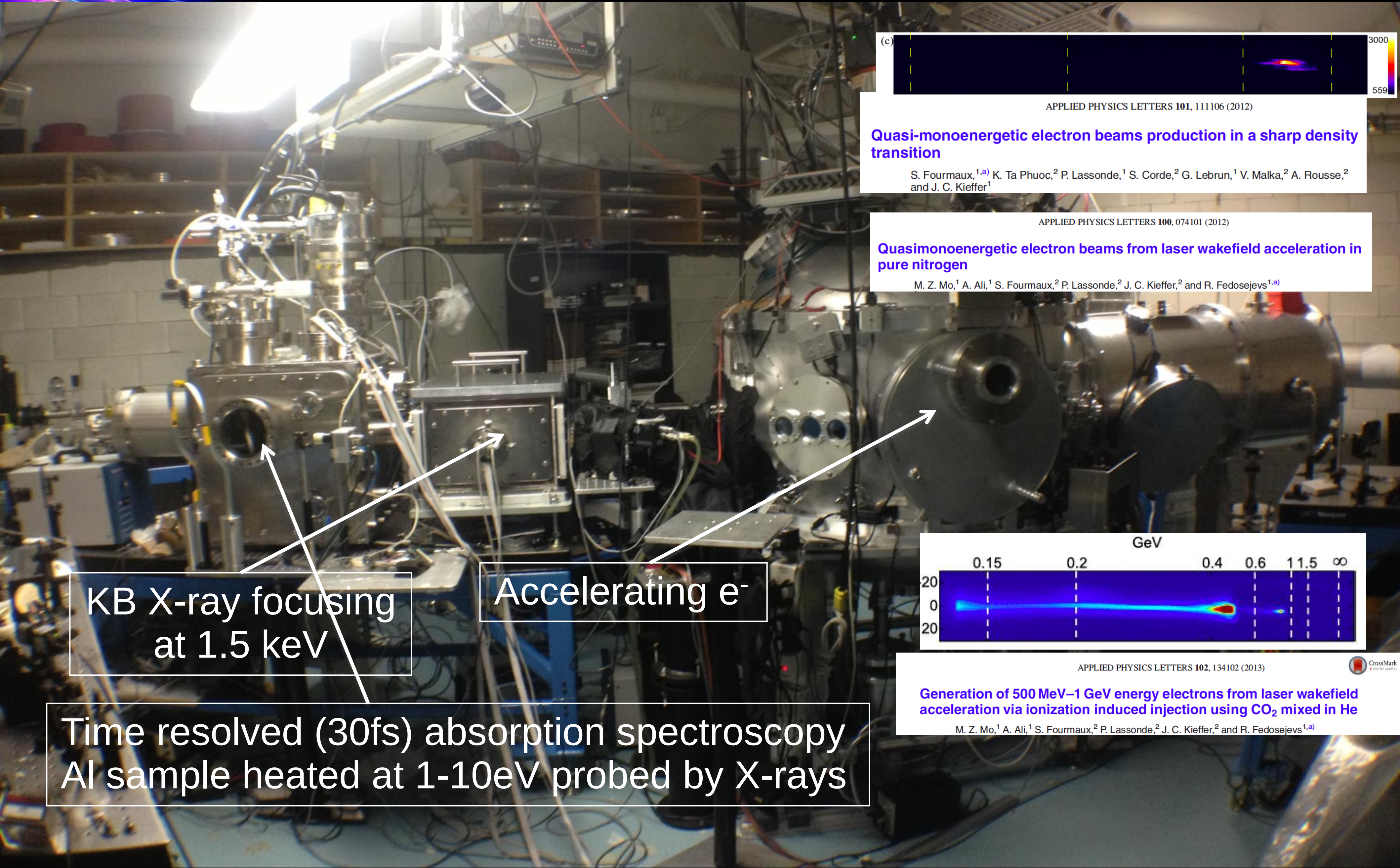


Montreal (Canada)

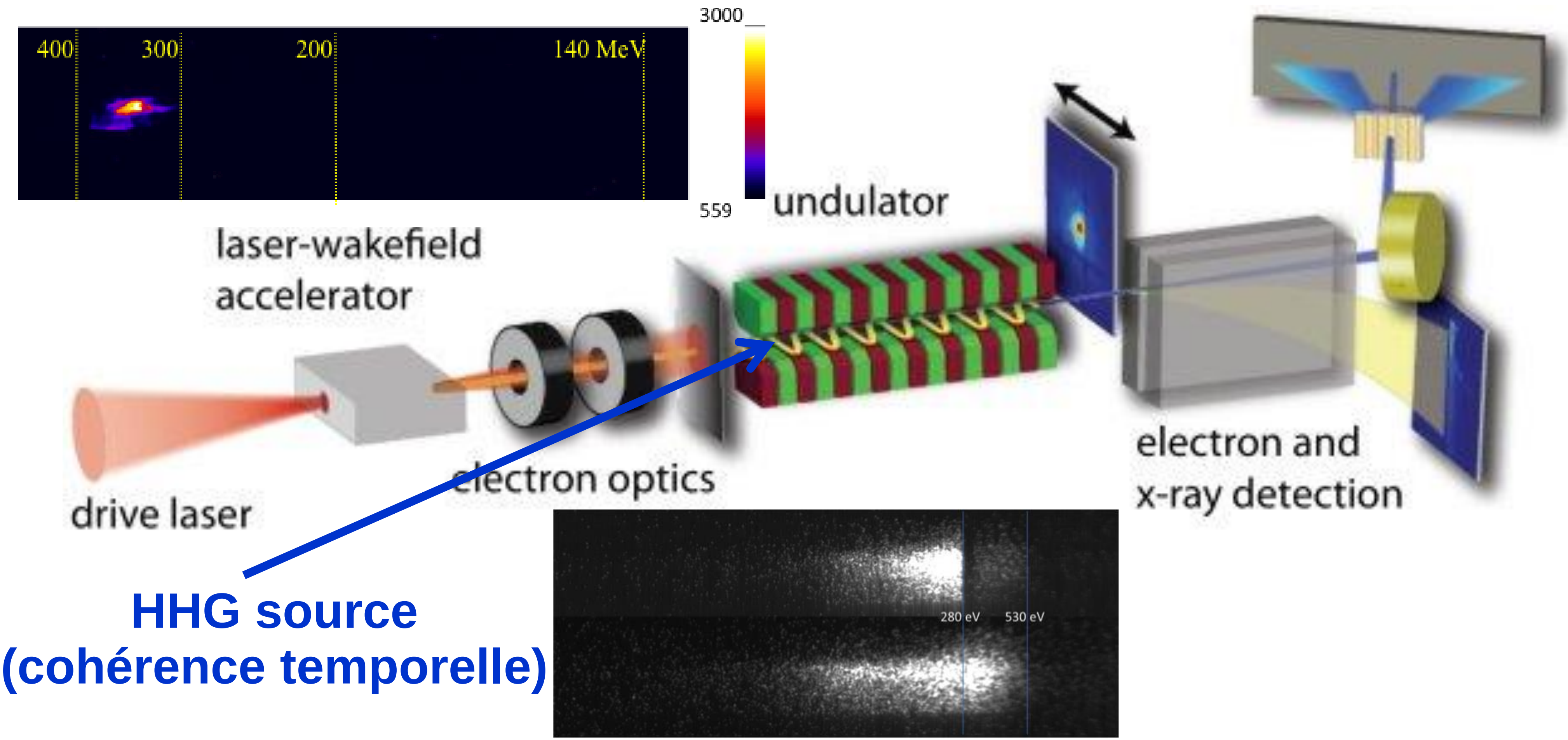
ALLS is developing electron and proton beam lines



Electron acceleration already existing



The CAPS CFI funded project



HHG source
(cohérence temporelle)

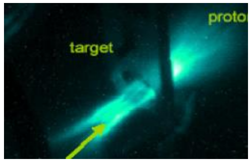
Next to come: proton driven beam lines (test facility)

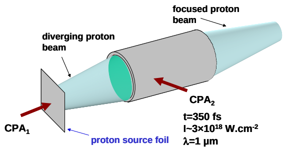
Motivation: Applications (not only medical, but also material science, nanotechnology etc.)

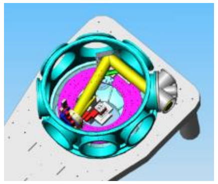
Hot Topics:

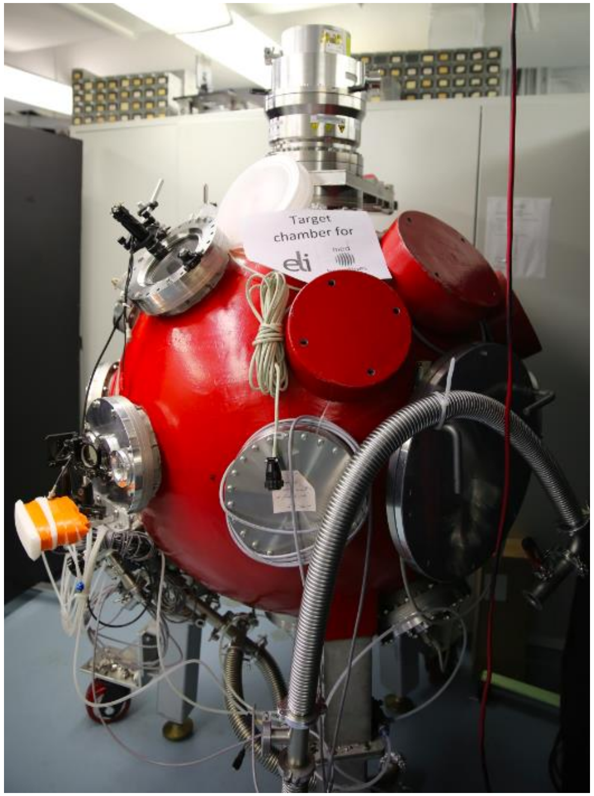
- targetry (Crysystems ?)
- higher repetition rate diagnostics and targetry
- stability and reproducibility
- energy tunability

Laser-generated proton source → Device to focus and energy-select protons → Drift space (to exit target chamber) → Conventional capturing section → **?**



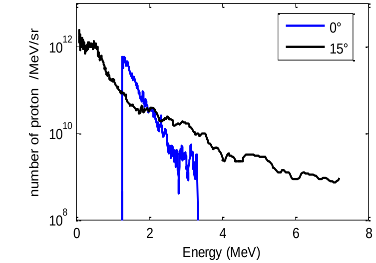




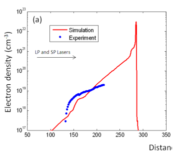
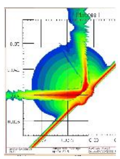


Summary

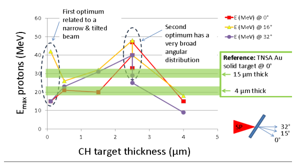
At medium laser energy (5J), we have shown that shock acceleration can produce beams similar to T..A



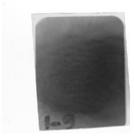
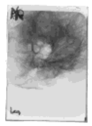
Playing with delay, laser energy and intensity allows to tune the plasma gradient

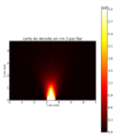
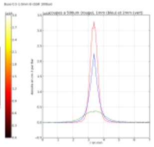
At high energy (180J) we have produced higher energy protons beams than T..A in a thin exploded foil set-up



Shock-produced beam exhibit no filamentation

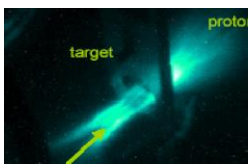
Perspective: High repetition rate operation will be achievable

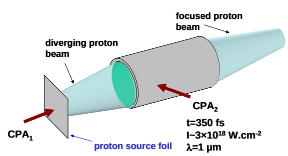



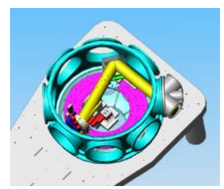
Laser-driven beam line on its way

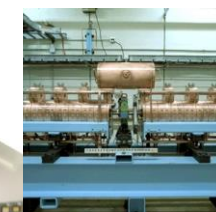
Next to come: proton driven beam lines

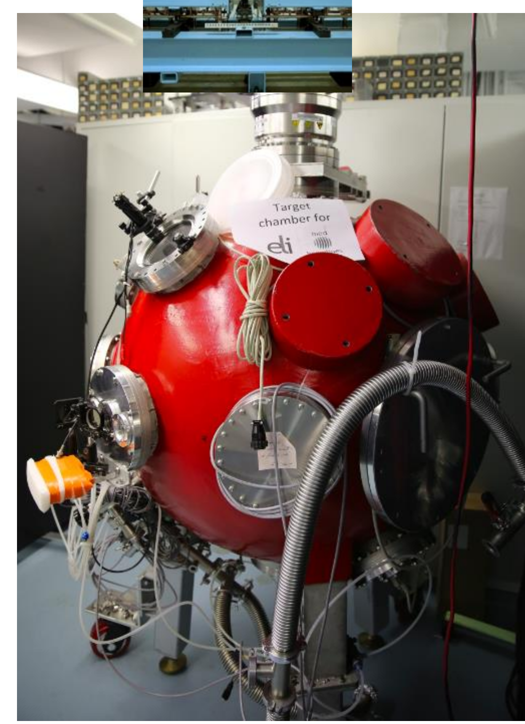
Laser-generated proton source → Device to focus and energy-select protons → Drift space (to exit target chamber) → Conventional capturing section (4 or 5 Quadrupoles) → Accelerating section (48 DTL cells)









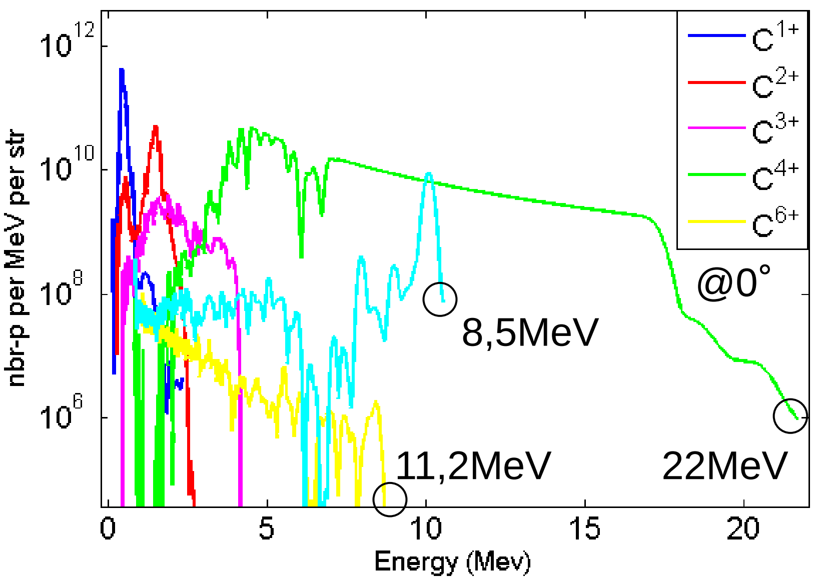


eli attosecond

CRISP eli med beamlines

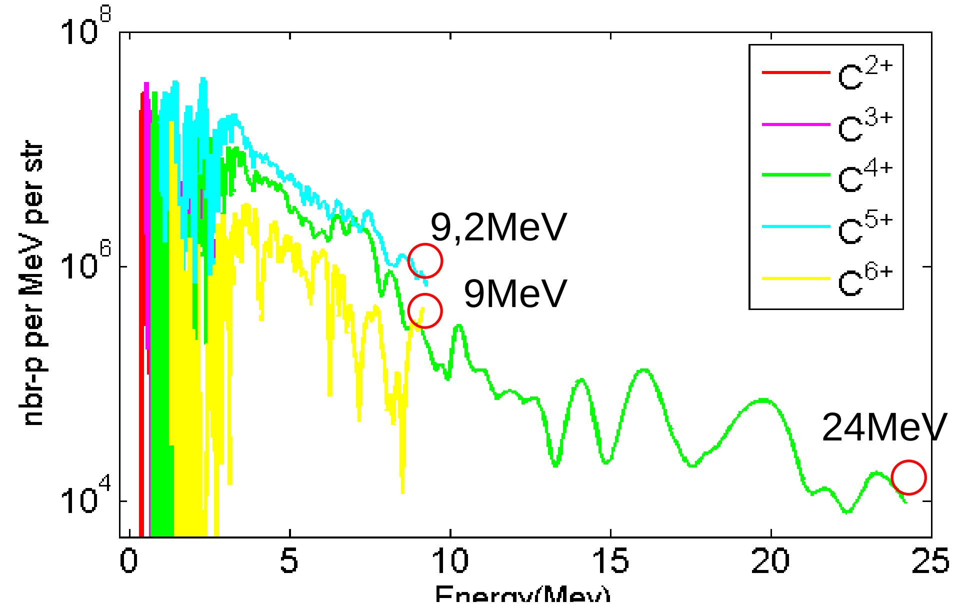
Carbon spectra show comparable energies but in direction of the long pulse beams

Shot3: 15um Au foil (TNSA)

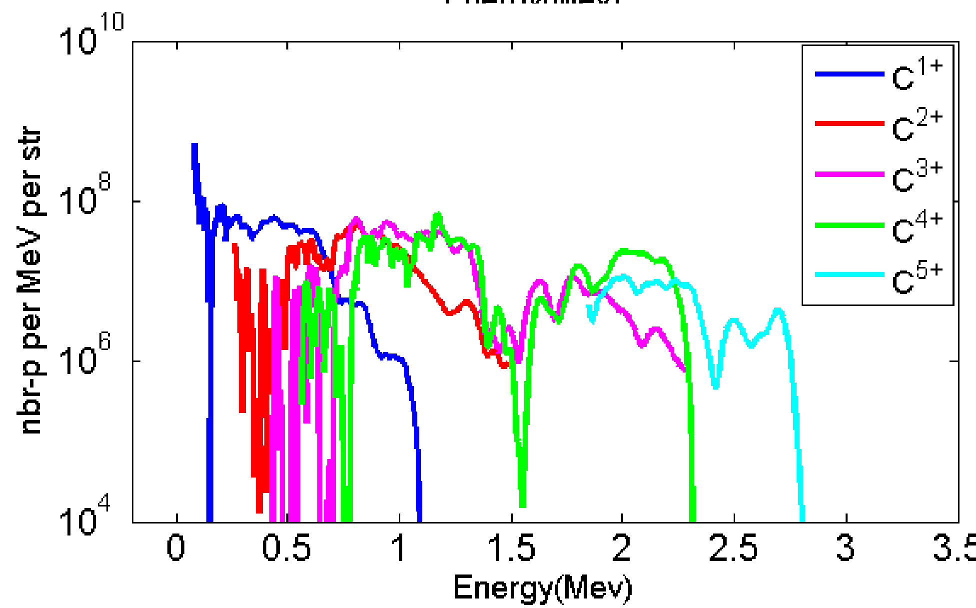


A 32° no carbons detected on TP

@32°

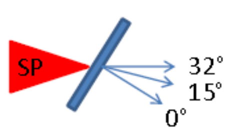


@0°



Shot41: 0,5um PET foil exploded

Best results are found NOT in the target normal



More

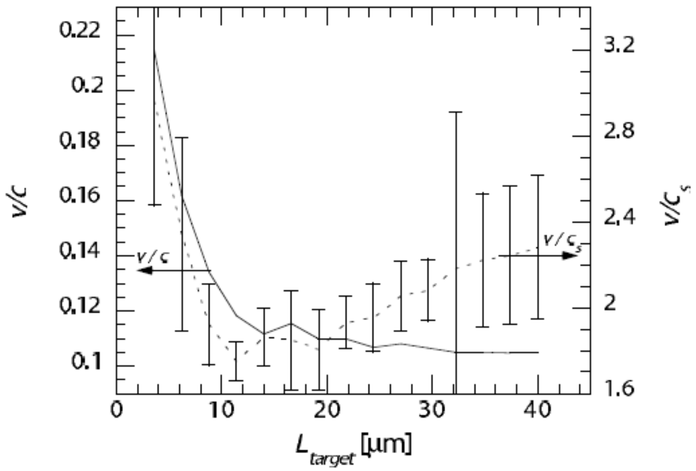
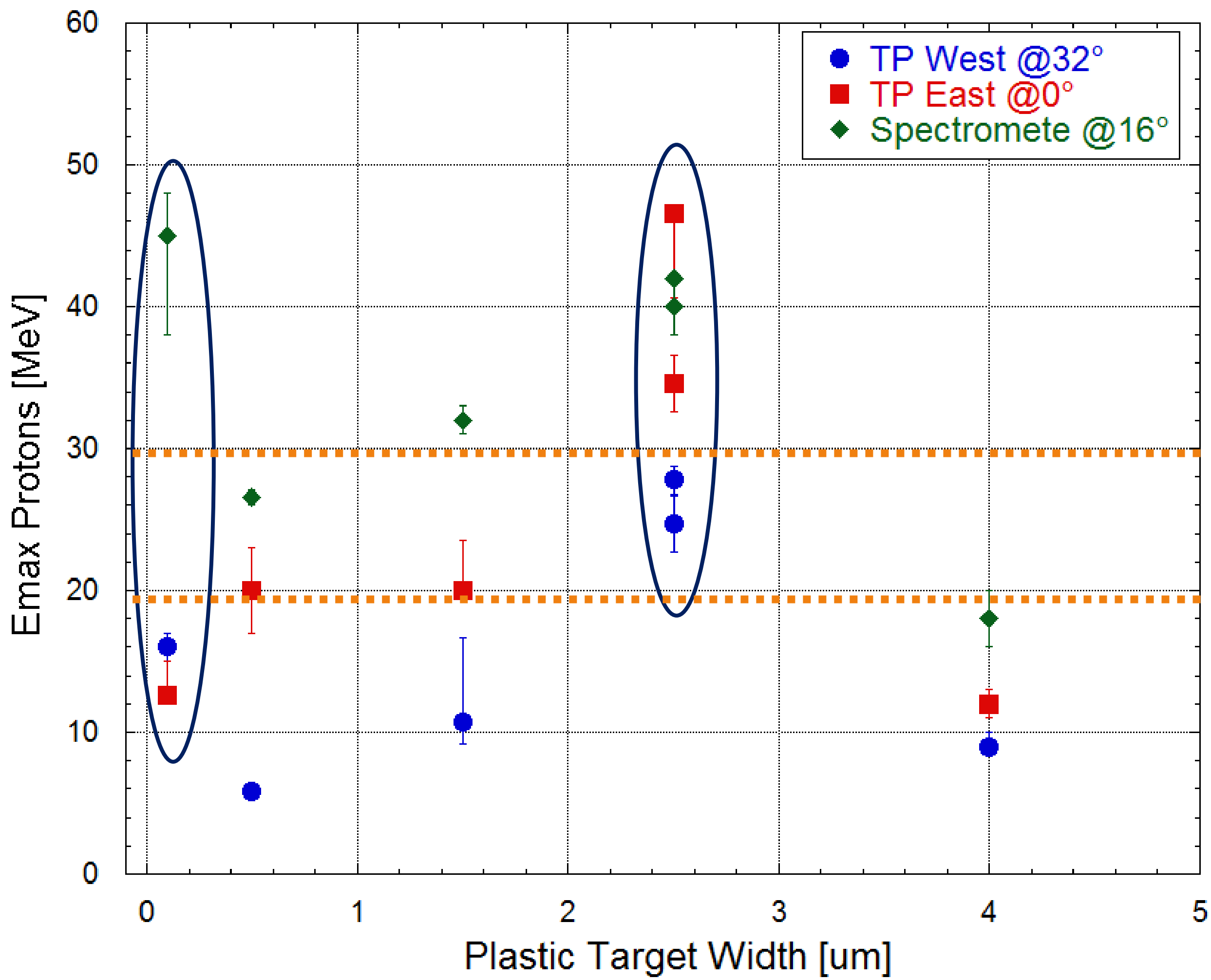


FIG. 2. Velocity of the shock as a function of the cold target thickness for $a_0 = 16$, $\tau_{\text{laser}} = 100$ fs, and $n_{e0} = 10n_{cr}$. The shock velocity is averaged over an interval of $255/\omega_0$, after the shock is formed. The formation time for these shocks is a few $2\pi/\omega_{pi0}$ [9]. (Solid line: shock Mach number; dashed line: shock velocity normalized to c.) Error bar in shock Mach number arises due to variation of c_s over the averaging time of the shock velocity.

Luı´s O. Silva,et all, PRL 92-1 (2004)

Energia Protoni vs Spessore Target

Per target plastici esplosi dall' ASE dello Short pulse, sono state registrate energie molto alte per i protoni, superiori a quelle ottenute tramite TNSA



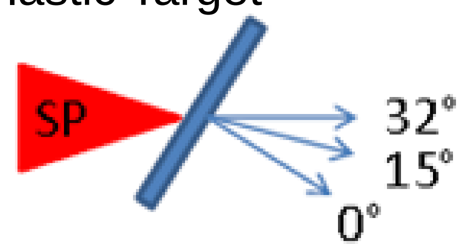
ASE dello Short pulse : ~J, 100-400ps

Riferimento TNSA: solid Au Target @0°

15um

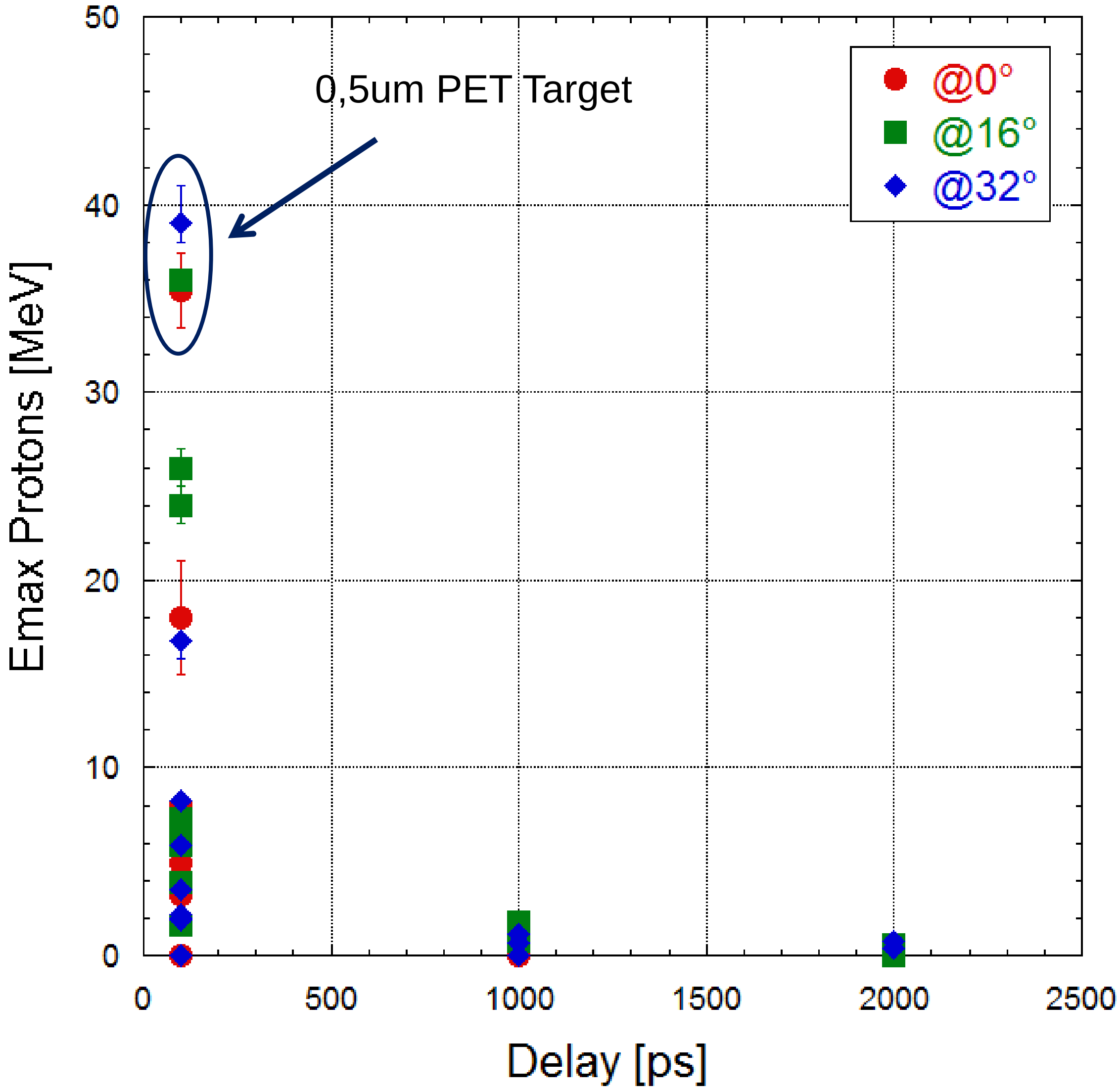
4um

Plastic Target



Pagina 28

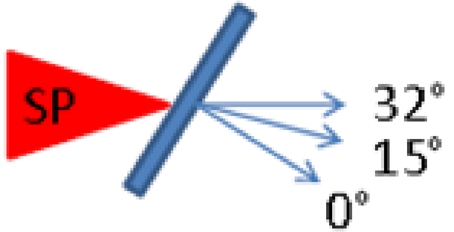
Energia Protoni vs Delay



Δt= t_{ps}-t_{ns}

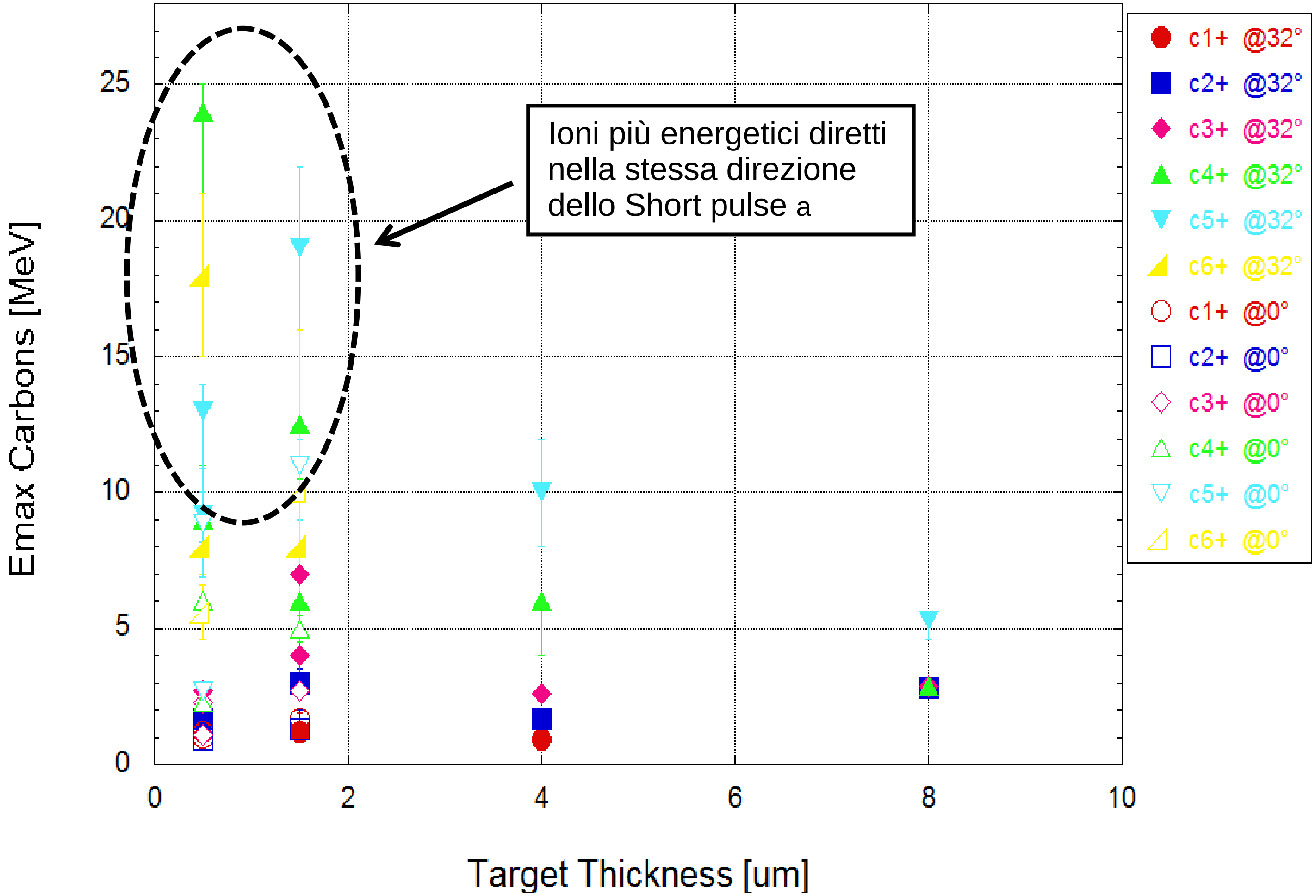
- Maggiore è il delay maggiore è l'espansione del target esploso
- Valori maggiori di energia si hanno per Δt=100ps
- Per valori di Δt molto alti (>1ns) l'accoppiamento laser-target diminuisce e si ottengono fasci di protoni a bassa energia (conferma simulazioni)

Plastic Target



Energia Ioni Carbonio vs Spessore del Target

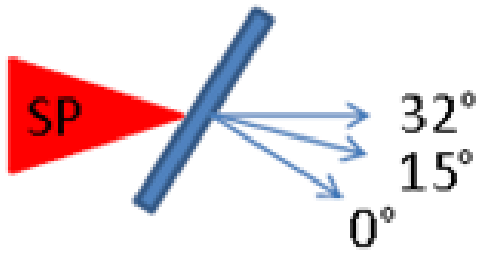
Per target plastici esplosi dal Long pulse, si ottengono energie più alte per le specie ioniche con rapporto q/m maggiore, usando target con spessore <2um
→ **energie comparabili a quelle ottenbili con Target solido**



Al variare dell'energia del LP: energie comparabili a quelle con Target solido per energie del laser <100J

Al variare dei parametri di interazione l'energia per le specie con q/m inferiore non varia molto

Plastic Target



Pagina 30

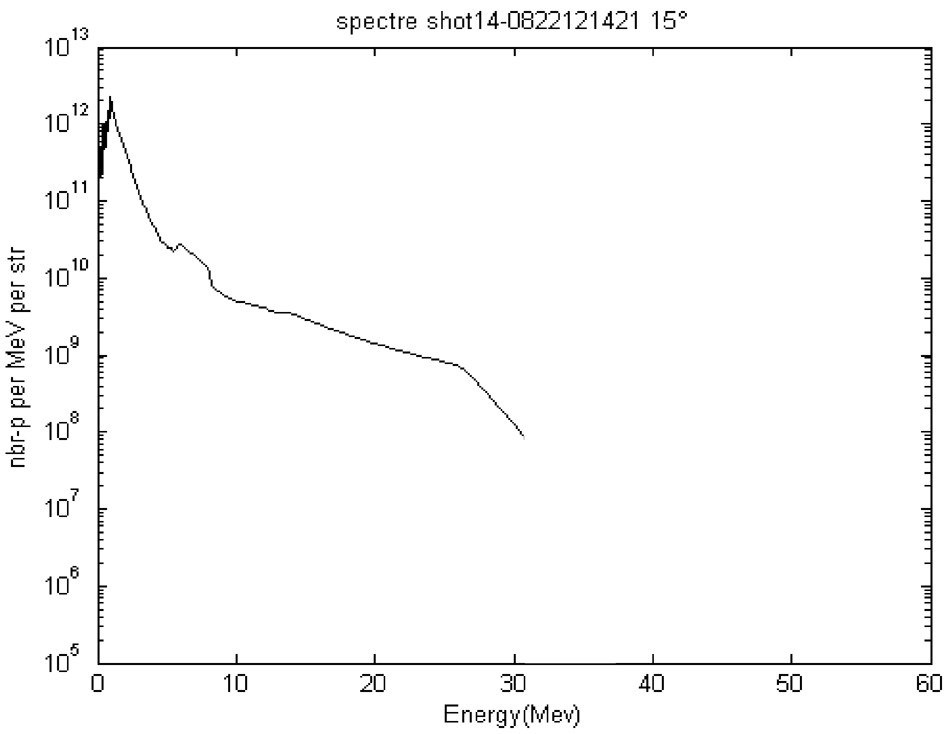
Conclusioni e Prospettive future

- Sviluppati **software per il post processing di IP** (Parabola di Thomson e Spettrometro)
  - ➡ ottimizzazione (confronto con LNS-INFN Catania)
  - ➡ sviluppo TP con MCP per esperimenti ad alto tasso di ripetizione (0,1-1KHz)
- **Uso di low-density target** è una strada promettente per migliorare le caratteristiche di fasci laser-driven e permettere il loro impiego nelle applicazioni
- Usando target a bassa densità ottenute **Energie superiori ~45 MeV per Protoni** e **comparabili ~25 MeV per Ioni Carbonio** a quelle ottenute da target solidi
- Beams con una **distribuzione angolare ampia** che deve essere controllata (limite di questo schema)
  - ➡ I parametri di interazione (Laser,Target) devono essere confermati da simulazioni CHIC e 2-D PIC
  - ➡ Aumentare il controllo sui parametri della sorgente per controllare i fasci prodotti
  - ➡ Sviluppo di Gas Jet (Target) di spessore opportuno per esperimenti ad alto tasso di ripetizione

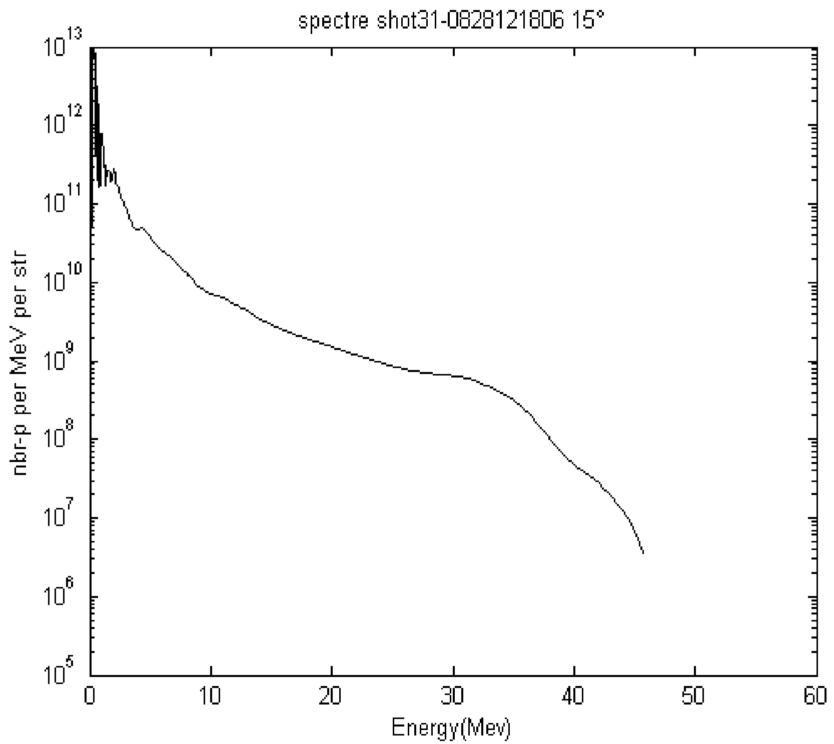
I risultati di questo lavoro sono stati presentati presso due conferenze :

- ***Laser Acceleration of Electrons, Protons, and Ions II* – SPIE Conference April 2013 (Prague)**
- ***CRISP 2nd annual meeting* (March 2013) at Paul Scherrer Institute (Zurich)**

Typical spectra



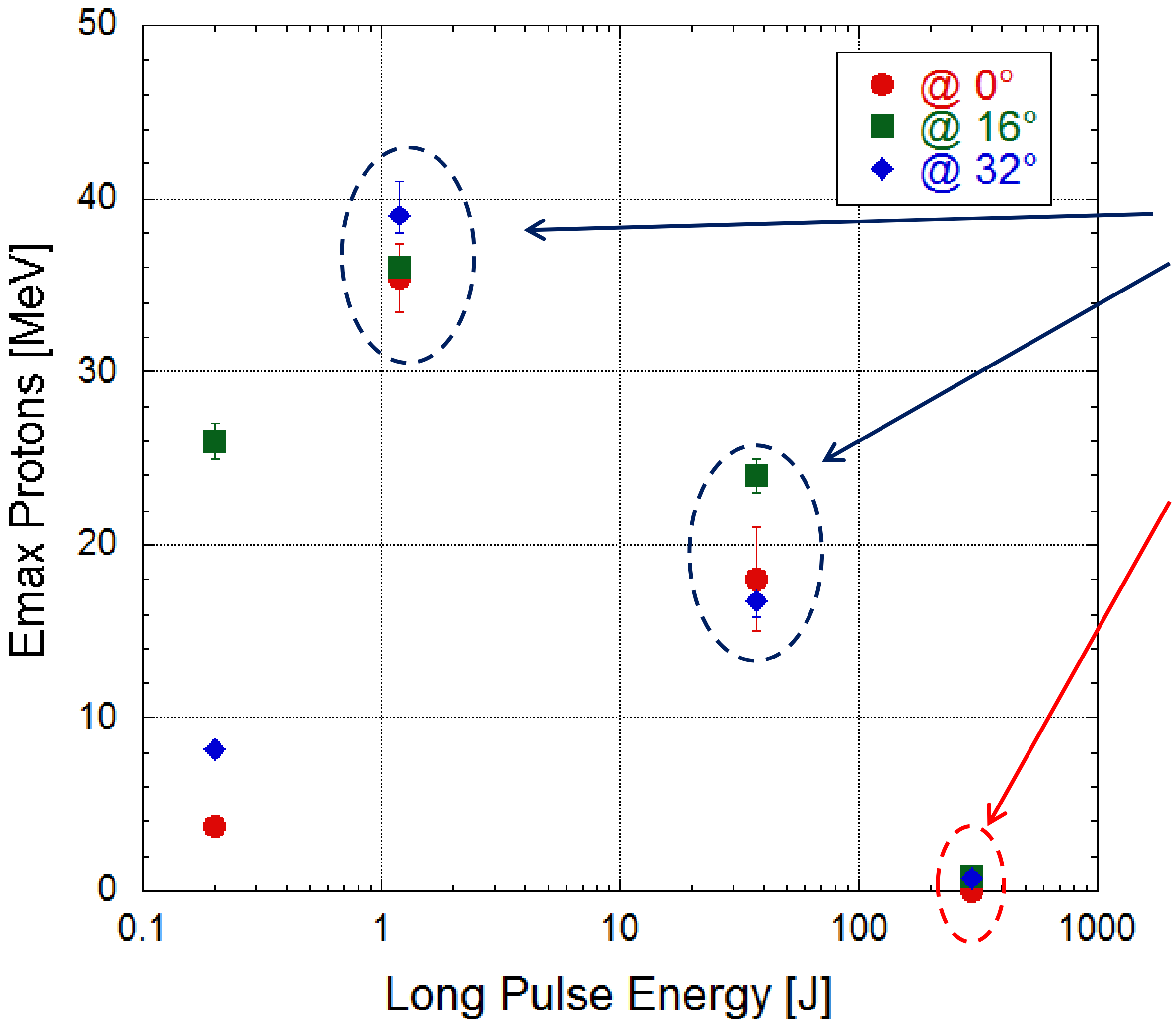
15 microns gold reference shot
E_{max} =30 MeV,
on the axis normal to the target.



2.5 microns plastic foil
exploded by the pre-pulse
E_{max} = 45 MeV
on the axis normal to the target.

Energia protoni vs Energia del Long Pulse

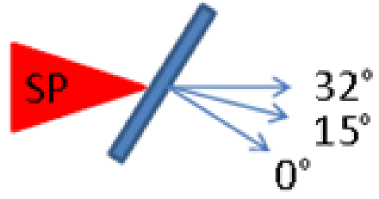
E' possibile variare l'energia massima del fascio di protoni variando l'energia del Long pulse prima dell'arrivo dell'impulso principale



Accelerazione maggiormente anisotropa

Per alte energie del LP (~300J) bassi valori di energia dei fasci prodotti

Target: 0,5um PET esploso dal LP



Pagina 33

Outline

- Introduction on laser ion acceleration and the interest in low density targets.
- A summary of the 2011 LULI experiment on laser acceleration with exploded foils.
- PIC simulations of TNSA and shock acceleration.
- A description of the Titan 2012 experiments setup.
- First experimental results for the 2012 Titan campaign.
- Description of the ongoing work (exp. and theory).
- Perspectives with high density short plasma length gas nozzles and other lasers.

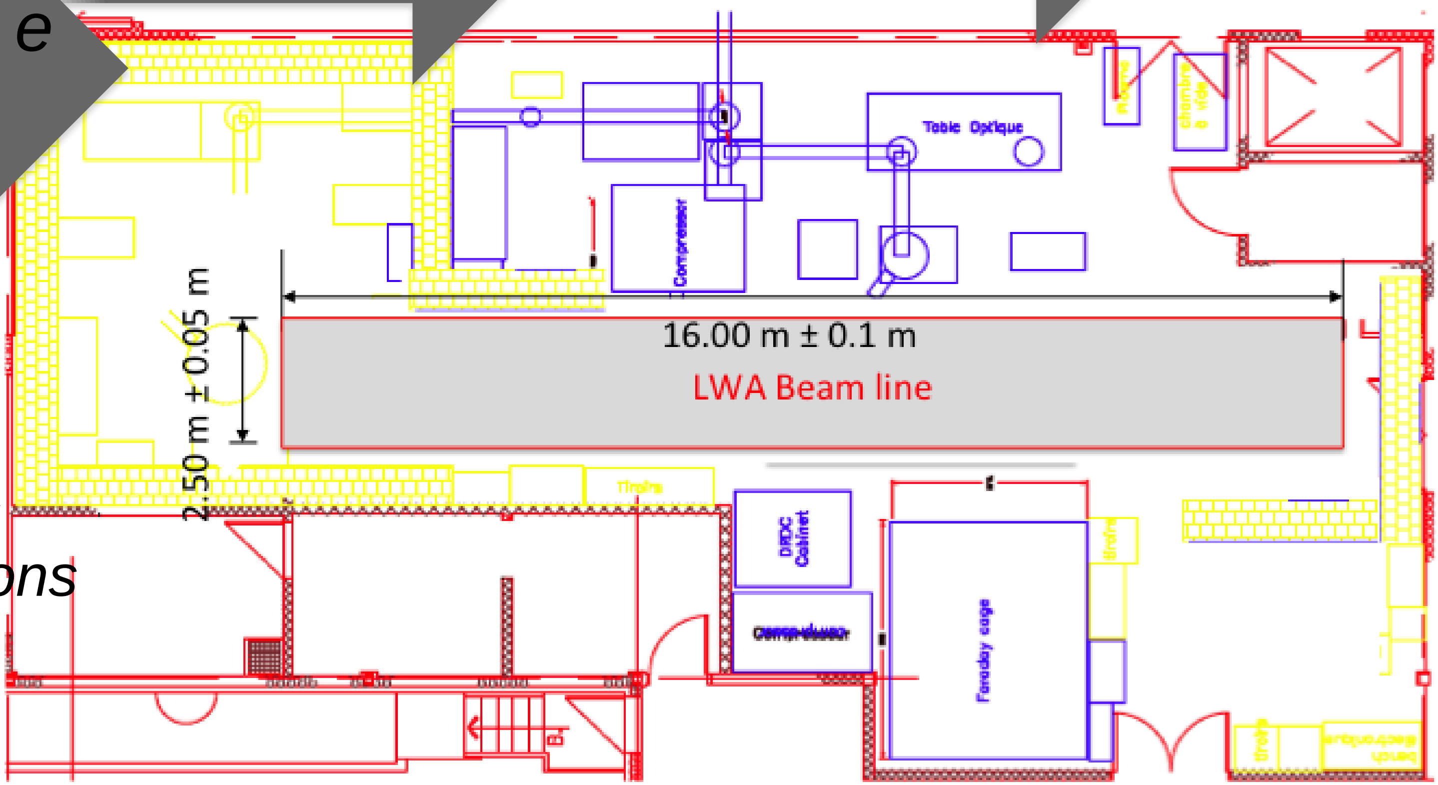
The CAPS CFI funded project

Optimization of the e
03/13 -12/13

Lab reorg
01/14-04/14

Expt start
08/14

- *Charge distribution*
- *Beam divergence*
- *Energy spread*
- *stability*
- *Designing e⁻ optics*
- *Testing configurations with PIC codes*



Planned collaboration
CAPS (CLS, ALLS, U of A) and LUNEX5 (SOLEIL, LOA)