High energy density laser-plasma research at Strathclyde

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Outline:

1. Brief overview of XFEL-relevant activities at Strathclyde
2. Probing ultrafast laser-dense-plasma interaction physics
3. Probing transient states of warm dense matter and electron transport physics

Experiments at external high power laser facilities

Vulcan petawatt, RAL, UK

Gemini 0.5 PW, RAL, UK

ORION, AWE, UK

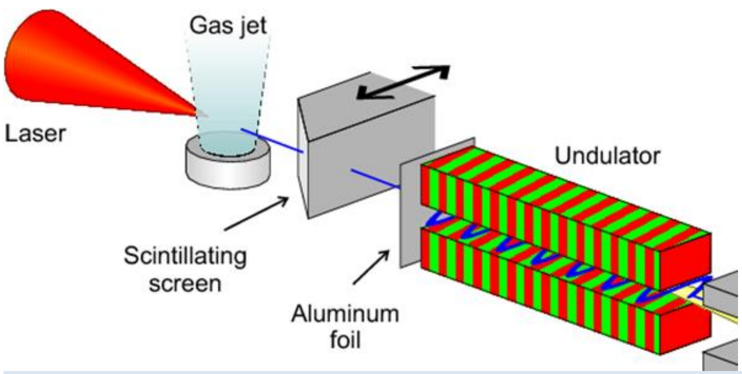
PHELIX – GSI, Germany

SCAPA: Scottish Centre for Applications of Plasma-based Accelerators

Director: Prof D. A. Jaroszynski

- **3 shielded areas** with multiple beam lines.
- High-intensity fs laser systems:
  - a) 350 TW at 5 Hz,
  - b) 40 TW at 10 Hz,
  - c) sub-TW at kHz.
- High-energy **ion and electron** bunches,
- Bright **X-ray/γ-ray** and **neutron** pulses.

Laser-plasmas as particle accelerators



Photon beams

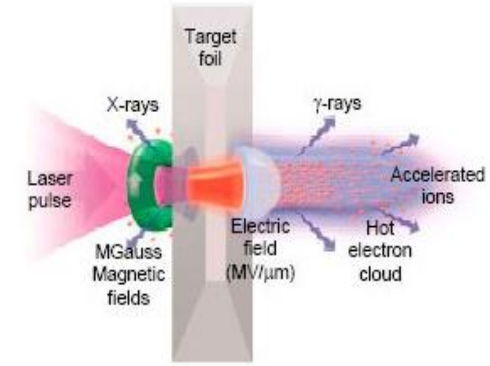
- peak brilliance >10^{23} photons/s/mm^2/rad^2/0.1%BW
- from VUV to 10 MeV gammas.
- Bright coherent sources in soft X-ray water window and shorter wavelengths.
- Bright (less coherent) pulses of very hard X-rays and gamma rays.

Electron beams

- up to 4 GeV
- 10 pC of charge,
- 0.3 mrad divergence,
- 3 fs duration, 3 kA peak current.
- Separately, 10-100 times more charge could be generated at 10-100 times more divergence in the 1-10 MeV electron energy range.
- Nominal rep rate is 1 Hz.

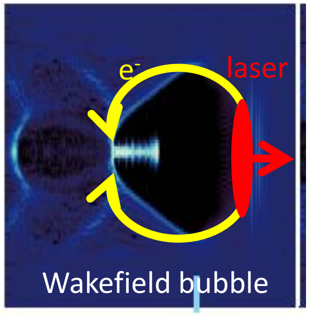
Proton beams

- up to ~30 MeV
- ~10^{10} protons / pulse
- ~30° divergence
- 40 fs at sources (increases due to time of flight spreading)
- Low rep rate due to focusing limitations at present.

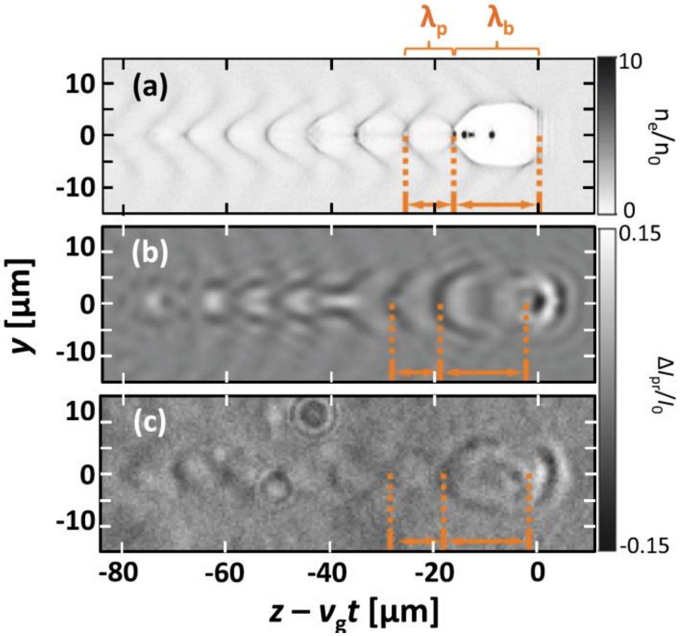


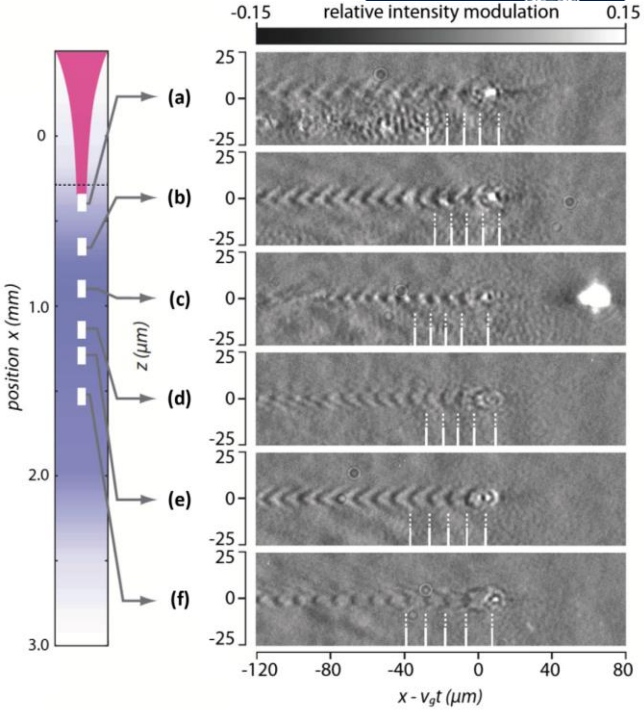
Probing laser-plasma interactions

Underdense plasma



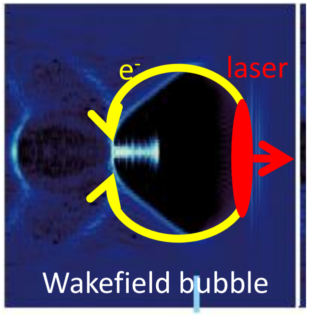
Wakefield electron acceleration



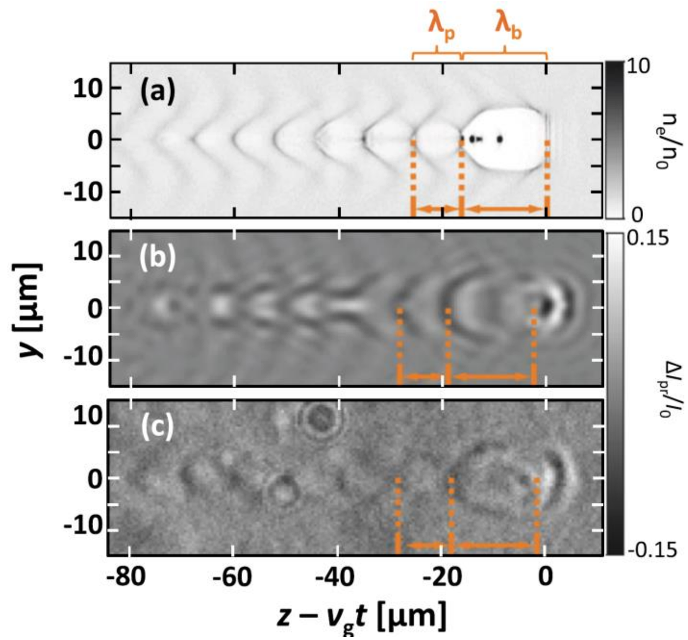


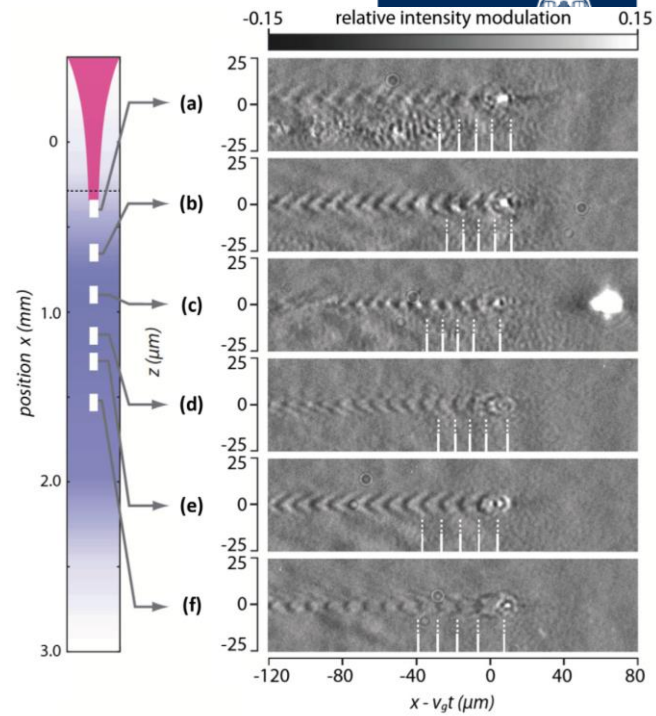
Probing laser-plasma interactions

Underdense plasma

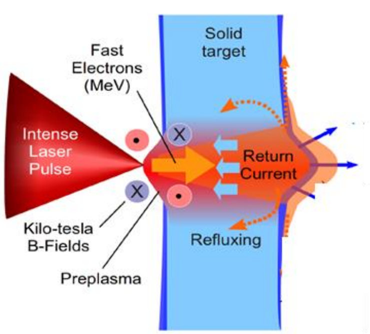


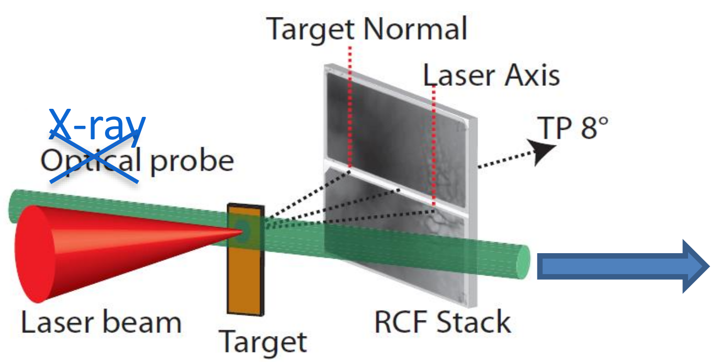
Wakefield electron acceleration

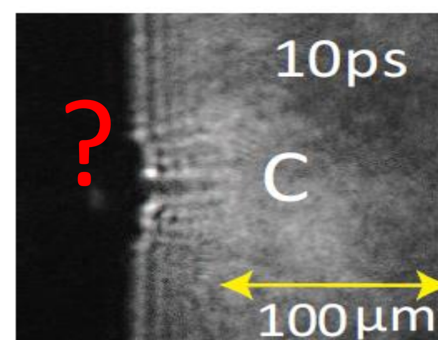




Overdense plasma

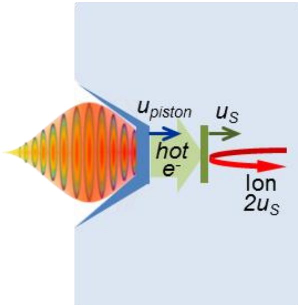




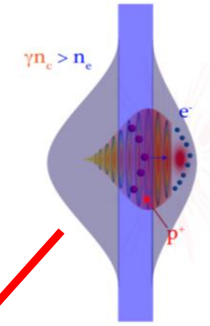


H. Powell et al, New J. Phys. 17, 103033 (2015)

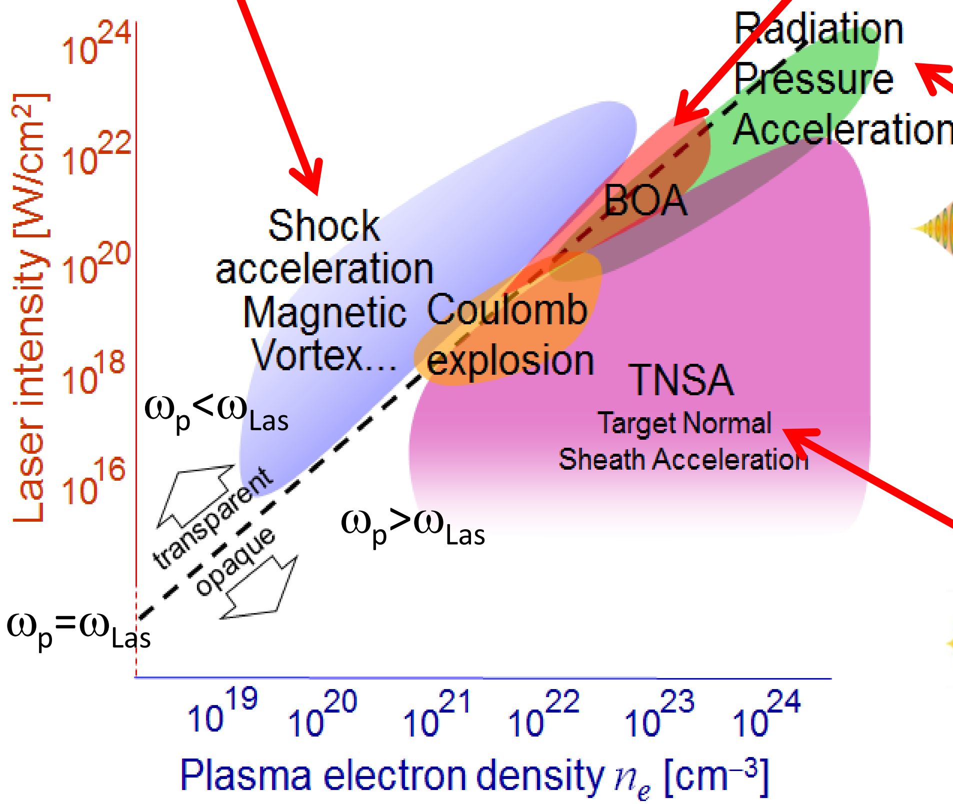
Laser-driven ion acceleration schemes

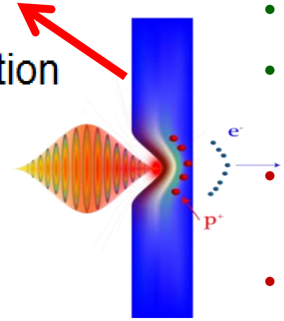


- Quasi-monoenergetic ions
- Suitable for high repetition rate (high density gas target)
- Order of magnitude higher density targets required for ~1μm wavelength lasers

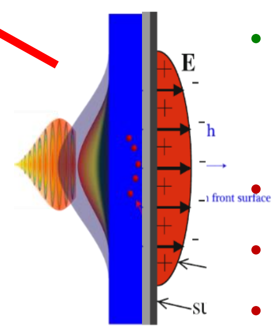


- Enhances energy of ions accelerated by TNSA / RPA
- Works over a small laser and target parameter space (ultrathin foils)
- Subject to non-linear interactions; more difficult to control



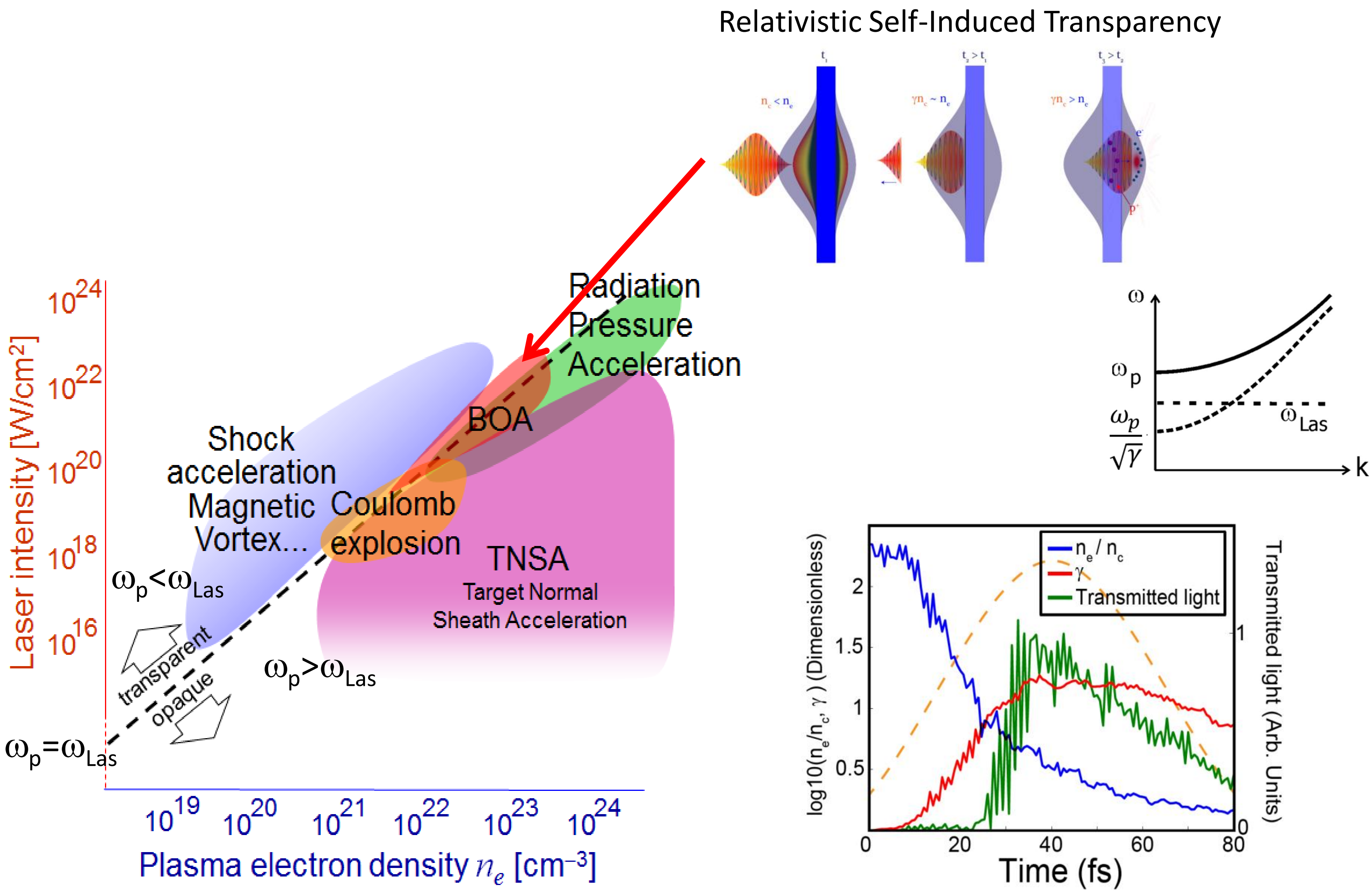


- Favourable intensity scaling
- High conversion efficiency and directed beam
- Requires high intensity, circular polarization and large focus
- Subject to instabilities



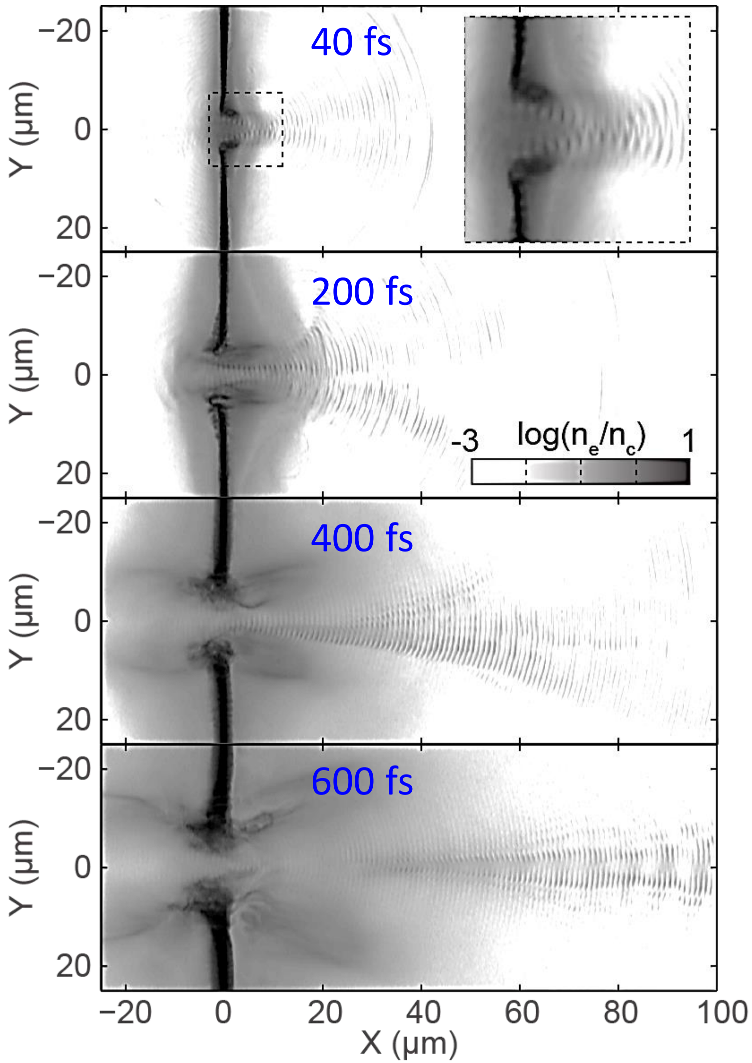
- Robust mechanism (over a wide range of laser and target parameters)
- Thermal spectrum
- Divergent beam
- Weak intensity scaling

Laser-driven ion acceleration schemes



Collective electron dynamics depends on degree of expansion and thus pulse duration:

Electron density maps from 2D PIC simulations using EPOCH code: 5×10^{20} Wcm^{-2}; ultrathin Al foils



Short pulse – minimal expansion – ‘relativistic plasma aperture’

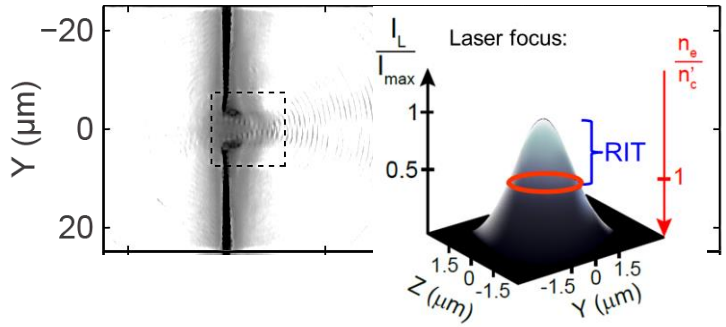
XFEL probe - measurements of relativistic laser-plasma effects such as induced transparency

Longer pulse – significant expansion – plasma jet of directly accelerated electrons

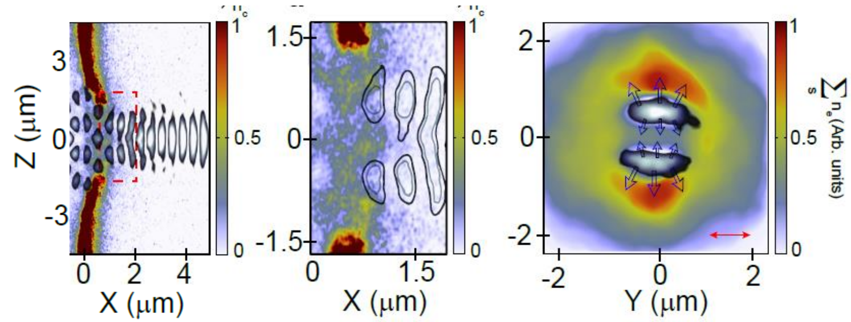
Collective plasma dynamics with tens of fs pulses

Electron density maps from 2D PIC simulations using EPOCH code: $5\text{x}10^{20}$ Wcm^{-2}; ultrathin Al foils

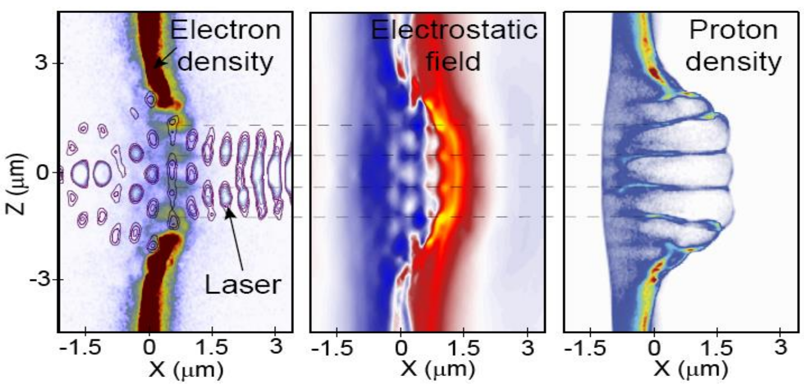
40 fs



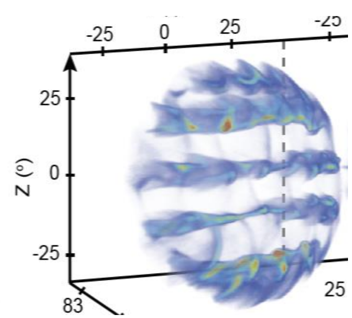
Short pulse – minimal expansion – ‘relativistic plasma aperture’



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



Proton beam profile:



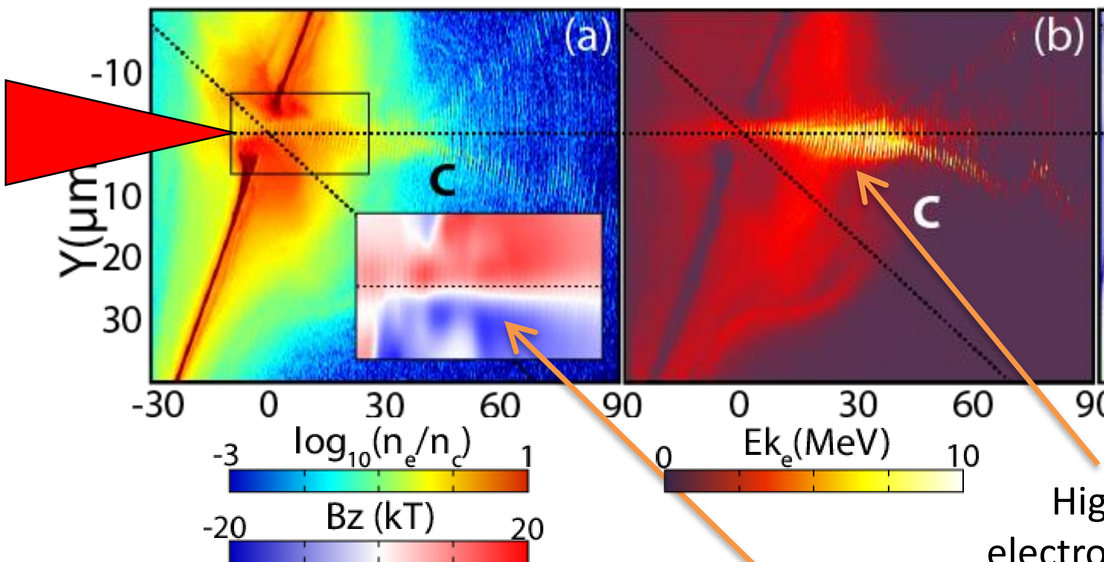
B. Gonzalez-Izquierdo *et al*, Nature Comms **7**, 12891 (2016)

XFEL probe - measurements of density structure evolution on ultrafast timescales

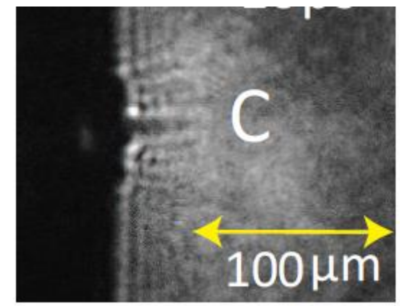
Transparency-enhanced acceleration

Transmission of part of the laser pulse can enhance the TNSA field, by further heating the electrons, resulting in RIT-enhanced acceleration

Electron density   Electron energy



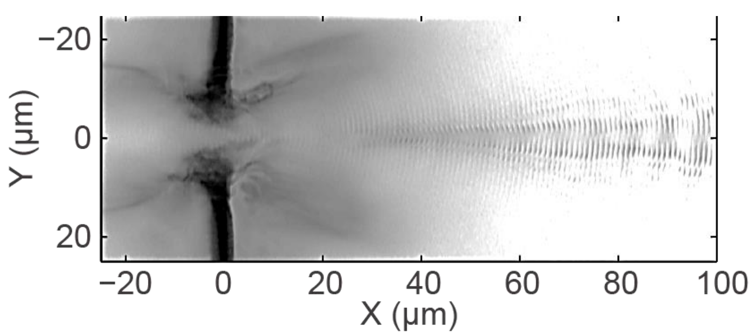
Experiment;
Optical probe:



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

High energy electron jet formed

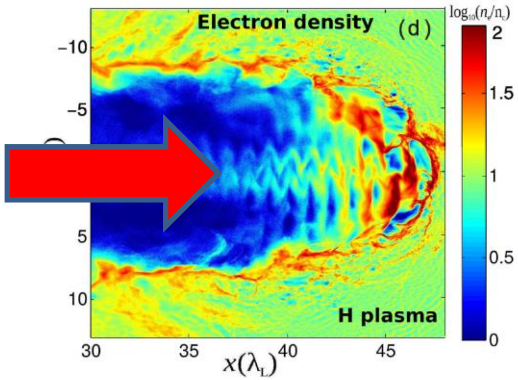
Azimuthal magnetic field surrounding electron jet

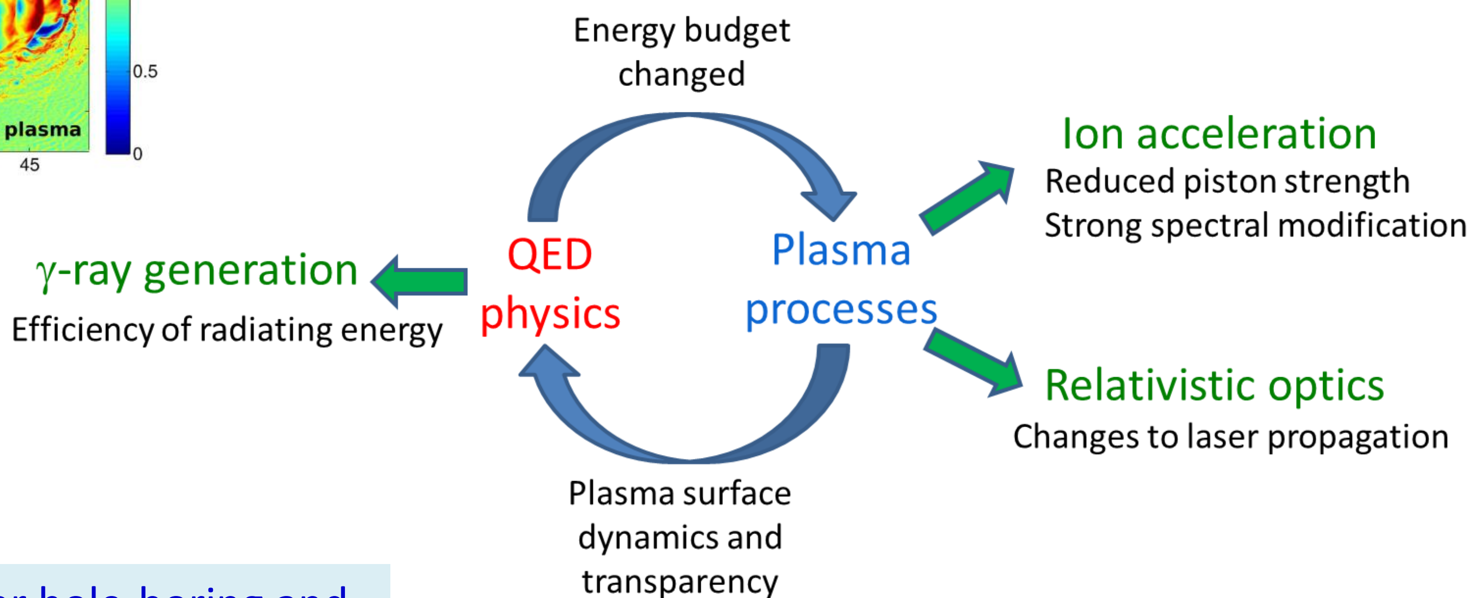


XFEL probe - Faraday rotation measurements of magnetic field evolution on ultrafast timescales

Probing high field effects at ~10^{23} Wcm^{-2}

Strong feedback between RR and plasma physics phenomena in 'QED-plasma' regime

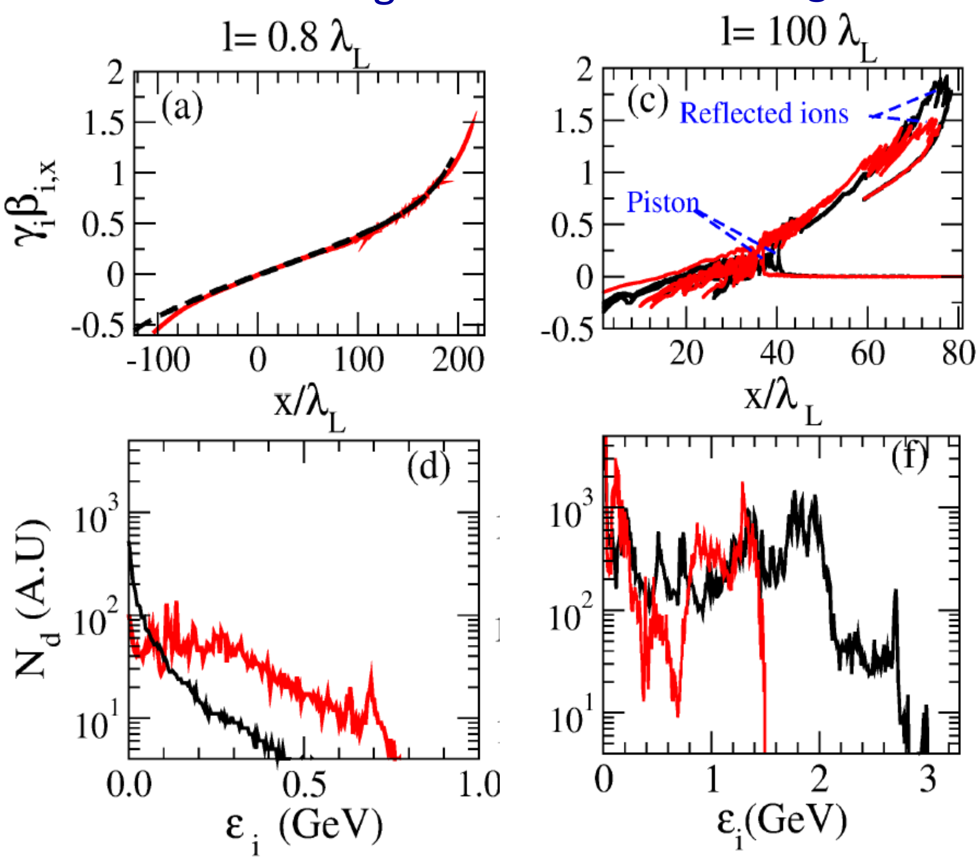


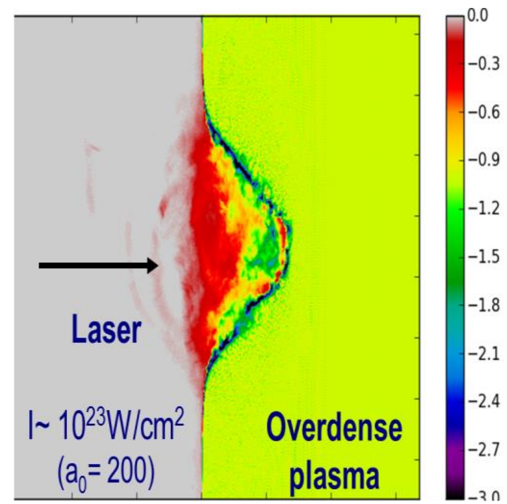


XFEL probe – laser hole-boring and the role of high field phenomena, such as radiation reaction

Probing high field effects at ~10^{23} Wcm^{-2}

Thin D target | Thicker D target





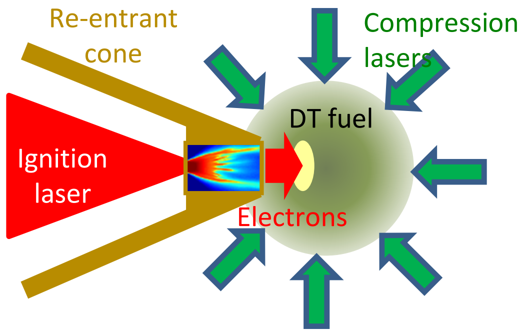
With radiation reaction

Without radiation reaction

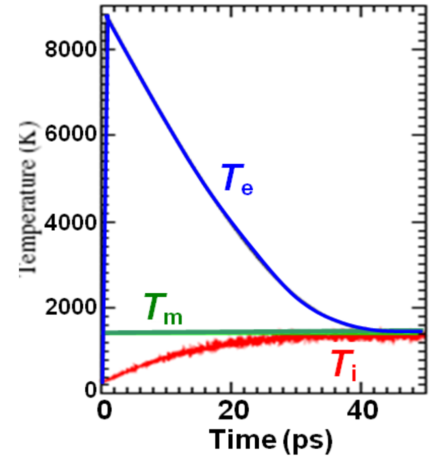
R. Capdessus and P. McKenna, Phys. Rev. E., 91, 053105 (2015)

XFEL could provide a time-resolving probe of hole-boring dynamics and the role of radiation reaction

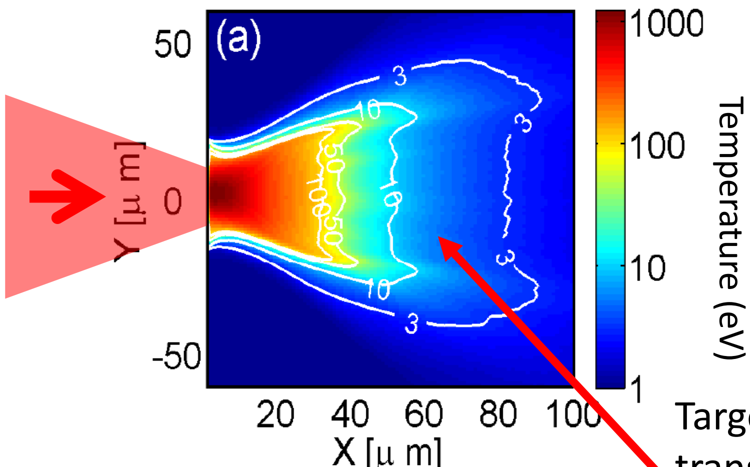
Probing transient states of warm dense matter: hot electrons and cold ions on picosecond timescale



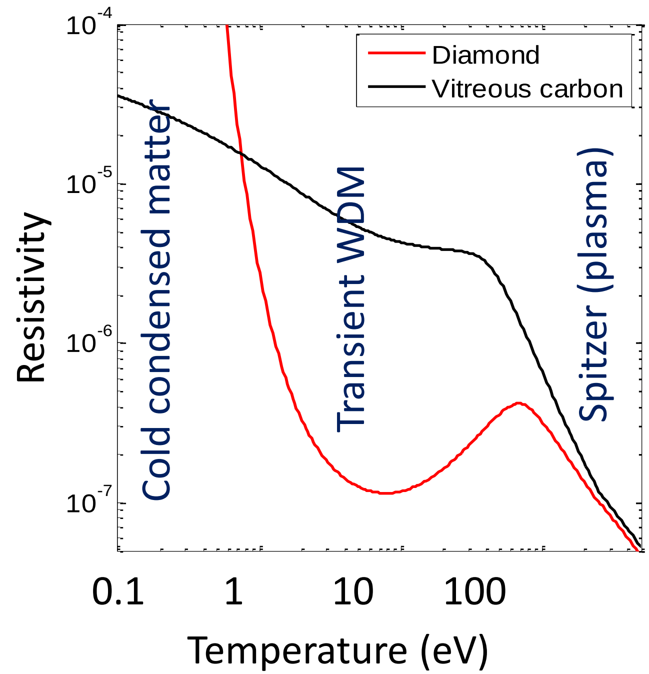
Electron-ion energy equilibration on tens of ps timescales



Mazevet et al., PRL 95, 085002 (2005)

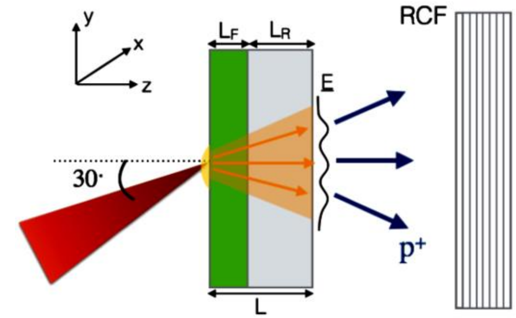


Target bulk in transient WDM state

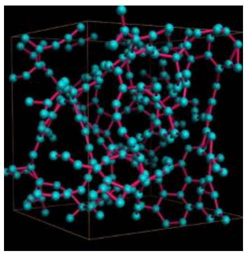


Lattice structure plays a defining role in the resistivity of transient WDM

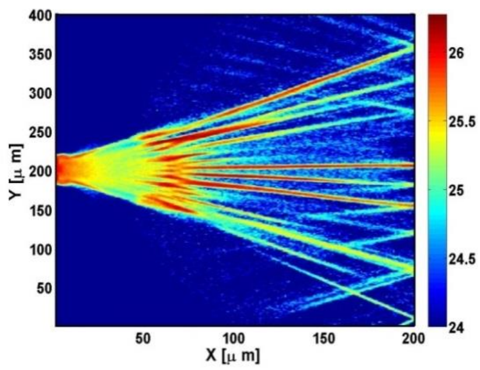
McKenna *et al*, Phys. Rev. Lett. 106, 184004 (2011)



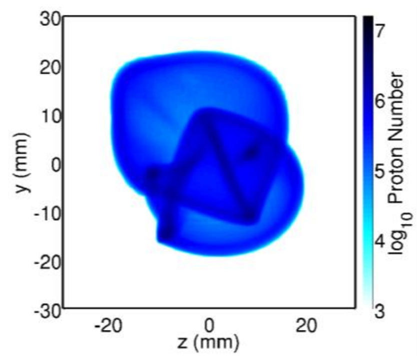
Vitreous carbon

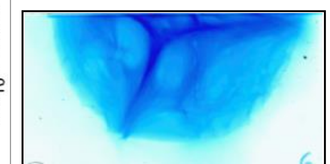


Fast electron distribution: simulation

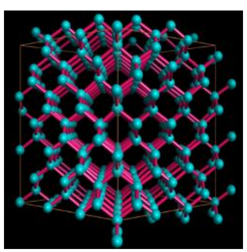


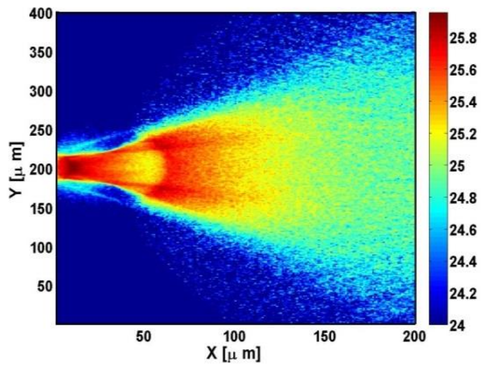
Resulting proton beam: model

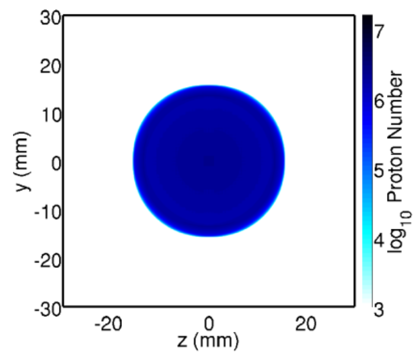




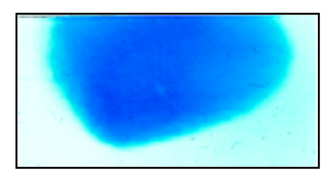
Diamond





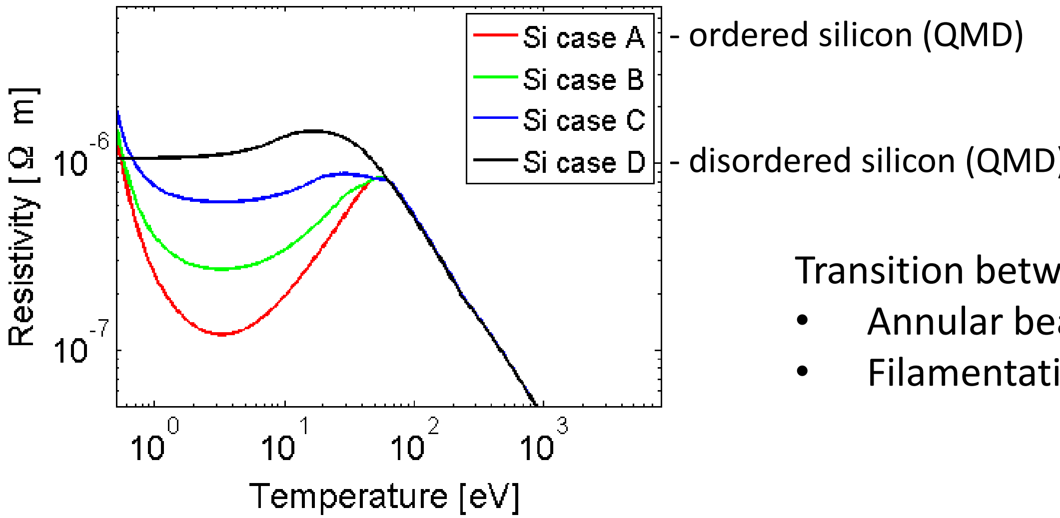


Proton beam: experiment (lower half)



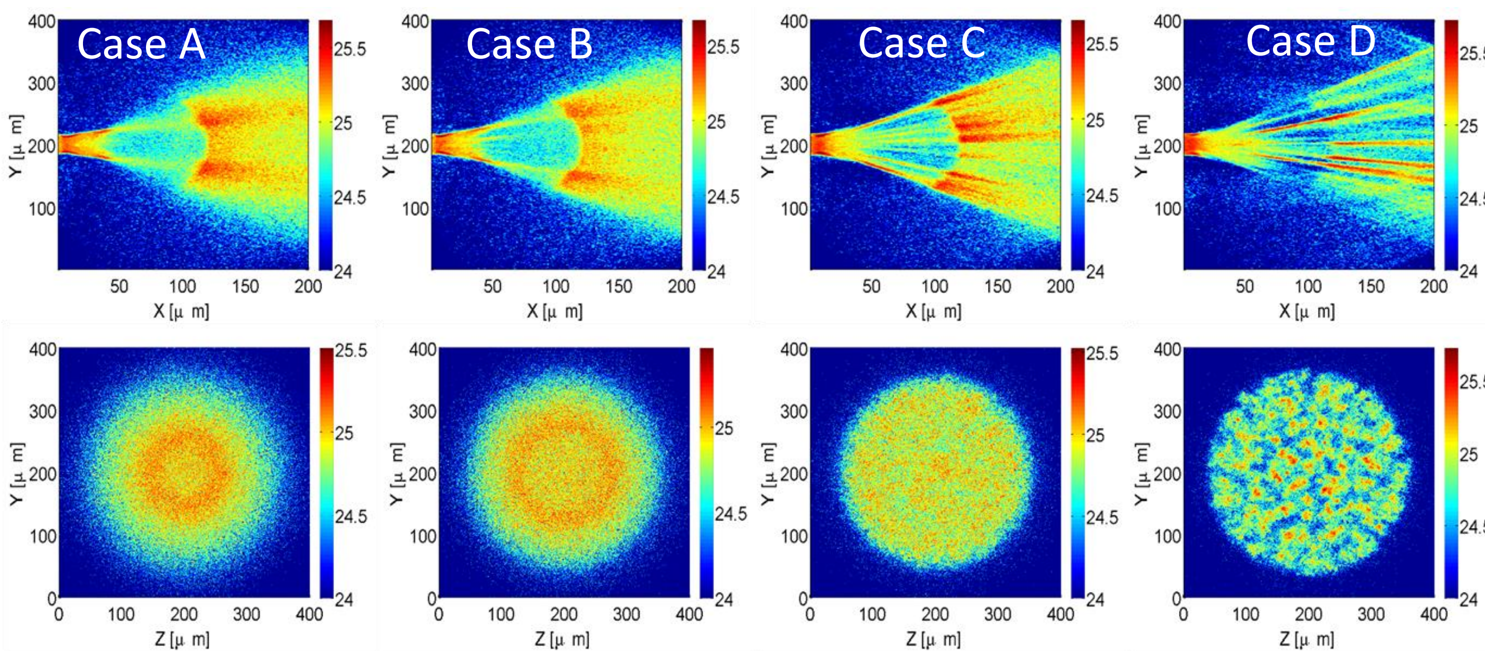
Lattice structure defines low temperature resistivity (in transient WDM), which in turn defines the onset of filamentation instability

Changing the degree of lattice order (target heating)



Transition between:

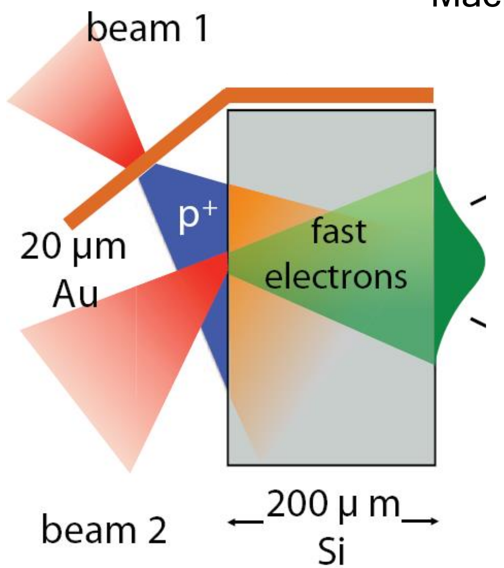
- Annular beam for ordered Si
- Filamentation for disordered Si



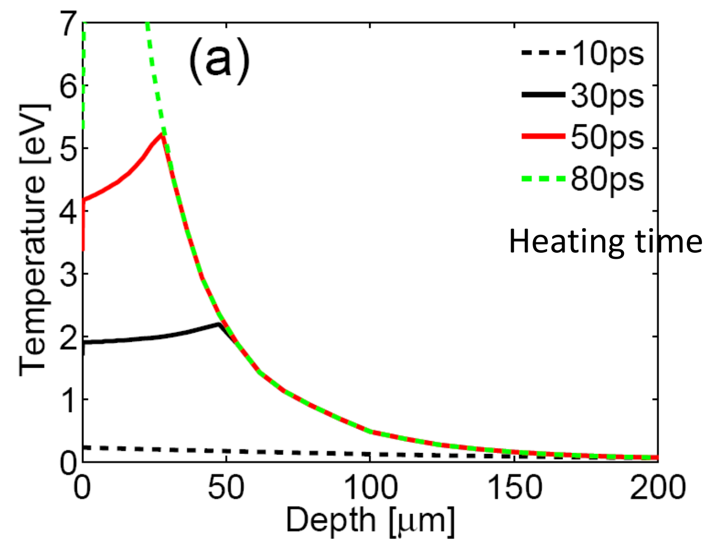
Effects of temperature and resistivity gradients on fast electron transport

MacLellan et al, Phys. Rev. Lett., 113, 185001 (2014)

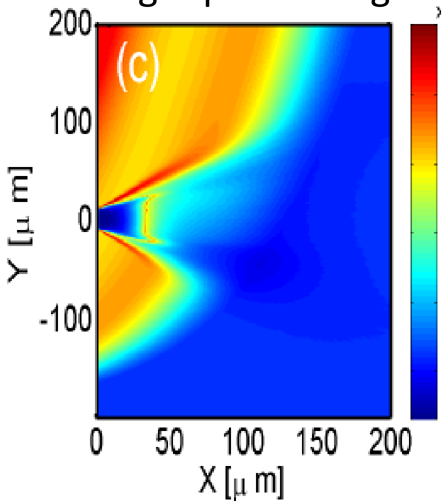
MacLellan et al, Phys. Rev. Lett. 111, 095001 (2013)



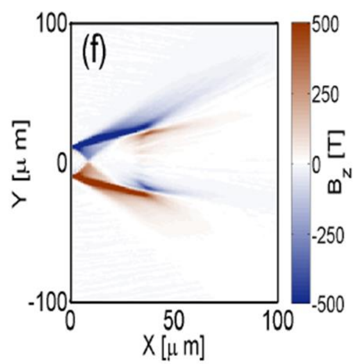
Target heating is modelled in Helios rad-hydro code



Target preheating



$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla \times \mathbf{j}_\mathbf{f} + (\nabla \eta) \times \mathbf{j}_\mathbf{f}$$



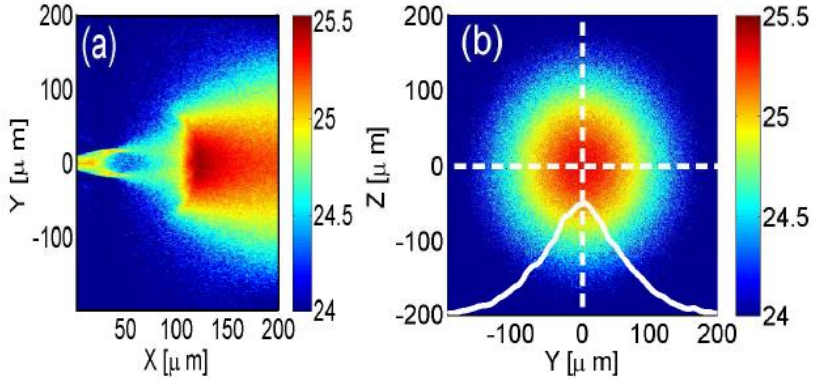
Laser-driven proton beam used to volumetrically preheat the silicon target

Temperature and resistivity gradients induced and their effects on fast electron transport investigated

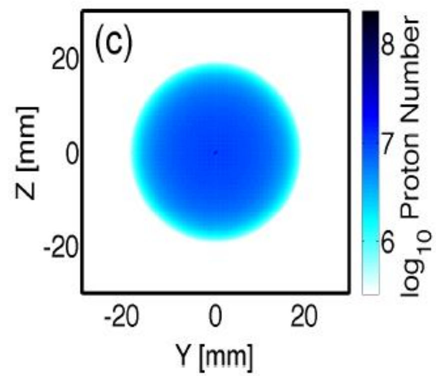
Modelling the resulting fast electron transport and proton beam

Cold (ordered) silicon

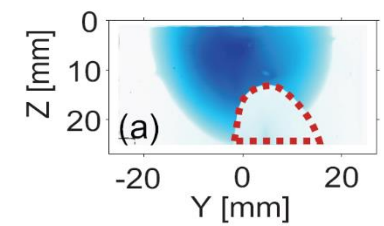
Fast electron distribution: simulation



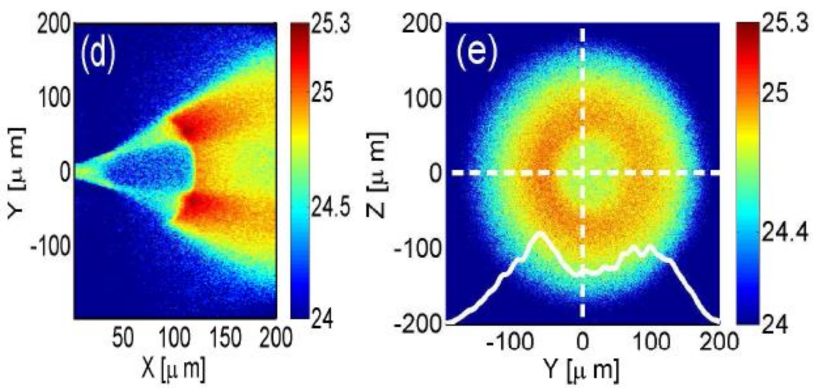
Resulting proton beam: **model**

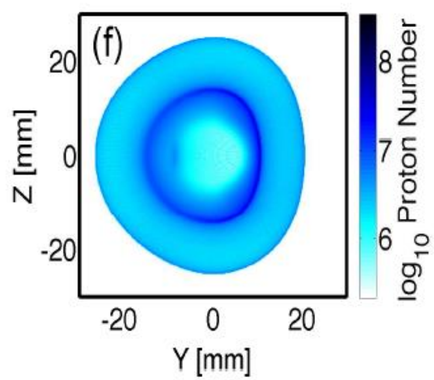


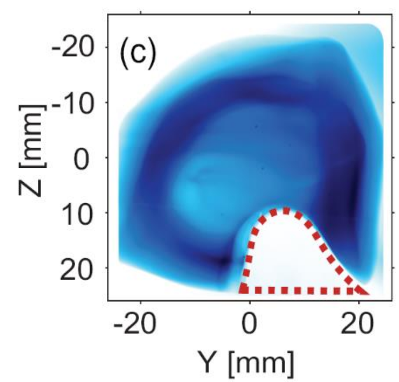
Proton beam: **experiment** (lower half)



Proton heated silicon (45° gradient)

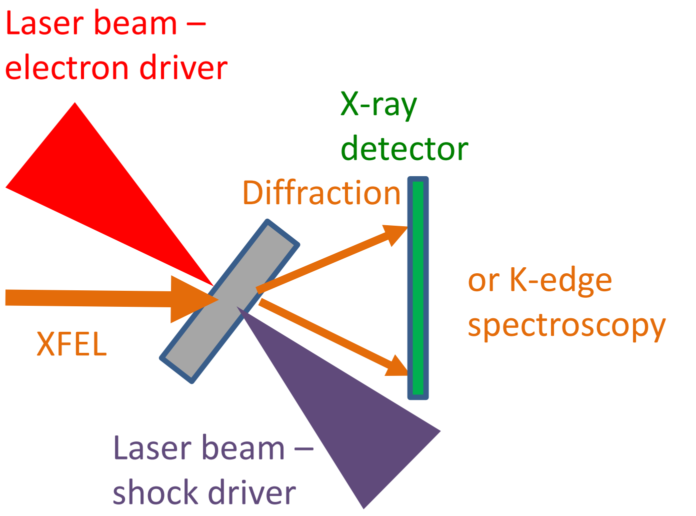






Probing fast electron transport in shock-compressed targets

Collaborative experiments using the Omega laser, led by F. Beg OCSD



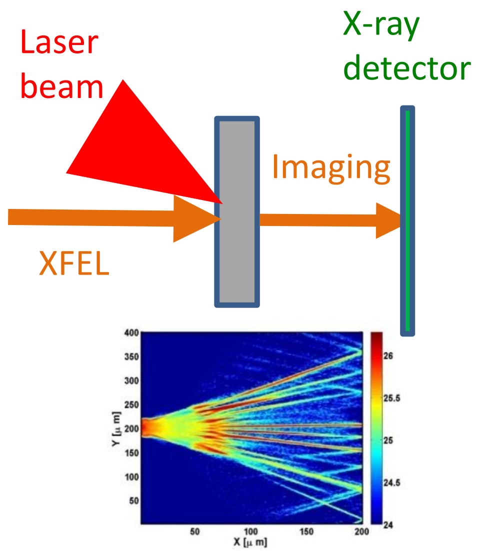
XFEL could enable investigation of electrical conductivity in shock-compressed targets

Coupled X-ray (XFEL) and high power laser would enable:

Direct probing of ultrafast plasma processes

- Ionisation physics
- Electron transport physics (e.g. filamentation)

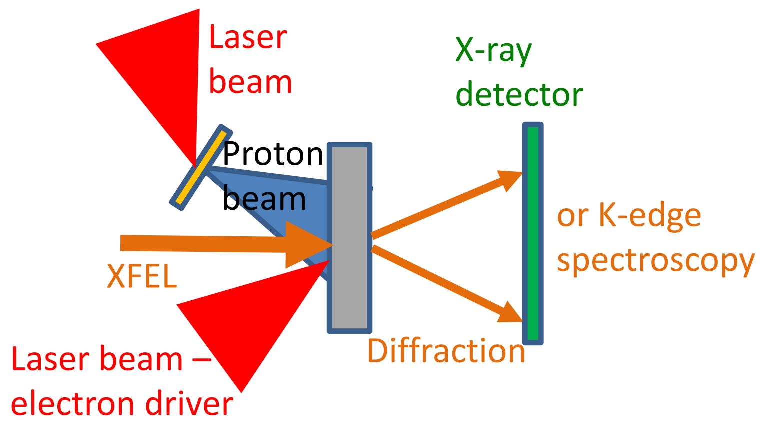
(Subject to scattering, smearing etc)



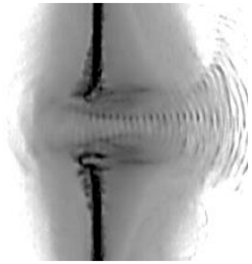
Time resolved measurements of

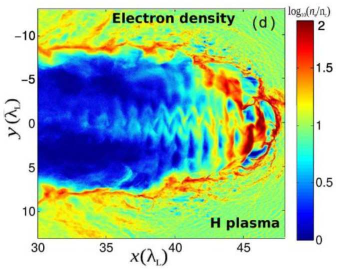
- Target heating
- Lattice melt
- Shock compression

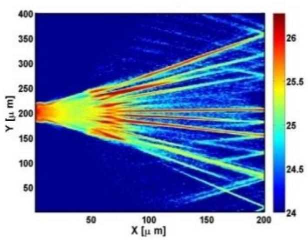
correlation to electron transport measurements

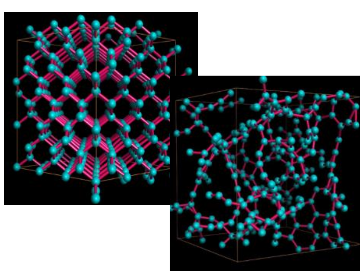


XFEL combined with an intense laser would enable:



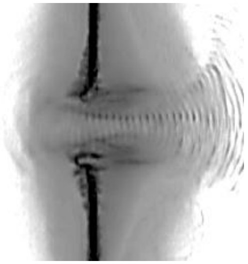


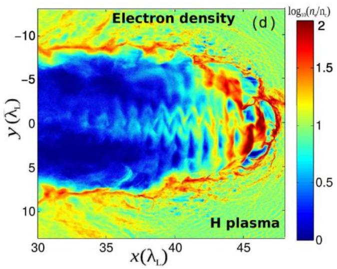


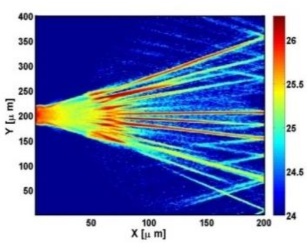


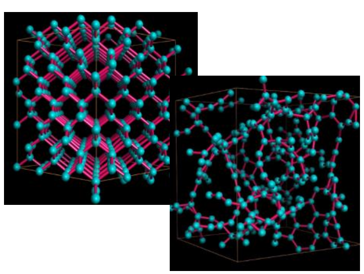
1. Plasma heating and expansion dynamics, including the formation of relativistic plasma aperture, plasma jets and density modulations
2. Relativistic phenomena, including induced transparency and self-focusing
3. Laser hole-boring (physics of radiation pressure acceleration of ions)
4. Physics of high field ‘QED-plasma’ regime
5. Probing of ionisation dynamics in dense plasma
6. Investigation of fast electron transport in dense plasma (fusion relevant) including transport instabilities / beam filamentation
7. Investigation of proton induced heating and correlations to electron transport physics

XFEL combined with an intense laser:









- 1-10keV energies
- Short bursts <0.5 fs
- Synchronised to <5 fs
- Rep rate – kHz already high
- High spatial resolution (tight focusing) for spatially resolved measurements
- Polarisation control for B-field measurements