Ion Acceleration: TNSA and beyond

Lecture 2

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Advanced Summer School on laser-driven sources of high energy particles and radiation
Anacapri, 10-16 July 2017

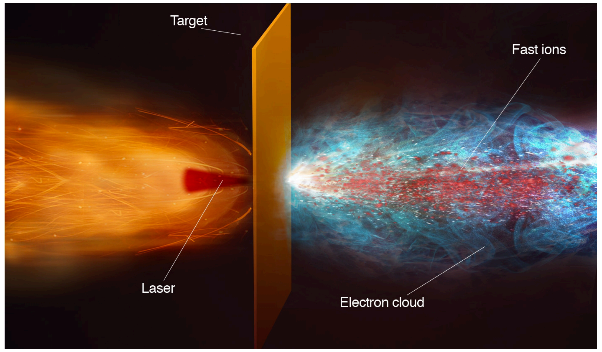
A-SAIL
ADVANCED STRATEGIES FOR ACCELERATING IONS WITH LASERS

Outline of Lecture 2 – Beyond TNSA

- **Recap (and leftovers) of lecture 1**

  TNSA models and scaling

  Target- based optimization of TNSA



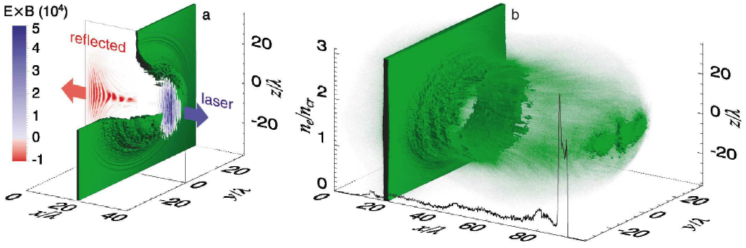
- **A travelling wave concept for post-acceleration**

- **Radiation pressure Acceleration**

  Hole boring

  (Shock acceleration)

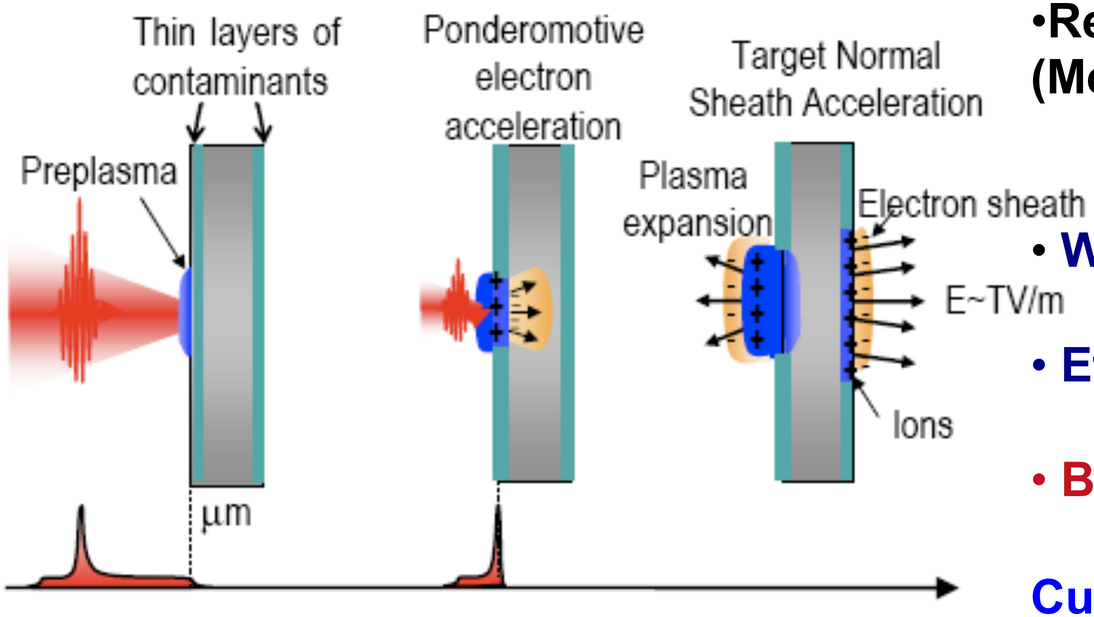
  Light Sail



- **Relativistic transparency regimes**

- **Technology for high-rep operation**

Established mechanism:
Target Normal Sheath Acceleration



S.P.Hatchett *et al*, Phys Plasmas, **7**, 2076 (2000)

P.Mora et al, PRL, **90**, 185002 (2003)

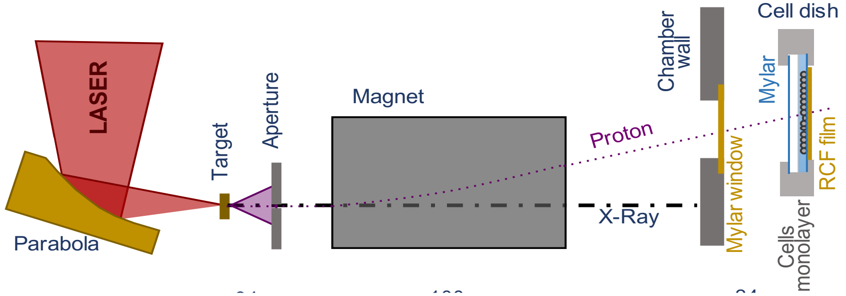
- **Relies on production of high energy (MeV) electrons**
- **Well tested and robust mechanism**
- **Effective at present intensities**
- **Broad spectrum, diverging beams**

Cut-off energies:
~80-90 MeV for high energy, ps systems
~ 40-50 MeV for fs, PW systems

Scaling of proton energies ~ $(I\lambda^2)^{0.5 - 1}$

TNSA limitations towards applicative use

Beam divergence → Issues with capture and transport
Flux limitations at a given distance



Example: Cell radiobiology

Many control techniques investigated:

- Magnetic selection
  Dipoles, quadrupoles, solenoids
- Laser-driven micro lenses
  Double pulse, self charging
- Target-based control
  Ultrathin, reduced mass,
  structured/curved surfaces….

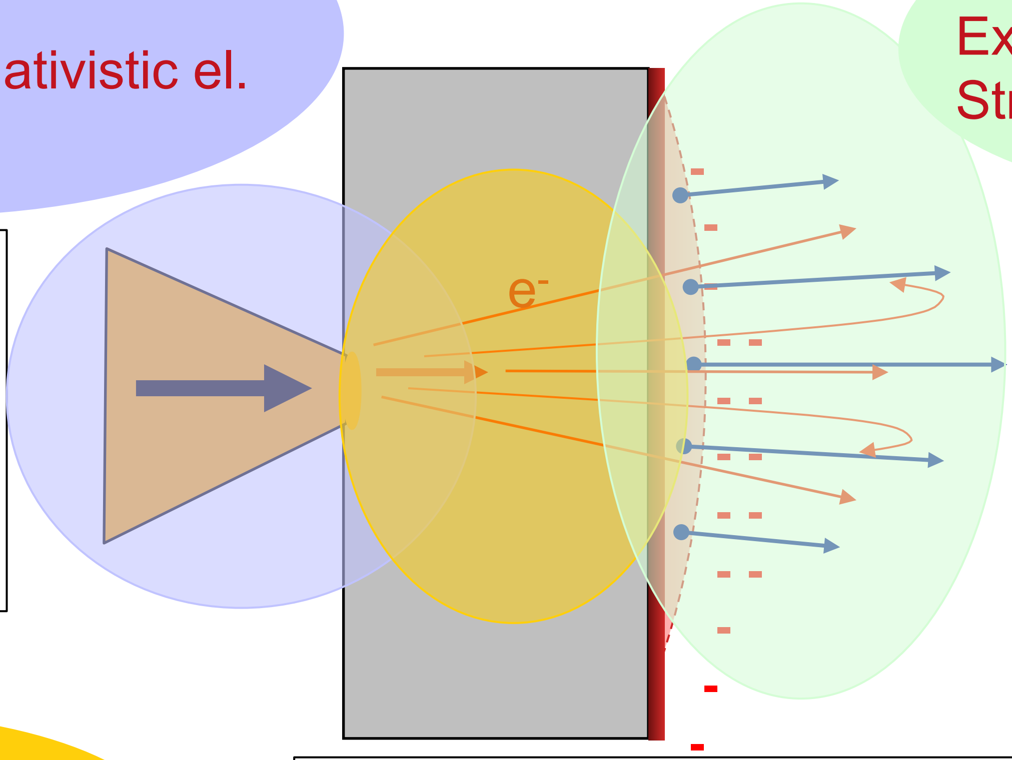
Broadband spectrum → Need of energy selection for controlled irradiation

Limited cut-off energy
for given laser parameters → Limitations in applicative usage

TNSA modelling is complex and requires a variety of approaches

Laser pulse-front surface interaction:
generation of relativistic el. current

- Plasma formation
- Hydrodynamics of preplasma
- Kinetic (PIC) modeling of interaction and electron production



Ion acceleration:
Expansion in vacuum
Strong charge separation

PIC modelling
Analytical models:
fluid (dynamic) models
quasi-static models

Current propagation through the target

- Effect of cold return current
- Target resistivity
- *Hybrid* PIC/fluid modeling
- Collisional PIC simulations

How to describe TNSA acceleration of ions in initial field?

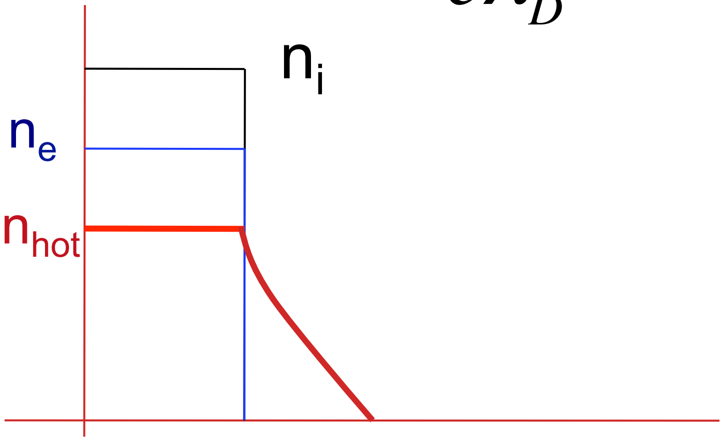
Two main theoretical approaches

1) consider ions and hot electrons as an expanding plasma described with fluid models (dynamic approach)

S. Wilks et al, Phys. Plasmas, **8**, 542 (2001)
P.Mora, Phys. Rev. Lett., **90**,185002 (2003)

2) Describe the accelerating field as a quasi-static electric field set up by the hot electrons, and consider ions as test particles (quasi-static approach)

$$E(0) = \frac{KT_h}{e\lambda_D}$$

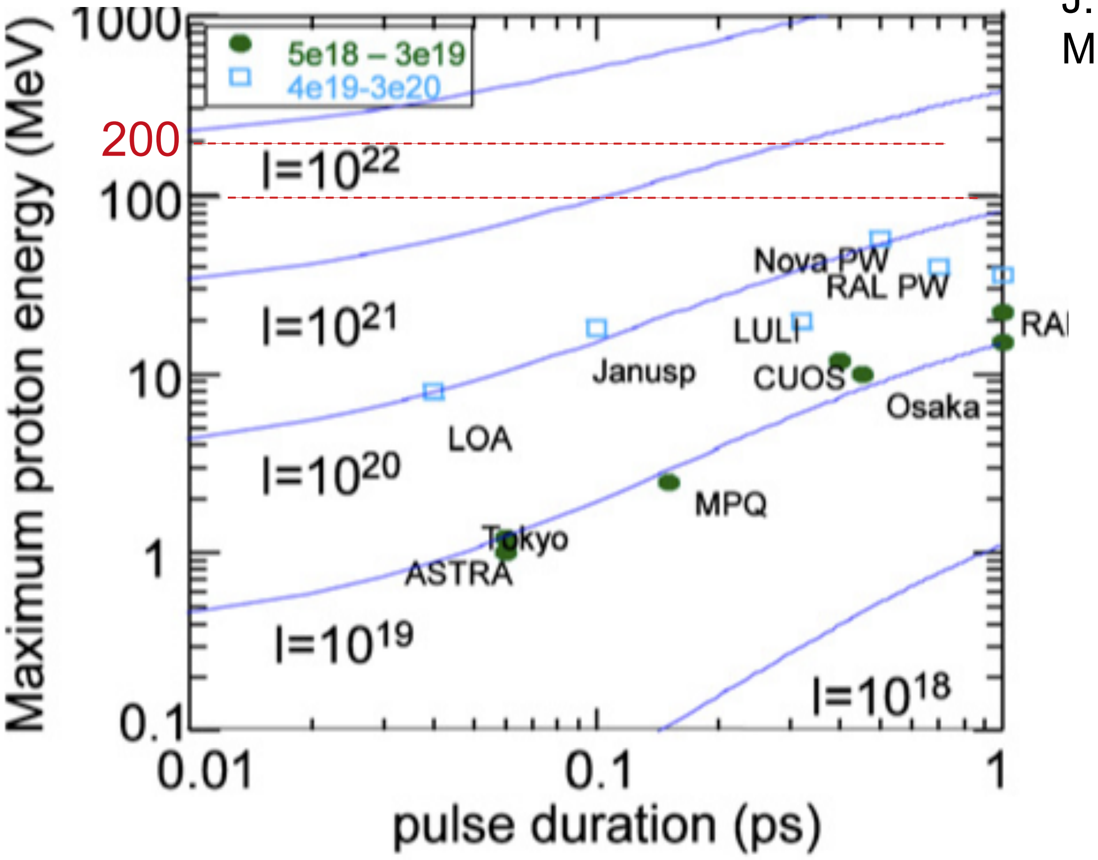


J. Schreiber *et al*, Phys Rev. Lett., **97**, 045005 (2006)
M.Passoni and M. Lontano, Phys . Rev. Lett.**101**, 15501 (2008)

Model predictions for energy increase

Fluid models (plasma expansion)

P.Mora, PRL, **90**,185002 (2003)

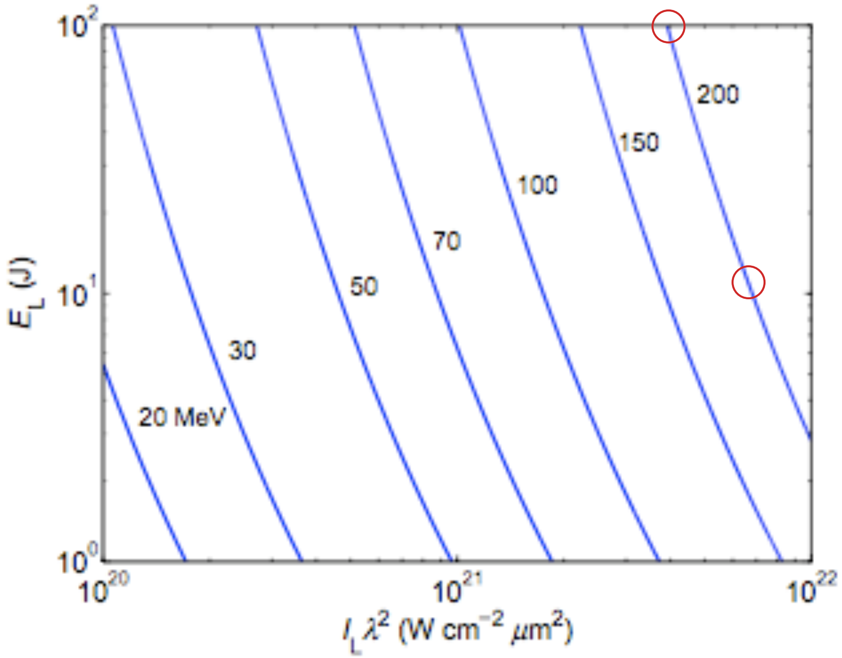


J. Fuchs *et al.,* Nature Physics 2, 48 (2006)

Quasistatic models (test particles)

J. Schreiber *et al*, PRL, **97**, 045005 (2006)

M.Passoni and M. Lontano, PRL, **101**, 15501 (2008)



M.Passoni *et al*, New J. Phys, 12, 045012 (2010)

TNSA optimization at present intensities

Aims:

- Increase energy
- Increase conversion efficiency/ion flux
- Divergence reduction/collimation
- Narrow-band spectra

- Magnetic selection

Dipoles + aperture

Miniature quadrupoles

S. Ter-Avetysian et al, LPB, 26, 637 (2009);
M. Schoellmeyer et al, PRL, 101, 055004 (2008)
A. Tramontana et al, JINST, 9, C0565 (2014)

- Laser-triggered micro-lens

Simultaneous energy selection and focusing/collimation

*T.Toncian et al, Science, **312**, 410 (2006)*

Self-triggered microlens for collimation

S. Kar *et al*, Phys. Rev. Lett., 100, 105004 (2008)

$$E(0)=\sqrt{\frac{n_h KT_h}{\varepsilon_0}}$$

$$T_h \sim m_e c^2\left(\sqrt{1+\frac{a_0^2}{2}}-1\right)\sim\sqrt{I}$$

For $a_0 >> 1$

STRATEGIES:

- Enhance energy coupling into electrons
- Manipulate electron density

- Reduction of foil thickness

D. Neely et al, APL, 89, 021502 (2006)

- Reduced mass targets

S. Buffechoux et al, PRL, 105, 015005 (2010)

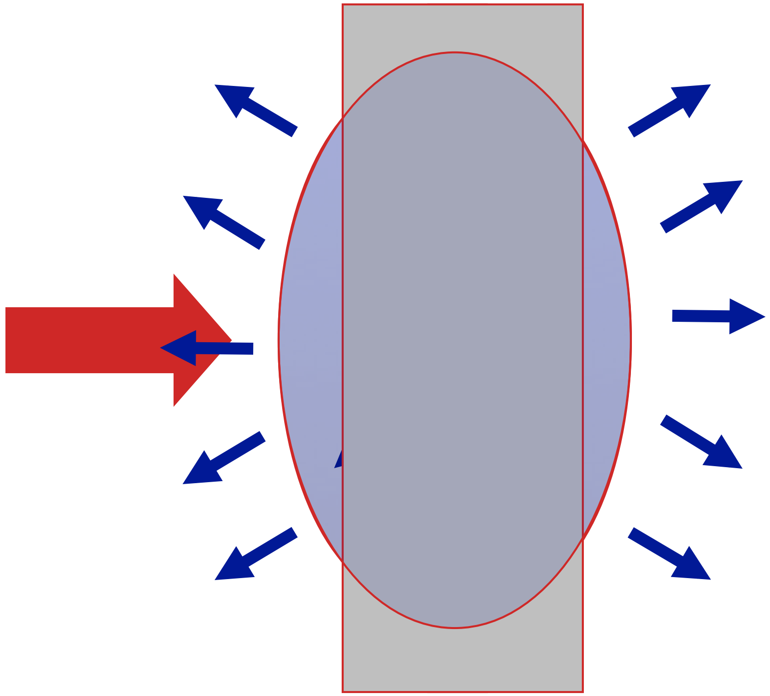
- Target structuring for enhanced coupling

D.Margarone et al, PRL, 109, 234801 (2012)
S. Gaillard et al, PoP, 18, 056710 (2011)

- Multipulse approach for shaping of electron population

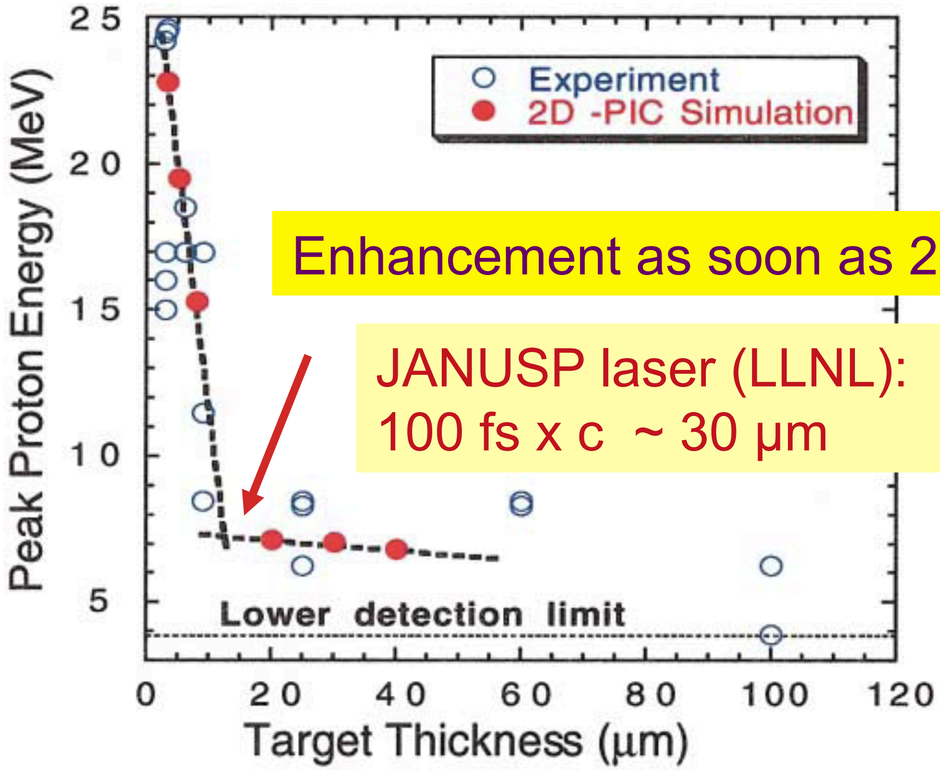
C. Brenner et al, APL, 104, 081123 (2014)

Electron concentration: enhancement due to electron refluxing



Reflection at surfaces confines electrons in a cloud surrounding the target

Decreasing target thickness Increases n_e



Enhancement as soon as $2d < c\tau$

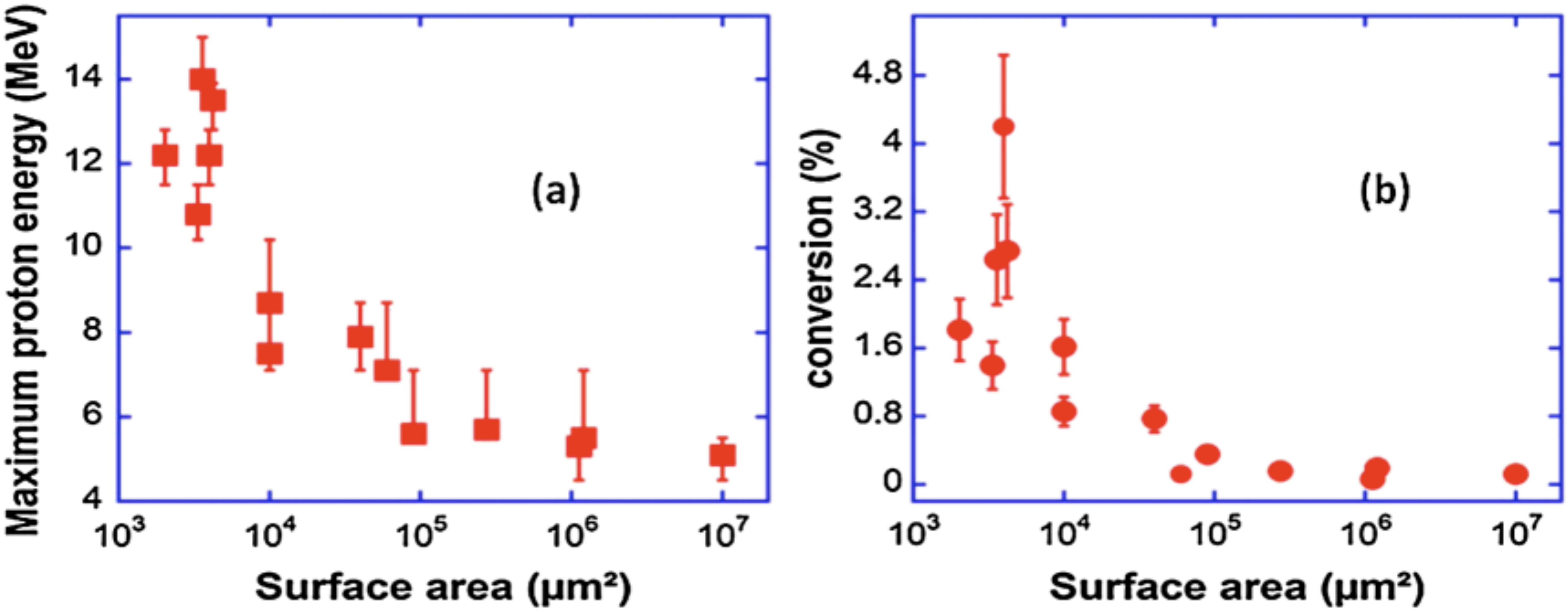
JANUSP laser (LLNL):
100 fs x c ~ 30 μm

A.J.Mackinnon et al, PRL, **88**,215006 (2002)
T. Ceccotti *et al.*, PRL, **99**, 185002 (2007)
A.Henig et al, Phys Rev Lett. **103**, 045002 (2009)

Nowadays foils as thin as a few nm are used!!

Reduced mass target :
Transverse confinement of electrons

S. Buffechoux *et al*, Phys Rev Lett.,**105**, 015005 (2010)



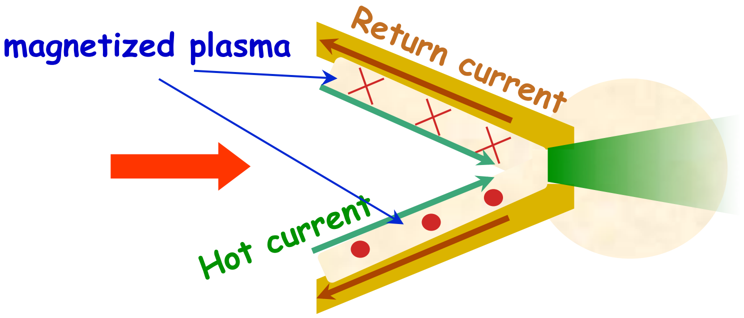
LULI, 100 TW, I~ 10^{19} W/cm^2
Targets as small as 20 µm x 20 µm were used

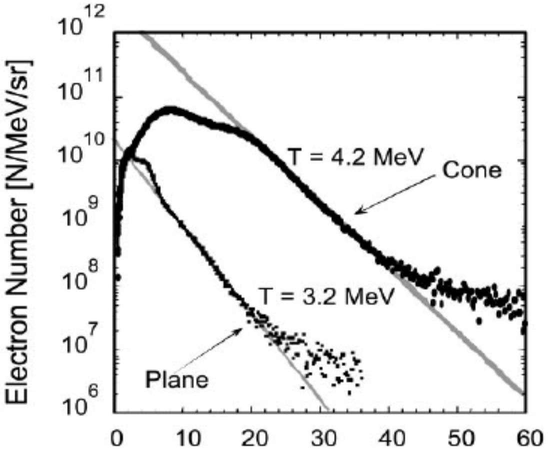
Confirmed by
O. Tresca et al PPCF, 53, 105008 (2011)

Enhanced acceleration from conical target

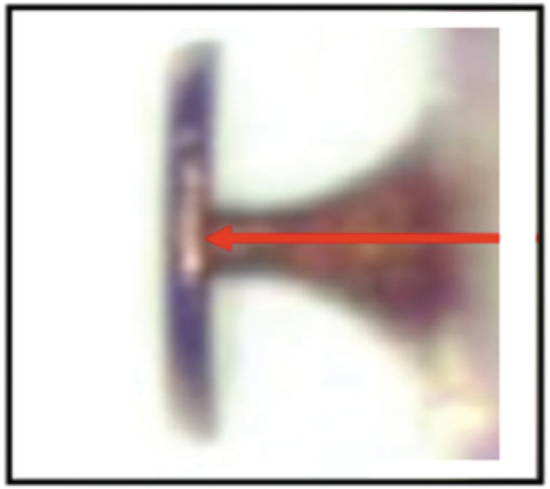
S. Gaillard *et al*, Phys. Plasmas, **18**, 056710 (2011)
T.Kluge *et al*, NJP, **14**, 23038 (2012)

Principle

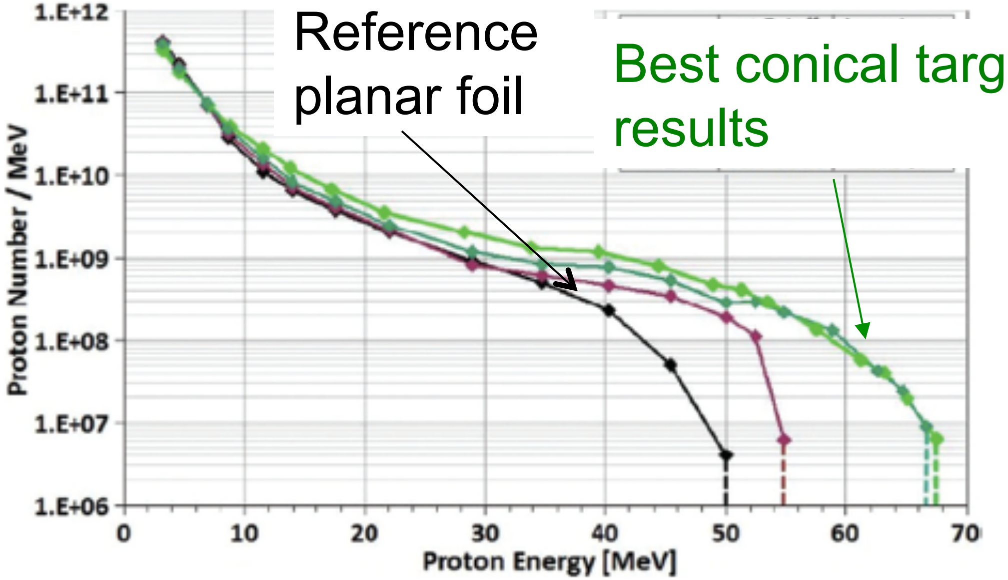




More efficient coupling into hot electrons due to interaction with walls (direct electron acceleration)



Trident laser, 80 J, 700 fs

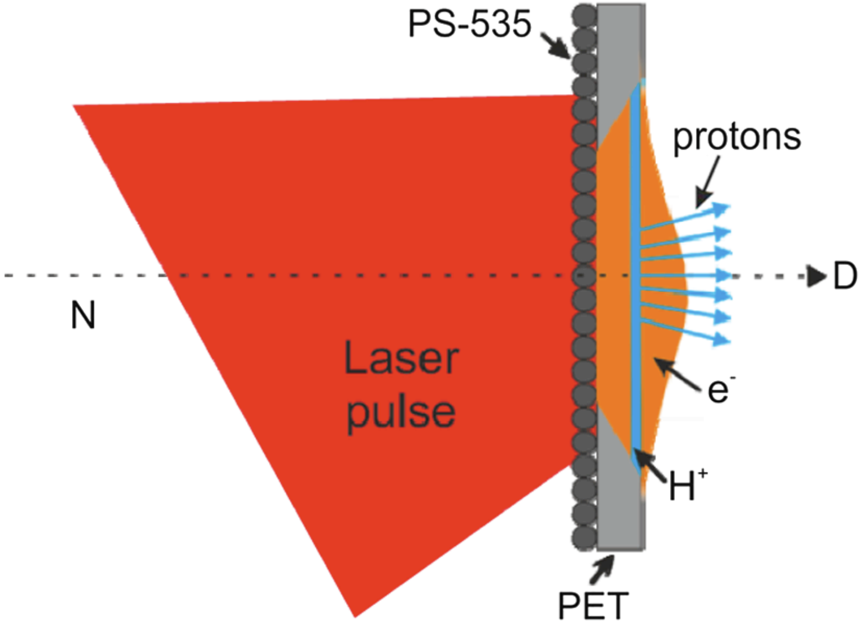


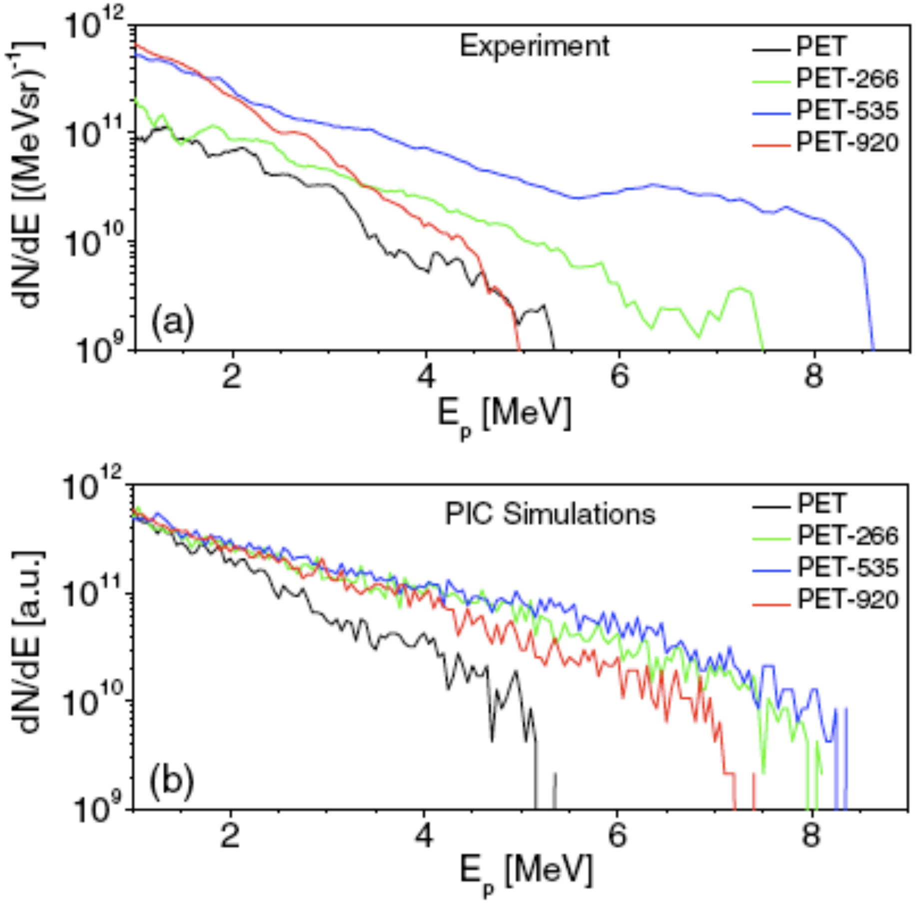
Reference planar foil

Best conical target results

Optimized TNSA in structured targets

D. Margarone *et al*, PRL,**109**, 234801 (2012)



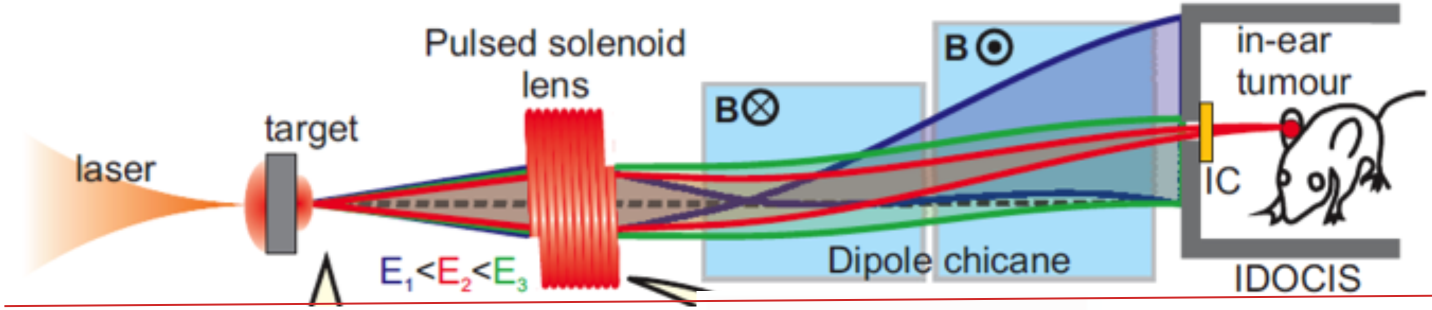


I ~ 5 10^{19} W/cm^2
30 fs, 2 μm f.s.
High Contrast: 5 1011 @ -10ps

Other approaches:
Foam layers, controlled preplasmas

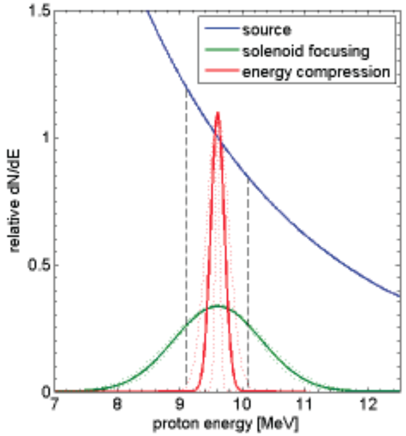
Best results at intermediate diameter of spheres (535 nm) which optimize absorption

Ideas and proposals for beam capture and transport

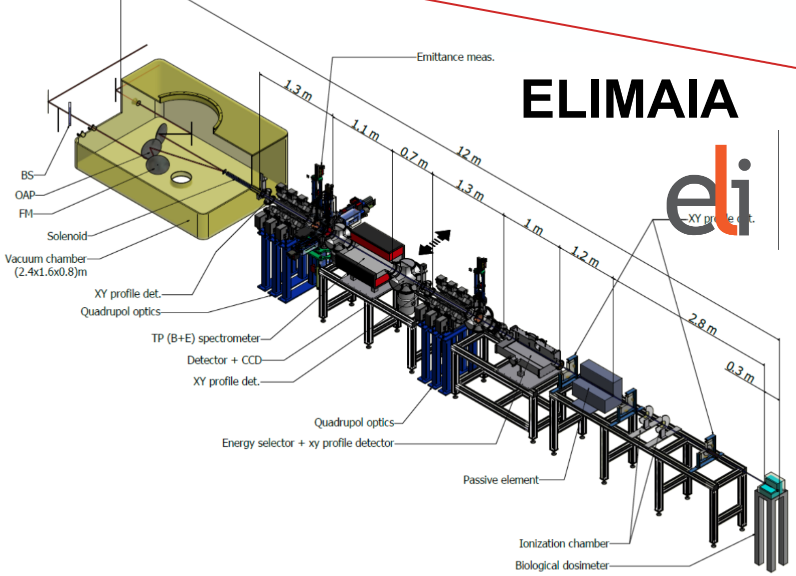


Zeil et al. Appl. Phys. B 110, 437 (2013)

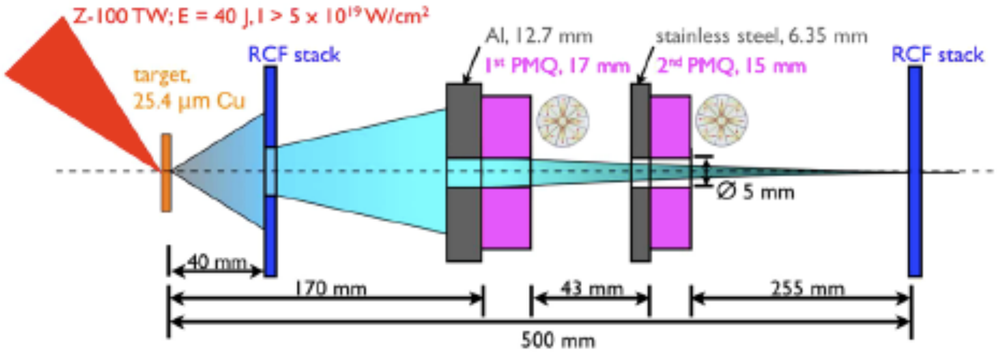
LIGHT @ GSI



ELIMAIA

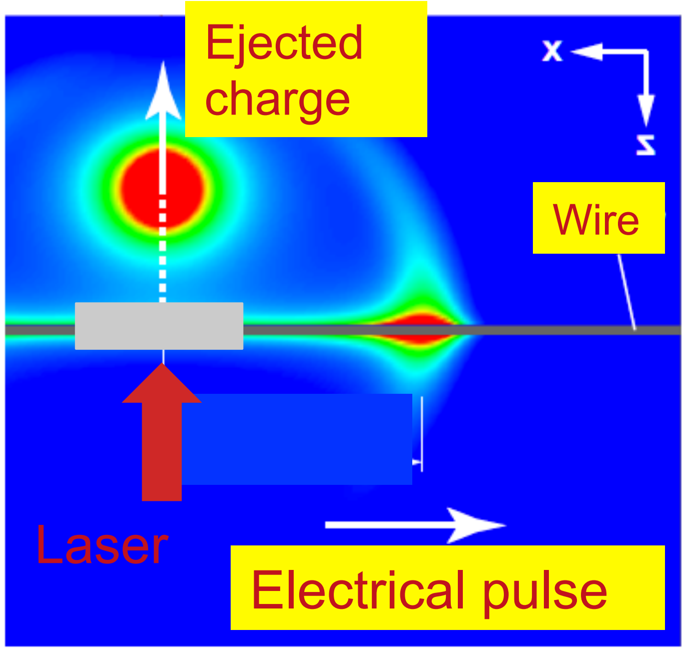


M.Schollmeyer et al, PRL, **101**, 055004 (2008)



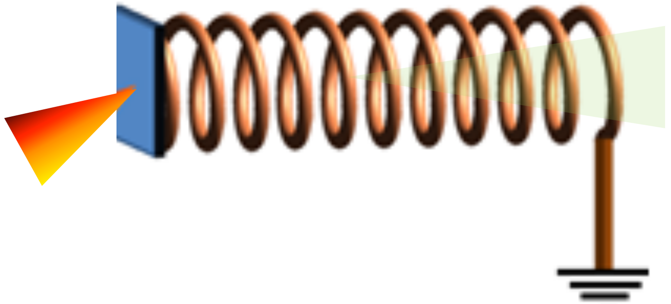
A travelling wave module for controlling TNSA beam properties

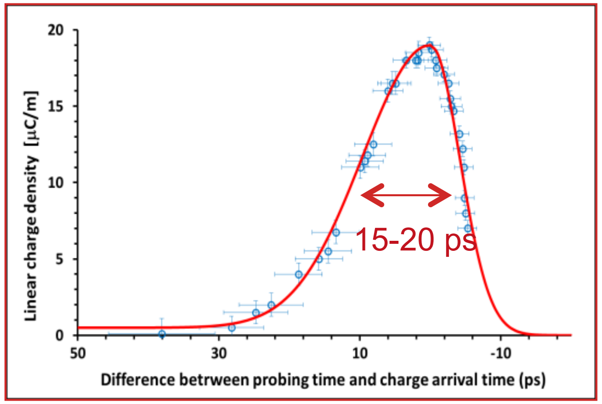
S.Kar *et al*, Nature Comm., **7**, 10792 (2016)

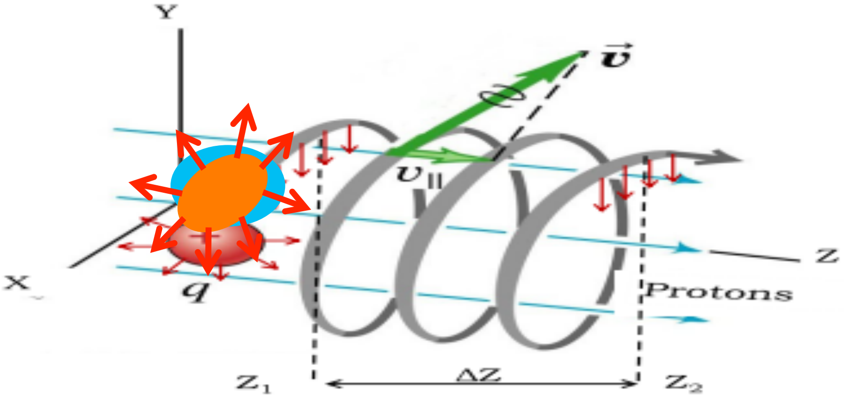


Large amplitude, ultrashort electrical pulses propagating at v ~ c are launched by high intensity interactions
K. Quinn et al, Phys. Rev. Lett., 102, 194801 (2009)
S. Tokita et al, Sci. Rep.,5, 8268 (2015)

In a suitable target geometry the electric pulse can be employed to improve the properties of TNSA ions



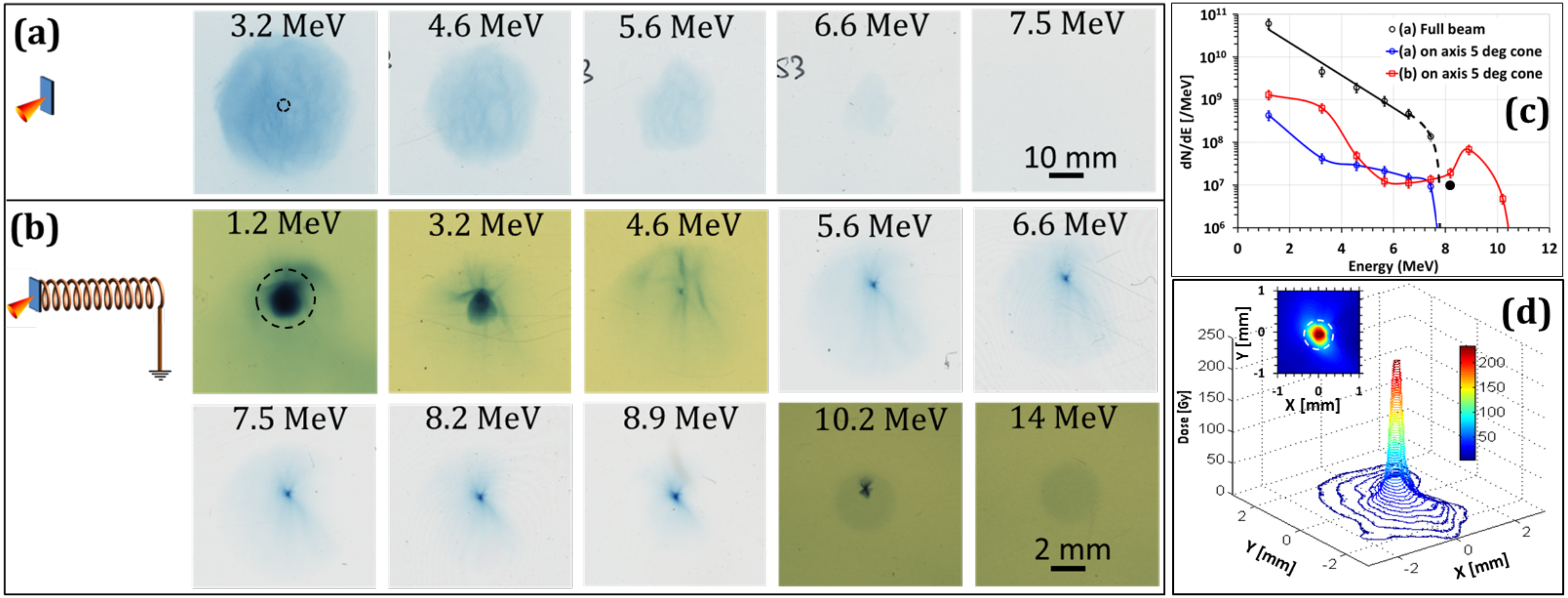




With a suitable choice of coil pitch and radius, the pulse can be synchronized with a group of ions within the TNSA spectrum

Beam collimation and re-acceleration clearly observed in recent experiment

S.Kar *et al*, Nature Comm., **7**, 10792 (2016)



Results obtained on ARTHURUS laser, Dusseldorf University,

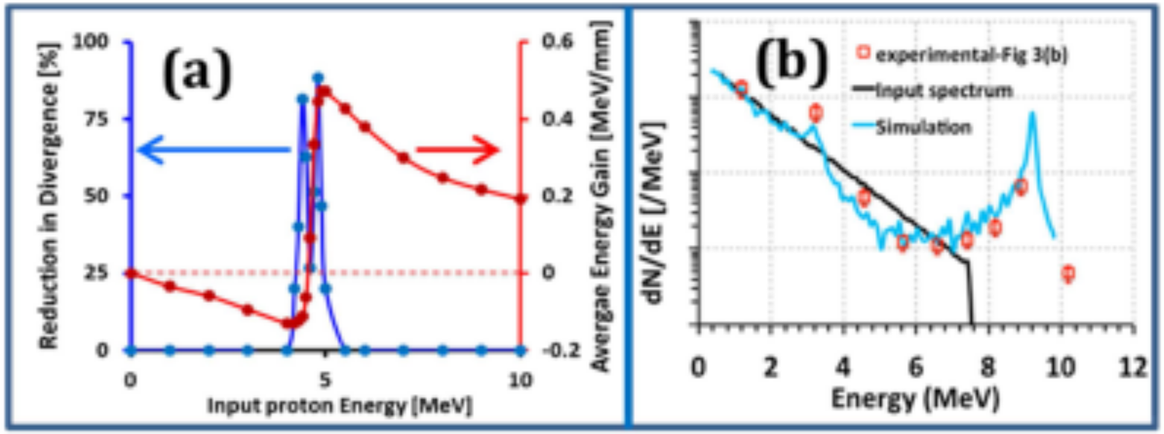
25 fs, I ~ 5 10^{19} W/cm^2

Foil, 3 µm Al target, wire: 100 µm Al

Campaigns on TARANIS, VULCAN (2014-15)

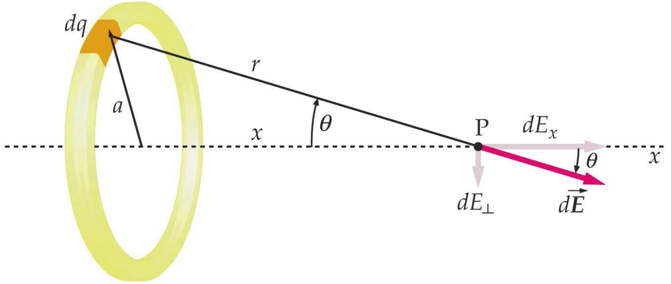
Particle tracing simulations clarify dynamics of focusing/reacceleration

S.Kar *et al*, Nature Comm., **7**, 10792 (2016)



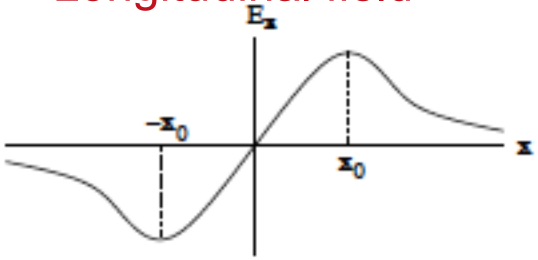
5 MeV protons are accelerated to 9 MeV over ~ 9 mm:

Energy gain ~ 0.5 MeV/mm



Analogy with the field of a charged ring

Longitudinal field



$$x_0 = \frac{a}{\sqrt{2}}$$

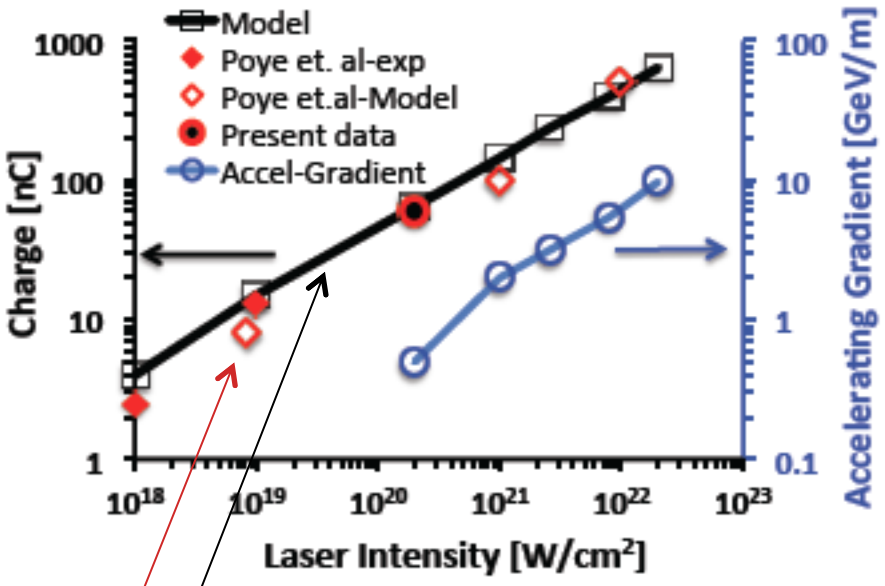
$$E_{\max} = \frac{Q}{2\pi\varepsilon_0 a^2}\frac{\sqrt{2}}{3\sqrt{3}}$$

Q~ 60 nC, a =0.4 mm ➡ E~ GV/m

Scaling and staging of the acceleration process

Scaling with intensity

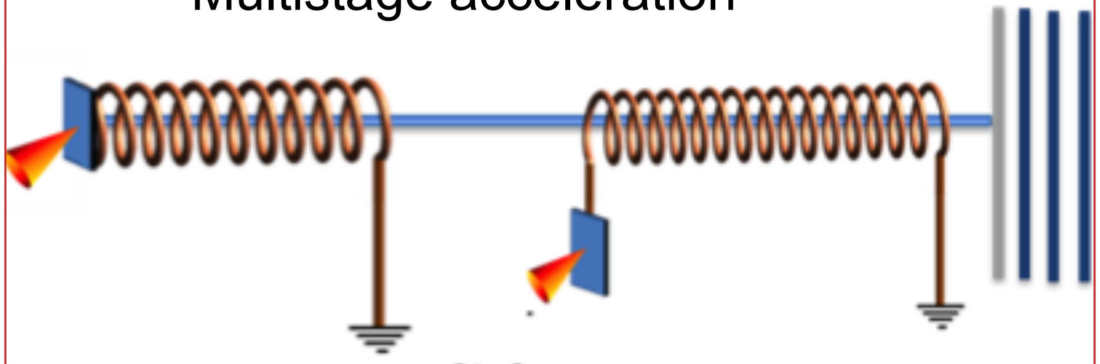
(varying energy, fixed focusing, 30 fs pulses)

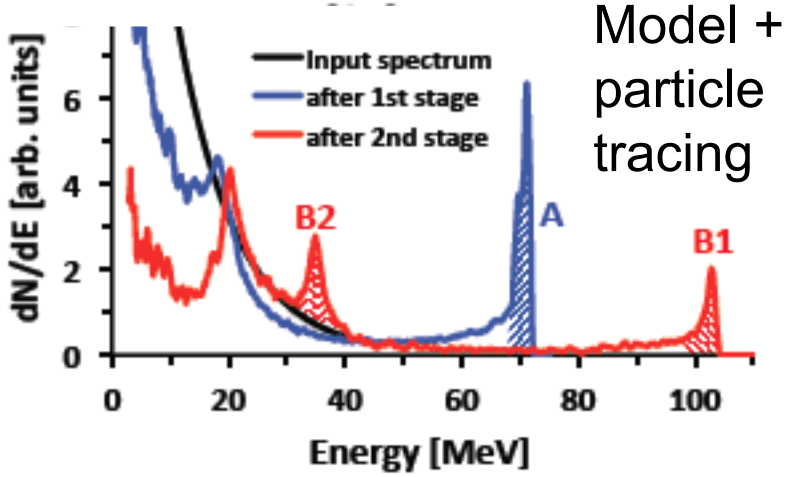


Simple phenomenological model based on target charging from electron escape : S.Kar *et al*, PRL, **100**, 105004 (2008)

Model and results from
A. Poye *et al.*, PRE, **91**, 043106 (2015)

Multistage acceleration





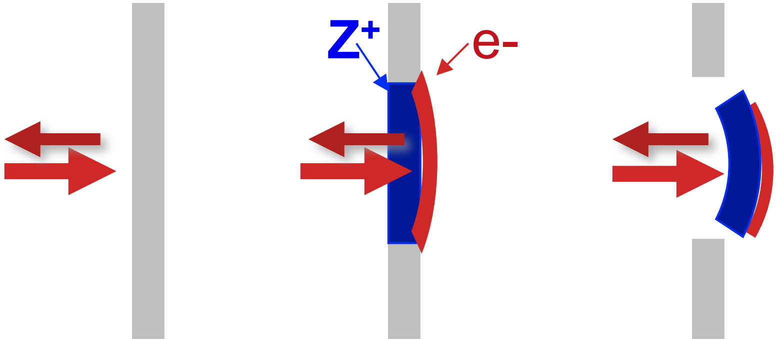
Model + particle tracing

40 MeV particles can be boosted to ~100 MeV by a double stage coil

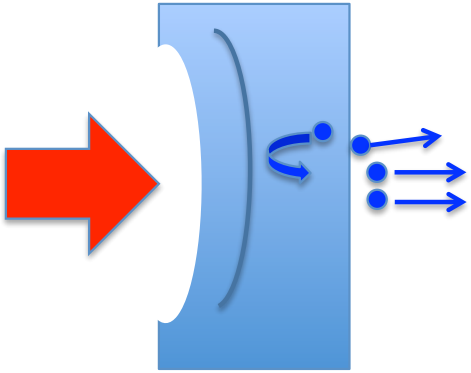
Emerging acceleration mechanisms

- **Radiation Pressure Acceleration**

  Hole Boring
  Light Sail

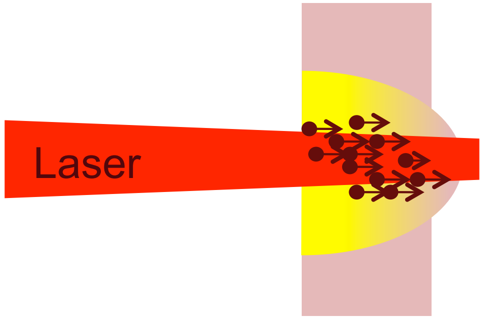


- **Shock acceleration**



- **Relativistic transparency acceleration**

  (Break Out Afterburner)



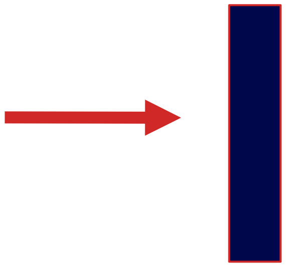
Light can exerts a force on a surface

Energy density $u = \varepsilon_0 E^2$

Momentum (flux) $p = \dfrac{E^2}{\mu_0 c^2} = \dfrac{I}{c}$

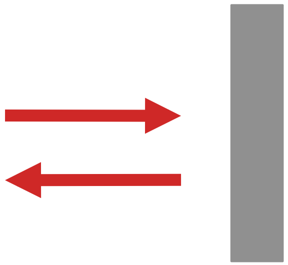
Pressure = Force per unit surface = Momentum transferred to the surface

Absorbing surface



$$|\Delta \mathbf{p}| = P$$

Reflecting surface



P = Radiation Pressure

$$P = \frac{I_L}{c}$$

$$P = \frac{2I_L}{c}$$

Radiation pressure in laser matter interaction

In a plasma the effect is felt by the electrons via the ponderomotive force

$$f_p = -\frac{m}{4}\frac{\partial}{\partial x}v_{os}^2(x)\left(1-\cos 2\omega_0 t\right)$$

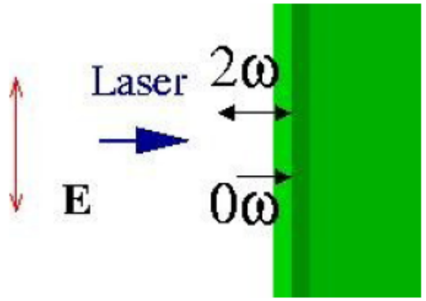
Non-oscillating term

Steady pressure,
transferred to ions via space-charge

Oscillating term

JXB heating,
hot electrons

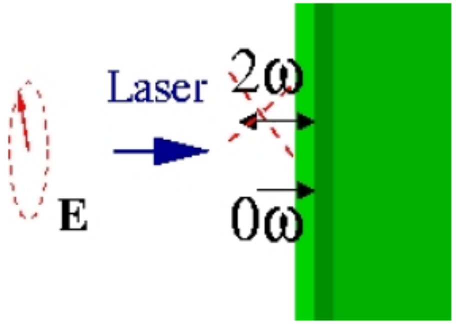
Normally, the electron heating effect masks any steady pressure effect



Linear polarization

Laser-polarization can be used to control the balance between the two terms

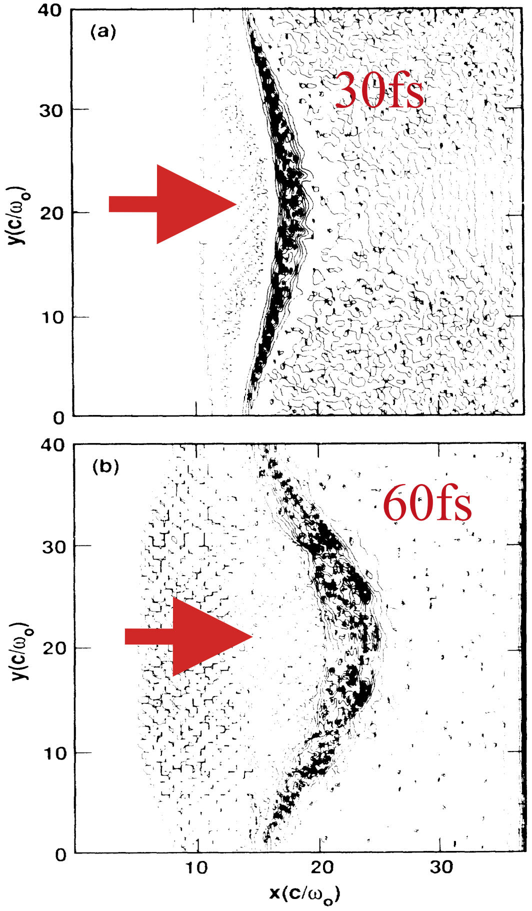
A.Macchi *et al*, PRL **94**, 165003 (2005)



Circular polarization

Hole boring acceleration

S. Wilks et al, Phys. Rev. Lett, 69,1383 (1992)



Momentum balance (EM vs mass flow):

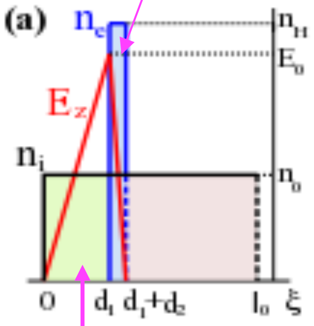
$$\frac{2I}{c} \sim n_i(m_i v_{hb})v_{hb} = \frac{n_e}{Z}\left(Am_p v_{hb}^2\right)$$

$$v_{hb} \sim \sqrt{\frac{I}{\rho c}} = a_0 c\sqrt{\frac{Z}{A}\frac{m_e}{m_p}\frac{n_c}{n_e}}$$

ρ= mass density

$$\varepsilon_{hb} = m\frac{v_{hb}^2}{2} \sim \frac{m_p I}{\rho c}$$

$$v_{i\max} \sim 2v_b$$



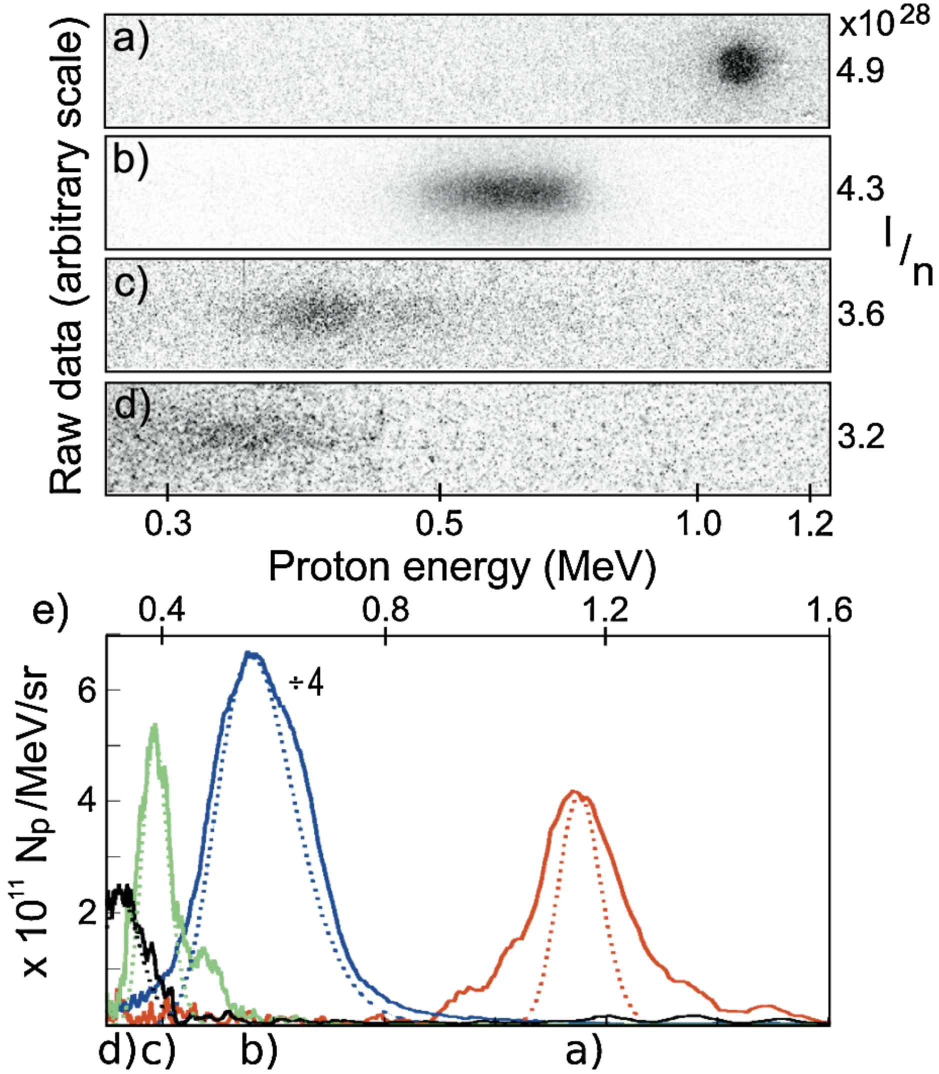
compression region

depletion region

Monochromatic proton beams due to HB acceleration

C.A. Palmer et al, Phys. Rev. Lett, **106**, 014801 (2011)

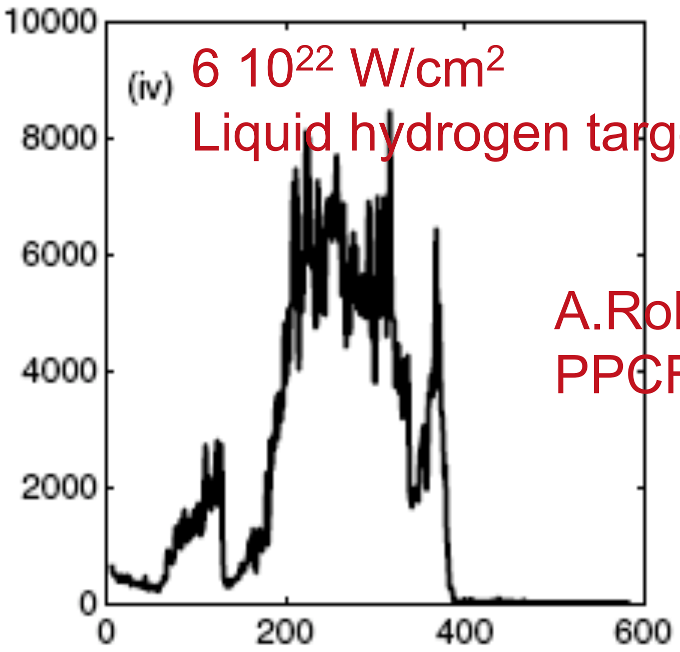
O.Tresca et al, Phys. Rev. Lett., 115, 094802 (2015)



IC/BNL collaboration

CO_2 laser, 0.5 TW, 5 ps, I ~ 5 10^{15} W/cm^2
Circularly polarized

Hydrogen gas jet , n ~ 10^{-19}-10^{20} cm^{-3}

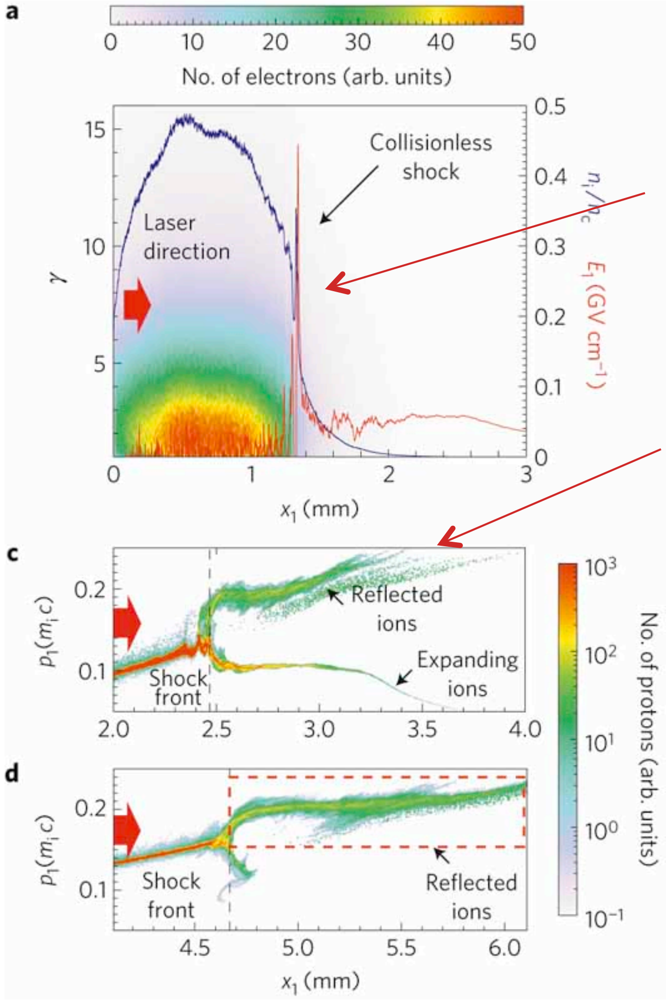


6 10^{22} W/cm^2
Liquid hydrogen target

A.Robinson
PPCF 2009

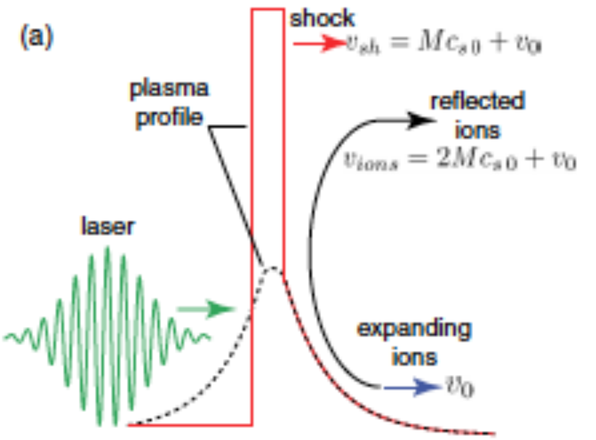
Shock acceleration

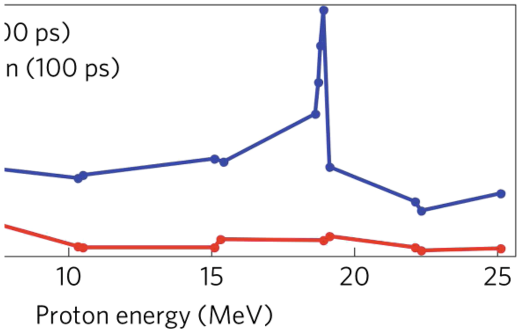
L.Silva *et al*, PRL **92**, 015002 (2004)
D.Haberberger *et al*, Nature Phys., **8**, 95 (2012)

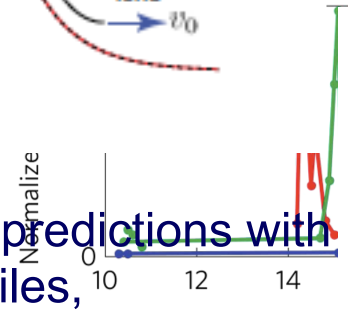


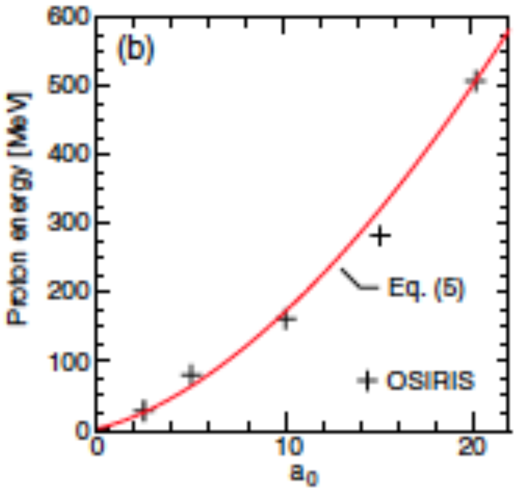
Laser pistor
high Mach r
electrostatic
an overdens

The propaga
electrostatic
reflects ions
to v ~2 v_s







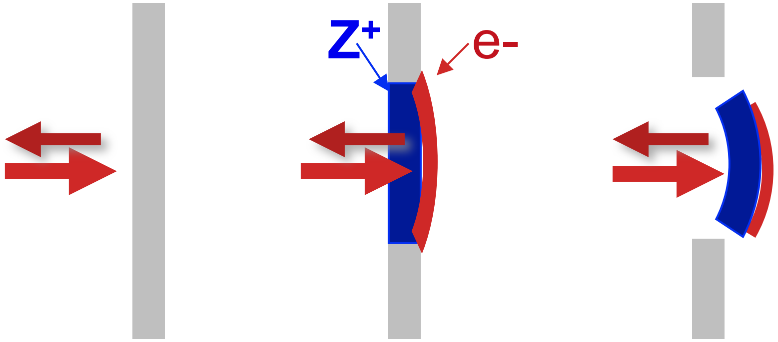


Very promising PIC predictions with shaped plasma profiles,
200 MeV at currently available intensities, with sufficient particle numbers

Monochromatic proton peaks observed experiments using overdense gas jet wi
cm^2(UCLA)

Fiuza et al, PRL, **109**, 215001 (2012)

Radiation Pressure applied to thin foils - light sail



- Cyclical re-acceleration of ions
- Narrow-band spectrum (whole-foil acceleration)
- Fast scaling with intensity

$$F_R = (1+R)A\frac{I_L}{c}$$

$$\Rightarrow v_i = \frac{(1+R)\tau}{m_i n_i d}\frac{I_L}{c} \propto I\tau\eta^{-1}$$

$\eta = m_i n_i d$ Areal density

$$E_{ions} \sim (I\tau/\eta)^2$$

Issues at present intensities

- Competition with TNSA
- Hot electron heating cause foil disassembly

(ultrathin foils are needed for moderate a_0)

Use of circular polarization:

No JxB acceleration

No TNSA

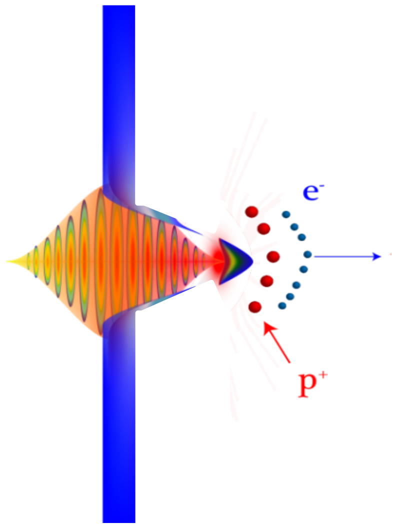
No target heating

Quasi-static pressure drive

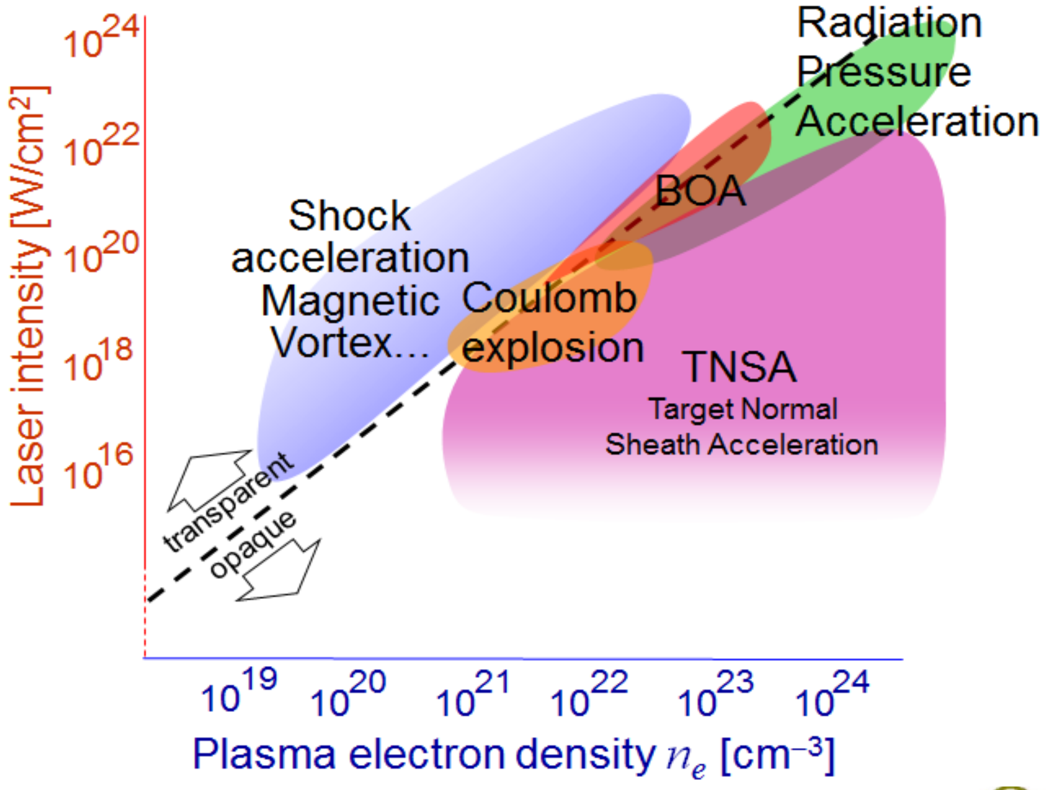
T.Esirkepov, et al. Phys. Rev. Lett., **92**, 175003 (2004)

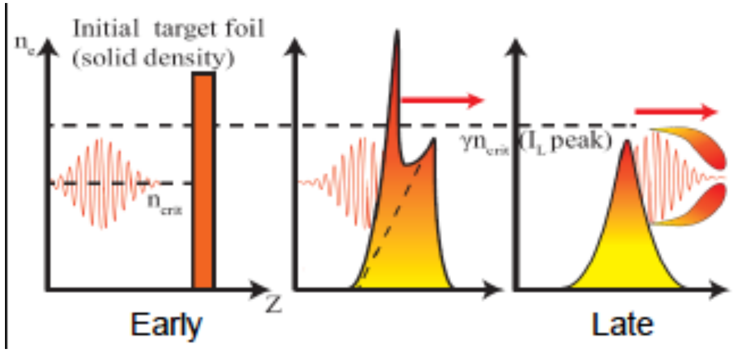
APL Robinson et al, NJP, **10**, 013021 (2009)

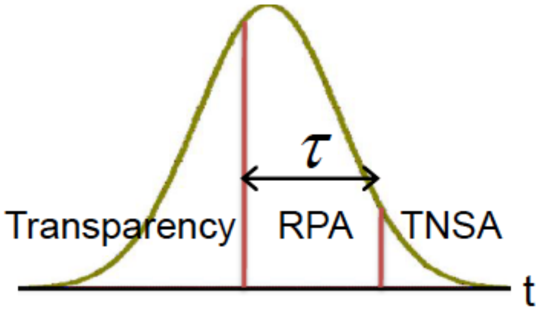
Opacity/transparency of the target plays a key role



RPA – Light Sail





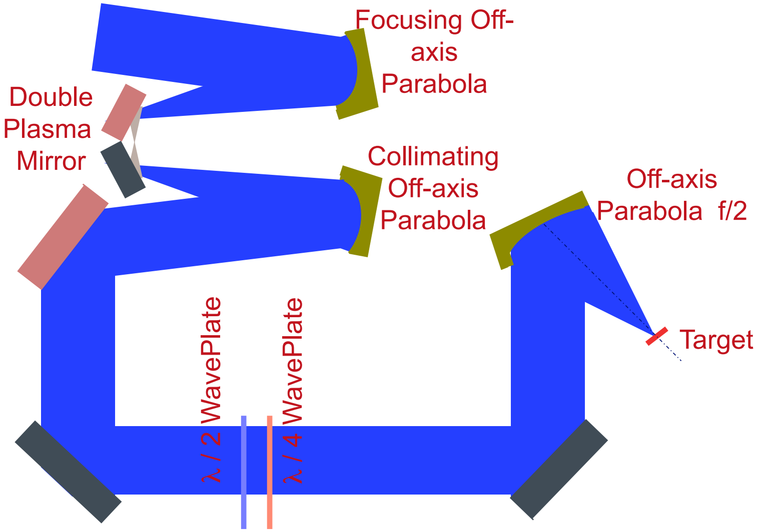


RPA effects in ultrashort pulse interactions

ASTRA GEMINI – CENTRAL LASER FACILITY

PhD thesis,
Clare Scullion (QUB)

Set Up



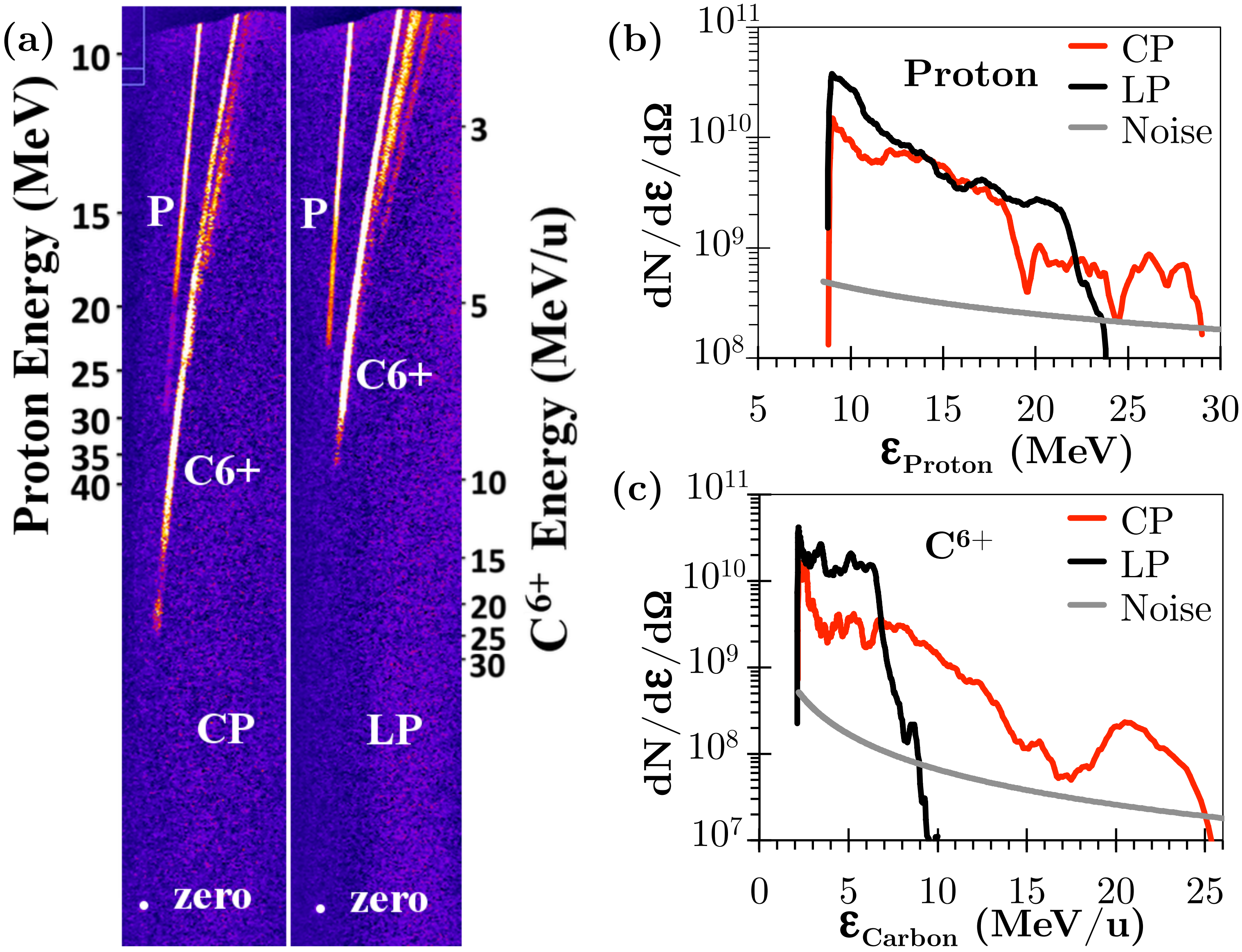
GEMINI Laser
Pulse length ~ 40 fs
Energy < 15 J
Power ~ 400 TW

➡

Experimental Conditions
Pulse length ~ 40-45 fs
Energy ~ 13 J ~ 6.5 J on target
PM ~ 50% and 10^{12} contrast
Intensity = $6 \times 10^{20} \pm 25\%$ W/cm^2

Ion spectra display a very strong polarization dependence

C.Scullion et al, PRL (2017, in press)

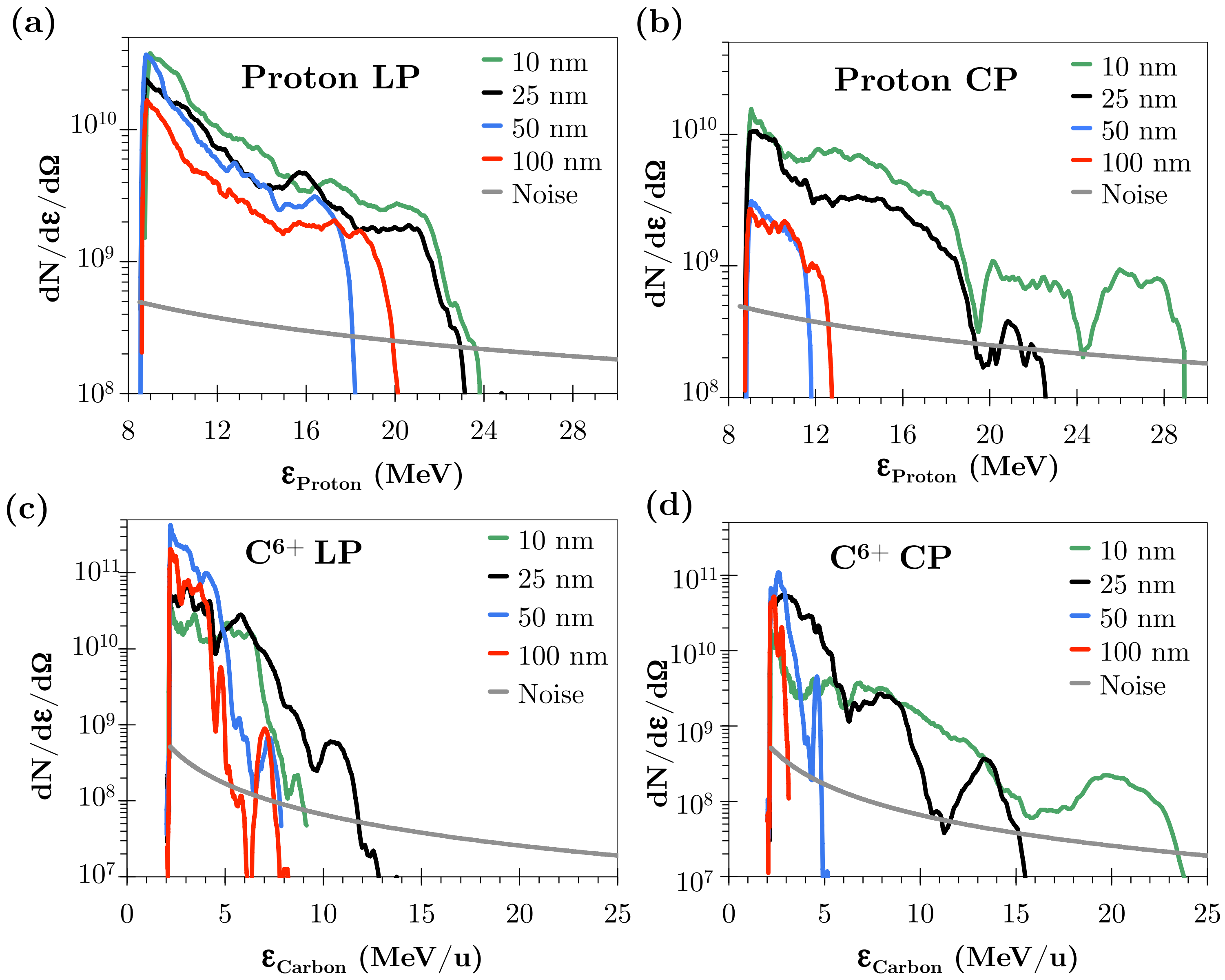


Thomson spectrometer data for 10 nm Carbon targets

Higher energies for circularly polarized pulses

Similar energies/ nucleon for protons and carbons

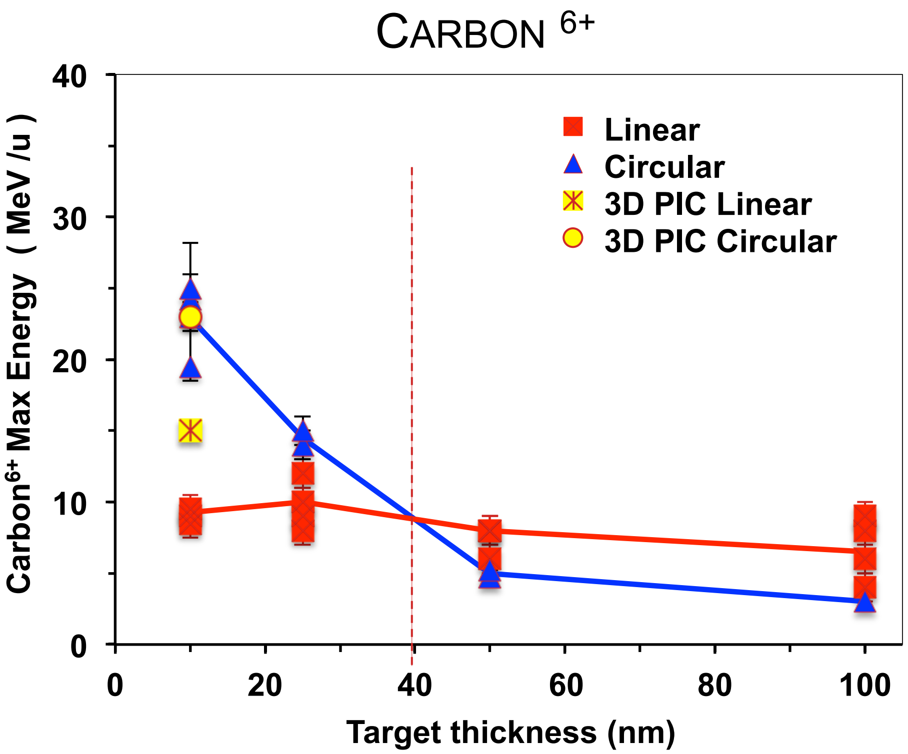
Dependence of spectra on target thickness

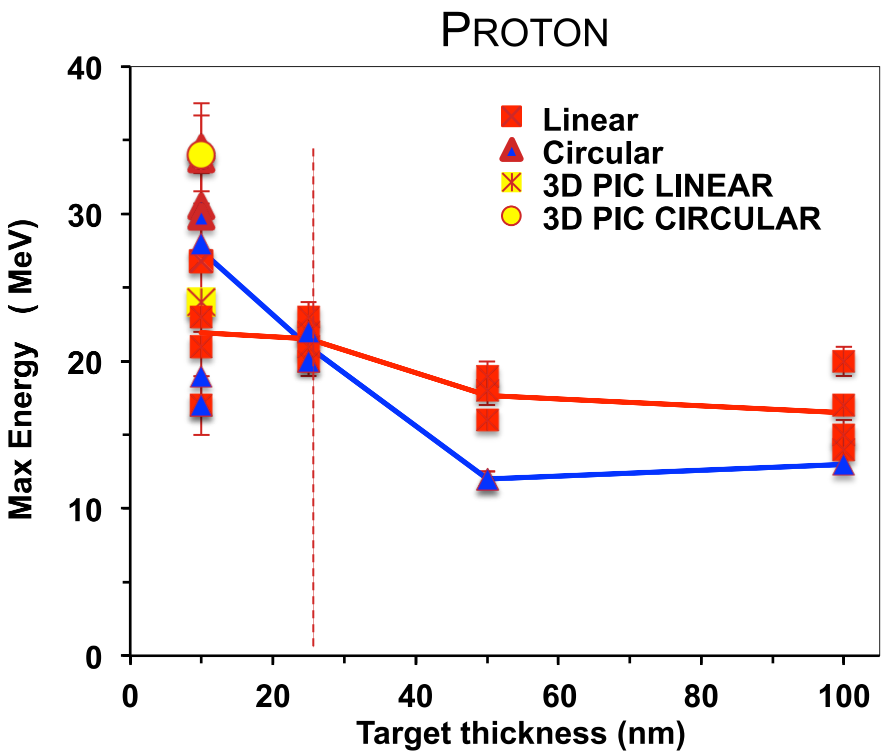


Strong dependence on target thickness for circularly polarized pulses

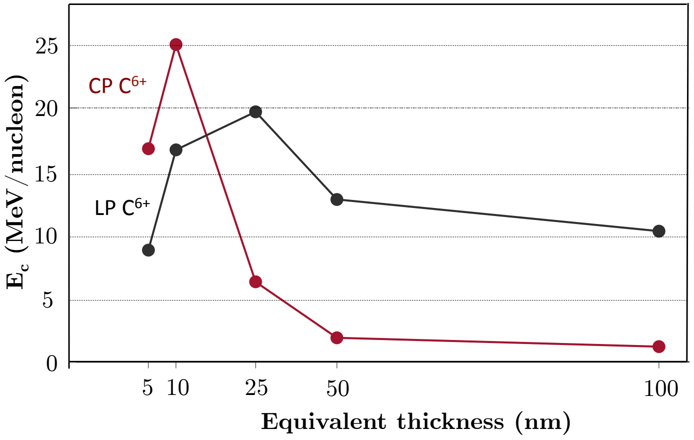
A regime transition is clear from the data

C.Scullion et al, submitted (2017)


CARBON 6+


PROTON

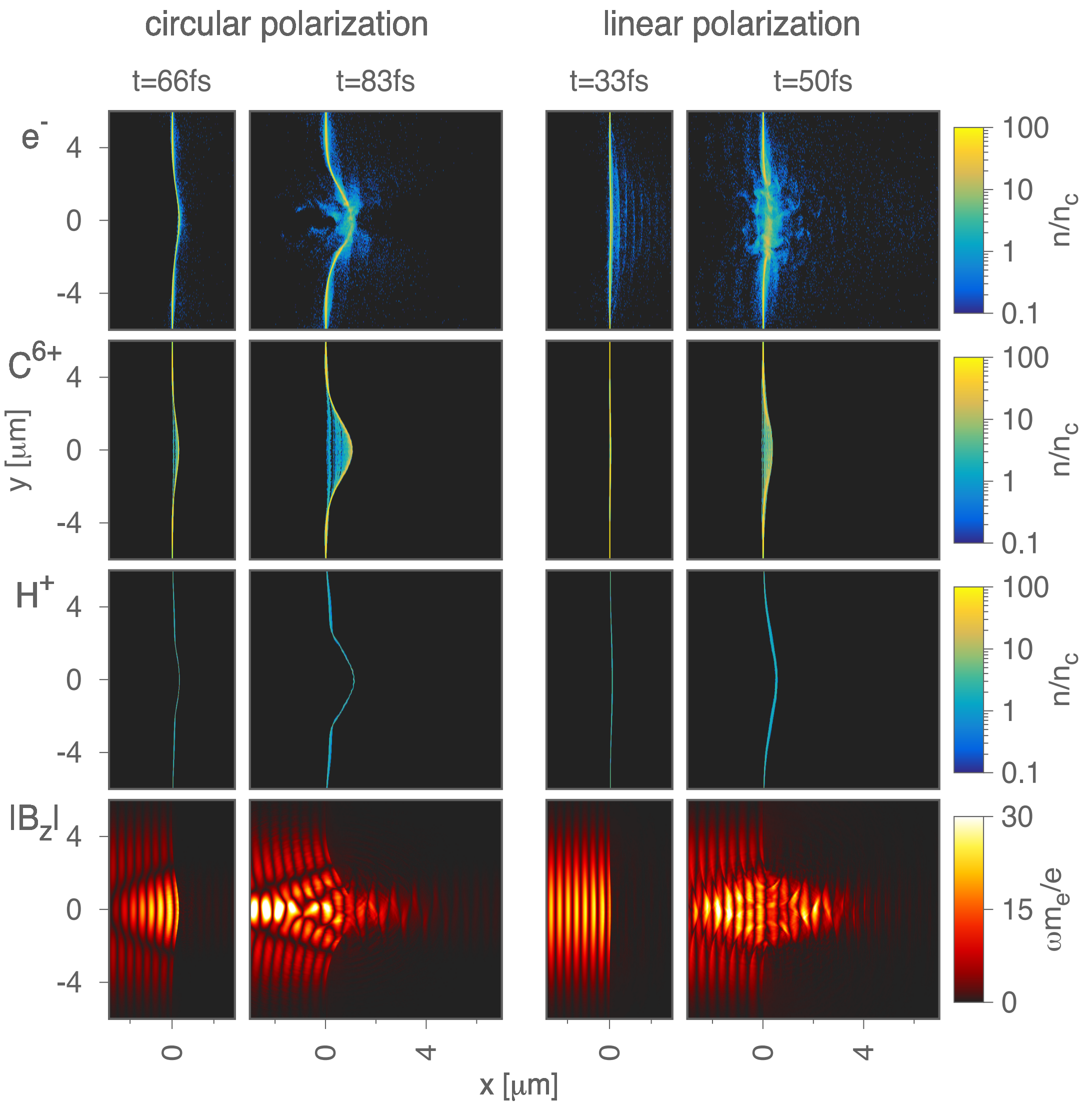
- Polarization dependent *cross*-over for the thinnest targets
- First time that circularly polarized pulse provide higher energy than linearly polarized



2D PIC simulations for C6+

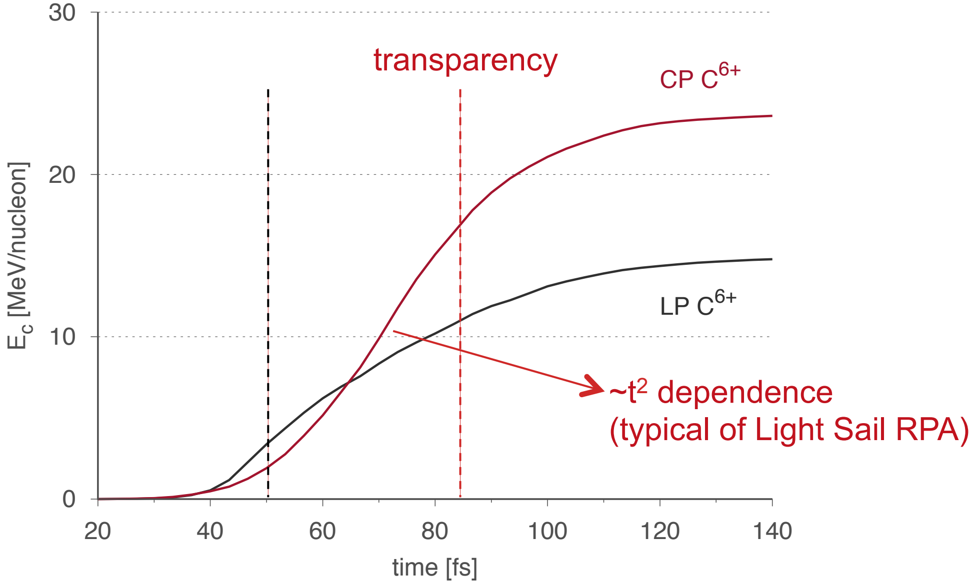
3D PIC simulations clarify the acceleration scenario

See A.McIlvenny's poster

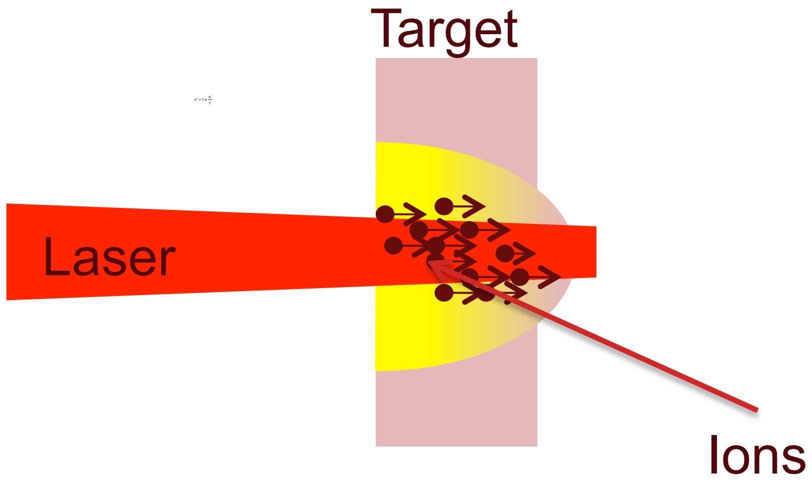


Linear polarization:
strong heating,
early transparency,
target decompression

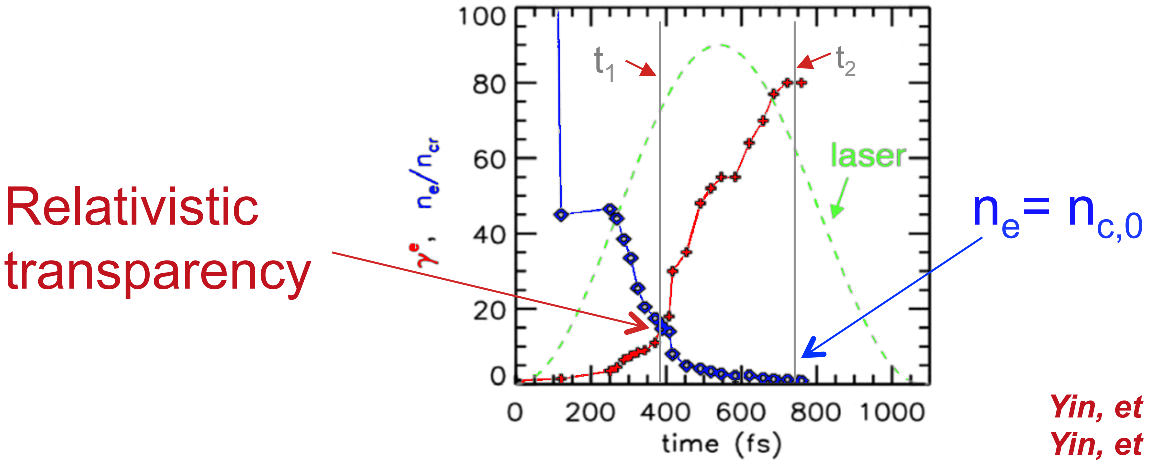
Circular polarization:
Opacity maintained for longer
Radiation pressure applied more efficiently



Ion acceleration in the relativistic transparency regime



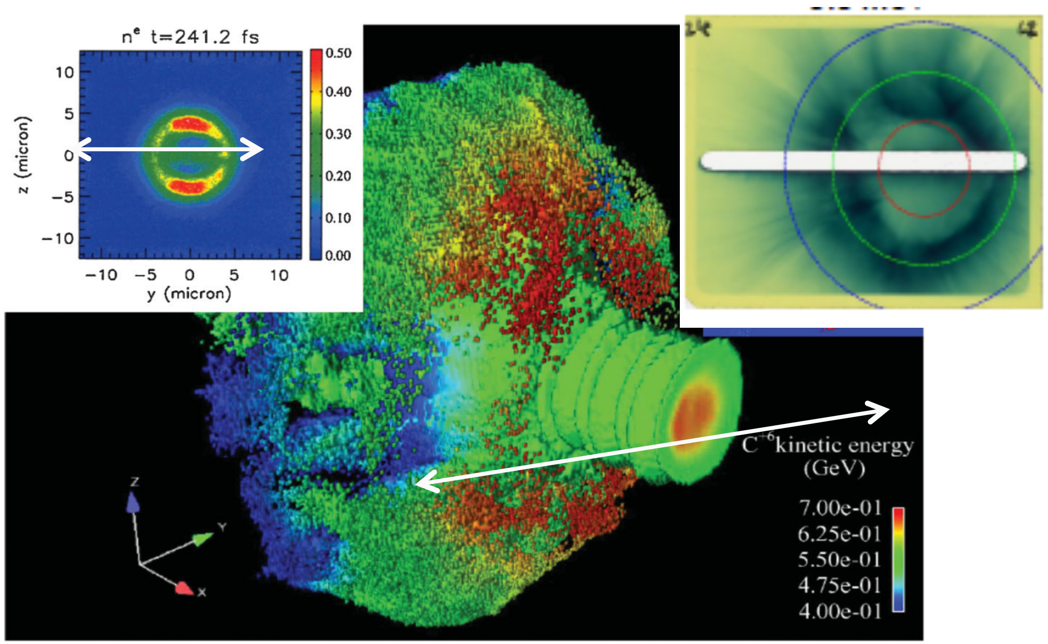
- ☐ Thin targets <<1μm
- ☐ Acceleration from bulk/volume



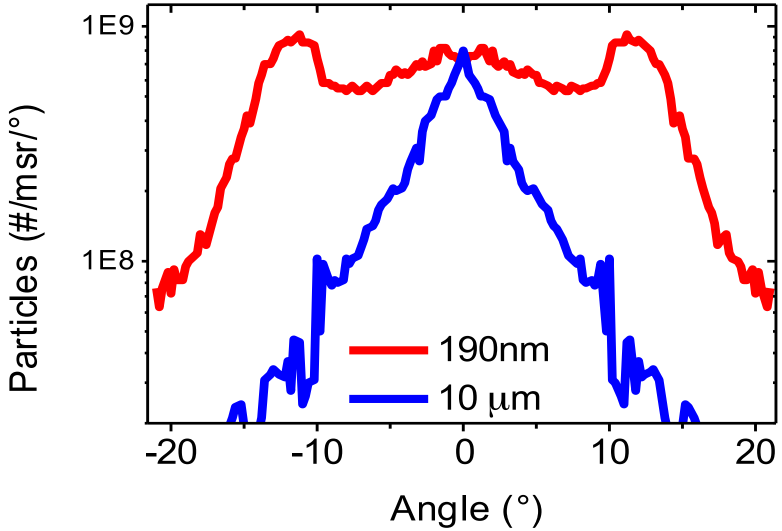
If the laser intensity peaks just after transparency, an enhanced electron heating, and an enhanced coupling of energy into ions is observed. This process has been named Break Out Afterburner (BOA)

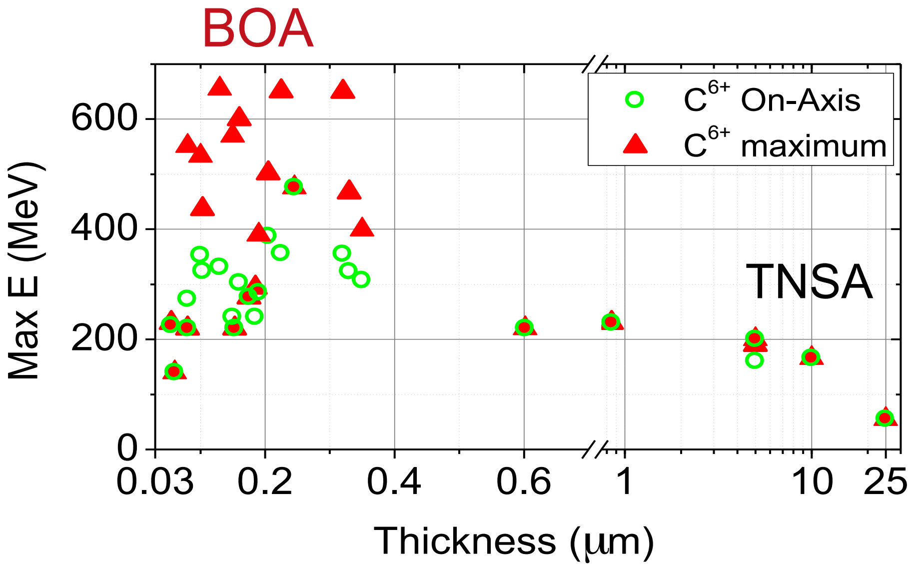
Yin, et al., Laser and Particle Beams 24 (2006),
Yin, et al., Phys. Rev. Lett. 107, 045003 (2011)
Yin, et al., Phys. Plasmas 18, 063103 (2011)

Relativistic transparency regime – Break Out Afterburner



[1]L. Yin, et al., Phys. Rev. Lett. 107, 045003 (2011)





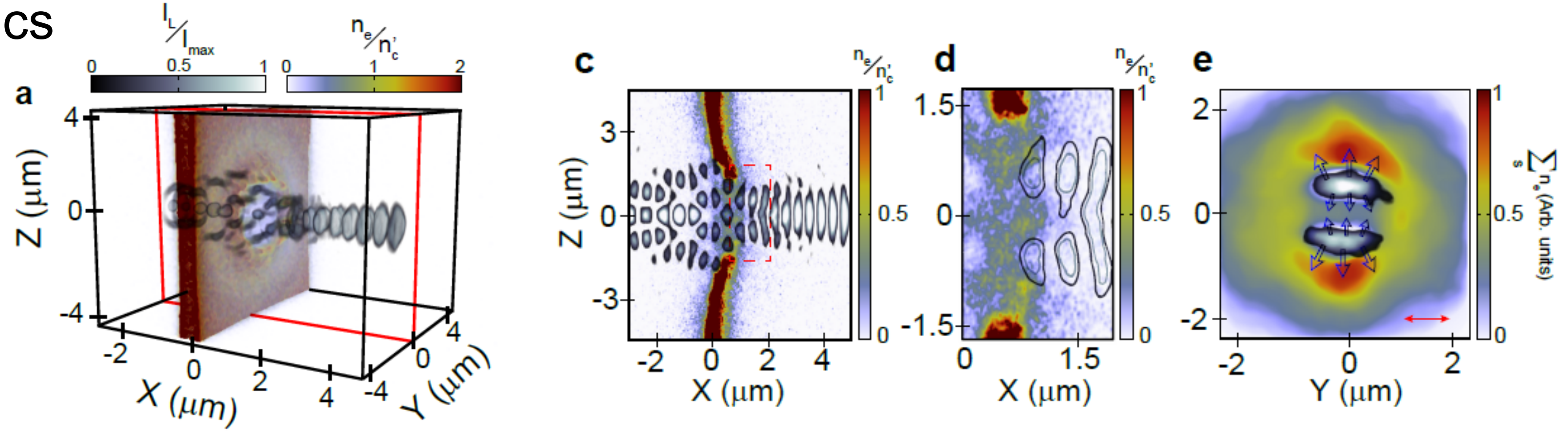
D.Jung *et al*, NJP, **15**, 023007 (2013)

This regime is characterized by a ring-like angular profile with off-axis energy maxima, which are thickness dependent for fixed laser conditions.

Spectra are broadband and continuous.

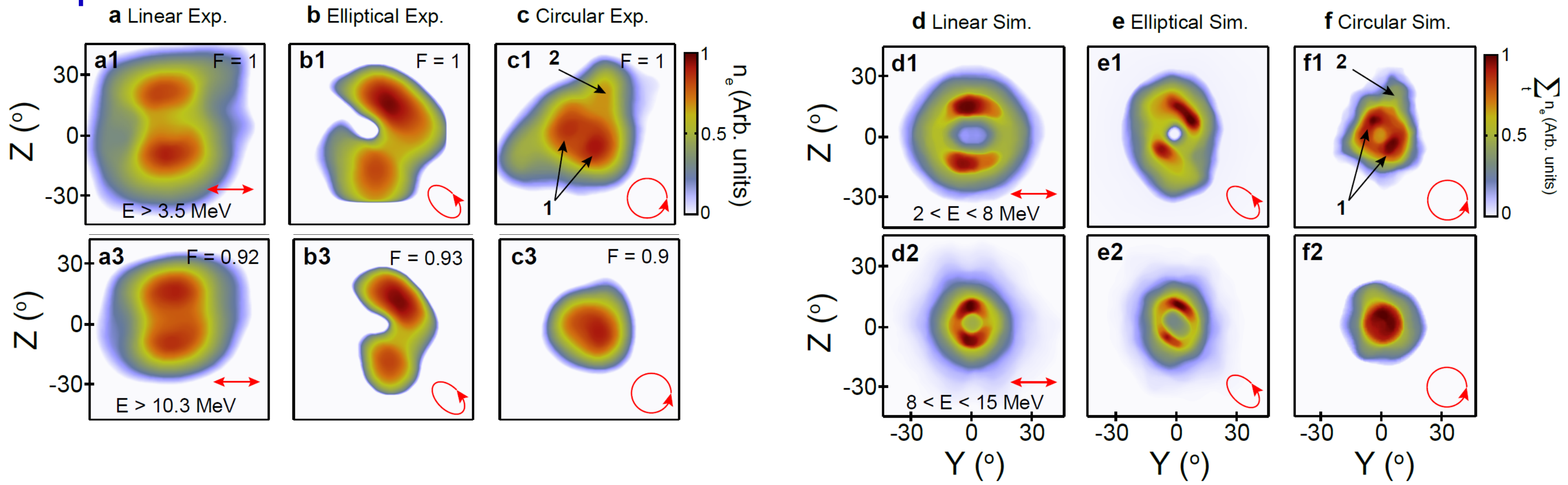
Collective electron response to the onset of relativistically induced transparency

Laser diffraction is shown to play an important role in collective charged particle dynamics



Experiment:

3D PIC simulation:



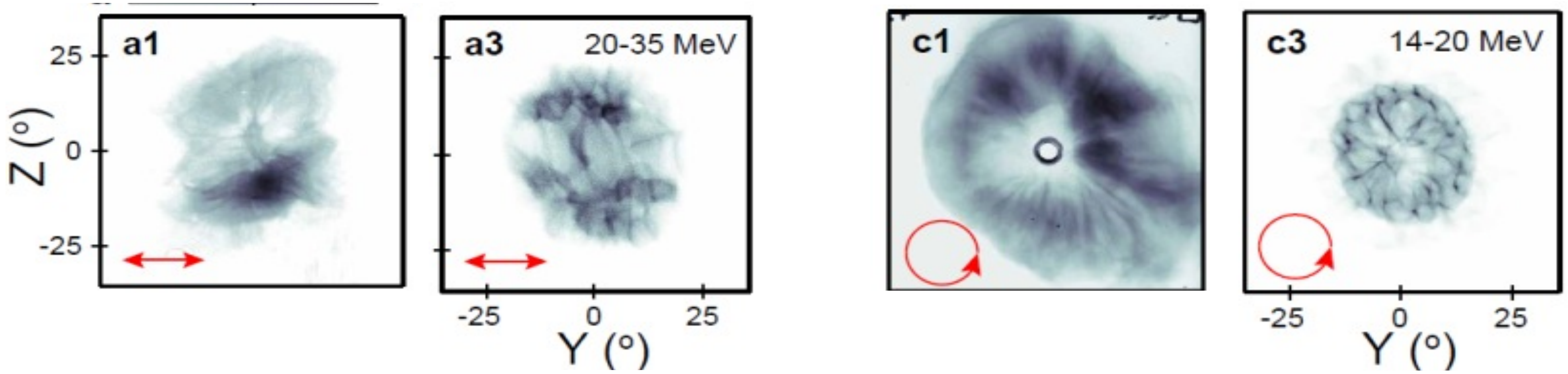
B. Gonzalez-Izquierdo et al., Nature Physics, **18**, 505 (2016)

Electron structure can be transferred to accelerated ions

B. Gonzalez-Izquierdo et al, Nature Comms. **7**, 12891 (2016)

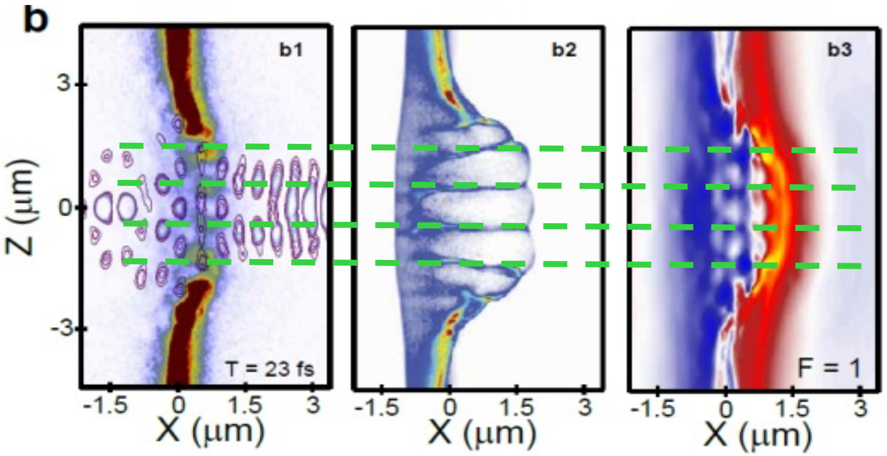
Linear pol. | Circular pol.

Experiment | 3D PIC simulation | Experiment | 3D PIC simulation

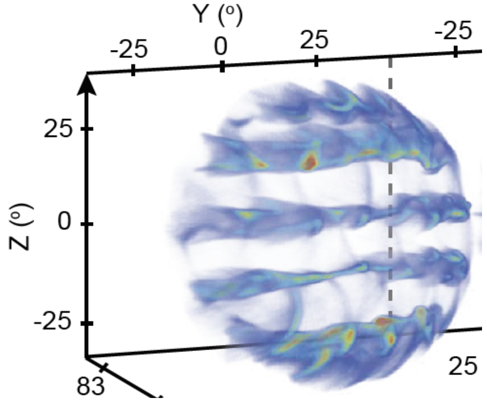


Electron density structure mapped into the proton beam via modulation of the electrostatic field

Electrons: | Protons: | E-field:

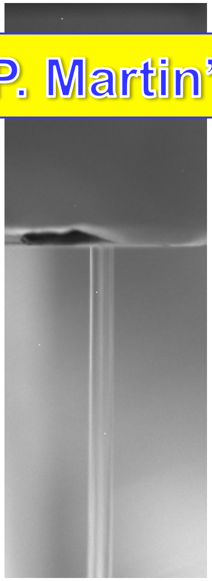


Proton beam profile:



Also important: development of technology allowing high repetition operation

Cryogenic targetry



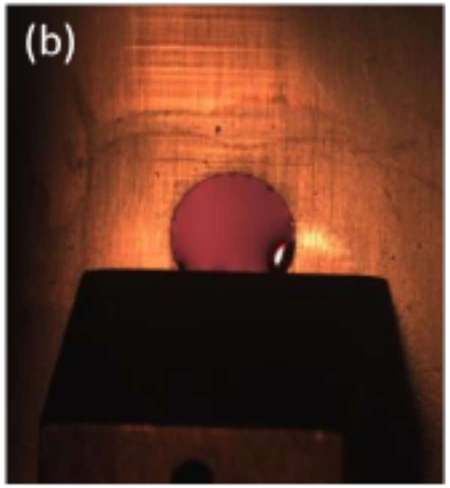
See P. Martin's poster

Pure hydrogen target
Continuous flow
Intermediate density

M.Gauthier, et al, RSI, 87, 11D827 (2016)
D.Margarone et al, PRX, 2016

Also liquid jets, dense gas jets

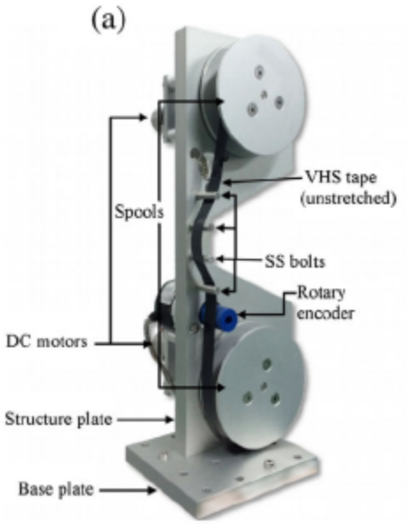
In-situ target forming



Liquid crystal technology
Self-forming targets in situ (µm precision)

D.W. Schumacher, et al, JINST, **12**, C04023, (2017)

Mechanical refreshment



Tape targets

M. Noaman-ul-Haq et al, PRSTAB, **20**, 041301 (2017)
M. Nishiuschi et al, APL, **94**, 061107 (2009)