Hybrid and near-source manipulation of Laser-Driven protons

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Outline :

- The "*classical*" mechanism – Sheath acceleration (TNSA)
  - Quick Overview/state of the art
  - Current research trends/ developments
- Short review of techniques to control beam properties
- Helical-Coil Accelerator (HCA)
  - The concept and proof-of-principle
  - High-energy implementation and Multi-staging
  - Phase-space Rotation of accelerated protons

Conclusions

Target Normal Sheath Acceleration (TNSA)

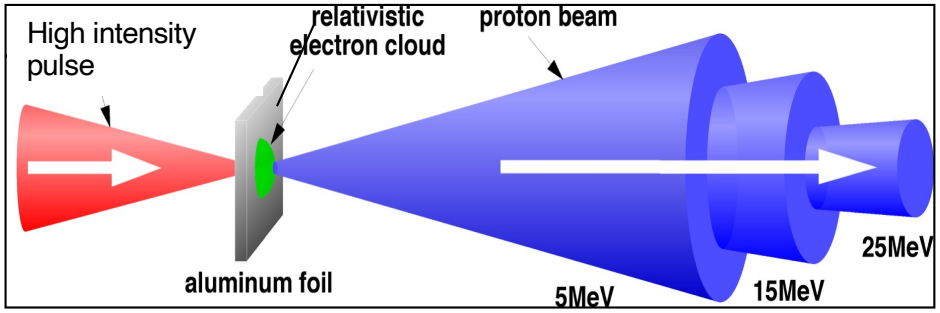
Short duration at source: **bursts with duration ~ ps**

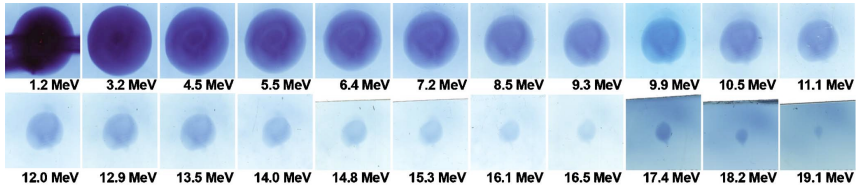
$$kT_{hot} \approx U_p = m_e c^2 \left(\sqrt{1 + \frac{a_0}{2}} - 1 \right)$$

Acceleration field: **TV/m**

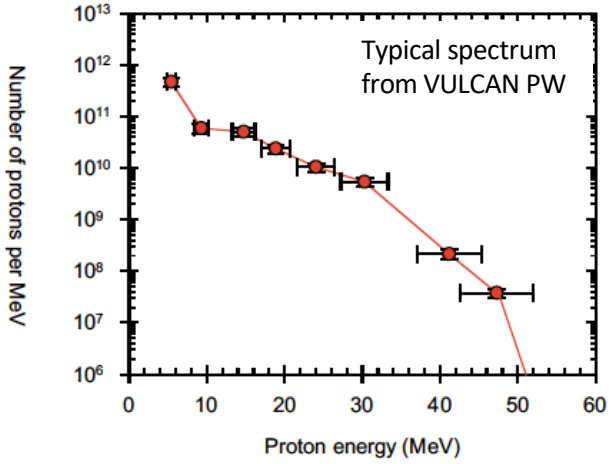
Acceleration time comparable with laser-drive duration

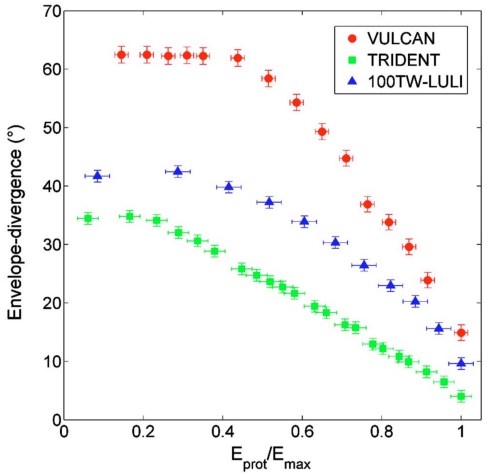
Strong ΔE-Δt correlation and ultralow transverse emittance (< 0.1 π mm.mrad @ 15 MeV)





Broad spectrum with low particle number at high energies





Several 10s of degrees of divergence

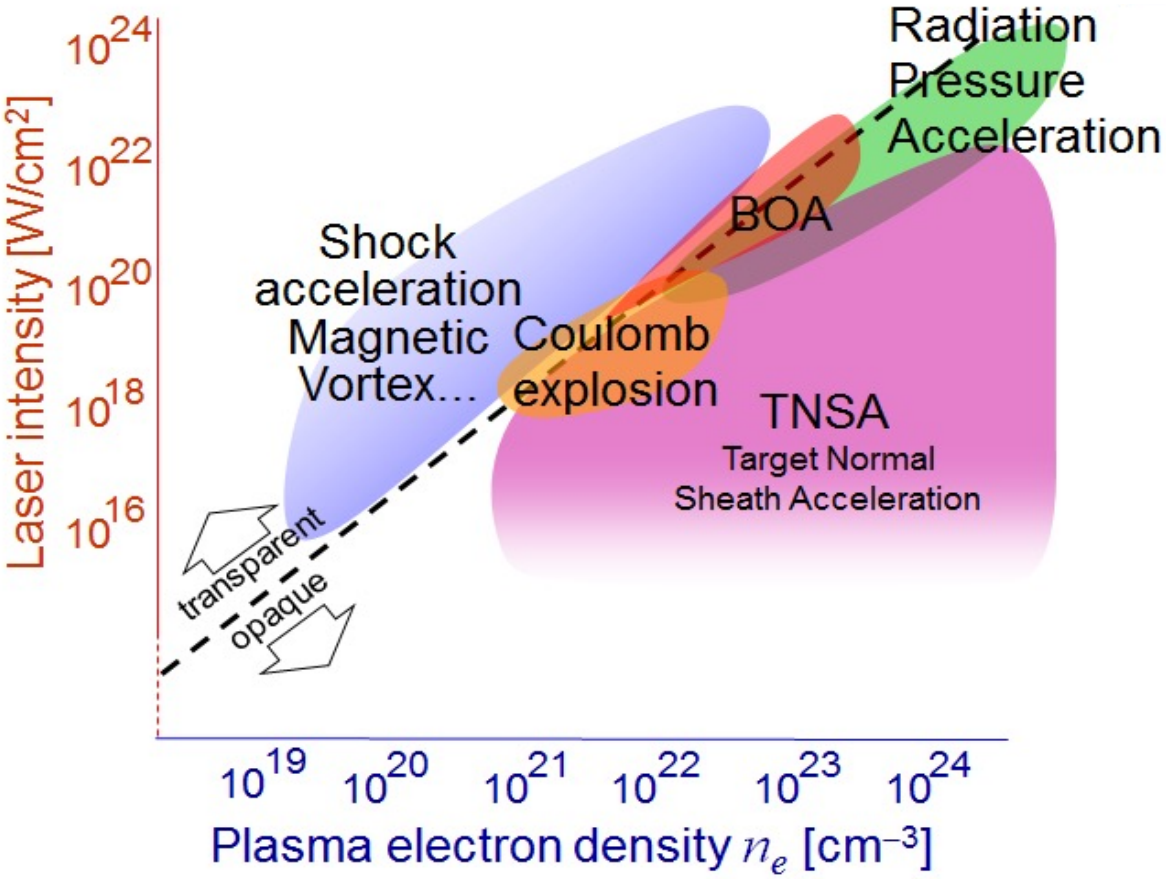
F. Nurnberg *et al*, RSI, **80**, 033301 (2019)

But, what missing for its applications?

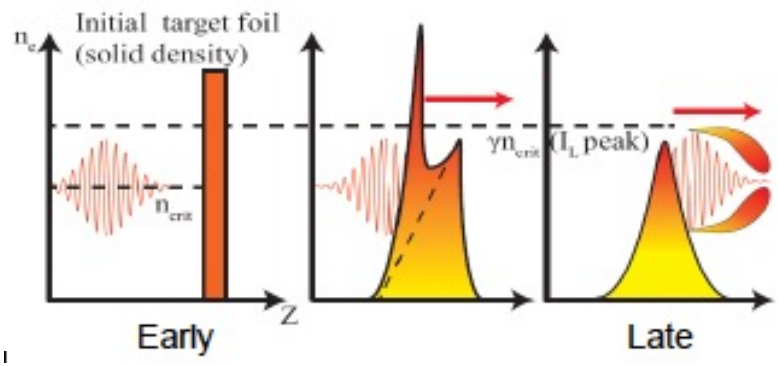
Fast ignition	➢ Low emittance ➢ Focusability ➢ High flux ➢ Spectral tailoring ➢ Short duration	Cancer therapy	➢ Small energy spread ➢ High energy ➢ High repetition ➢ Removal of co-moving electron
Warm dense matter production (Isochoric Heating)		Positron emission tomography	➢ High energy ➢ High flux ➢ High repetition
Injection into accelerator	➢ Low emittance ➢ Ultra-Low divergence ➢ High flux ➢ Small energy spread ➢ High repetition	Industrial application (Lithography, ion implantation)	➢ Small energy spread ➢ High flux ➢ High repetition ➢ Removal of co-moving electron

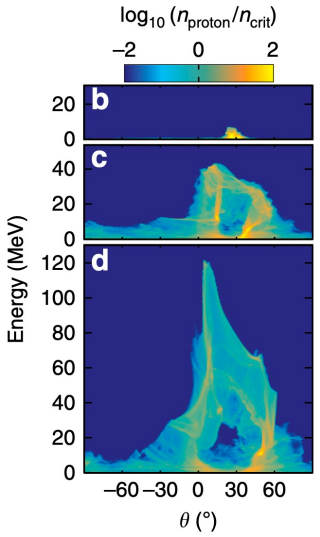
Green : available; red: technological advances required; **black: scientific challenges**

Advanced acceleration mechanisms

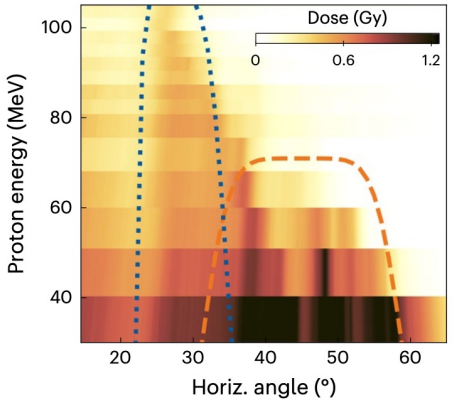


Relativistic transparency enhanced acceleration



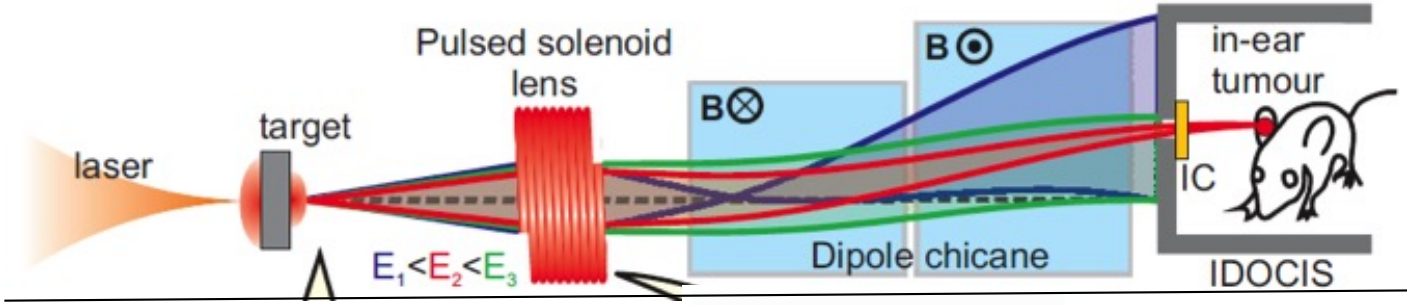


Higginson et al, Nat Comm 2018



Ziegler et al, Nat Phys 2023

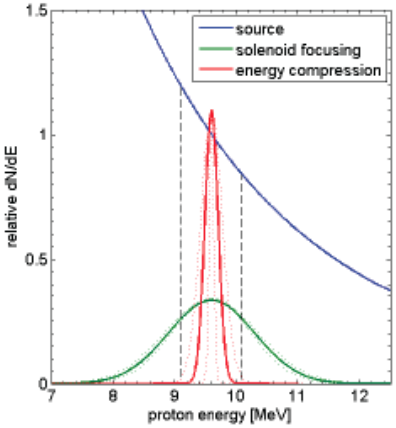
Several approaches pursued for beam delivery for pre-clinical studies

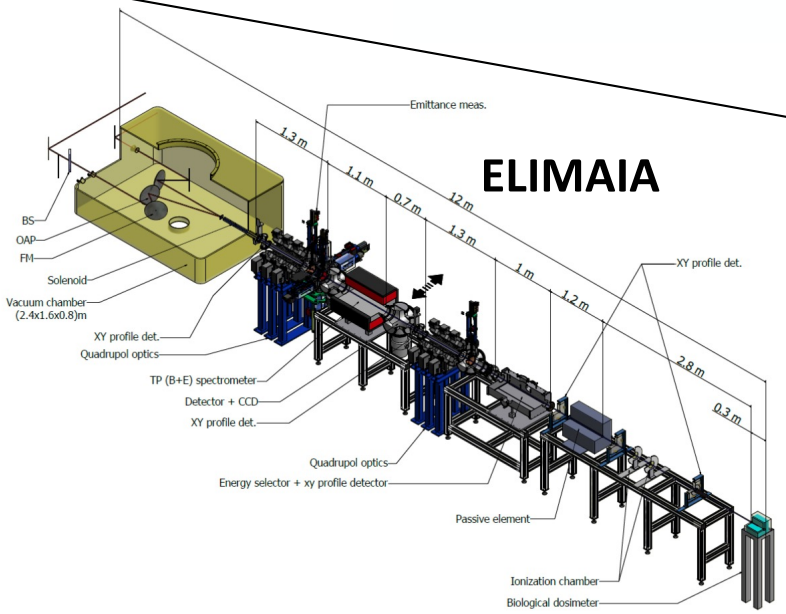


HZDR

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







eli beamlines

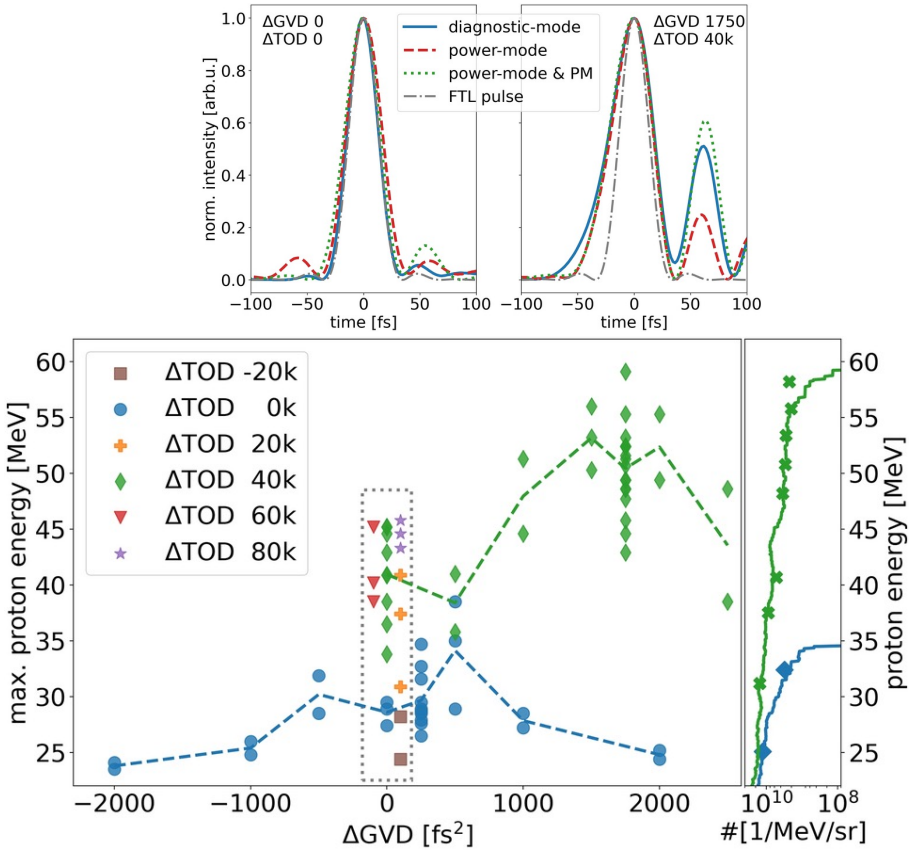
1 PW, 10 Hz laser source
Targeting 60 MeV delivery
Conventional elements for controlling beam properties

Proton energy optimization via phase management and beam delivery for in-vivo studies

DRACO laser at HZDR (Dresden)

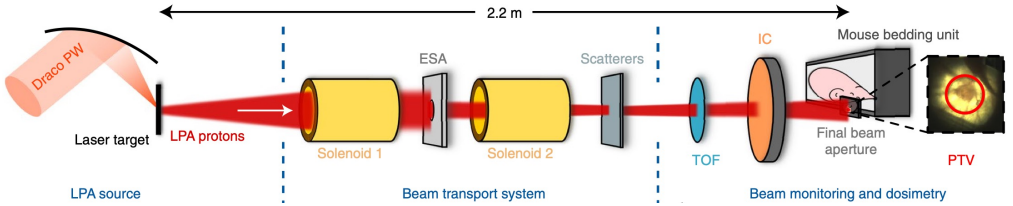
18 J in 30 fs irradiated on few 100s nm plastic targets

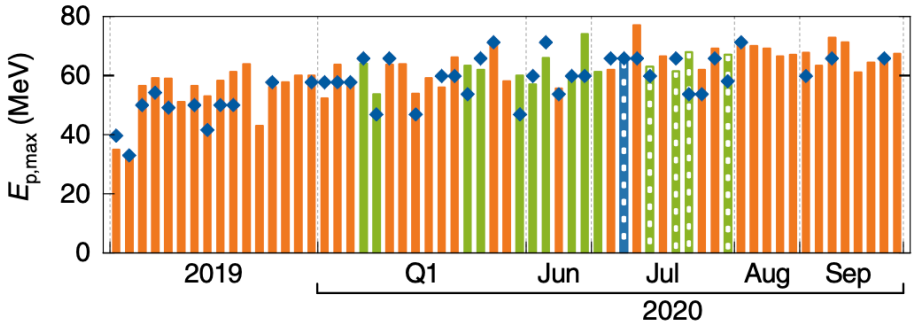
T. Ziegler et al, Sci. Rep.,11, 7338 (2021)

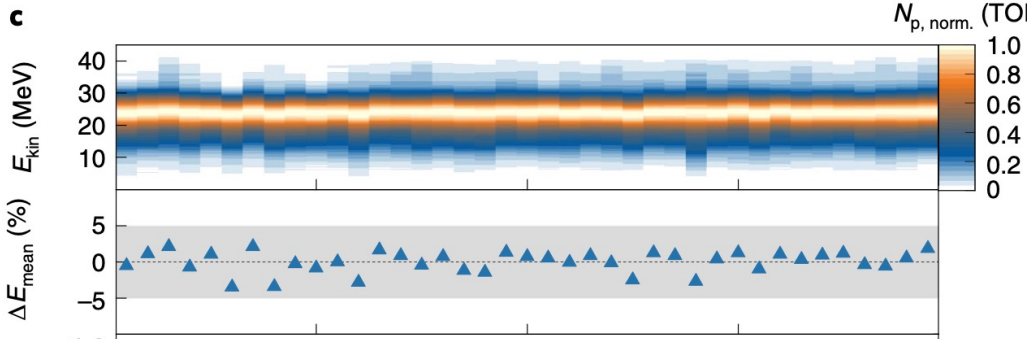


Significant proton energy improvement by spectral phase (and pulse profile) modification through DAZZLER

F. Kroll et al, Nat. Physics, 18, 316 (2022)

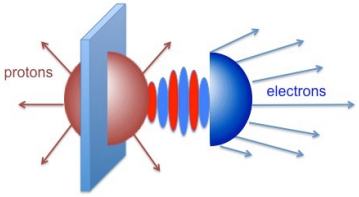




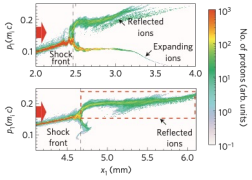


Current motivations in the field of laser-ion acceleration

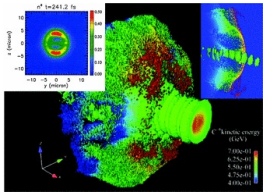
Energy increase



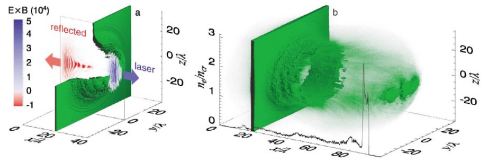
Coulomb explosion



Shock acceleration

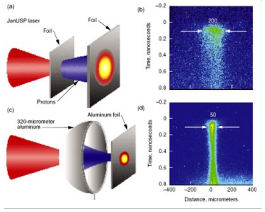


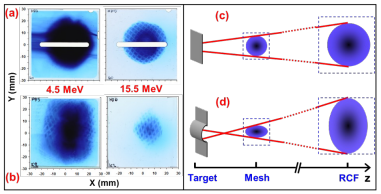
Relativistic transparency

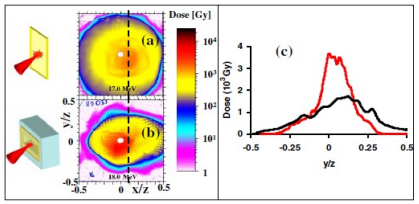


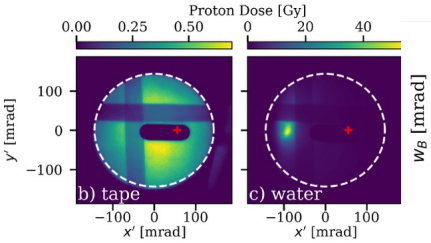
Radiation pressure acceleration

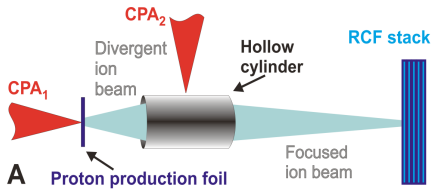
Focusing and Energy selection

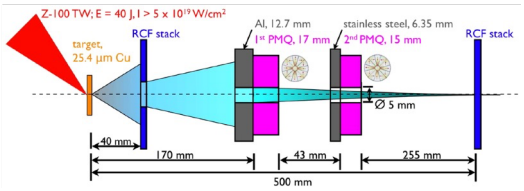


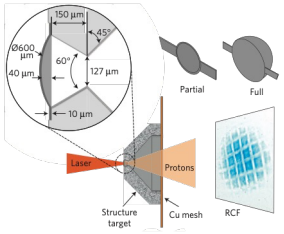


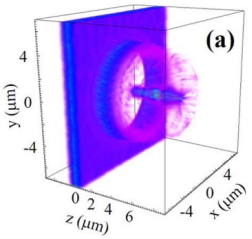






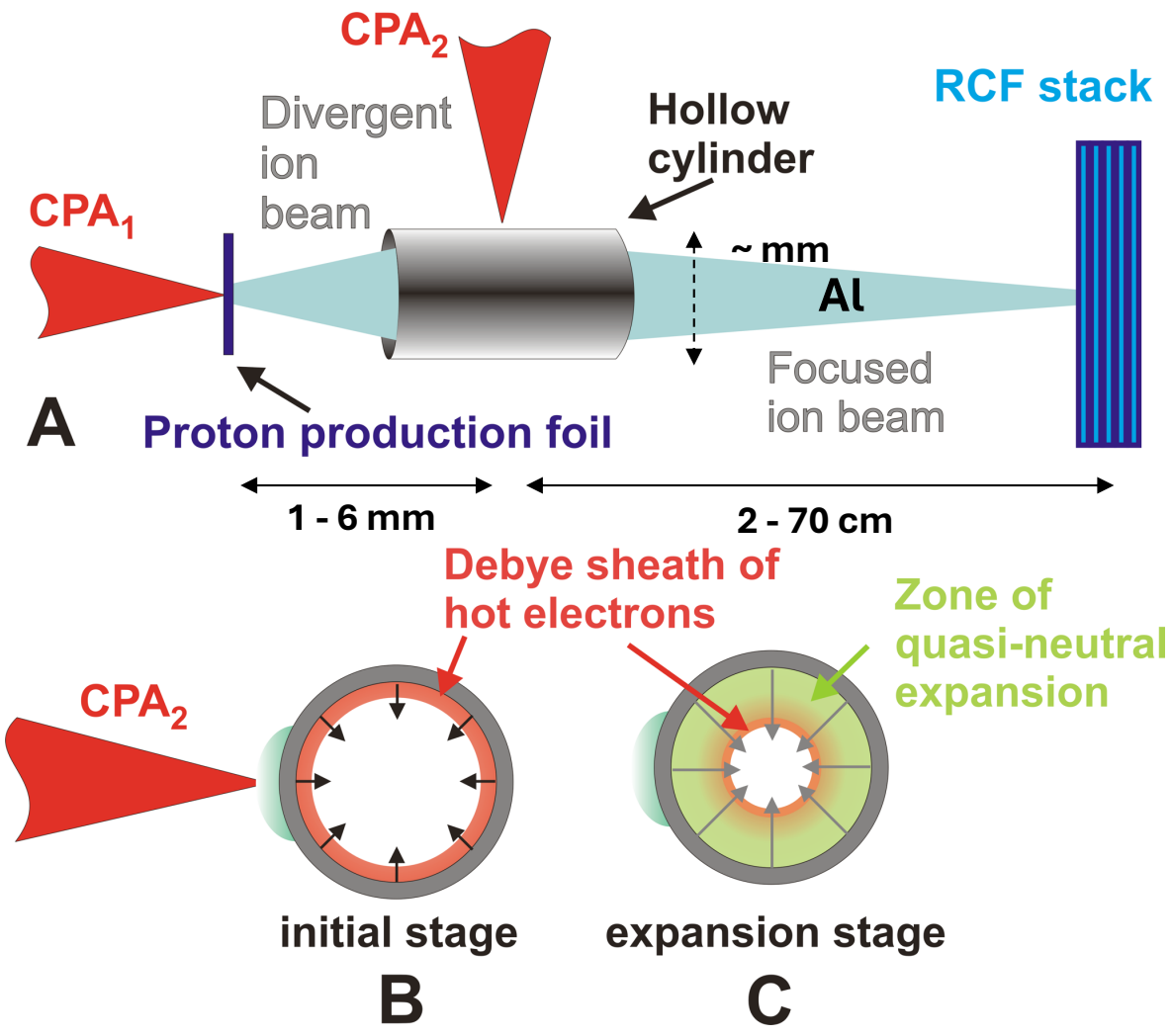




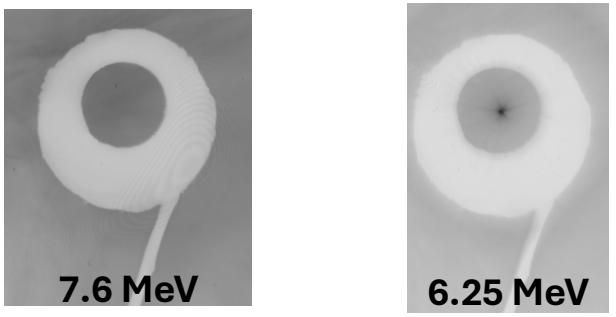


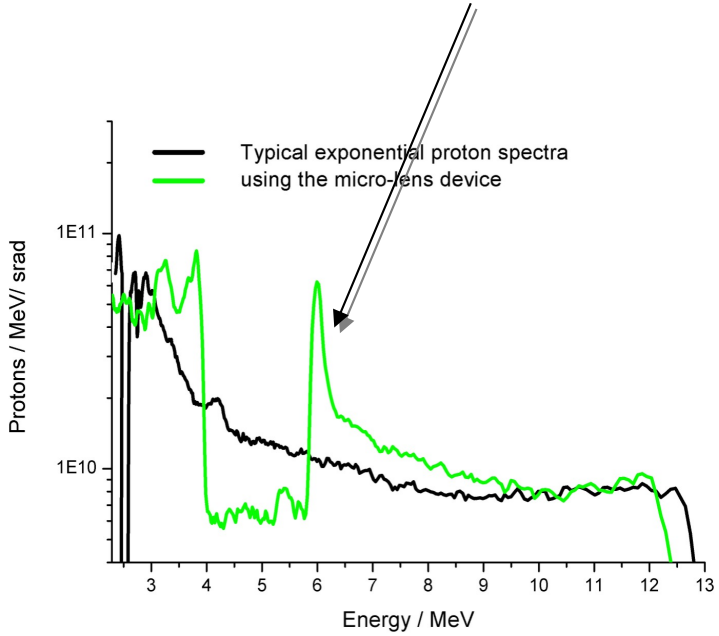
Laser-driven micro-lens

T. Toncian M. Borghesi, J. Fuchs et al, Science, 312, 410 (2006)



Ions transiting soon after the peak of CPA_2 are focused



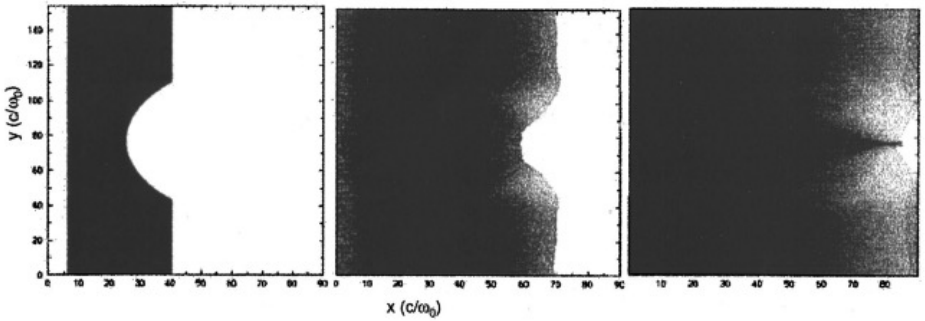


Focusing in hemispheres

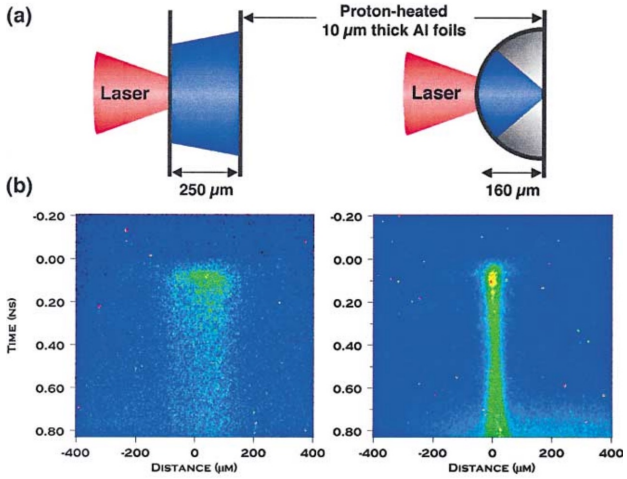
Concept: The shape of the sheath field at the target rear surface can be manipulated by changing the target shape. For hemispheric surfaces, the sheath field has a radial component pointing toward the axis, which creates a converging proton beam.

The 'focal length' is linked to the radius of curvature of the surface, and to the initial size of the laser focus with minimum focus size limited by hot electron pressure.

S. Wilks *et al*, Phys. Plasmas, 8, 542(2001)

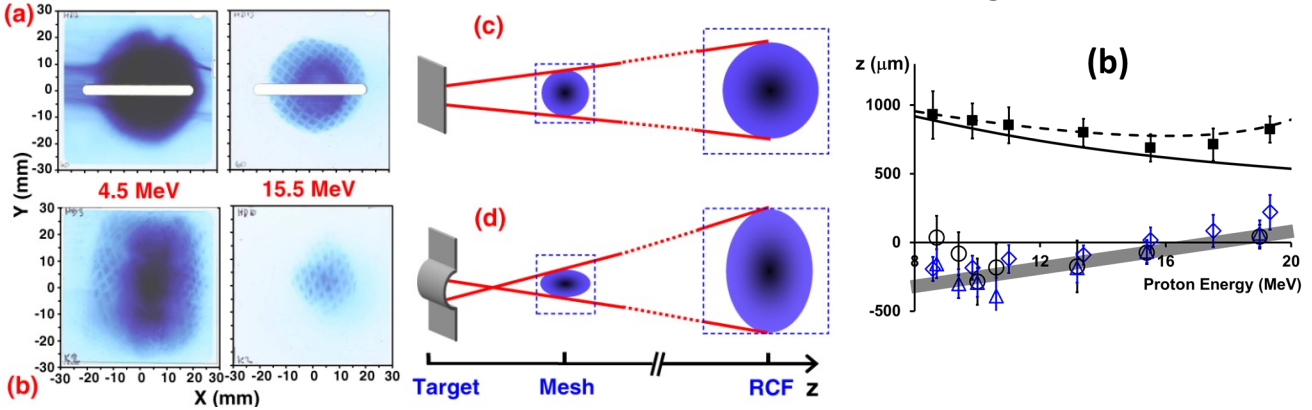


Patel et al. PRL 91 (2003)



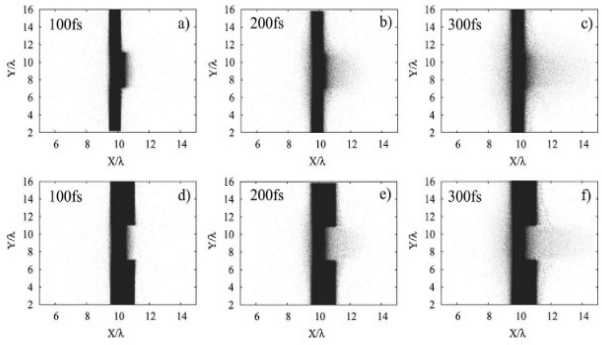
Kar et al. PRL 106, 225003 (2011)

Reduces the divergence, but achromatic!

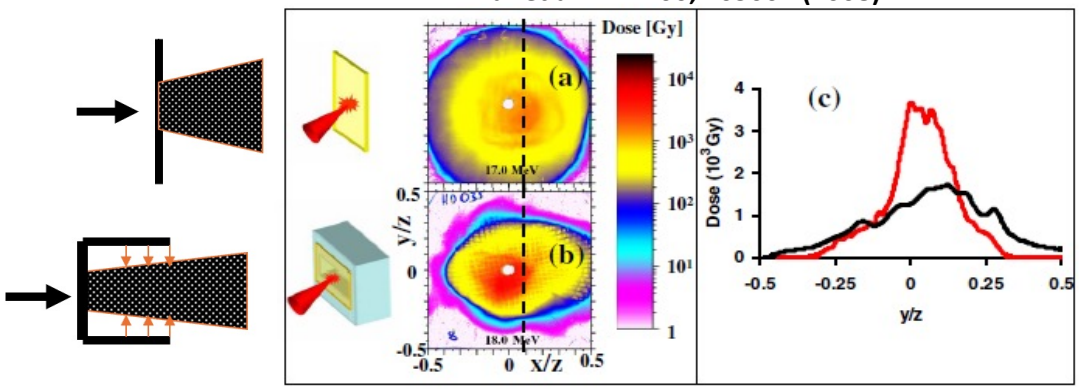


Adding guiding structure to Hemispheres

Sonobe et al. PoP 12, 073104 (2005)

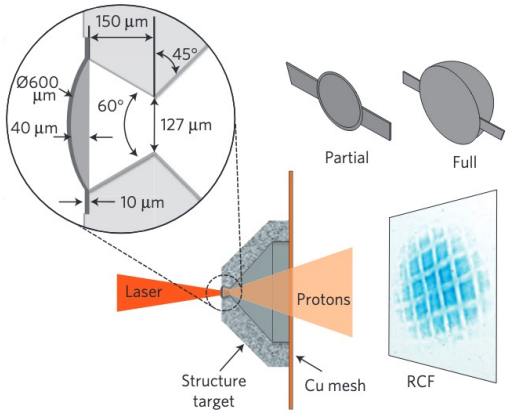


Kar et al. PRL 100, 105004 (2008)

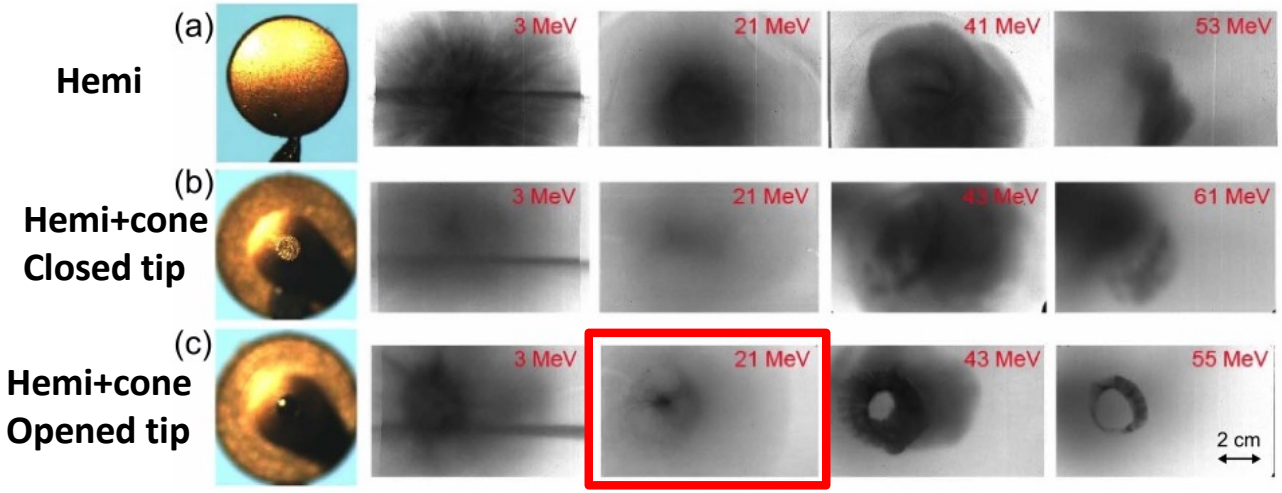


Combination with a cone target supports focusing as the cone is charged by hot electrons, leading to an inward radial electrostatic sheath field along the proton path.

Bartal et al. Nat. Phys. 8 (2012)



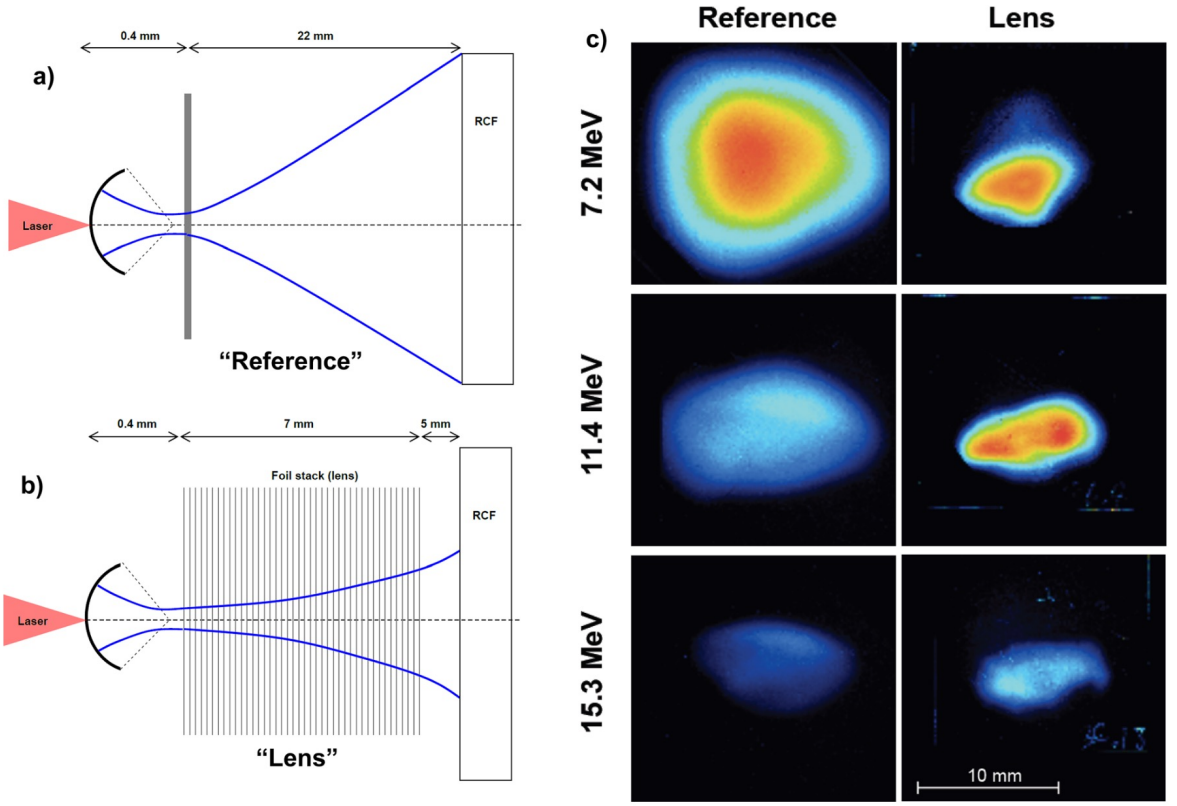
King et al. PPCF, 66, 015001 (2024)



Focusing by a stack of foils

Ni et al. Phys. Plasmas 20, 083111 (2013)

Concept: When propagating the proton beam through a stack of conducting foils the action of the mirror charges acts to cancel the radial electric field of the beam such that the azimuthal magnetic field can focus the beam.



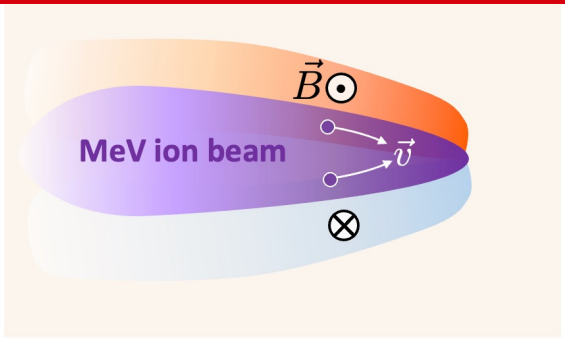
Details: Response time of neutralising fields is linked to plasma frequency (<fs for Al foils).

Self-focusing is independent of radial charge distribution if beam density varies slowly in axial co-ordinate.

Final focus size strongly dependent on gap between foils. Foil transverse size > beam radius, foil thickness must be sufficient to stop co-propagating electrons and be mechanically strong, and foils must survive heating over duration of the beam.

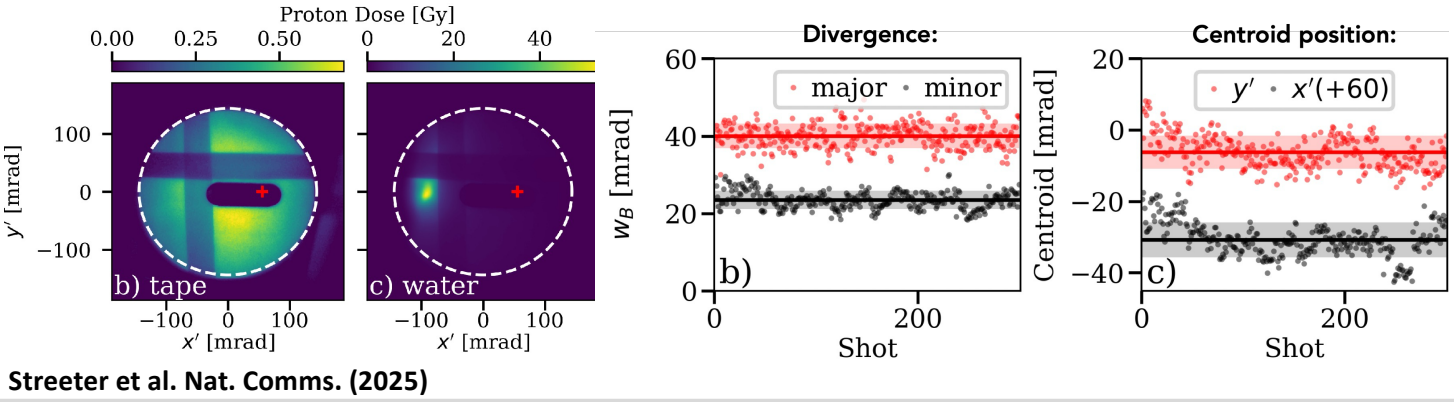
Focusing by a low-density plasma

Concept: When the proton beam is propagating through a low-density plasma, the co-propagating electrons are separated from the beam and space-charge electric fields are compensated by background plasma electrons while proton current remains unneutralised and the azimuthal field of the beam can drive focusing.



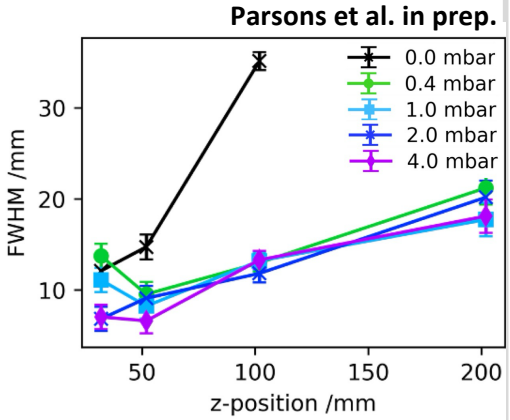
Similar to foil focusing, exploiting the beam self-field for focusing, but with a refreshing target.

Proton beam from liquid leaf target



Streeter et al. Nat. Comms. (2025)

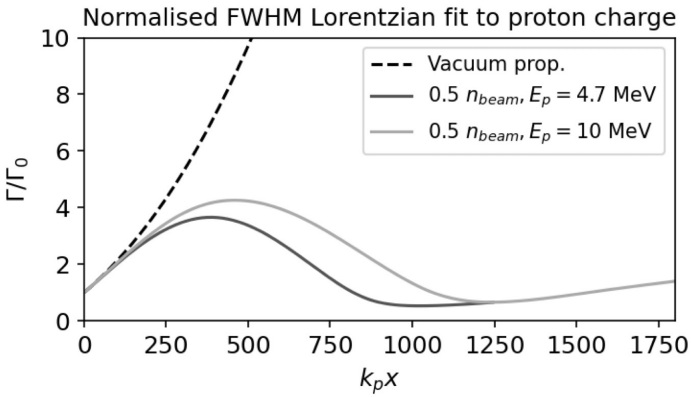
Evolving beam size from foil + gas target:

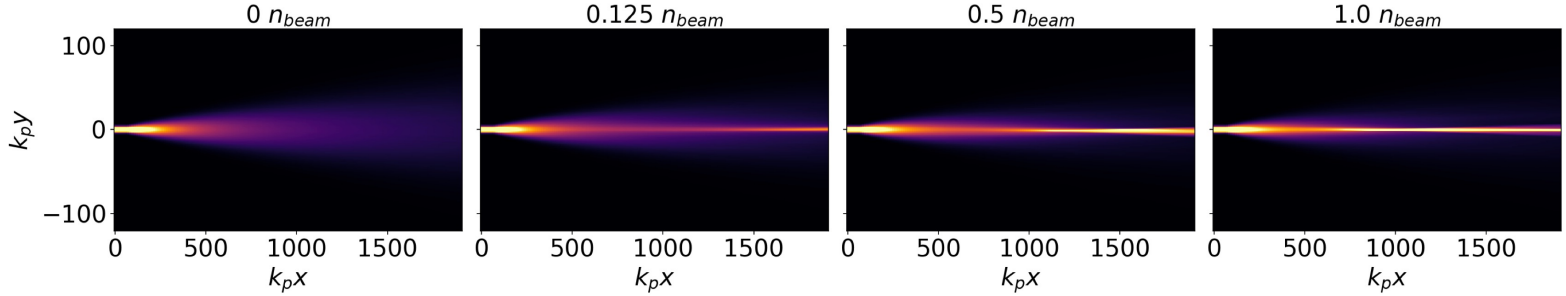


Focusing by a low-density plasma

PIC simulations indicate that focusing is strongly dependent on beam and background parameters – e.g., a higher-energy proton beam focuses over a longer distance.

Minimum focus size occurs for matched beam density and background plasma density.

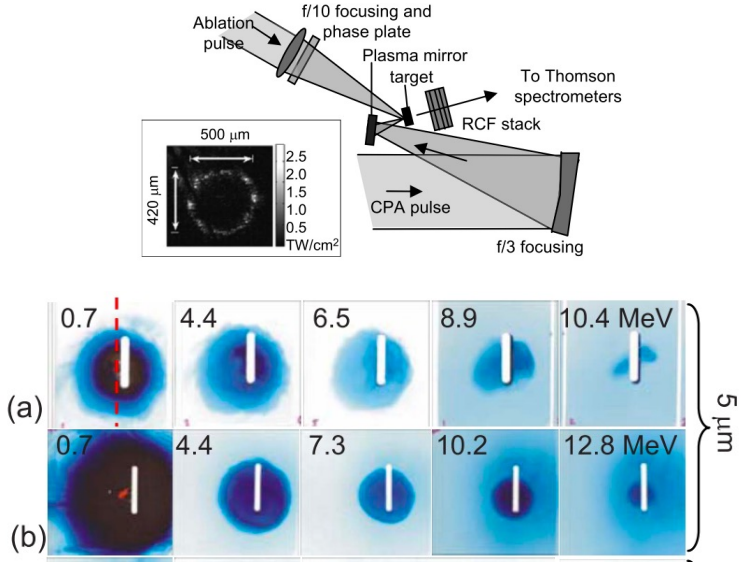




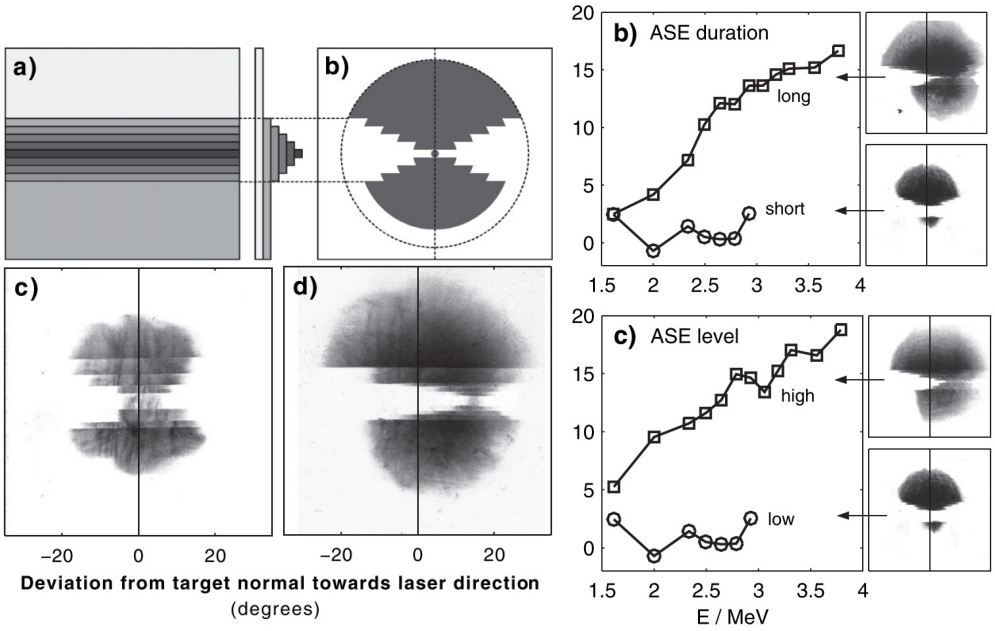
Limitations: Complex interplay of beam characteristics, plasma ionisation and focusing is still under study to determine feasibility in different regimes.

Beam manipulation by laser profiling

Carroll et al, PRE, 76, 065401 (2007)

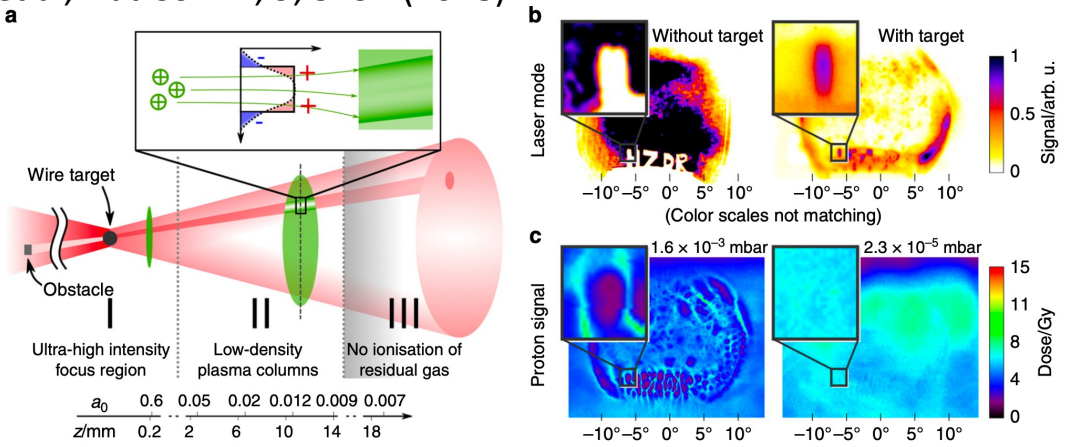


Lindau et al, PRL, 95, 175002 (2005)



Obst-Huebl et al, Nat Comm, 9, 5292 (2018)

The formation of quasi-static electric fields in the beam path by ionisation of residual gas. Essentially acting as a programmable memory, these fields provide access to a higher level of proton beam manipulation.

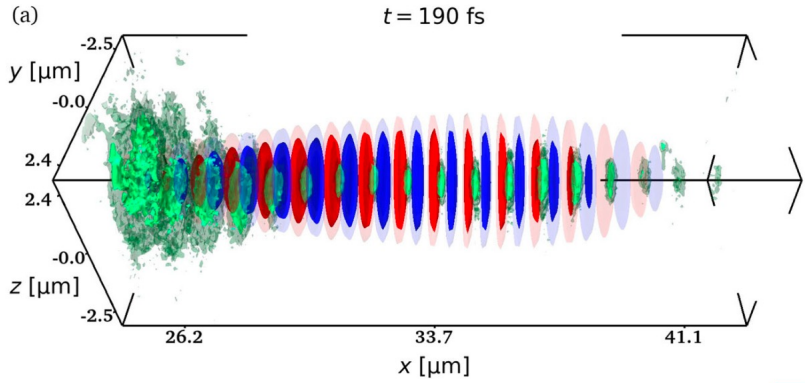


Using twisted light

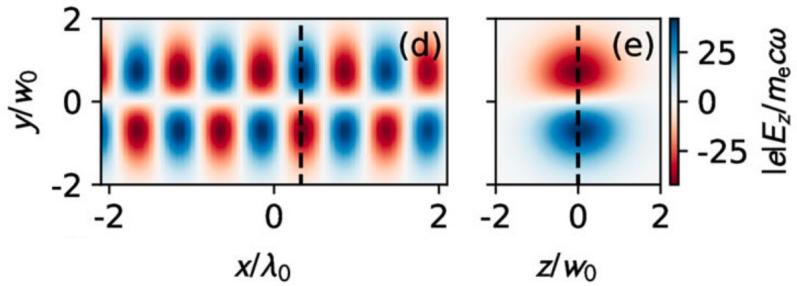
Twisted light: A Laguerre-Gaussian laser pulse produces a collimated hot electron beam at the target (or in the surface layer), which drives low-divergence proton acceleration.

Blackman et al, Comm Phys, 5, 116(2022)

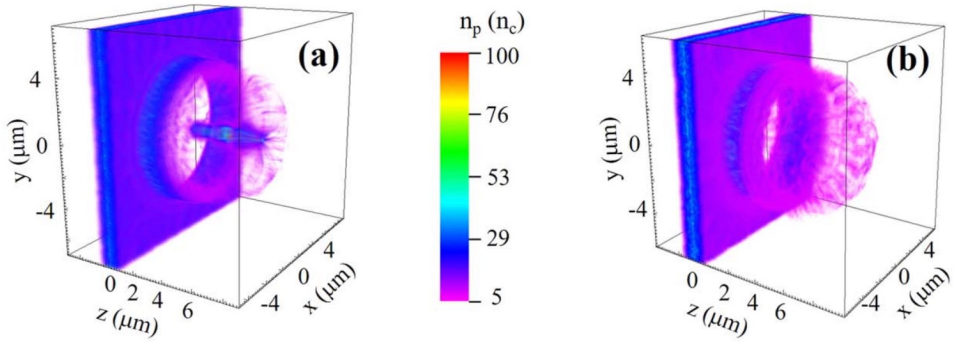
Longitudinal Field



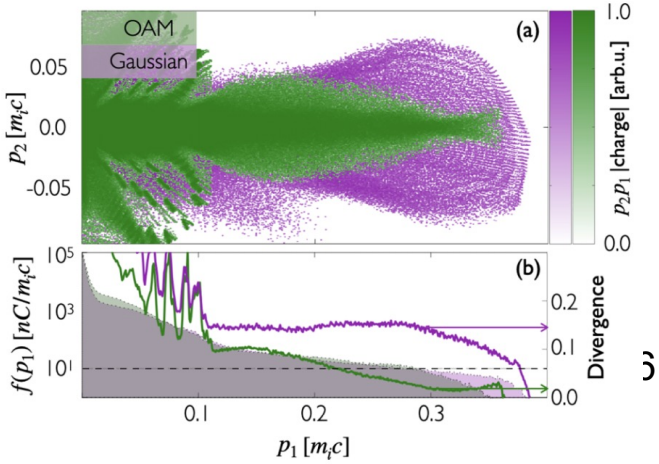
Transverse Field



Pae et al PPCF 62, 055009 (2020)

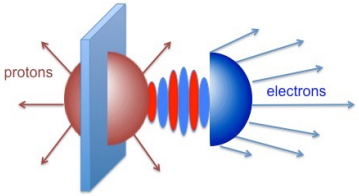


Willim et al. PRR 5, 023803 (2023)

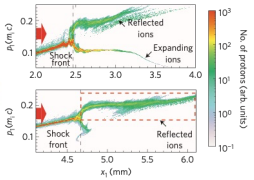


Current motivations in the field of laser-ion acceleration

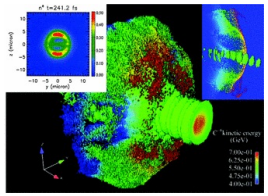
Energy increase



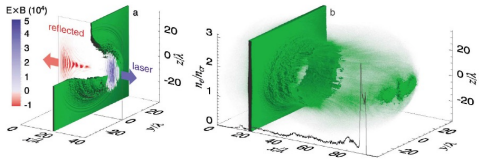
Coulomb explosion



Shock acceleration

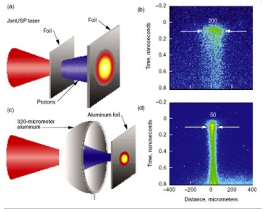


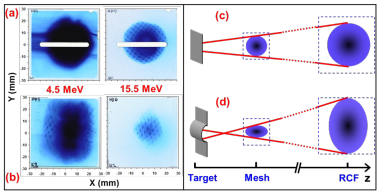
Relativistic transparency

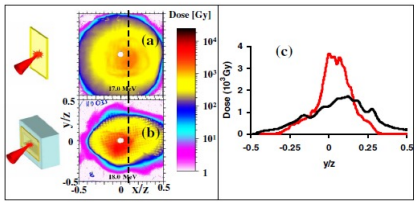


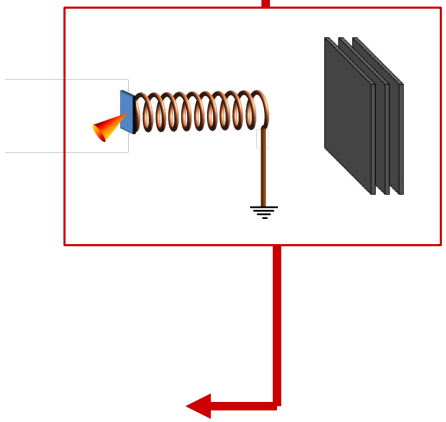
Radiation pressure acceleration

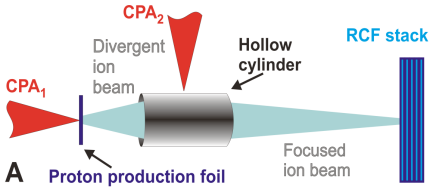
Focusing and Energy selection

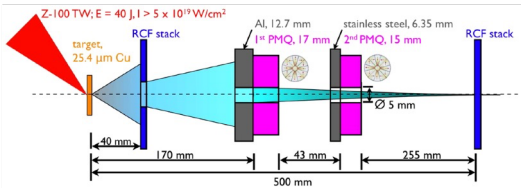


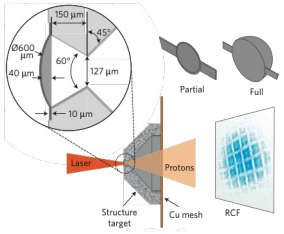








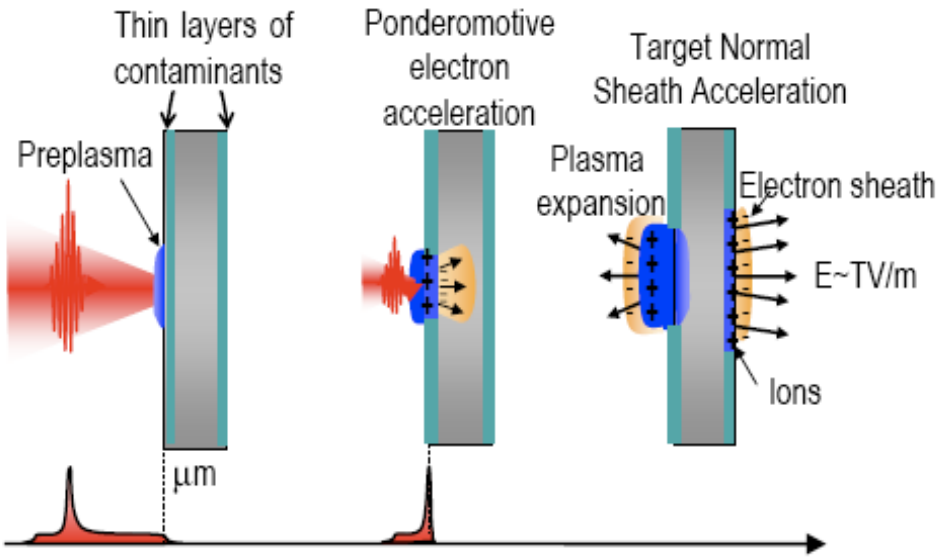




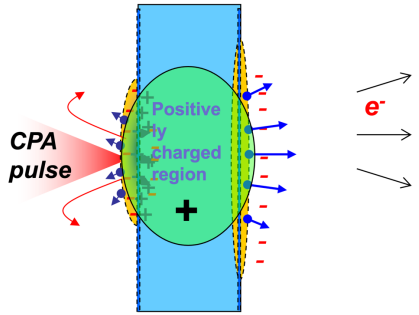
EPSRC
Engineering and Physical Sciences Research Council

Invest Northern Ireland

Laser target interaction
- rapid target charging by electron escape

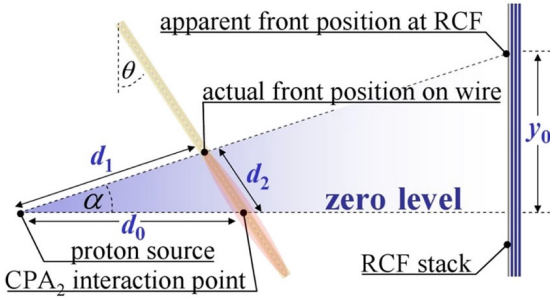


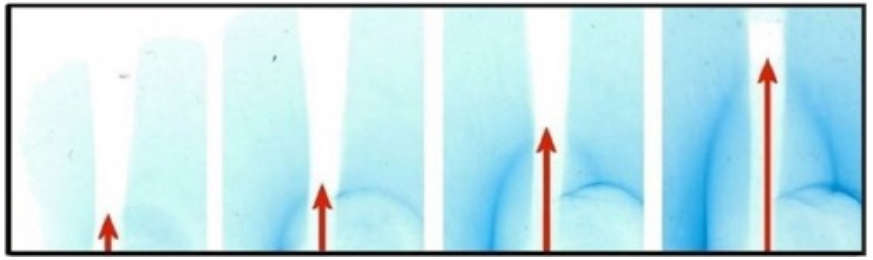
A fraction of hot electrons can escape the target, leaving it positively charged

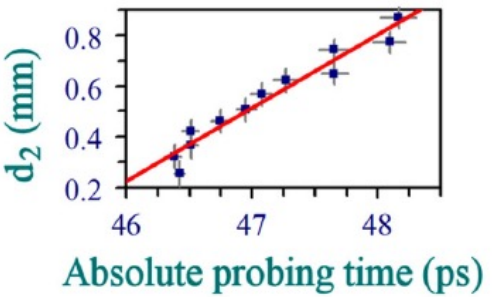


The irradiated region will neutralise to the ground by drawing return currents from the remainder of the target and supporting stalks

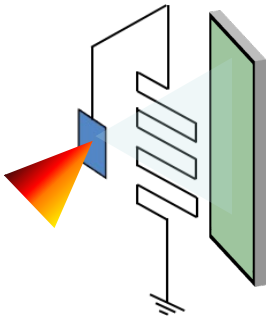
Charge Front propagating away from the interaction point: (K. Quinn PRL, 102, 194801 (2009))

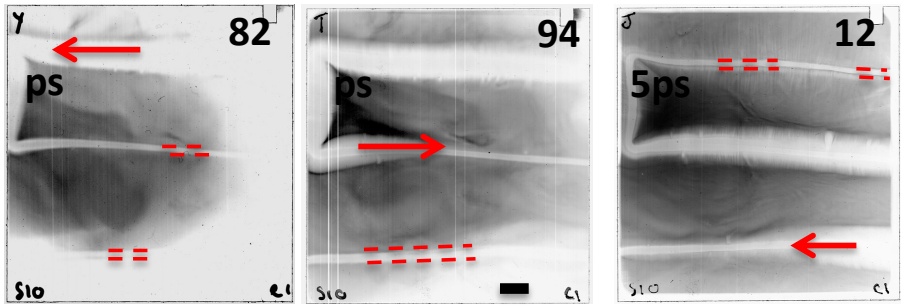


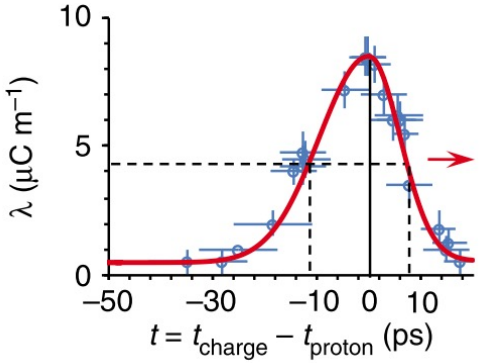




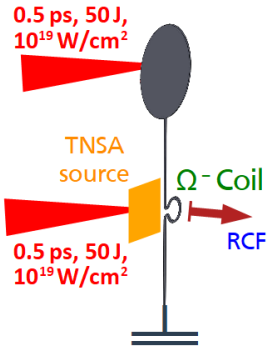
And far from target, travels as KAmp pulse

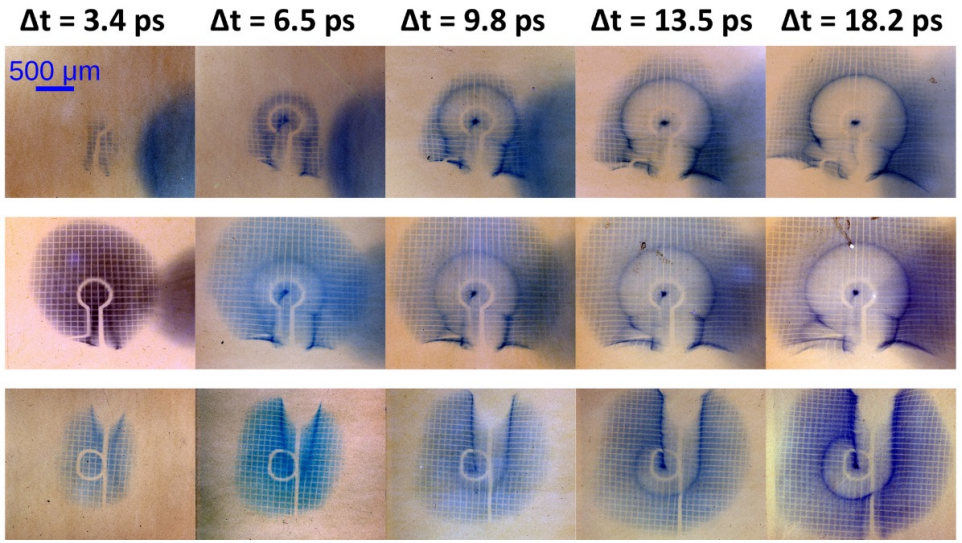


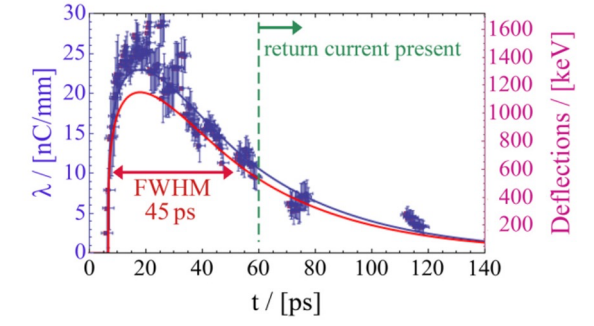




S. Kar et. al., Nature Communications, 7:10792 (2016); S. Kar et. al., Phys. Plasmas, 23, 055711 (2016); ; H. Ahmed, S. Kar et. al., Nucl. Instrum. Methods A, 829, 172 (2016).

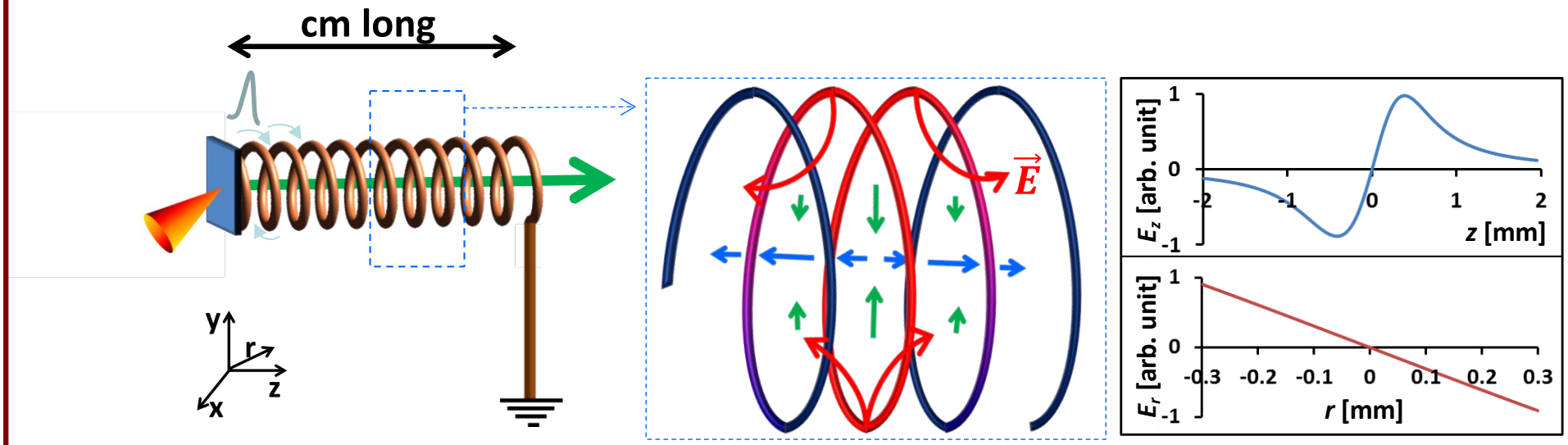


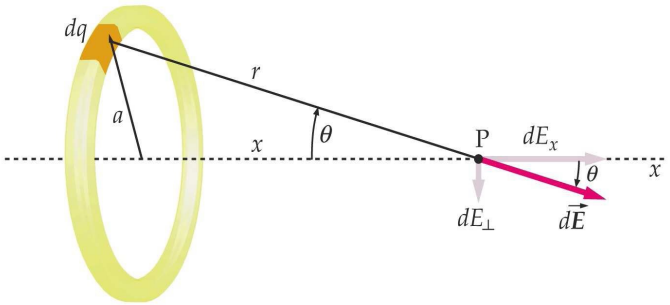




M. Ehret *et al.* Phys. Plasmas 2023

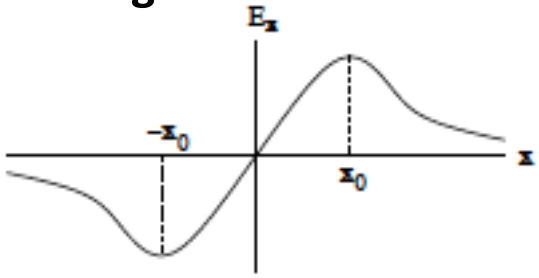
Laser driven Travelling wave Accelerator





Analogy with the field of a charged ring

Longitudinal field



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

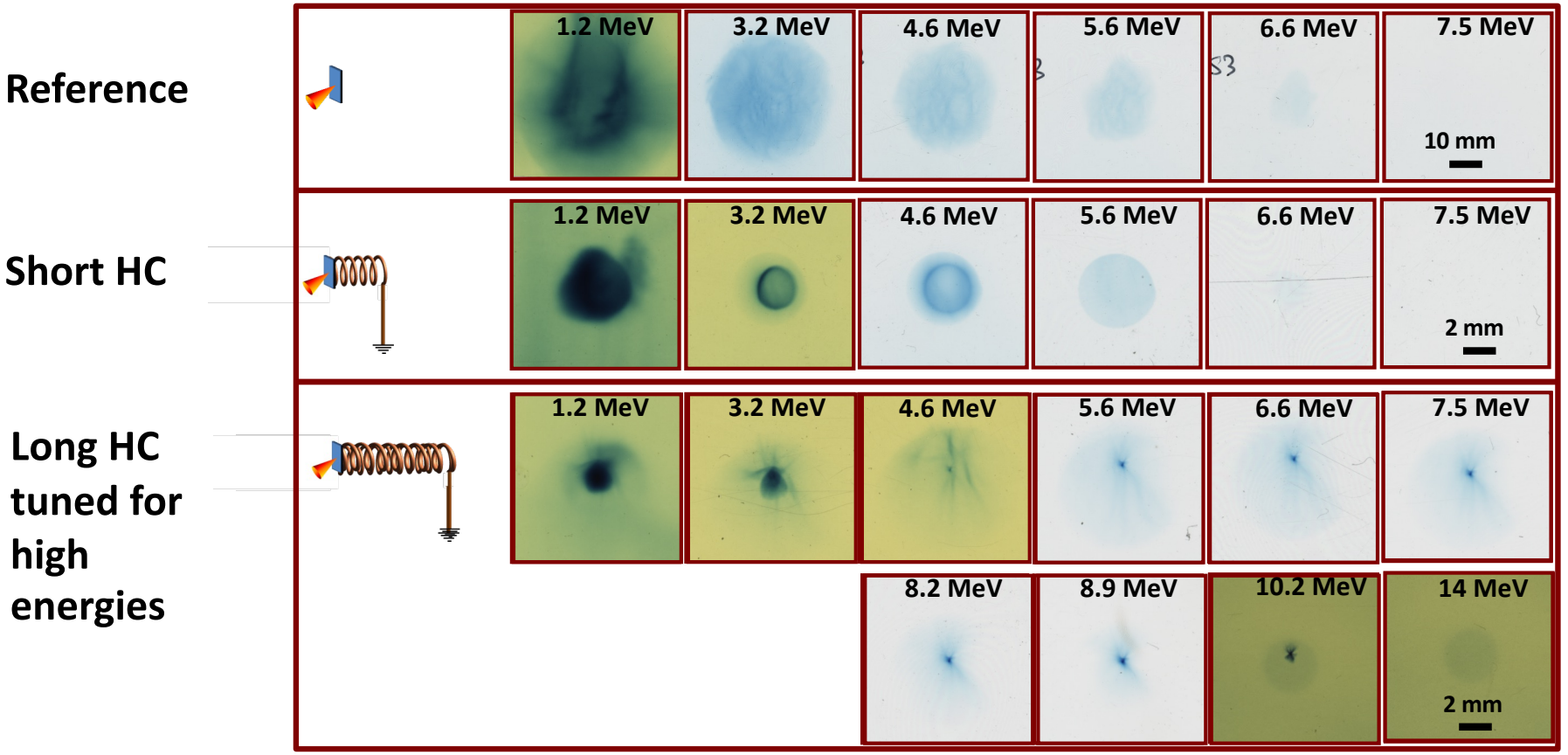
$$E_{max} = \frac{Q}{2\pi\varepsilon_0 a^2}\frac{\sqrt{2}}{3\sqrt{3}}$$

Q~ 60 nC, a =0.4 mm

E~ MV/mm

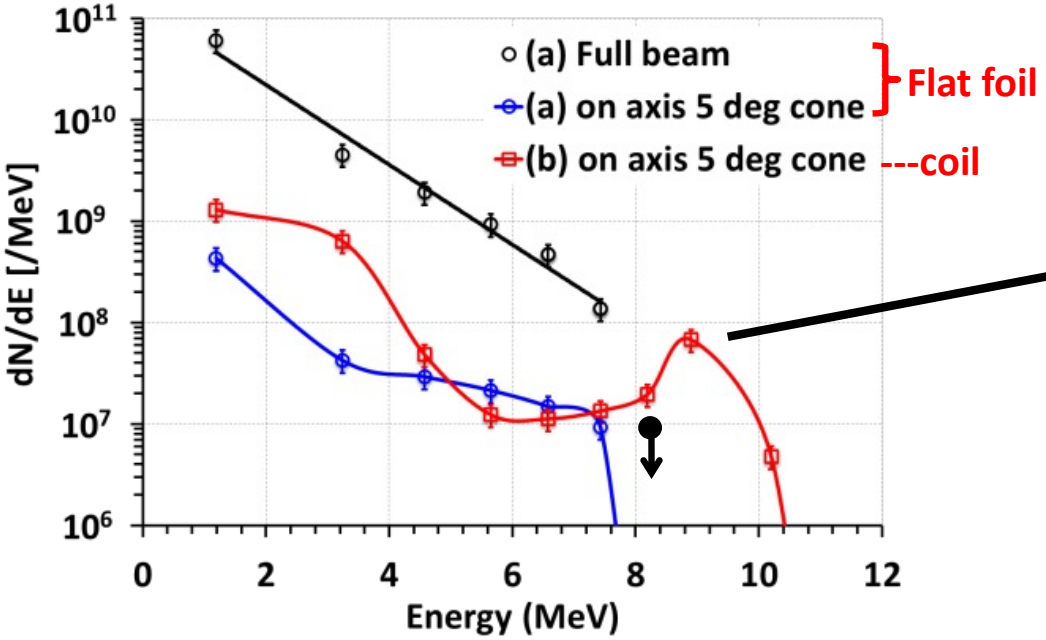
Proof-of-principle experiment

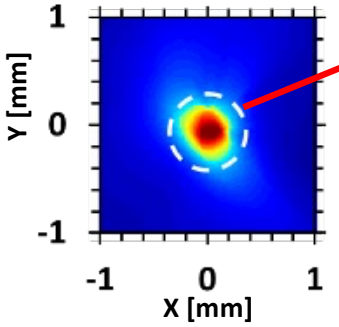
S. Kar et. al., Nature Communications, 7, 10792 (2016)



Proof-of-principle at University-scale laser (ARCTURUS)

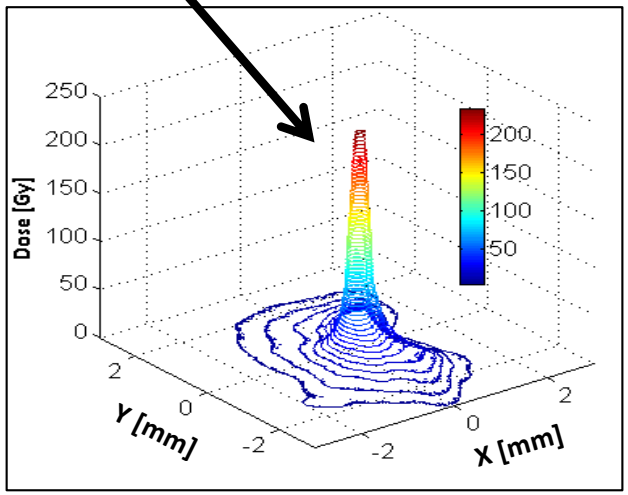
S. Kar et. al., Nature Communications, 7, 10792 (2016)





Inner diameter of the coil

⇒Divergence < 1° measured at 35 mm from the target



HcA provides *simultaneously*:

- High degree of collimation
- Chromatic (energy selection)
- Post-acceleration (GeV/m)

➢ Ultra-high flux by acting close to target and lower energy part of exponential spectrum

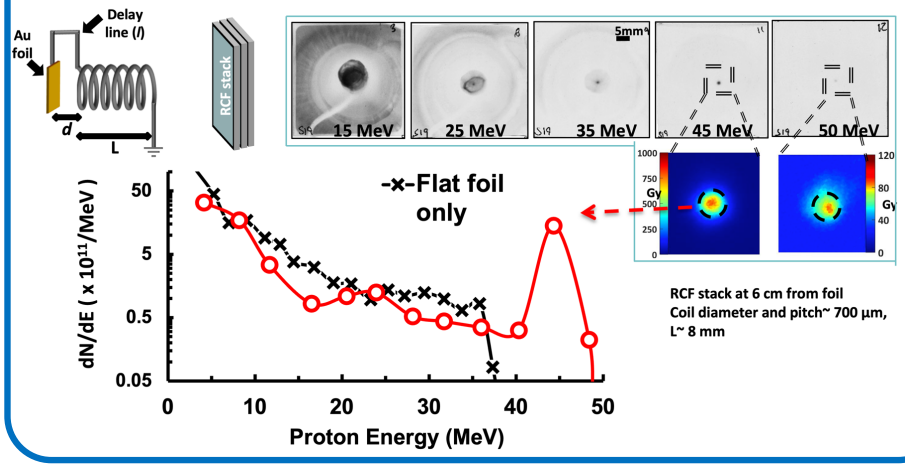
High energy implementation

H. Ahmed *et al*, Sci. Rep., 11, 699 (2021)

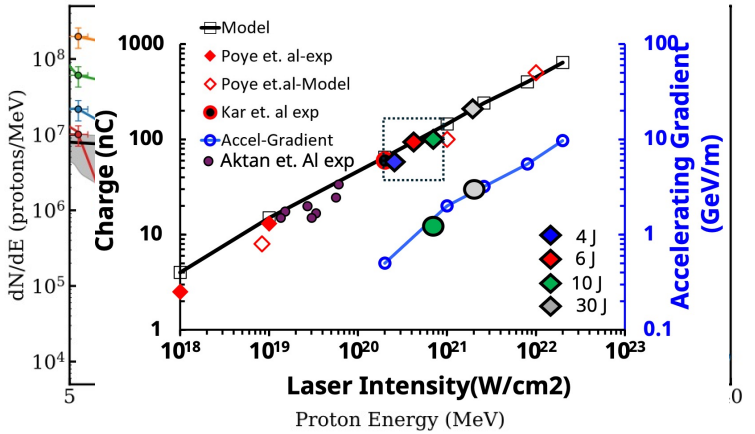
P. Martin *et al*, High Power Laser Sc. Eng., 12, 88 (2024)

O. Cavanagh *et al*, in preparation

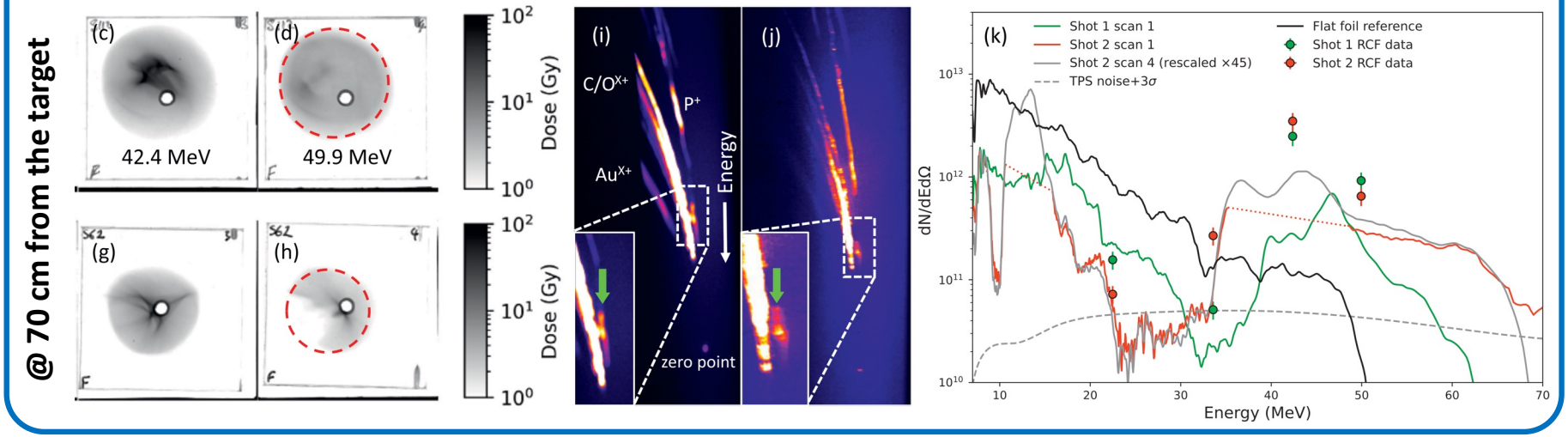
Titan Laser, LLNL; Vulcan PW, CLF
150-300 J, 750 fs, 2x10^{20} W/cm^2



ELI-Bl, Prague
10 J, 30fs, 5x10^{20} W/cm^2

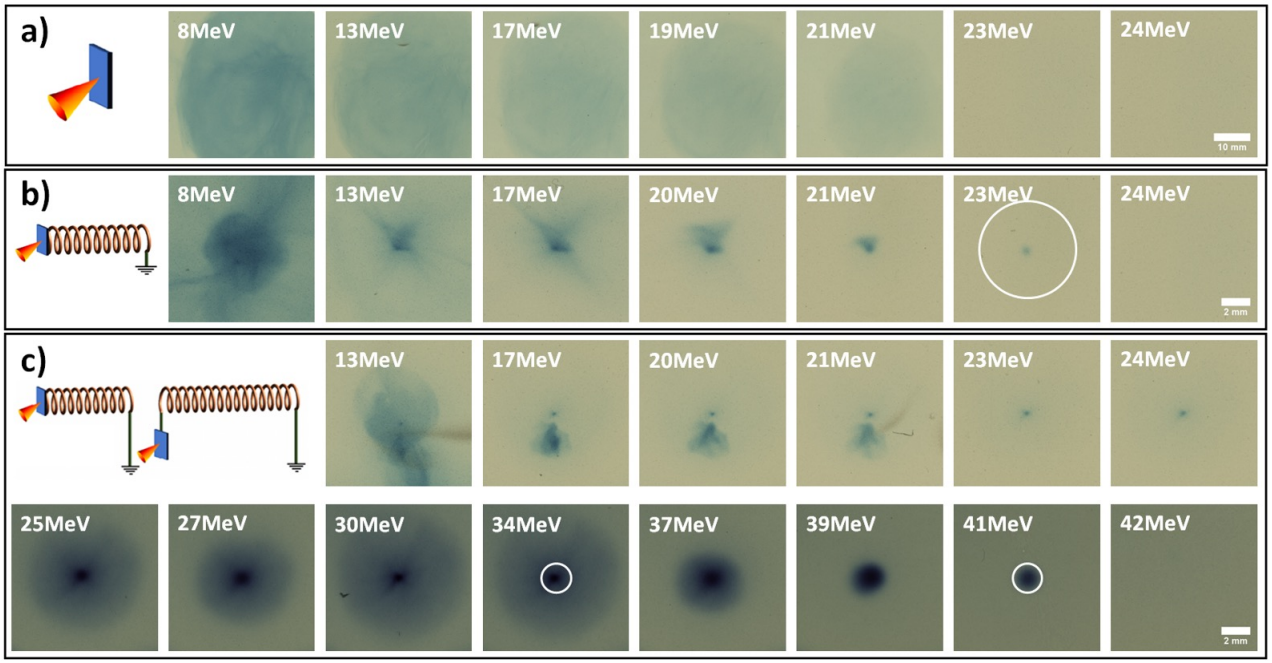


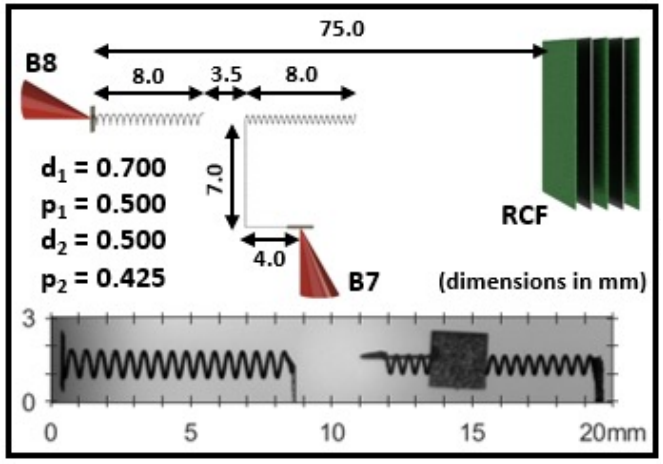
Vulcan PW, CLF: 300 J, 750 fs, 3x10^{20} W/cm^2

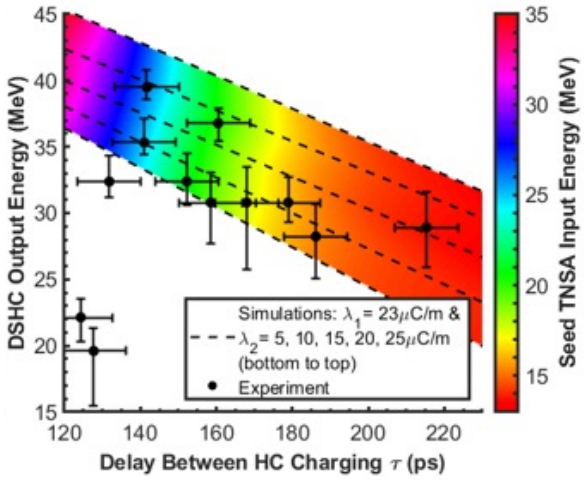


STAGING – Energy boost

S. Ferguson et. al., New J. Phys. 25, 013006 (2023)



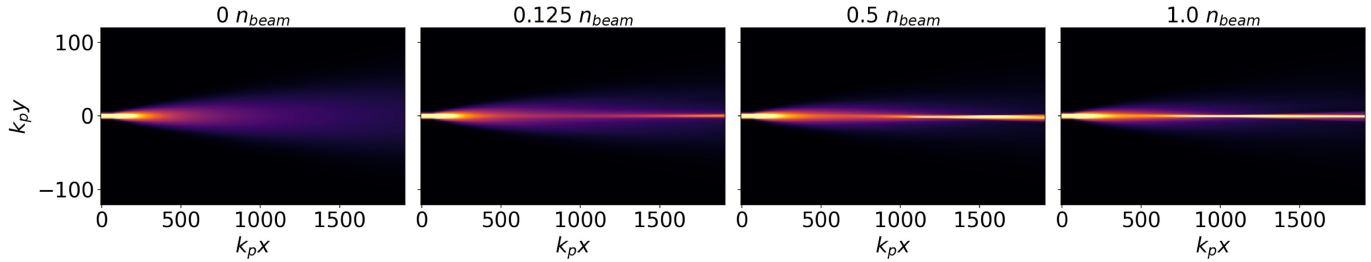




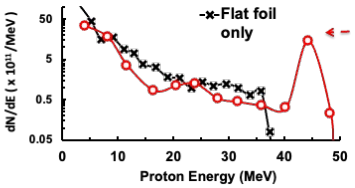
Timing is key to optimised performance

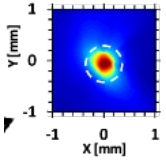
Conclusions :

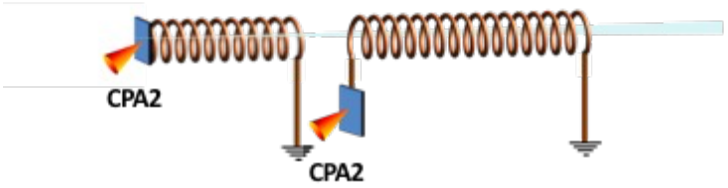
- Laser-driven acceleration techniques - a promising route to miniature accelerators.
- Yet, many challenges to overcome – e.g. control of its inherent divergence and spectrum
- Various avenues have been explored and are being developed by groups worldwide.
- At QUB, we work on two promising techniques.
  - (1) Using low-density plasma to strip co-moving electrons, and

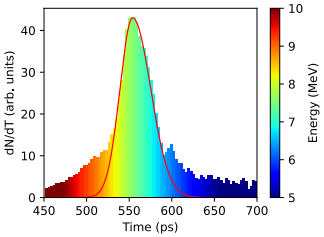


  - (2) using helical coil targets to simultaneously control divergence, spectrum and phase space, while re-accelerating the bunch at a GeV/m rate.









Thank you for your attention.