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Stable laser-acceleration of high-flux proton beams from liquid leaves

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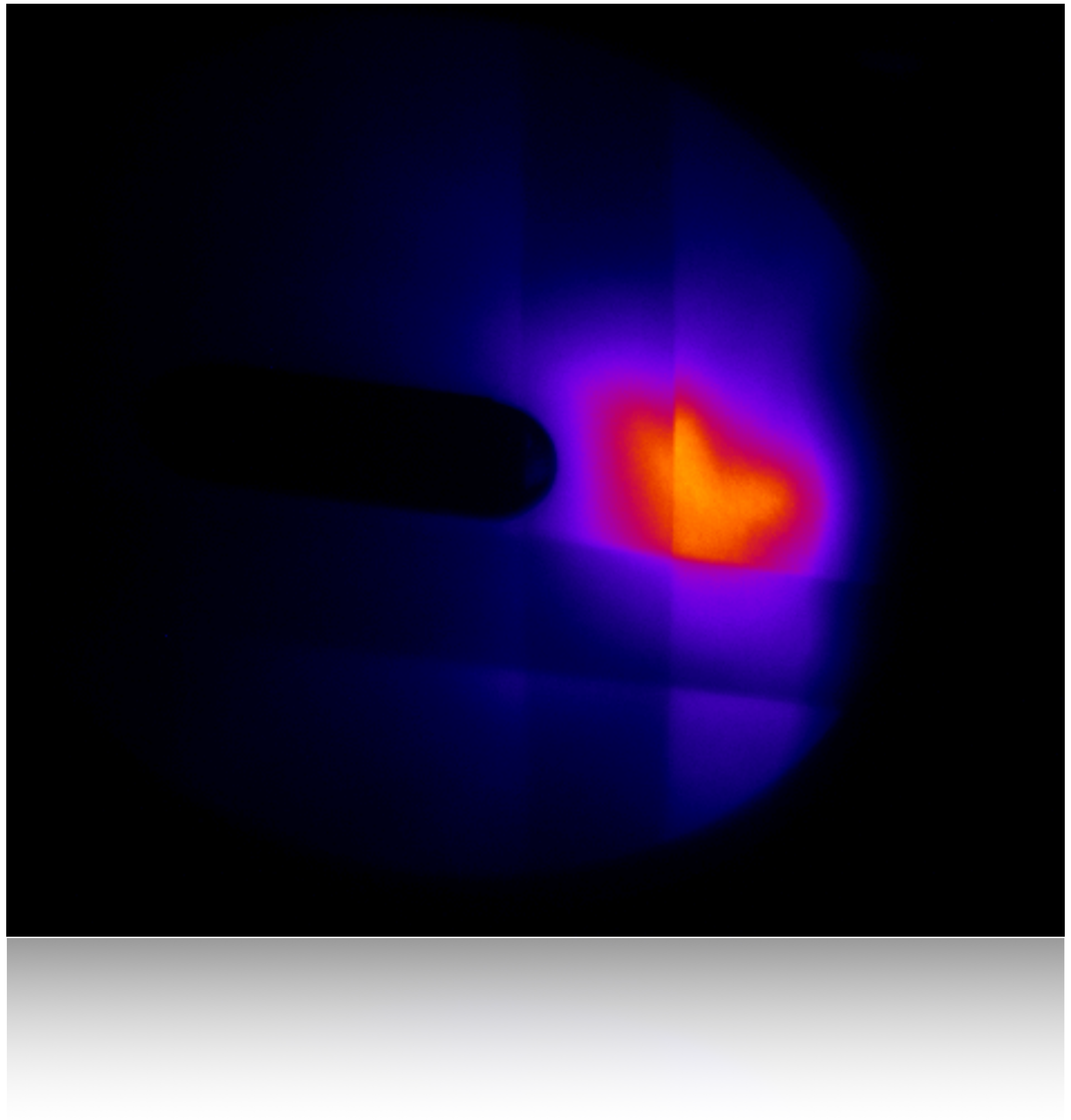


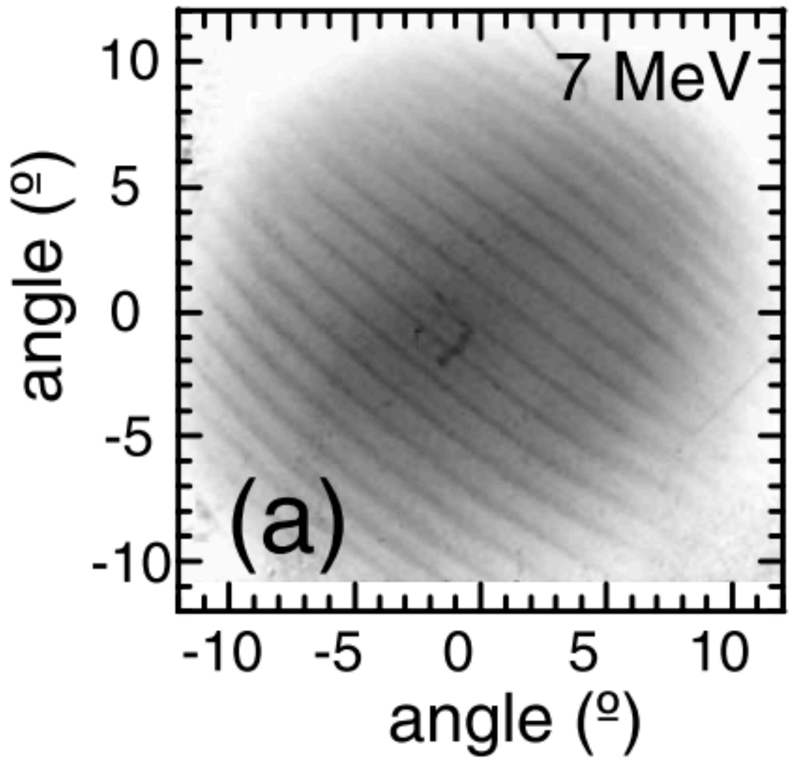
Overview:

- Motivation for development of laser-driven ion sources
- Brief introduction to TNSA
- Current challenges
- Novel beam properties from recent experiments using liquid sheet targets

Laser-driven ion sources provide unique beam properties for applications

Micron 'source' size

Low-emittance (μm mrad) supports imaging with high spatial resolution.

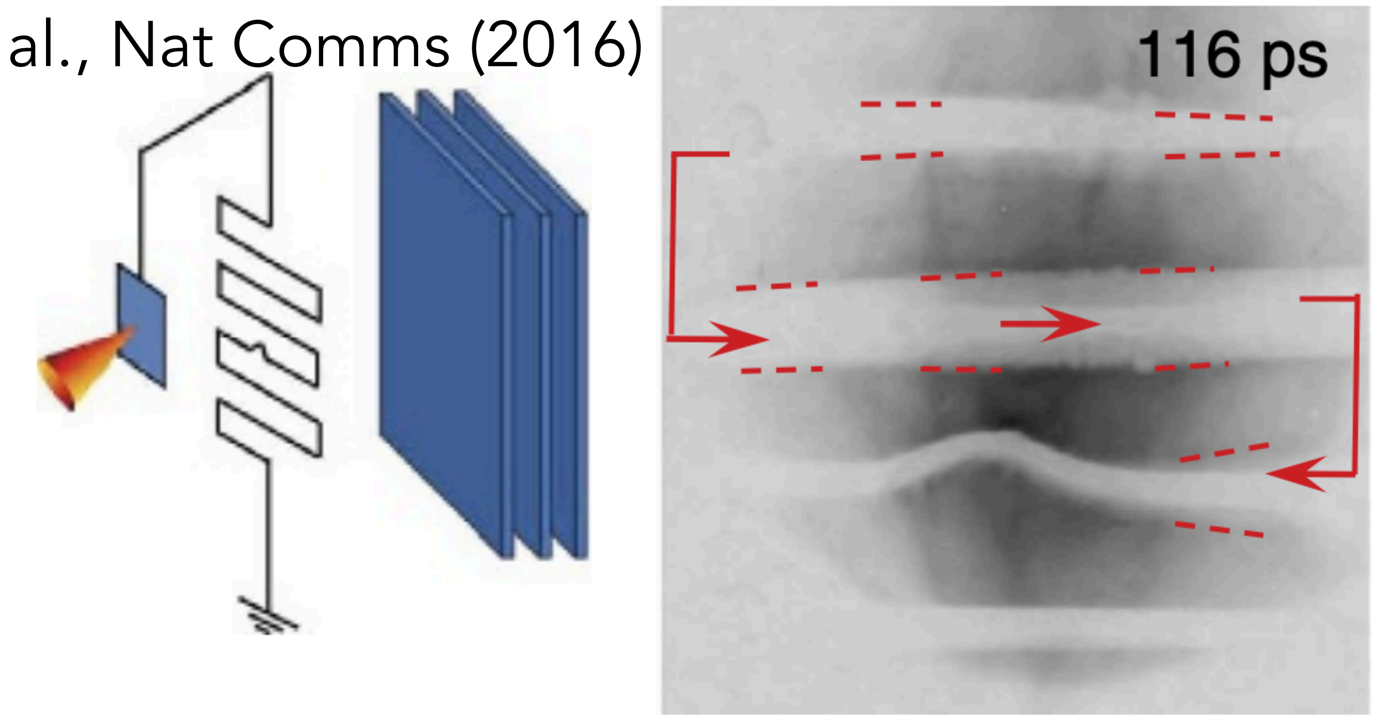


Cowan et al., PRL,(2004)

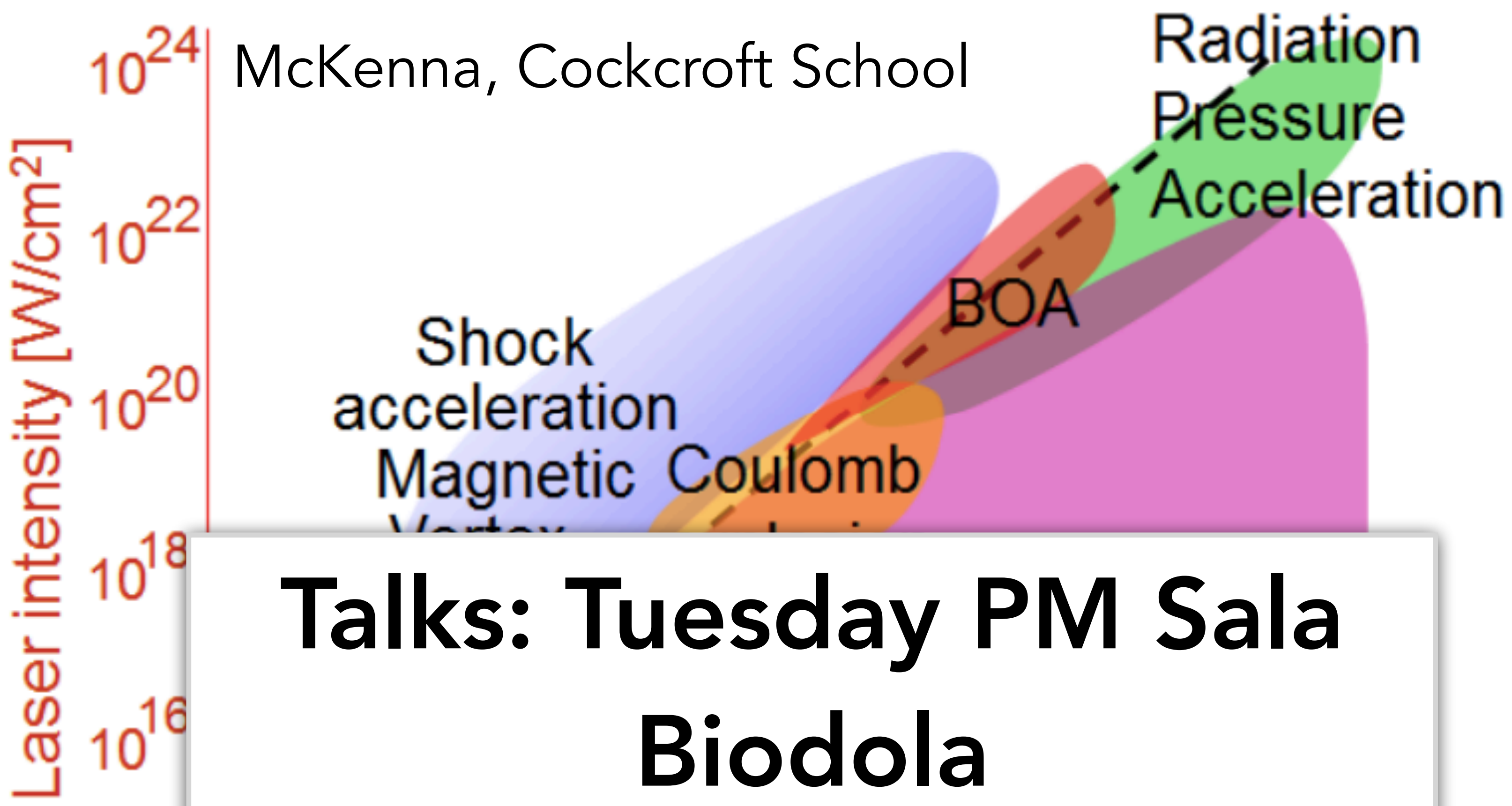
Ultra-short duration

Source duration comparable to laser-pulse length (<picoseconds) with short duration maintained in narrow energy slices.

Kar et al., Nat Comms (2016)



'Versatile' beam parameters



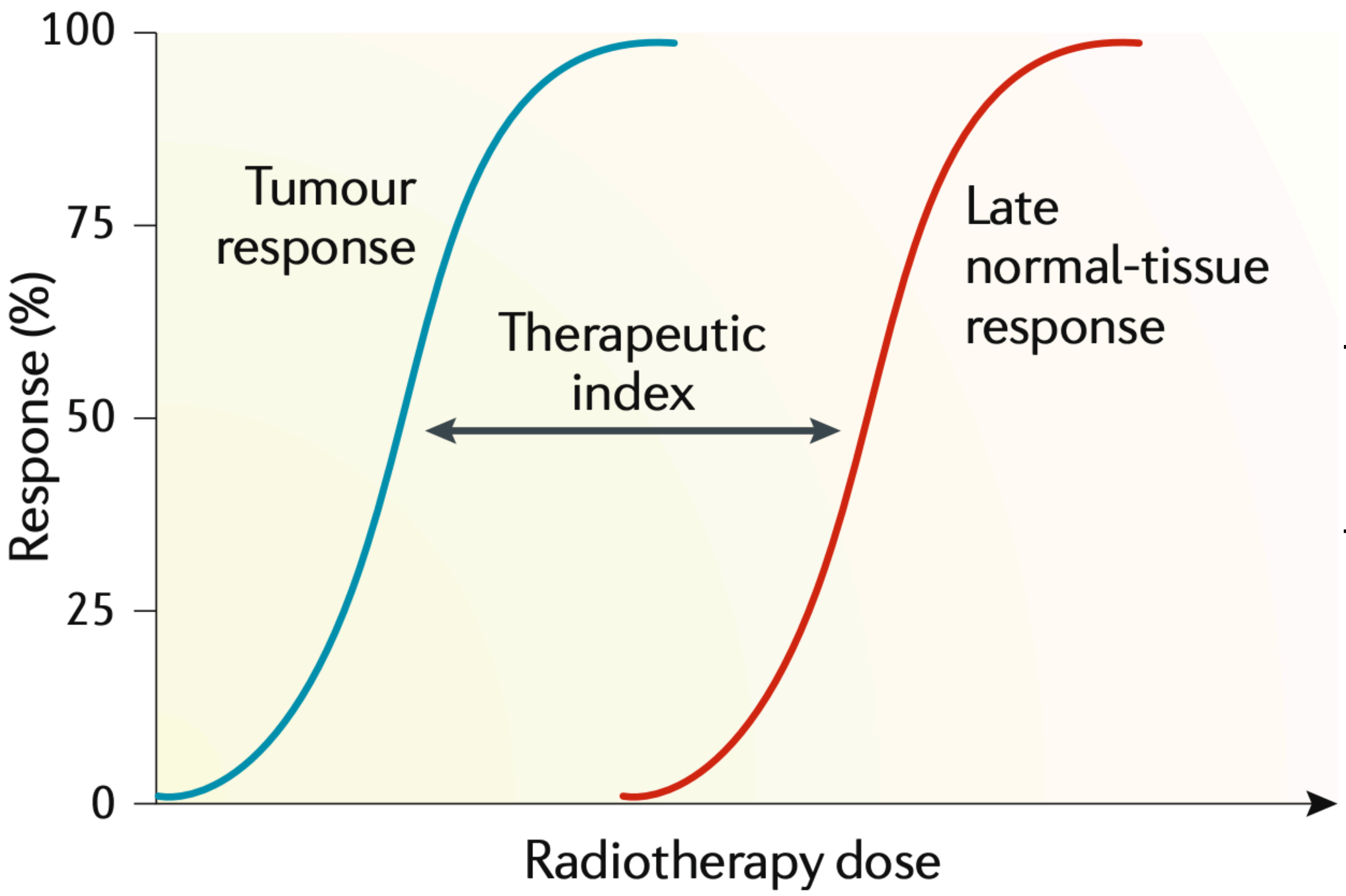
Talks: Tuesday PM Sala Biodola

Ion acceleration and developments towards fusion

Properties of ion beams are strongly dependent on interaction conditions providing access to different beam properties and ion species (but also adding complexity to beam tuning!)

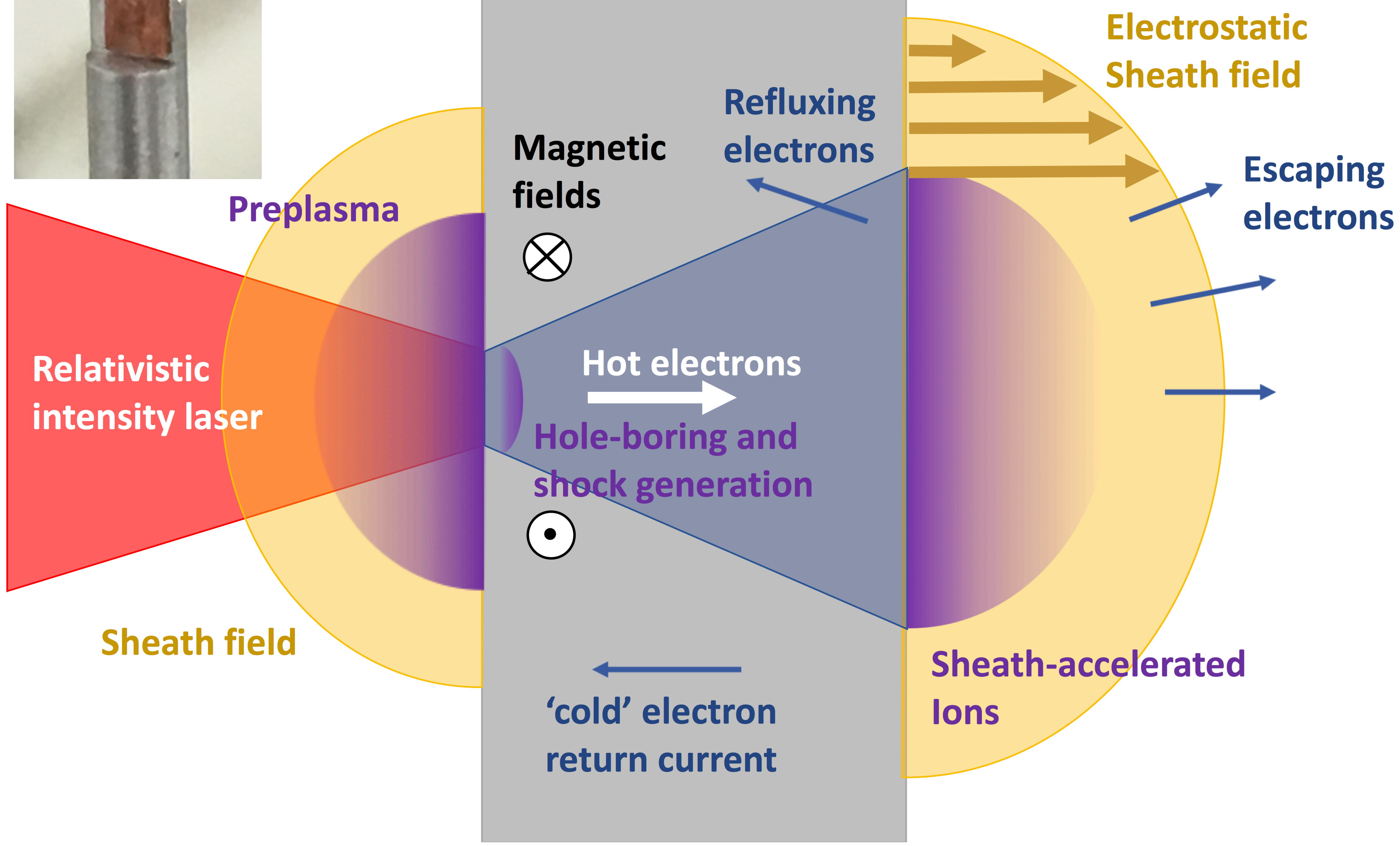
Example application:

High-dose rates (kGy/s) of laser-driven ion accelerators can be used to study the radiobiological FLASH effect which has demonstrated a widening of the therapeutic window.



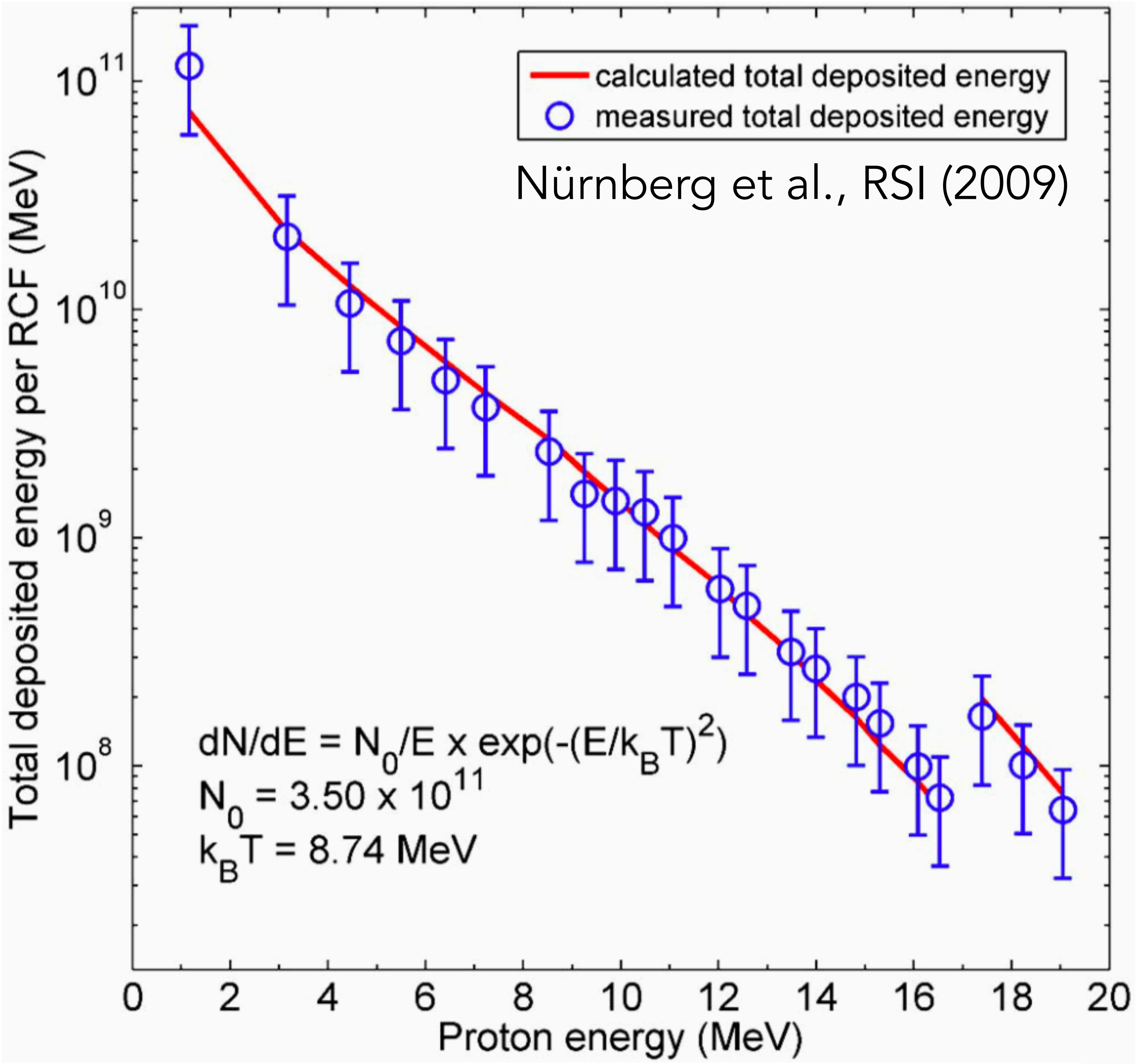
De Ryusscher et al., Nat. Rev. Disease Primer (2019)

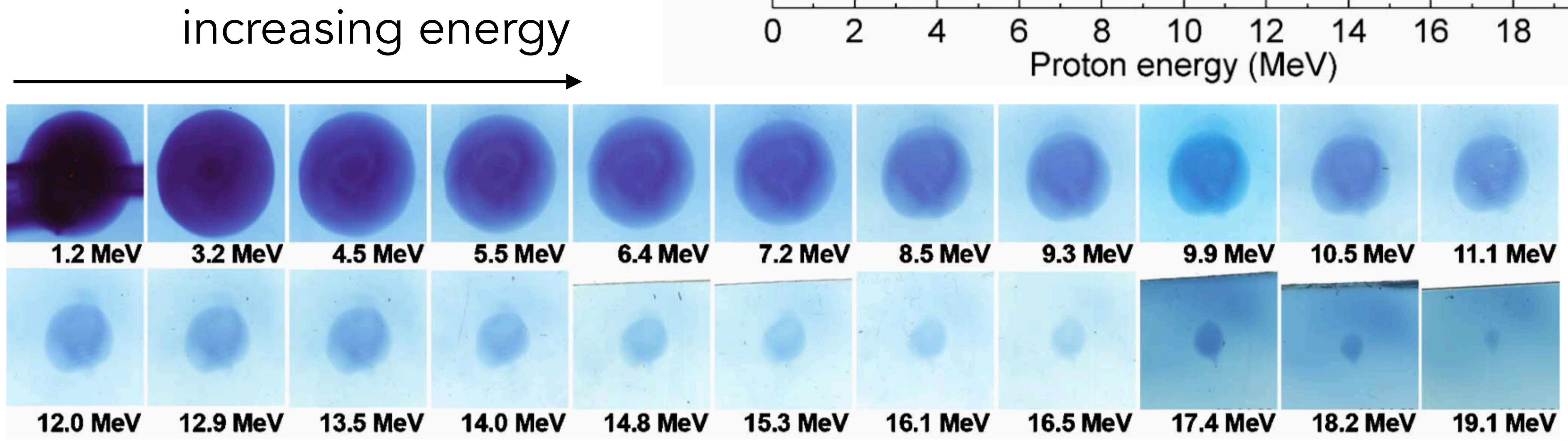
Target Normal Sheath Acceleration



TNSA proton beams

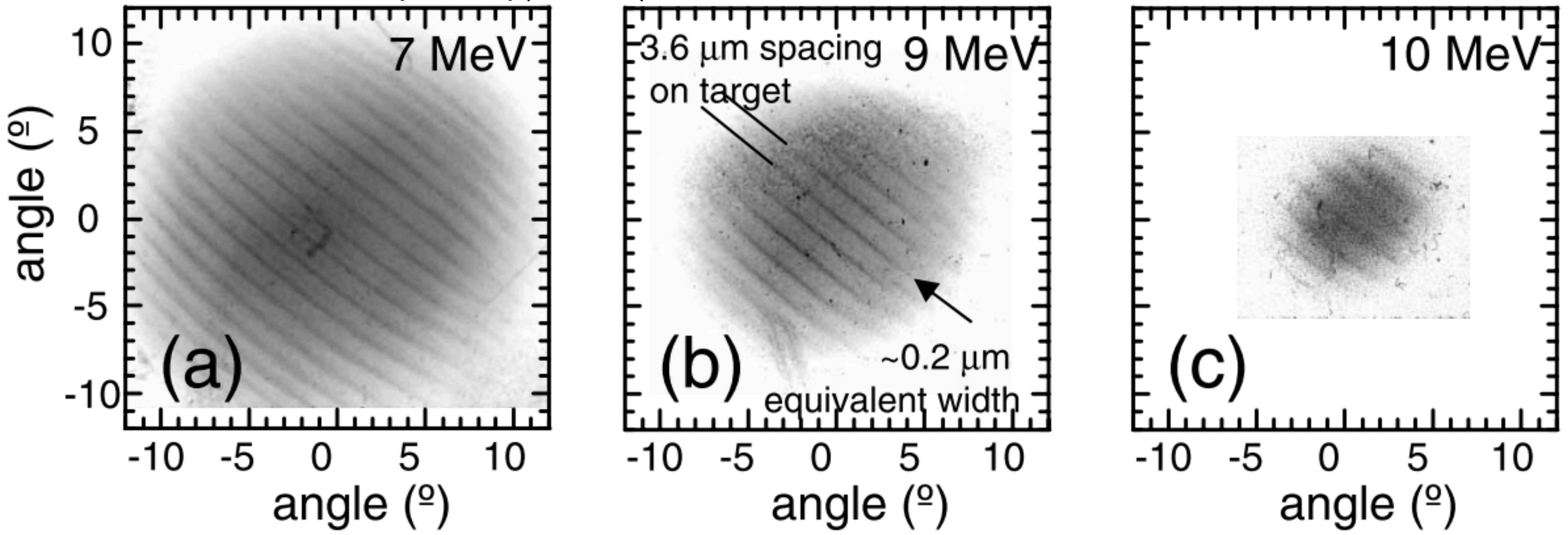
- MeV energies.
- nC bunch charges.
- ps duration at source.
- **10s degrees divergence.**





Micron structure etched into target surface is preserved in proton beam flux profile indicating scale of emission region and beam laminarity.

Cowan et al., PRL,(2004)



TNSA trends:

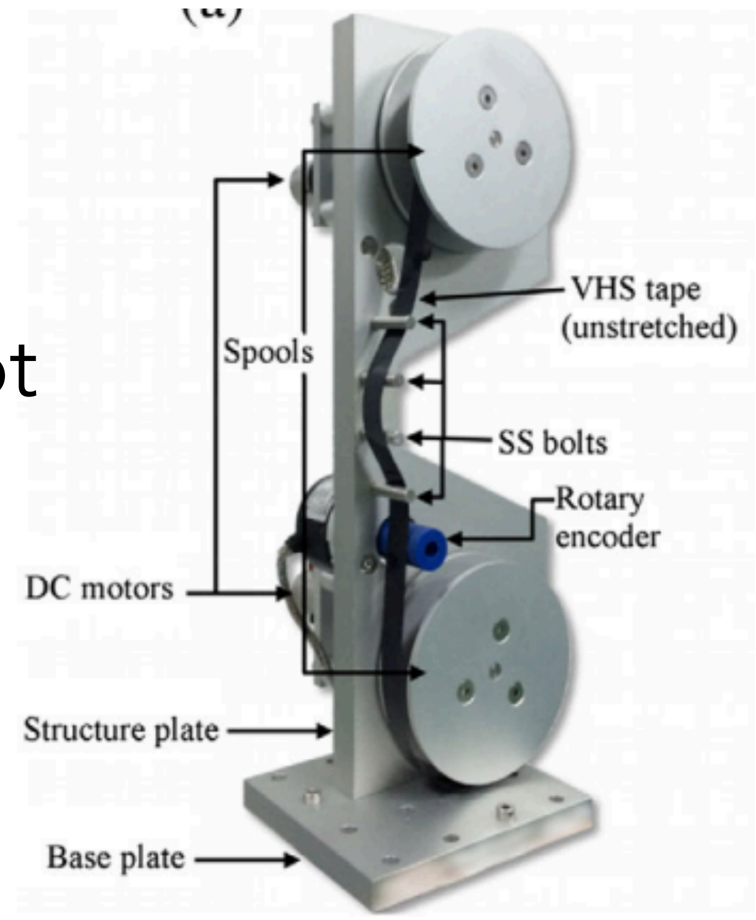
- Higher energy ⟶ higher proton flux
- Higher intensity ⟶ higher max proton energy
- **Thinner targets ⟶ higher max proton energy**

(Some) Challenges hampering wider adoption of laser-driven ion sources

Operation of the accelerator at multi-Hz rep. rates

Targets destroyed in each interaction require replacing with micron precision at the shot rate. Many novel targets and diagnostics under development.

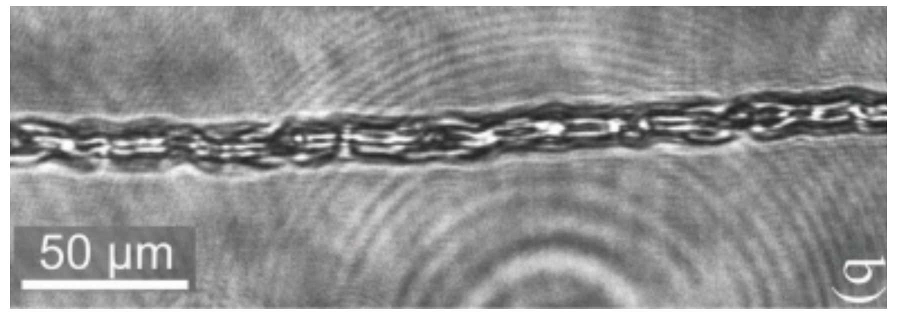
Tape target:



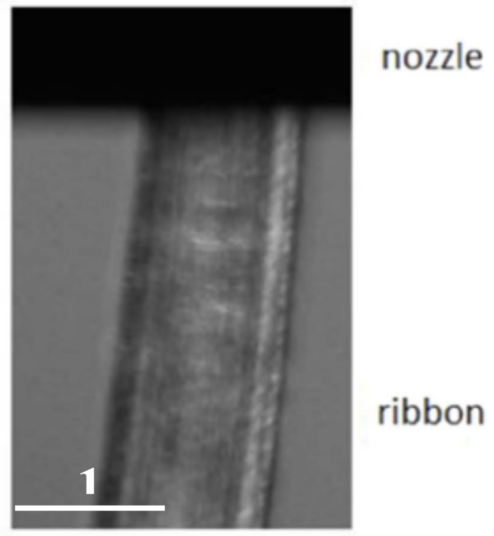
Noaman-ul-Haq et al., PRAB (2017)

Cryogenic targets:

Propp et al., SLAC. Rep.



Polz et al., Sci. Rep. (2019)

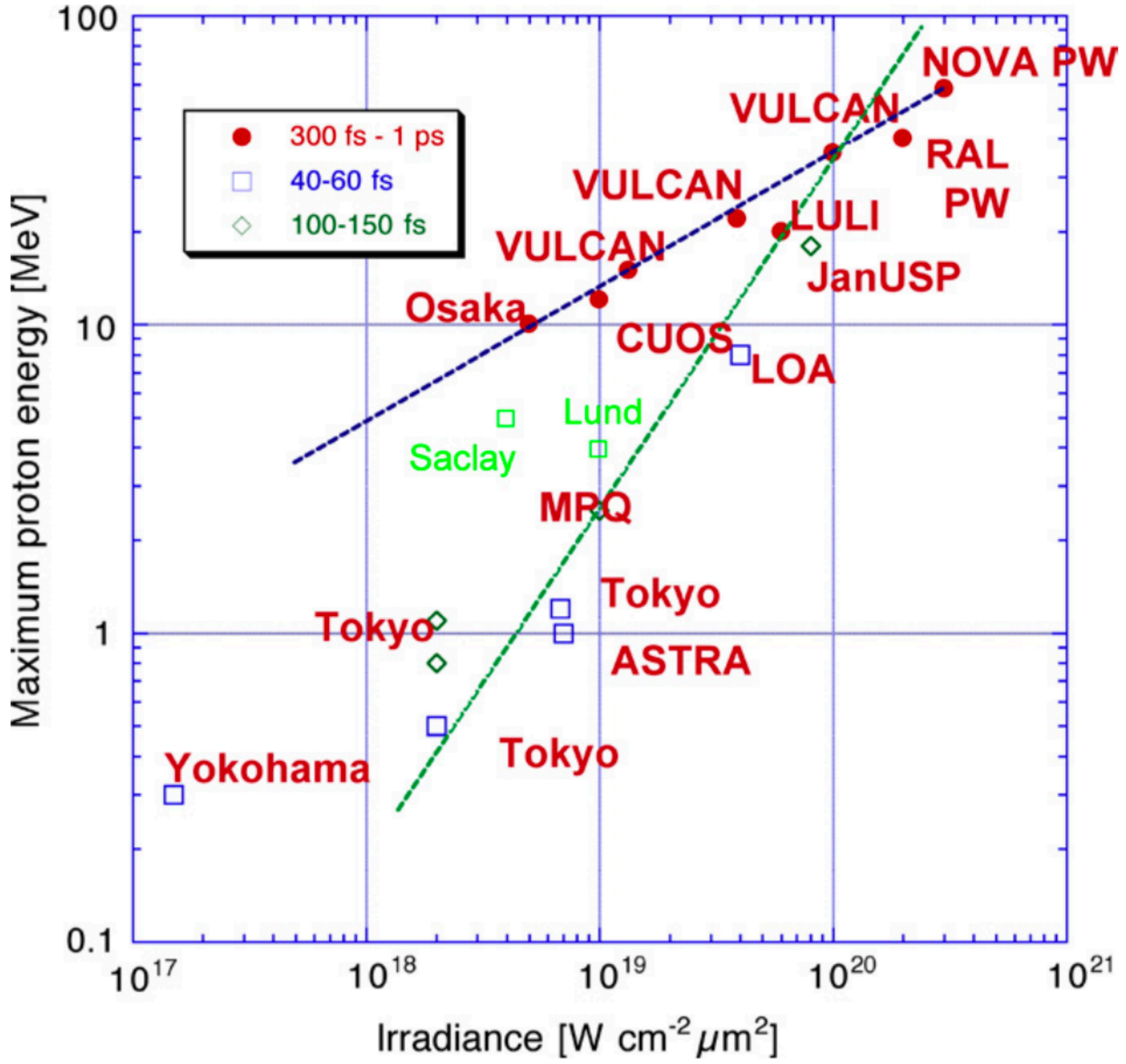


Kraft et al., PPCF (2018)

Optimisation of beam parameters

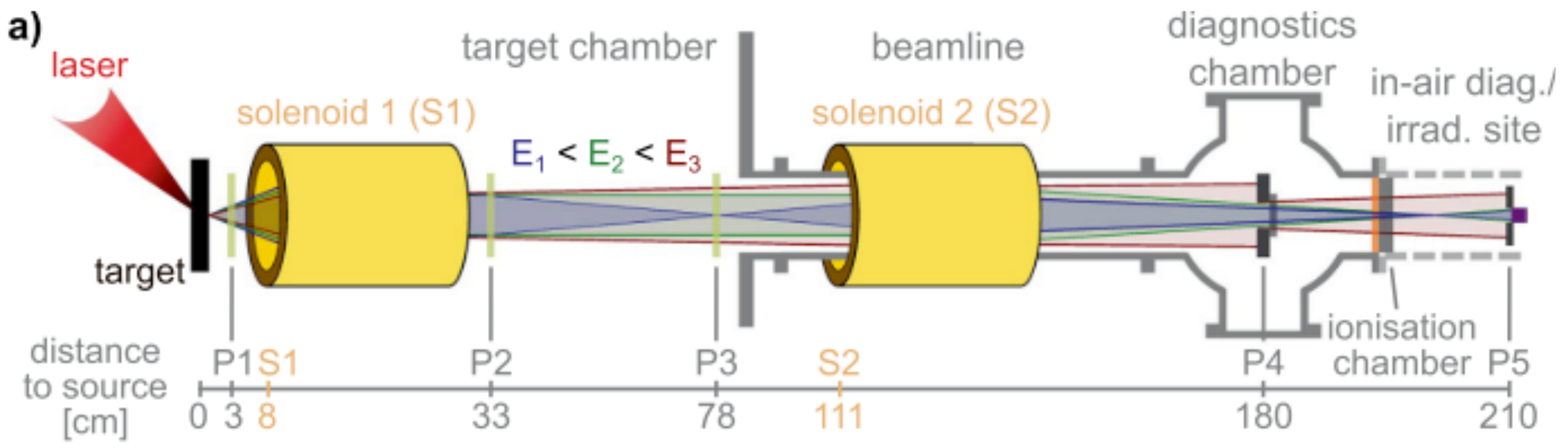
Highly nonlinear multi-dimensional parameter space in which beam parameters are challenge to predict.

Macchi et al., Rev. Mod. Phys. (2013)

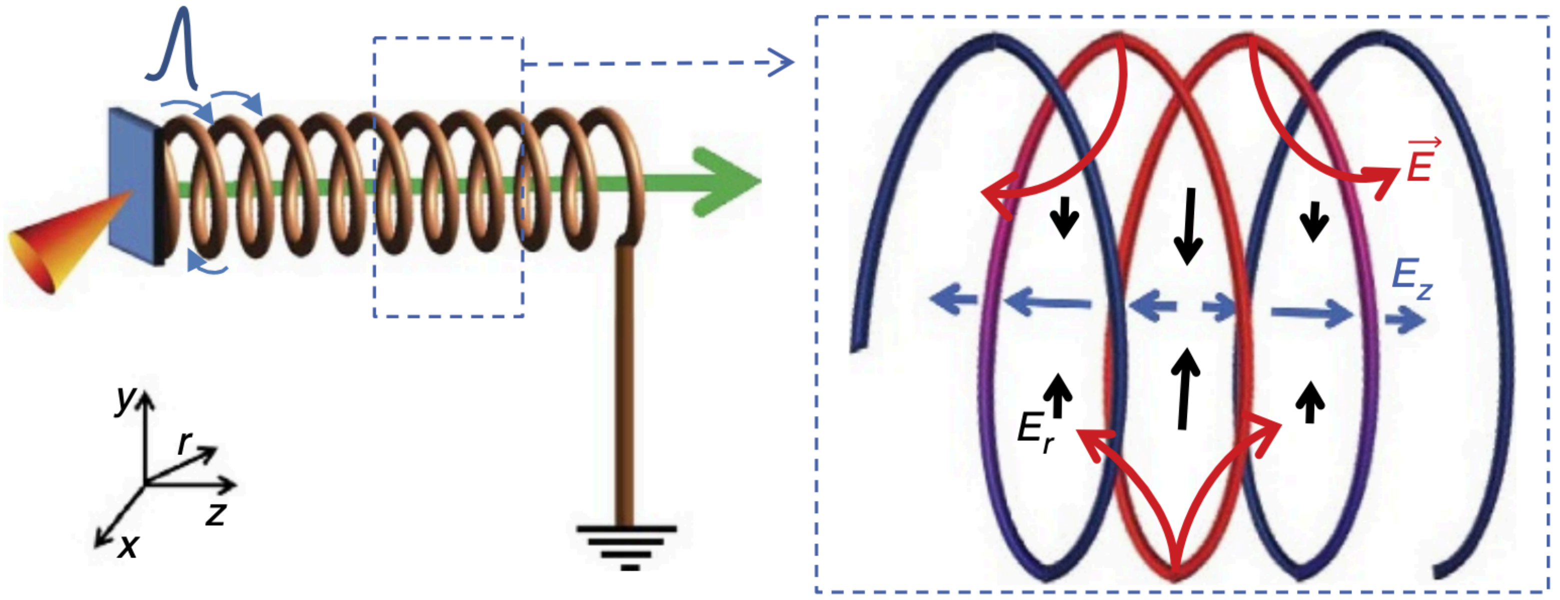


Capture, transport and conditioning of the ion beams

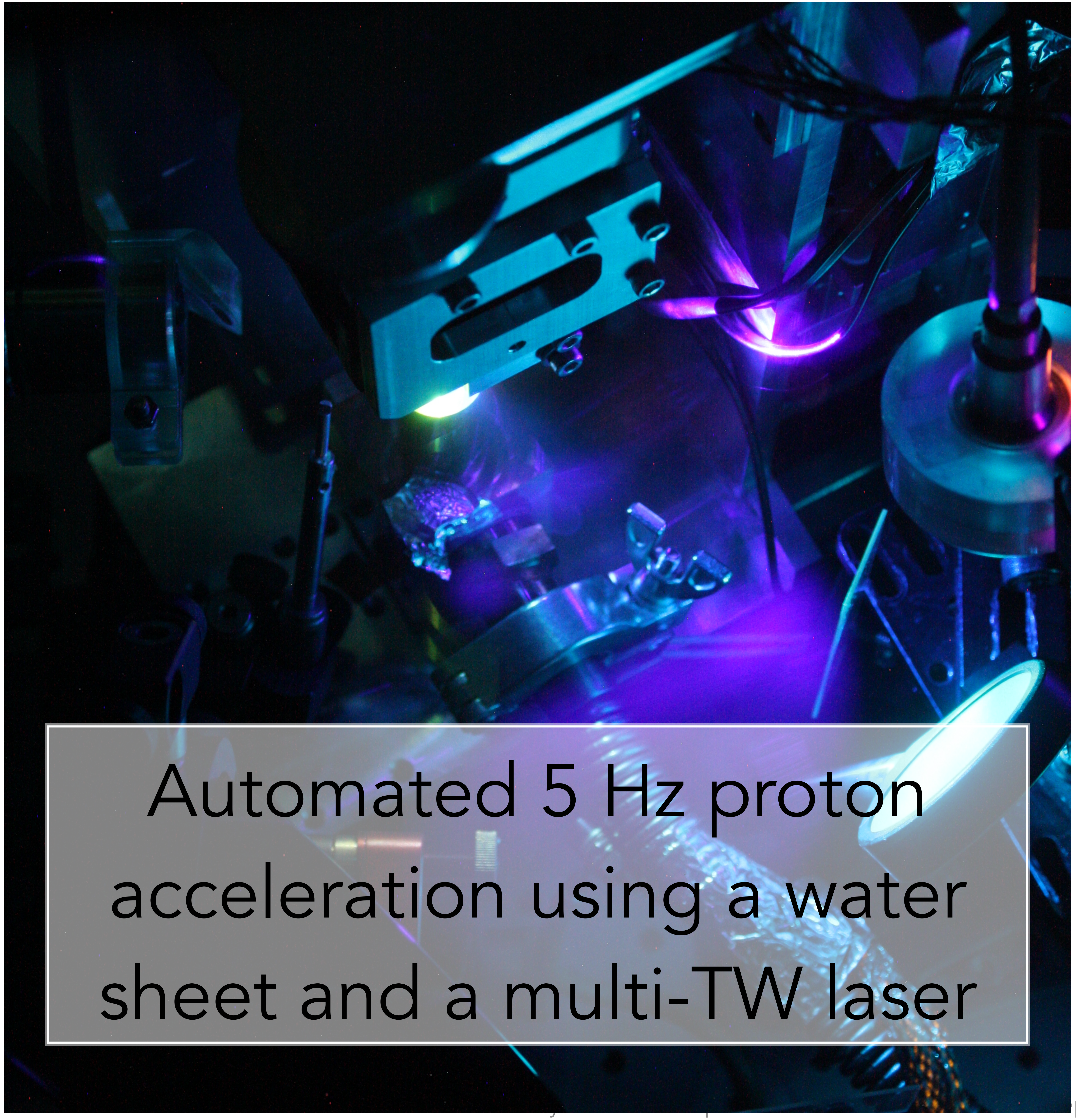
Samples typically cannot be placed close to the ion source and the beam often requires conditioning/energy selection before use but large divergence complicates capture.



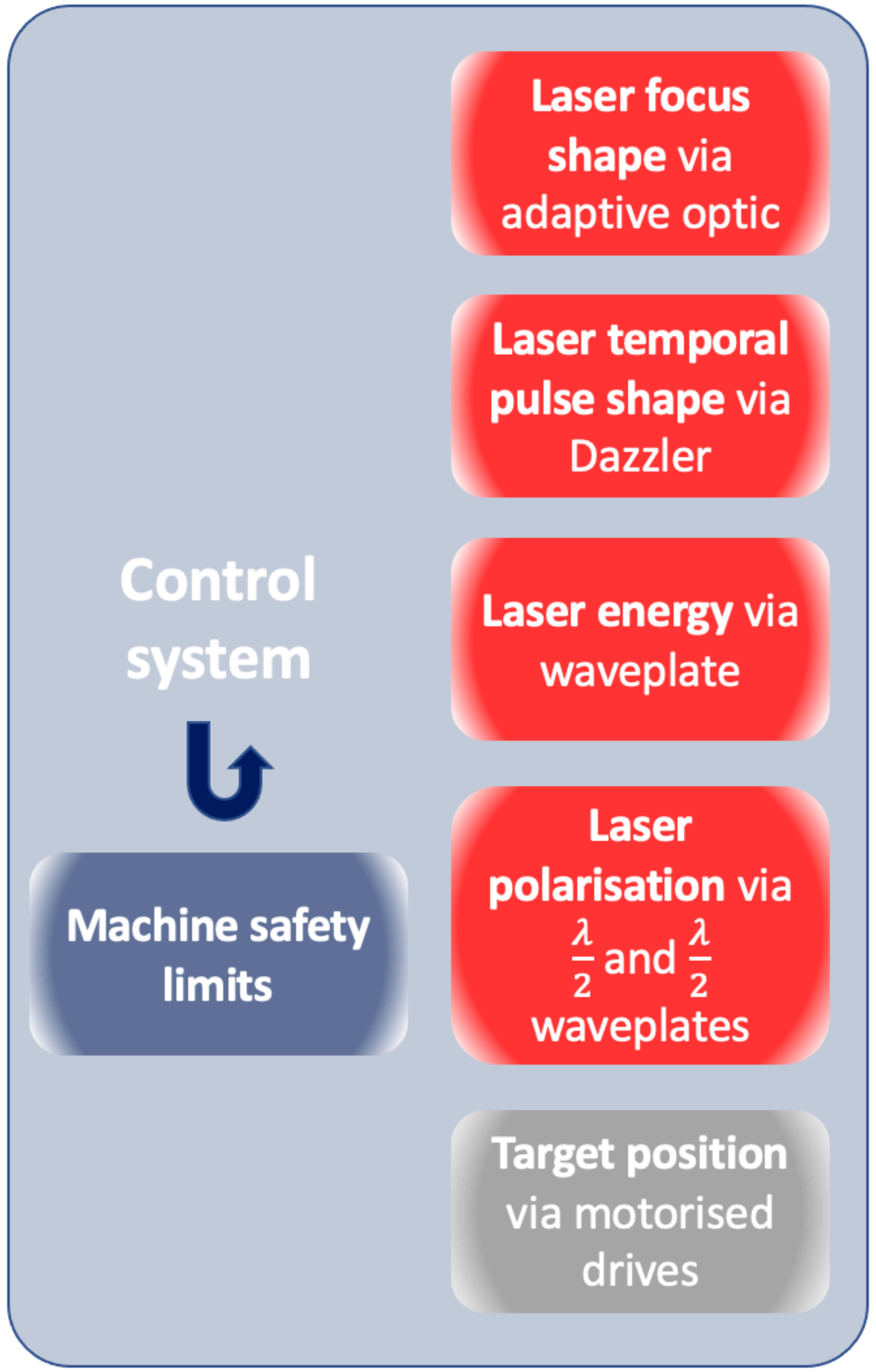
Brack et al., Sci. Rep., 10, 2020



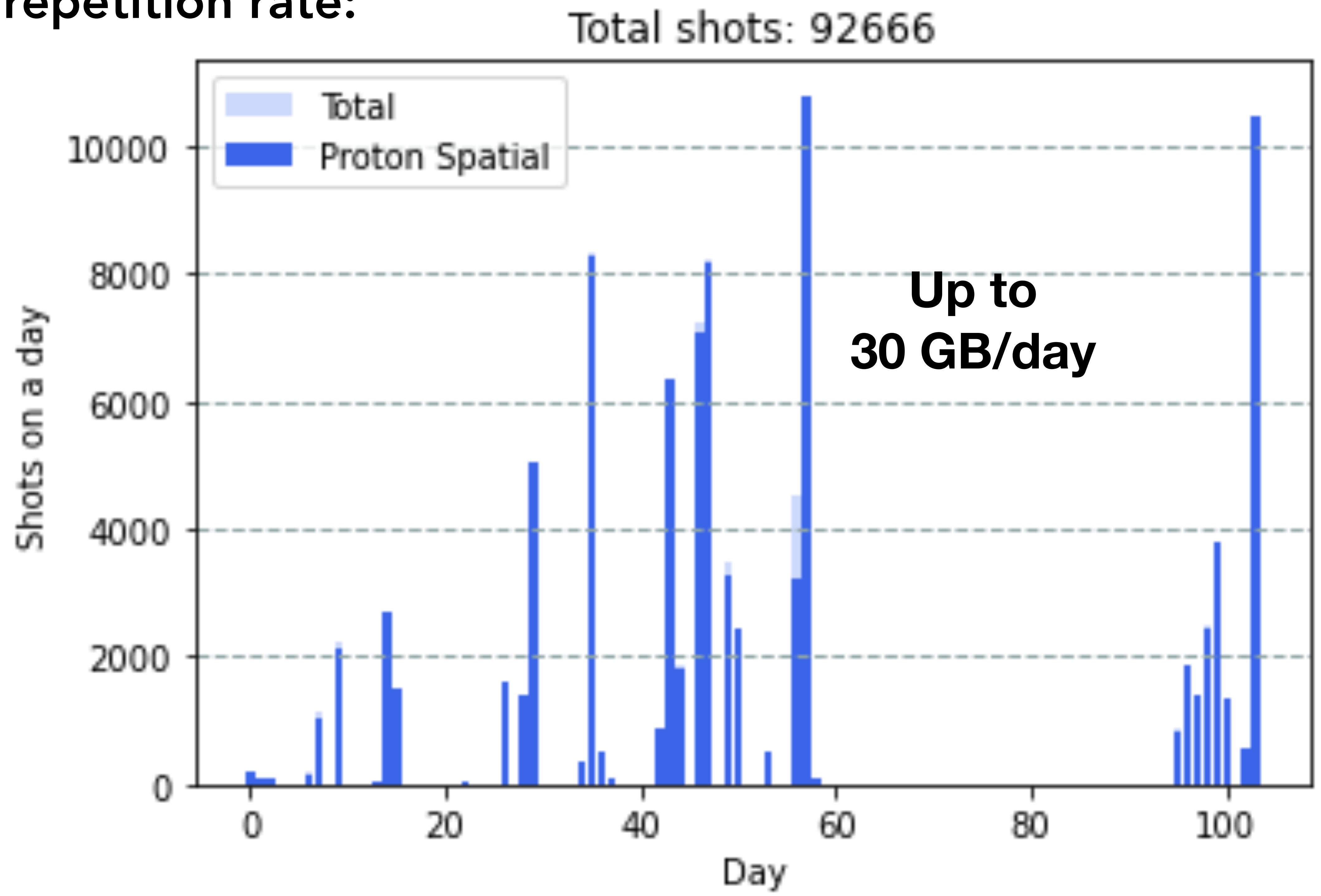
Kar et al., Nat. Comms. (2016)


Automated 5 Hz proton acceleration using a water sheet and a multi-TW laser

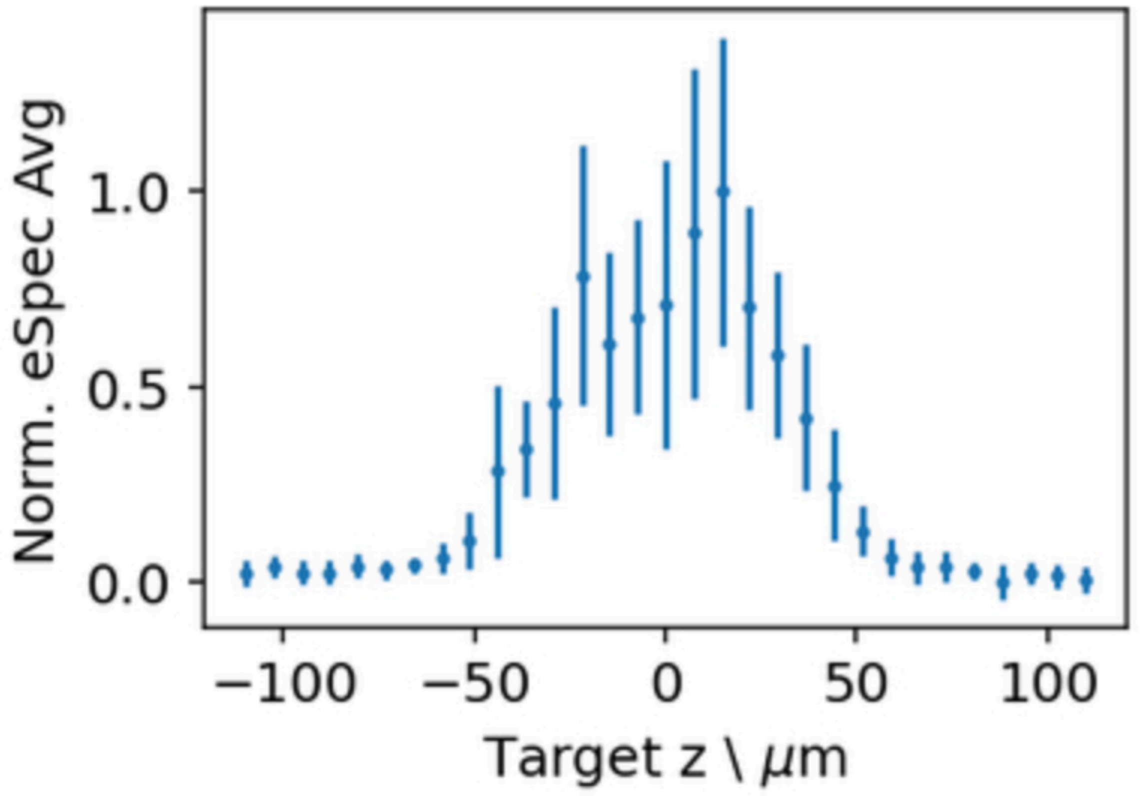
Automated control system at Gemini TA2



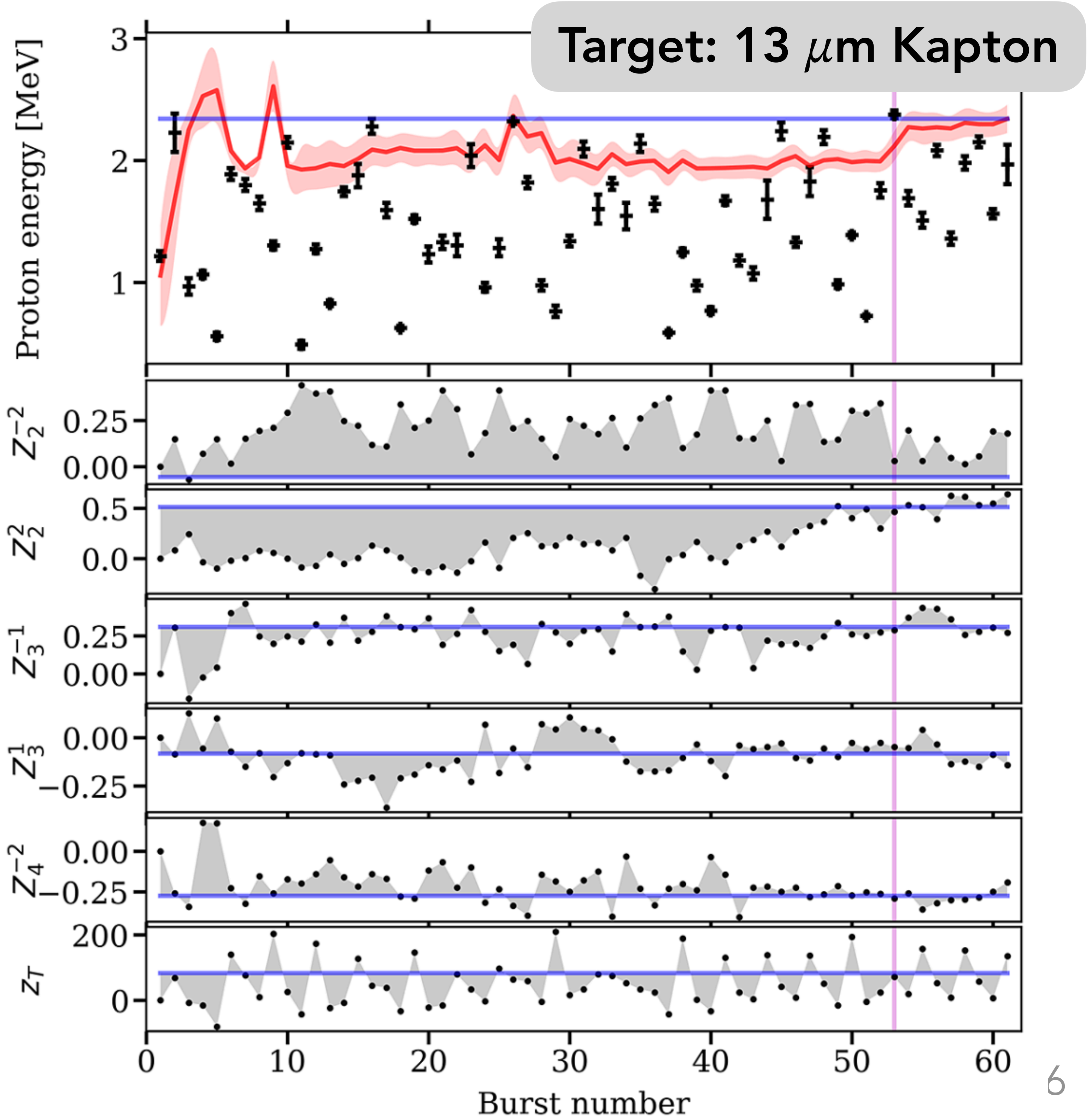
Automation enables data acquisition at maximum laser-repetition rate:



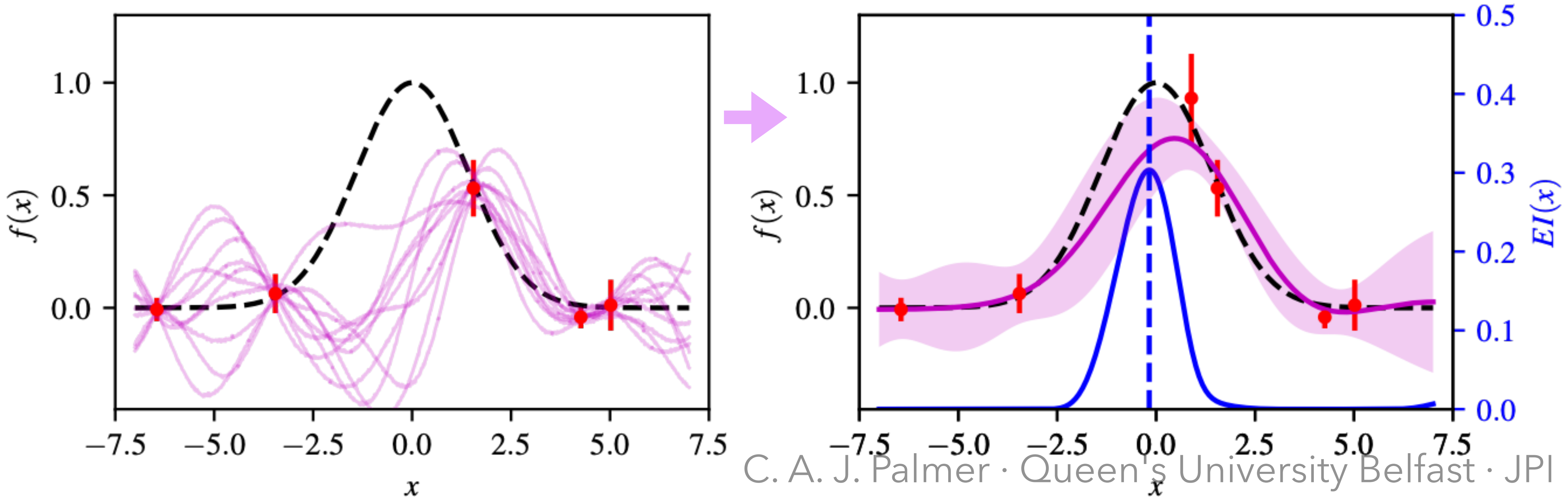
Single target position scan:



Optimisation within 6D parameter space



Bayesian optimisation using Gaussian process regression:

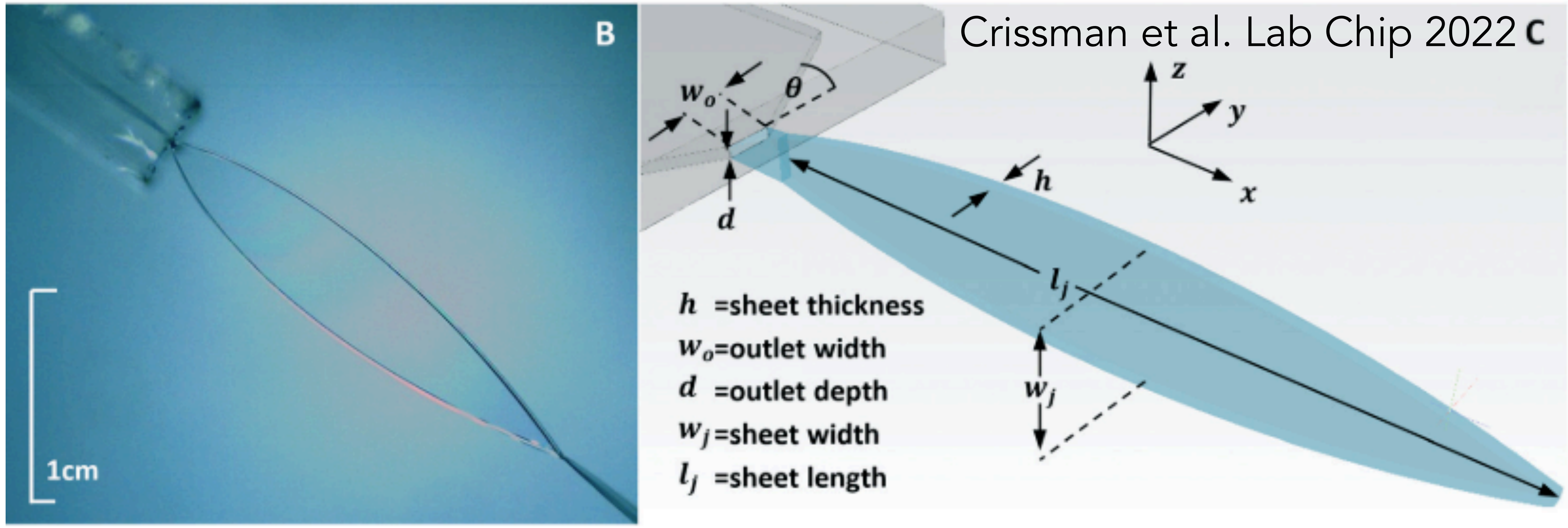


Bayesian optimisation of TNSA from Kapton tape

Loughran et al., HPLSE 11, e35 (2023)

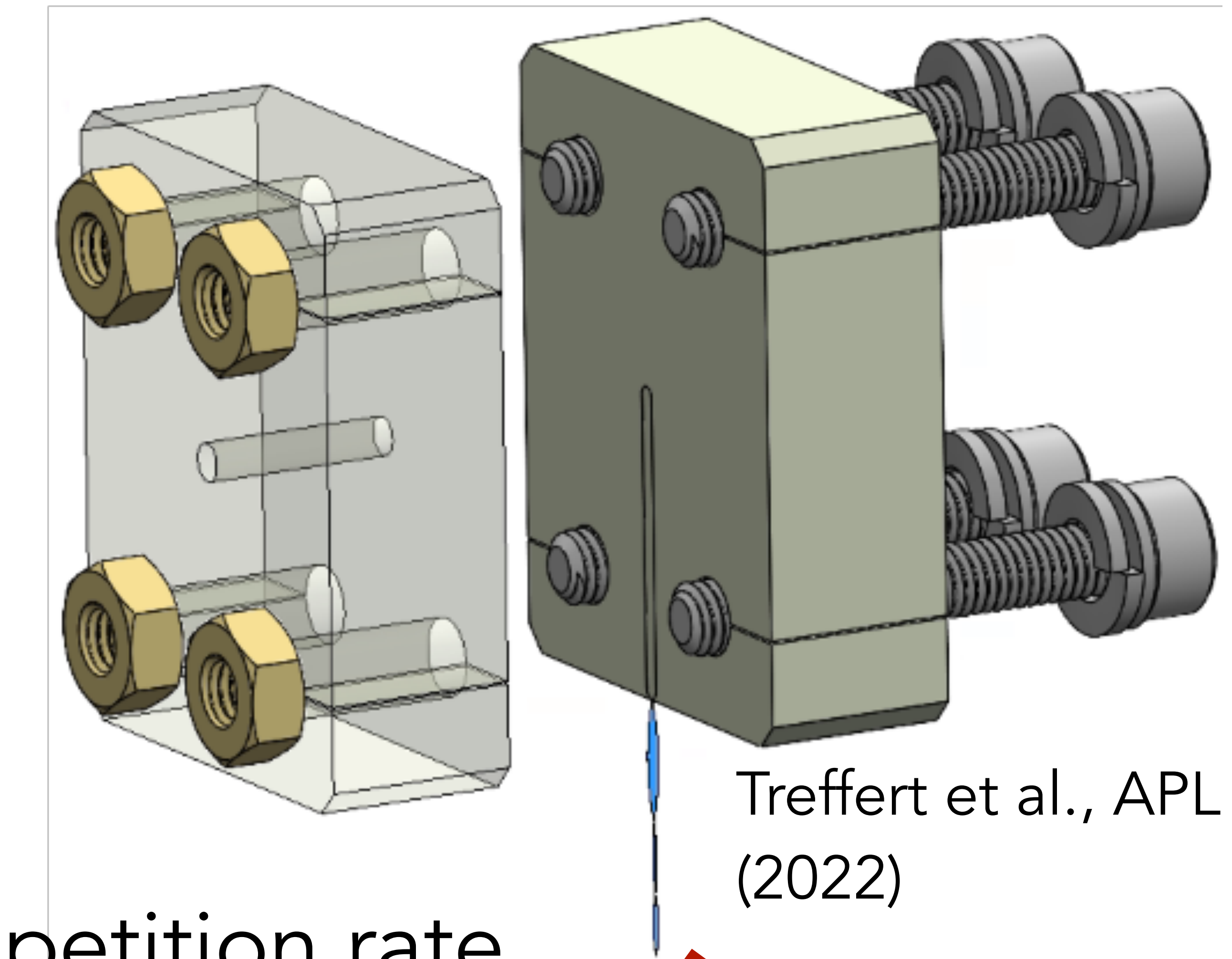
Liquid leaf targets

Typically formed via colliding or converging liquid streams with fluid momentum and surface tension governing the dynamics of the flow.



Crissman et al. Lab Chip 2022

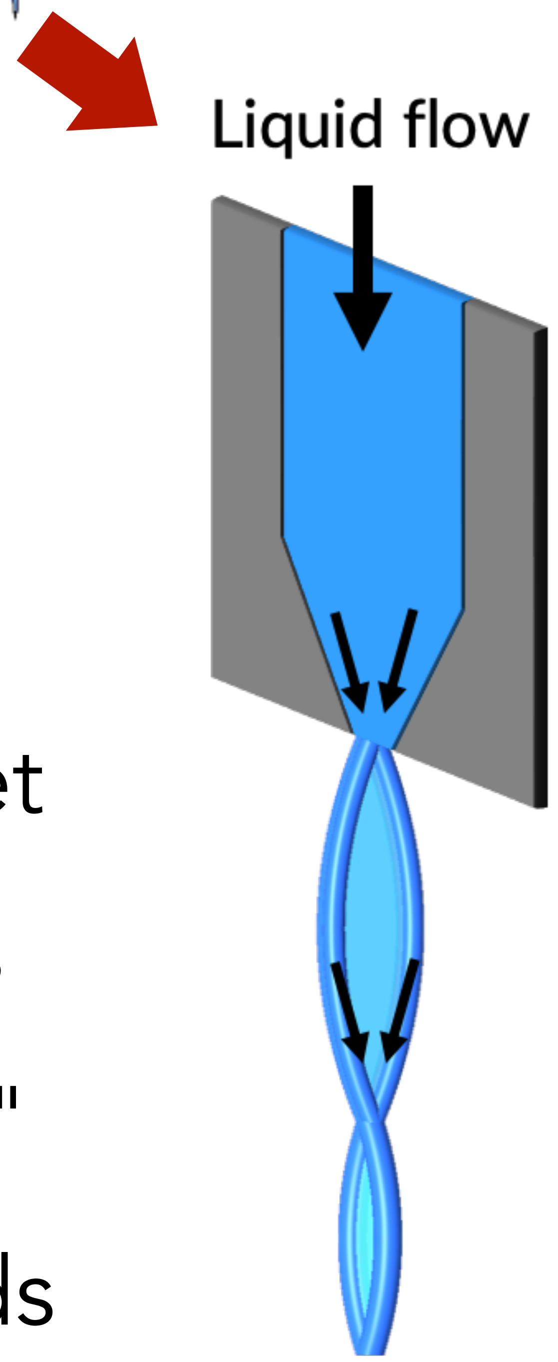
Used for sample delivery over many hours at LCLS.



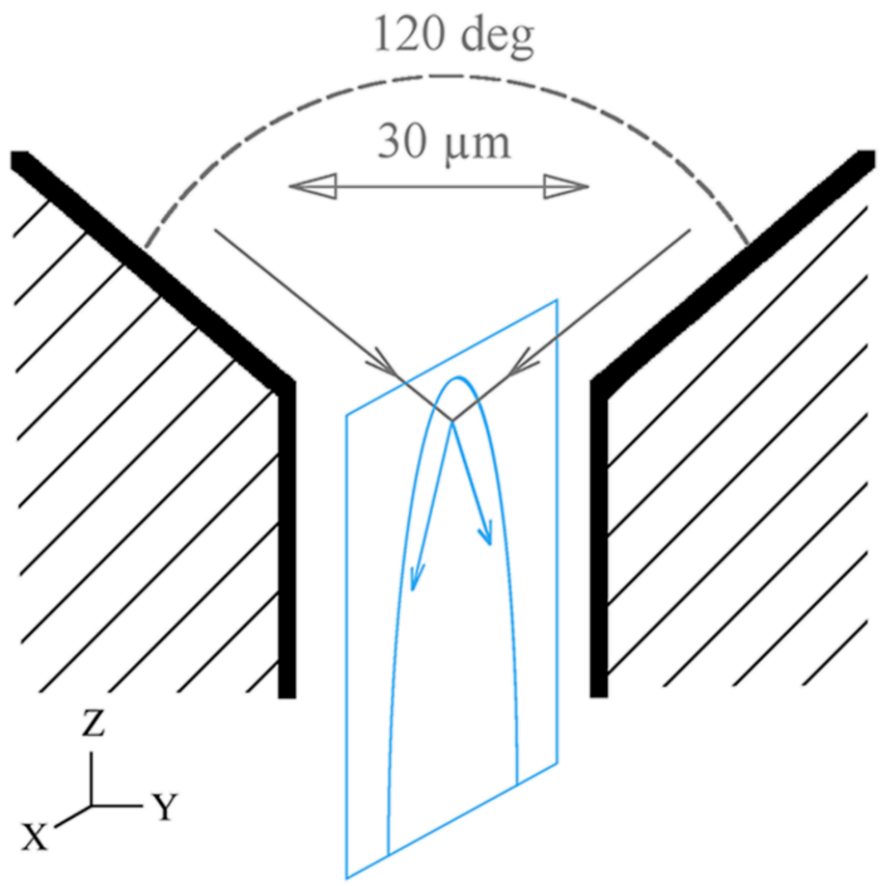
Treffert et al., APL (2022)

Valuable high-repetition rate targets for laser-driven ion acceleration due to:

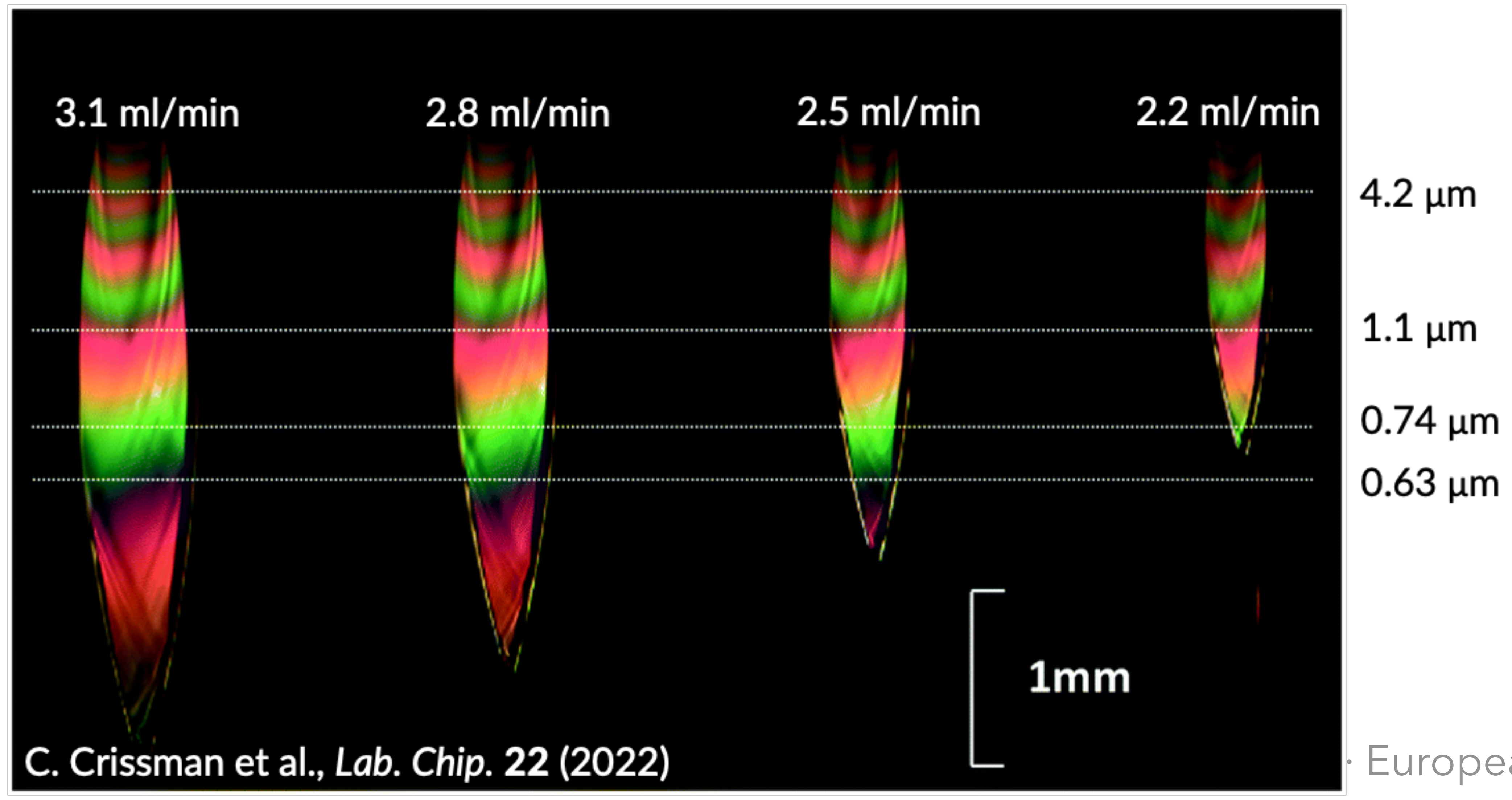
- Planar geometry
- Fast-replenishing flow
- Thickness variation along sheet
- Stability to flow-rate variations
- Formation of multiple "leaves"
- Compatibility with many liquids



Thickness mapped using thin film interferometry



Galinis et al. RSI 2017



C. Crissman et al., *Lab. Chip.* **22** (2022)

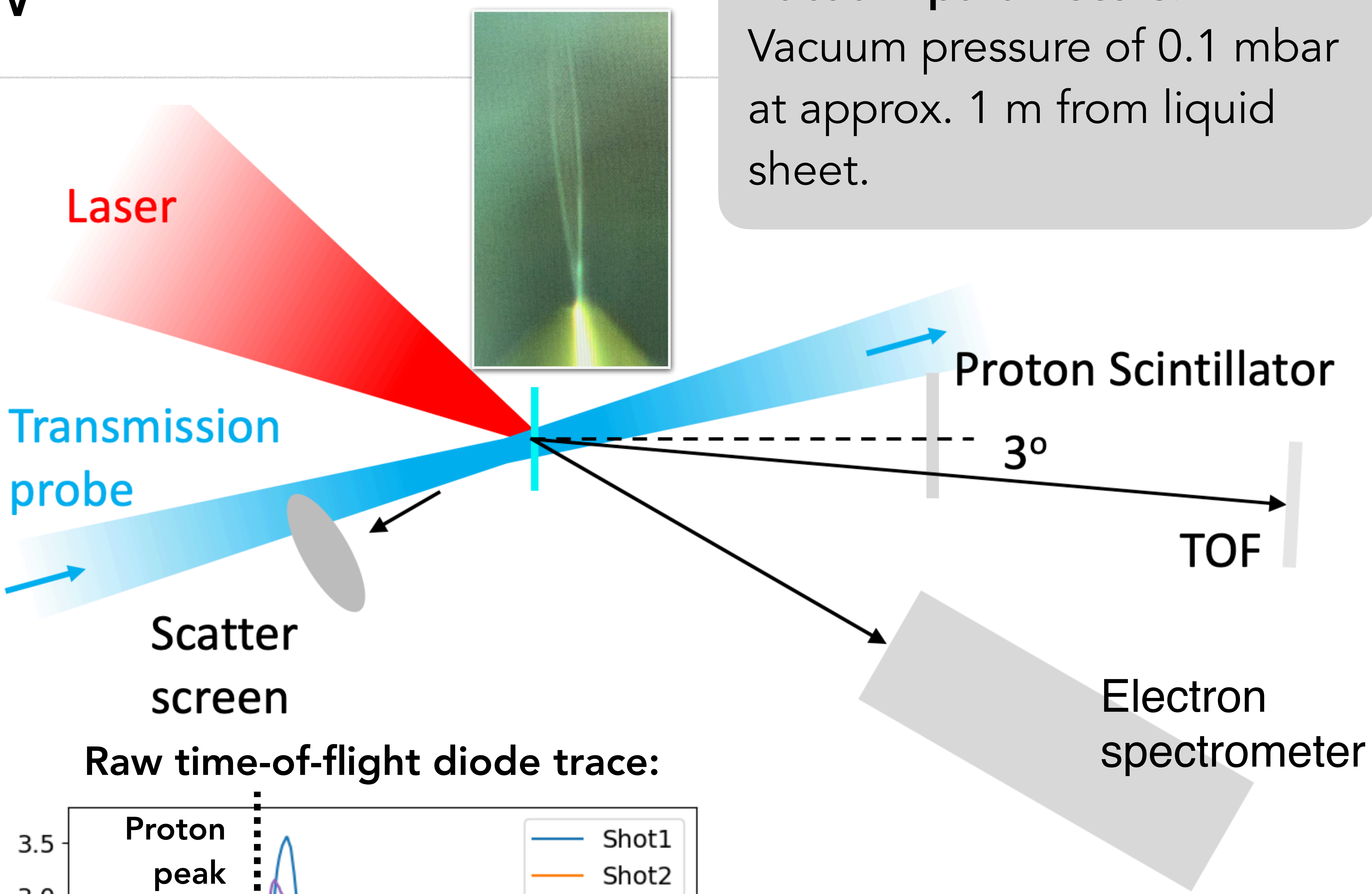
Experimental overview

Vacuum parameters: Vacuum pressure of 0.1 mbar at approx. 1 m from liquid sheet.

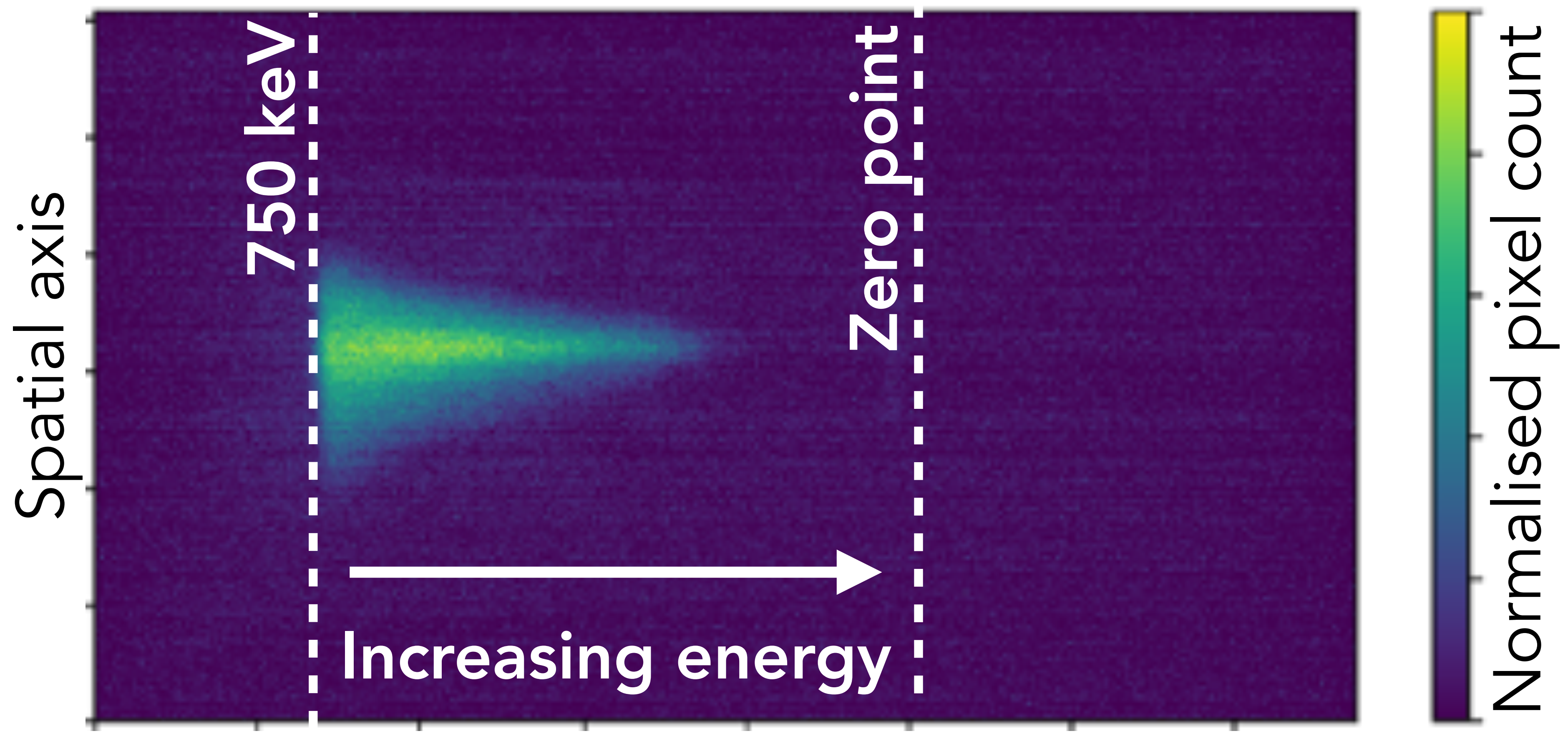
Laser parameters: Up to 200 mJ on target in 60 fs focused with F/2.5 OAP (Z_R ~ 15 μm). No contrast enhancement.

Target parameters: Ultra-pure water with (600 ± 100) nm thickness at 2.8 mm below nozzle outlet.

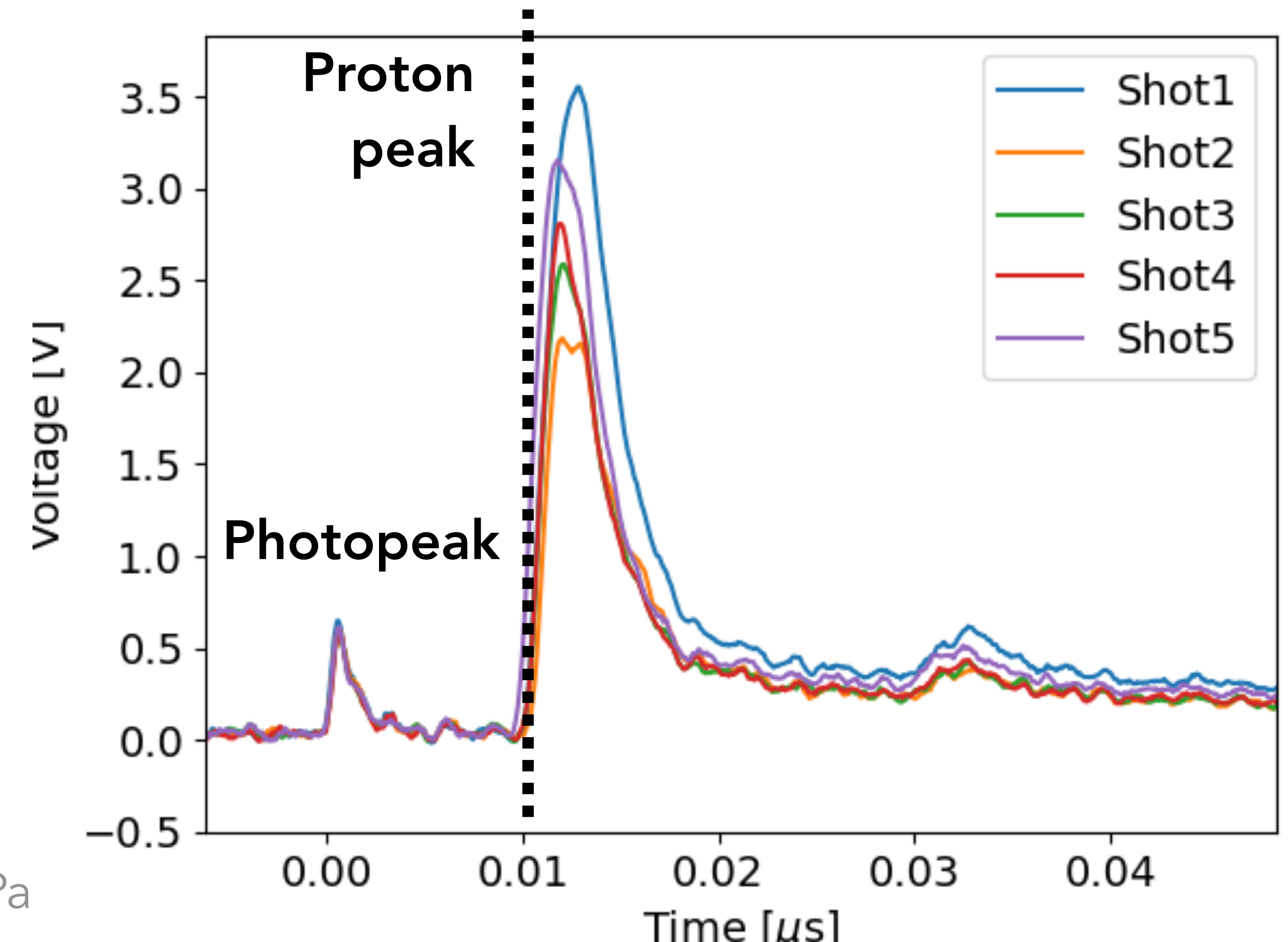
Results compared with 13 μm Kapton tape target in same experimental configuration.



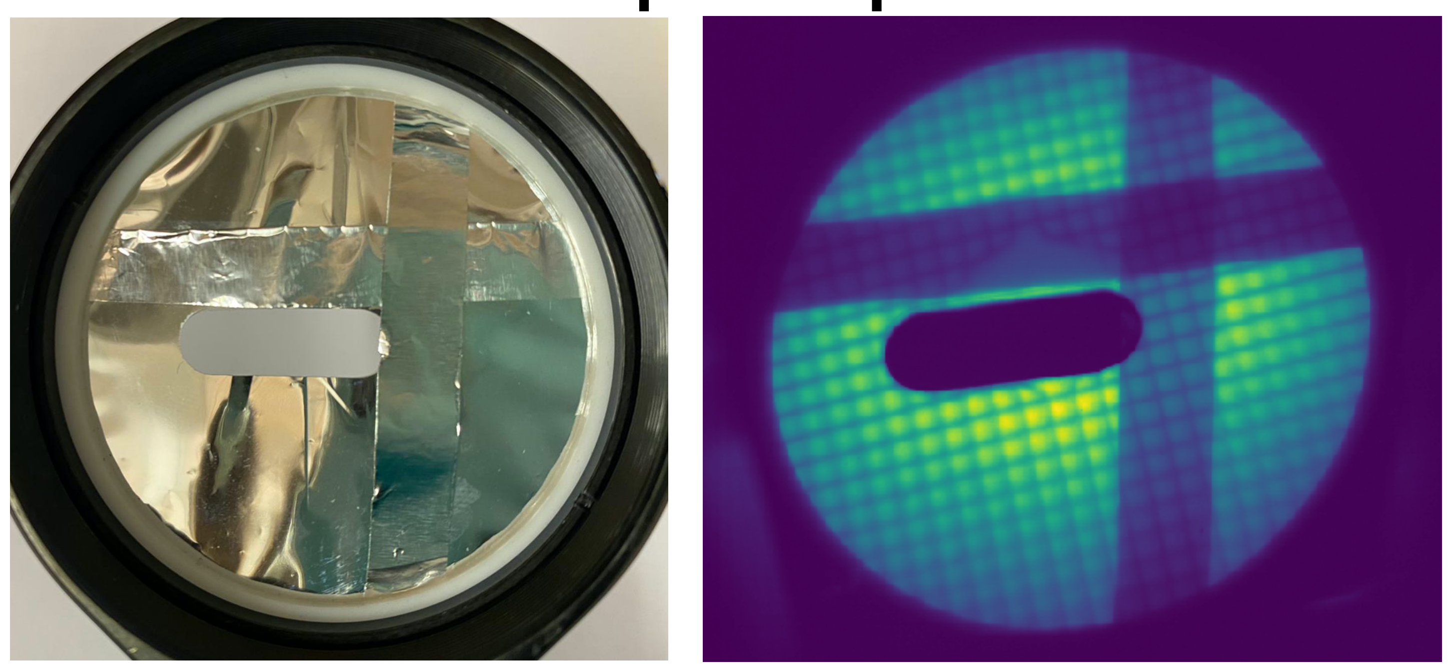
Electron spectrometer signal:



Raw time-of-flight diode trace:



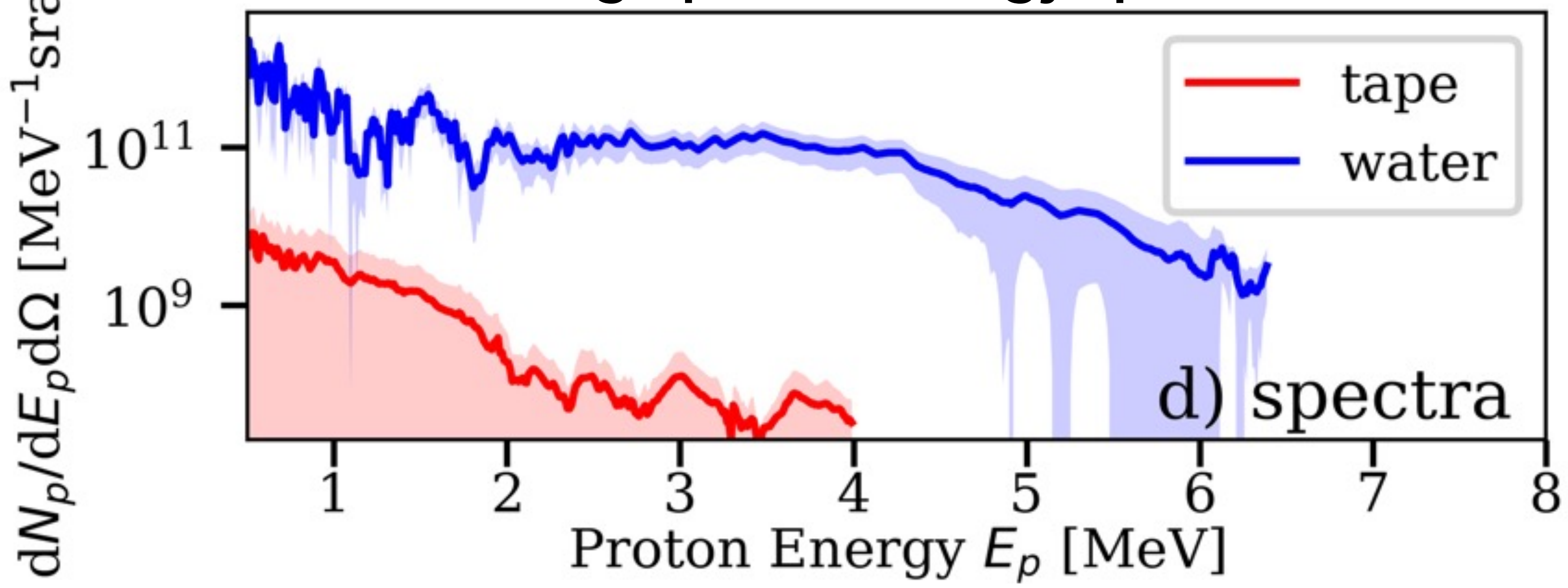
Proton spatial profile:



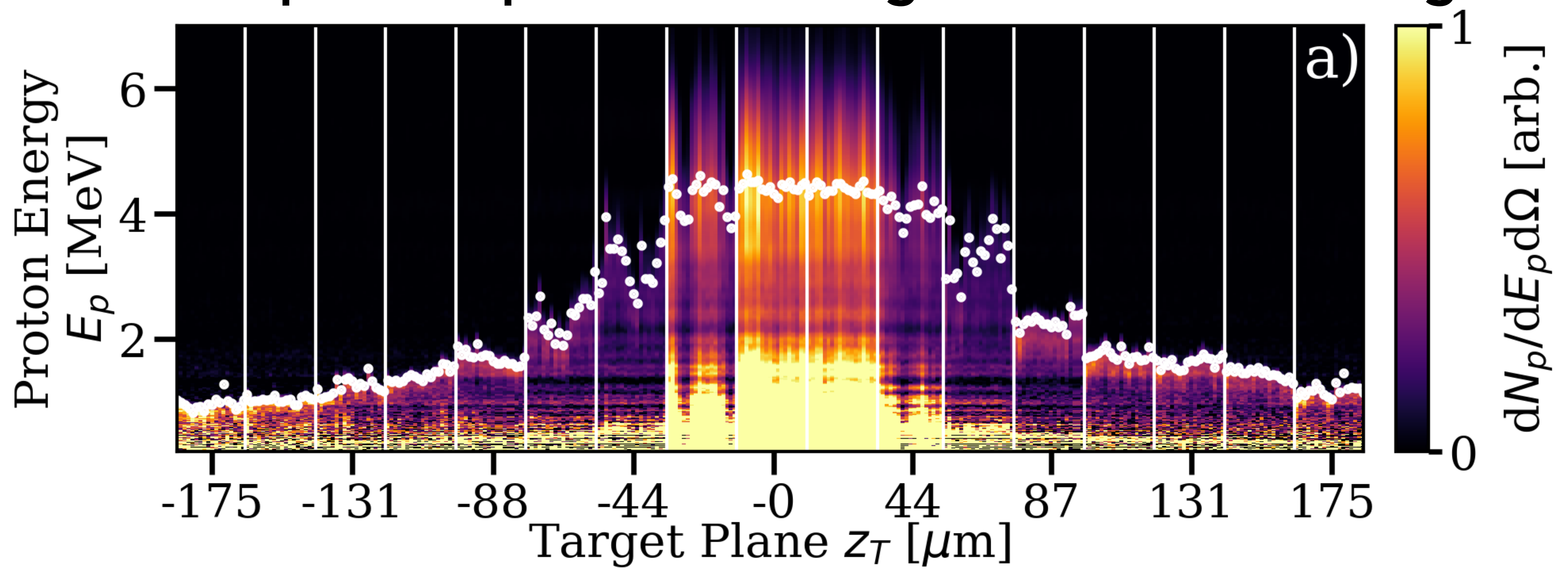
High-flux, low-divergence MeV proton beams from the liquid leaf

Proton beam energy spectrum:

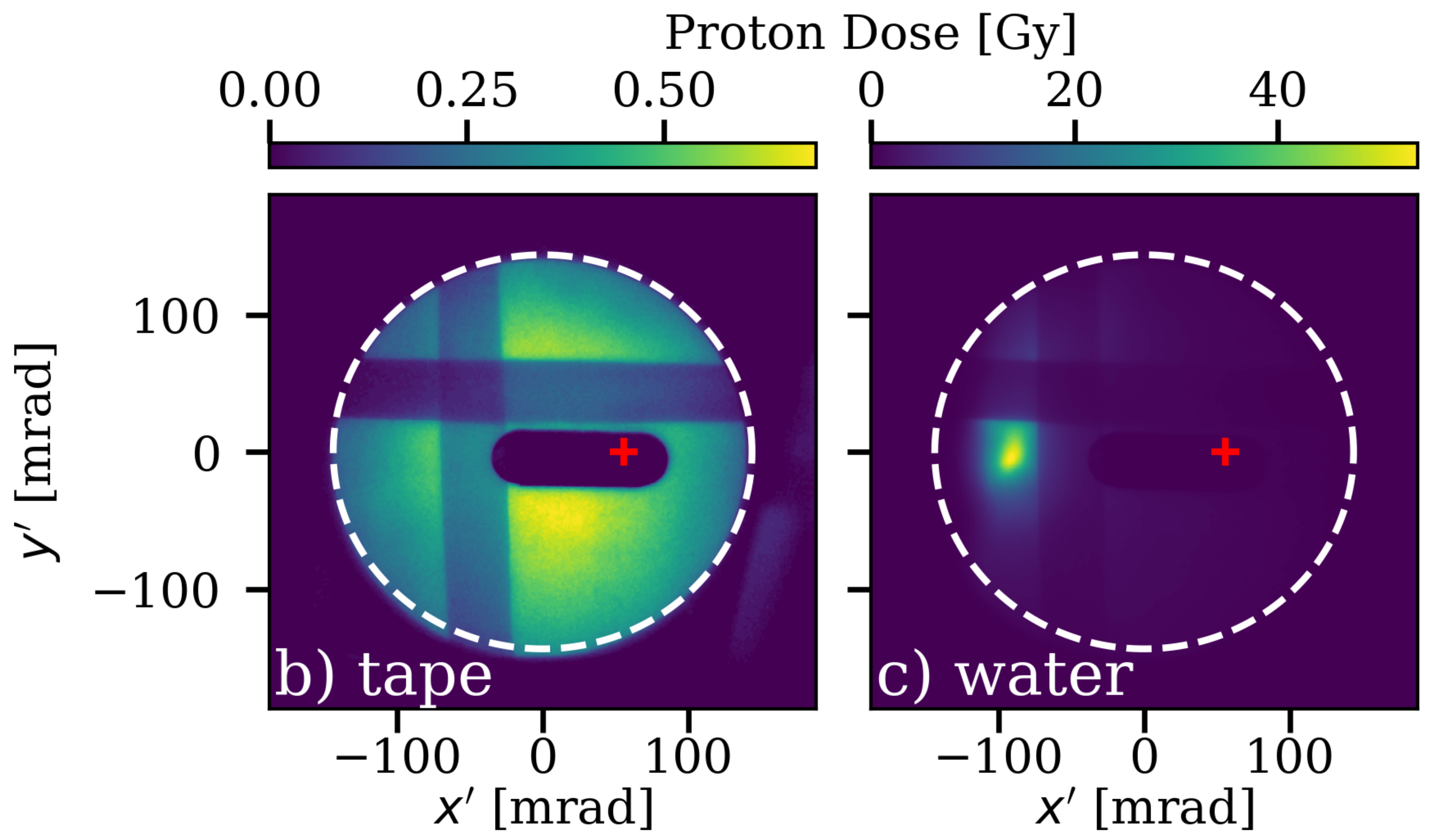
Average proton energy spectrum:

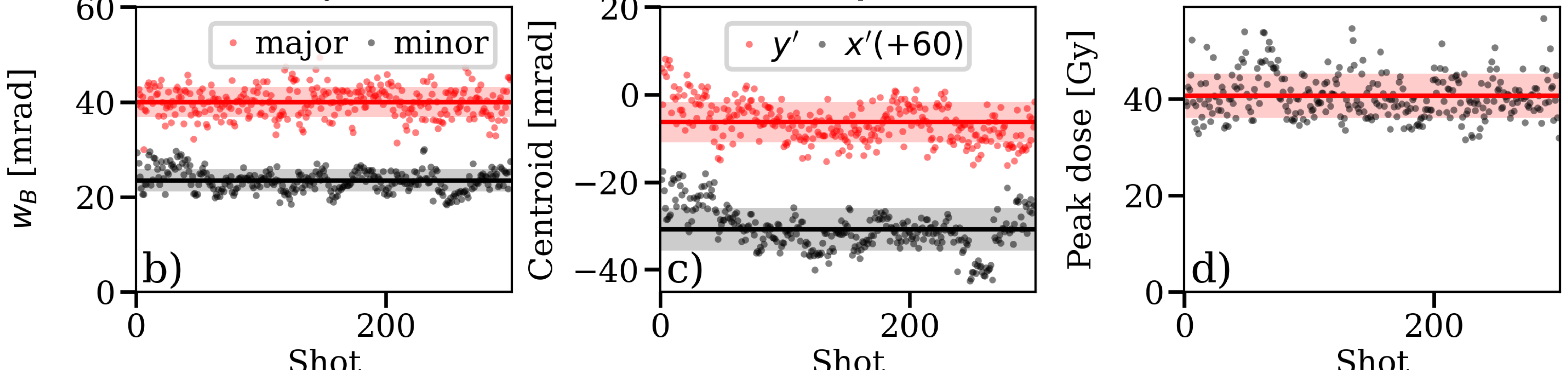


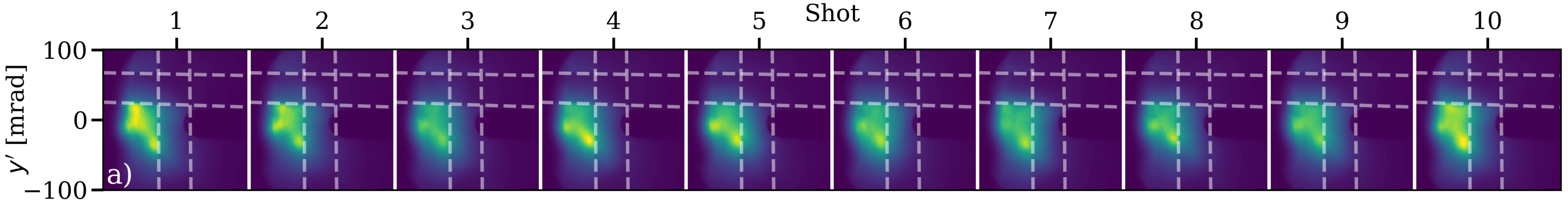
Variation in proton spectrum as target is scanned through focus:



Proton beam spatial profile:



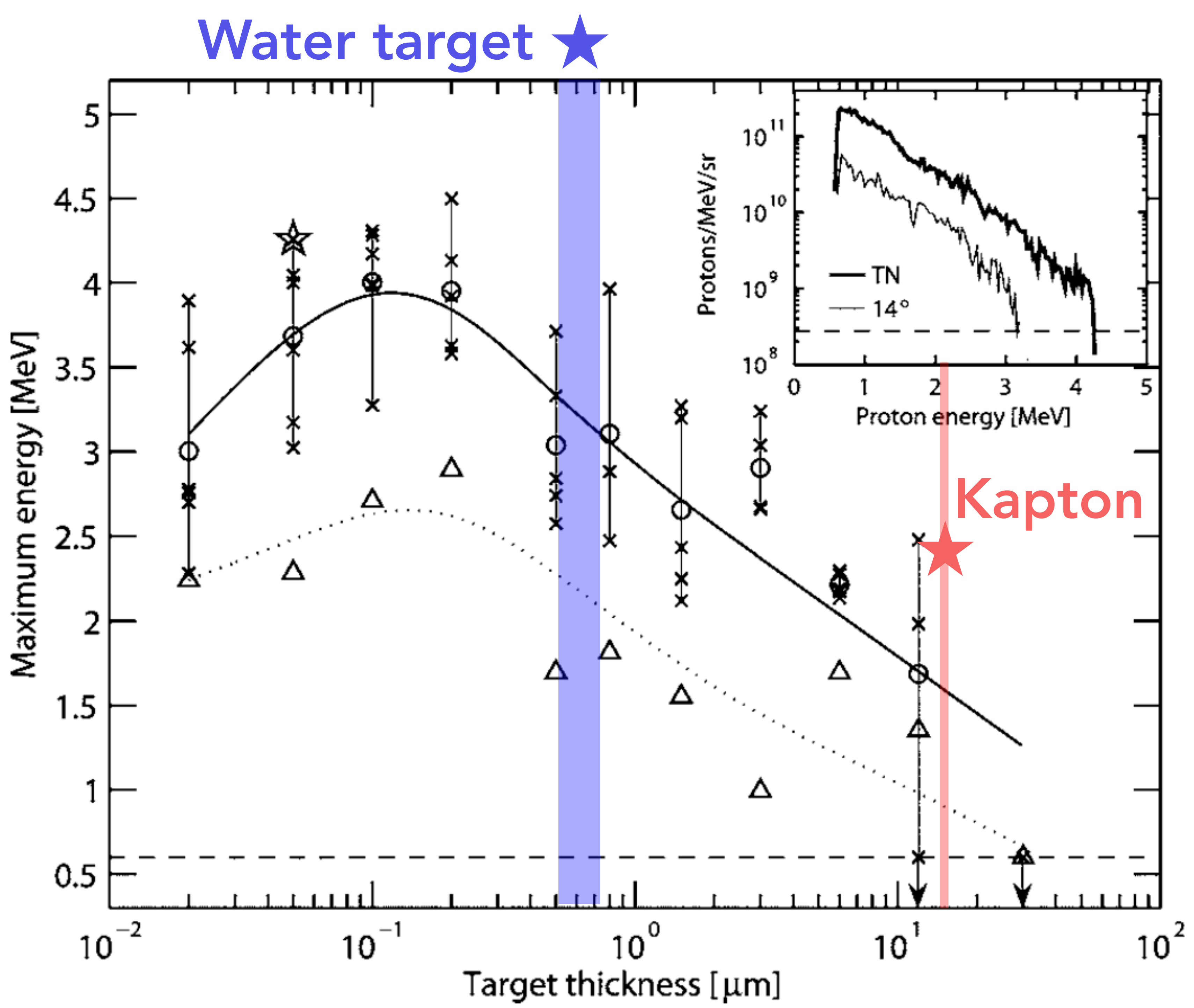




Impact of interaction conditions on proton beam divergence

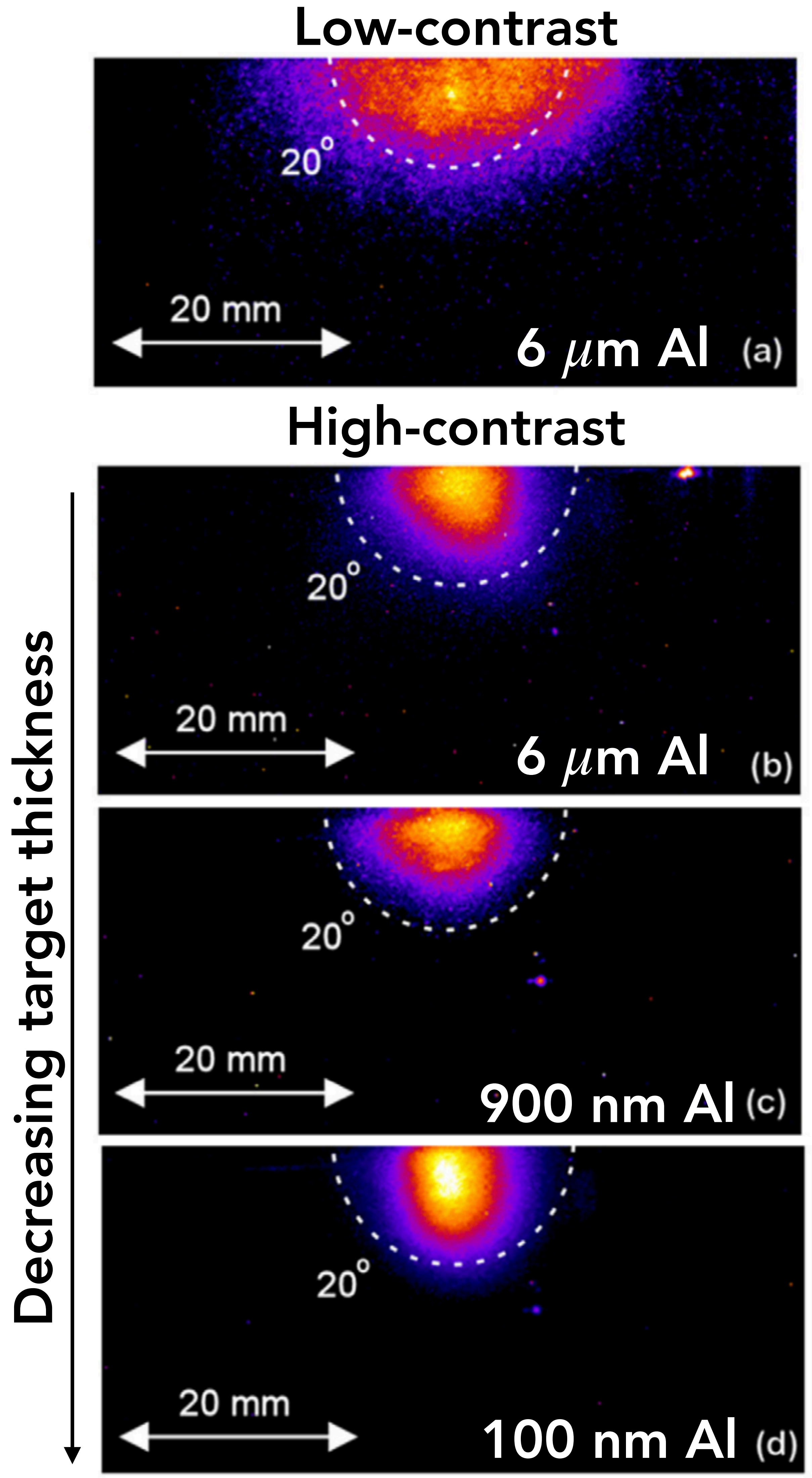
At similar laser intensity - no change in proton flux or divergence (15°) with changing thickness but increase in proton energy with improve laser contrast.

Neely et al., APL (2006)

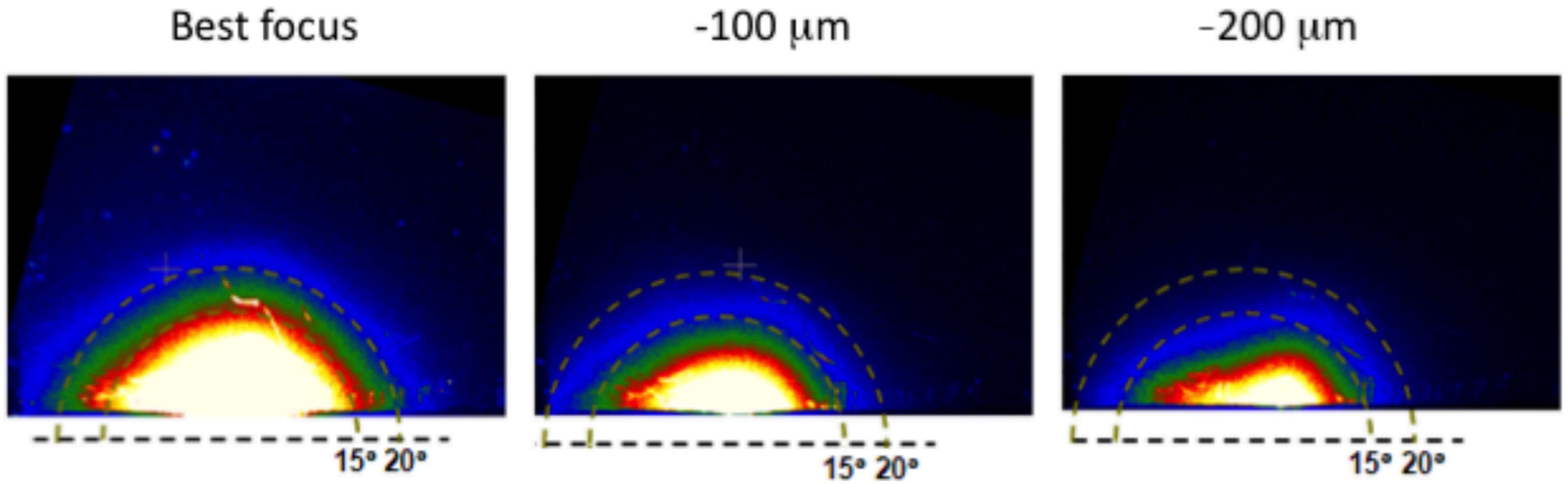


At higher laser intensity - reduction in beam divergence from 20-30° to 5-10° with improve laser contrast.

Green et al., PPCF (2014)



At similar laser intensity - reduction in beam divergence with increasing laser spot size on the target.



Green et al., NJP (2010)

Liquid evaporation in vacuum

At low pressures, liquid will evaporate forming a vapour cloud and rapidly cooling the sheet.

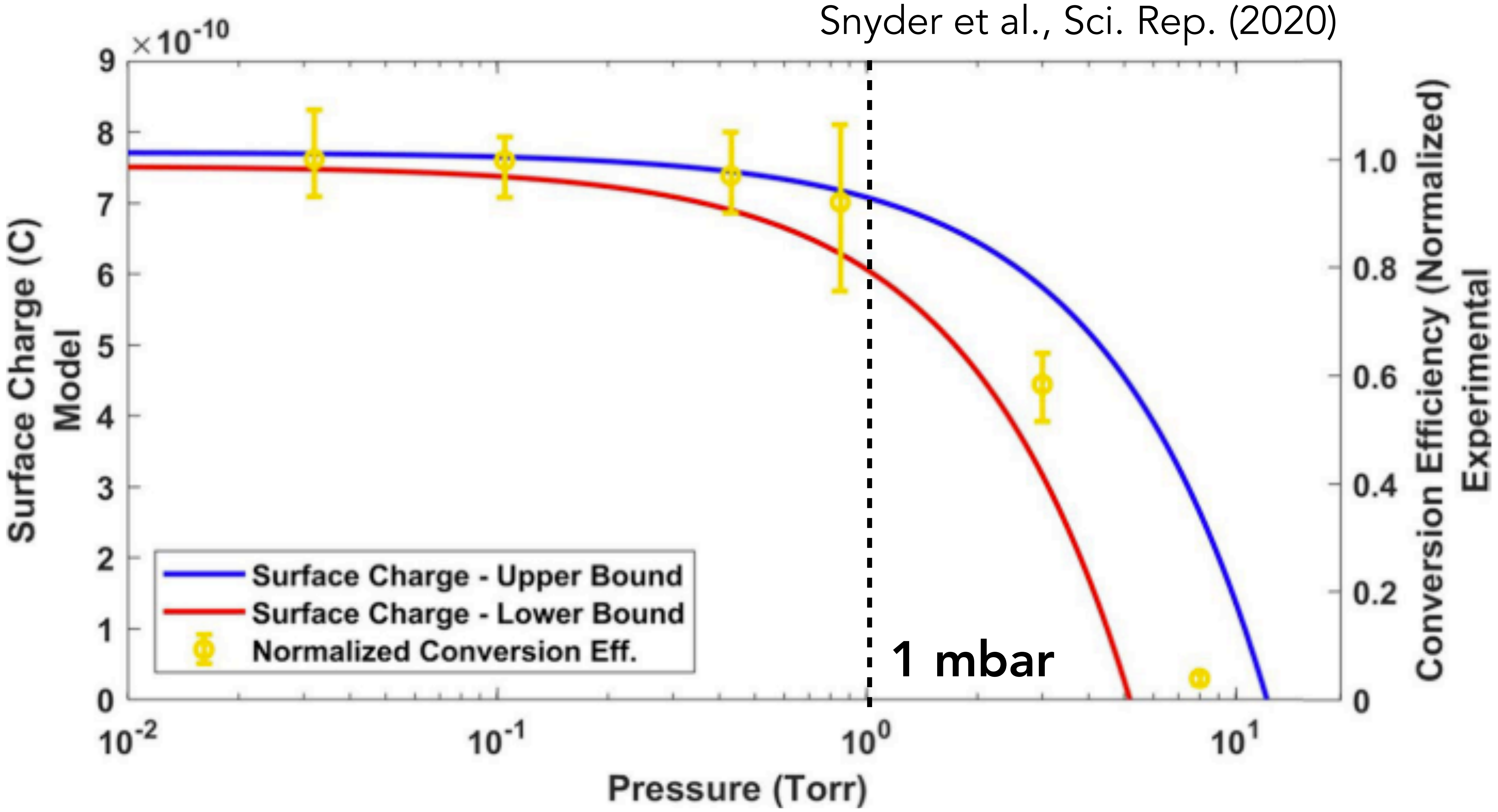
Primary evaporation minimisation strategies:

- Heated catcher units with custom skimmers and cold traps.
- Choice of low vapour pressure liquids such as ethylene glycol.

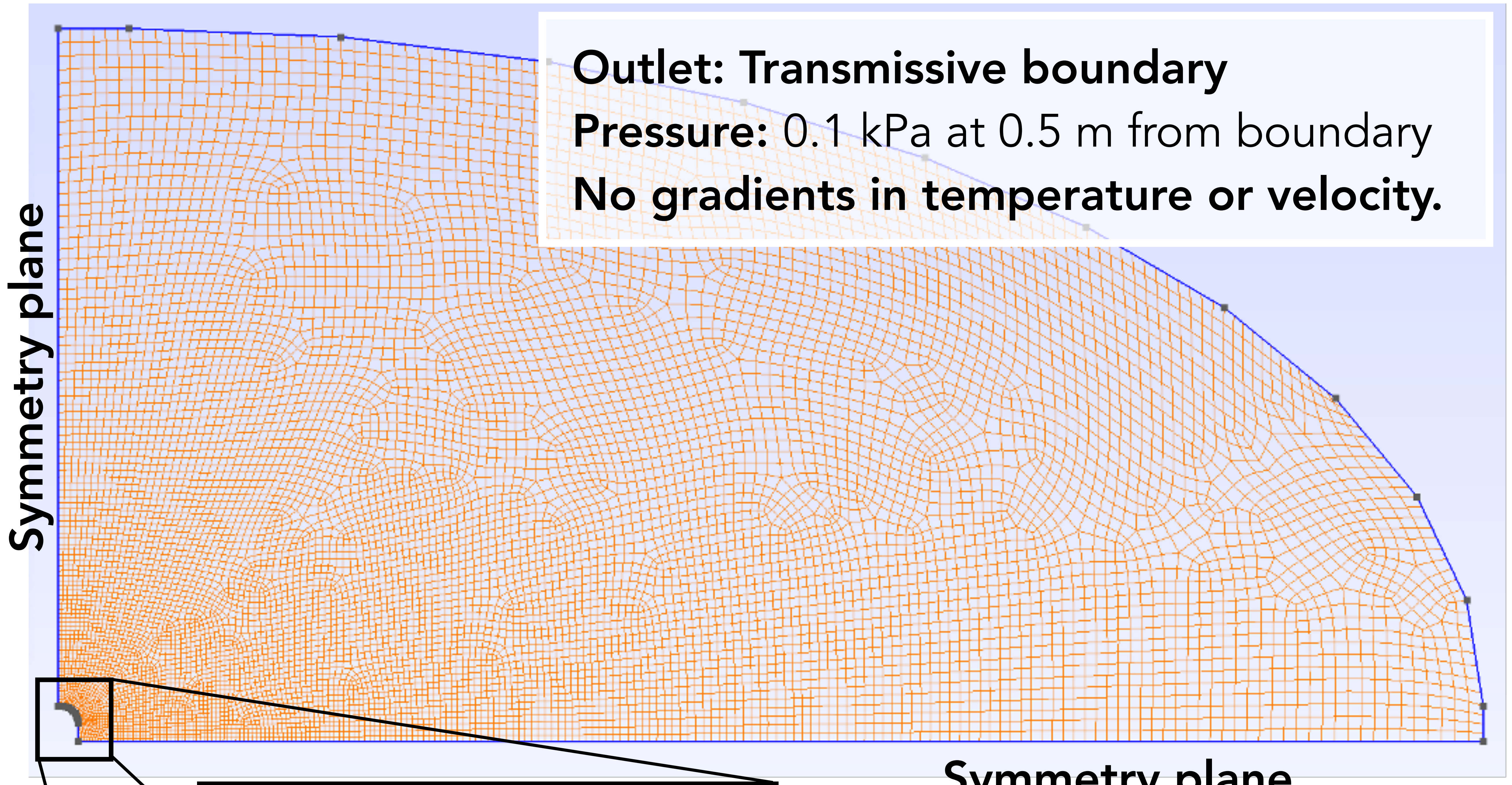
Vacuum pressures of 10^{-5} mbar have been achieved using cryopumps and cold traps.

Here chamber pressure was approx. 0.1 mbar.

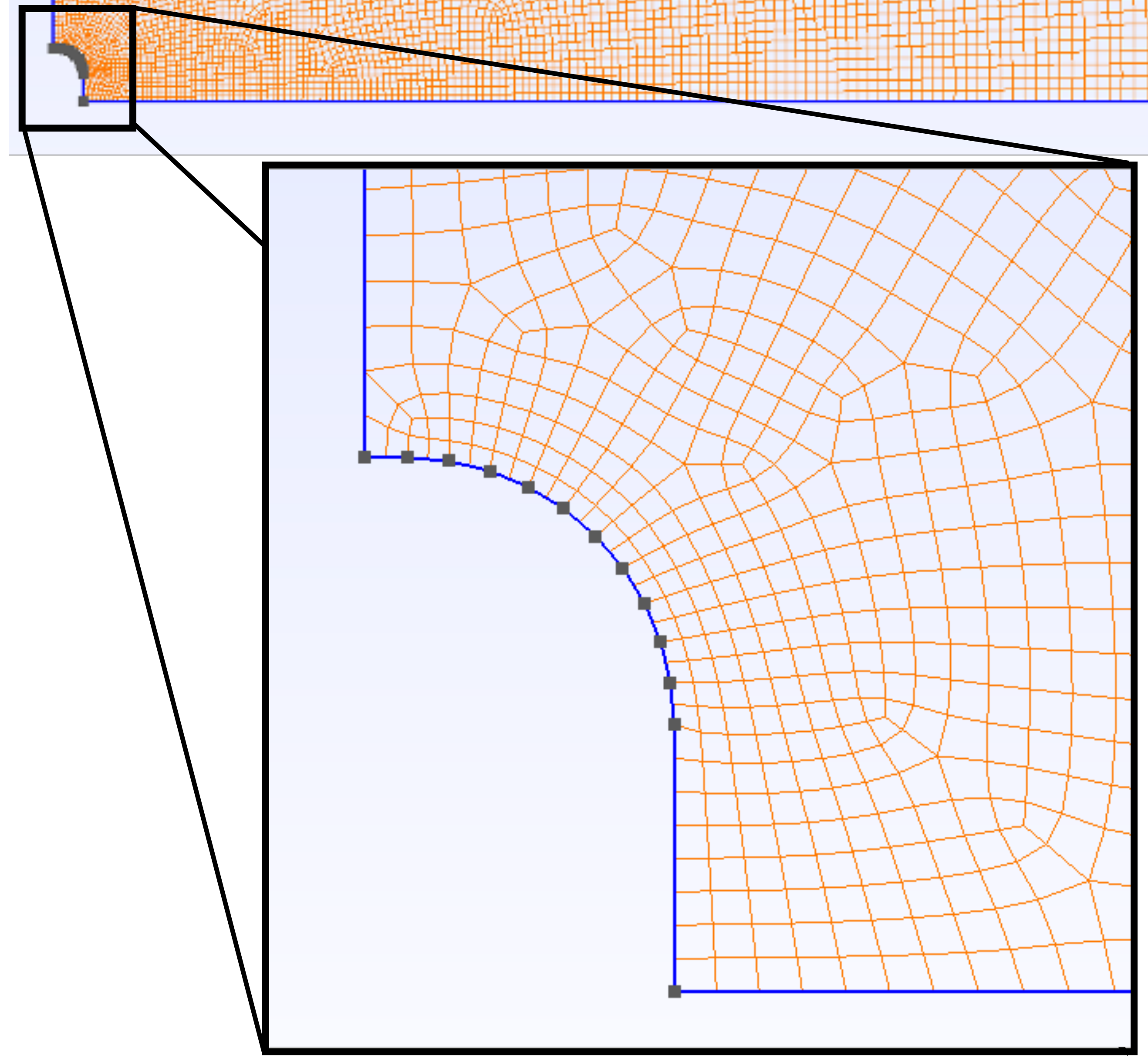
Snyder et al., Sci. Rep. (2020)



Modelling of neutral vapour profile

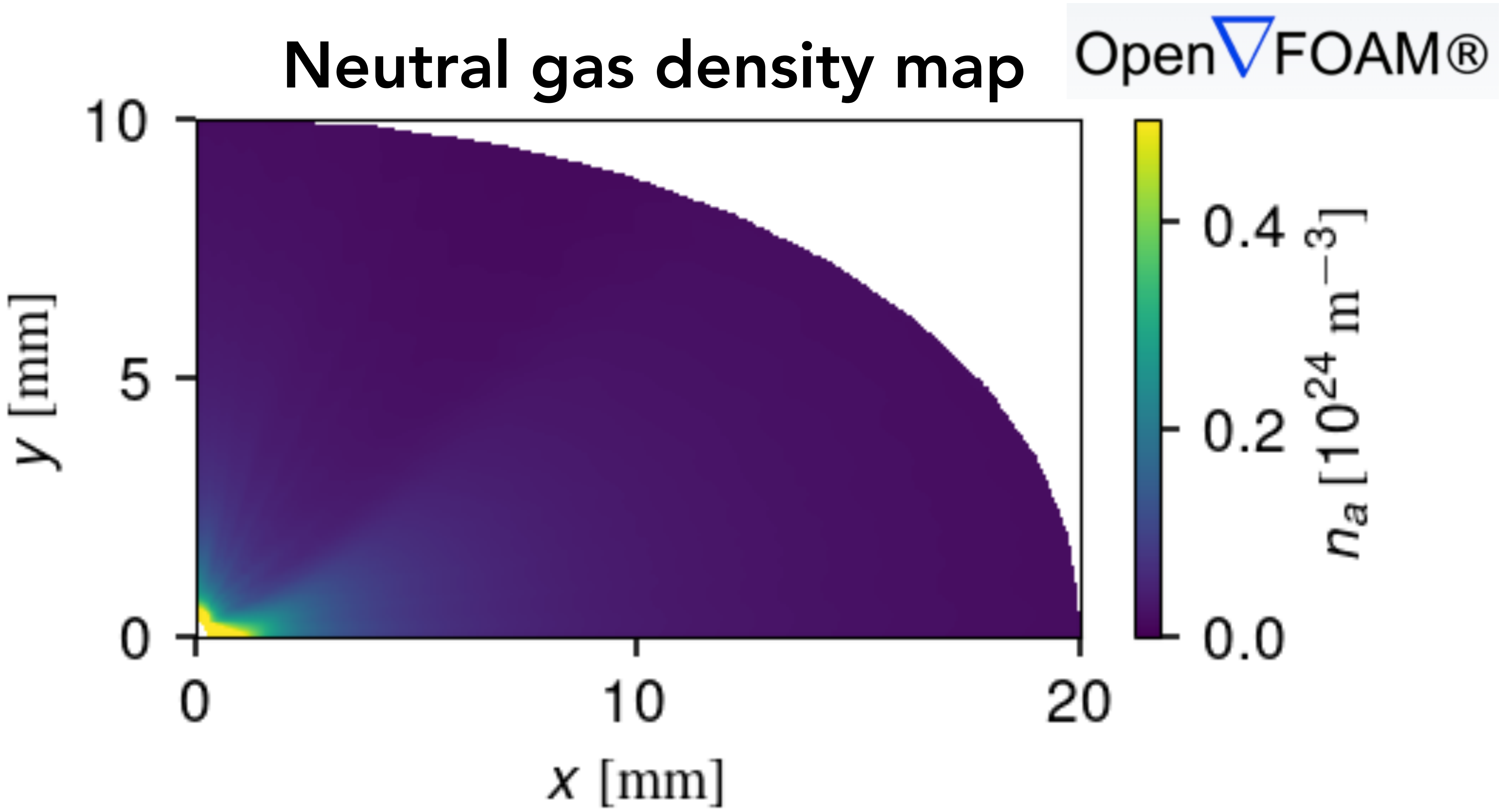


Outlet: Transmissive boundary
Pressure: 0.1 kPa at 0.5 m from boundary
No gradients in temperature or velocity.

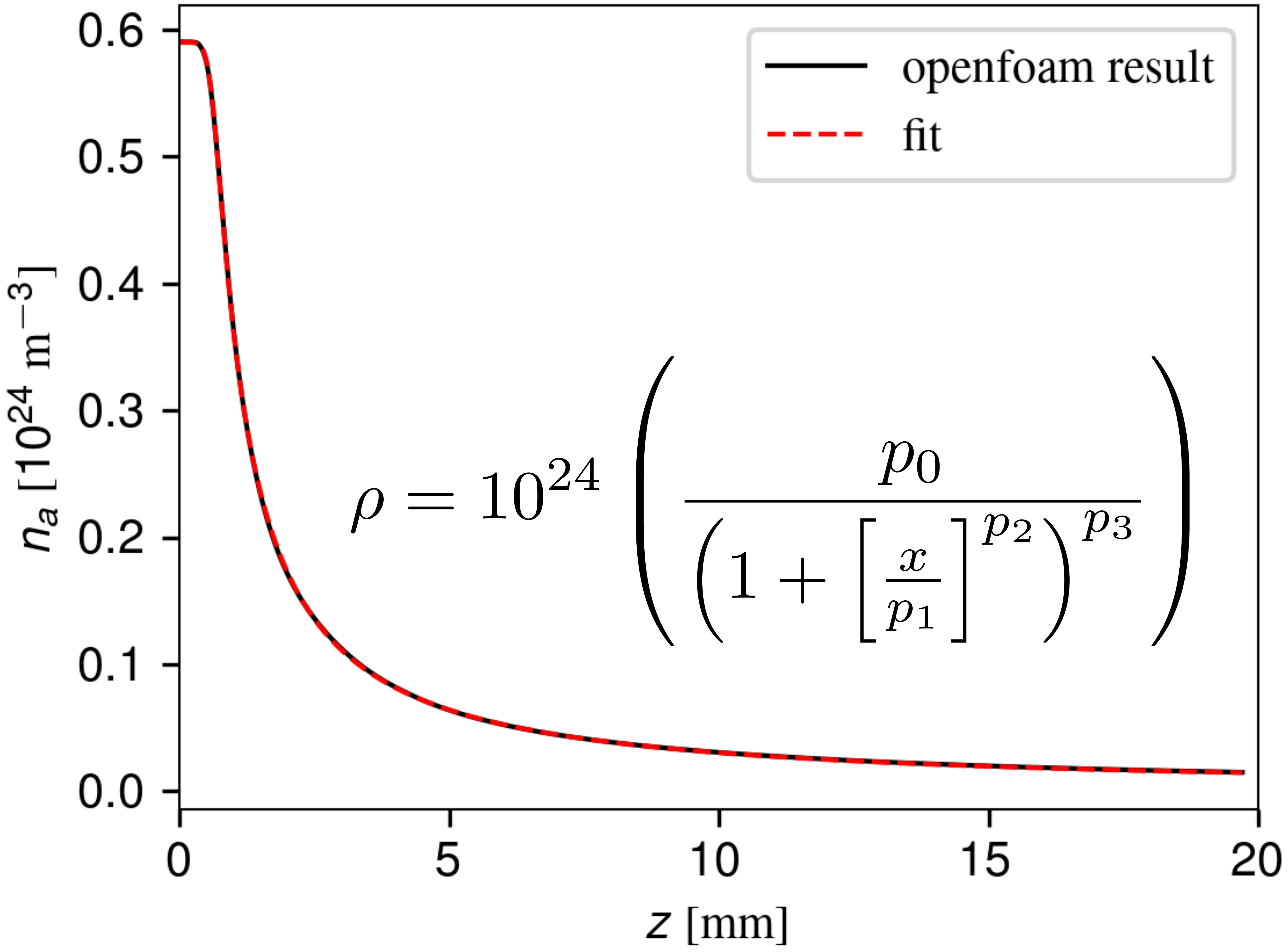


Inlet: Pressure driven flow
Pressure: 2 kPa
Temperature: 293 K
Width: 250 microns with rounded edges

Neutral gas density map



Axial line out of gas density with analytic fit



Simulations of proton bunch propagation through vapour

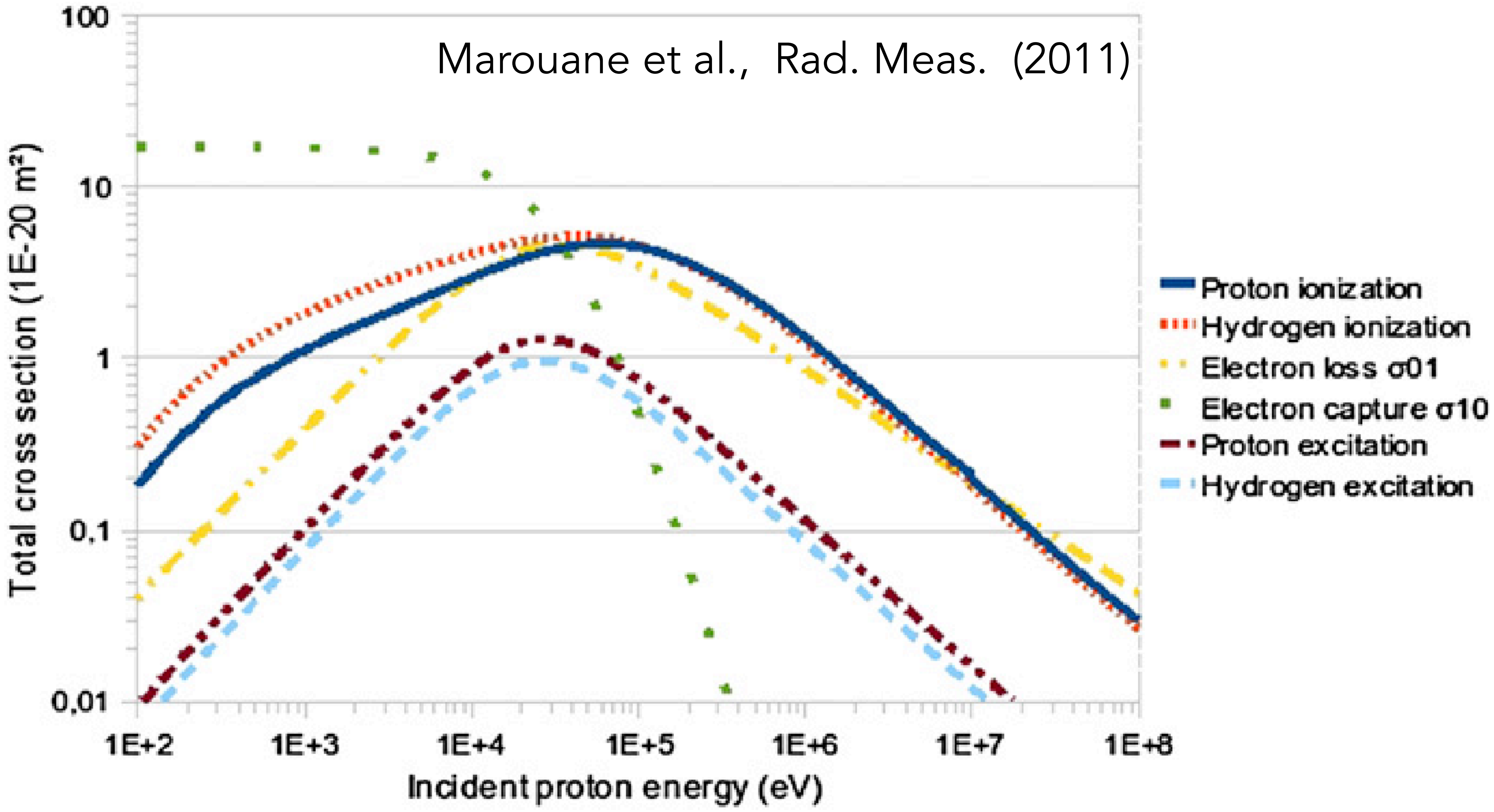
- 2D3v Particle-in-cell simulations used to explore the propagation of charge-neutral particle bunch of electrons and protons through a neutral water vapour.
- Custom impact ionisation model developed at Uni. Michigan for the ionisation of the neutral vapour by MeV protons. Plasma collisions not modelled.

Osiris

Simulation parameters:

Box size	1.2 x 26 mm
Grid size	240 x 1300
Timestep	30 fs
Macroparticles /cell	Beam: 1296 protons, 36 electrons. Vapour: up to 900 for Z_{max} = +1.
Initial energetic electron-proton beam	2D Gaussian(w_z = 500 μm; w_x = 20 μm) with peak density 1.1 x 10^{17} cm^{-3}. Divergence 20 mrad, ε_n = 2 μm mrad Proton momentum 0.1 c with 20% energy spread. Electron beam 200 eV thermal spread

Impact ionisation cross sections:

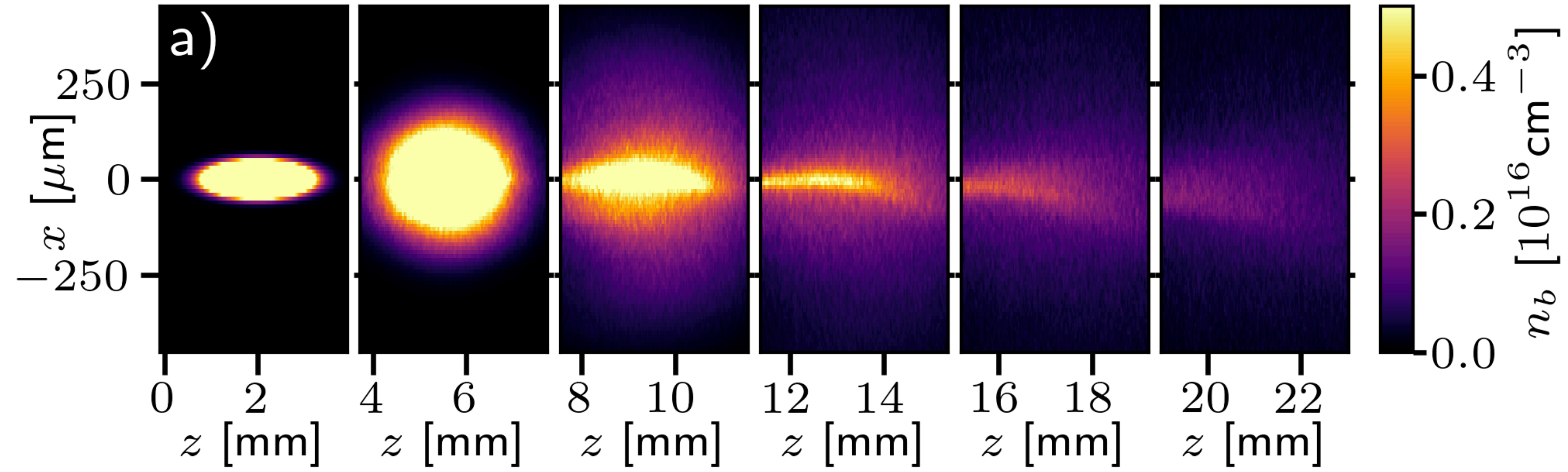


R. A. Fonseca et al., LNCS 2331, 342-351 (2002)

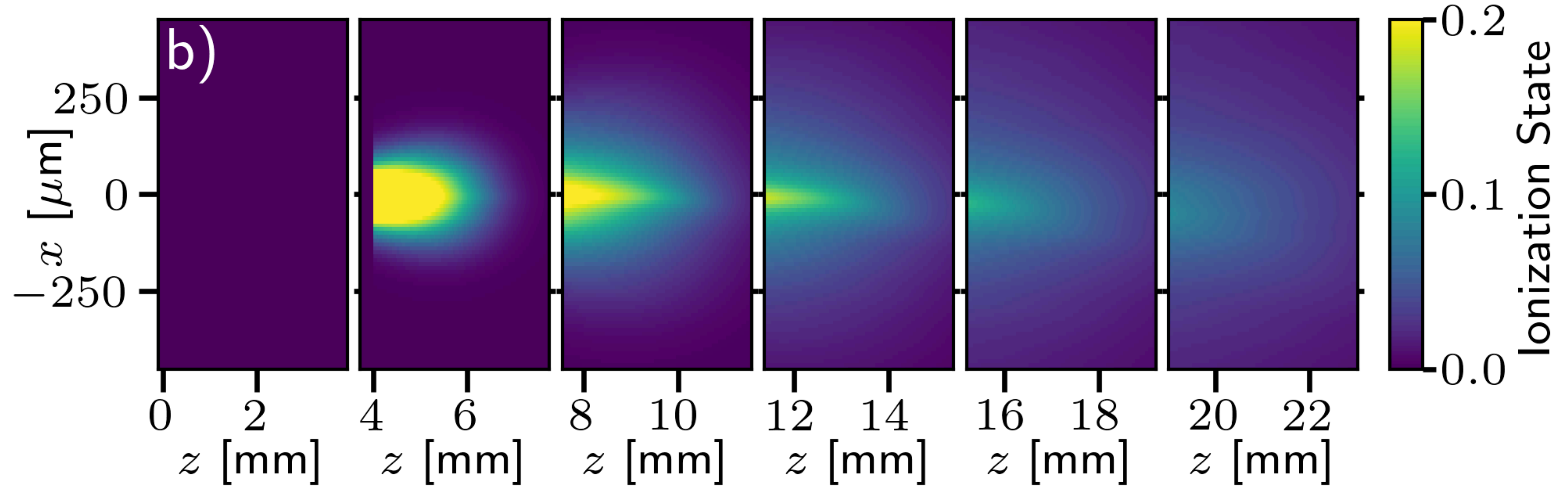
Osiris Simulations using simulated neutral vapour density profile

Streeter et al., Nat. Comms. 16, 1004 (2025)

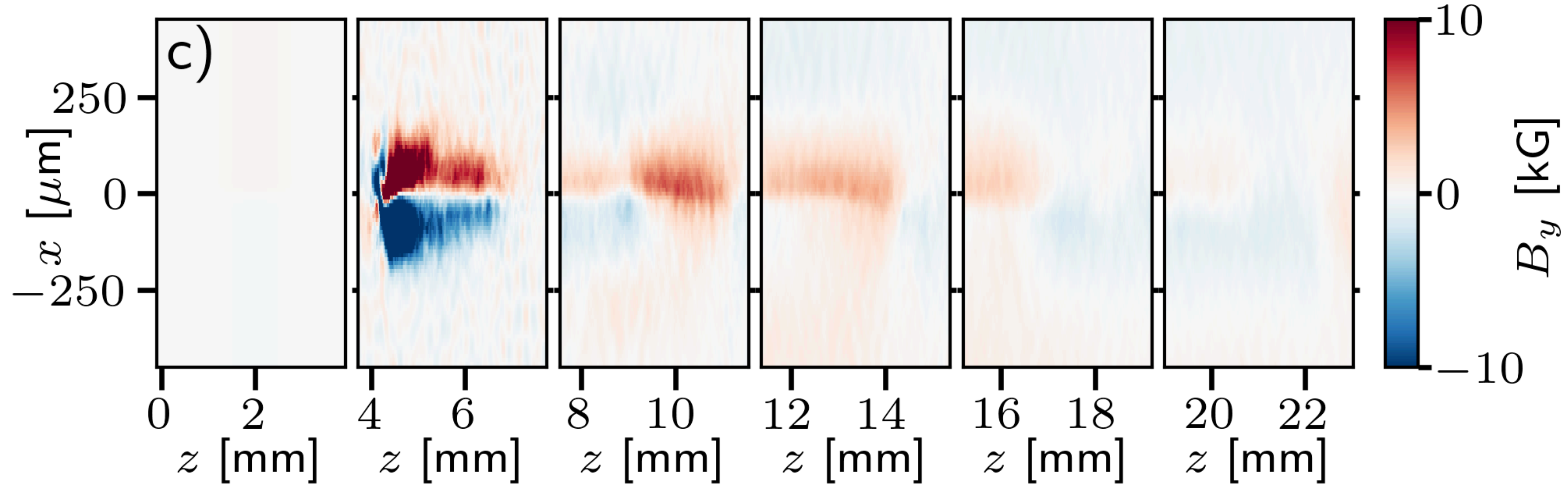
1) Central region of proton bunch pinches onto the axis.



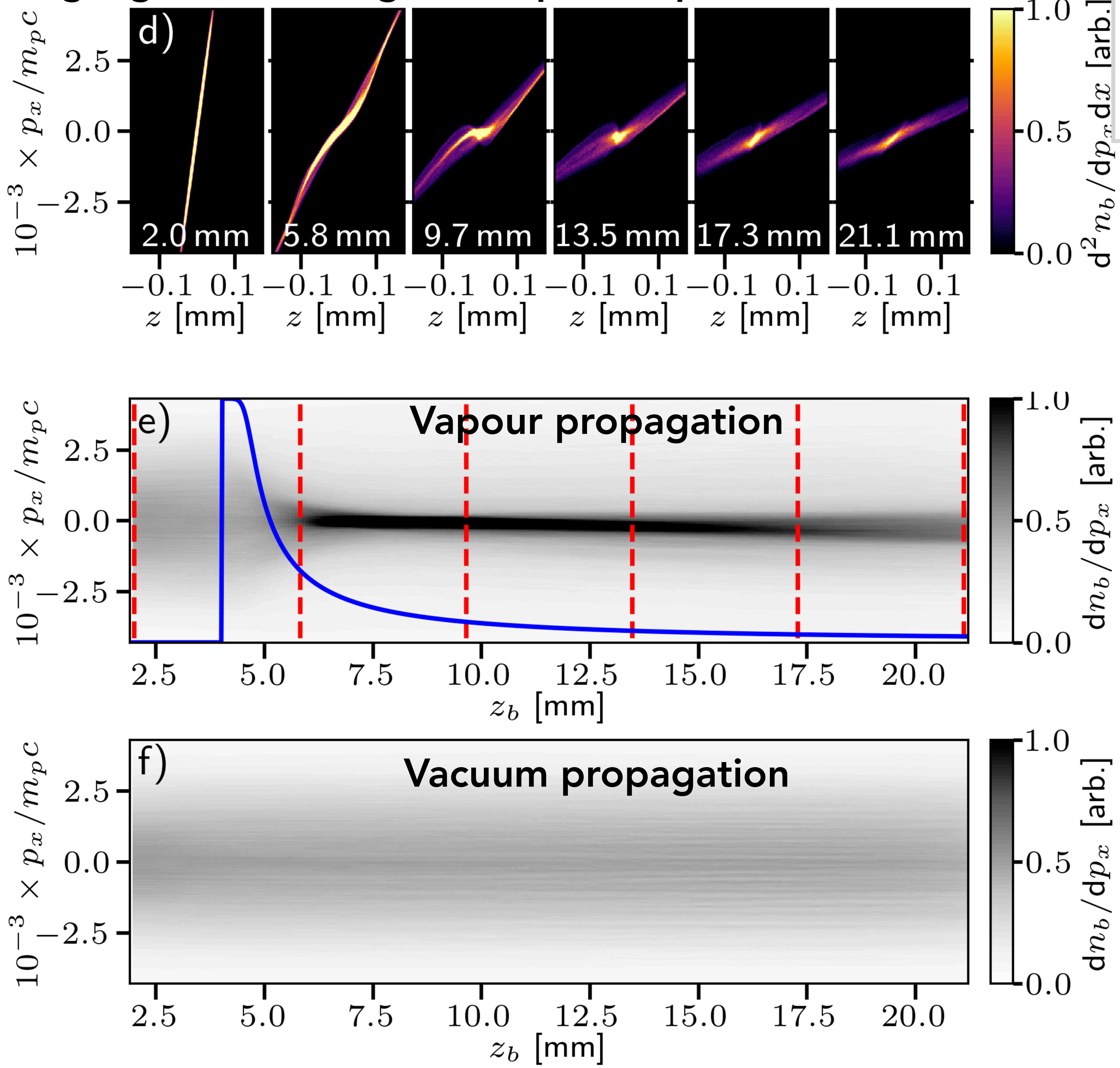
2) Ionisation of background vapour by proton impact.



3) Magnetic field grows around energetic proton bunch.



4) Phase space of proton bunch in vapour and vacuum highlights flattening of the phase space



R. A. Fonseca et al., LNCS 2331, 342-351 (2002)

Reproducing the effect over a variety of interaction conditions

Talk: Peter Parsons (Tuesday PM)
Ion acceleration and developments towards fusion session - Sala Biodola

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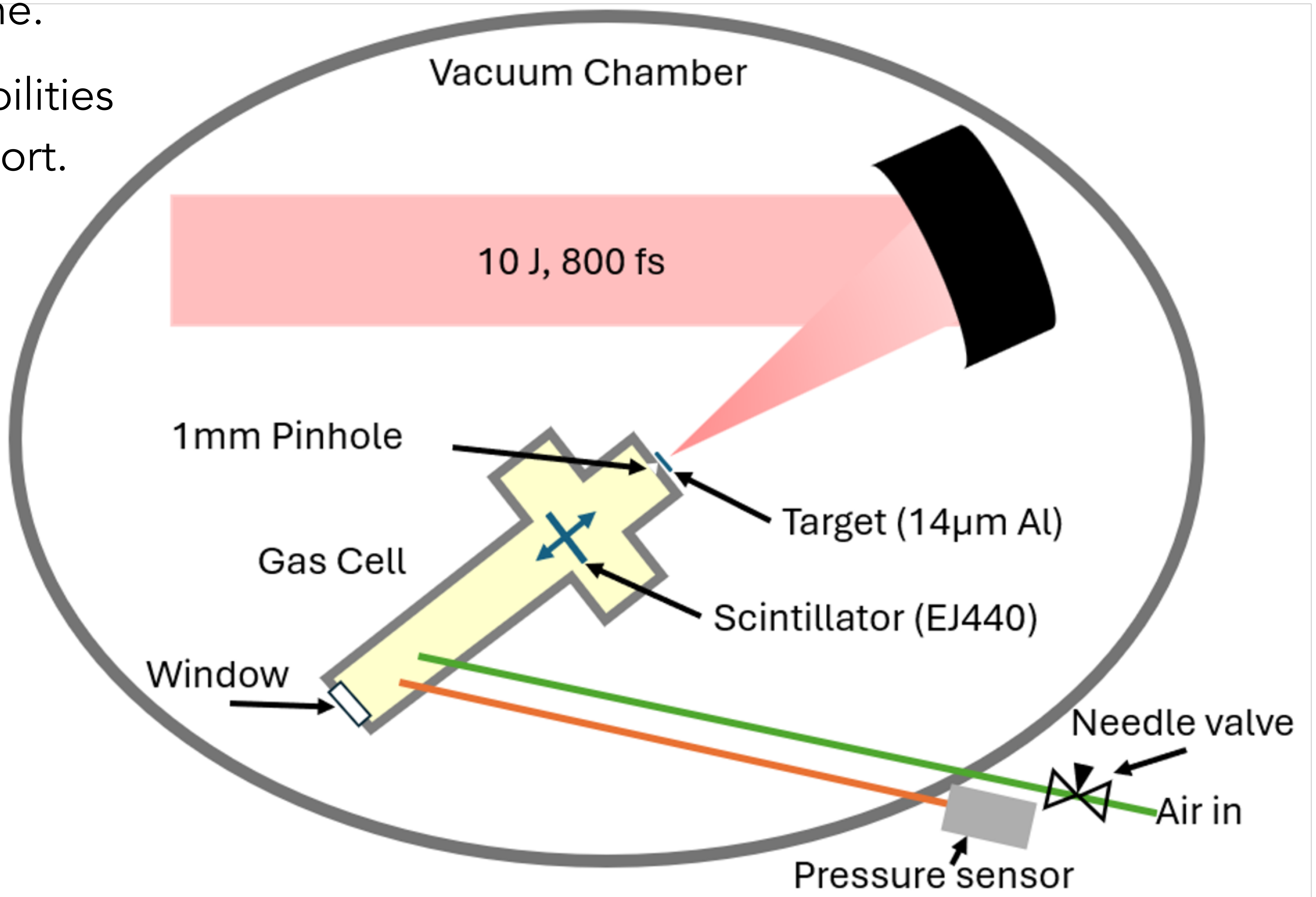
- Experiments at QUB's **TARANIS** laser to explore focusing independently from novel target using traditional foil target and low-pressure gas volume.
- Effect is reproduced and presents exciting possibilities for reducing divergence to improve beam transport.



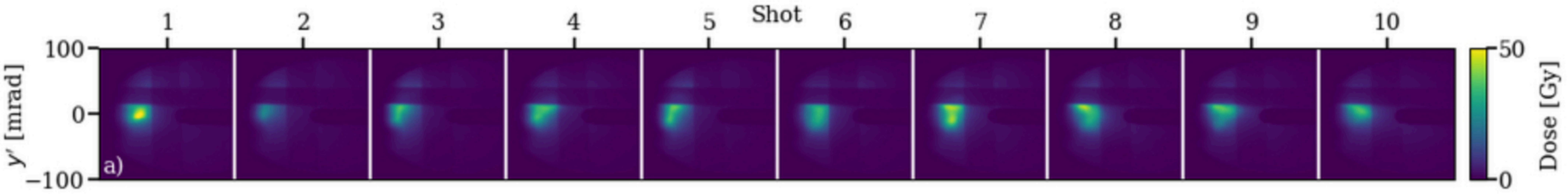
Summary

- Liquid sheet targets present an exciting, versatile opportunity for high repetition rate proton acceleration with lasers in the milli-Joules to few Joule regime.

- MeV energy high-flux low-divergence proton beams have been measured with high shot to shot stability at 5 Hz.

- Simulation indicate that the presence of the vapour plays a key role in evolution of the proton bunch phase space during propagation and this is likely to be influenced by vapour composition, temperature and density potentially allowing tailing energetic proton propagation.

- Repeat experiments indicate the effect can be exploited over a wide range of operating conditions.



Thank you again to our collaborators

and to you for your attention

QUB: B. Loughran, M. Borghesi, C. Hyland, O. McCusker, D. Margarone, P. Parsons, M. J. V. Streeter. + C. I. Prestwood, J. Weeks, N. Kehoe, C. McHugh, J. Young, S. McLoughlin, G. Nersisyan.

CLF: H. Ahmed, S. Astbury, N. Bourgeois, S. Dann, T. Dzelzainis, J. S. Green, C. Spindloe, D. R. Symes (+ the laser and engineering teams + C. Armstrong).

Imperial College London: N. P. Dover, O. Ettlinger, G. Hicks, N. Xu, Z. Najmudin.

SLAC National Accelerator Laboratory: C. Curry, M. Gauthier, G. Glenn, F. Treffert, C. Parisuana, S. Glenzer,

Strathclyde University: R. Gray, M. King, P. McKenna.

ELI Beamlines: V. Istokskaiia, L. Giuffrida.

University of Michigan: S. DiIorio, A. G. R. Thomas.

Talks: Tuesday PM Sala Biodola

Ion acceleration and developments towards fusion

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Science & Technology Facilities Council Central Laser Facility

Imperial College London

SLAC NATIONAL ACCELERATOR LABORATORY

University of Strathclyde

eli beamlines

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