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

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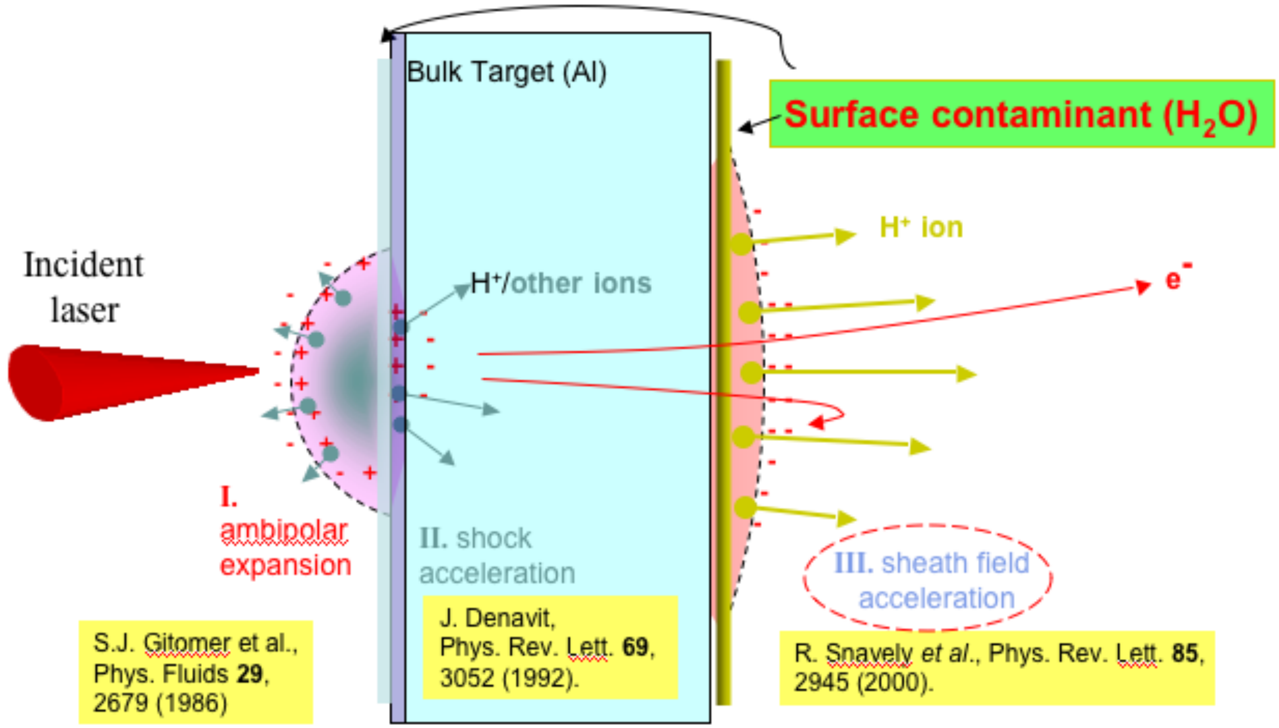
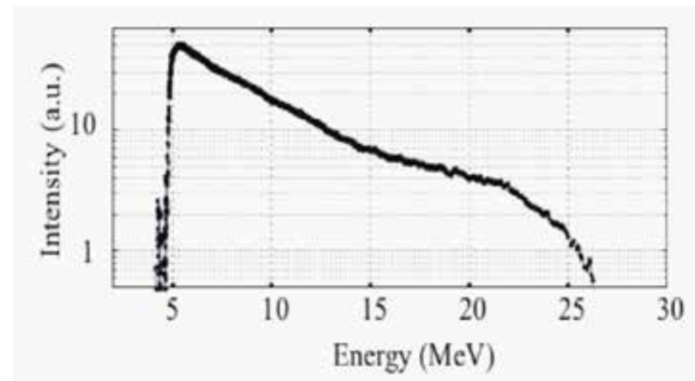
Standard proton acceleration mechanism in high intensity laser plasma interaction (TNSA)



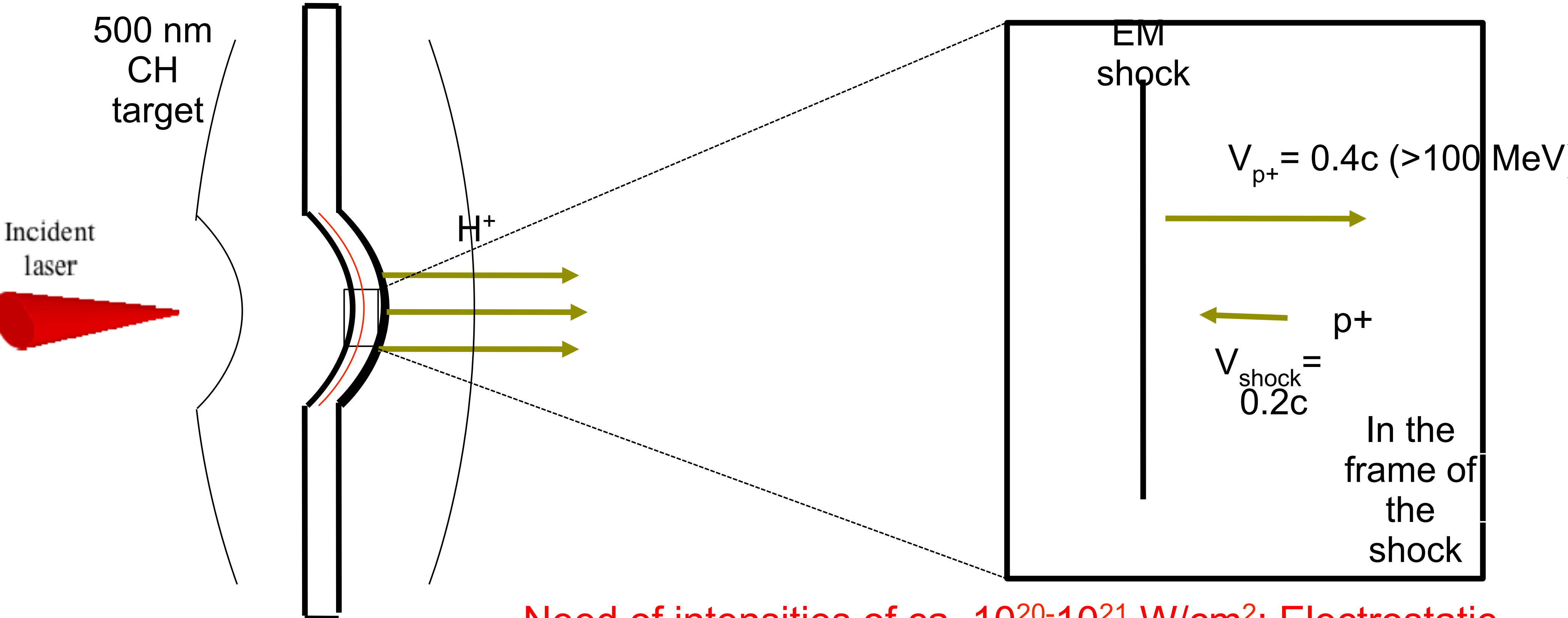


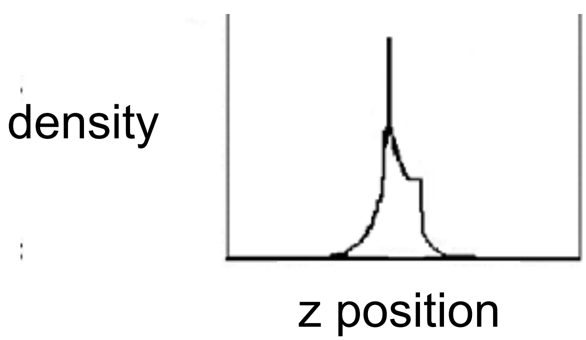
Typical proton spectrum obtained at LULI.

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

- Low emittance and high brightness
- Short duration (ps at the source)
- High spectral cut-off
- **Applications:** Inertial Confinement Fusion, probing electromagnetic fields in plasmas, isochoric heating, proton-therapy, tomography, laboratory astrophysics, ...

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





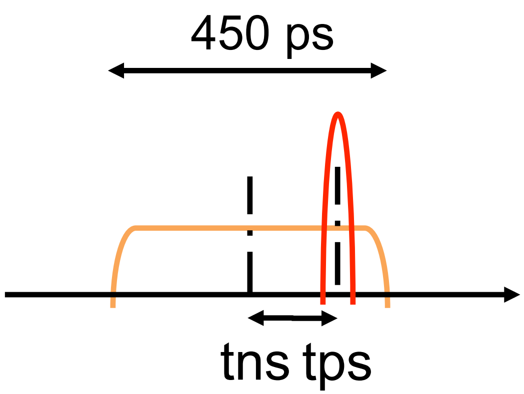
Need of intensities of ca. 10^{20}-10^{21} W/cm^2: Electrostatic wave travels fasten than sound speed and generates shock: protons rebounce on surface

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), LLE
- Our aim: explore this mechanism using high-energy, high-intensity laser pulses, and its transition from TNSA, wavelenght 1 micron

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

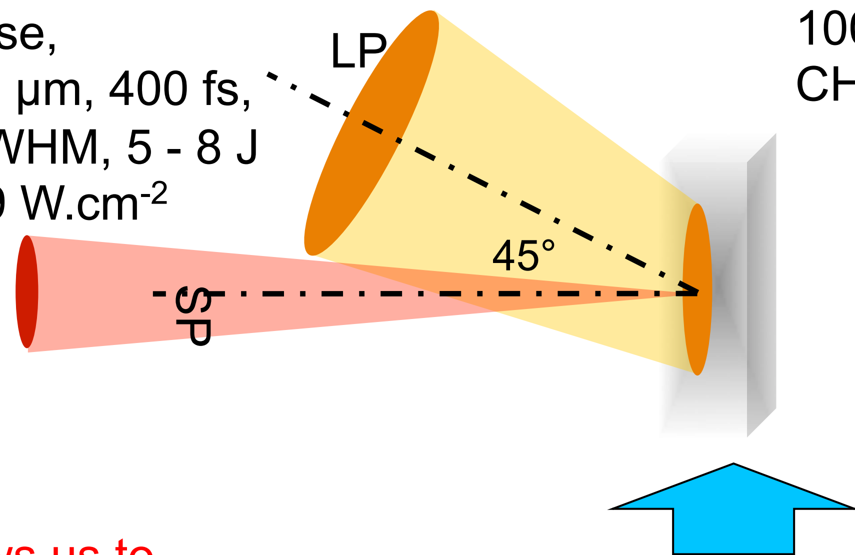


Dt = tps- tns

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

Short pulse,
λ = 1.054 µm, 400 fs,
10 µm FWHM, 5 - 8 J
I=1-2e19 $W.cm^{-2}$

100 nm or 500 nm
CH foils



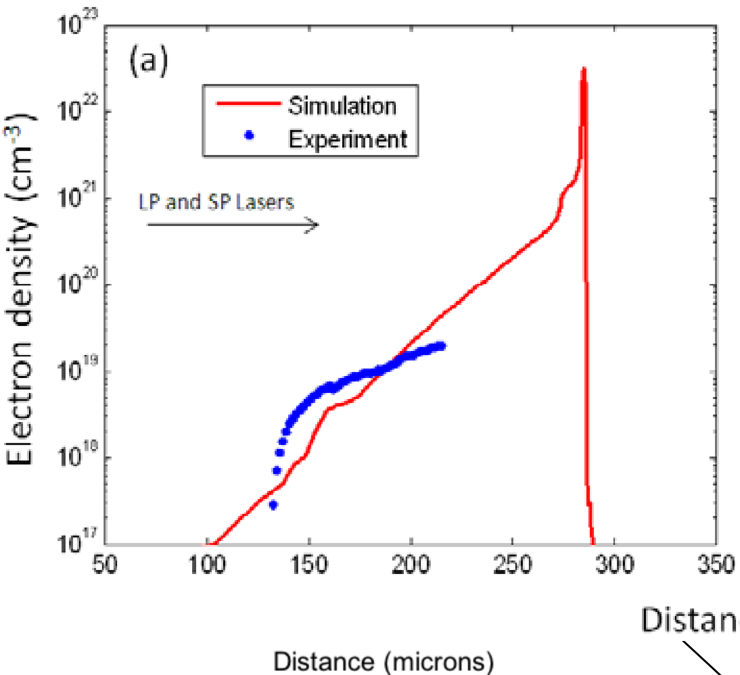
2 Thomson
Parabolas
at 0° and 15°

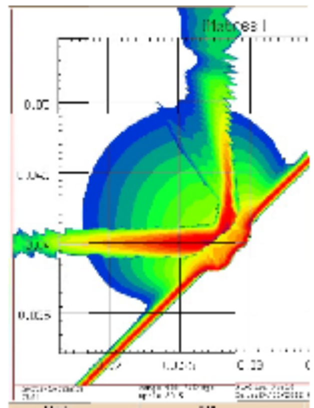
Interferometry
measurements of the
exploded foil density
profile

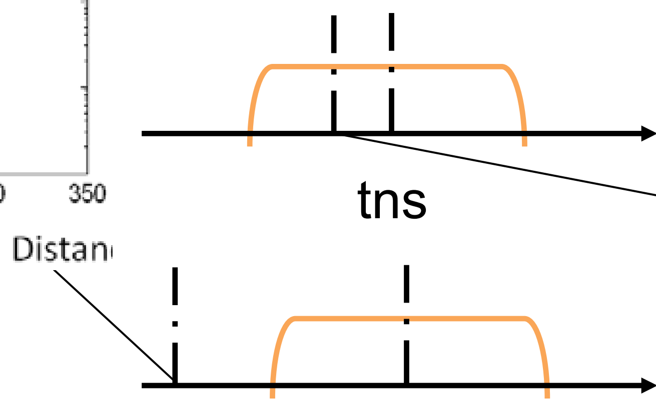
The expansion of the thin foil allows us to explore various types of gradients by changing Δt and t_{ns}.

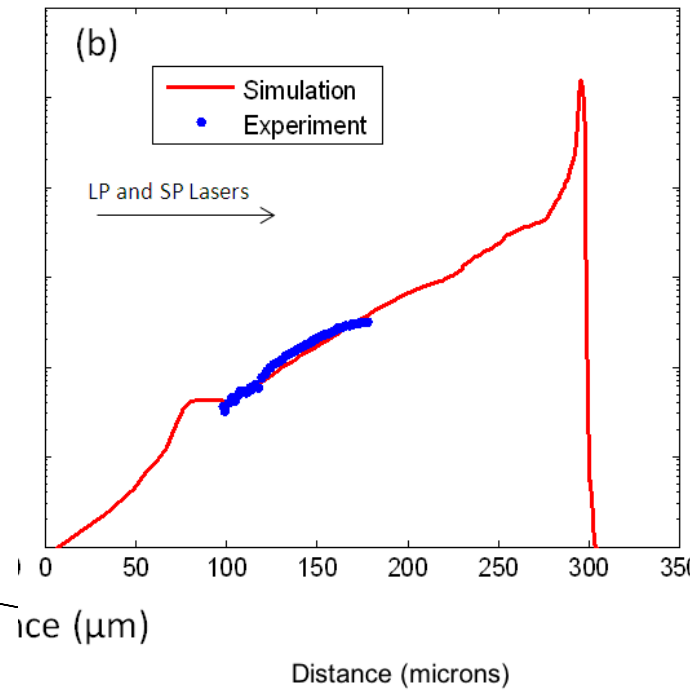
Experimental plasma profile with interferometry results Vs 2-D hydro simulation (CHIC) results show good agreement

- 2-D hydrocode with experimental parameters : 500 nm foil, Ins = 10^{12} -10^{13} W/cm²
- 45° incidence yields asymmetric profiles.









Exp[redacted]^{13} W/cm², -500 ps delay

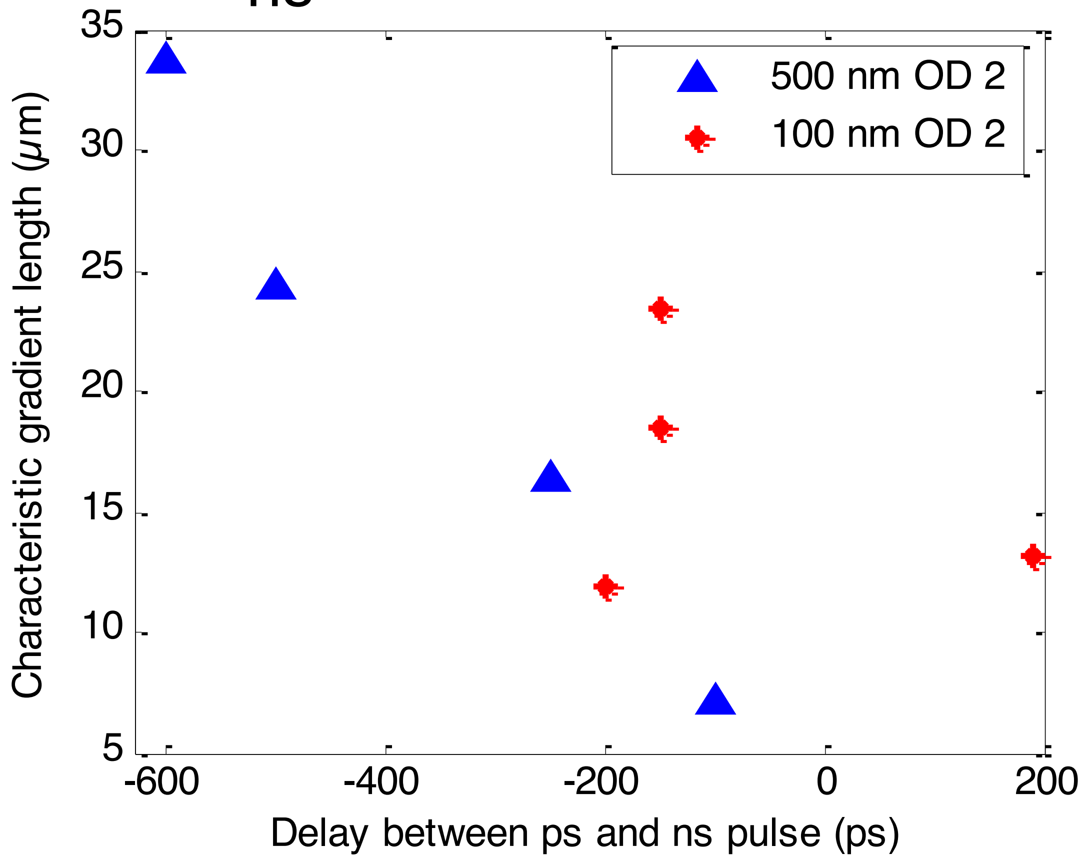
Exp.: 10^{12} W/cm², -100 ps delay

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 ns 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)

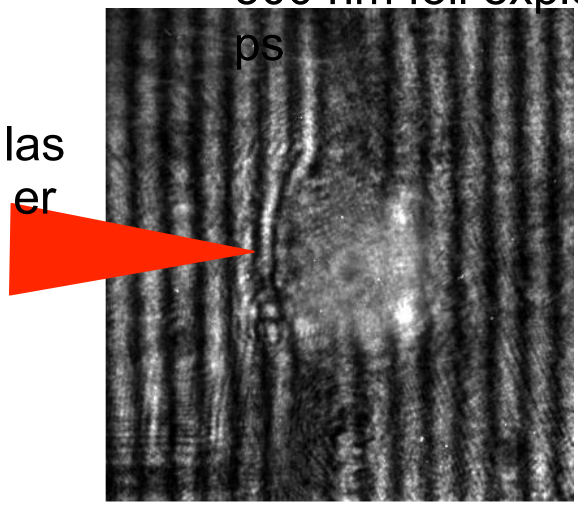
$I_{ns} = 10^{12}$ W/cm²

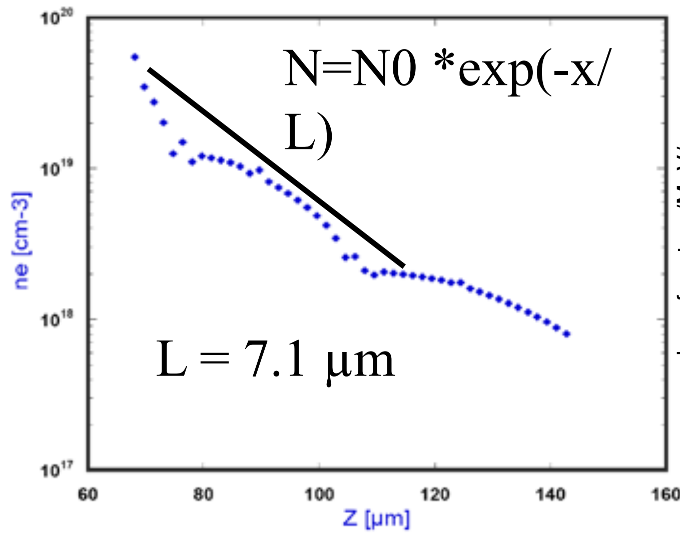


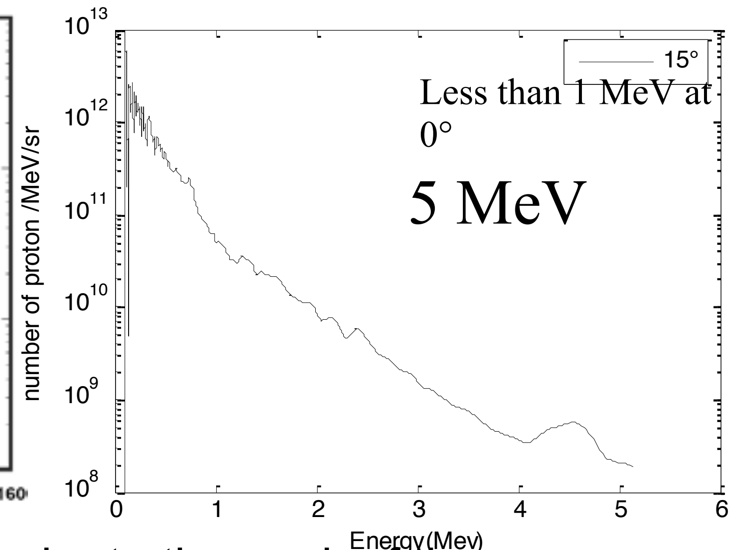
Experimental results @ LULI show that exploded targets can reach similar energy than TNSA

Solid target Ref ca 7 MeV

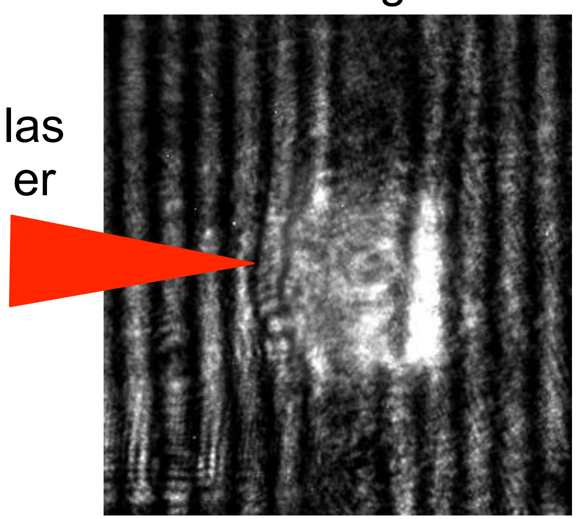
500 nm foil exploded by the long pulse (10^{12} W/cm²) 100 ps prior to the peak of the ps

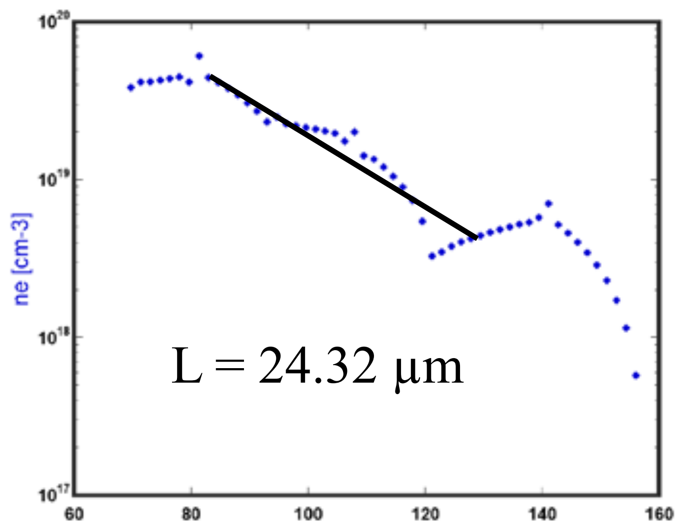


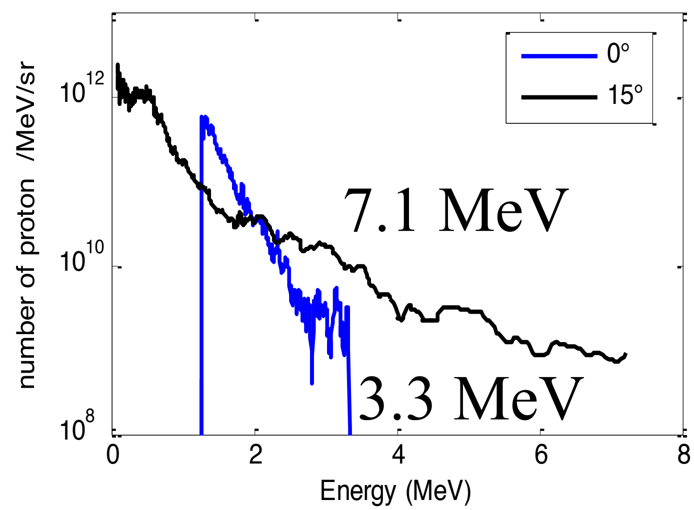




500 nm foil exploded by the long pulse (10^{12} W/cm²) 500 ps prior to the peak of the ps , similar to TNSA on gold 10 micron.







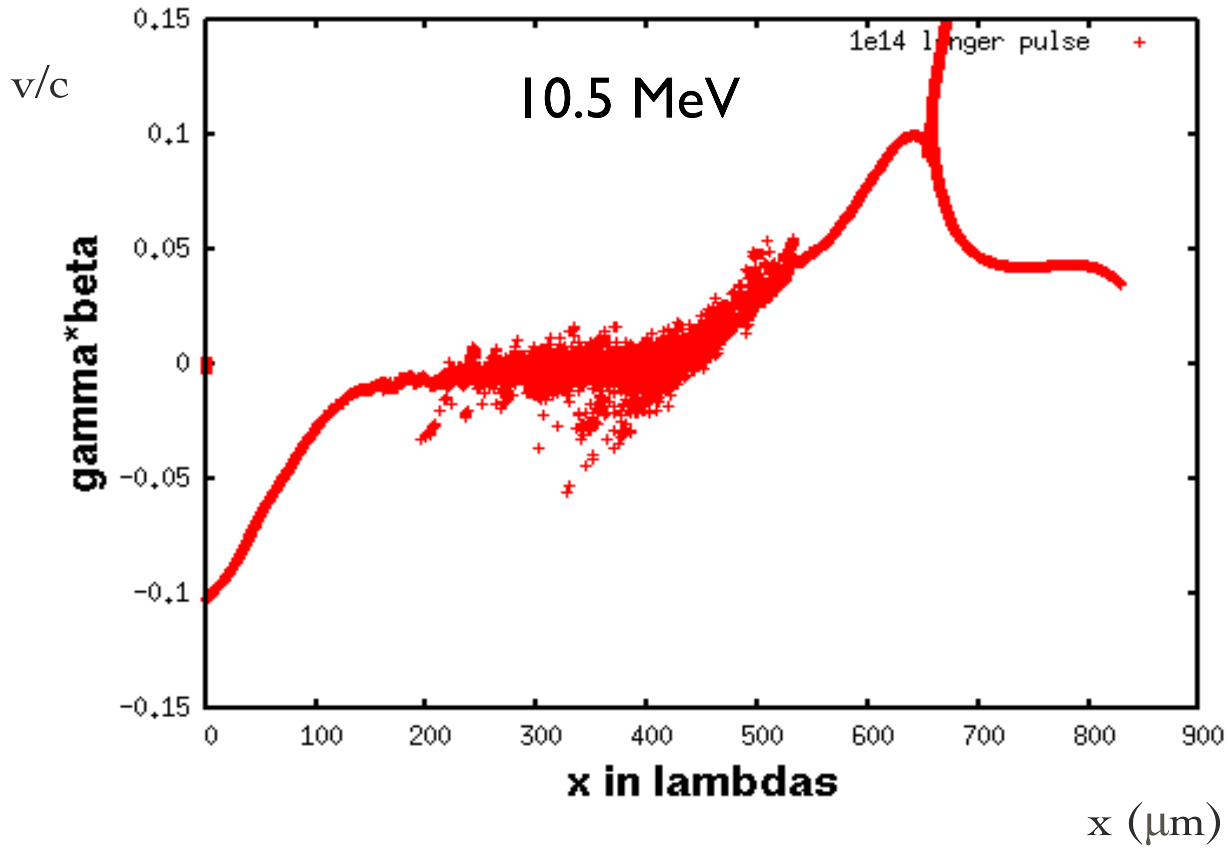
Low energy, 2D PILCS results using CHIC profiles show that we approach the shock acceleration

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.

$E_{laser} \sim J$



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

PICLS

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

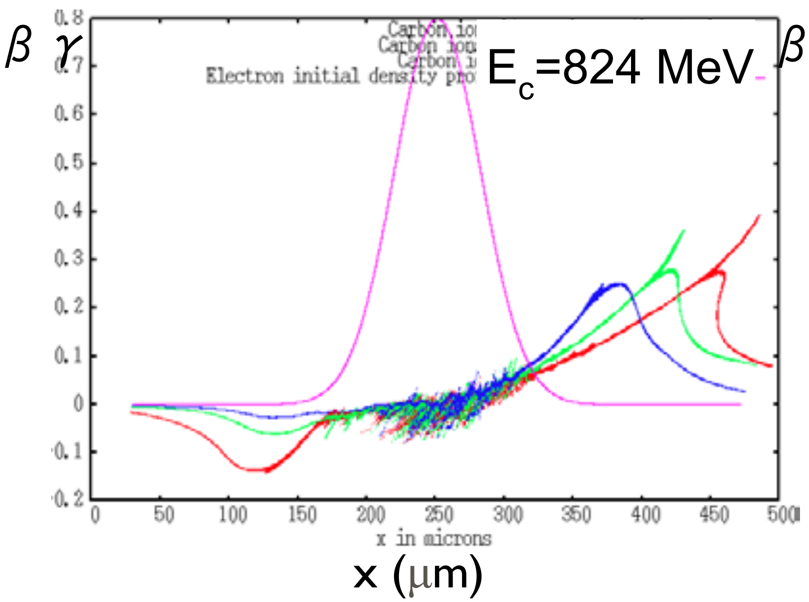
Simulations show that shock acceleration becomes much more interesting in the high laser energy, high-intensity regime -> we repeat experiment on TITAN

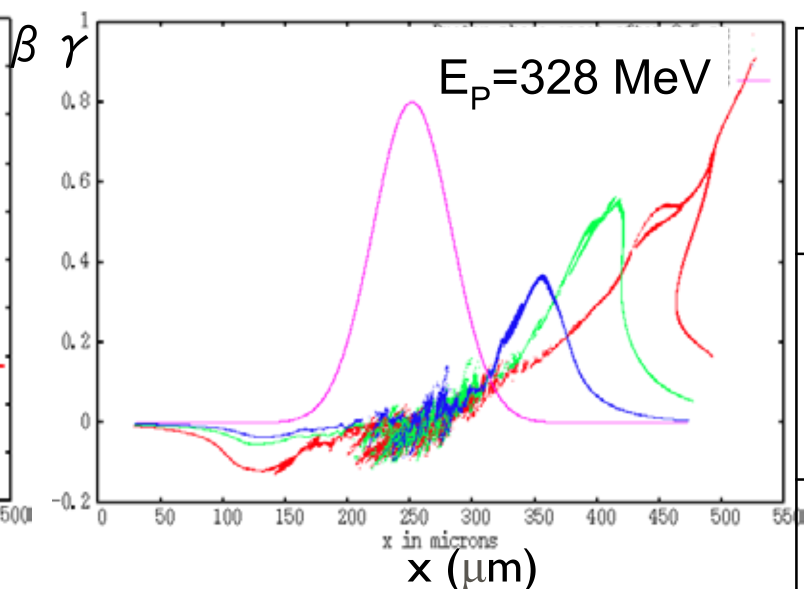
Target FWHM: 80 microns. Laser intensity: 5×10^{20} W/cm^2, pulse duration: 700fs FWHM, focal spot width: 6 microns FWHM.

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.





Exploded foil regime

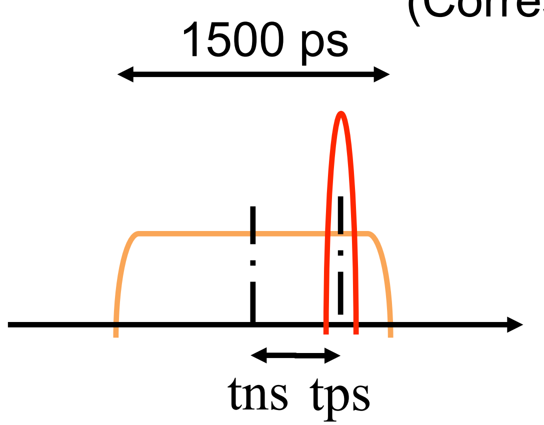
Influence of the target thickness

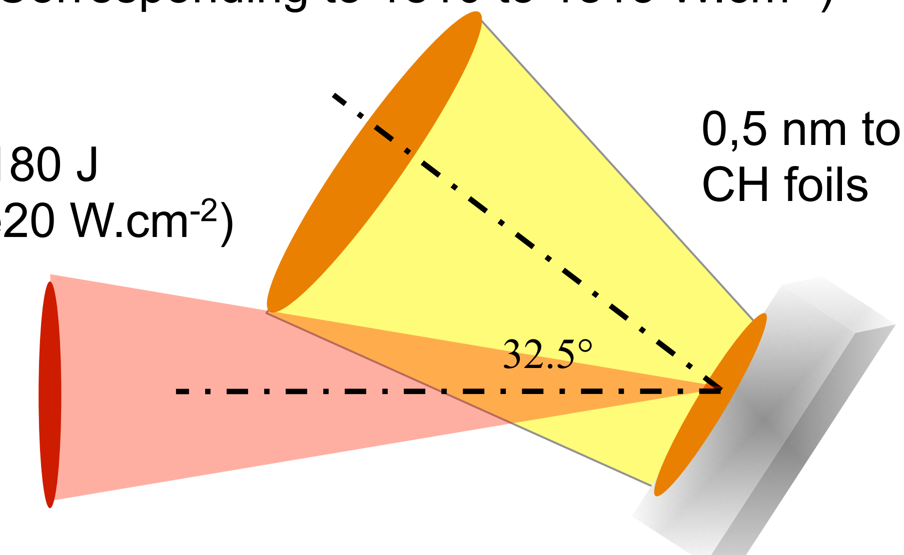
Plasma FWHM	35 microns	50 microns	80 microns
Max H energy	280 MeV	296 MeV	328 MeV
Max C energy	803 MeV	889 MeV	824 MeV

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})





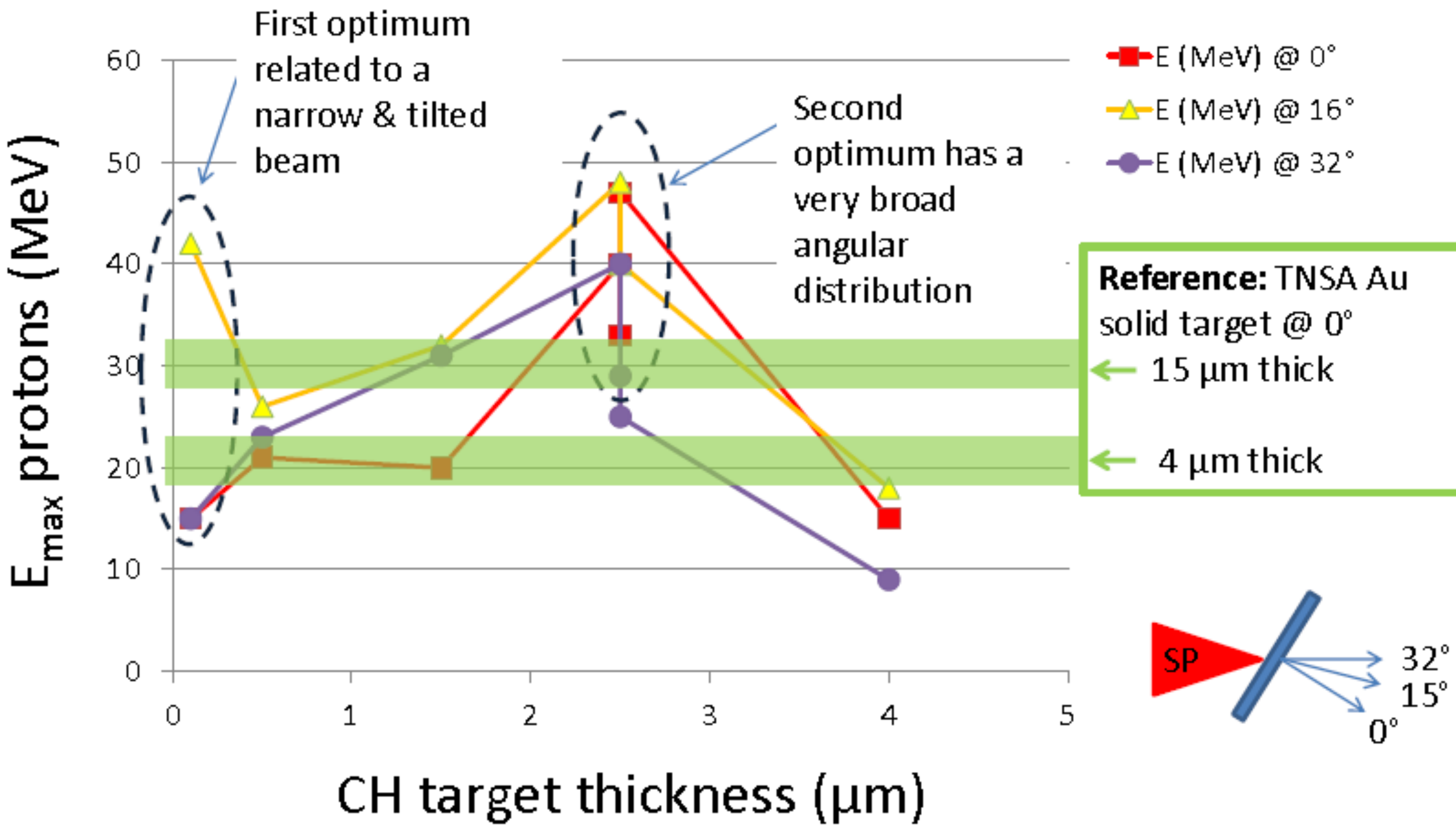
0,5 nm to 4 micron
CH foils

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

$\Delta t = t_{ps} - t_{ns}$

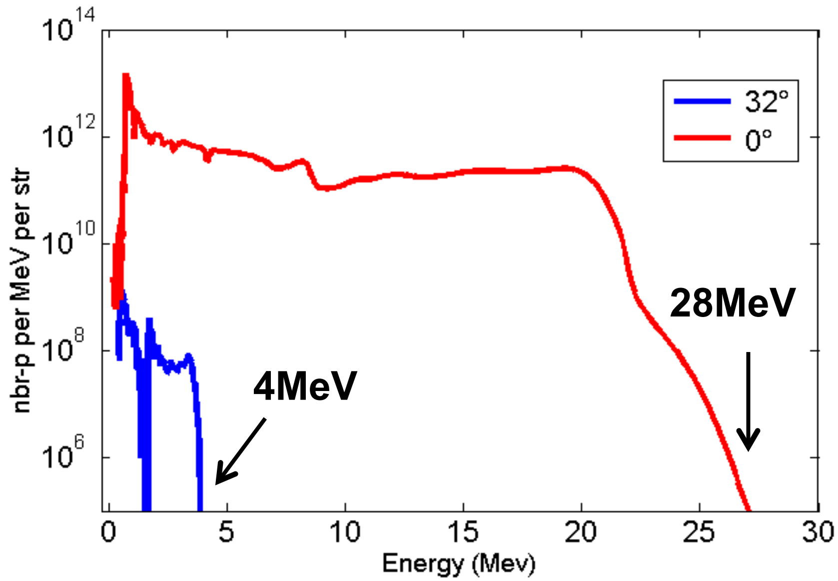
The expansion of the thin foil allows us to explore various types of gradients by changing Δt and t_{ns}.

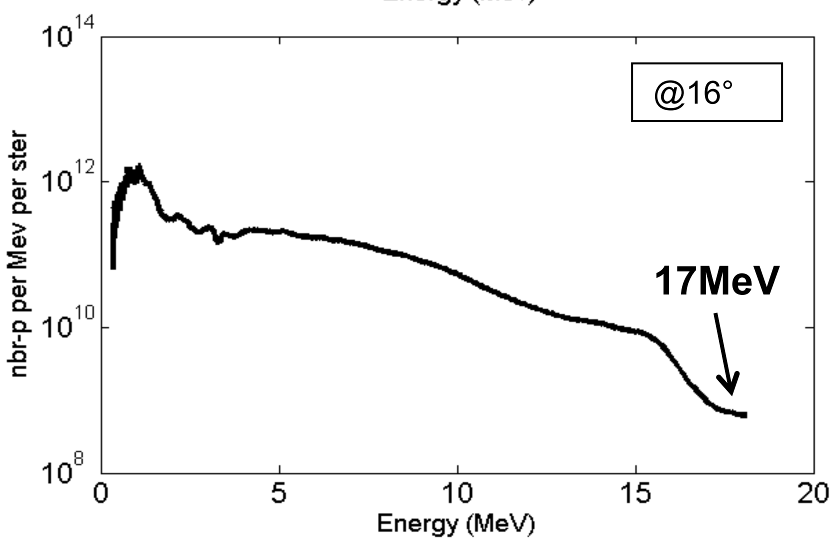
For thin CH targets exploded by the short-pulse ASE, very high proton energies are recorded, well above standard TNSA in the same conditons



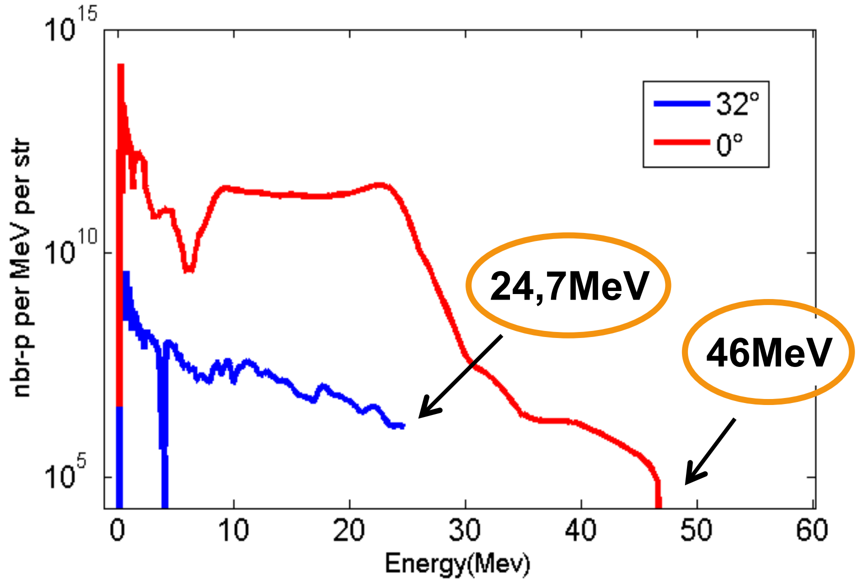
Exploded foils show similar spectral shape than TNSA but with higher maximum proton energy

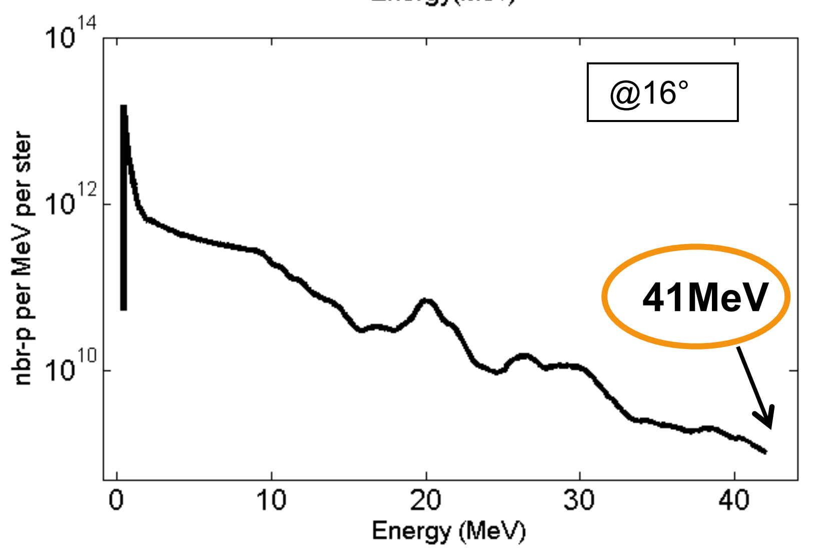
Shot 14: 15um Au foil (ref TNSA)

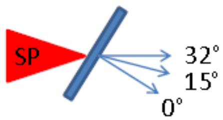




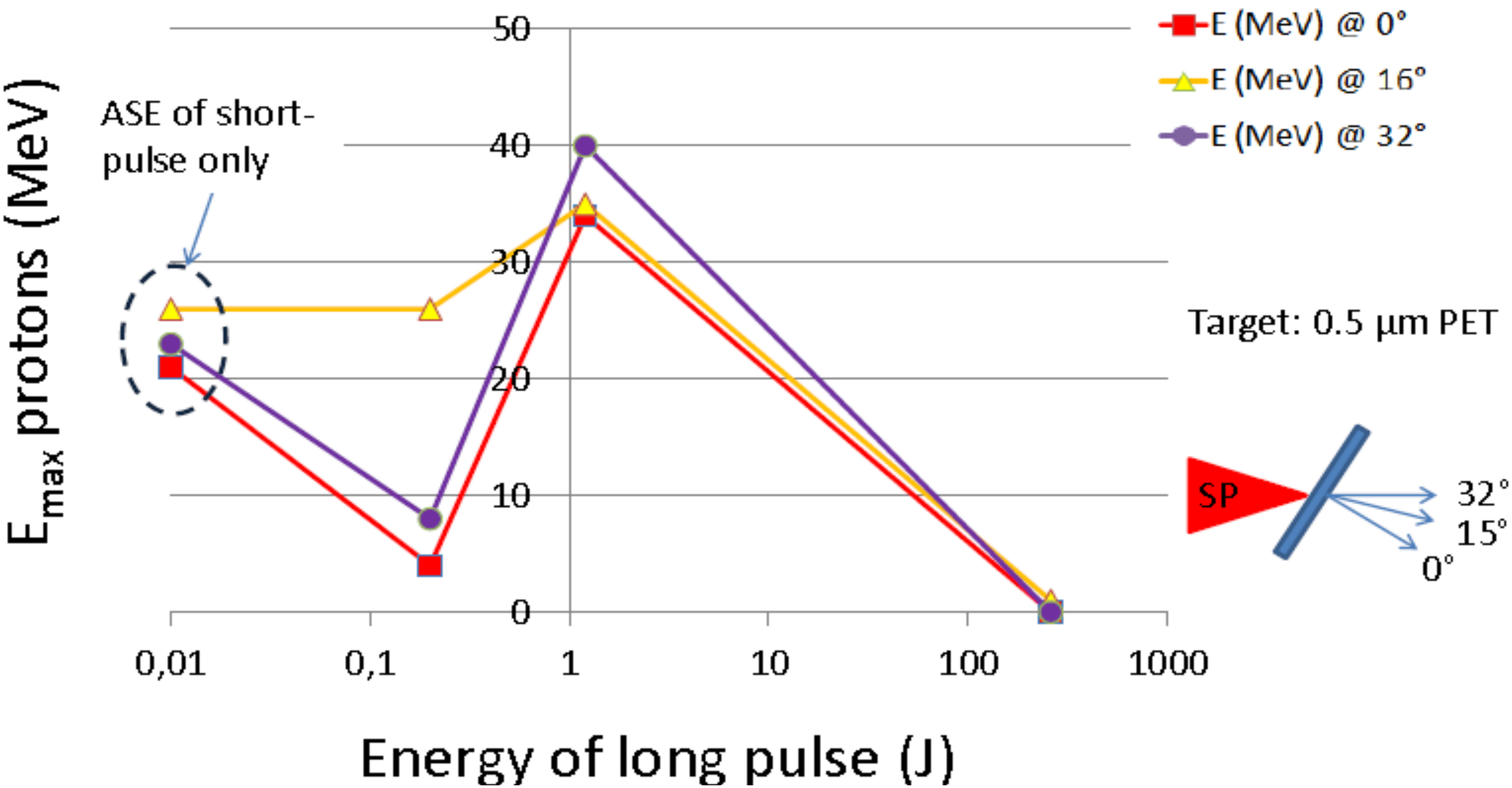
Shot 31: **2,5um PET foil exploded**





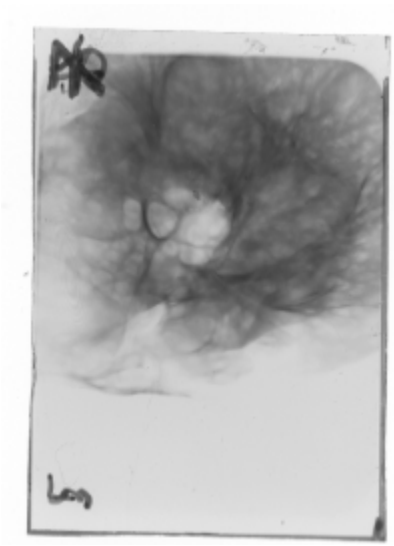


We can tune the proton energy by varying the level of the long-pulse energy prior to the short-pulse

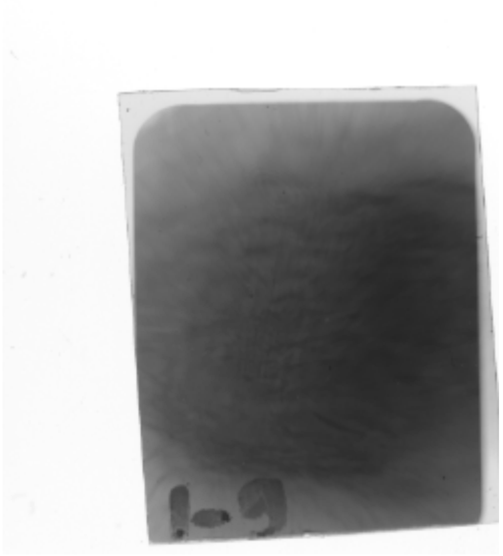


We observe interesting angular features and similar filamentation in RCFs

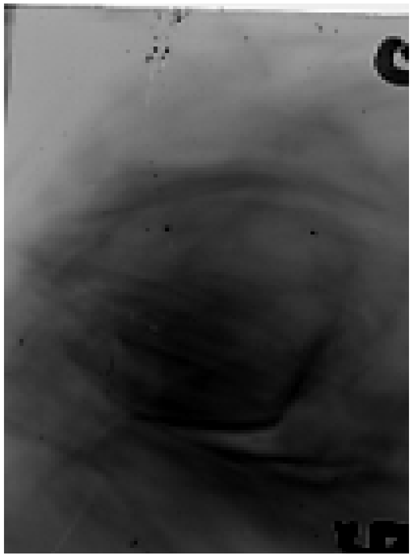
RCF Images



Ref shot
10 micron gold
Emax=28 MeV



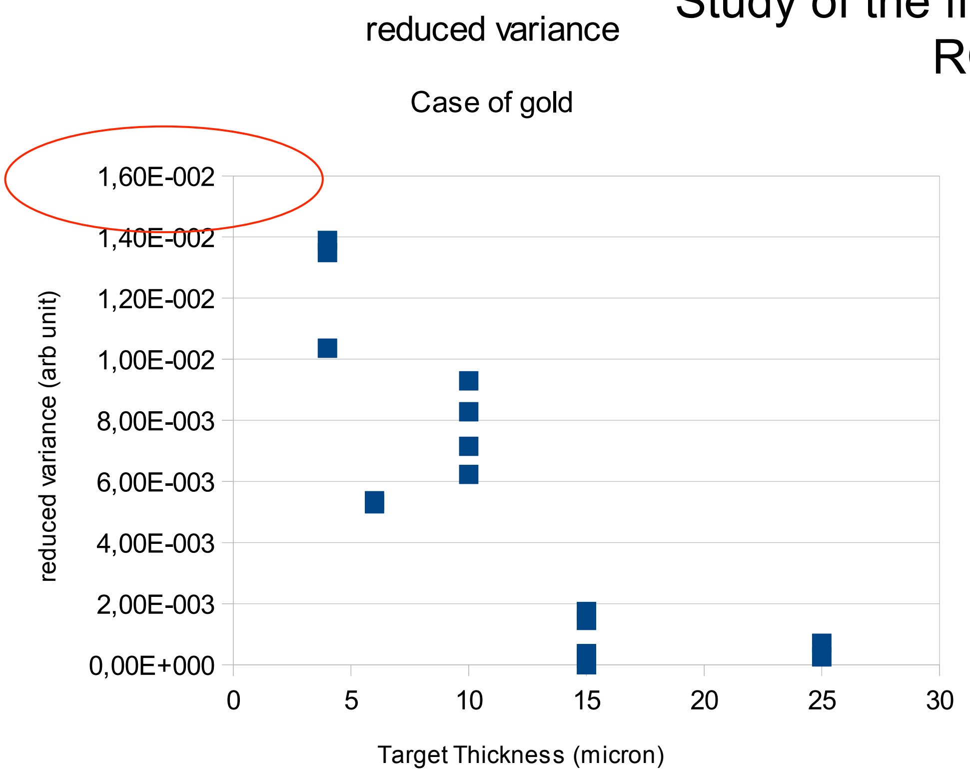
Ref shot
25 micron gold
Emax=20 MeV

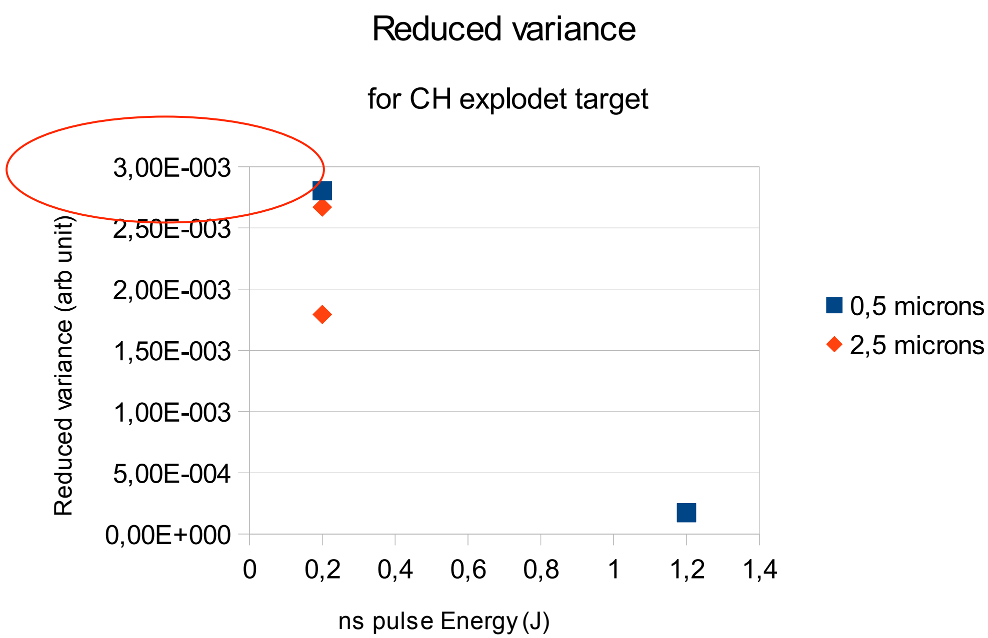


500 nm foil
exploded by 1.2J ns laser
Emax=40 Mev

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





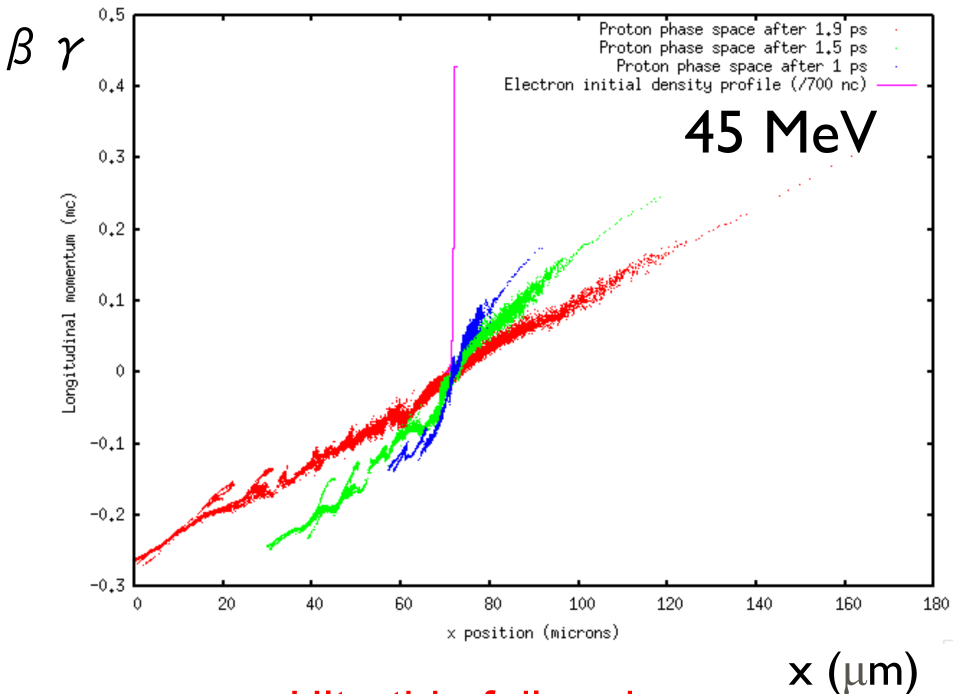
Reference filamentation for gold target of different thickness.

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

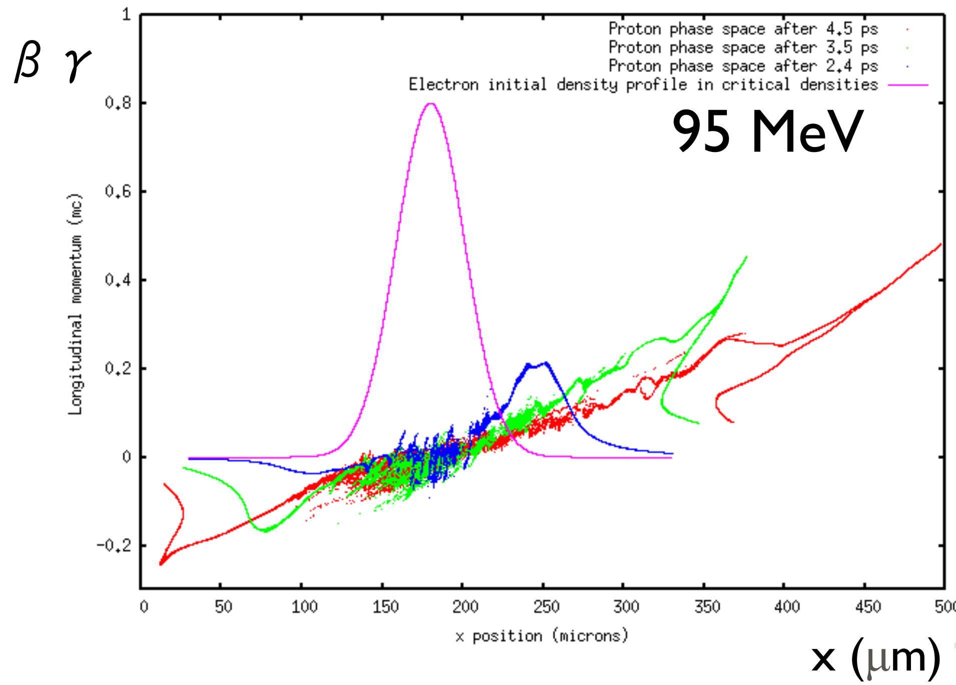
Very low resistivity of the cold electrons = plasma
Beam is little perturbated as in thick gold target, no filamentation

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.

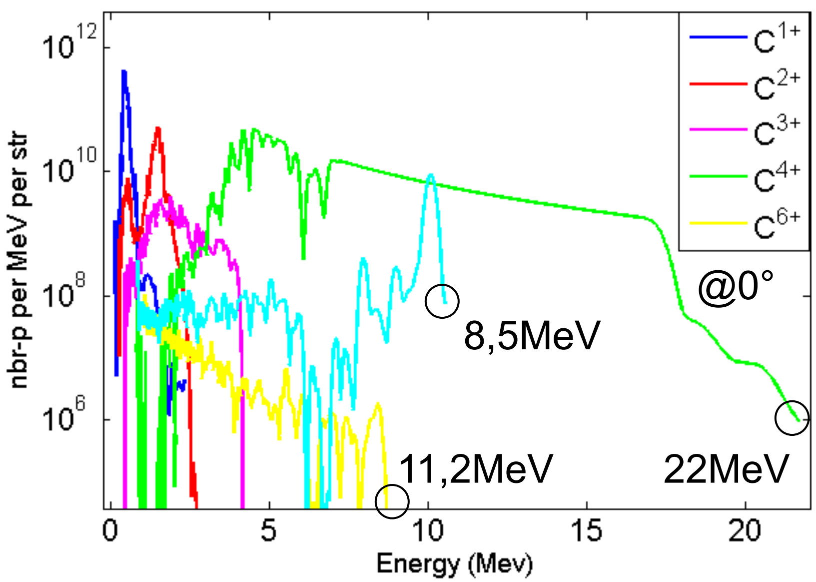


Exploded foil regime
Target FWHM (Gaussian): 35 microns.

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.

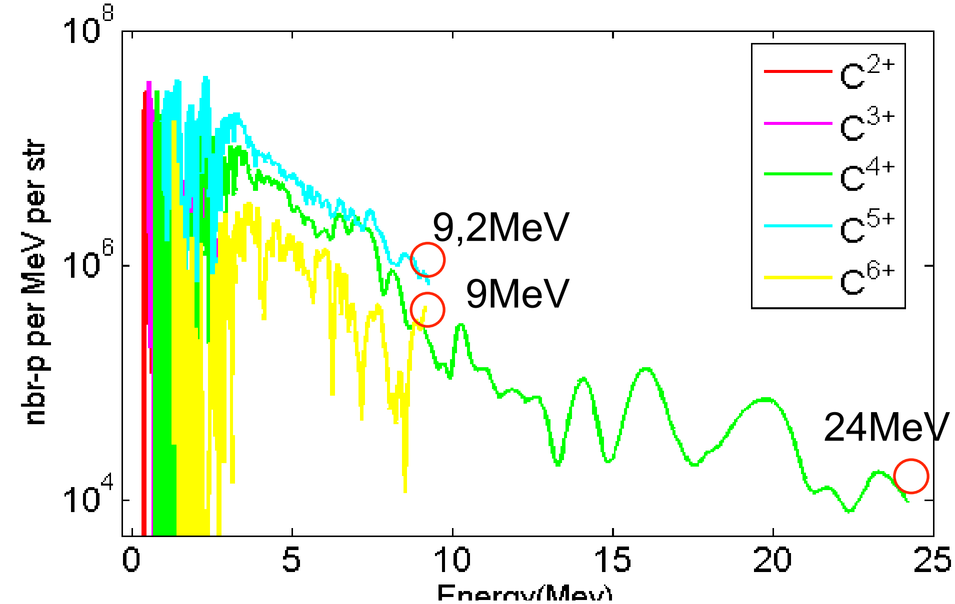
Carbon spectra show comparable energies but in direction of the long pulse beams

Shot3: 15um Au foil (TNSA)

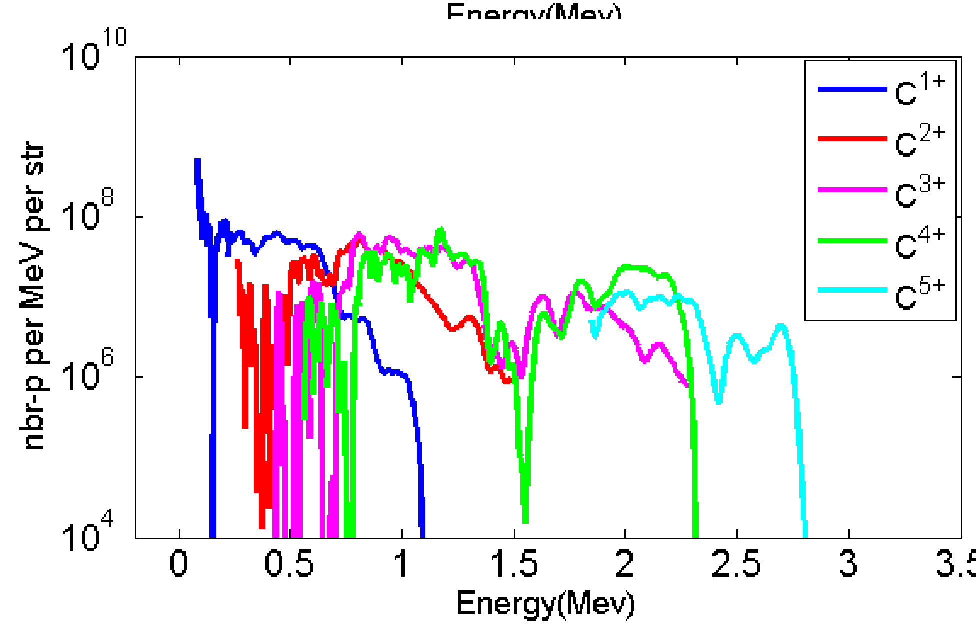


A 32° no carbons detected on TP

@32°

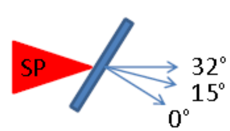


@0°



Shot41: 0,5um PET foil exploded

Best results are found NOT in the target normal



Summary

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

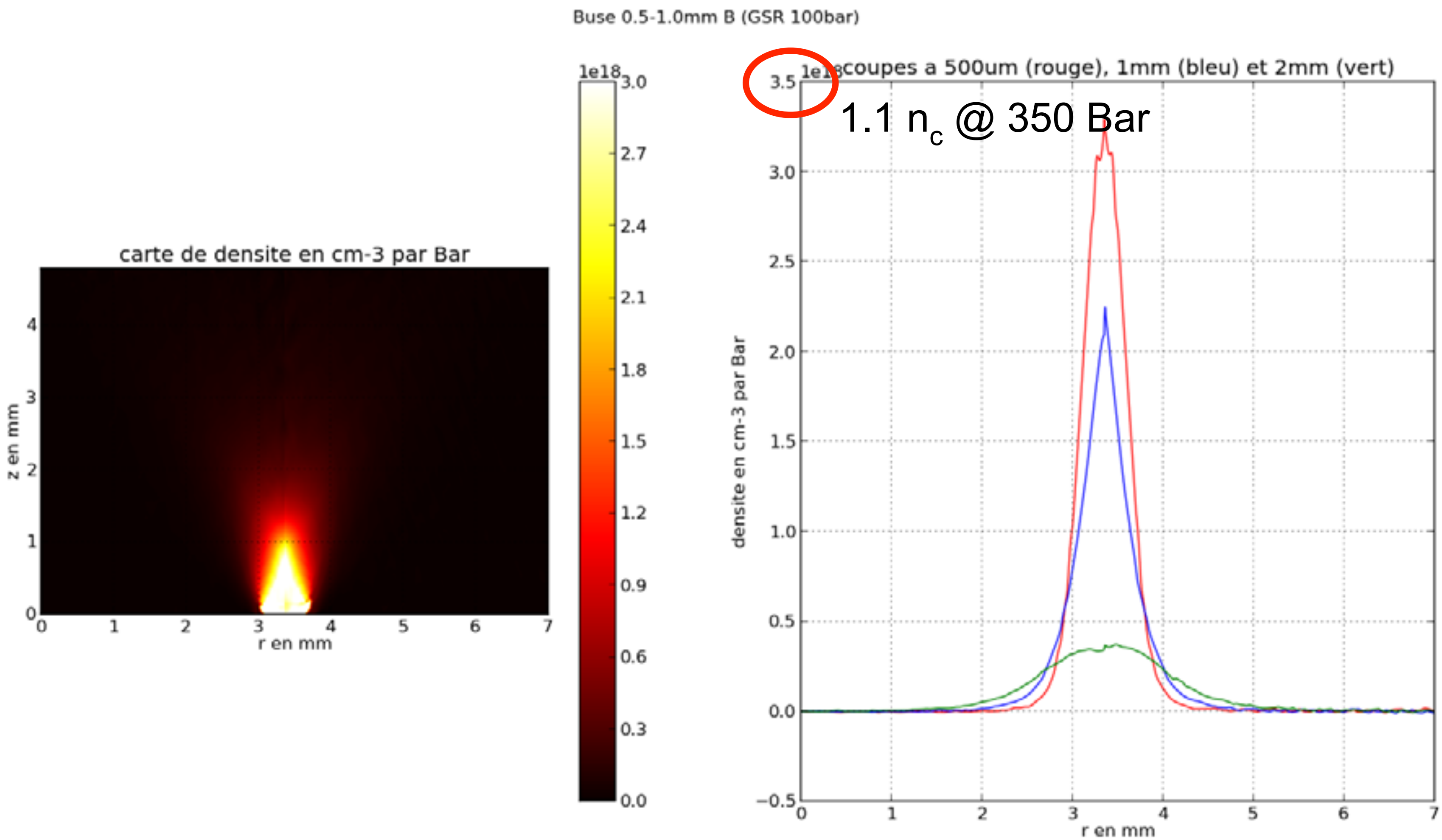
In agreement with simulations, increasing the laser energy and intensity allows to improve significantly the efficiency of shock acceleration

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

Shock-produced beam exhibit no filamentation

Perspective: High repetition rate operation will be achievable

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



Thank you