Laser-driven ion acceleration from ultra-thin foil targets

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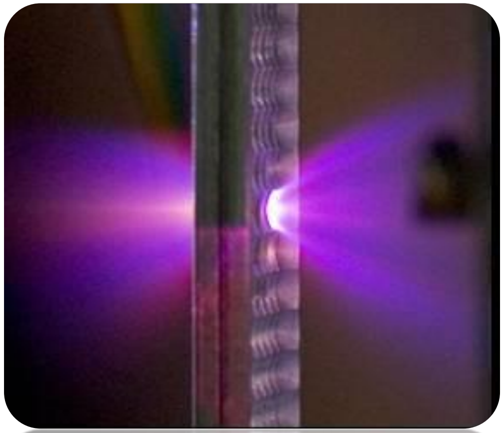


A-SAIL

ADVANCED STRATEGIES FOR ACCELERATING IONS WITH LASERS

PROGRAMME GRANT

(2013-2019)

EPSRC

Pioneering research and skills

Queen's University Belfast
University of Strathclyde
Imperial College London
CLF RAL - STFC

1. Laser-ion acceleration – M Borghesi, QUB

- Proton and ion energy generation
- Spectral control
- Low divergence beam

2. Underpinning physics – P McKenna, Strath

- Understanding of the acceleration mechanisms and related physics
- Optimisation of source parameters

3. Technology developments – D Neely, CLF

- Laser development
- Targetry development
- Beam delivery
- Dosimetry

4. Radiobiology – K Prise, QUB

- Biological effectiveness RBE of high doses
- Testing clinically relevant dose delivery patterns

ASAIL programme towards laser-ion oncology

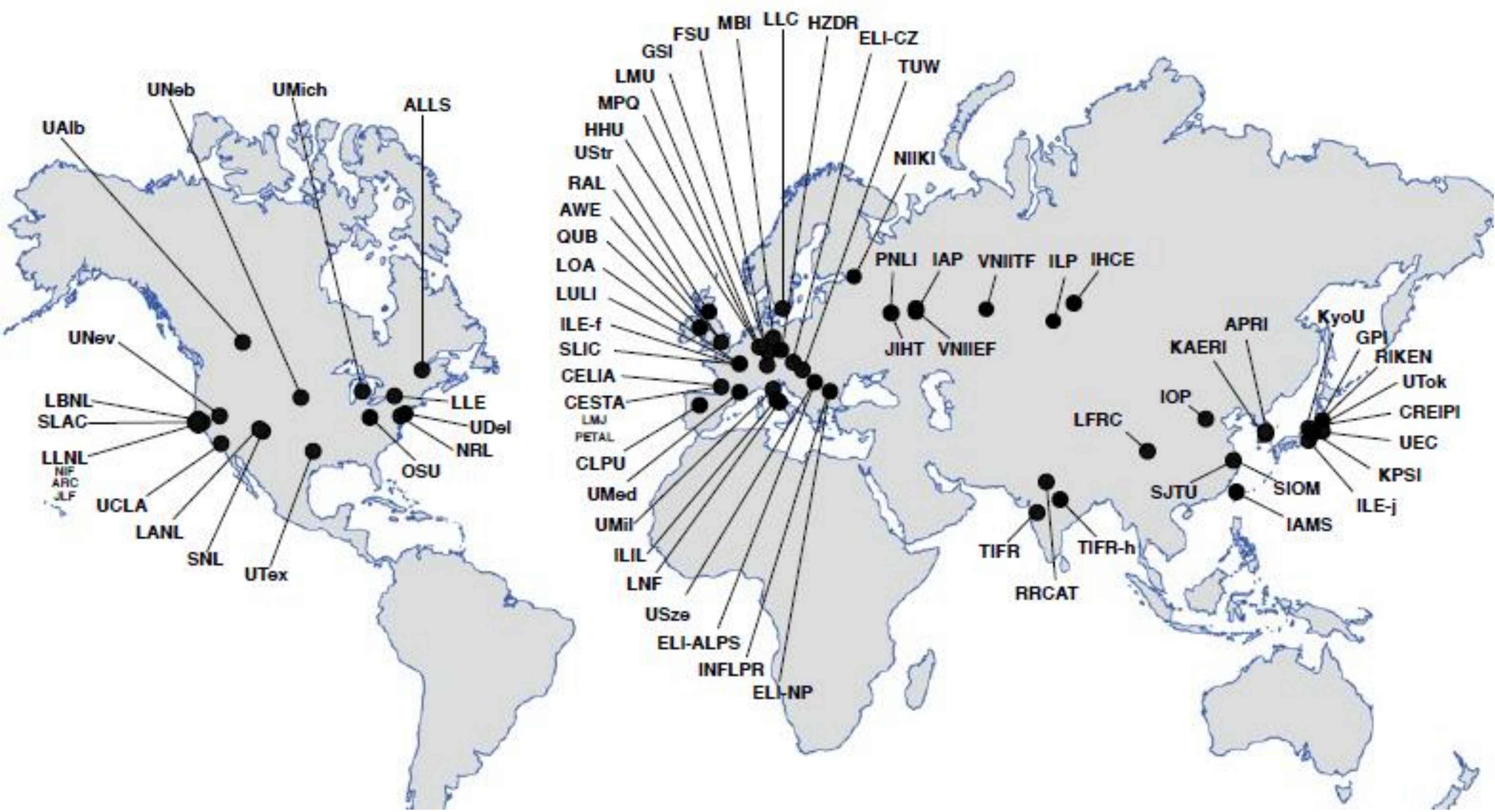
Talk overview

- Introduction to ion acceleration from laser-irradiated foils
  - TNSA and optimisation strategies
  - Transition to volumetric ion acceleration schemes
- Radiation pressure acceleration
  - Underpinning physics and predictions
  - Energy scaling experiment results
- Transparency-enhanced acceleration
  - Underpinning physics: collective plasma response
  - Jet formation and enhanced energy coupling
  - Diagnosing intra-pulse transition between acceleration mechanisms
  - Using diffraction to control ion acceleration
- Towards ultra-intense laser-driven ion acceleration

Laser-plasma acceleration offers the potential for compact accelerators

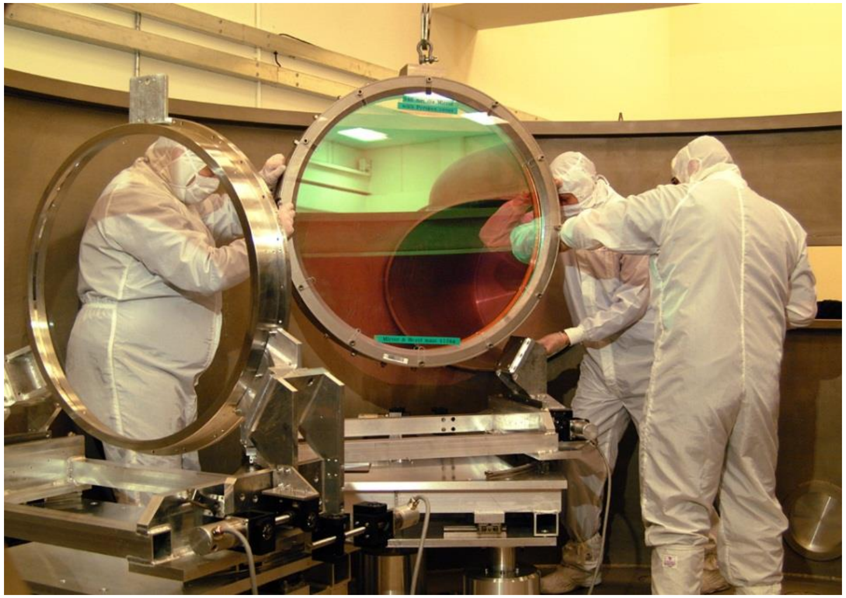
- RF acc. fields 10-100 MV/m
- Laser-plasmas 10^3-10^4 higher
- Will these machines really be smaller and cheaper?

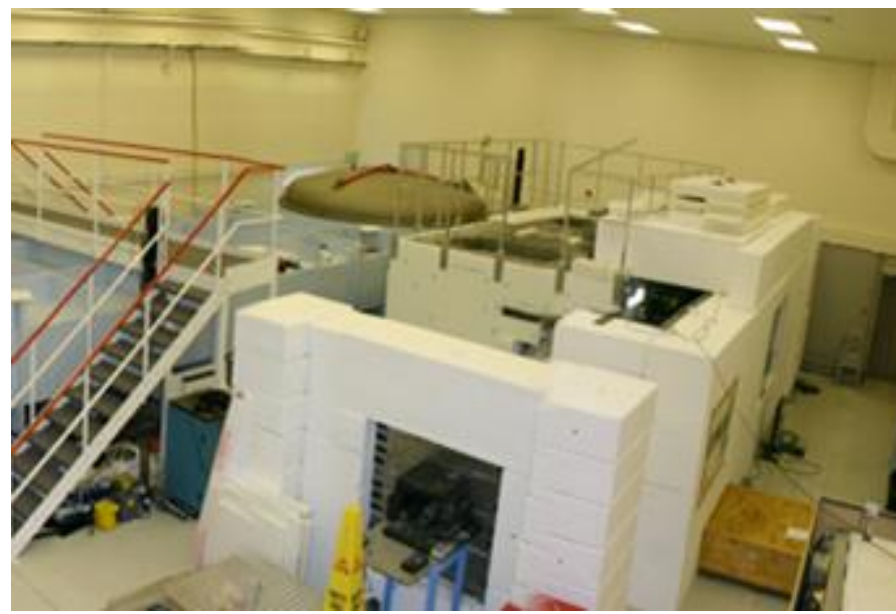
Laser-plasma accelerator activity worldwide



adapted from ICUIL

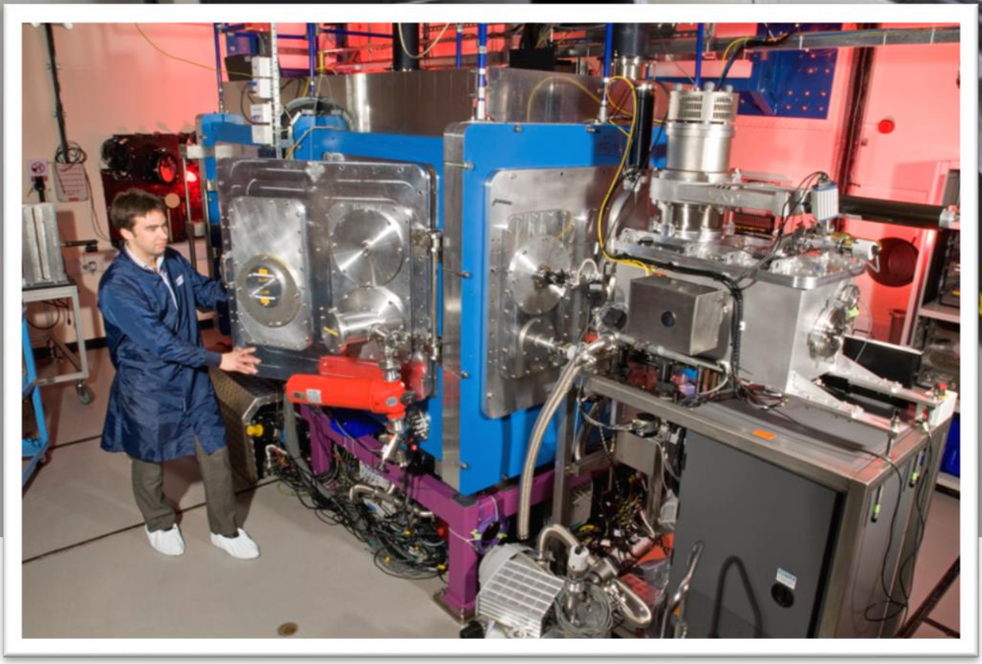
Laser systems: High intensity, e.g. Vulcan





Power	1 PW
Energy	>500 J
Wavelength	1.05 μm
Pulse duration	0.5 ps (+ 6 x 5ns beams)
Intensity	~10^{21} Wcm^{-2}
Repetition	8 to 10 shots / day

Laser systems: Ultra-short, e.g. Astra-Gemini



Power	0.5 PW
Energy	>6 J (on target)
Wavelength	0.8 μm
Pulse duration	35 fs
Intensity	~10^{21} Wcm^{-2}
Repetition	3 shots / minute

Scottish Centre for Applications of Plasma Accelerators

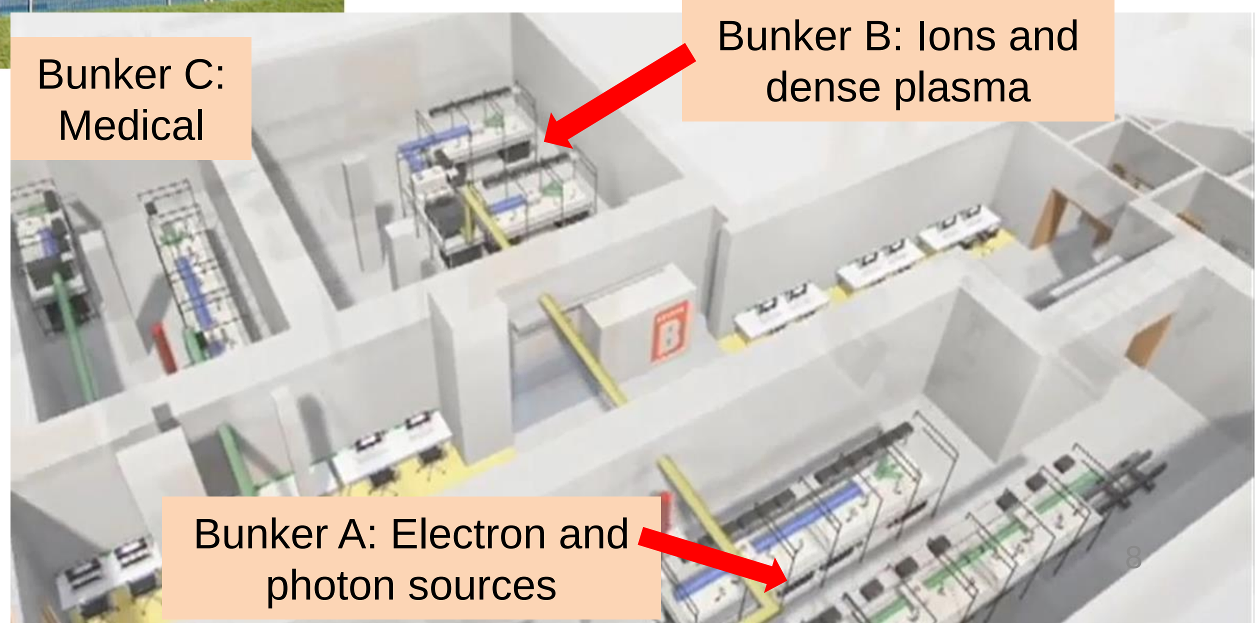
paul.mckenna@strath.ac.uk; Cockcroft

New extension to the Physics building completed

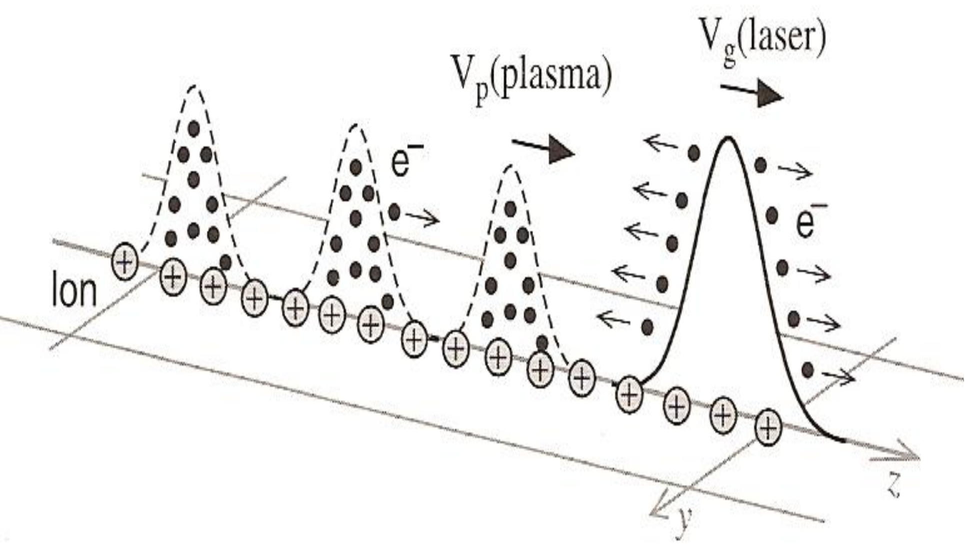
350 TW laser to be commissioned January 2017

3 shielded bunkers:

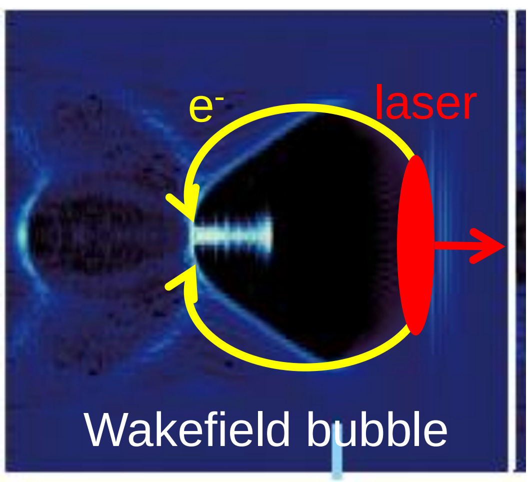
- Electron acc and radiation
- Ion acc and dense plasma
- Medical applications



Laser wakefield plasma electron accelerator



Electrons 'surf' a plasma wave

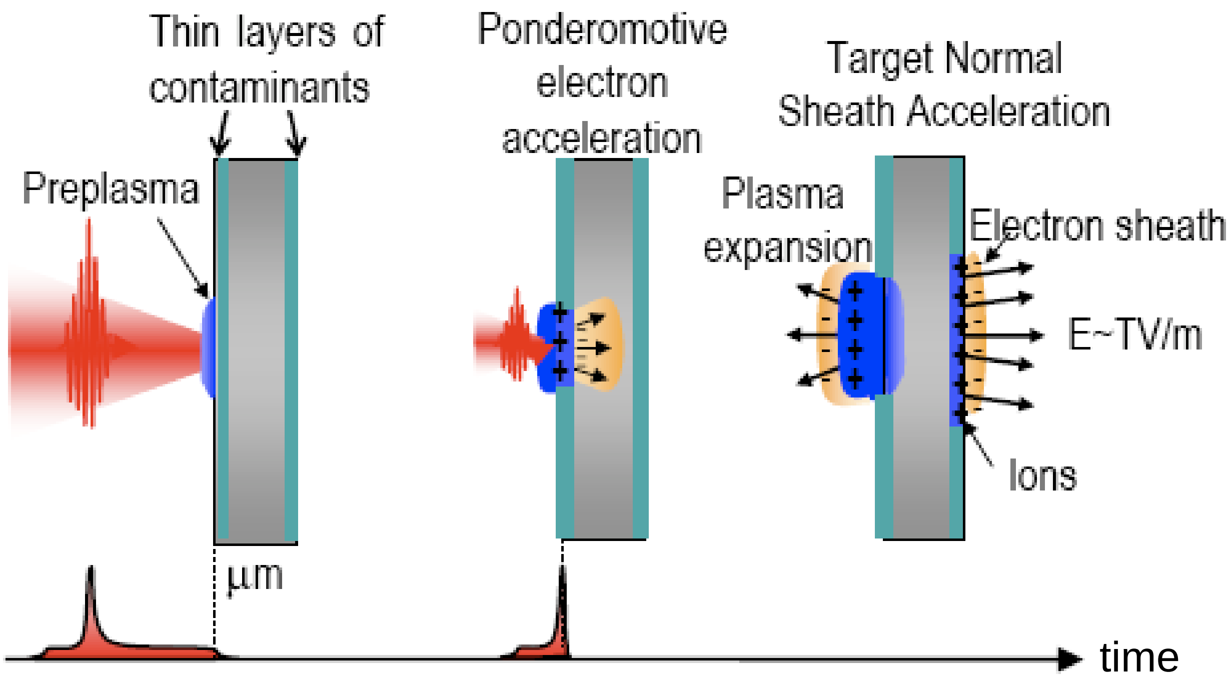


- Electron beam quality, dE/E ~1%
- Very stable
- Energy is tunable ~4.2GeV demonstrated
- Charge is tunable tens of pC
- Low divergence: 2mrad
- Low emittance: π.mm.mrad
- Driver of energetic photon sources
- Phase contrast imaging application

Surfing in the wake of a boat

Target normal sheath acceleration

(in micron-thick targets)

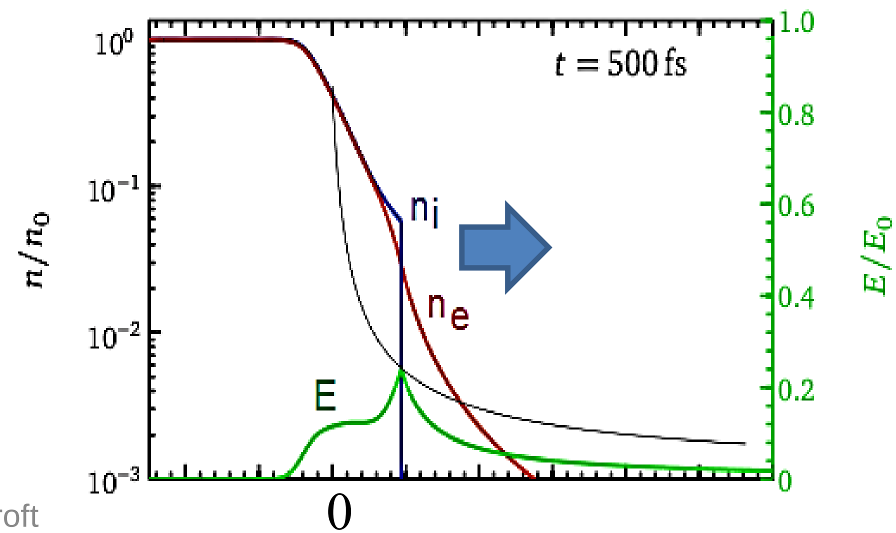


Clark et al, PRL, 84 ,670 (2000)

Maksimchuk et al, PRL, 84, 4108 (2000)

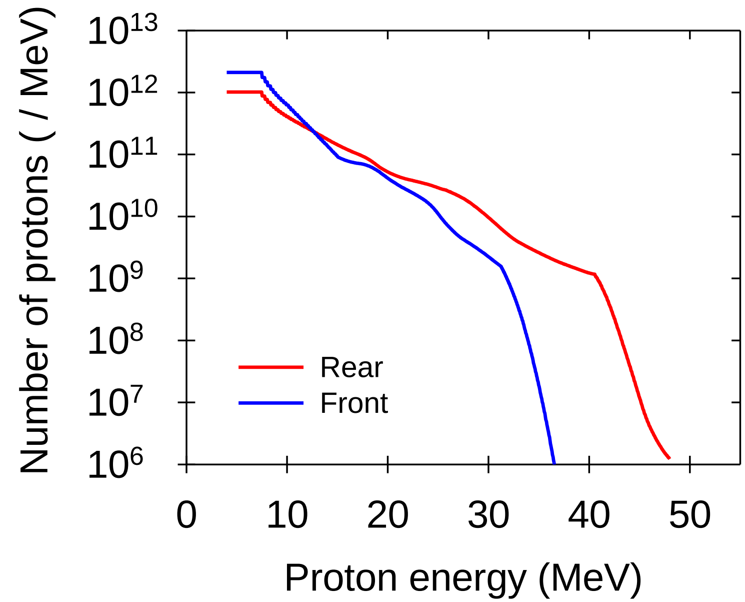
Snavely et al, PRL, 85,2945 (2000)

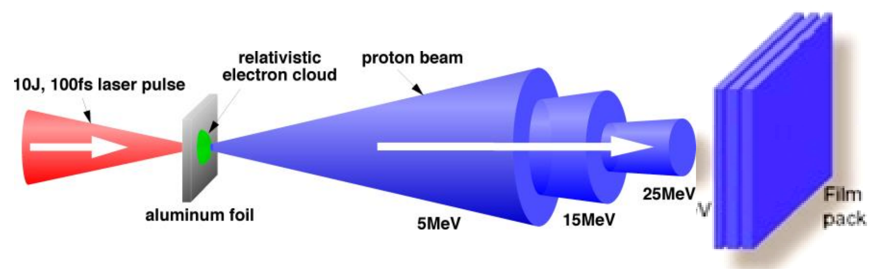
Wilks et al, PoP, 8, 542 (2001)

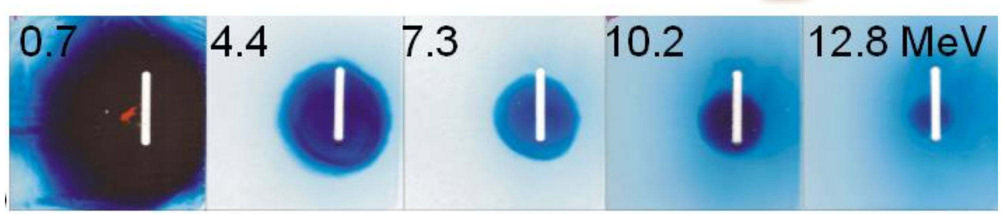


TNSA beam properties

- Maximum energy: ~90 MeV protons (~10 MeV/nucleon ions);
- Typically >10^{12} protons per pulse (laser energy dependant);
- Bunch duration: tens of fs-ps at source (laser duration dependant);
- Source size ~20-100 μm (laser duration dependant);
- Emittance $\varepsilon_N < 0.005\pi$ mm.mrad



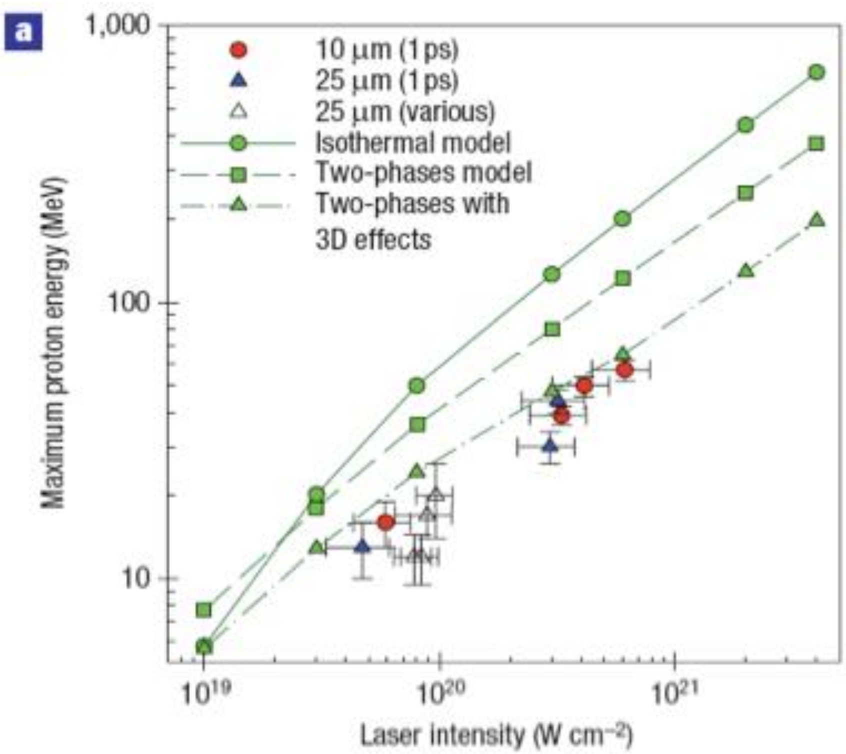


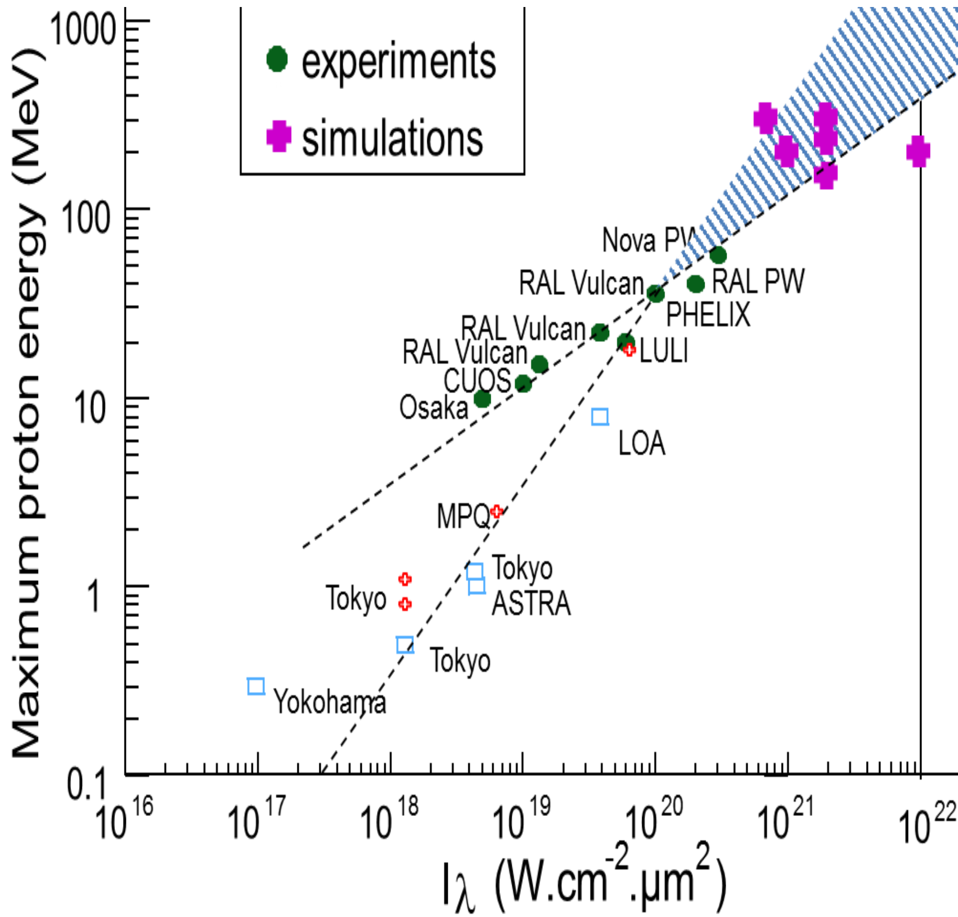


TNSA-ion energy scaling

Typically the maximum ion energy scales with $(I_L\lambda^2)^{1/2}$

Fluid models (plasma expansion)
P.Mora, PRL, **90**,185002 (2003)

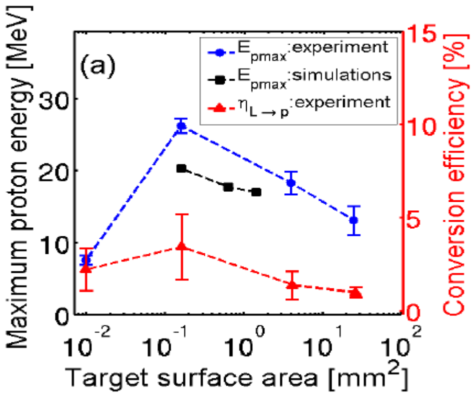


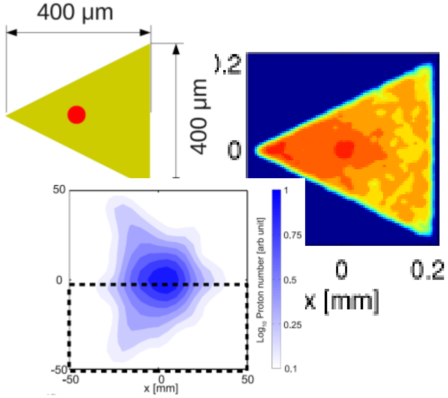


L Robson,…, P McKenna,
Nature Phys.,**3**, 58 (2007)

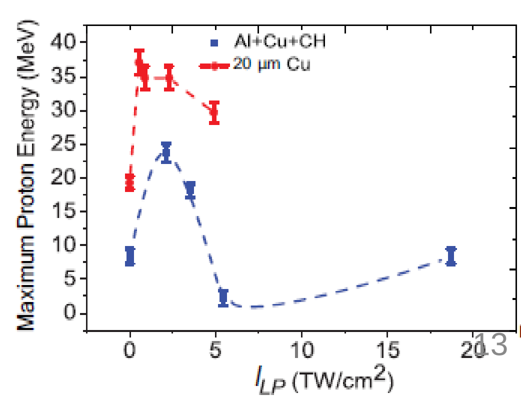
TNSA optimisation and control strategies

- Reduction of foil thickness
  D. Neely et al, APL, 89, 021502 (2006)
- Reduced mass targets
  S. Buffechoux et al, PRL, 105, 015005 (2010)
  O. Tresca et al, PPCF 53, 105008 (2011)
- Target structuring for enhanced coupling
  D. Margarone et al, PRL, 109, 234801 (2012)
  S. Gaillard et al, PoP, 18, 056710 (2011)
  J.H. Bin et al, PRL, 115, 064801 (2015)
- Multipulse for enhancing energy coupling
  C. Brenner et al, APL, 104, 081123 (2014)
- Multi-pulse for shaping the proton beam
  B. Aurand et al, PoP (2015)
- Controlled plasma scale length
  R. Gray et al, NJP, 16, 113075 (2014)



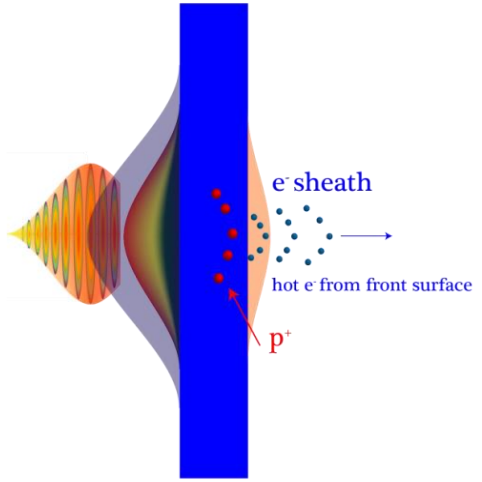


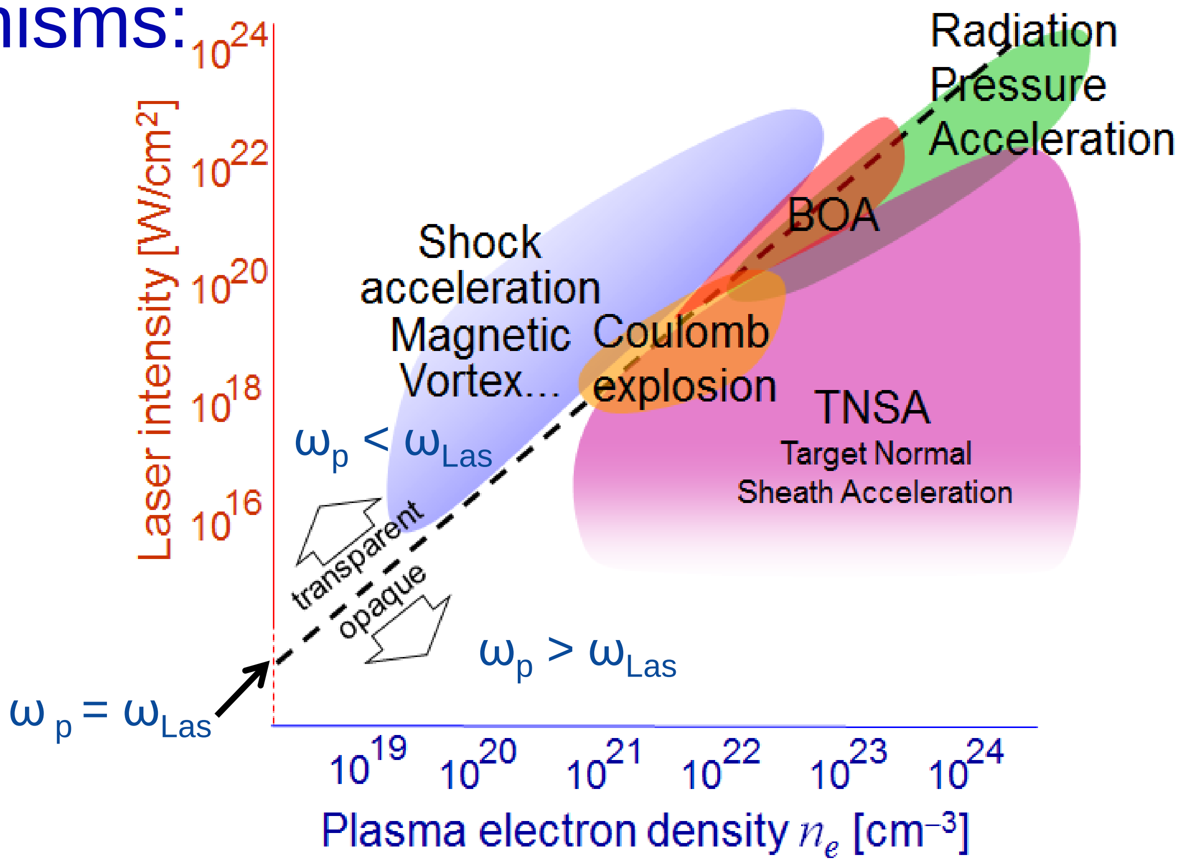
Tresca et al PPCF 53, 105008 (2011)



Acceleration mechanisms:

Sheath (surface) acceleration:
(in micron-thick targets)





In the interaction of a laser pulse with plasma, electrons collectively quiver around the (almost) stationary ions $\Rightarrow$ plasma oscillations

Electron plasma frequency:

$$\omega_{\text{plasma}} = \sqrt{\frac{e^2}{\varepsilon_0} \frac{n_e}{m_e}}$$

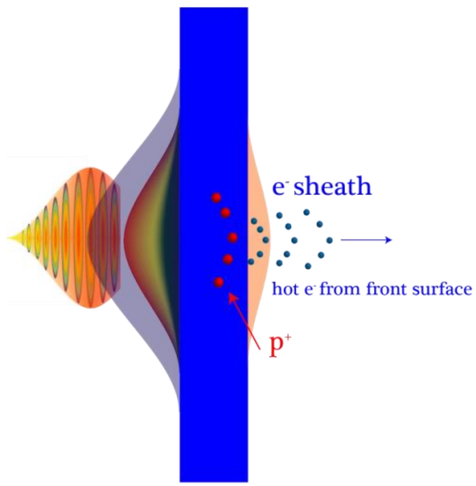
n_e ← Electron density

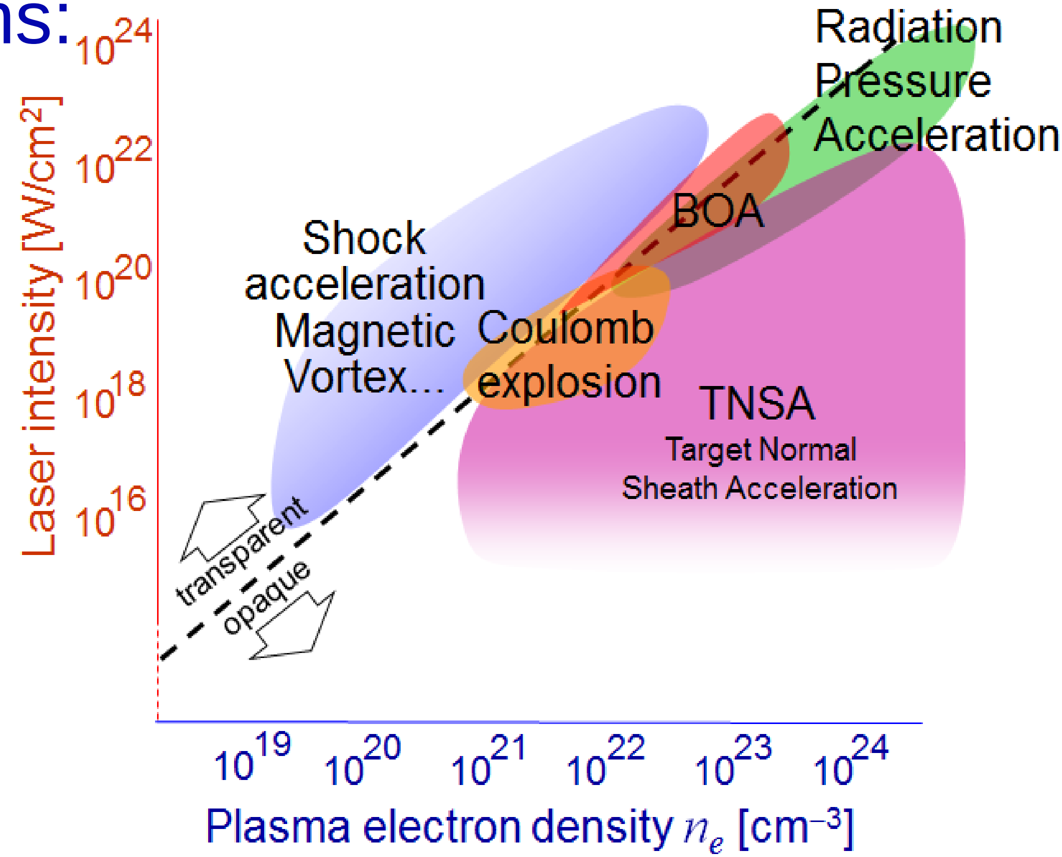
m_e ← Electron mass

If $\omega_{\text{plasma}} > \omega_{(\text{Laser})}$ the plasma electrons can follow the light oscillations and therefore cancel the light propagation.

Acceleration mechanisms:

Sheath (surface) acceleration:
(in micron-thick targets)

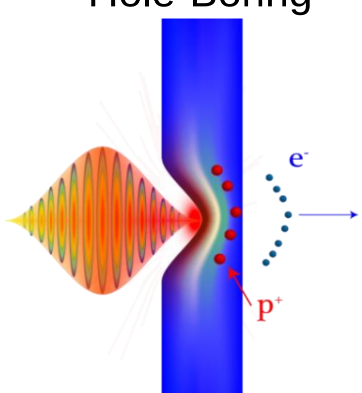




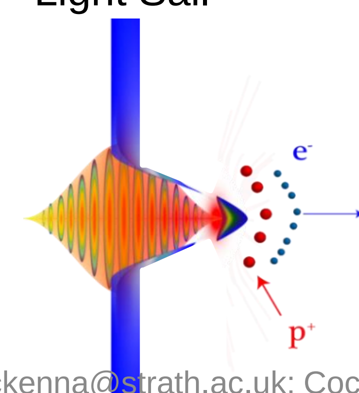
Volumetric acceleration:
(in nanometre-thick targets)

Radiation pressure acceleration

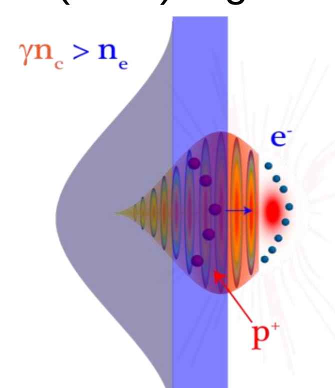
Hole-Boring



Light Sail



Relativistic transparency
(BOA) regime



Laser radiation pressure acceleration

Radiation pressure via Photons

Photon flux (no. of photons per sec per unit area; units $cm^{-2}s^{-1}$): $F_{ph} = \frac{I}{\hbar\omega}$

Momentum flux or Pressure (force per unit surface):

$$P_{rad} = \hbar k F_{ph} = \frac{Ik}{\omega}$$

EM waves carry momentum. Radiation pressure is the flow of delivered momentum per unit surface

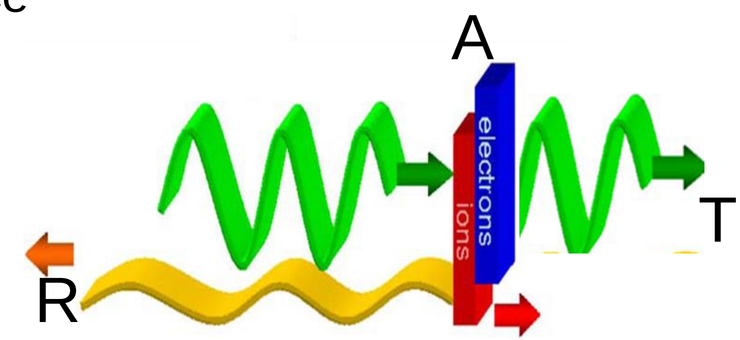
Reflection Transmission

$$P_{rad} = (1 + R - T)\frac{I}{c}$$

Intensity

$$= (2R + A)\frac{I}{c}$$

Absorption



$$(R + T + A) = 1$$

T. Esirkepov et al, PRL 92 (2004)

A.P.L. Robinson et al, NJP 10 (2009)

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Light Sail for thin targets

$$F_R = (2R + A)S\frac{I}{c}$$

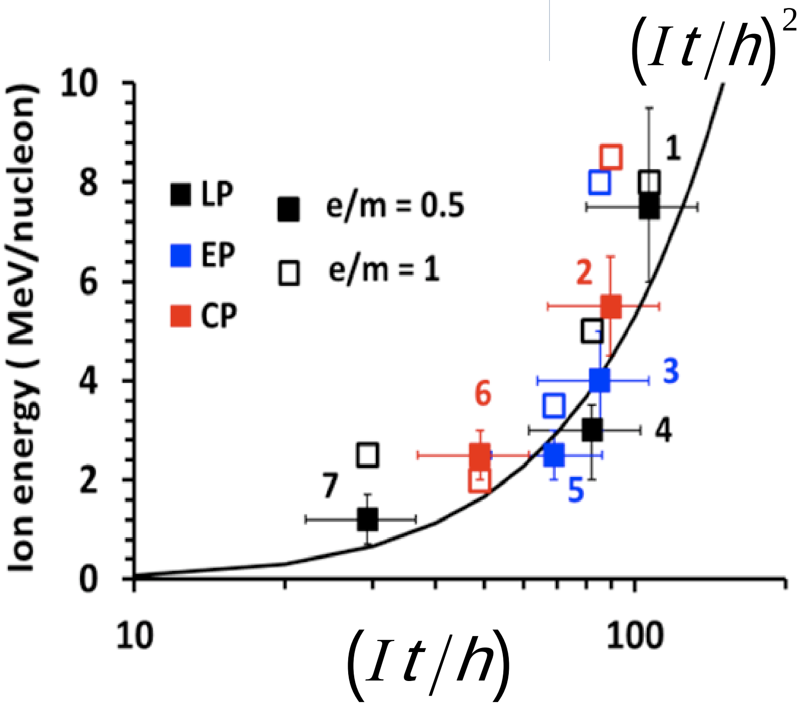
Surface Area

$$\Rightarrow v_i = \frac{(2R + A)\tau}{m_i n_i d}\frac{I}{c} \propto I\tau\eta^{-1}$$

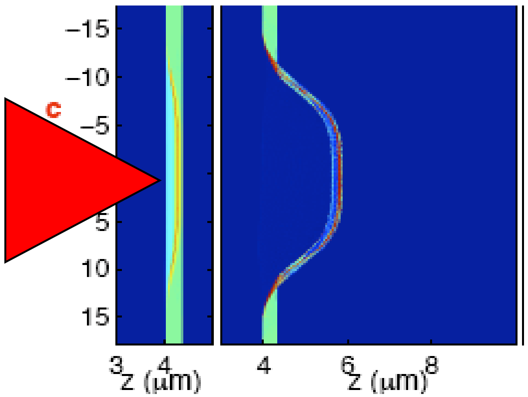
$$\eta = m_i n_i d$$

Areal density

$$E_{\max} \sim \left(I_L\,\tau/\eta\right)^2$$



S. Kar et al, PRL, **109**, 185006 (2012)



B. Qiao *et al,* Phys Rev Lett,**102,**145002 (2009)

- Fast scaling with laser intensity
- Narrow-band spectrum (whole-foil acceleration)
- Narrow divergence

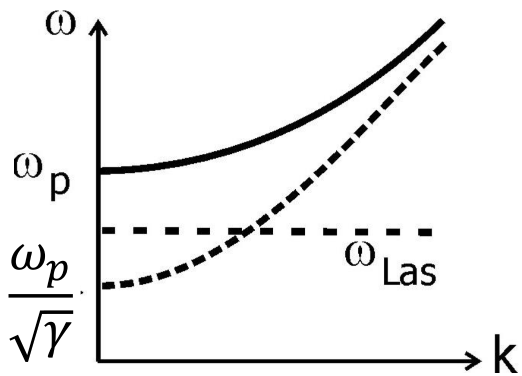
paul.mckenna@strath.ac.uk; Cockcroft

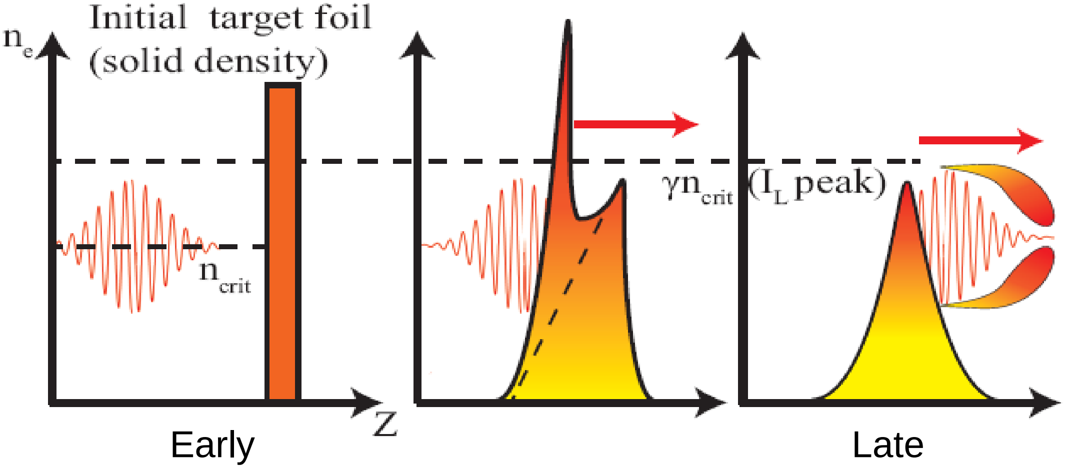
Onset of relativistic induced transparency due to increase in the electron mass

Plasma frequency:

$$\omega_p = \sqrt{\frac{e^2}{\varepsilon_0}\frac{n_e}{m_e}}$$

Transparency when $\omega_p < \omega_{Las}$:

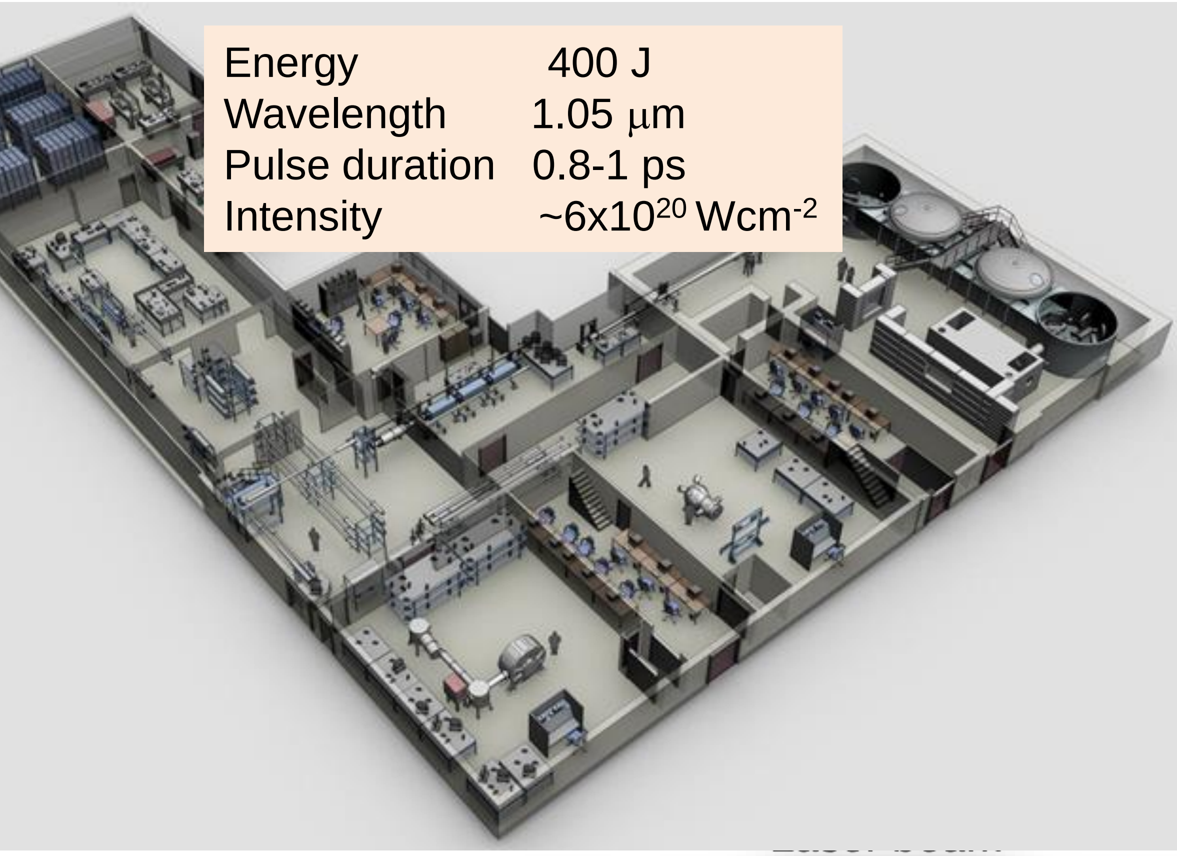


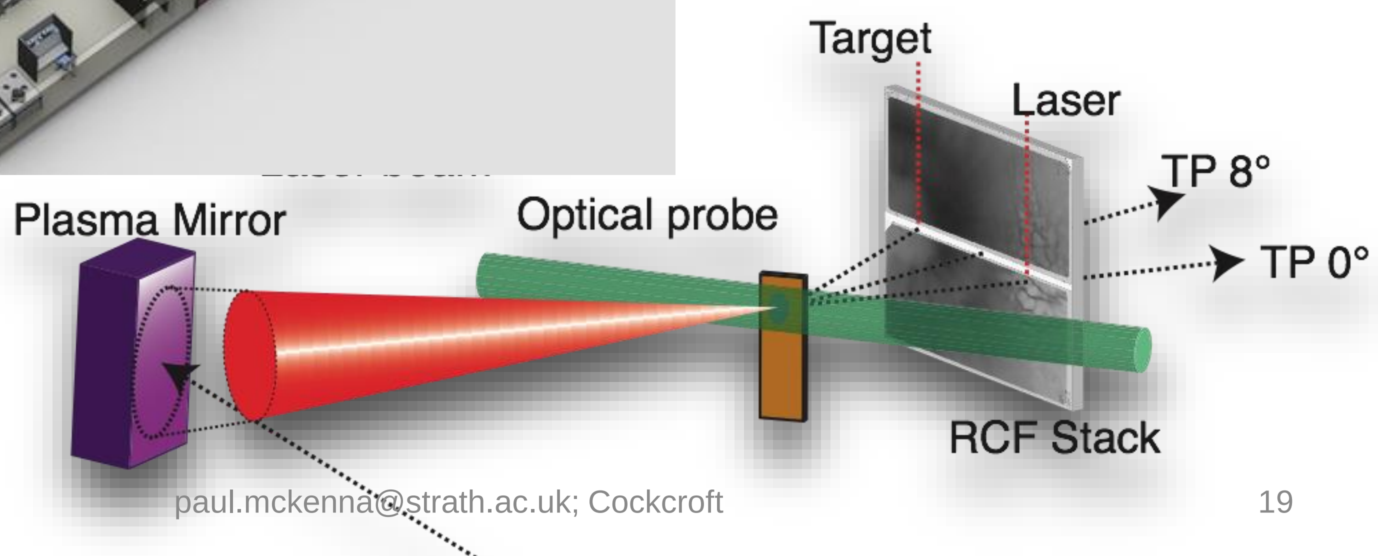


Ion acceleration from ultrathin foils on Vulcan

University of Strathclyde Glasgow

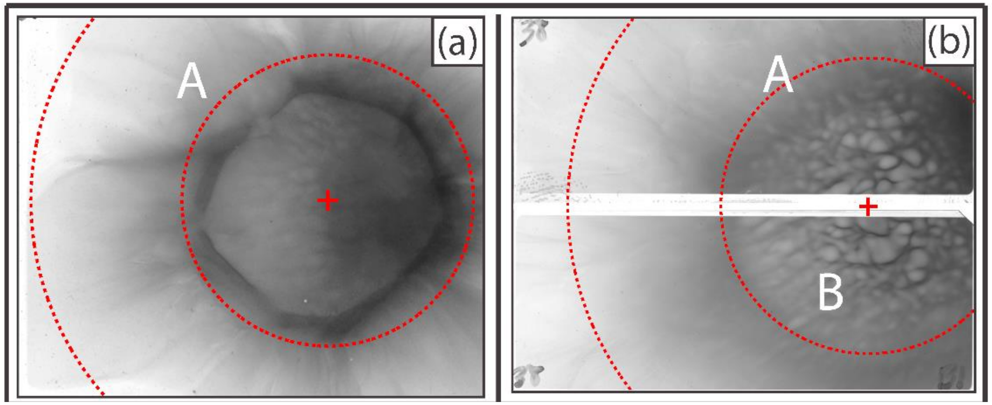
Energy	400 J
Wavelength	1.05 μm
Pulse duration	0.8-1 ps
Intensity	~6×10^{20} Wcm^{-2}

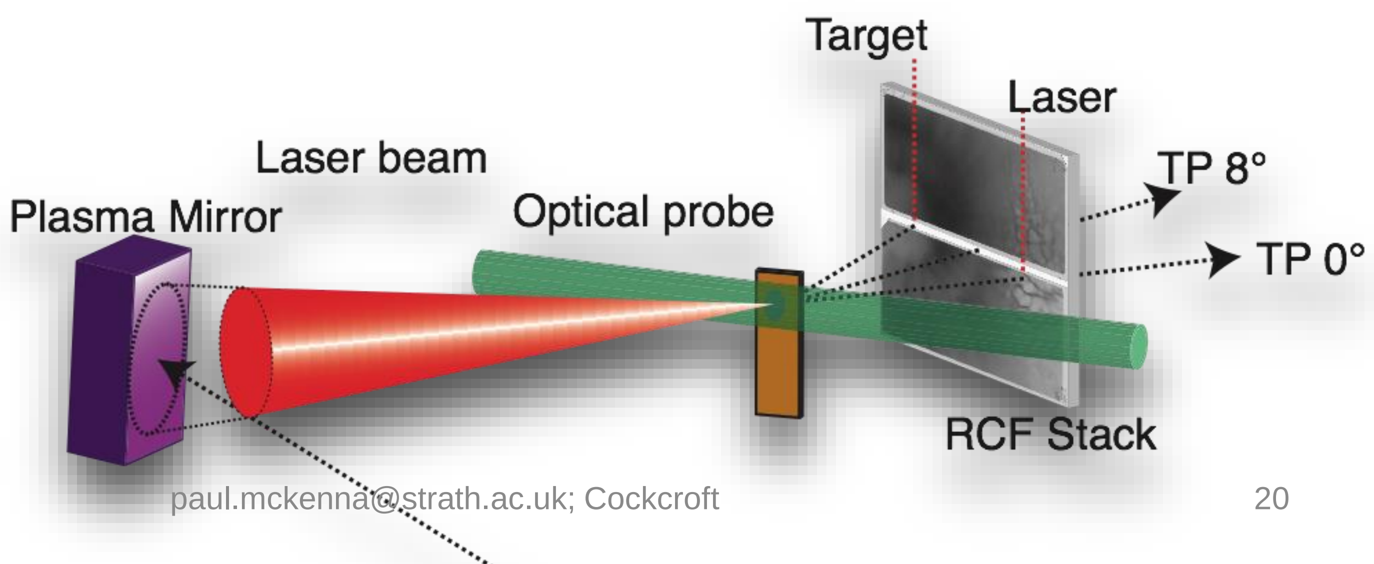




Proton spatial-intensity distribution in ultrathin foils undergoing transparency

10nm, 0 degrees 40nm, 0 degrees





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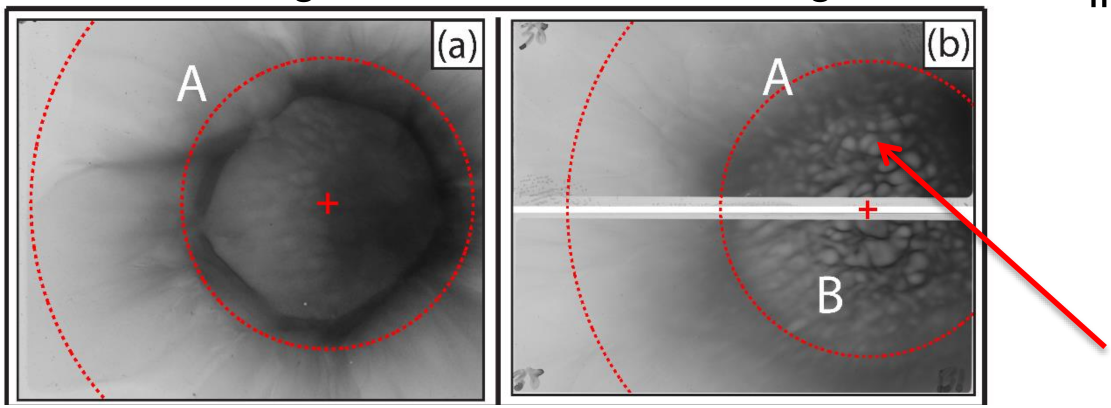
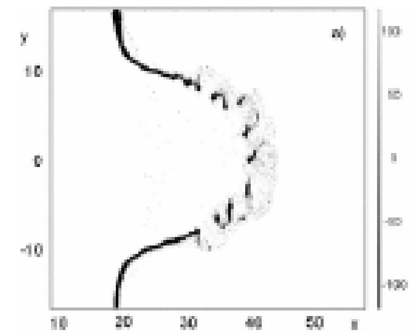
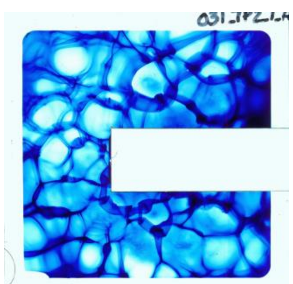


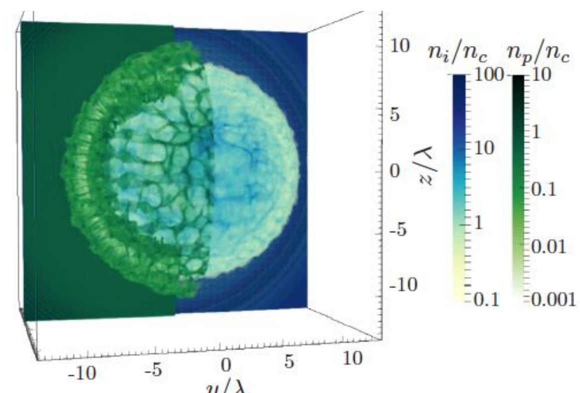
Rayleigh-Taylor-like instability – Unstable RPA



F.Pegoraro and S.V. Bulanov, PRL, **99**, 065002 (2009)



Previously observed experimentally by:
C. A. J. Palmer et al,
PRL **108**, 225002 (2012)

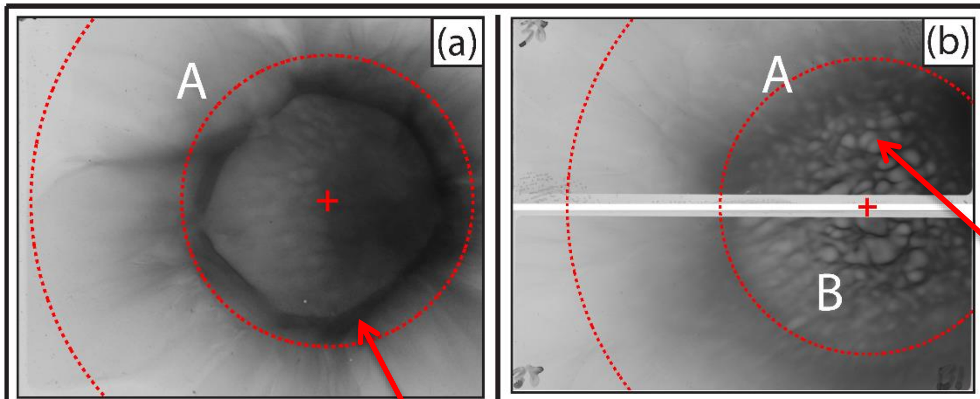


A.Sgattoni et al.,
PRE **91**, 013106 (2015)

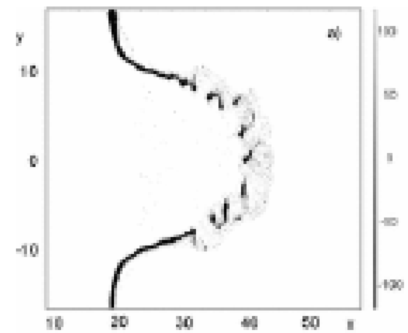
- 'R-T Instability occurs when a light fluid is accelerated into a heavy fluid'
  - Light "fluid" = photons of laser beam.
  - Heavy fluid = plasma of ionised target.

Proton spatial-intensity distribution in ultrathin foils undergoing transparency

10nm, 0 degrees | 40nm, 0 degrees

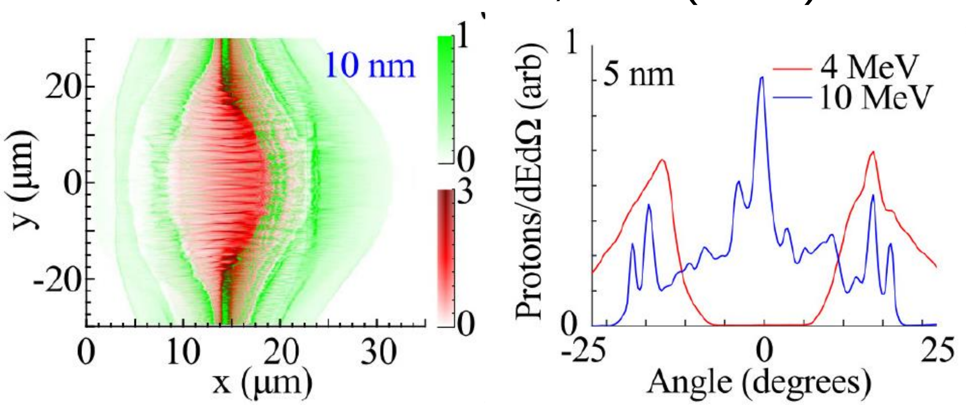


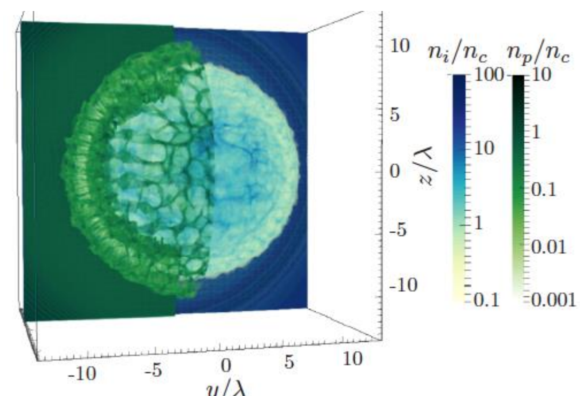
Rayleigh-Taylor-like instability – Unstable RPA



F.Pegoraro and S.V. Bulanov, PRL, **99**, 065002 (2009)

Buffered proton acceleration – N. Dover et al, NJP (2015)



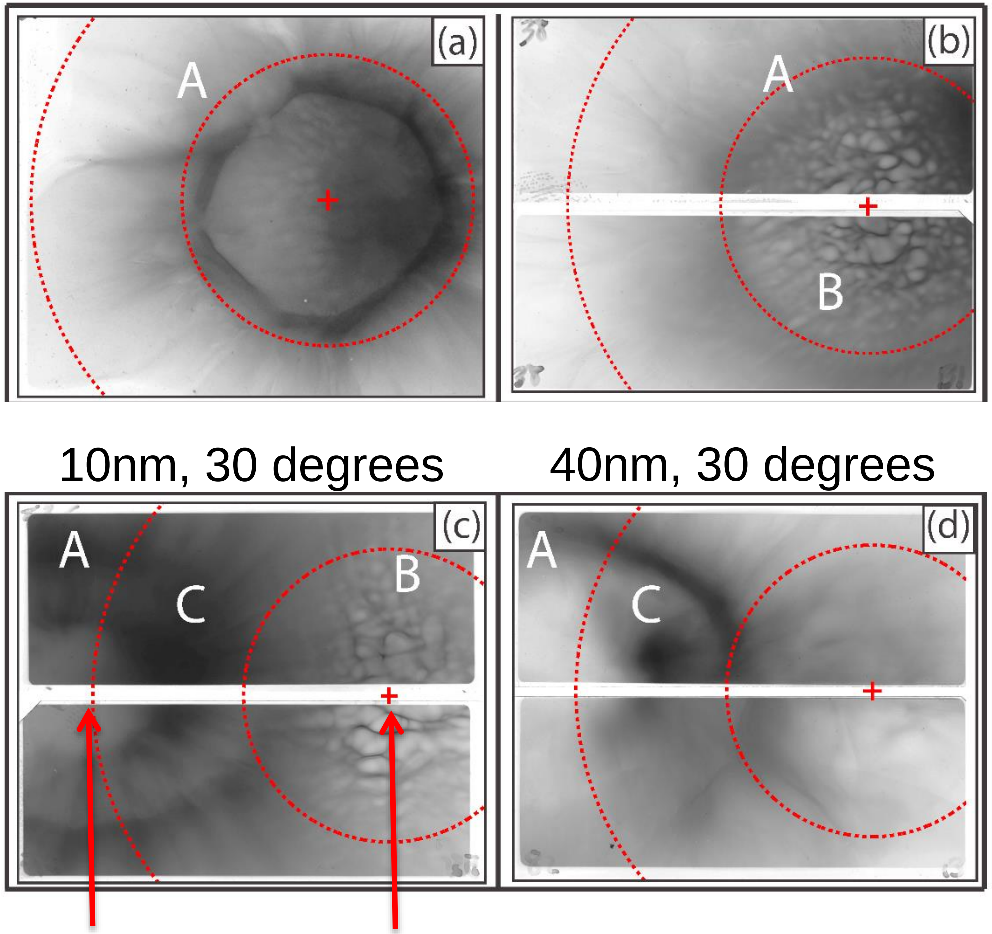


A.Sgattoni et al., PRE **91**, 013106 (2015)

Three proton populations angularly separated

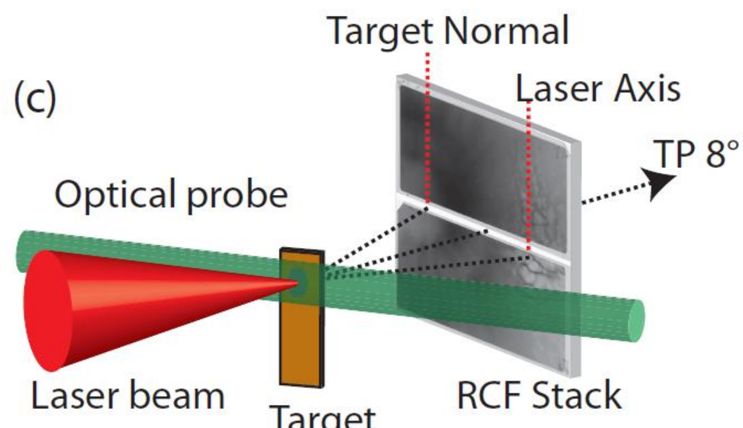
10nm, 0 degrees | 40nm, 0 degrees

10nm, 30 degrees | 40nm, 30 degrees



Target normal

Laser axis



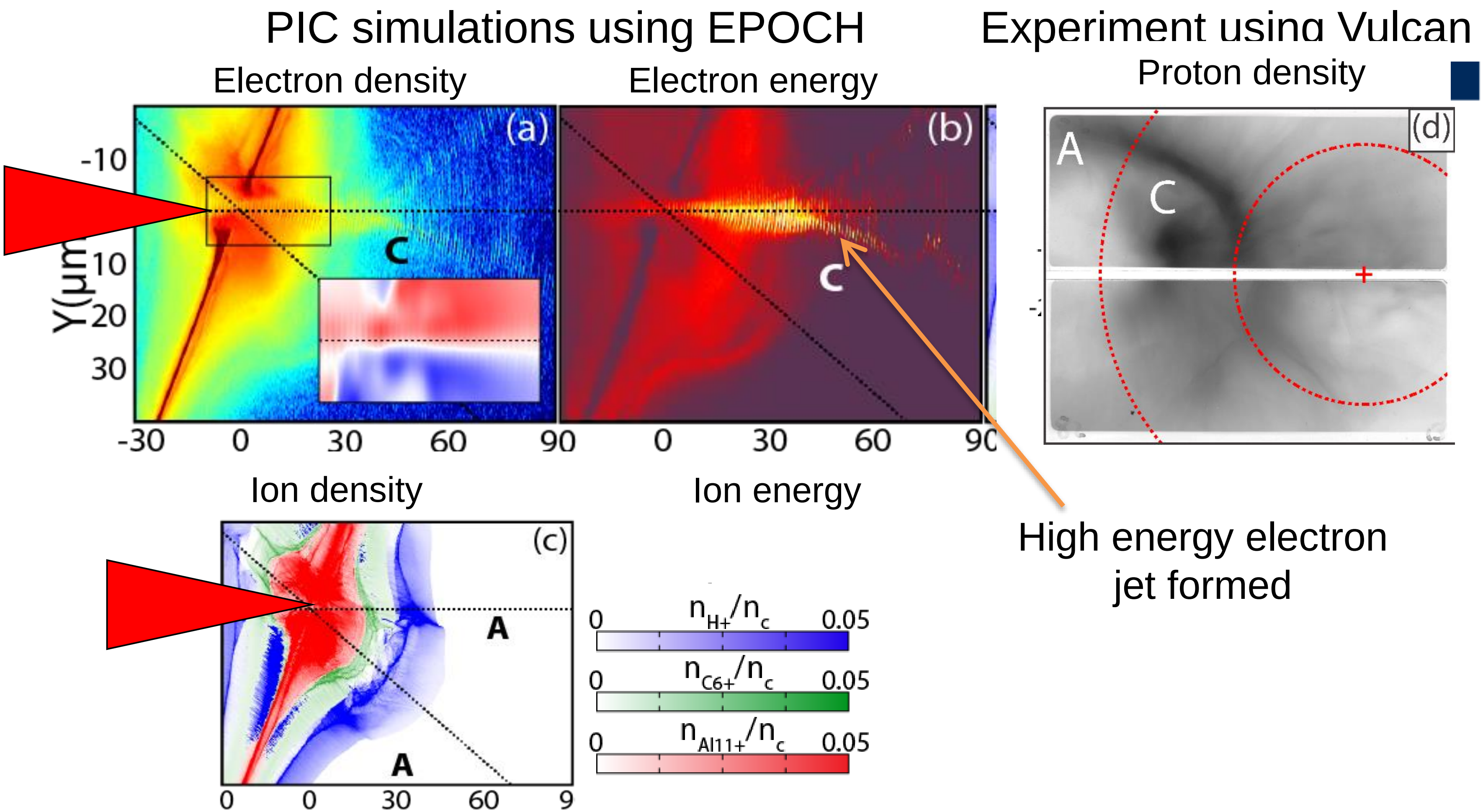
A = buffered sheath acc. along target normal

B = unstable RPA along laser axis

C = unknown high energy component

H. Powell et al, New J. Phys. 17, 103033 (2015)

Jet formed in targets undergoing relativistically induced transparency

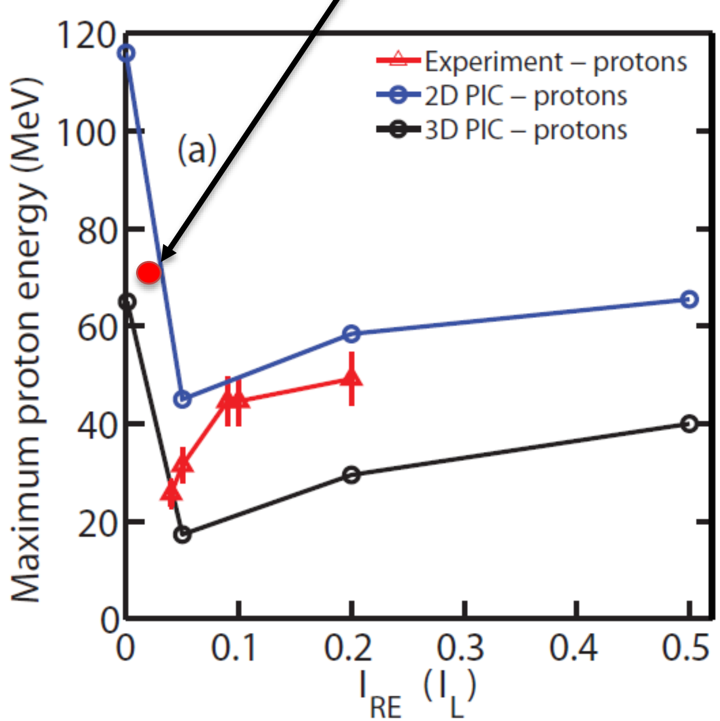


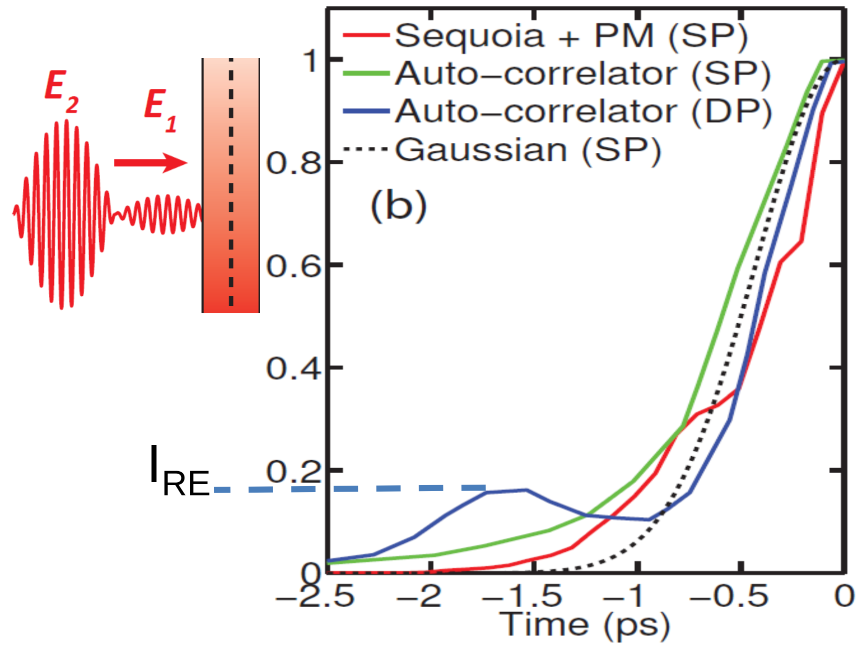
H. Powell et al, New J. Phys. 17, 103033 (2015)

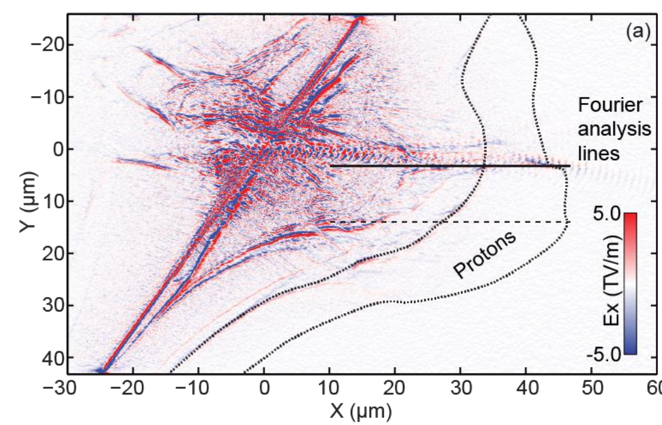
M. King et al, Nuc. Ins. Meth. A, At press (2016)

Proton energy scaling with pre pulse level – comparing experiment and simulations

New data point with improved laser contrast on picosecond rising edge





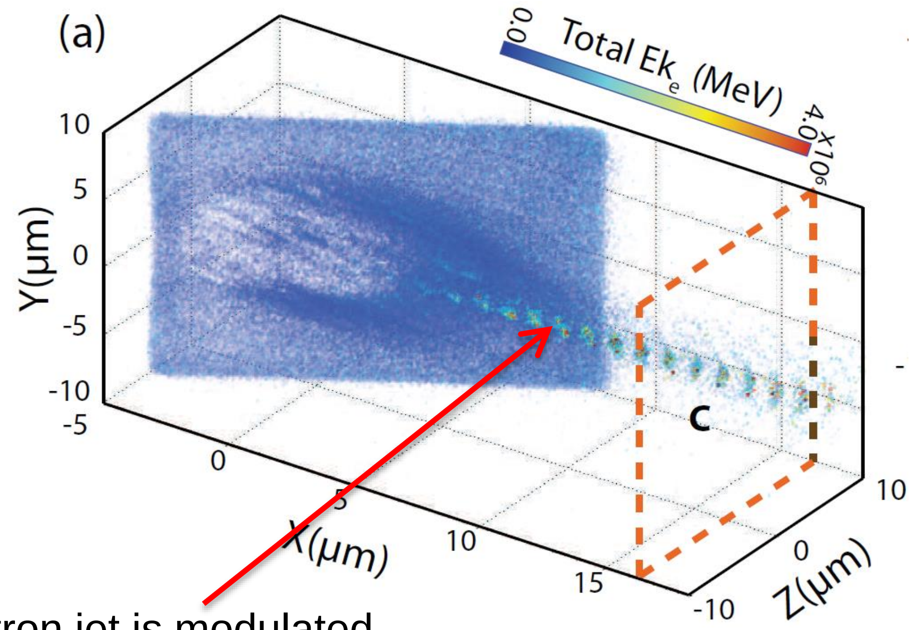


Controlled prepulse to vary the picosecond rising edge enables control on ion energy

paul.mckenna@strath.ac.uk; Cockcroft

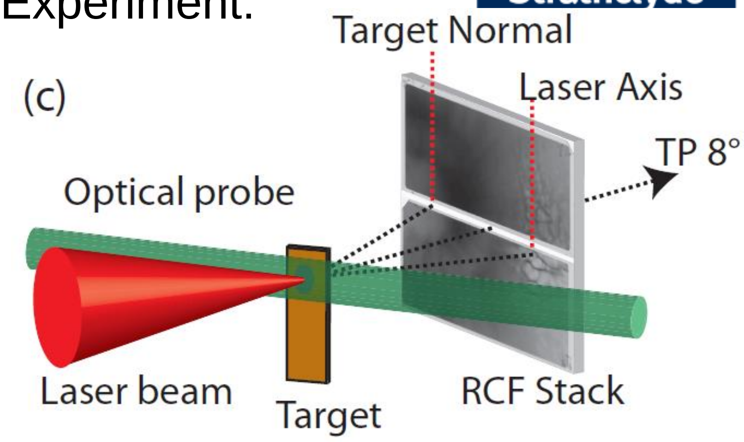
Plasma jet also observed in 3D PIC and a signature observed in optical probe images

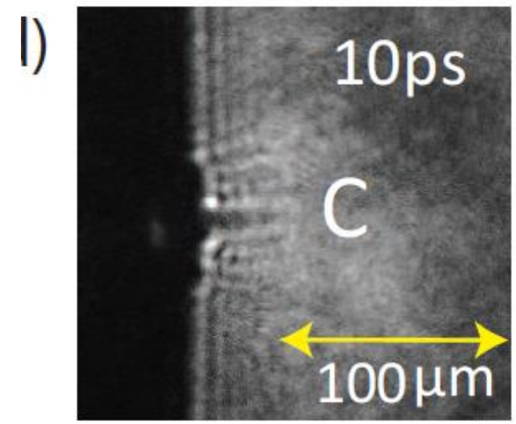
3D PIC simulations using EPOCH



Electron jet is modulated at laser frequency

Experiment:





Direct laser acceleration of electrons by the propagating portion of the laser pulse

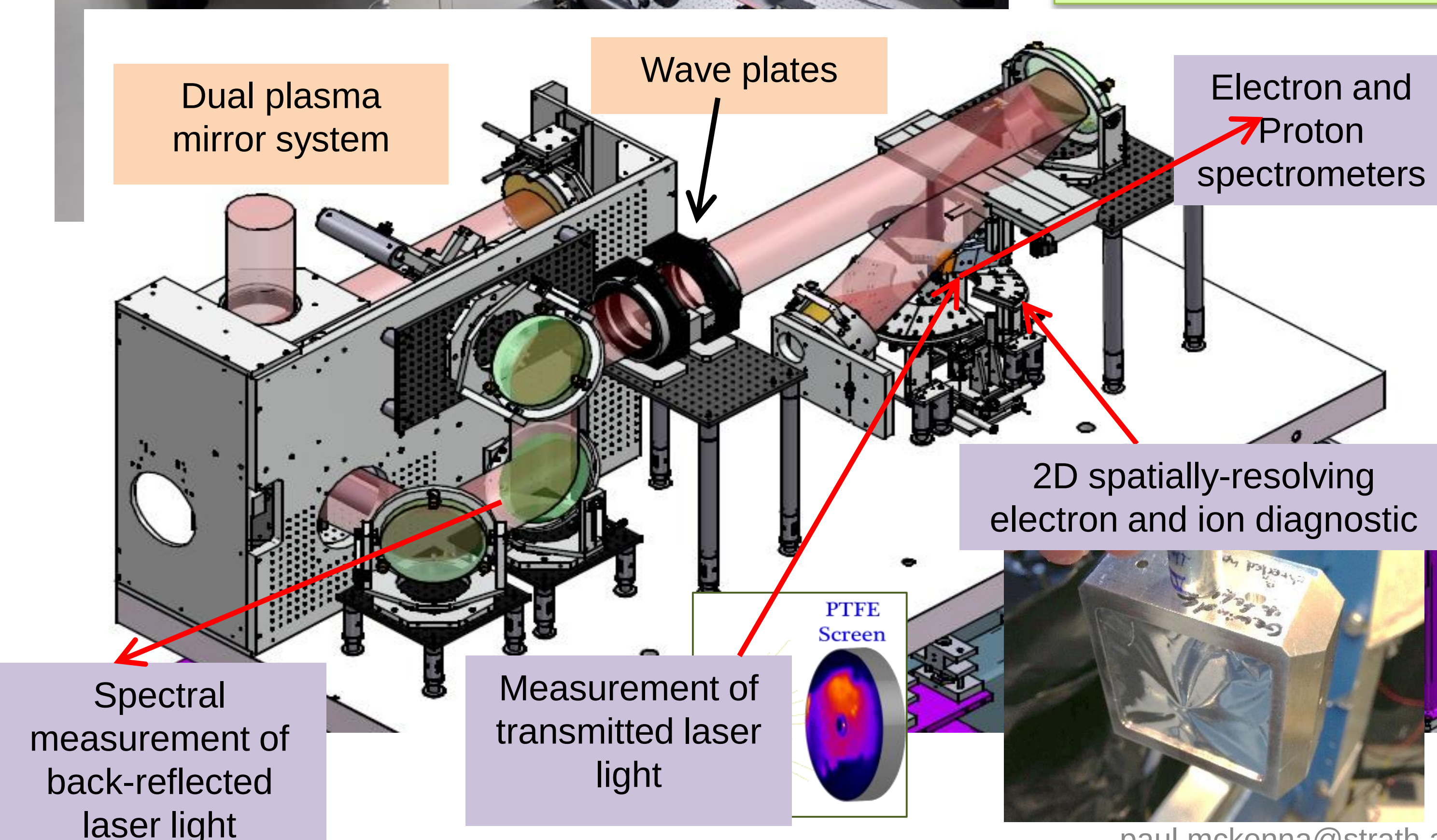
Similar features observed in optical probe images

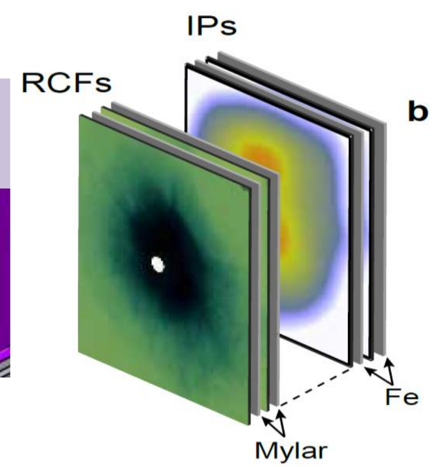
H. Powell et al, New J. Phys. 17, 103033 (2015)

M. King et al, Nuc. Ins. Meth. A, At press (2016)

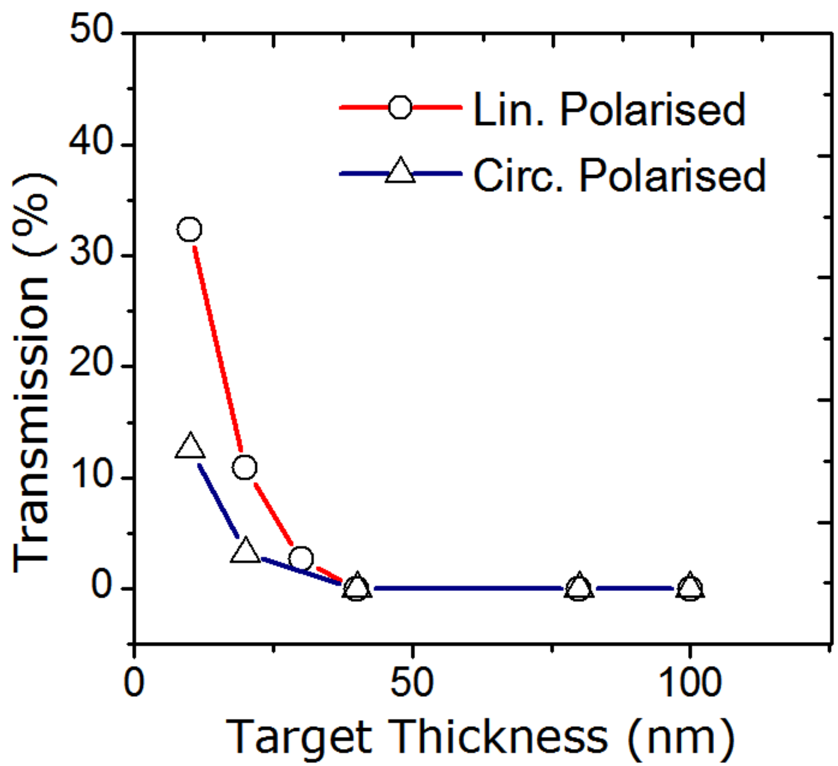
Experiments using the Gemini laser at RAL

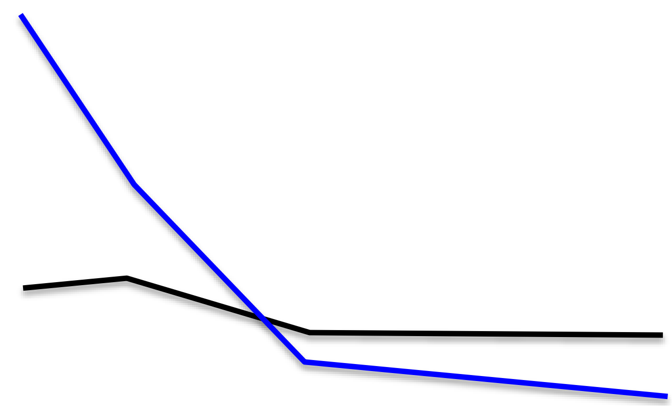
Power	0.5 PW
Energy	~6 J (on target)
Wavelength	0.8 μm
Pulse duration	40 fs
Intensity	mid-10^{20} Wcm^{-2}
Repetition	3 shots / minute





Onset of self-induced transparency: Optical transmission results - Gemini, RAL





Inverse correlation between transmission and maximum ion energy in ultrathin foils

Relativistic induced transparency due to :
increase in γn_c + target decompression due to electron heating

Intensity dependant

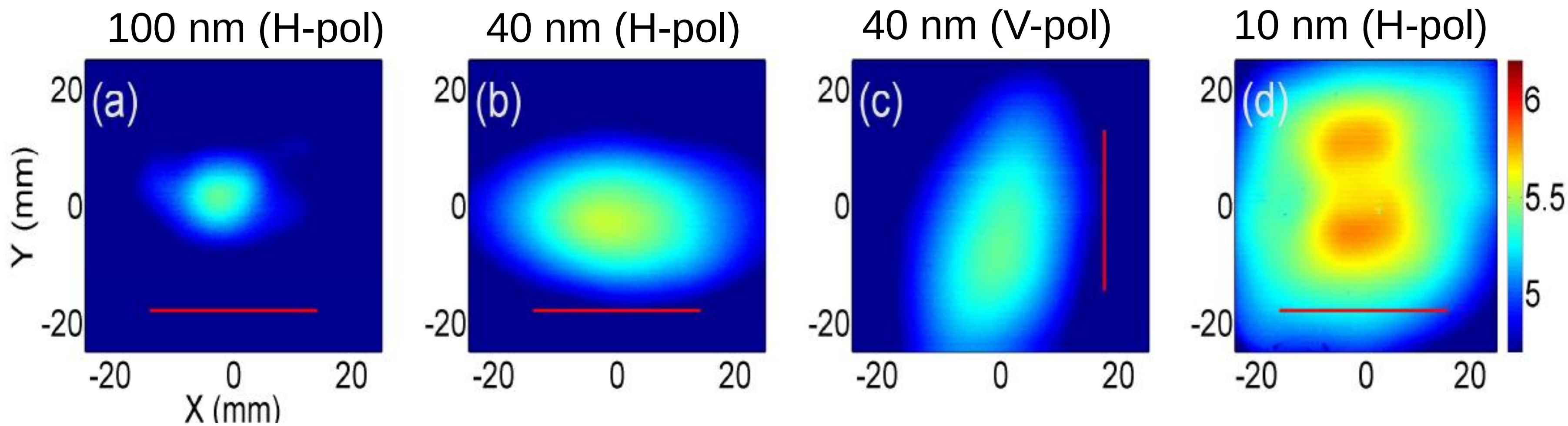
Target areal density (thickness x density) dependant

Polarisation dependant

paul.mckenna@strath.ac.uk; Cockcroft

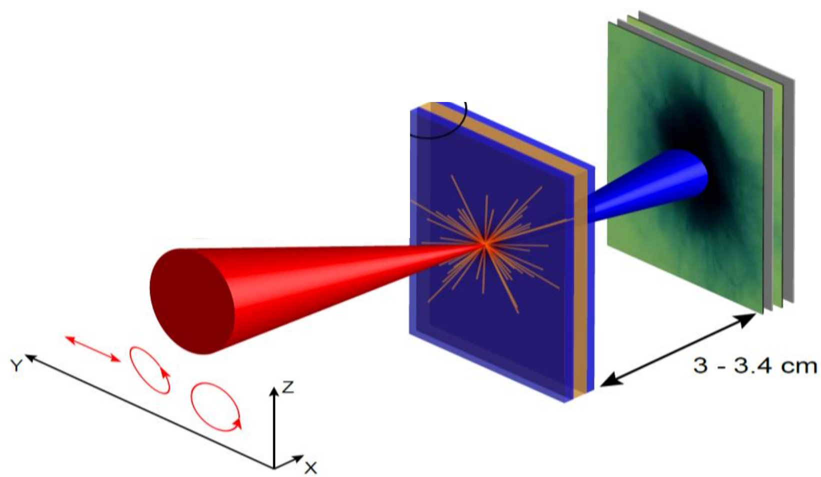
Asymmetry in the collective electron response

Electron beam spatial-intensity distribution measured as a function of target thickness and polarisation – experiment:



All linear polarisation with direction given by red line

R.J. Gray et al, New J. Phys. 16, 093027 (2014)



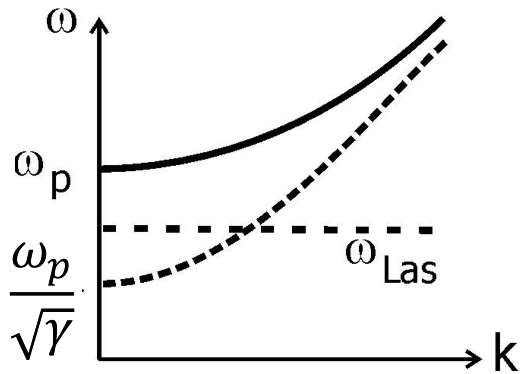
paul.mckenna@strath.ac.uk; Cockcroft

Formation of a 'relativistic plasma aperture'

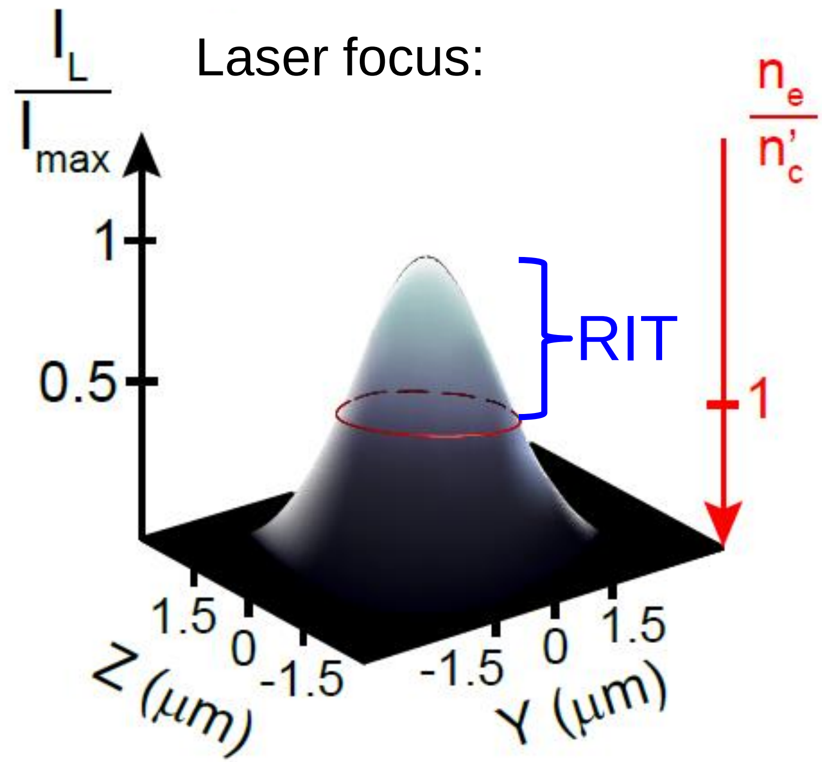
Plasma frequency:

$$\omega_p = \sqrt{\frac{e^2}{\varepsilon_0}\frac{n_e}{m_e}}$$

Transparency when $\omega_p < \omega_{Las}$:



Laser focus:

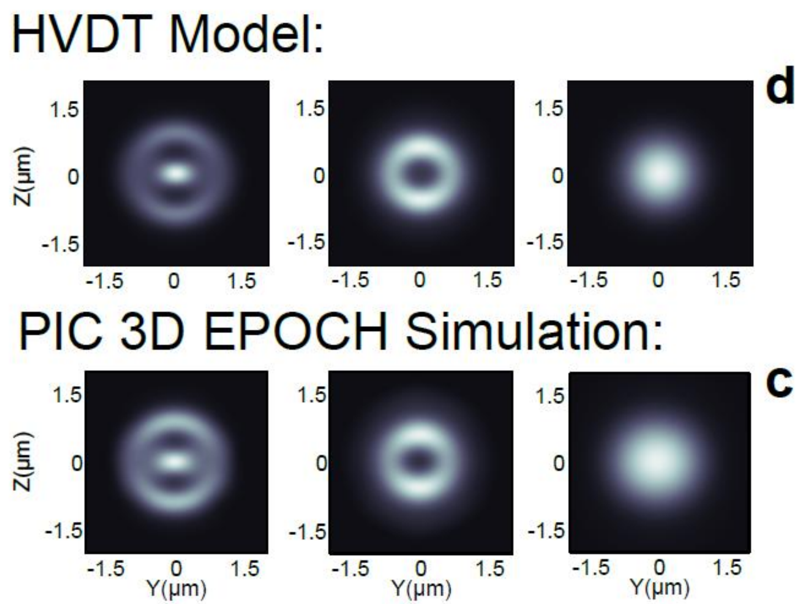


Decrease in plasma frequency near the peak of the focus produces Relativistically Induced Transparency over a diameter of a few times the laser wavelength

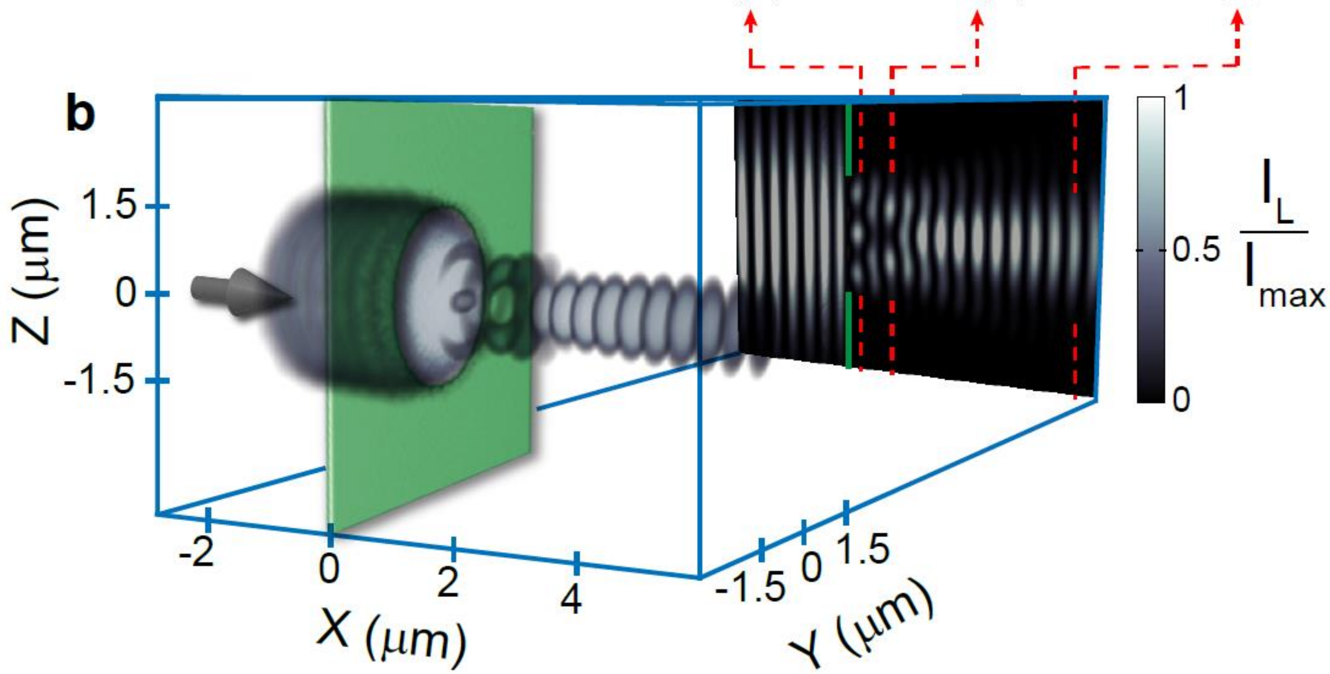
B. Gonzalez-Izquierdo et al, Nature Phys, 12, 505 (2016)

Diffraction through a fixed aperture (no plasma)

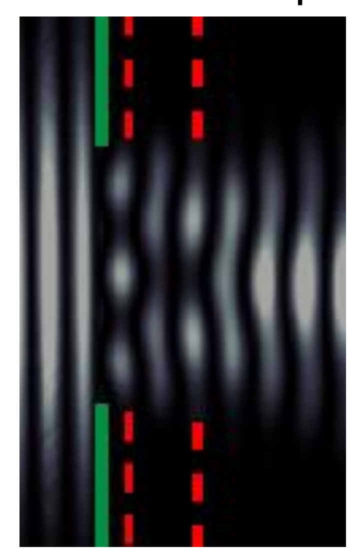
Calculated diffraction patterns using Hertz vector diffraction theory (HVDT):



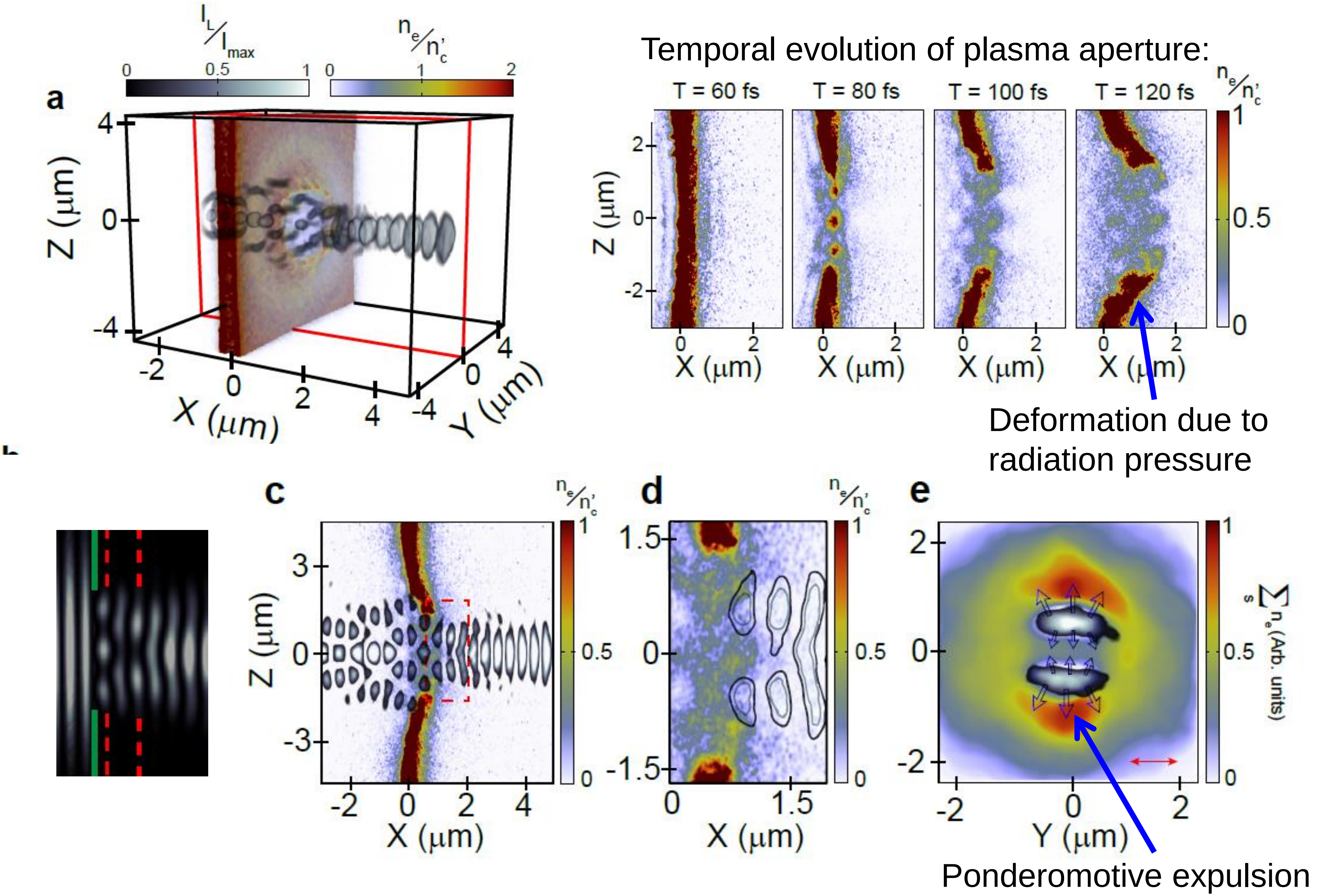
Simulated diffraction pattern with a fixed aperture (no plasma)



Structure in the near-field diffraction pattern



3D PIC simulations with a uniform planar target foil



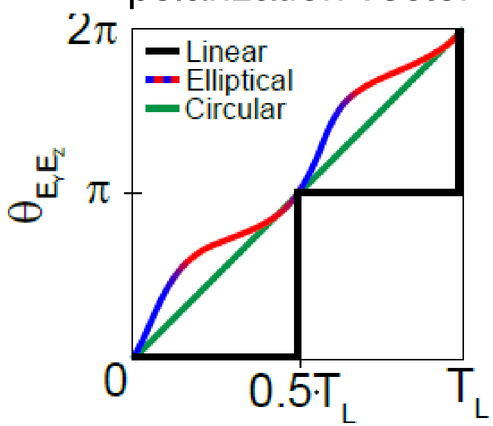
Influence of laser polarisation

Linear – fixed diffraction pattern

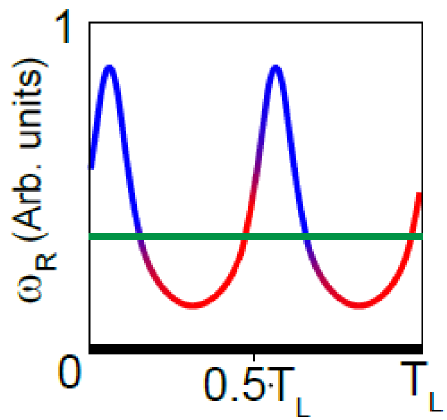
Circular – rotating pattern at constant velocity

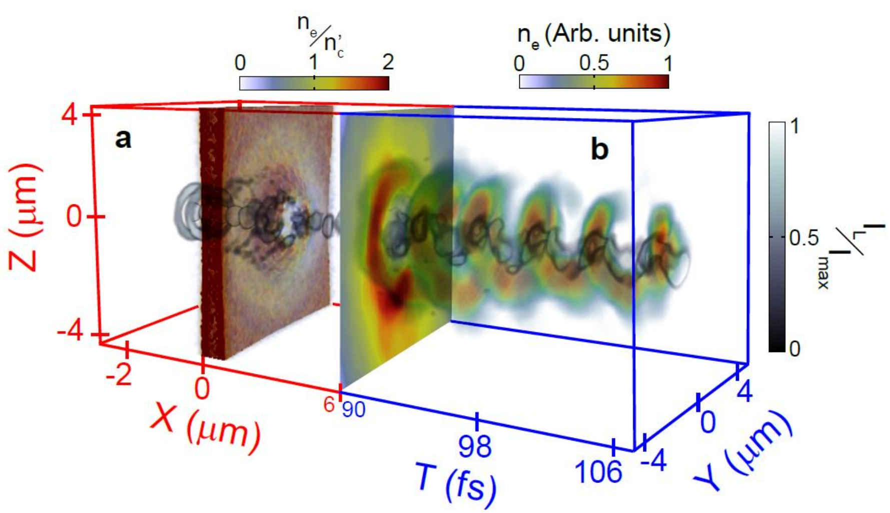
Elliptical – variable velocity of rotation

angle of the polarization vector

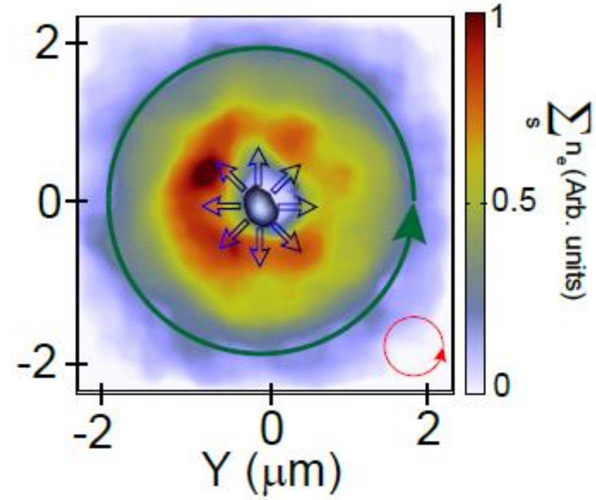


angular velocity of vector rotation

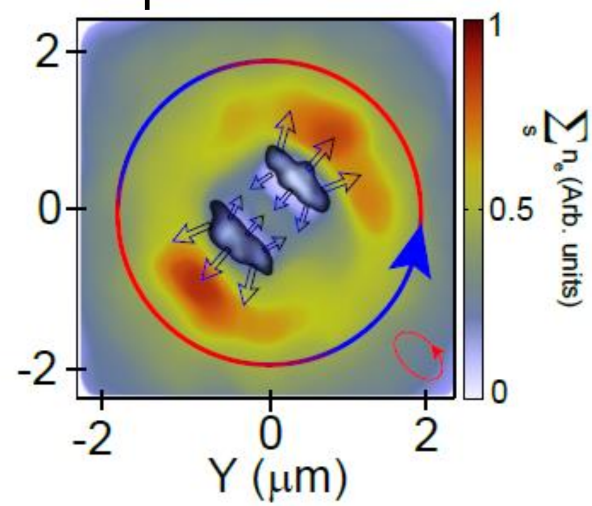




Circular



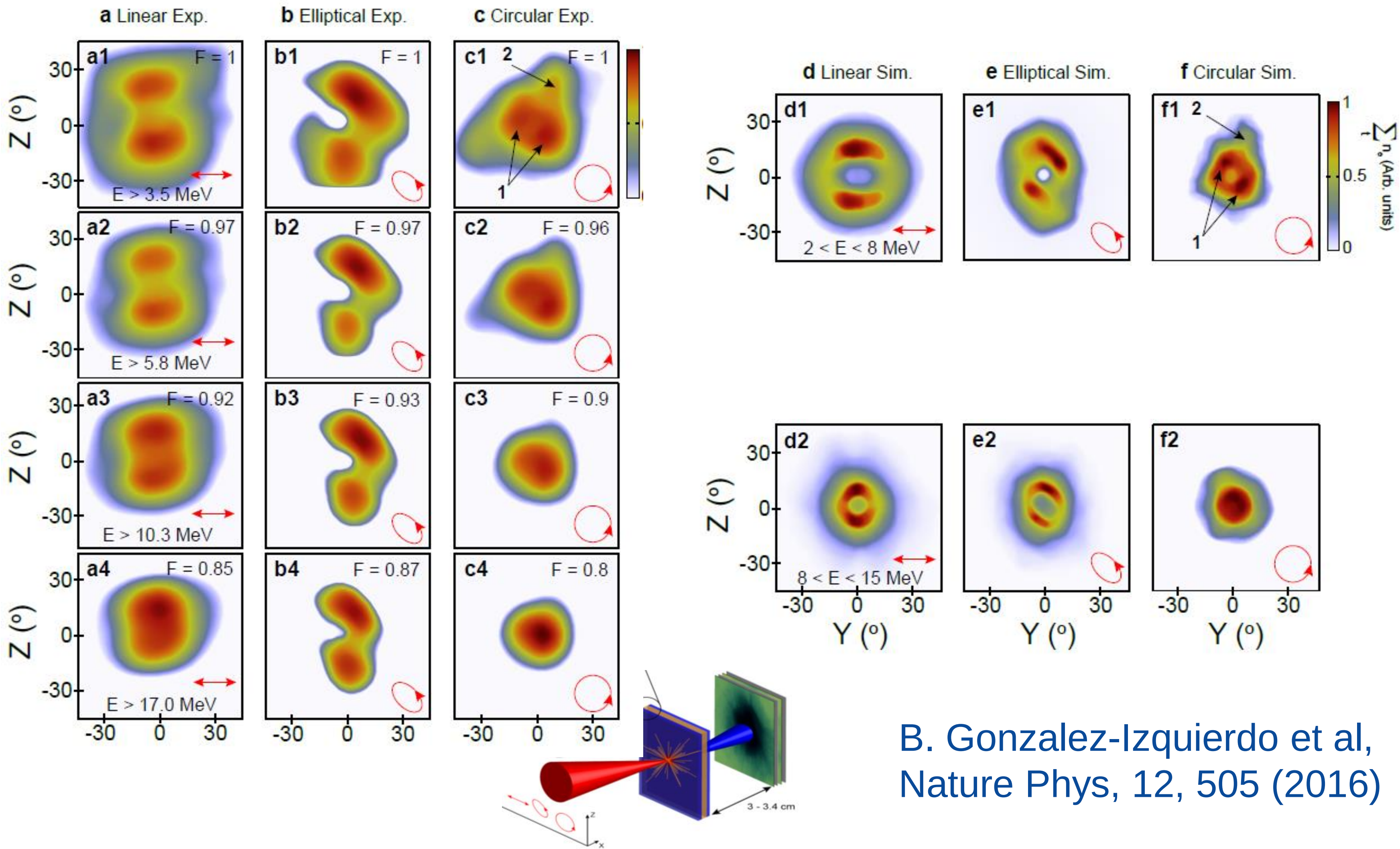
Elliptical



Experiment and 3D PIC simulation results for the electron density distribution

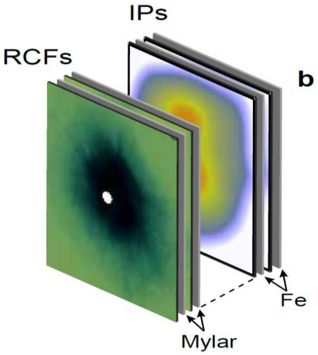
Experiment | 3D PIC Simulation

Linear | Elliptical | Circular | Linear | Elliptical | Circular



B. Gonzalez-Izquierdo et al, Nature Phys, 12, 505 (2016)

Electron distribution maps into the protons via the electrostatic field

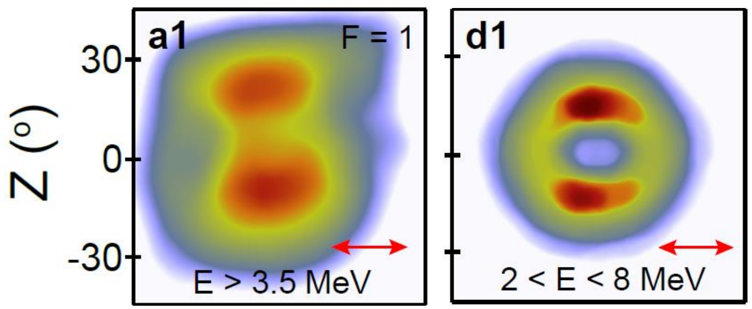


Linear pol.

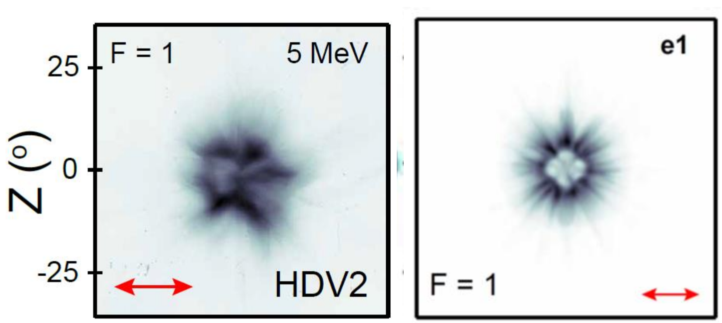
Experiment

3D PIC simulation

Electrons:



Protons:



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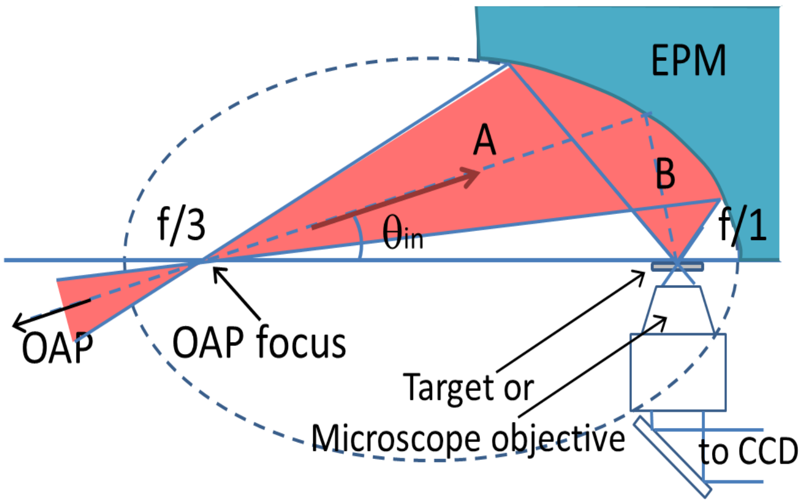
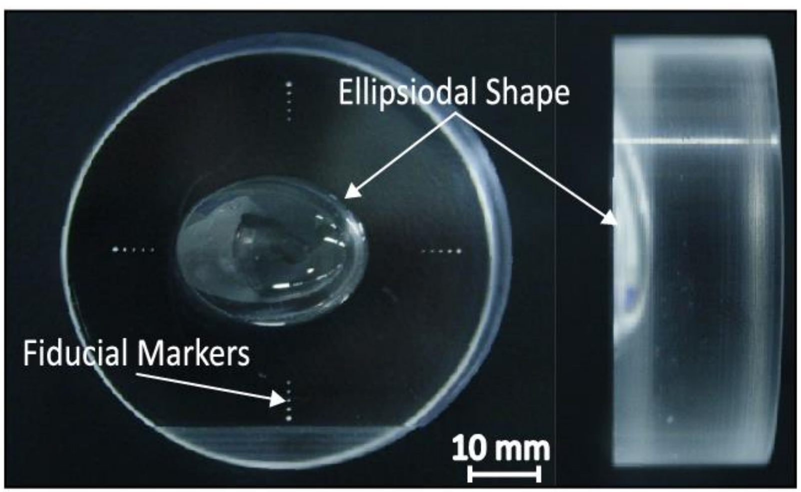
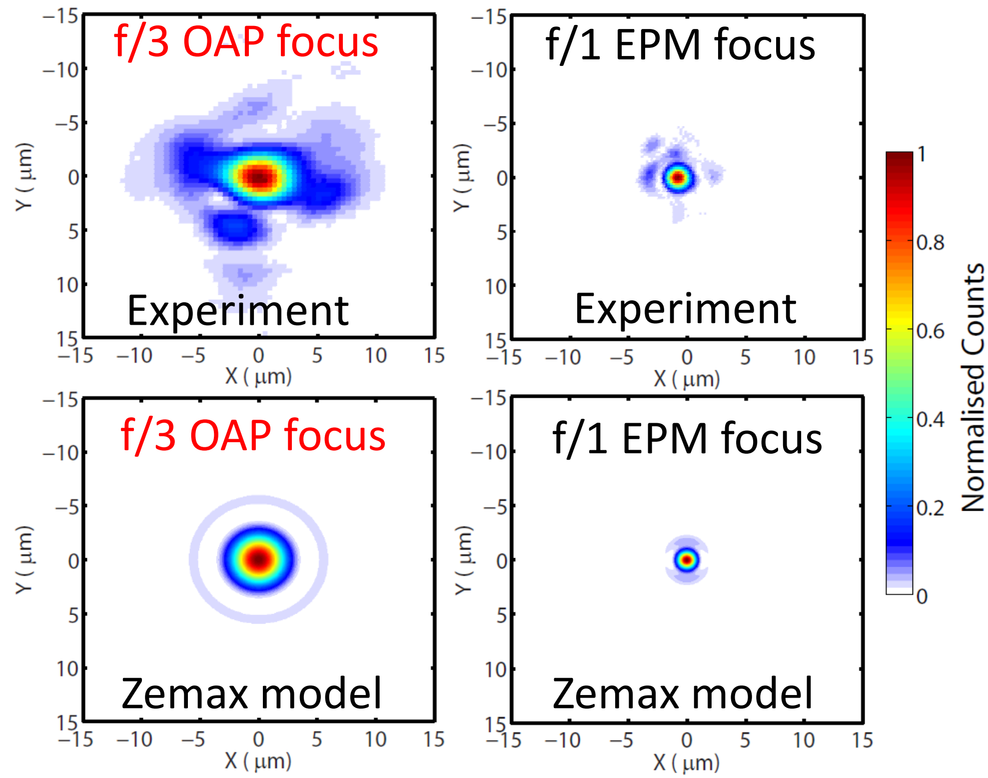
Focusing plasma mirrors to enhance achievable intensity on Vulcan



FPM Focus	FWHM (µm)	Energy Within FWHM (%)
Input f_1	4.0	28.1
Output f_2	1.6	36.5

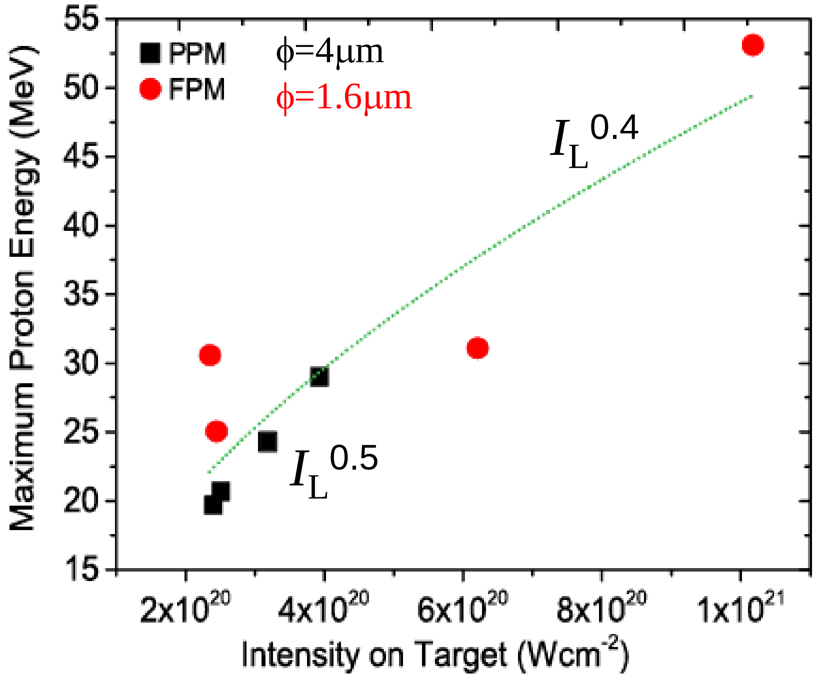




Near diffraction limit focal spot achieved – mid-10^{21} Wcm^{-2}.
10^{22} Wcm^{-2} achievable with further development to increase reflectivity.

FPM Operation: Proton Acceleration

- FPM operation diagnosed via measurements of the maximum energy of protons accelerated from 6 μm-thick Al foils



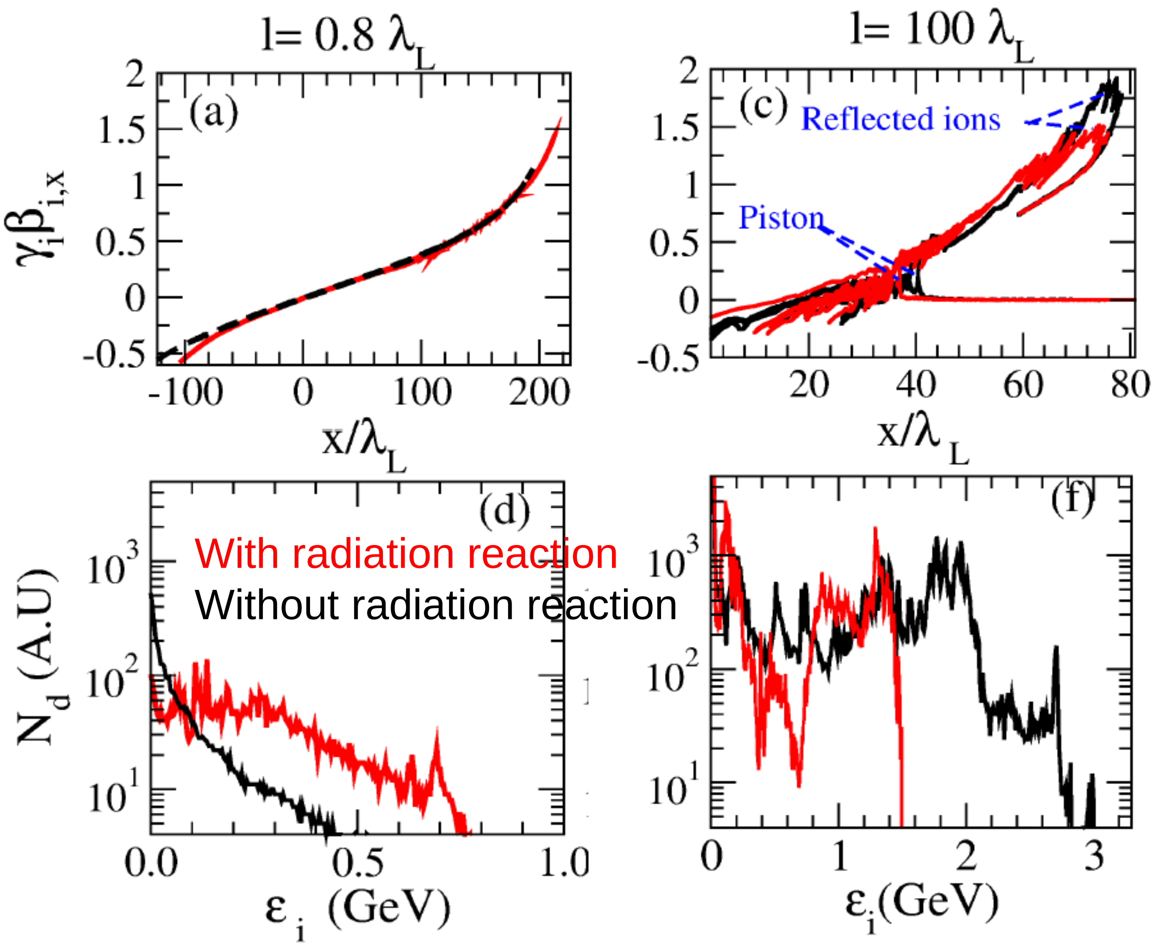
R. Wilson et al, Phys. Plasmas 23, 033106 (2016)

paul.mckenna@strath.ac.uk

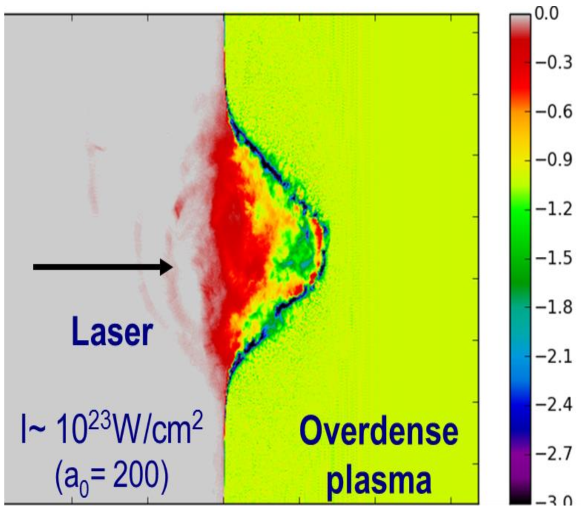
Radiation damping effects on ion acceleration at ultrahigh intensities (10^{23} Wcm^{-2})

Thin D target

Thicker D target



Extreme Light Infrastructure (ELI), Prague, Bucharest,



R. Capdessus & P. McKenna, Phys. Rev. E., 91, 053105 (2015)

Summary points:

University of

1. After ~15 years of research, the established TNSA mechanism offers a robust mechanism for multi-MeV proton acceleration. New optimization schemes being developed
2. Emerging acceleration mechanisms (e.g Radiation pressure acceleration) promise a step-change in performance of laser-ion accelerators (p+ and higher Z)
3. Understanding the onset of transparency and the collective electron response during transparency is essential to optimise and control ion acceleration
4. Processes such as jet formation and diffraction can potentially be used to enhance and control ion acceleration in ultrathin foils
5. Radiation reaction will strongly effect ion acceleration with the next generation of high power (multi-PW) lasers

Thank you for your attention!

Acknowledgements:

- The staff at the Central Laser Facility, RAL
- EPSRC (UK) research funding council
- Laserlab-Europe (CHARPAC JRA)

1. B. Gonzalez-Izquierdo et al, Nature Phys, 12, 505 (2016) – Relativistic aperture
2. R.J. Gray et al, New J. Phys. 16, 093027 (2014) – Onset of transparency
3. H. Powell et al, New J. Phys. 17, 103033 (2015) – Jet formation & ion energy
4. M. King et al, Nuc. Instrum. Meth. A, At press (2016) – Jets and transparency
5. H. Padda et al, Phys. Plasmas, At Press (2016) – Intra-pulse transition on ion acc
6. R. Wilson et al, Phys. Plasmas 23, 033106 (2016) – Focusing plasma mirrors
7. R. Capdessus & P. McKenna, Phys. Rev. E., 91, 053105 (2015) – Radiation reaction