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Laser driven ion acceleration developments

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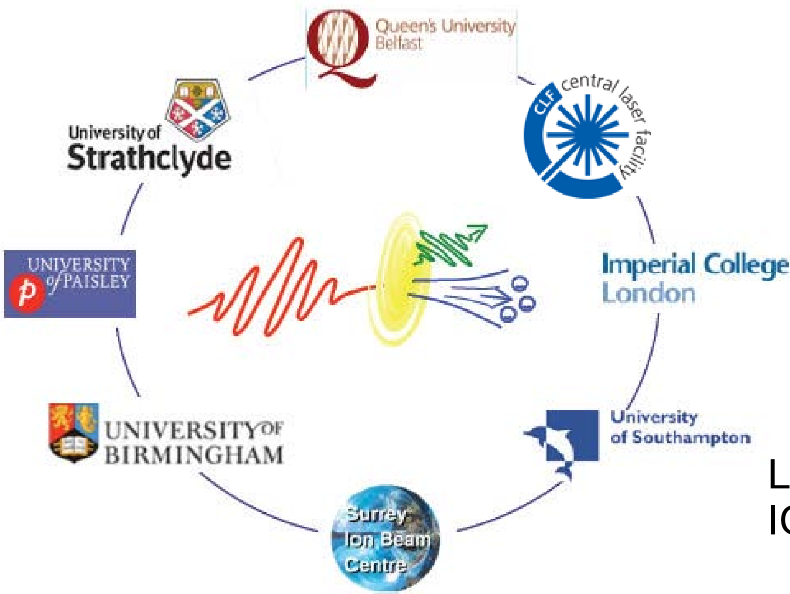
Central Laser Facility

Astra Gemini Ti:Sapphire 40 fs, 12 J
Vulcan Nd:Glass 700 fs, 240 J



LULI, PMRC, GSI,
IOP, BNL, FZD

LIBRA –
Laser
Induced
Beams of
Radiation for
Applications
£5M, 2007 -2012

Laserlab Europe

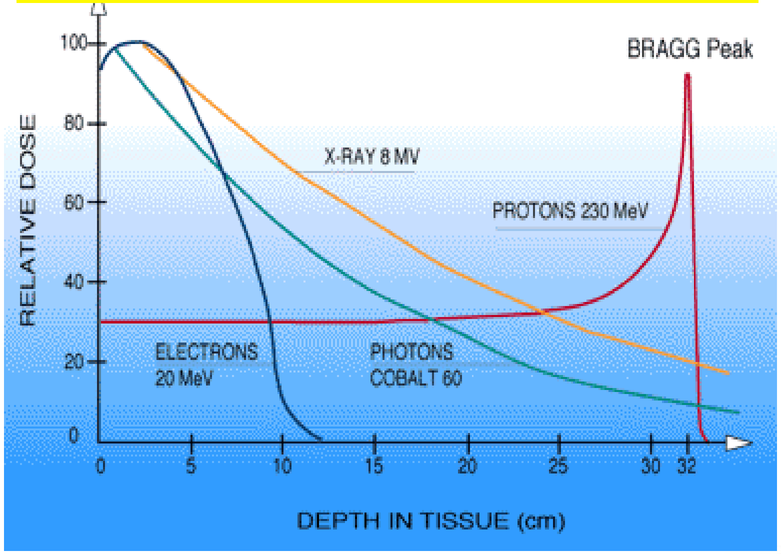
Science & Technology Facilities Council

Ion application requirements

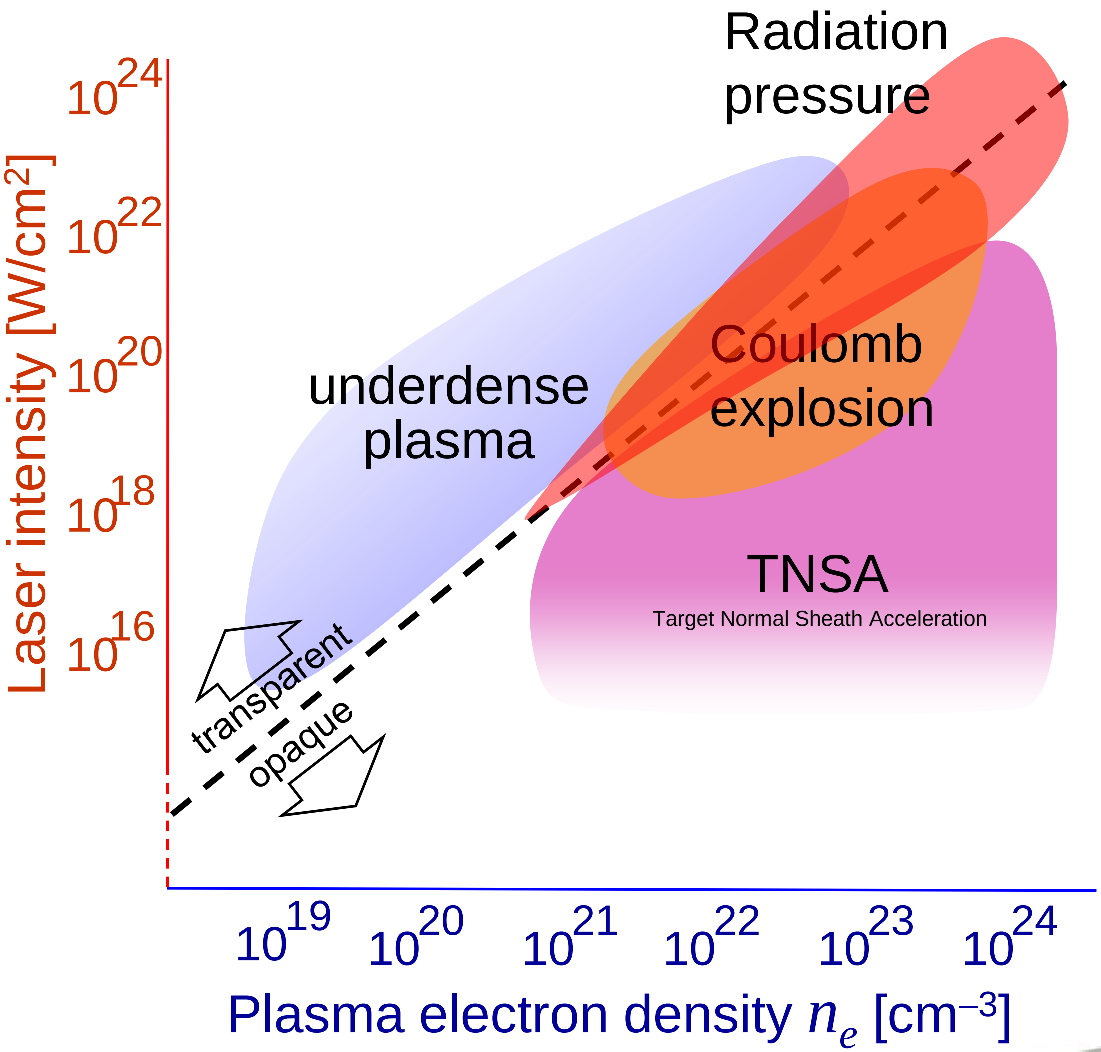
•Radiography (density measurements)
•Deflectometry (field measurements)
•Isochoric heating of matter
•Fusion Energy (Fast Ignition)
•Injection into conventional accelerators
•Cancer therapy
•Production of isotopes for PET
Industrial applications (implantation, lithography)
Nuclear/particle physics applications
.....

Med-energy (5-25 MeV p^+)
Broad band
Med - High efficiency

High-energy (50-250 MeV p^+)
Narrow band ($\Delta E/E$ ~ %)
Divergence control/transport



Ion acceleration regimes

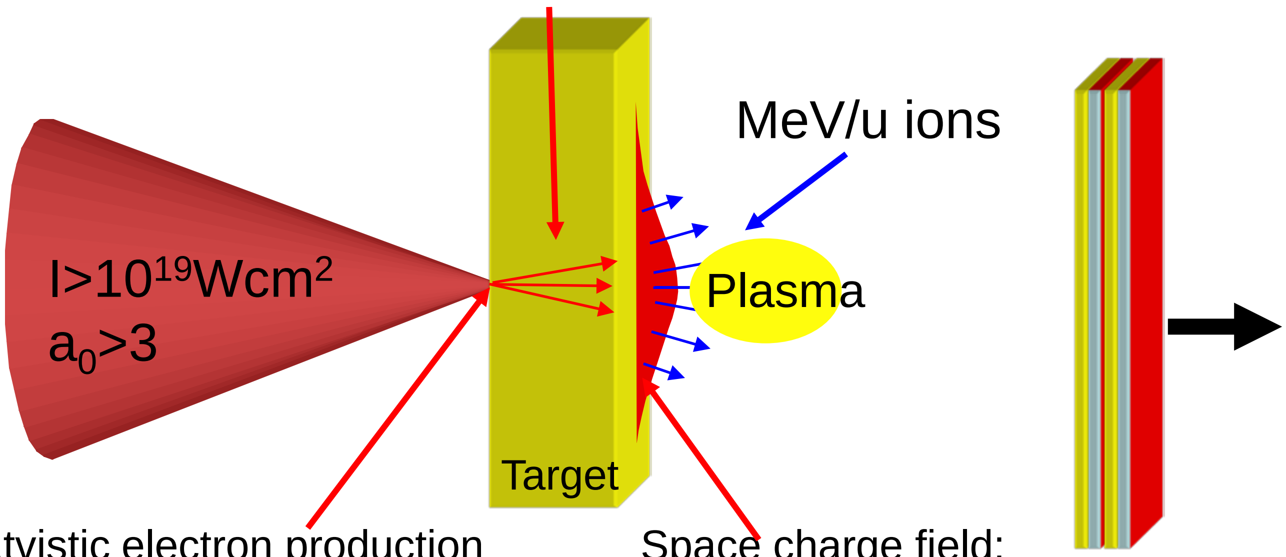


Courtesy of T. Esirkepov (adapted)

LIBRA experiments:

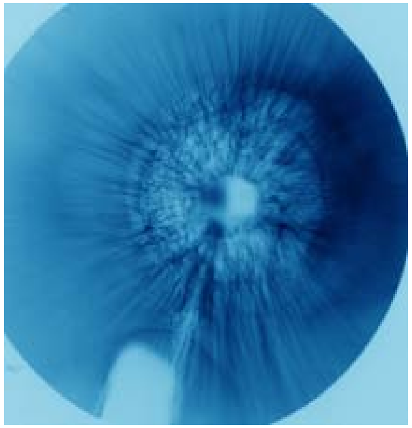
- TNSA ion scaling with laser parameters
- Influence of target properties on TNSA ions
- Enhanced TNSA with limited mass targets
- Enhanced TNSA with controlled density gradients
- Enhanced TNSA with foam layers
- Acceleration from liquid drops and spray
- RPA with ultrathin targets
- Acceleration from gas jets

Target normal sheath acceleration



$E \sim T_{hot}/\lambda_{Debye} \sim MeV/\mu m = 10^{12} V/m$

M Borghesi et al.,

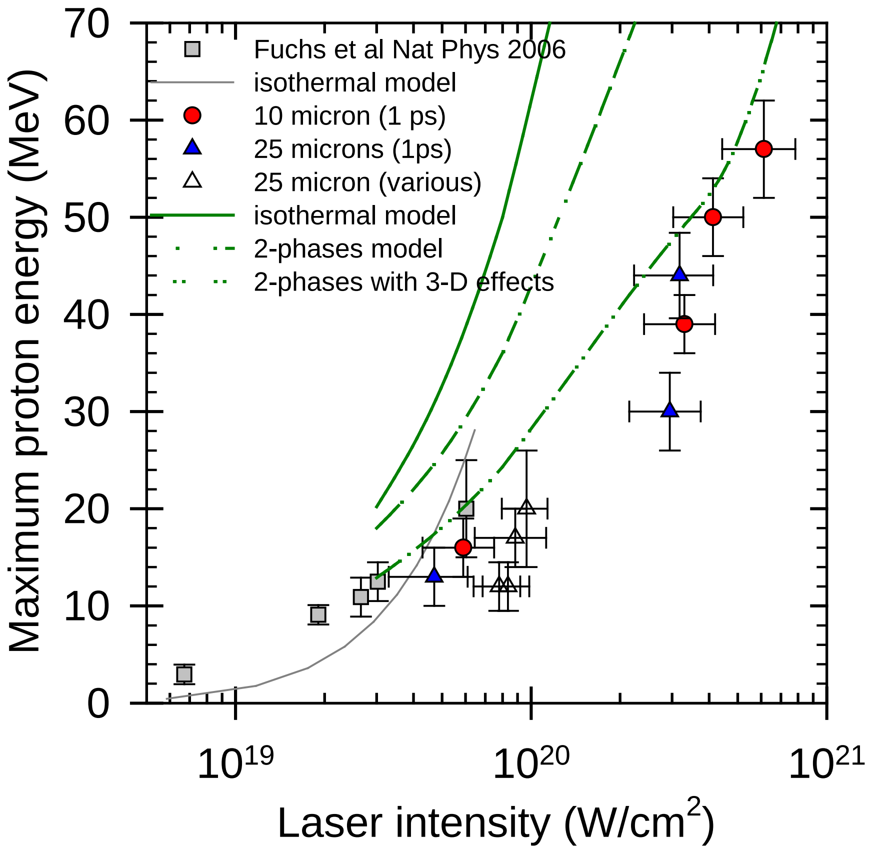


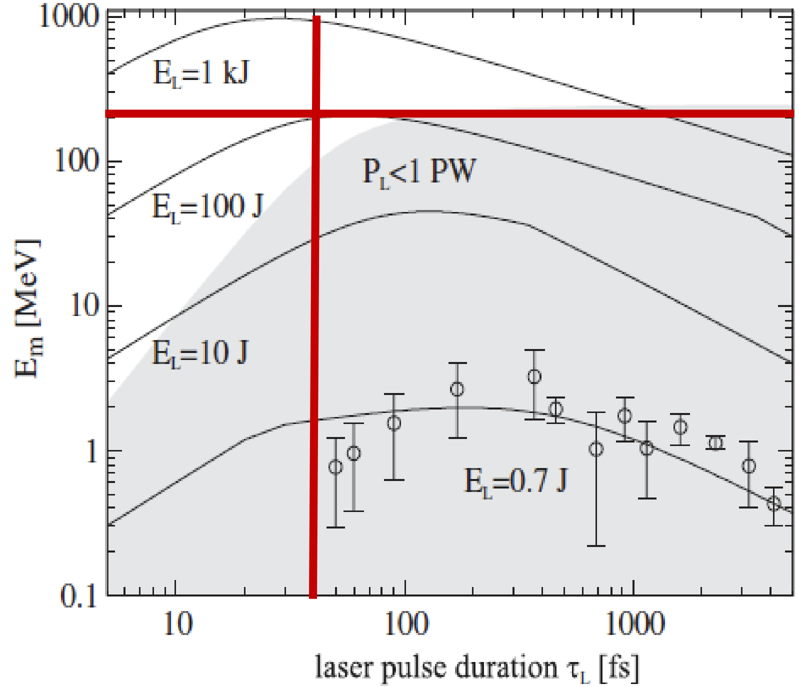
Excellent probe fo
fields in plasmas

<u>Properties:</u>

- Maximum energy: protons ~65 MeV; ions ~10 MeV/u;
- High brightness: $>10^{12}$ protons in ps pulse
- Source size ~100 μm; (virtual source ~10 μm);
- Emittance ε_N ~0.005π mm.mrad
- Energy conversion efficiency up to 10%

TNSA ion max energy scales with ~$I^{1/2}$





Schreiber et al., PRL (2006)

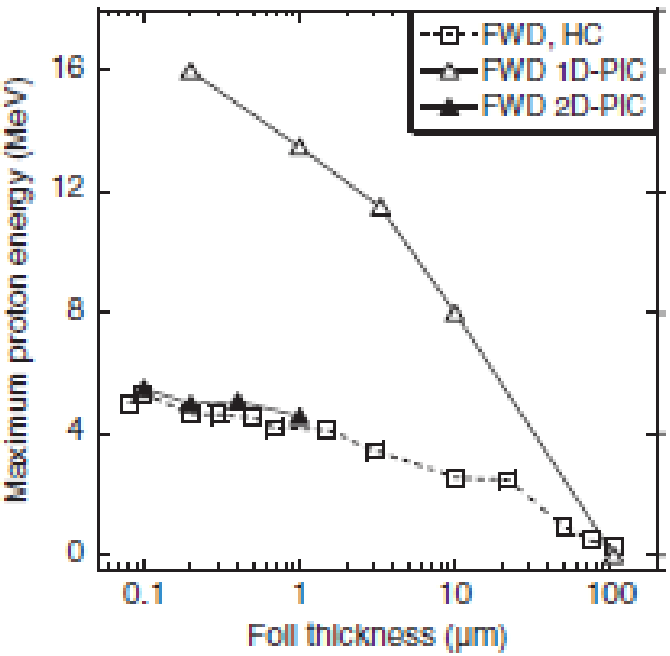
- Mora PRL 90, 185002 (2003): isothermal expansion
- Fuchs et al Nat. Phys. 2, 48 (2006):
- Scaling study up to ~5×10^{19} W/cm^2;

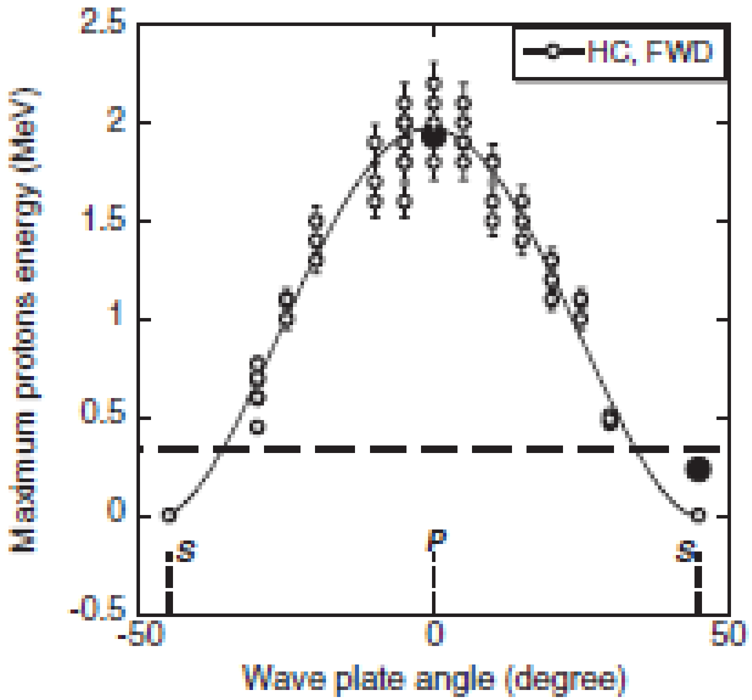
Model revised to include dual temperature phase; Mora, PRE 72, 056401 (2005)

Robson et al, Nat. Phys. 3, 58 (2007)

500fs scaling: 200 MeV protons requires >4 10^{21}Wcm^{-2} (>1kJ)
Schreiber Scaling: 200 MeV @ 100J 40fs

TNSA polarisation dependence at 10^{18} Wcm^{-2}

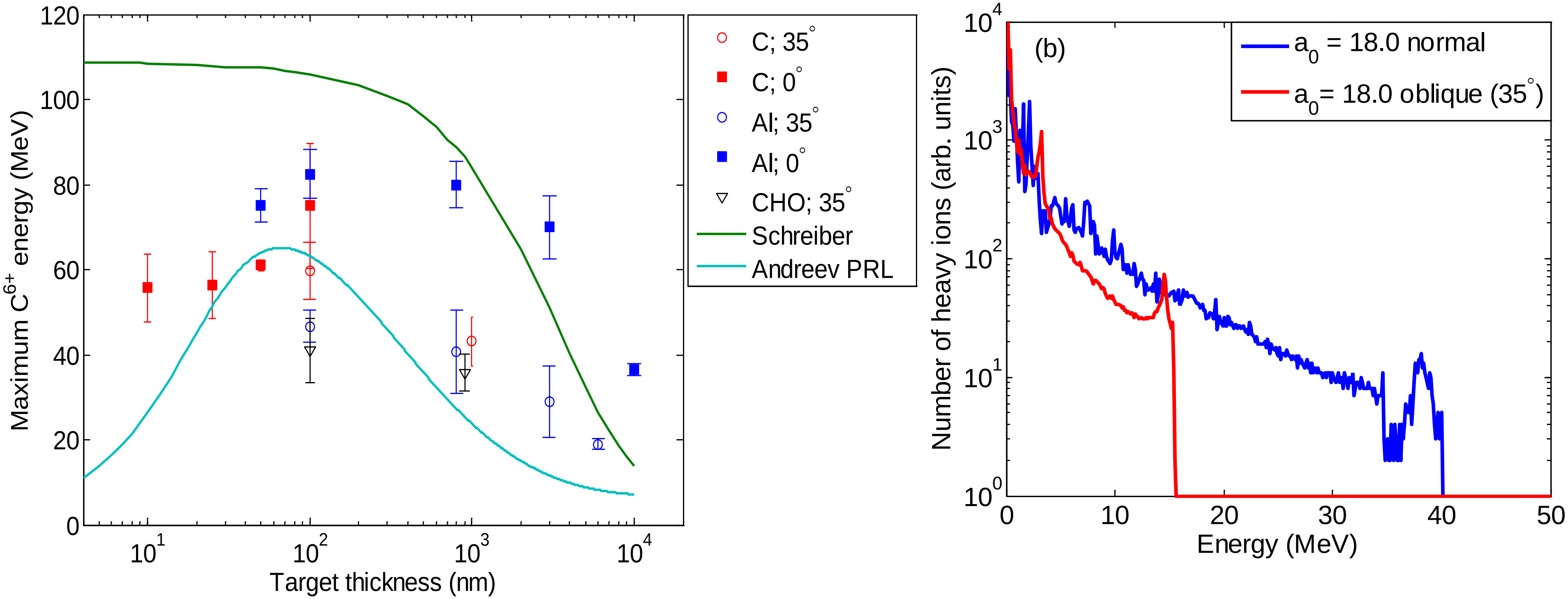




At 10^{18} Wcm^{-2} the hot electron and proton energies are more related to the P component of the electric field than the ponderomotive potential.

Figures from Cottei et al,
Phys. Rev. Lett. 99, 18, 18502 (2007)

TNSA ion energy scaling at 10^{20} Wcm^{-2}

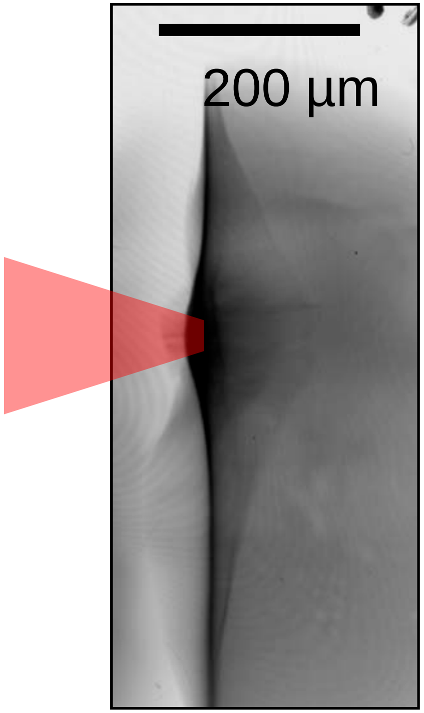


DC Carroll et al.
New Journal of Phys 2010,

- Maximum ion energy increases with decreasing target thickness (saturation achieved for TNSA from ultrathin targets)

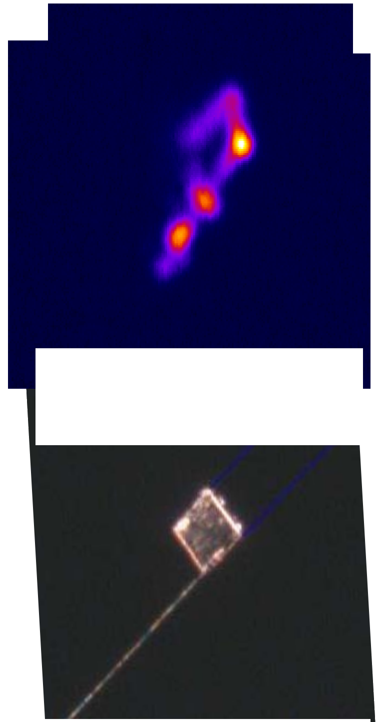
- Higher maximum ion energy and flux with 0° compared to 35° incidence – new energy absorption mechanism?

Enhancing TNSA - Limited mass targets

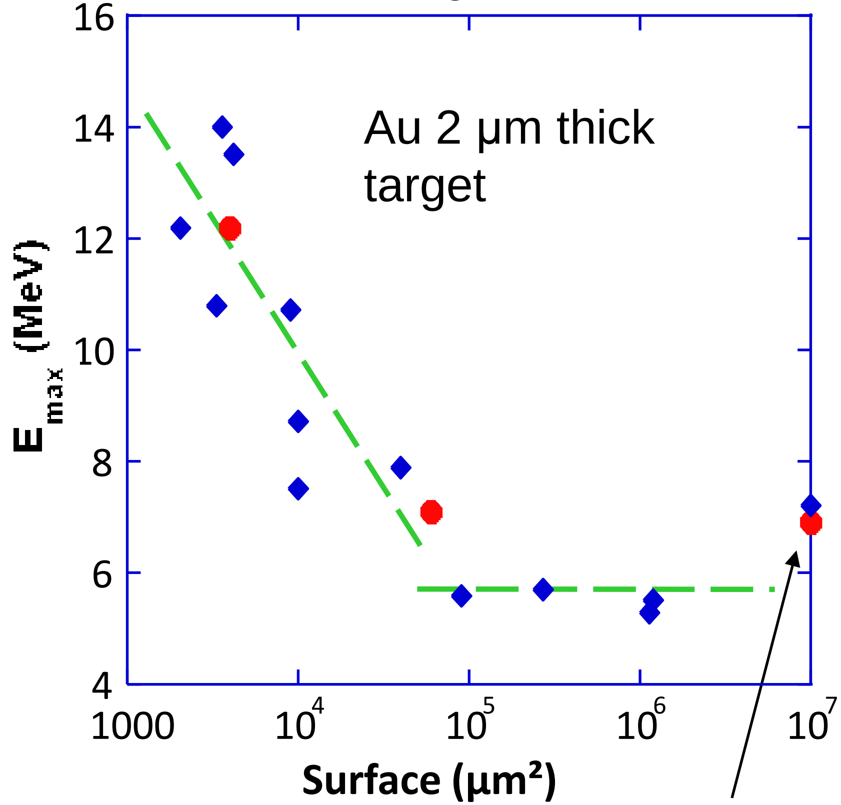


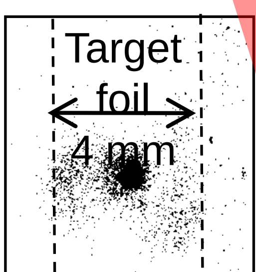
L.Romagnani *et al*, PRL, *95,195001* (2005)

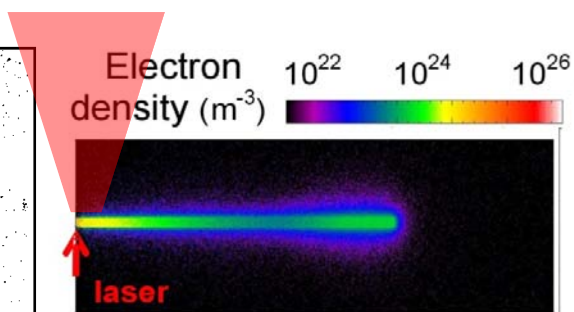
X-ray pinhole imaging



J Fuchs, M Borghesi T Cowan et al.,







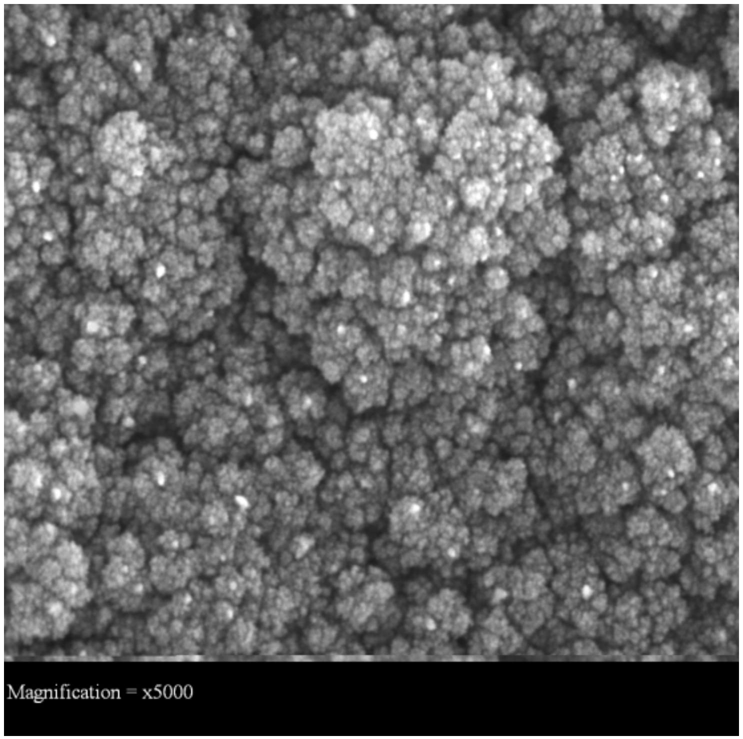
McKenna et al, Phys Rev Lett (2007)

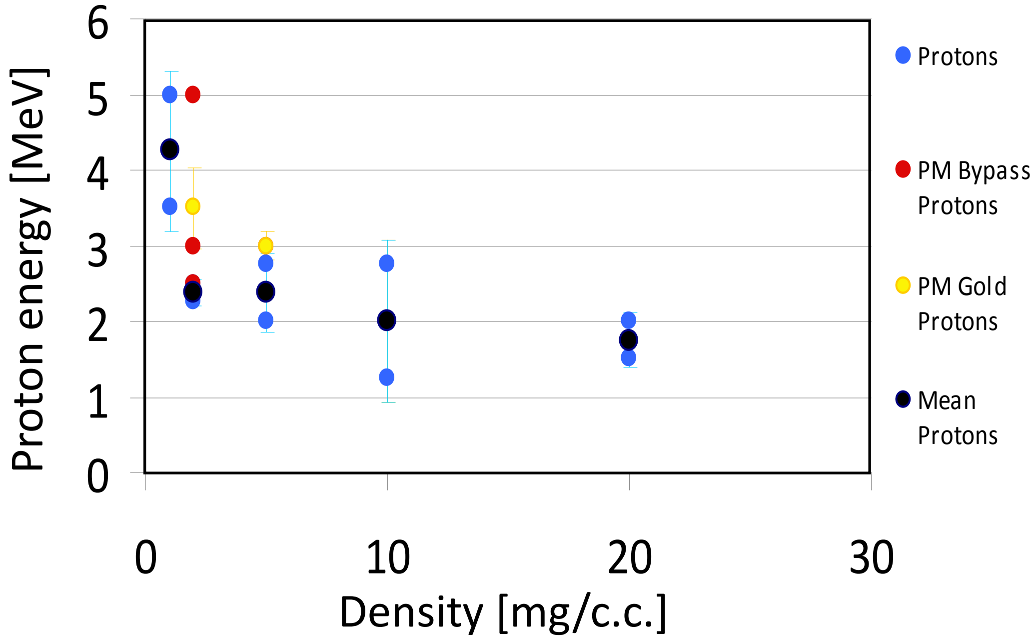
Increase in both the maximum ion energy <u>and</u> conversion efficiency

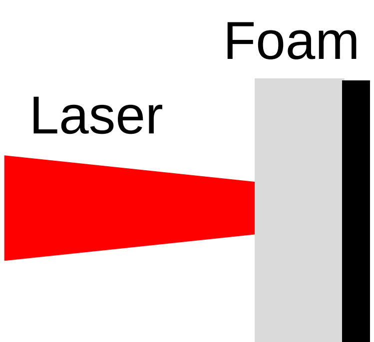
Enhancing TNSA – Targets with foam layers

P Gallegos et al.

Optimize energy conversion into electrons using foam layers (increases the surface area)



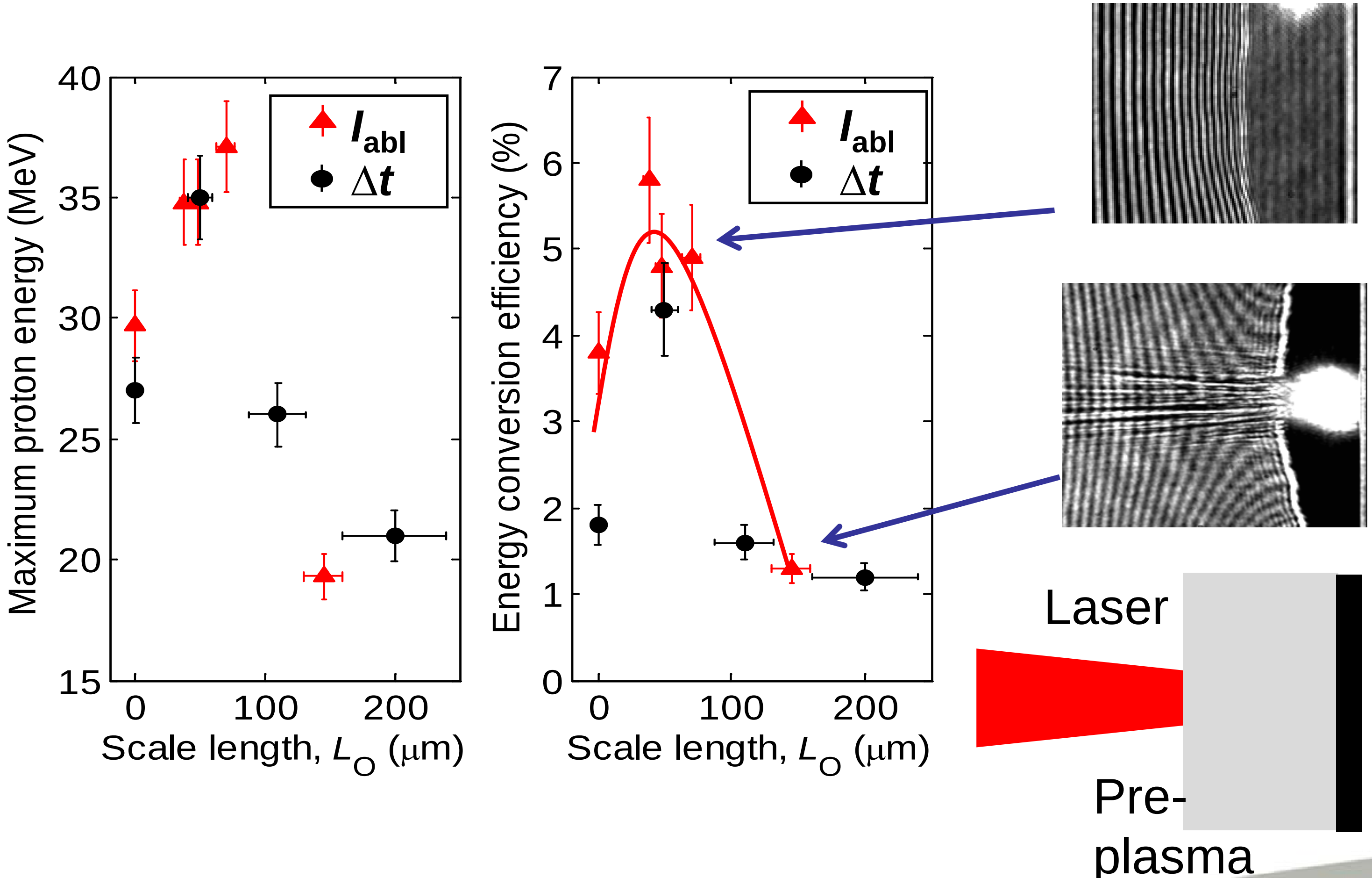




The maximum proton energy is sensitive to the density of the foam layer

Enhancing TNSA controlled pre-plasma

→ Proton measurements show that controlled pre-plasma expansion leads to enhanced energy coupling to fast electrons



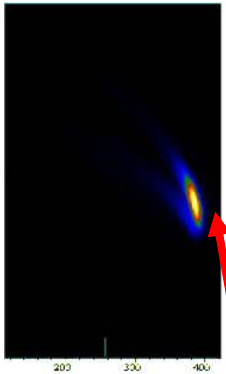
P. McKenna et al, LPB **26** 591-596 (2008)

D.C. Carroll et al, CRP **10** 188-196 (2009)

V Malka this conference

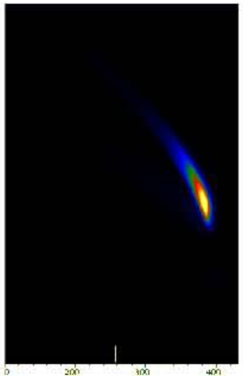
Target Normal Sheath Acceleration- tuning

Axial Spectra

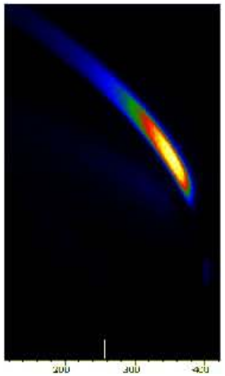


Best

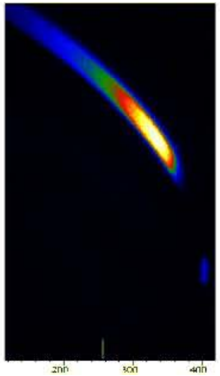
focus



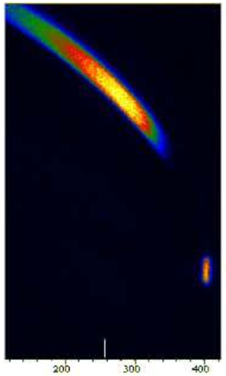
-100um



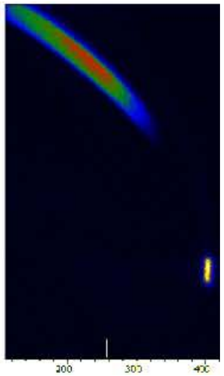
-200um



-300um



-400um



-500um

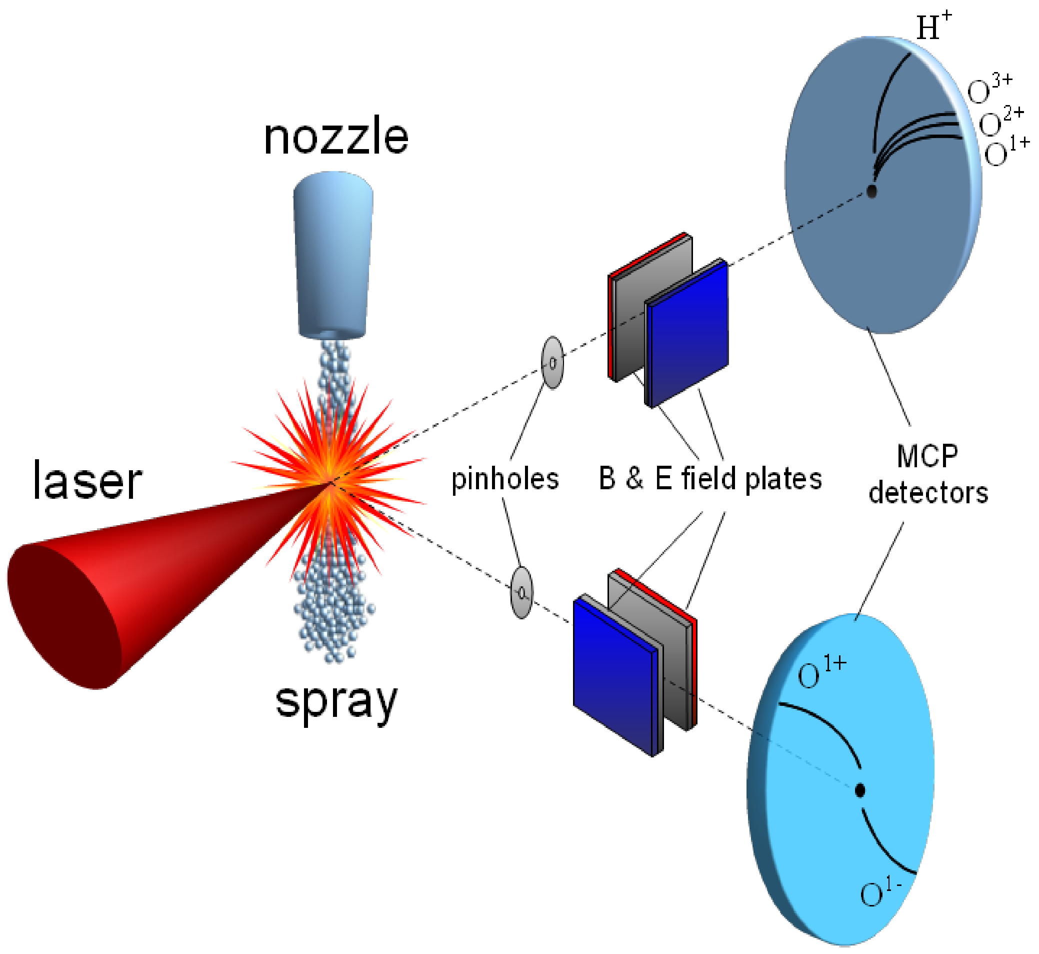
Beam energy tuneable shot to shot

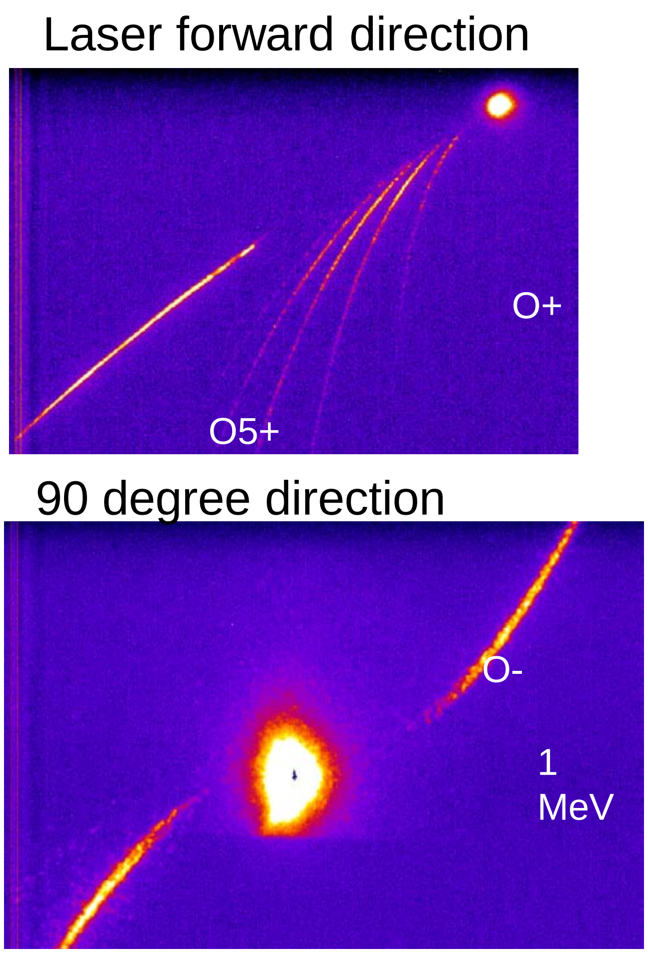
Al 50nm, 35fs 10^{19} Wcm^{-2}@ 10^{10} contrast

-ve moves target towards parabola

Ion acceleration from droplet and spray targets

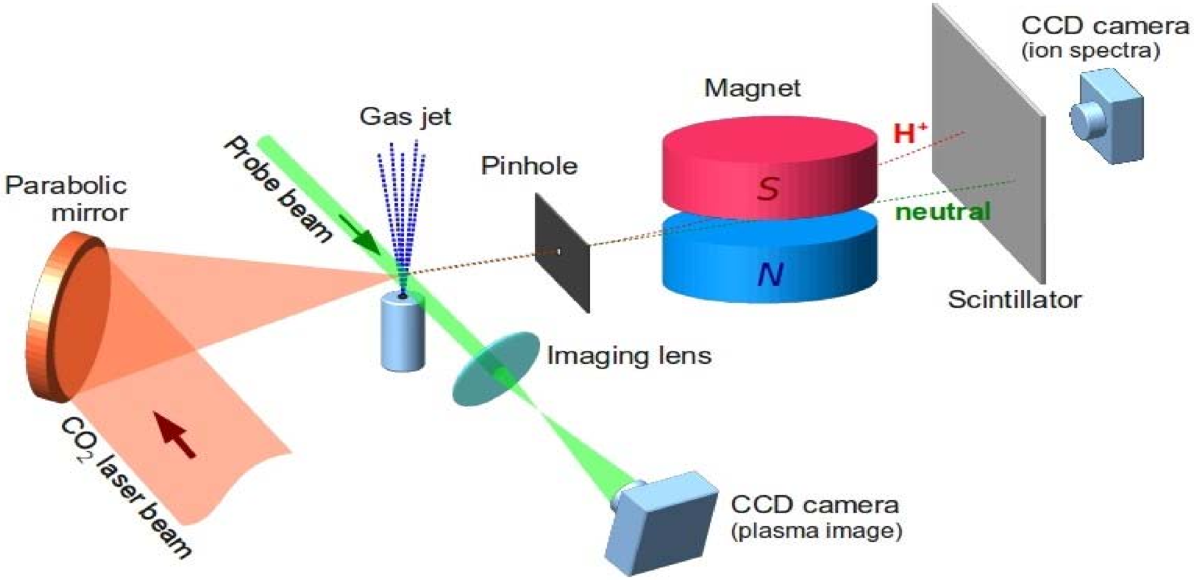
S Ter-Avetisyan et al.,



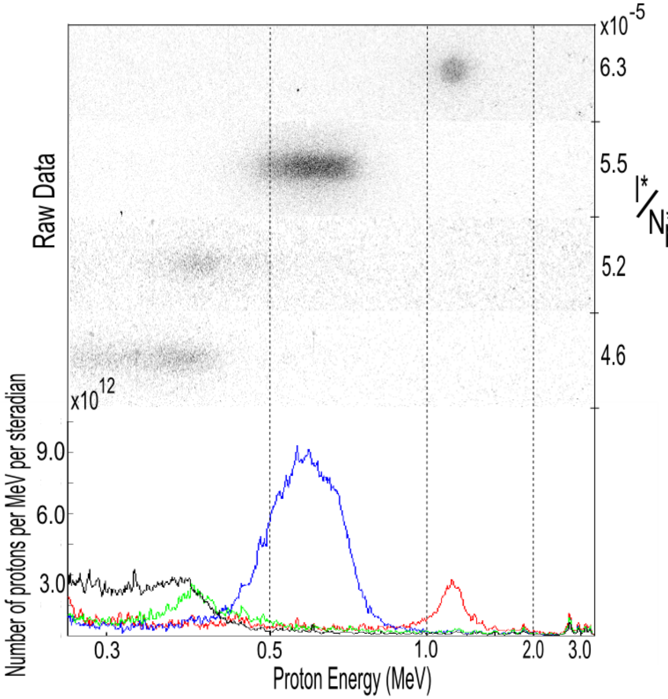


First observation of MeV negative ions

Ion acceleration from gas jet targets



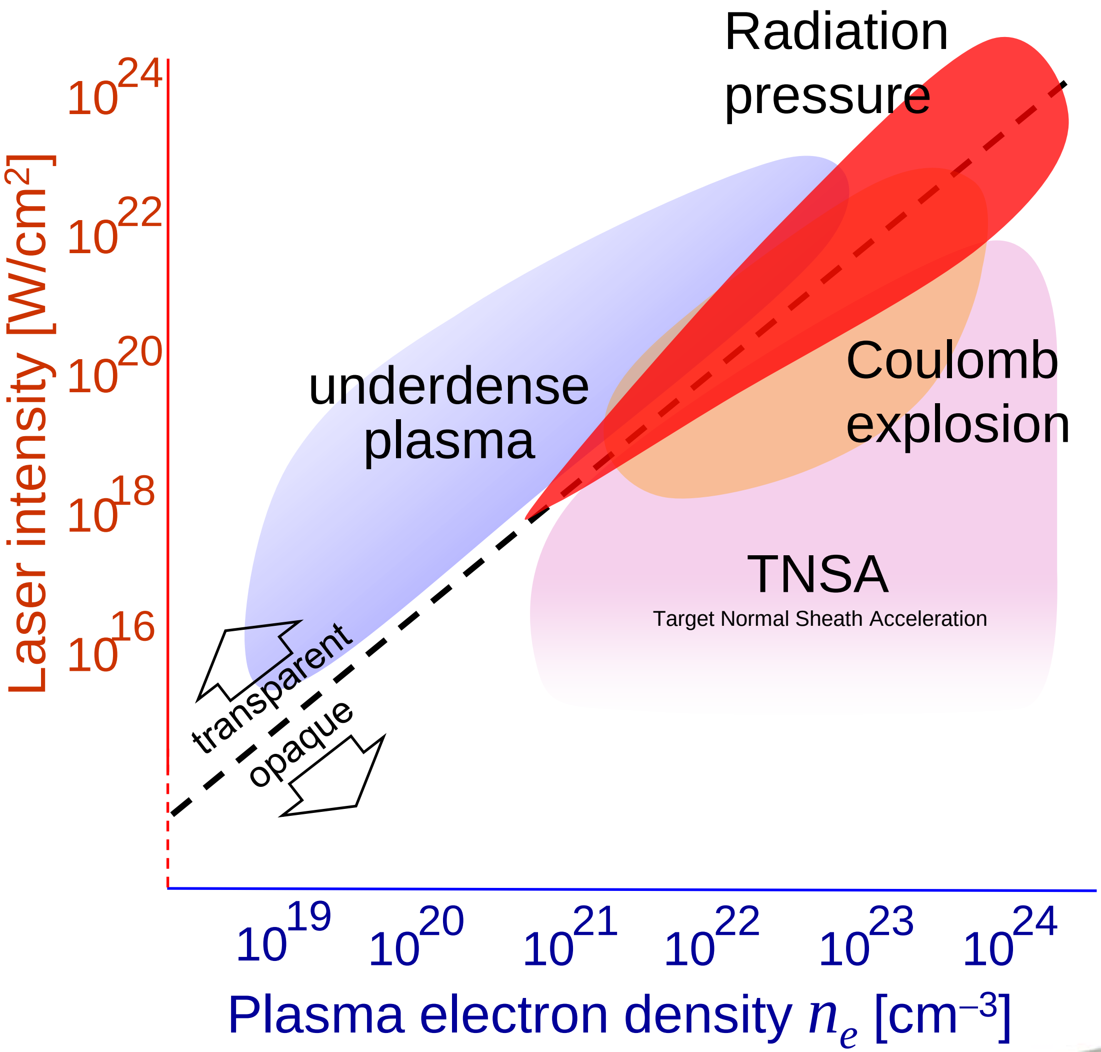
P. Shkolnikov, I Pogorelsky, Z Najmudin, UCLA
this conference



- **ATF Laser:**
  - $CO2$ λ=10.6μm
  - Contrast ratio 10^{-3}
  - Pulse energy ~ 3J
  - Pulse length ~ 6ps
  - I ~ 5×10^{15}W/cm^2
- **Target:**
  - Hydrogen Gas Jet, 1mm nozzle.

Science & Technology Facilities Council

Ion acceleration regimes



- TNSA ion scaling with laser parameters
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- Enhanced TNSA with limited mass targets
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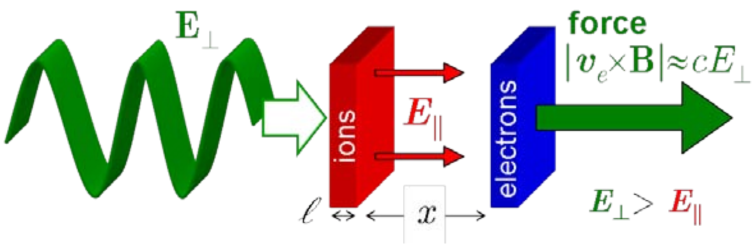
- Enhanced TNSA with foam layers
- Acceleration from liquid drops and spray
- RPA with ultrathin targets

Courtesy of T. Esirkepov (adapted)

Radiation pressure acceleration of ions

Stage 1

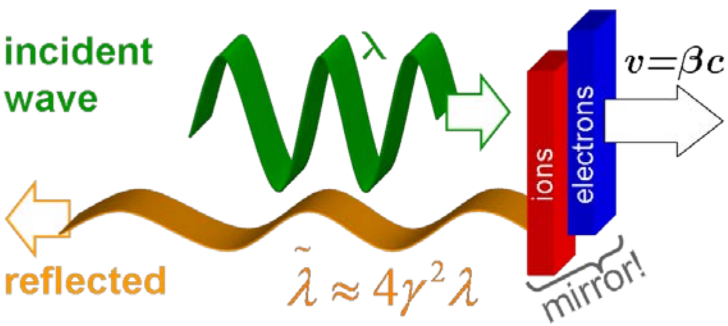


Laser field sweep away all electrons, forming an electrostatic field

To produce 1 GeV protons in $\tau = 1$ laser period we need $I \sim 1.2\times10^{23}$ W/cm^2.

Ions pulled by the charge separation field move together with electrons.

Stage 2



Plasma forms a mirror accelerated by the laser field radiation pressure.

The difference between the incident and reflected wave energy is taken by the mirror:

$$\Delta E \approx E_L - \tilde{E}_L \approx \left(1 - 1/4\gamma^2\right) E_L$$

Because $m_e << m_i$ almost all energy transfers to ions:

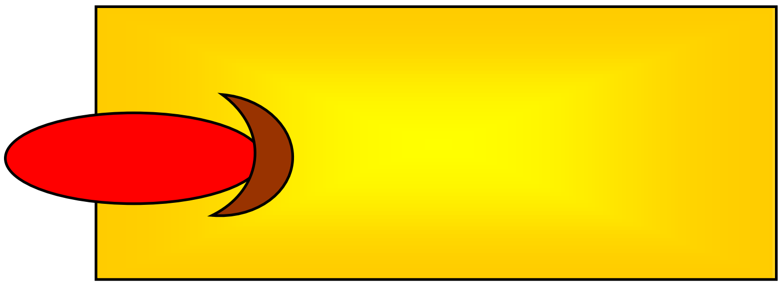
$$\Delta E_{ion} \approx \left(1 - 1/4\gamma^2\right) E_L.$$

T. Esirkepov *et al.,* PRL 92, 175003 (2004)
B. Qiao *et al*, PRL, 102, 145002 (2009)

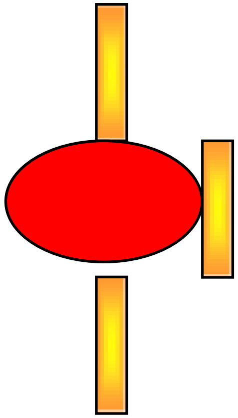
Courtesy of T. Esirkepov

Two Modes of RPA

Hole-Boring Mode (HB)



Light-Sail Mode (LS)



In both modes it has been found that circular polarization (at normal incidence) results in an interaction which is much more clearly radiation pressure dominated than linear polarization at all intensities.

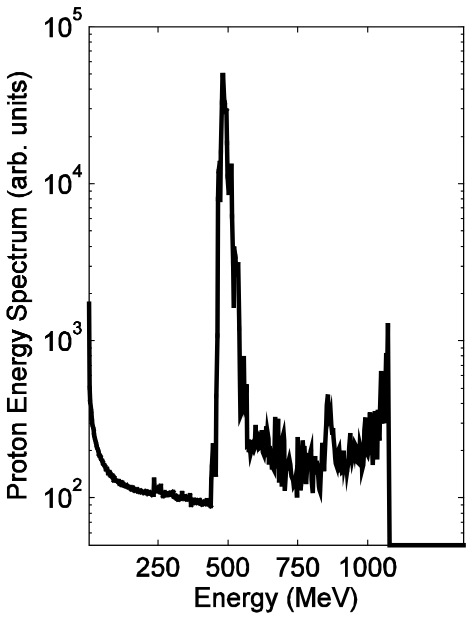
$$\frac{dp}{dt} = \frac{2I}{c}\left(\frac{1-v/c}{1+v/c}\right)$$

RPA has potential to reach high energies and conversion efficiencies.

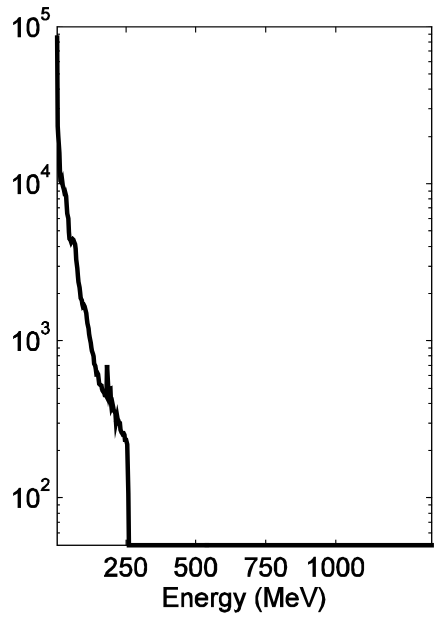
Does Elementary RPA work? – 1D Numerical Validation

- 1D3P Electromagnetic PIC simulations.
- Used 100fs $\sin^4 t$ circularly polarized pulse.
- Peak intensity of 2×10^{21} Wcm^{-2}. λ = 1μm.
- $80n_{crit}$, 150nm thick foil composed of protons.
- Run simulations up to 400fs.

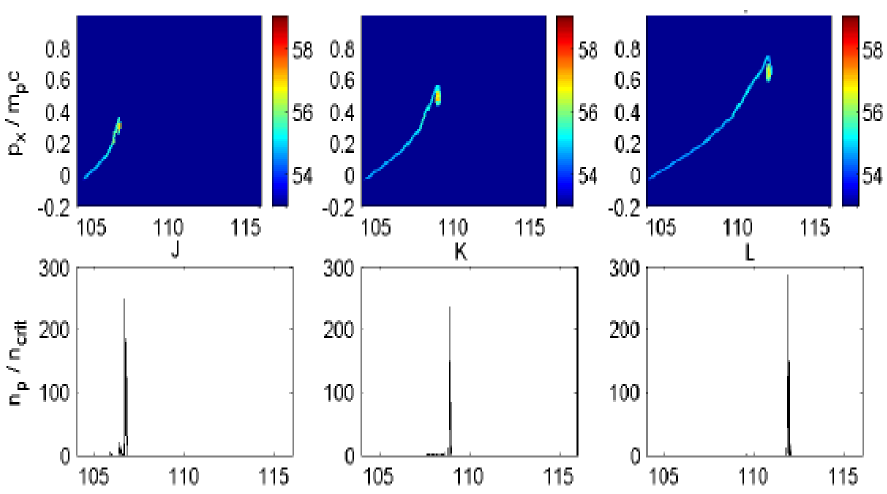
Circular Polarization



Linear Polarization



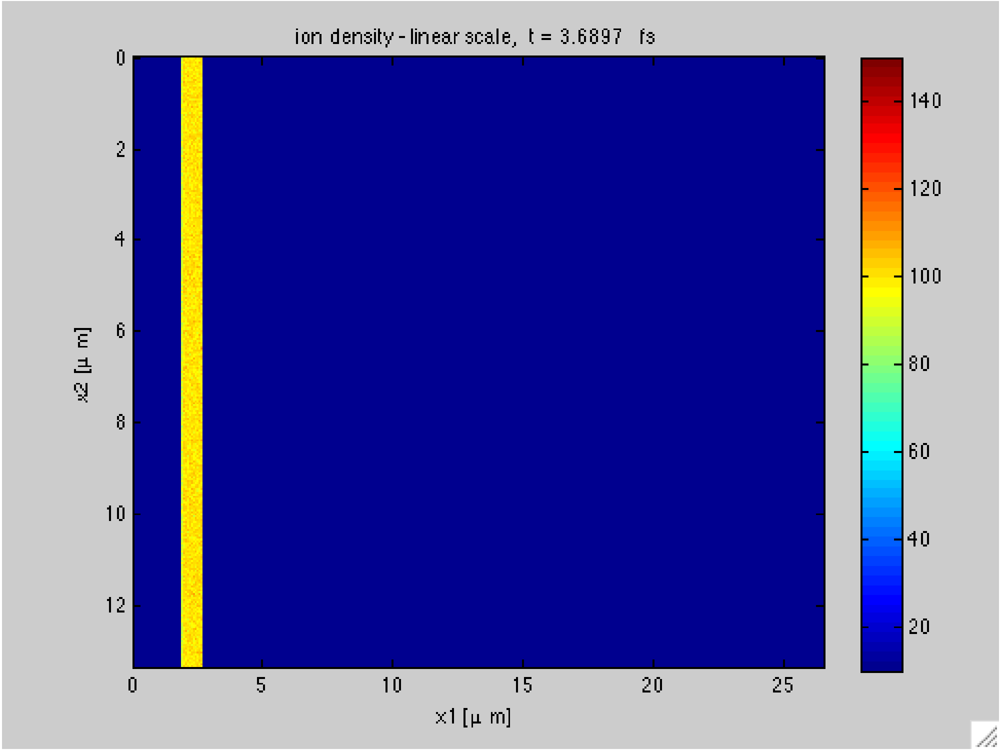
Phase Space



RPA with circular polarised laser pulses

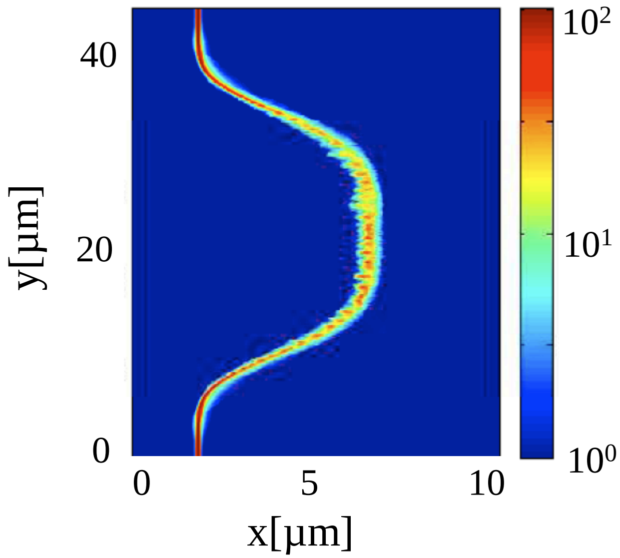
Issues :

- **Electron heating** (competition with TNSA)
- **Stability of acceleration** (Rayleigh-Taylor- like instabilities)



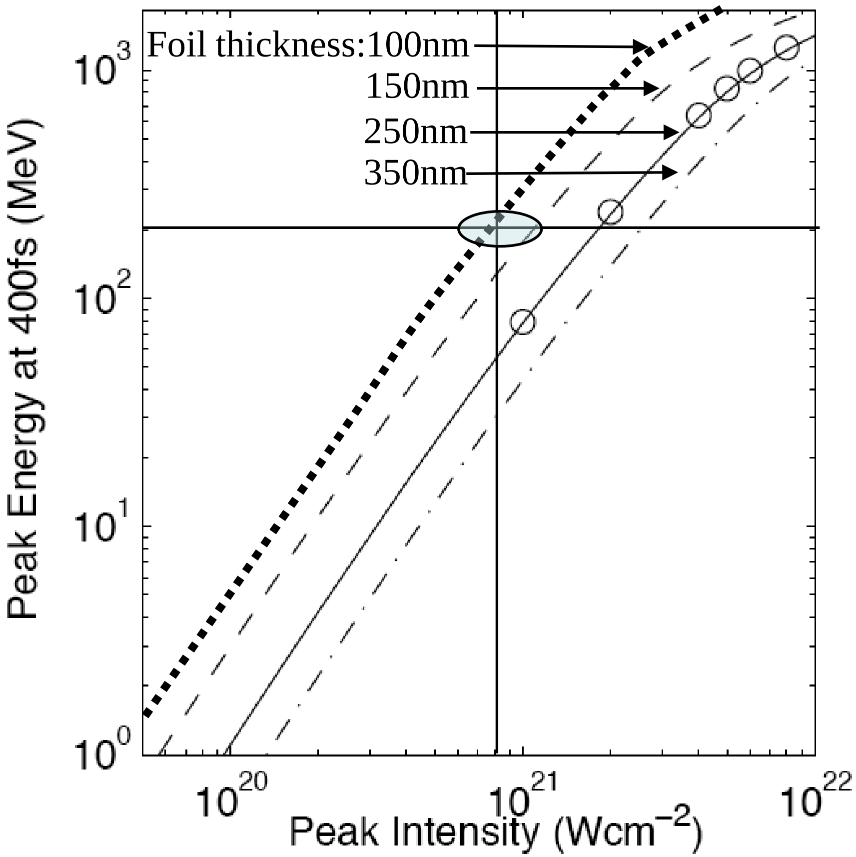
Movie by C.Bellei

For I=10^{21} Wcm^2
Circular polarisation suppresses hot electron generation
- no TNSA, few γ-rays

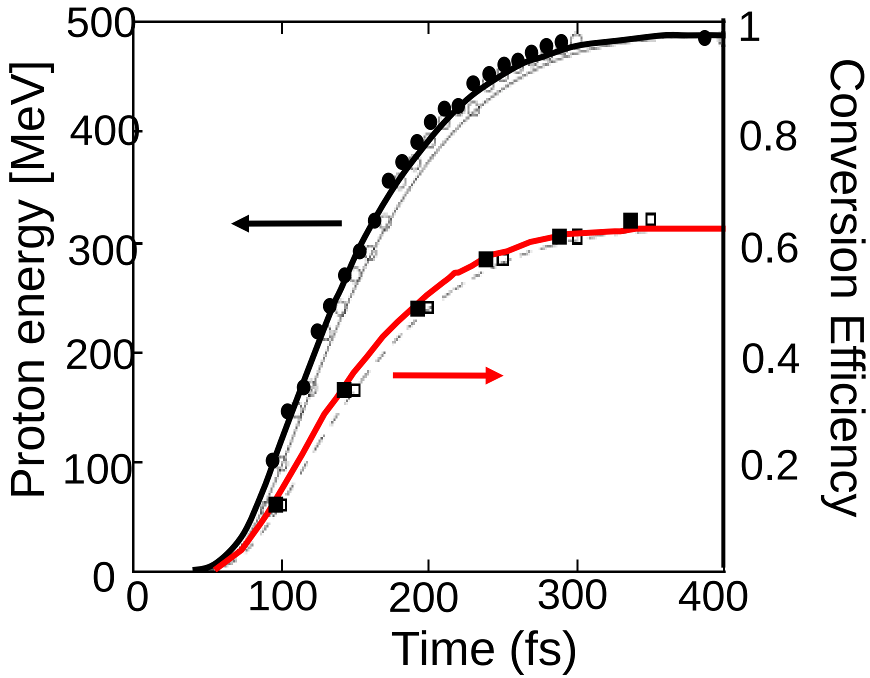


Robinson et al., New J.Phys, **10**, 013021 (2008)

RPA: a promising ion source



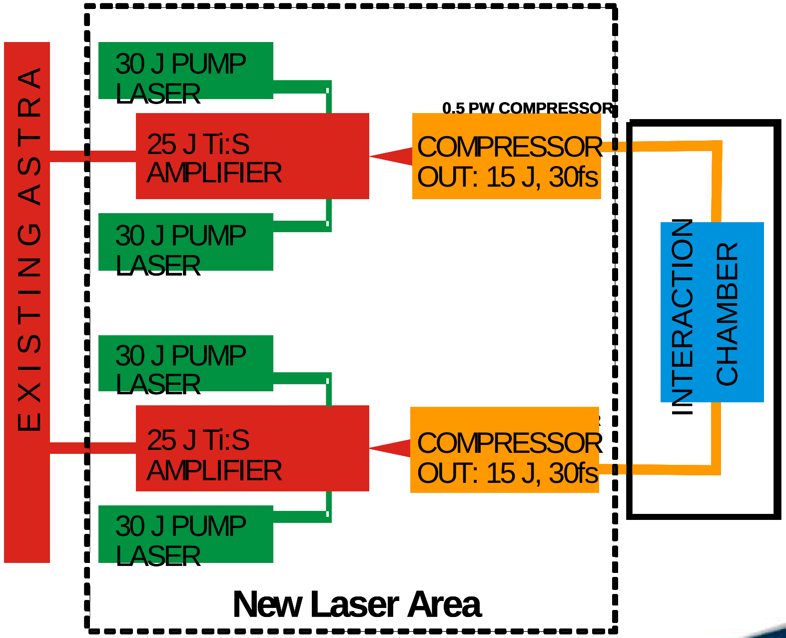
200 MeV predicted in **quasi-monoenergetic** beam at ~ 10^{21} Wcm^{-2}
Efficiency into 200 MeV peak >60%
Divergence angle: 4°
Feasible with current generation of lasers assuming supergaussian spot.
(~50J in 50 fs - Astra Gemini Parameters)



Changing Z of target ions, but keeping mass density and target thickness constant did not change results.
Changing wavelength of radiation did not change results (provided target was still opaque).

Astra GEMINI laser facility

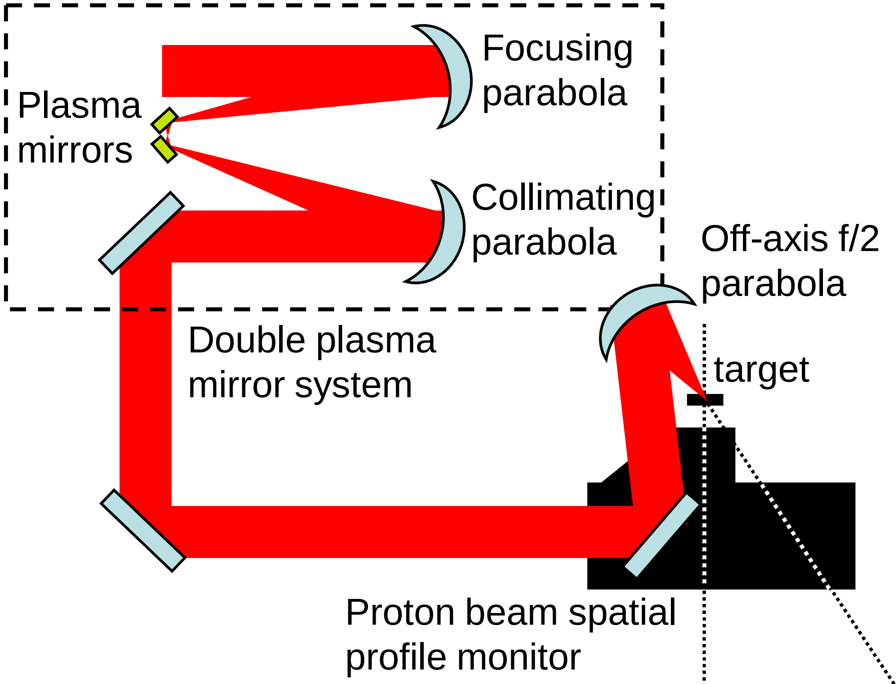
Petawatt upgrade to existing Astra Ti:Sapphire Laser
Two synchronised CPA beams, independently configurable

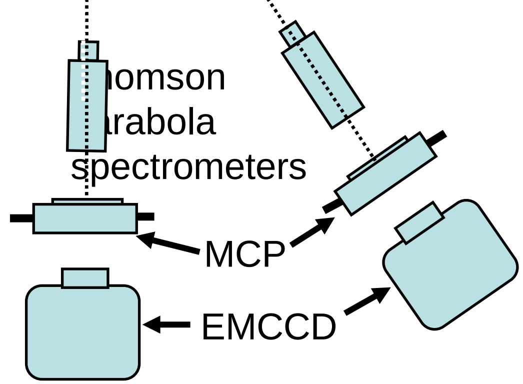


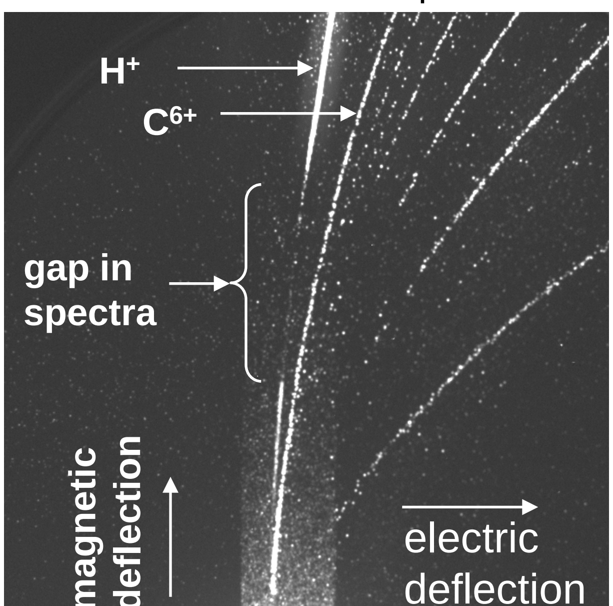
Status for ion acceleration:

- Repetition rate ~1 shot/minute
- Pulse duration ~ 50 fs
- Energy on target up to 10 J (~200 TW)
- Intensity up to 0.5-1x10^{21} W/cm^2
- Contrast ~ 10^7, 10^{10} with plasma mirrors (50%)

Gemini experiment arrangement







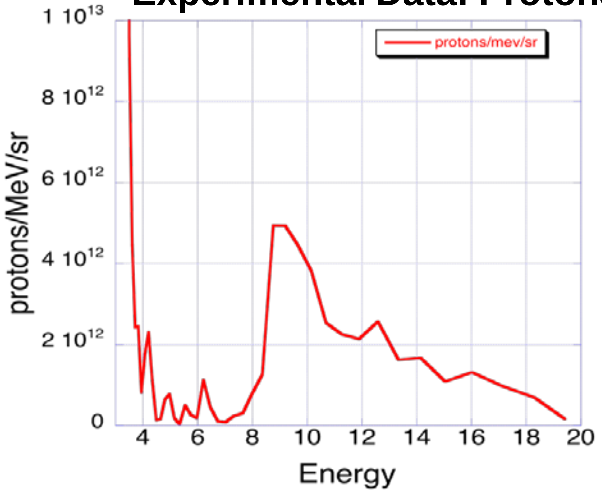
Laser Conditions:

- Linear polarisation @ 35˚
- Linear polarisation @ 0˚
- Circular polarisation @0˚
- Intensity ~7×10^{20} Wcm^{-2}
- Contrast ~10^{10}

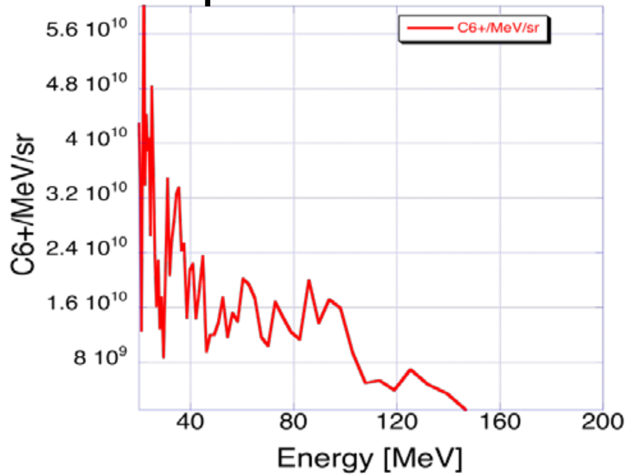
Experimental results

First clear evidence of quasi-monoenergetic RPA acceleration

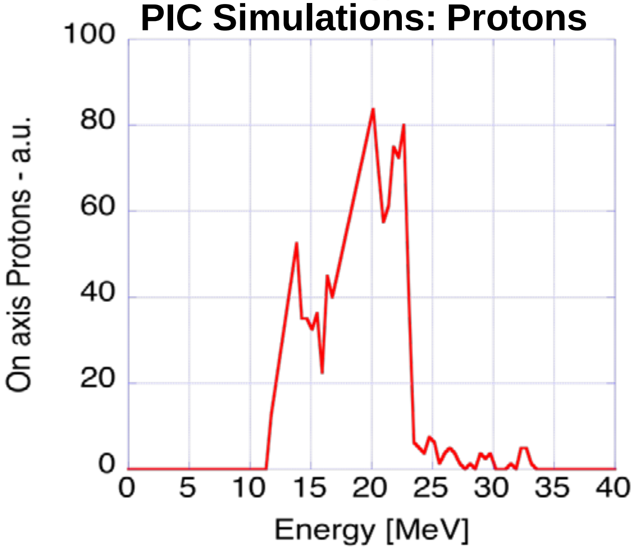
Experimental Data: Protons



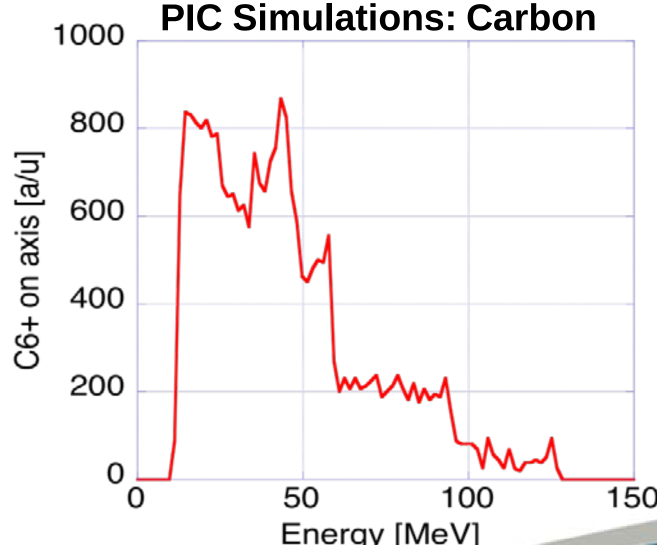
Experimental Data: Carbon



PIC Simulations: Protons



PIC Simulations: Carbon



Experimental Parameters:

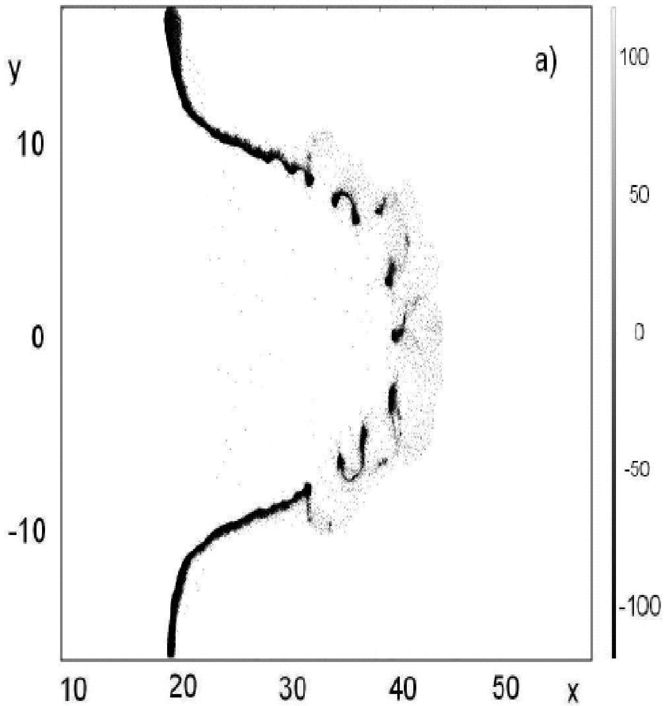
6J, 40fs, 5 10^{20} Wcm^{-2}, circular polarisation, 10 nm C

Simulations: 2D PIC, On axis data shown

Evidence of Rayleigh-Taylor instabilities in RPA?

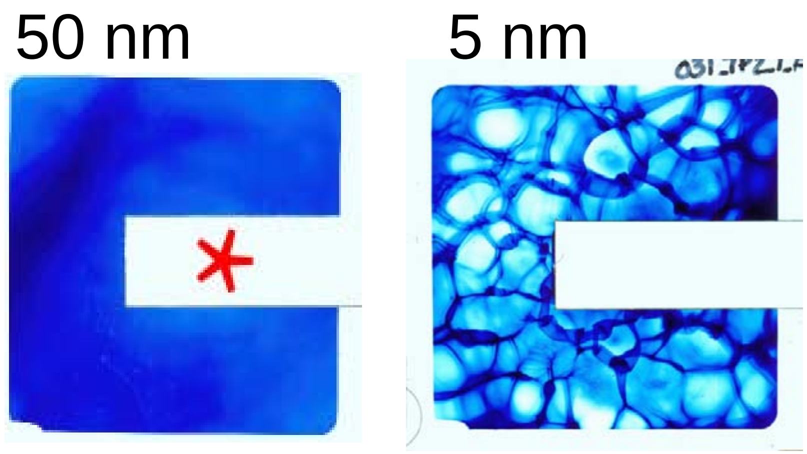
Z Najmudin et al.

Rayleigh-Taylor-like structures observed in proton beam acceleration from ultrathin foil targets driven by the Vulcan PW laser



Pegoraro et al, PRL 99 (2007)
E. Ott et al, PRL 29 (1972)

Proton beam profiles:



- 'R-T Instability occurs when a light fluid is accelerated into a heavy fluid'
  - Light "fluid" = photons of laser beam.
  - Heavy fluid = plasma of ionised target.

RPA with 10 PW pulses should generate relativistic protons

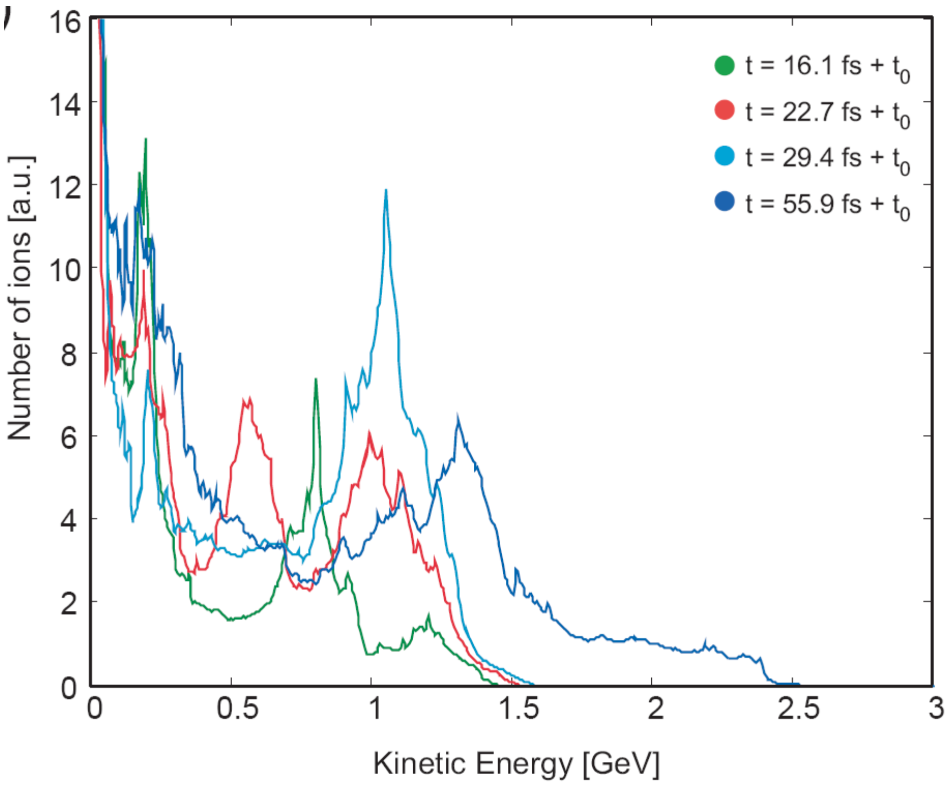
2D OSIRIS PIC simulations performed by C. Bellei, Imperial College and A.P.L. Robinson, RAL

Cyrogenic H target, density = 40 n_{cr}

$I_L = 1.25 \times 10^{23}$ Wcm^{-2}, t_L=25 fs

→ Relativistic ion energies obtained

(p up to 2.5 GeV, C^{6+} up to 1 GeV/u)



Conclusion

- Target Normal Sheath Acceleration
  - Robust, High efficiencies 9%
  - Delivering many (20) scientific application suitable beams
  - Improved absorption and coupling understanding

- Radiation Pressure
  - High Efficiency
  - First indications of RPA dominance observed
  - Future experiments needed to measure new scaling

- Future directions
  - 40 fs 700 TW (2010) @10^9 contrast, 10PW (2013), ELI,
  - Targetry
  - Multi-pulse options

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