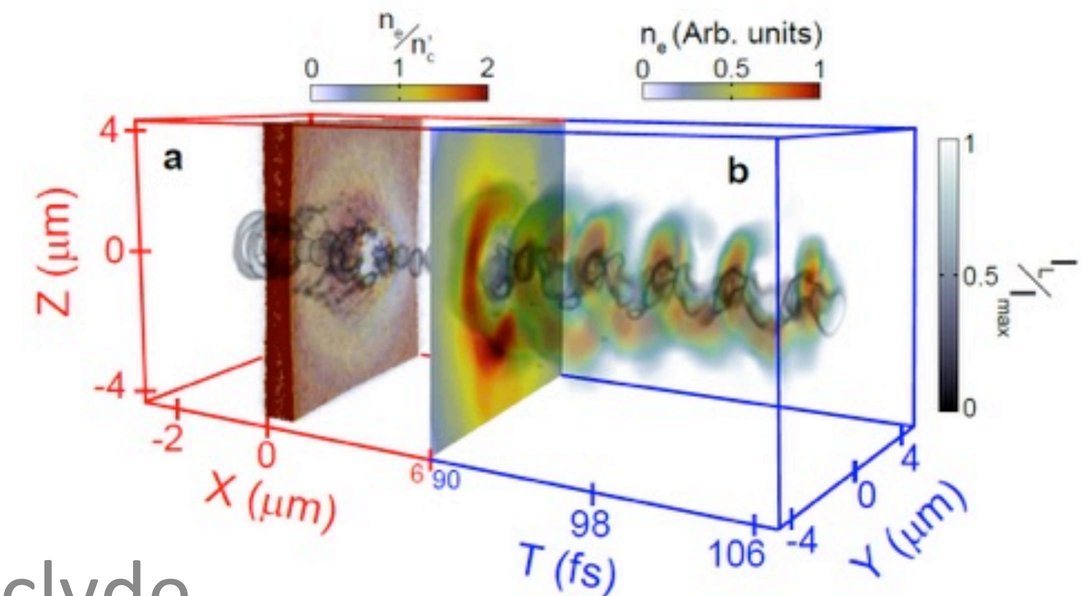
Laser-driven charged particle beam structures from targets undergoing relativistic induced transparency



Dr Martin King

University of Strathclyde

3rd European Advanced Accelerators Concepts Workshop
24-30 September 2017, La Biodola, Isola d'Elba

Contributors

nature physics

ARTICLES

PUBLISHED ONLINE: 11 JANUARY 2016 | DOI: 10.1038/NPHYS3613

Optical controlled dense current structures driven by relativistic plasma aperture-induced diffraction

Bruno Gonzalez-Izquierdo[1], Ross J. Gray[1], Martin King[1], Rachel J. Dance[1], Robbie Wilson[1], John McCreadie[1], Nicholas M. H. Butler[1], Remi Capdessus[1], Steve Hawkes[2], James S. Green[2], Marco Borghesi[3], David Neely[1,2] and Paul McKenna[1]*

Nature Phys 12, 505 (2016)

[1] University of Strathclyde, UK
[2] Rutherford Appleton Laboratory, UK
[3] Queens University Belfast, UK
[4] University of York, UK
[5] CLPU, Salamanca, Spain

nature COMMUNICATIONS

Towards optical polarization control of laser-driven proton acceleration in foils undergoing relativistic transparency

Bruno Gonzalez-Izquierdo, Martin King, Ross Gray, Robbie Wilson, Rachel Dance, Haydn Powell, David MacLellan, John McCreadie, Nicholas Butler, Steve Hawkes, James Green, Chris Murphy, Luca Stockhausen, David Carroll, Nicola Booth, Graeme Scott, Marco Borghesi, David Neely & Paul McKenna

Nature Comms 101038/NCOMMS12891 (2016)

Contributors

New J. Phys. 17 (2015) 103033 doi:10.1088/1367-2630/17/10/103033

New Journal of Physics
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IOP Institute of Physics

Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

PAPER

Proton acceleration enhanced by a plasma jet in expanding foils undergoing relativistic transparency

H W Powell[1], M King[1], R J Gray[1], D A MacLellan[1], B Gonzalez-Izquierdo[1], L C Stockhausen[2], G Hicks[3], N P Dover[3], D R Rusby[1,4], D C Carroll[4], H Padda[1], R Torres[2], S Kar[5], R J Clarke[4], I O Musgrave[4], Z Najmudin[3], M Borghesi[5], D Neely[4] and P McKenna[1]

1 SUPA Department of Physics, University of Strathclyde
2 Centro de Láseres Pulsados (CLPU)
3 The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London
4 Central Laser Facility, STFC Rutherford Appleton Laboratory
5 Centre for Plasma Physics, Queens University Belfast

STFC Central Laser Facility

CLF and support team

EPSRC Engineering and Physical Sciences Research Council

EPSRC (UK) research council

Laser-driven ion acceleration

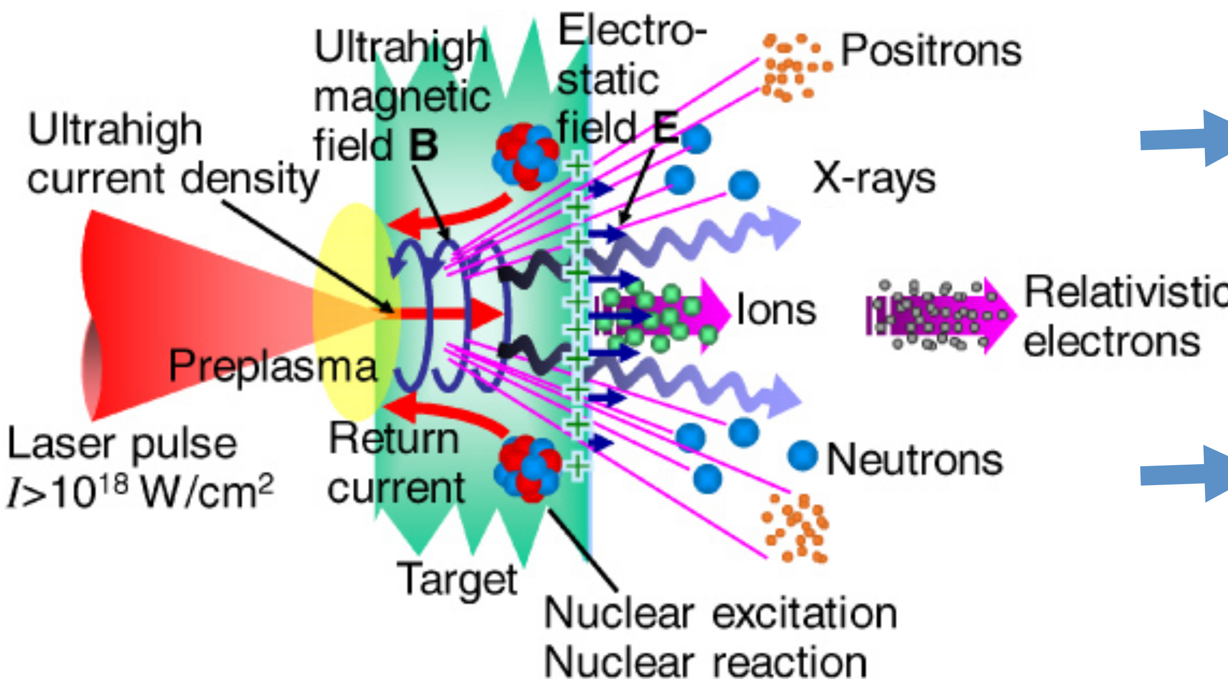
Advantages

- Targets form dense plasma (electron density ~10^{25} cm^{-3})
- Large accelerating gradients (~TV/m)
- High flux beams
- Compact interaction (~10's µm)

Current Challenges

- Maximum energies
  - Predicted highest ion energies with ultrathin targets (~10's nm)
- Controllable beam structures

Ultra-intense laser solid interactions



H Daido et al, Rep Prog Phys Physics 75, 056401 (2012)

Applications

Oncology

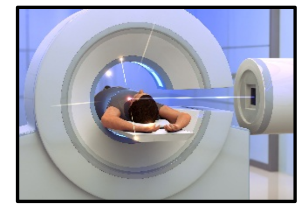
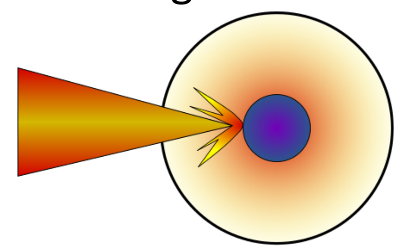


Image: http://envisionwebcernch/ENVISION/

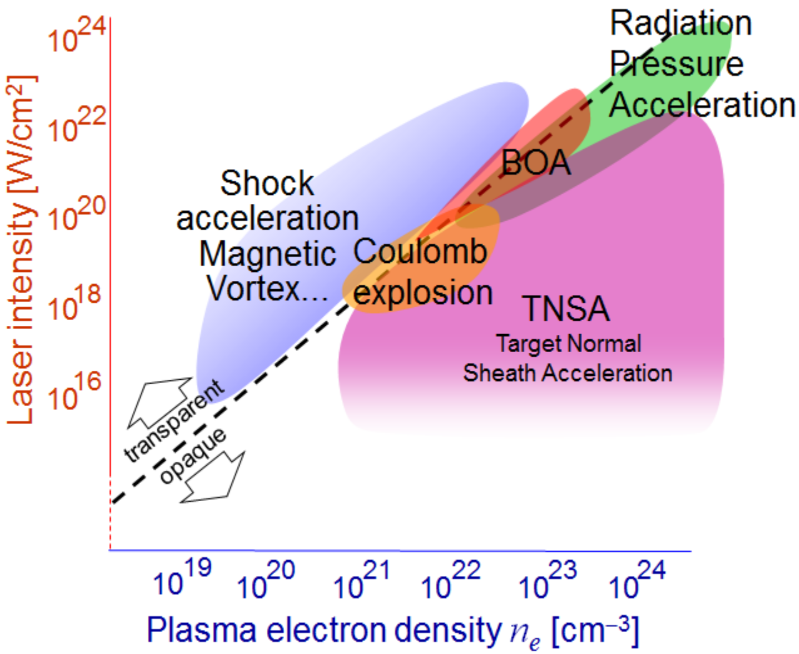
Fast ignition



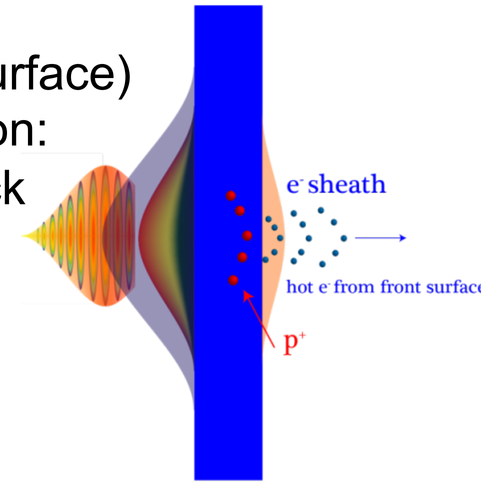
Laboratory astrophysics

Image: NASA Goddard Space Flight Center

Ion acceleration processes

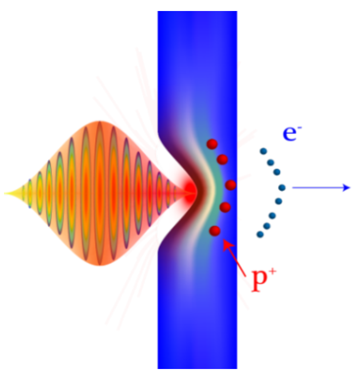


Sheath (surface) acceleration:
(in µm-thick targets)

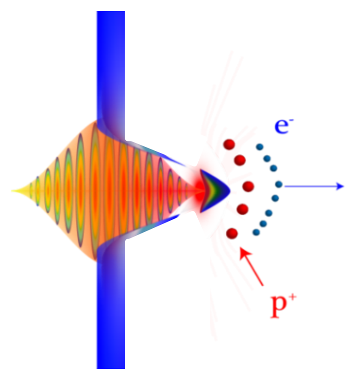


Radiation pressure acceleration

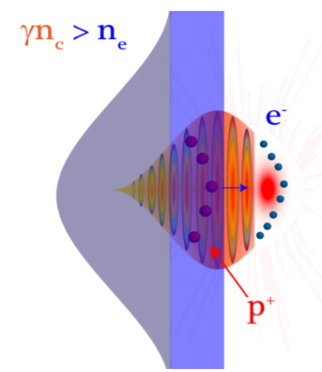
Hole-Boring



Light Sail



Relativistic transparency (BOA) regime



Volumetric acceleration:
(in nm-thick targets)

Experiments at 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

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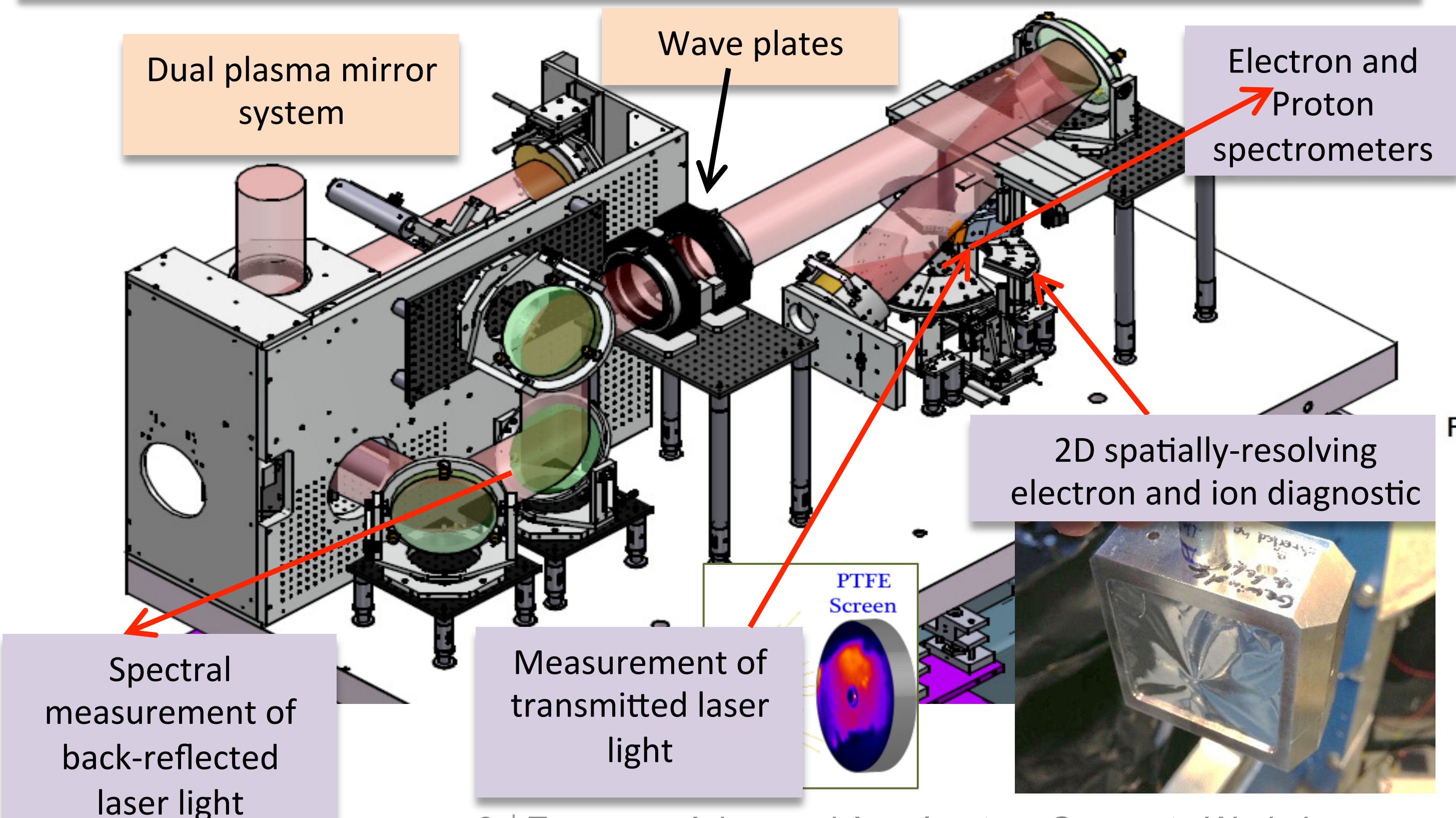
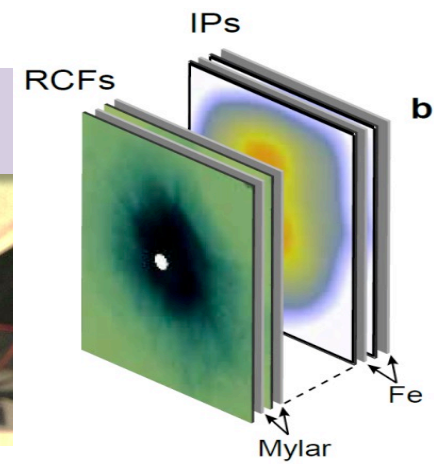




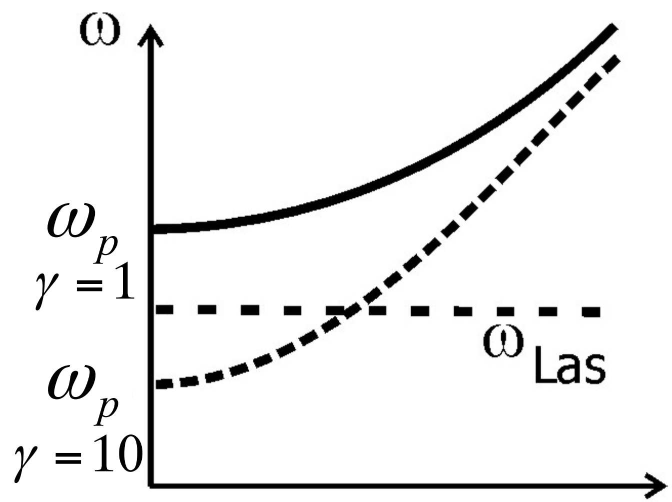
Formation of a 'relativistic plasma aperture'

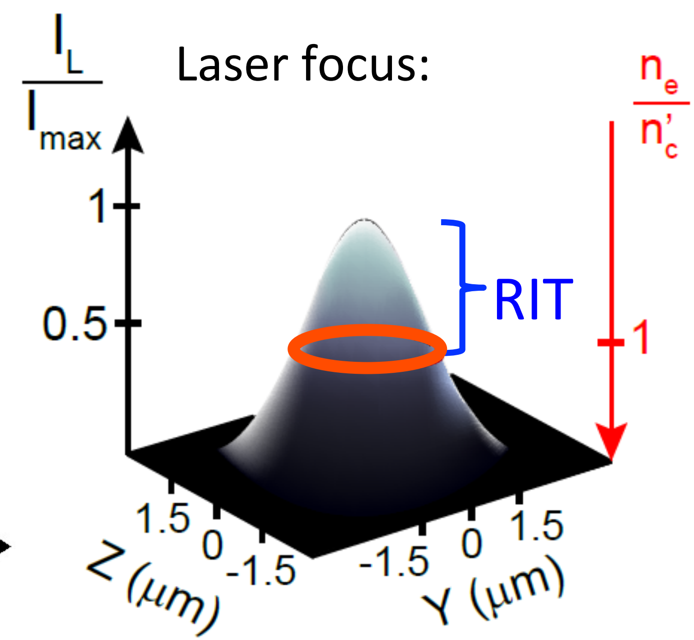
$$n'_c = \frac{n_c}{\gamma} = \frac{\omega_{las}^2 \varepsilon_0 m_0}{e^2}$$

Decrease in relativistic plasma frequency near the peak of the focus produces relativistically induced transparency over a diameter of a few times the laser wavelength

$$\omega_p = \sqrt{\frac{e^2}{\varepsilon_0} \frac{n_e}{\gamma m_0}}$$

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

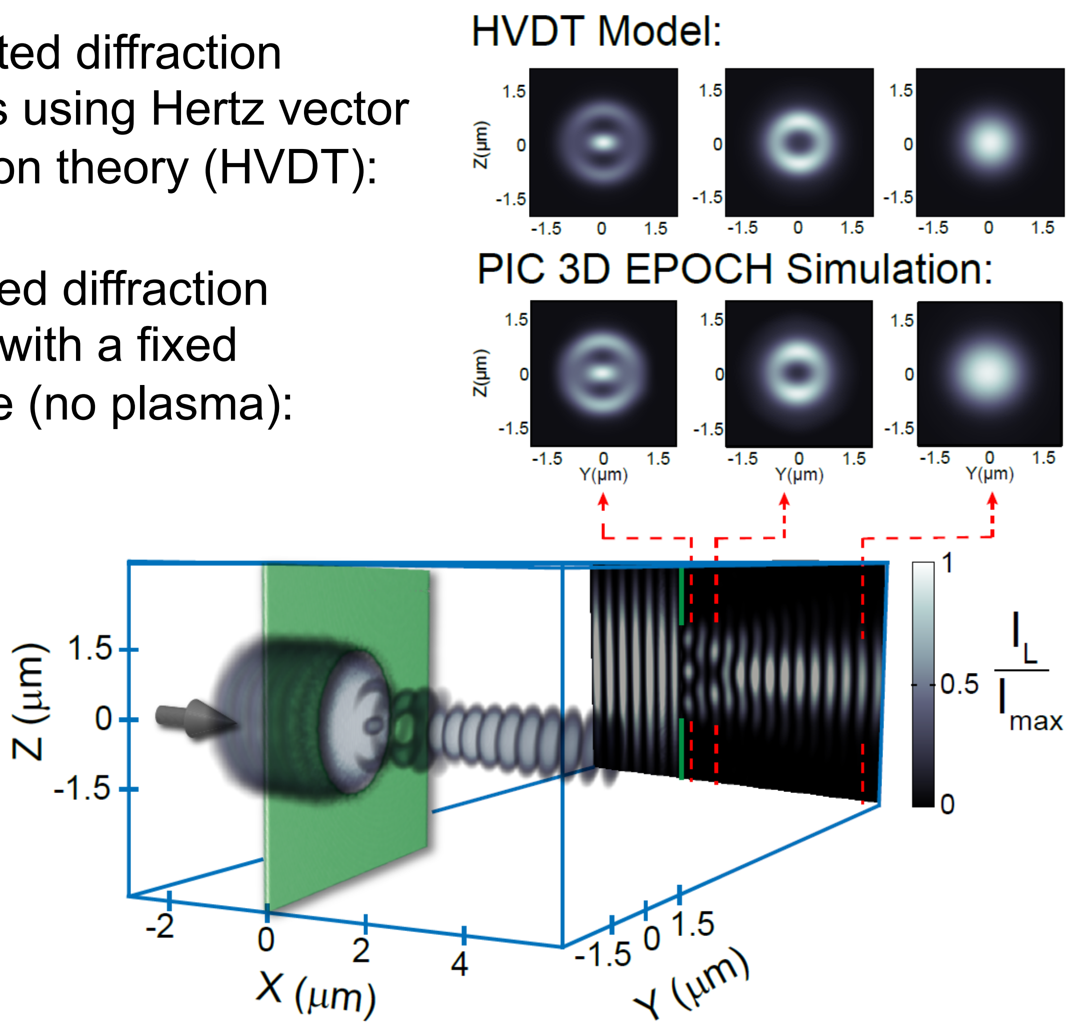




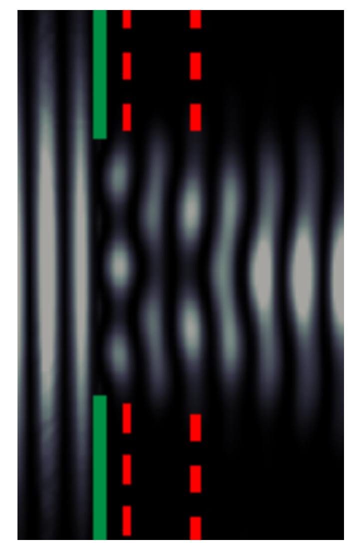
Diffraction through a fixed aperture

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

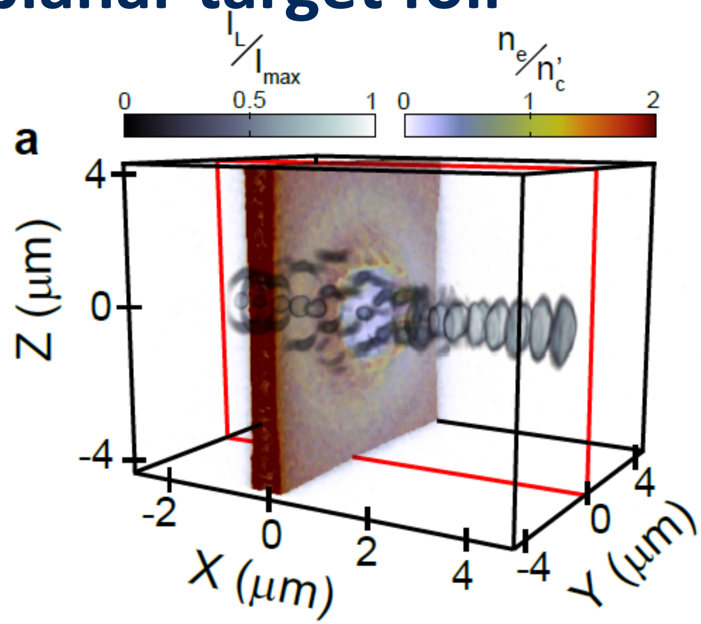
Simulated diffraction pattern with a fixed aperture (no plasma):



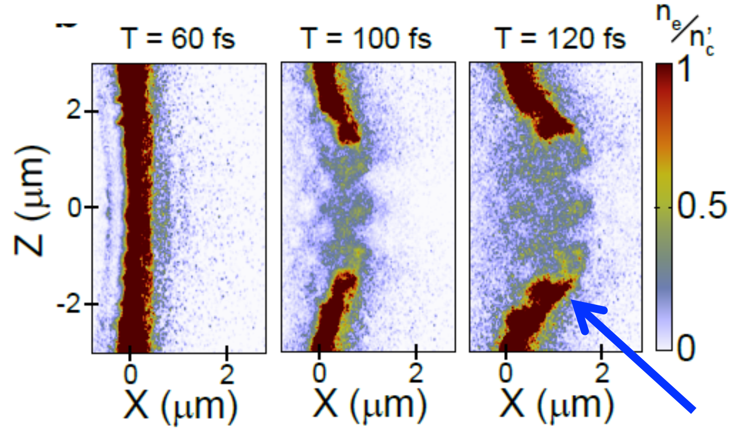
Structure in the near-field diffraction pattern



3D PiC Simulations with an expanded uniform planar target foil



Temporal evolution of plasma aperture:



Deformation due to radiation pressure

- 2048 - 4096 cores
- 1000 x 720 x 720 mesh cells
- 20 x 20 x 20 μm box size
- Initial electron temperature = 100 keV
- Target thickness, L= 10 nm to 40 nm
- Target bulk: $30n_c$ electron density, $23n_c$ Al^{11+} ,
- Layers $23n_c$ H^+ and $08n_c$ C^{6+} (front and rear)
- $I_L = 6x10^{20}$ W/cm^2 , τ = 40 fs (FWHM), diameter = 3 μm (FWHM)

3D PiC Simulations with an expanded uniform planar target foil

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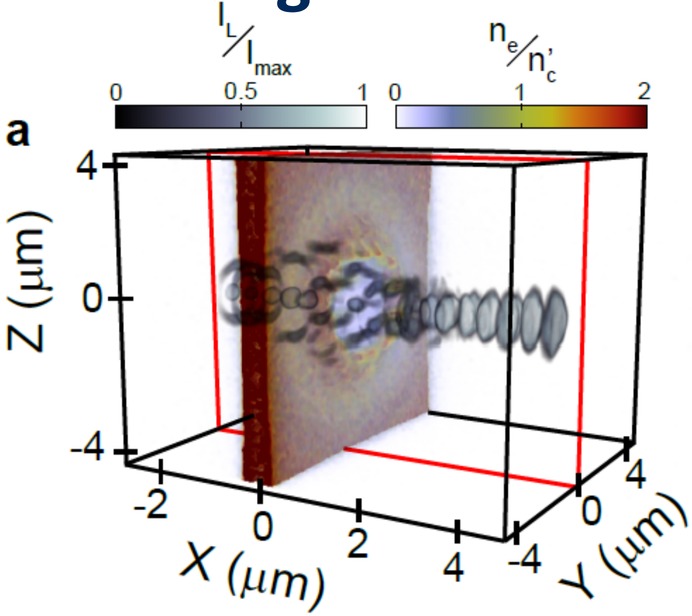
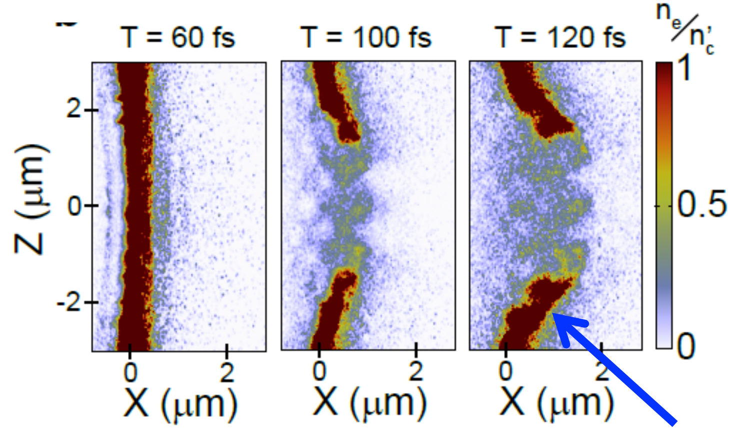
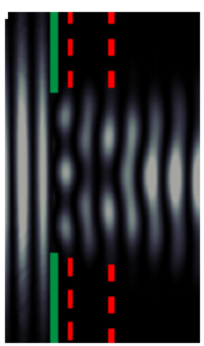


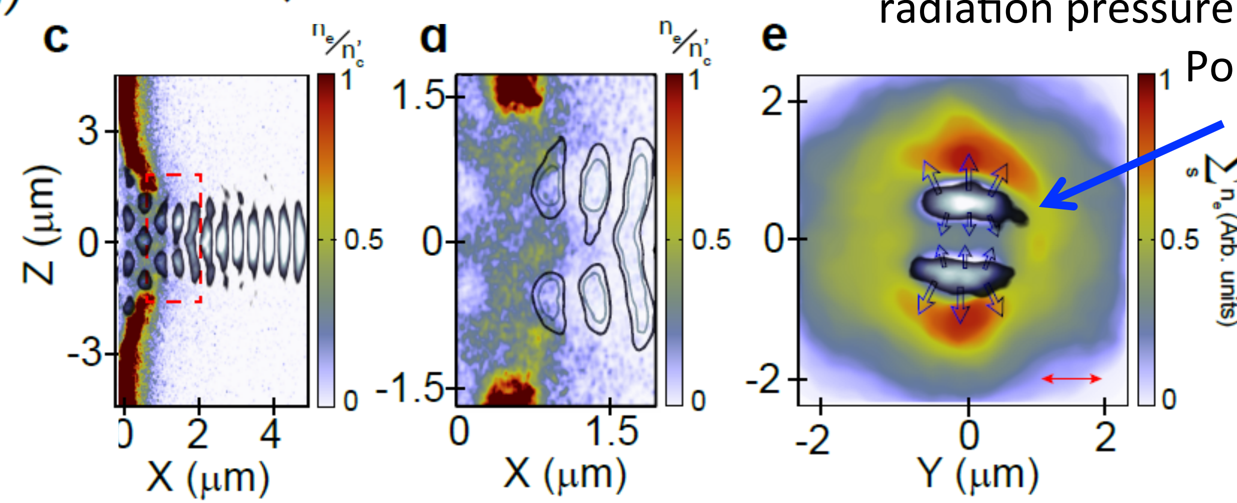
Temporal evolution of plasma aperture:



Deformation due to radiation pressure



Hertz vector diffraction theory for a fixed aperture



Ponderomotive expulsion

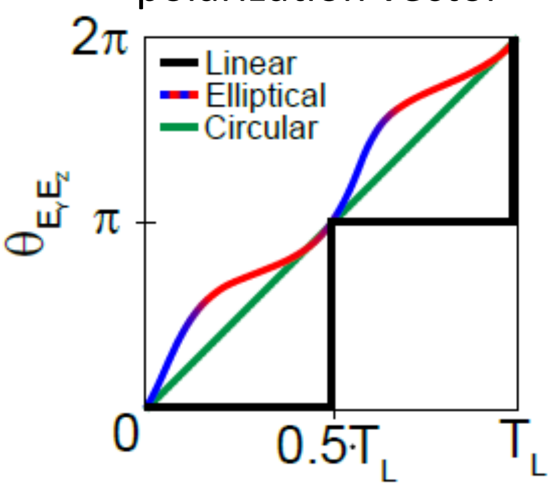
Effects of incoming laser polarisation

Linear: fixed diffraction pattern

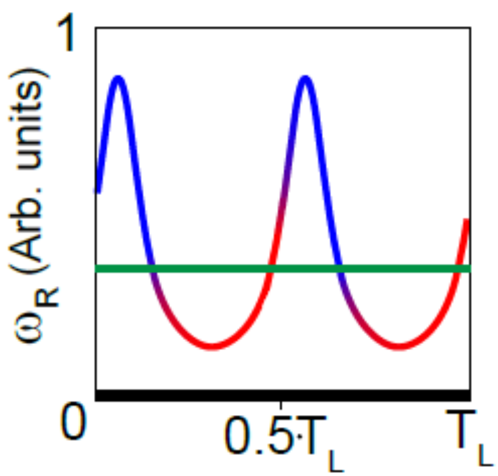
Circular: rotating pattern at constant velocity

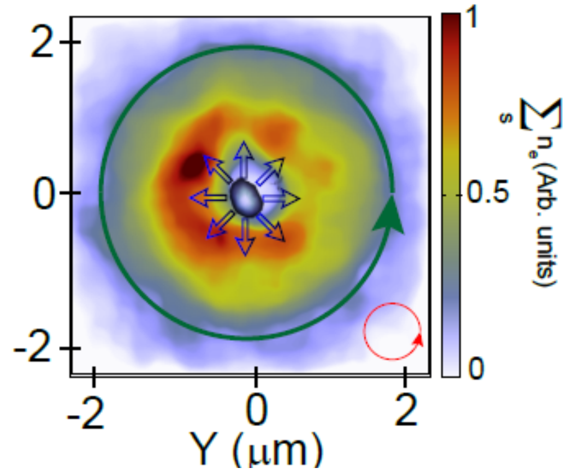
Elliptical: variable velocity of rotation

Angle of the polarization vector

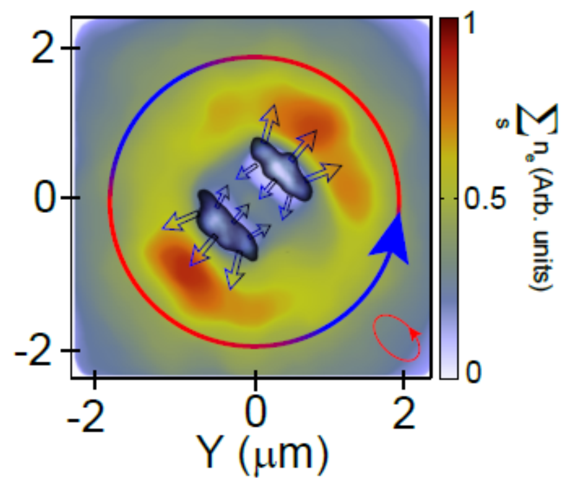


Angular velocity of vector rotation



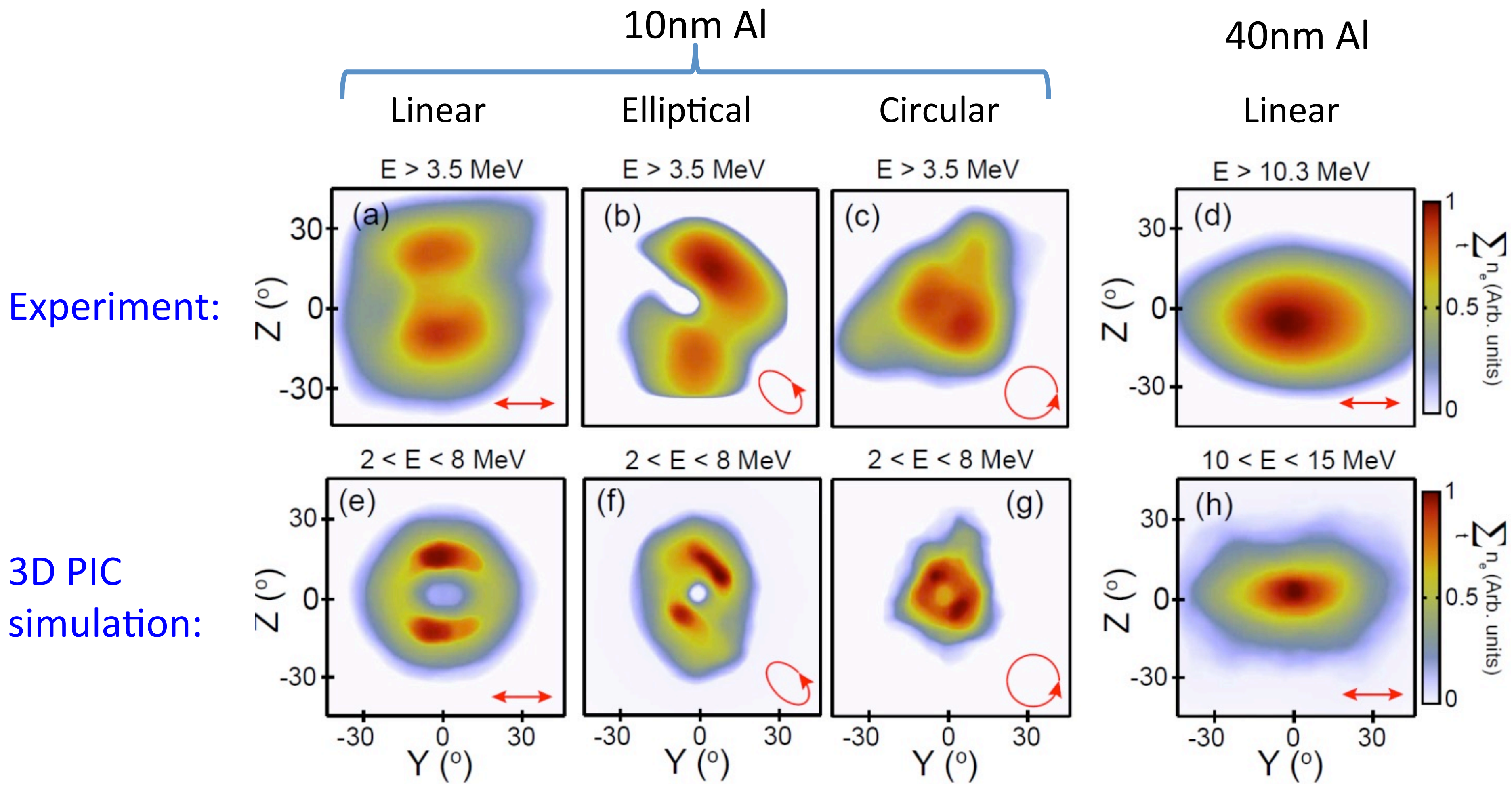


Circular

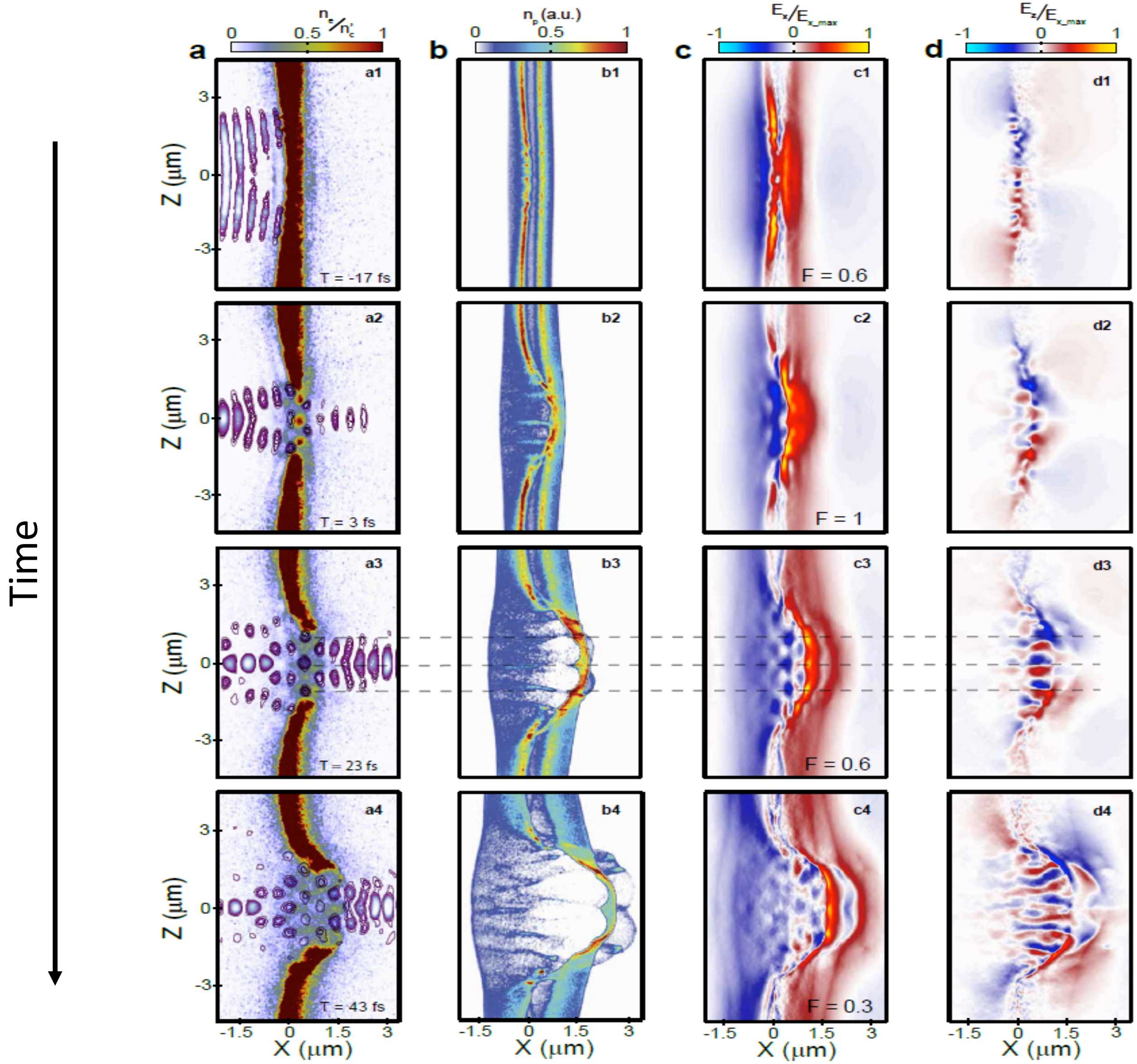


Elliptical

Comparison of accelerated electrons from experimental and simulation results



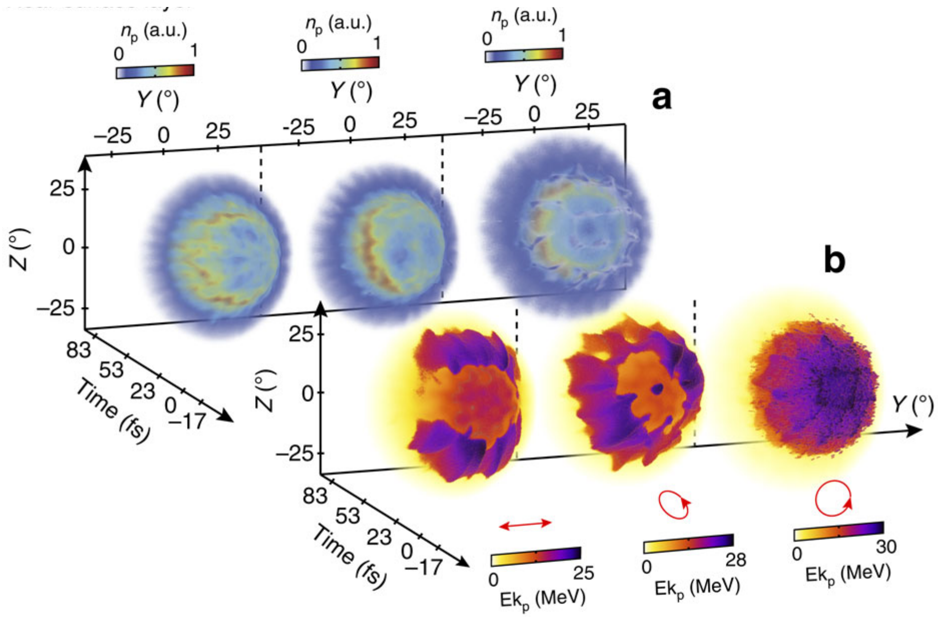
Impact upon accelerated ion beams



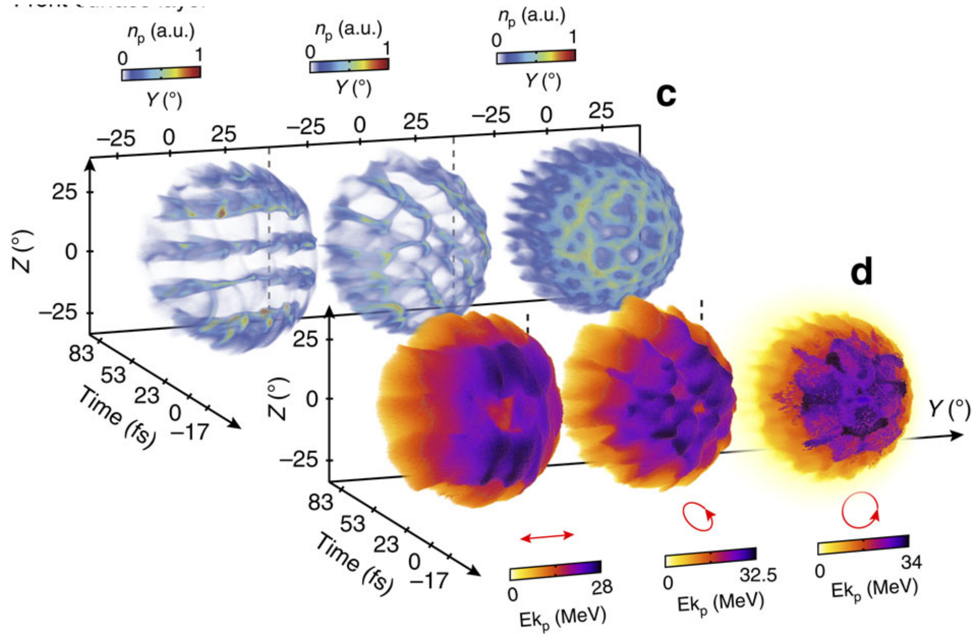
Electron density structure mapped into the proton beam via modulation of the electrostatic field

Front and rear proton surfaces

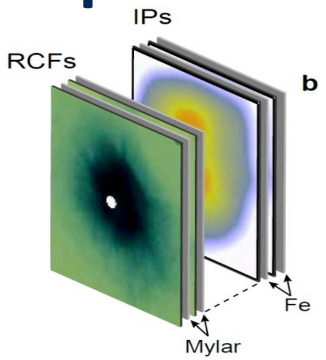
Rear surface



Front surface



Electron distribution maps into accelerated proton beam via electrostatic fields



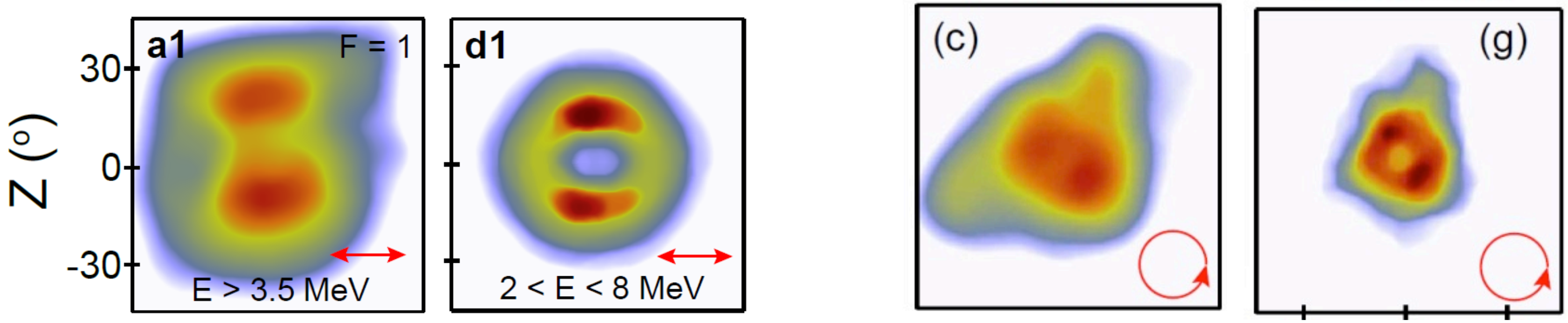
Linear pol

Experiment | 3D PIC simulation

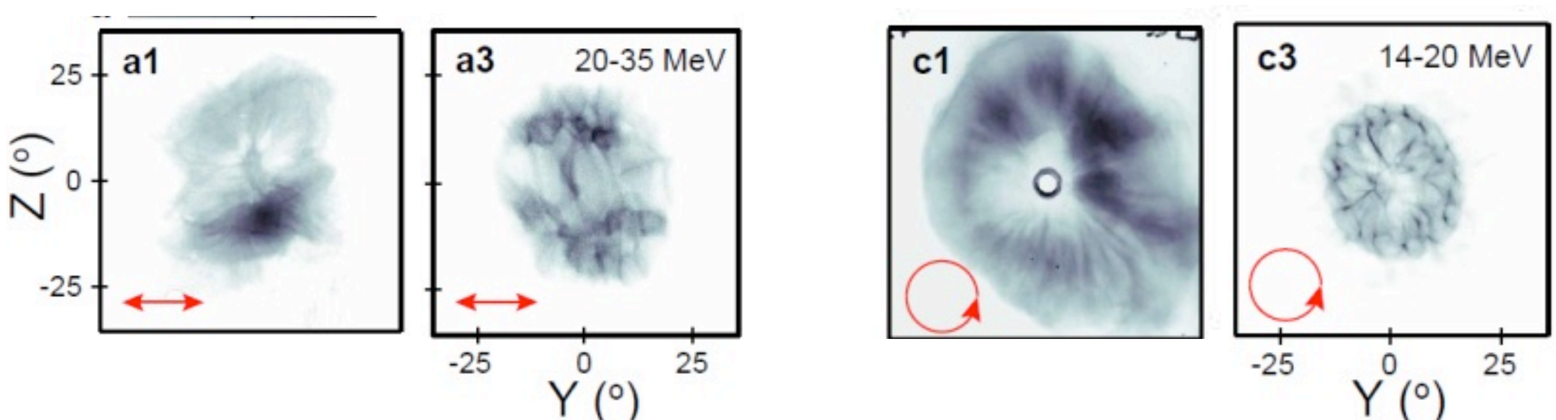
Circular pol

Experiment | 3D PIC simulation

Electrons:

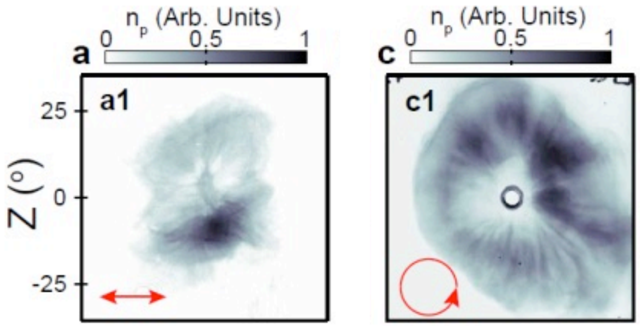


Protons:

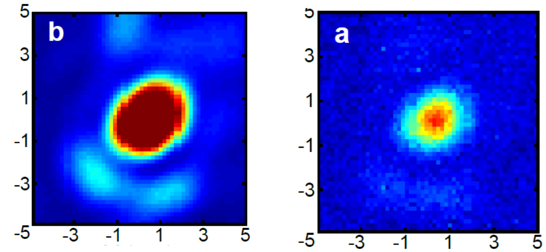


Influence of laser focus intensity distribution

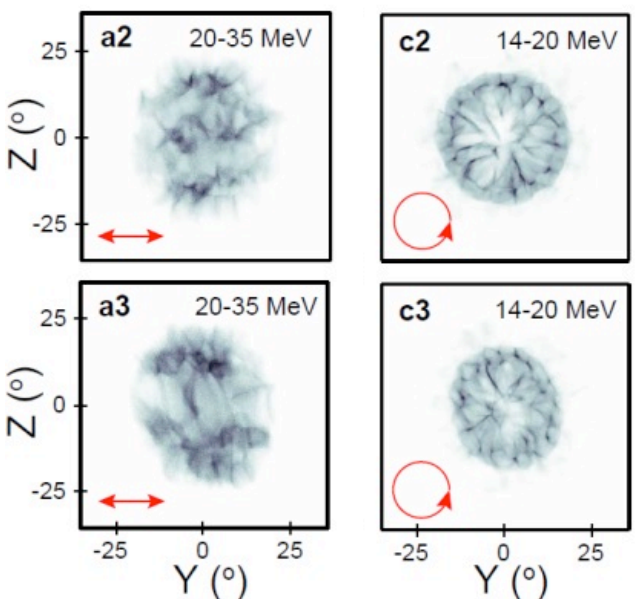
Experiment:



Measured focal spot:



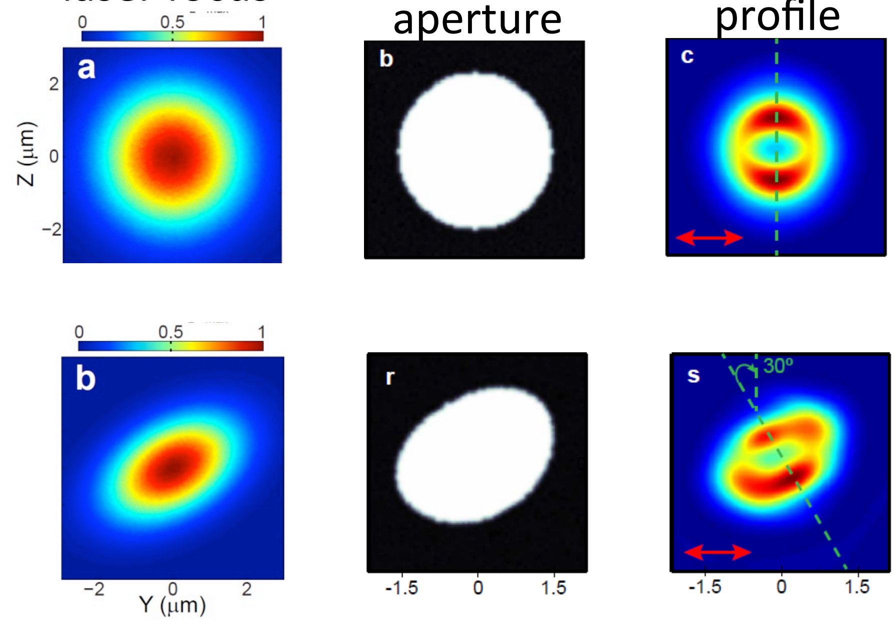
Simulation:



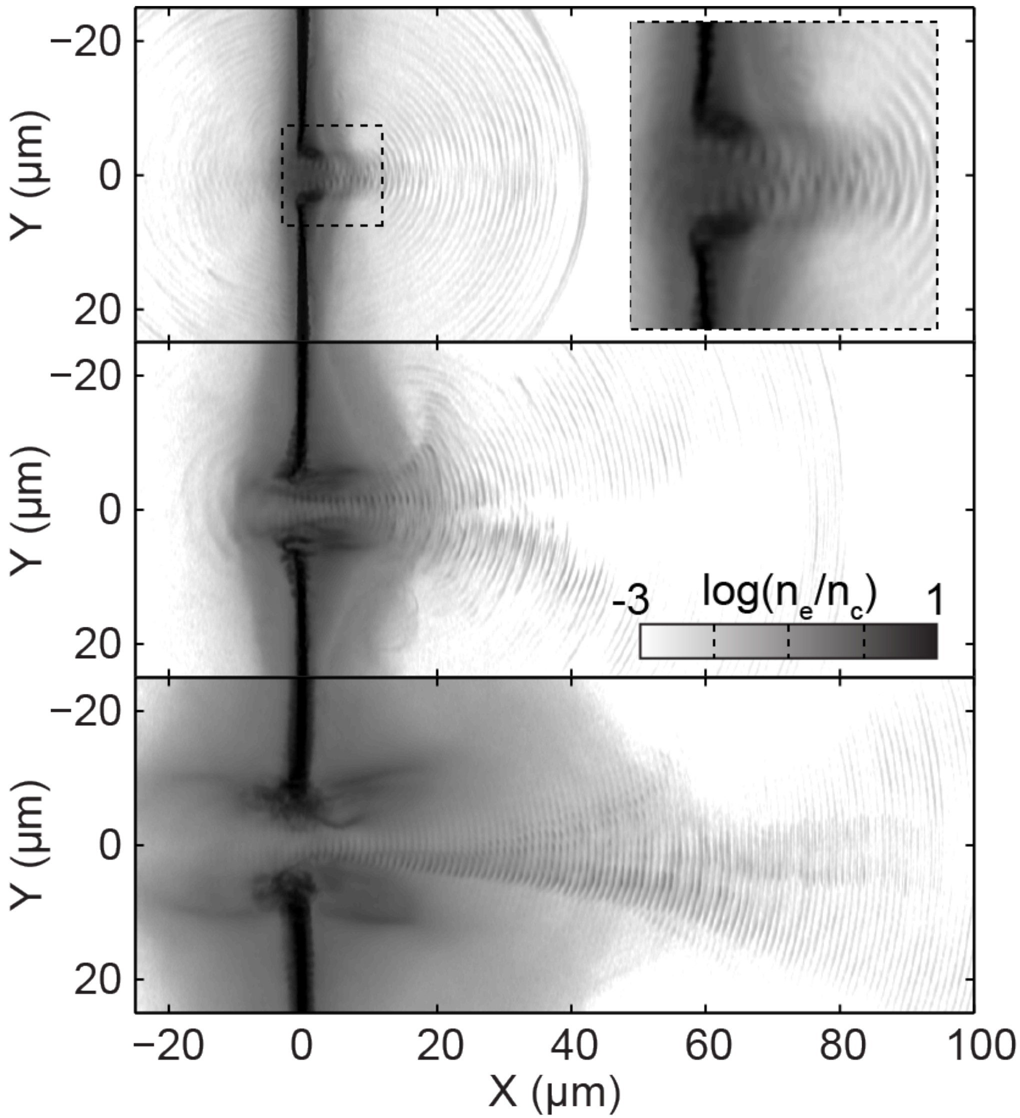
Incident laser focus

Resulting relativistic aperture

Transmitted laser profile



Effect of pulse duration on diffraction effects



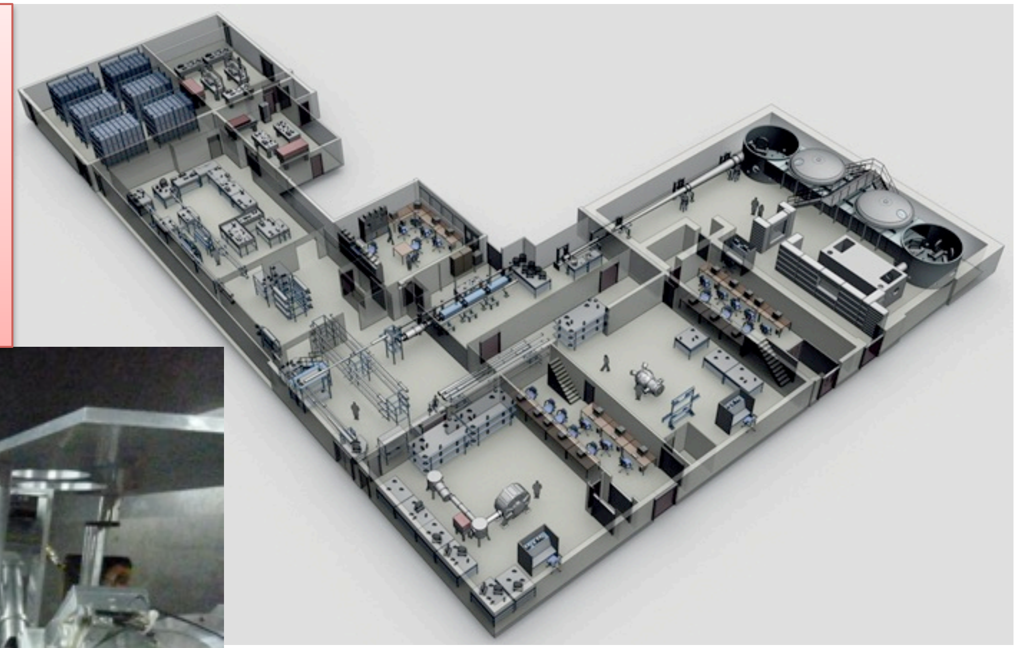
100 fs

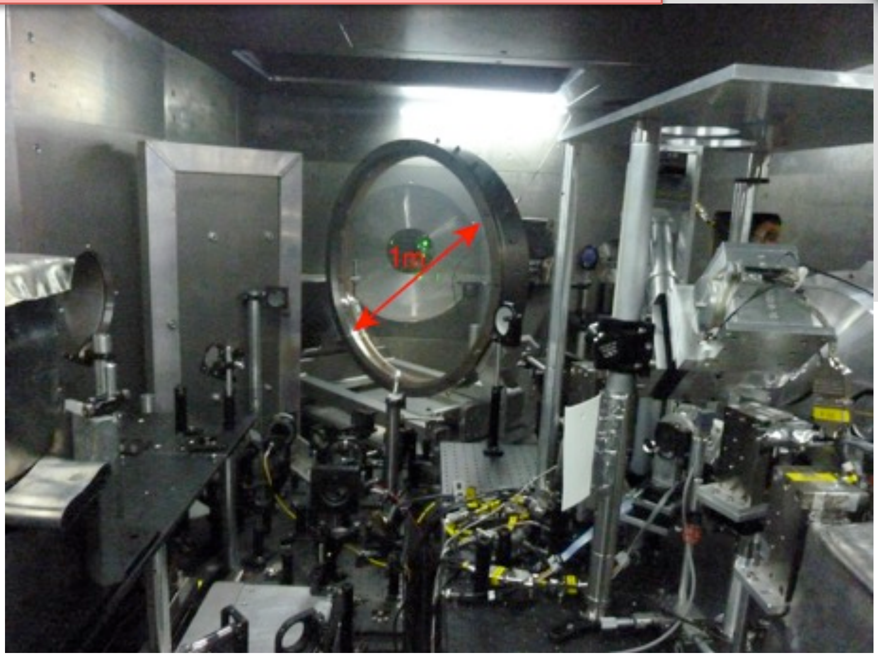
200 fs

400 fs

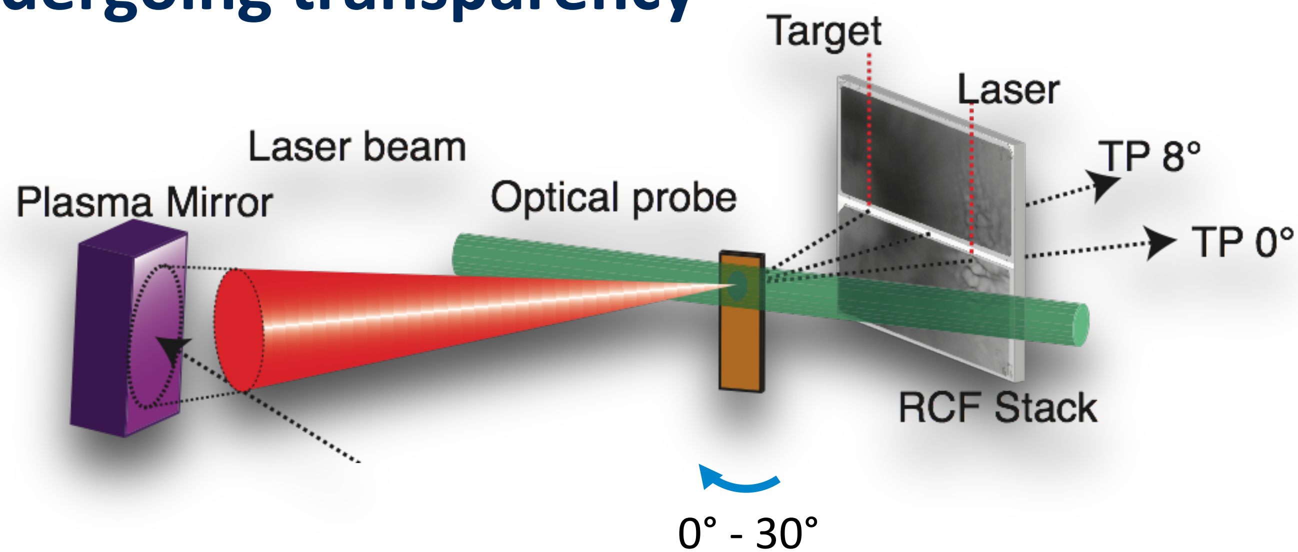
Experiments at the Vulcan laser at RAL

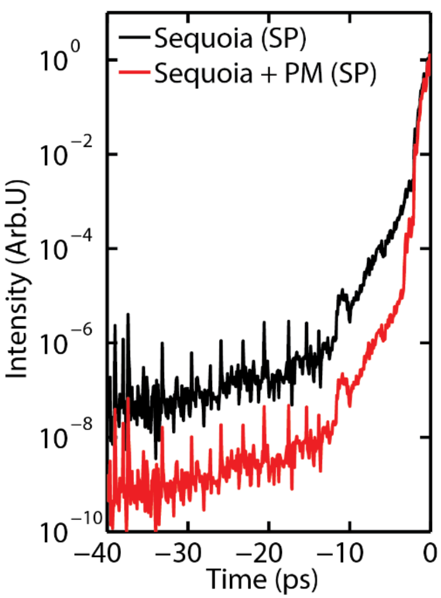
Power	1 PW
Energy	~200 J (on target)
Wavelength	1.053 μm
Pulse duration	1 ps
Intensity	mid-10^{20} Wcm^{-2}

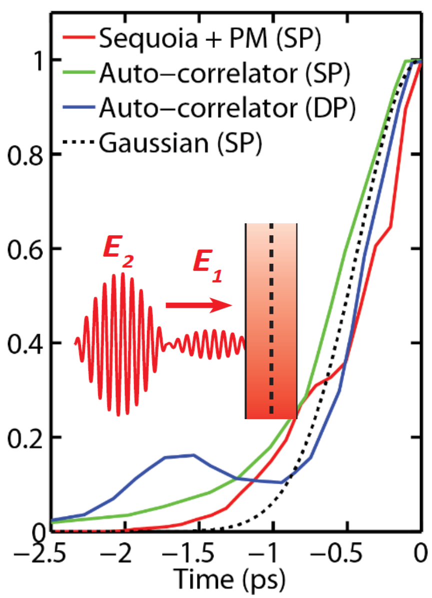




Proton spatial-intensity distribution in ultrathin foils undergoing transparency

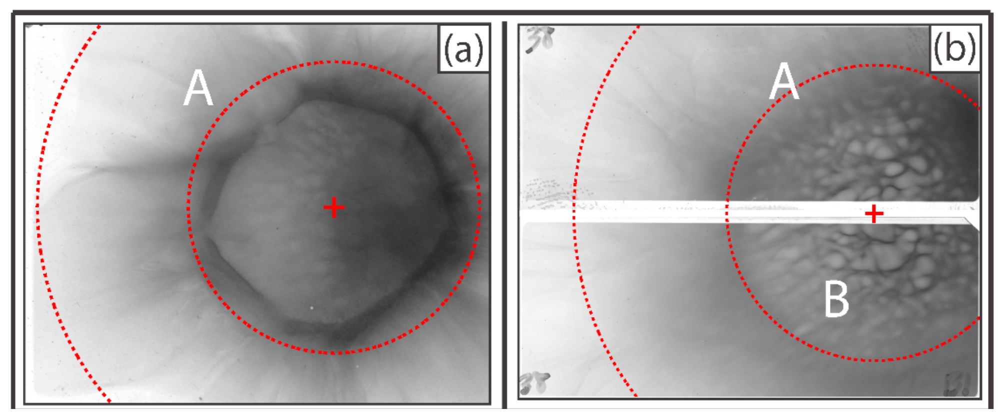






Al 10nm, 0 degrees
$I_{RE} = 0.04\ I_L$

Al 10nm, 0 degrees
$I_{RE} = 0.1\ I_L$

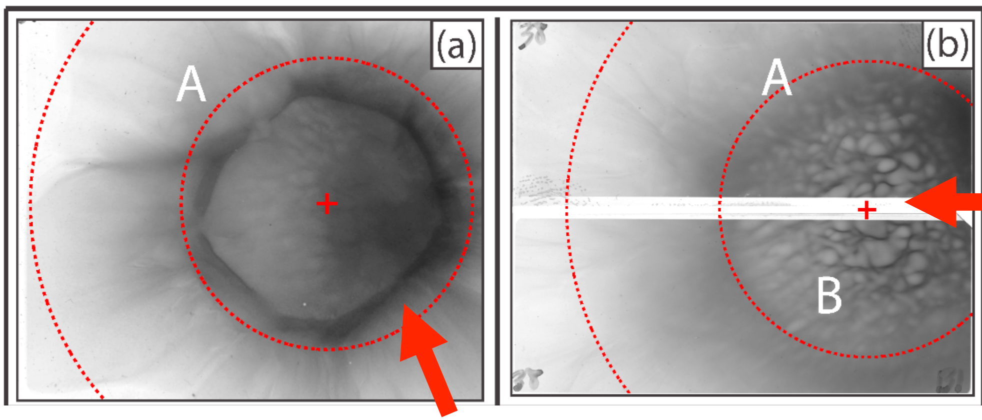


Proton spatial-intensity distribution in ultrathin foils undergoing transparency

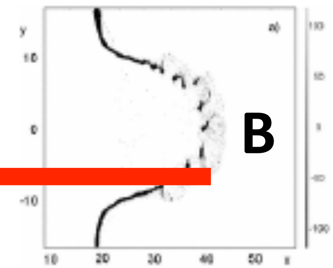
University of Strathclyde Glasgow

Al 10nm, 0 degrees
$I_{RE} = 0.04\ I_L$

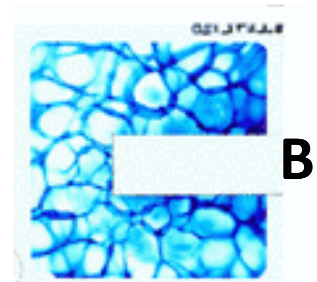
Al 10nm, 0 degrees
$I_{RE} = 0.1\ I_L$



Rayleigh-Taylor-like instability

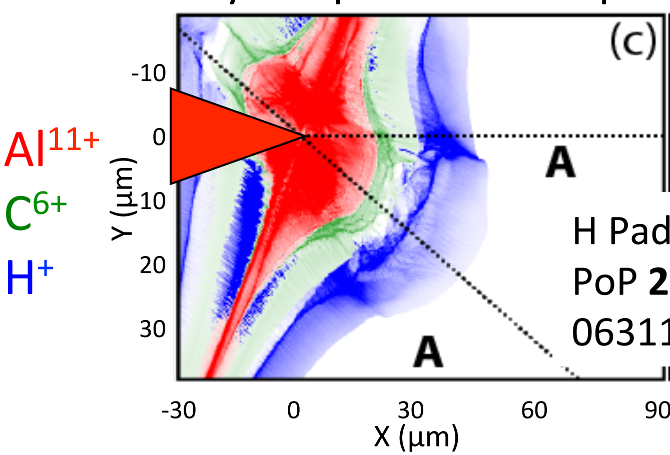


F. Pegoraro and S. V. Bulanov, PRL, **99**, 065002 (2009)

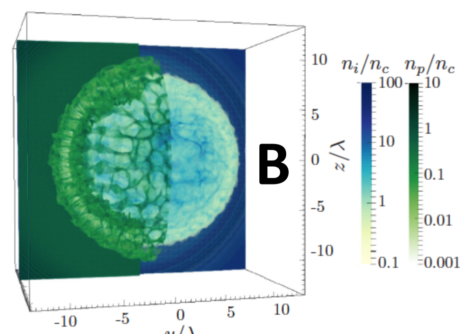


C.A.J Palmer et al. PRL, **108**, 225002 (2012)

2D EPOCH - Multiple ion species can modify the proton beam profile

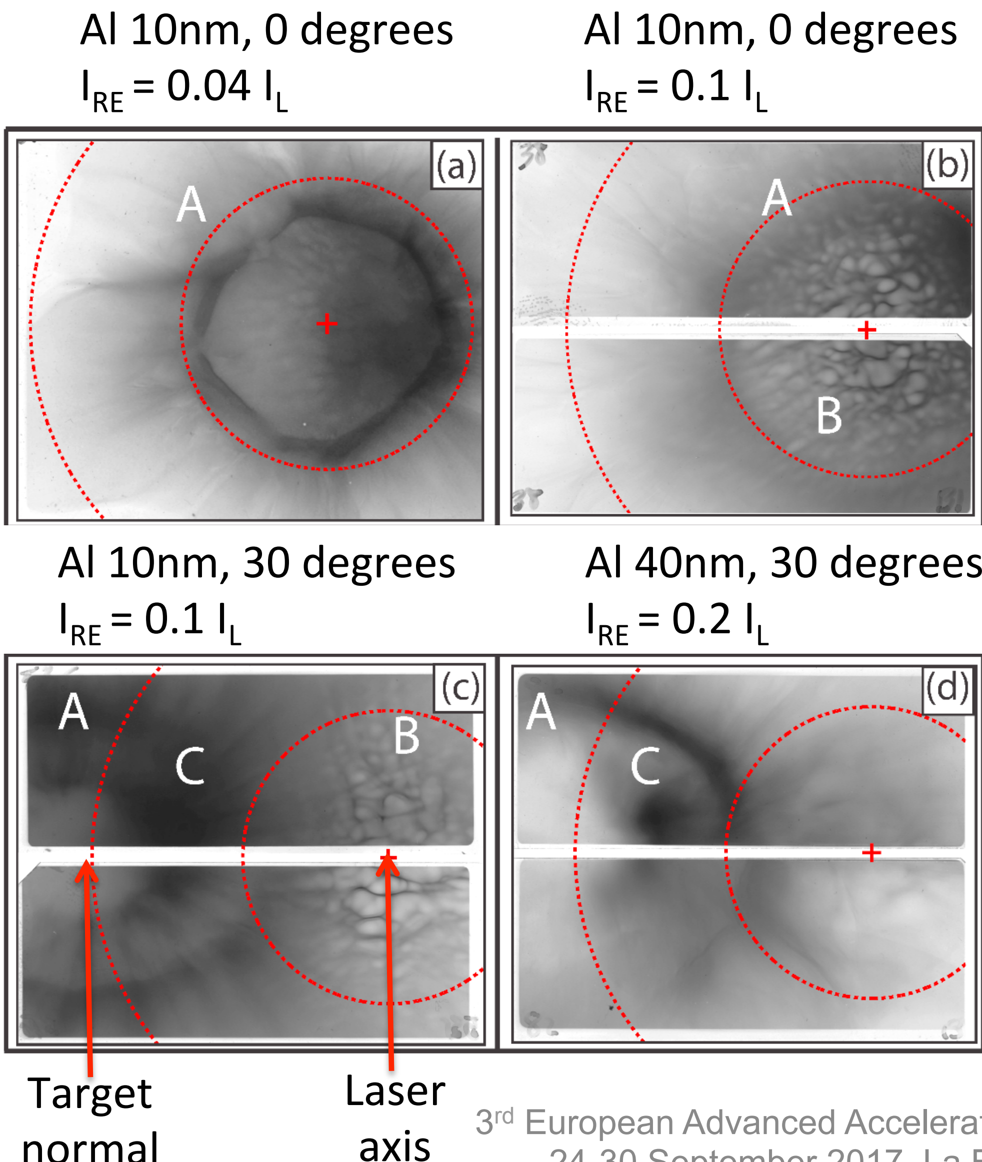


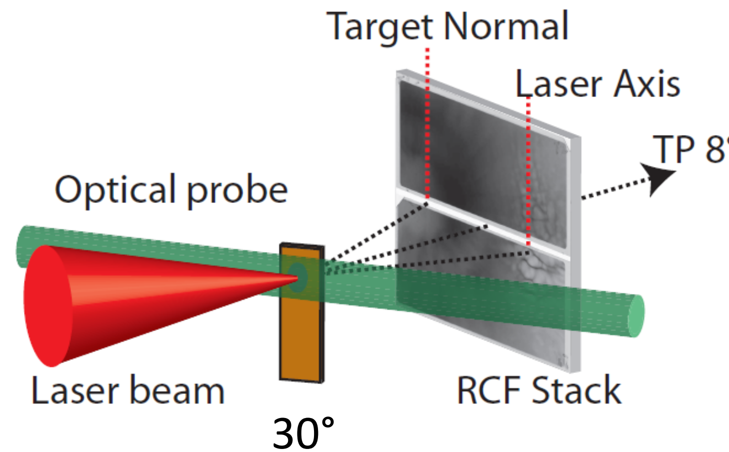
H Padda et al, PoP **23**, 6, 063116 (2015)



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

Angular separation of three proton populations



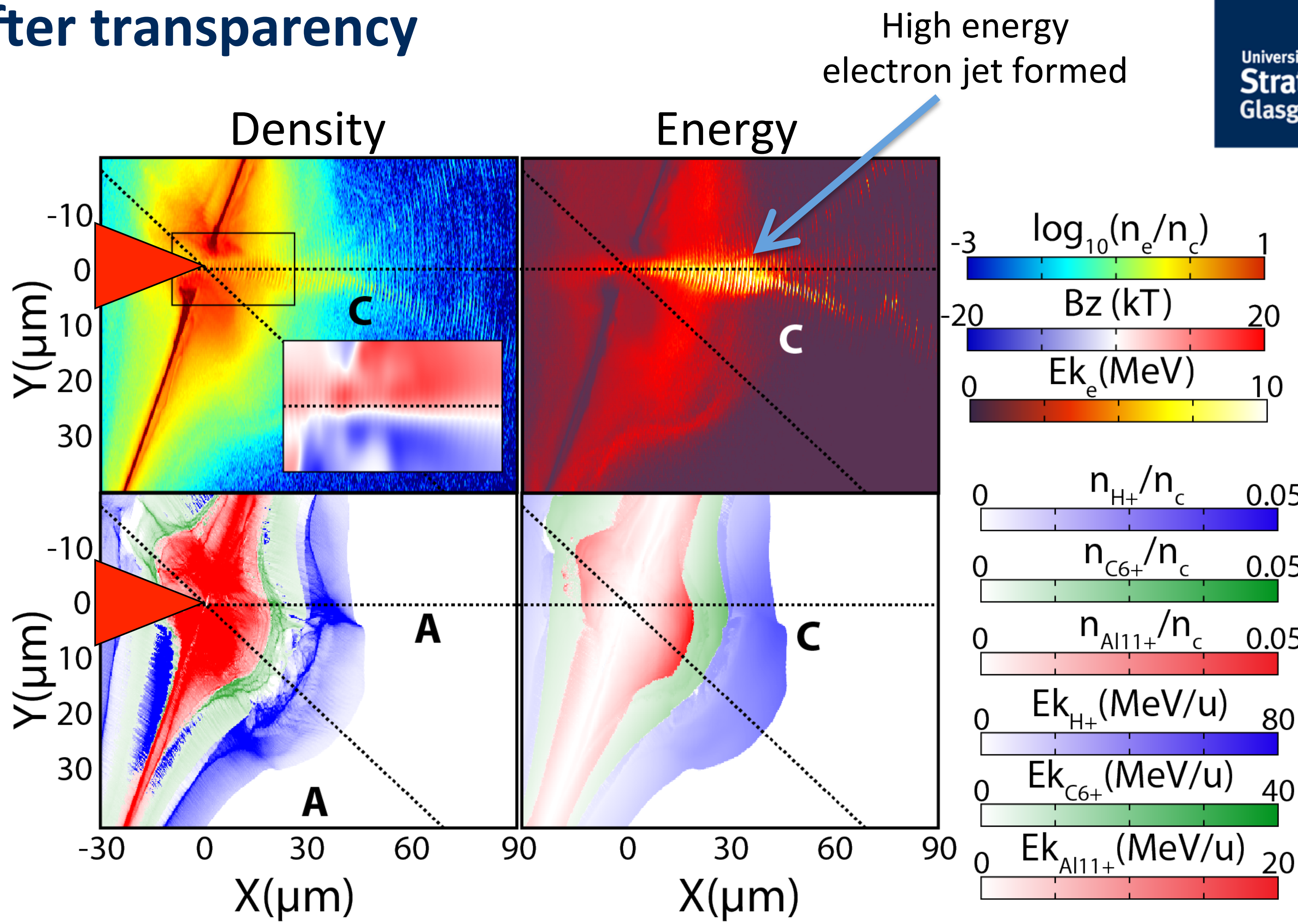


A = Buffered sheath acc along target normal

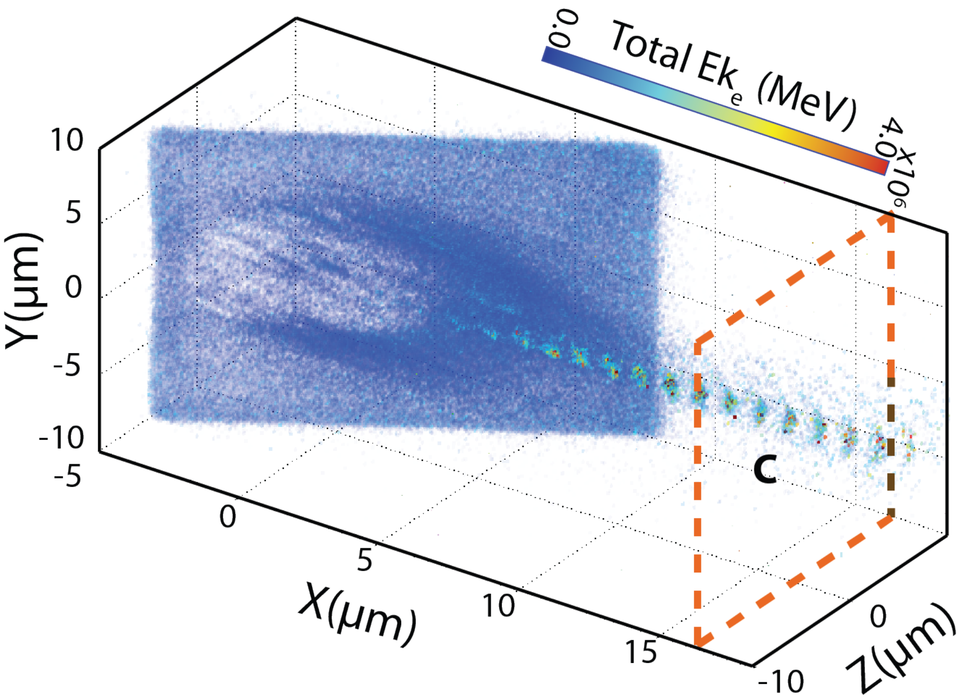
B = Unstable RPA along laser axis

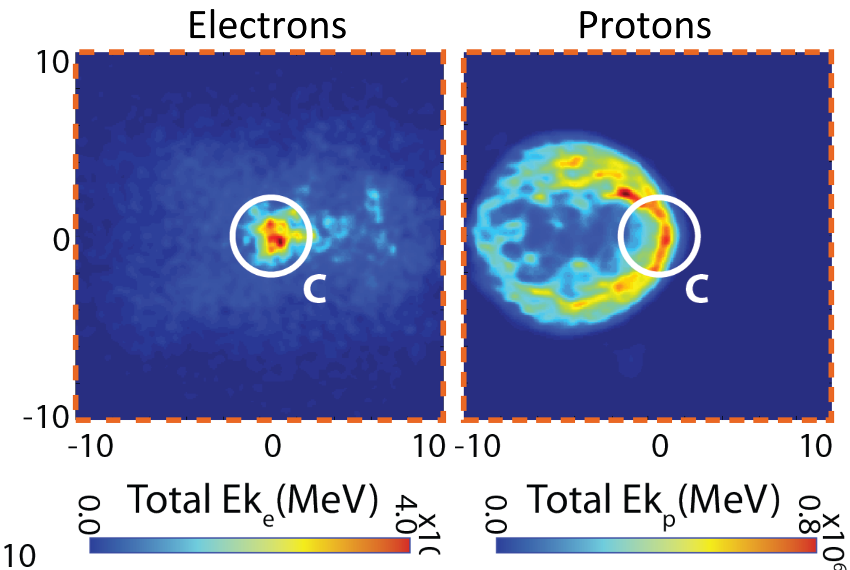
C = Localised high energy component

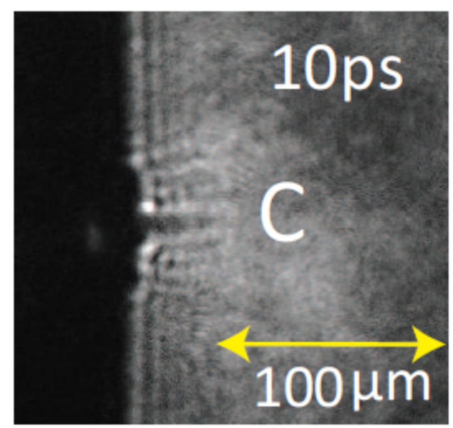
Fast electron jet enhances a localised ion region after transparency



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







Similar features observed in optical probe images

Summary

University of Strathclyde Glasgow

- Localized relativistic self-induced transparency can produce a self-induced ‘plasma aperture’
- Diffraction effects through this aperture can directly influence the accelerated electron beam structures and in turn the ion structures
- Polarization and focal spot parameters can modify the electron and ion response in the near field
- Diffraction effects are reduced as the laser pulse duration is increased
- For picosecond timescales annular structures form due to plasma expansion
- Unstable radiation pressure structures can form along the laser axis
- Localised enhancement of the proton beam can be associated with the formation of a modulated electron jet

Further information

Gonzalez-Izquierdo, B Gray, R J, King, M, Dance, R J, Wilson, R, McCreadie, J, Butler, N M H, Capdessus R, Hawkes, S, Green, Borghesi, M, Neely, D & McKenna, P, *Optical controlled dense current structures driven by relativistic plasma aperture-induced diffraction*, Nature Physics **12**, 505 (2016)

Gonzalez-Izquierdo, B, King, M, Gray, R J, Wilson, R, Dance, R J, Powell, H, MacLellan, D A, McCreadie, J, Butler, N M H, Hawkes, S, Green, J S, Murphy, C D, Stockhausen, L C, Carroll, D C, Booth, N, Scott, G G, Borghesi, M, Neely, D & McKenna, P, *Towards optical polarization control of laser-driven proton acceleration in foils undergoing relativistic transparency*, Nature Communications **7**, 10 (2016)

Gonzalez-Izquierdo, B, Gray, R J, King, M, Wilson, R, Dance, R J, Powell, H, MacLellan, D A, McCreadie, J, Butler, N M H, Hawkes, S, Green, J S, Murphy, C D, Stockhausen, L C, Carroll, D C, Booth, N, Scott, G G, Borghesi, M, Neely, D & McKenna, P, *Influence of laser polarization on collective electron dynamics in ultraintense laser-foil interactions,* High Power Laser Science and Engineering, **4**, 7 (2016)

Powell, H W, King, M, Gray, R J, MacLellan, D A, Gonzalez-Izquierdo, B, Stockhausen, L C, Hicks G, Dover, N P, Rusby, D R, Carroll, D C, Padda, H, Torres, R, Kar, S, Clarke, R J, Musgrave, I O, Najmudin, Z, Borghesi, M, Neely, D, and McKenna, P, *Proton acceleration enhanced by a plasma jet in expanding foils undergoing relativistic transparency*, New Journal of Physics, **17**, 103033 (2015)

King, M, Gray, R J, Powell, H W, Capdessus, R & McKenna, P, *Measurement of the angle, temperature and flux of fast electrons emitted from intense laser-solid interactions*, Plasma Physics and Controlled Fusion **8** (2016)

King, M, Gray, R J, Powell, H W, Maclellan, D A, Izquierdo, B, Stockhausen, L C, Hicks, G S, Dover, N P, Rusby, D R, Carroll, D C, Padda, H, Torres, R, Kar, S, Clarke, R J, Musgrave, I O, Najmudin, Z, Borghesi, M, Neely, D & McKenna, P, *Ion acceleration and plasma jet formation in ultra-thin foils undergoing expansion and relativistic transparency*, Nuclear Instruments and Methods in Physics Research Section A **829**, p 163-166 (2016)

Padda, H, King, M, Gray, R J, Powell, H W, Izquierdo, B, Stockhausen, L C, Wilson, R, Carroll, D C, Dance, R J, MacLellan, D A, Yuan, X H, Butler, N M H, Capdessus, R, Borghesi, M, Neely, D & McKenna, P, *Intra-pulse transition between ion acceleration mechanisms in intense laser-foil interactions*, Physics of Plasmas **23**, 6, 6 p, 063116 (2016)

Thank you for you attention