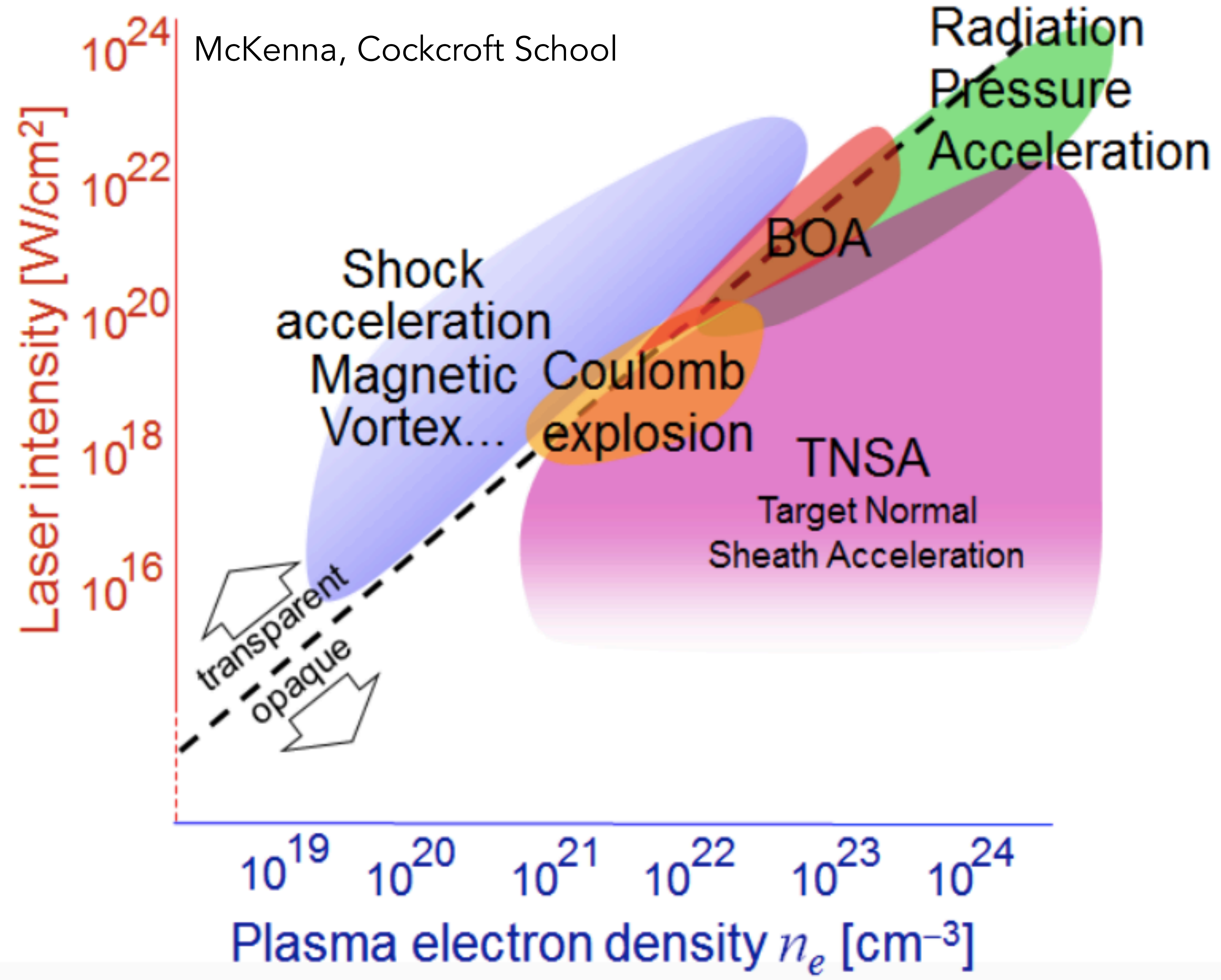
QUEEN'S UNIVERSITY BELFAST

Exploiting novel liquid sheet targets for the generation of bright MeV proton beams

C. A. J. Palmer (she/her)
Centre for Light Matter Interactions, QUB

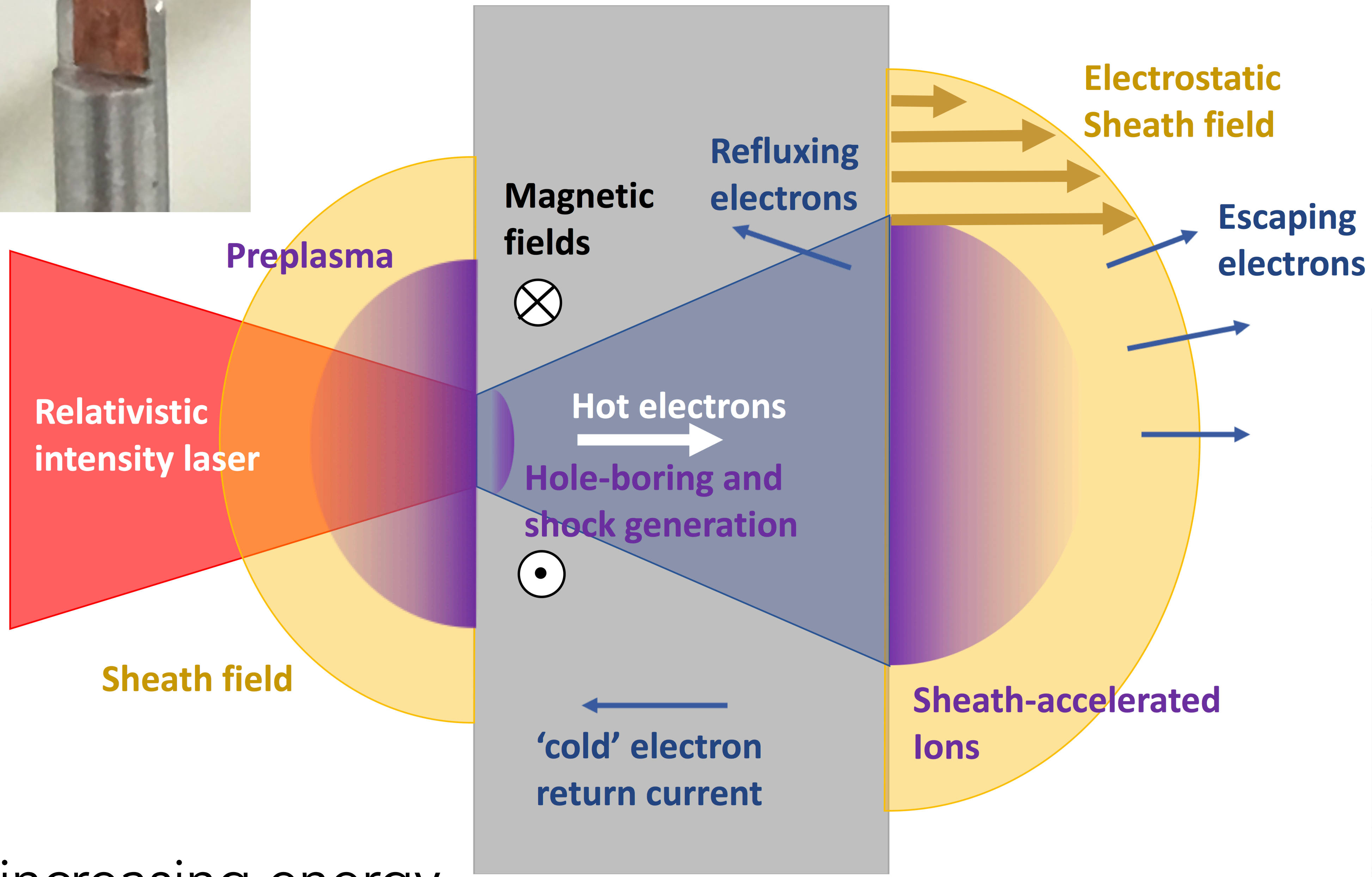
c.palmer@qub.ac.uk

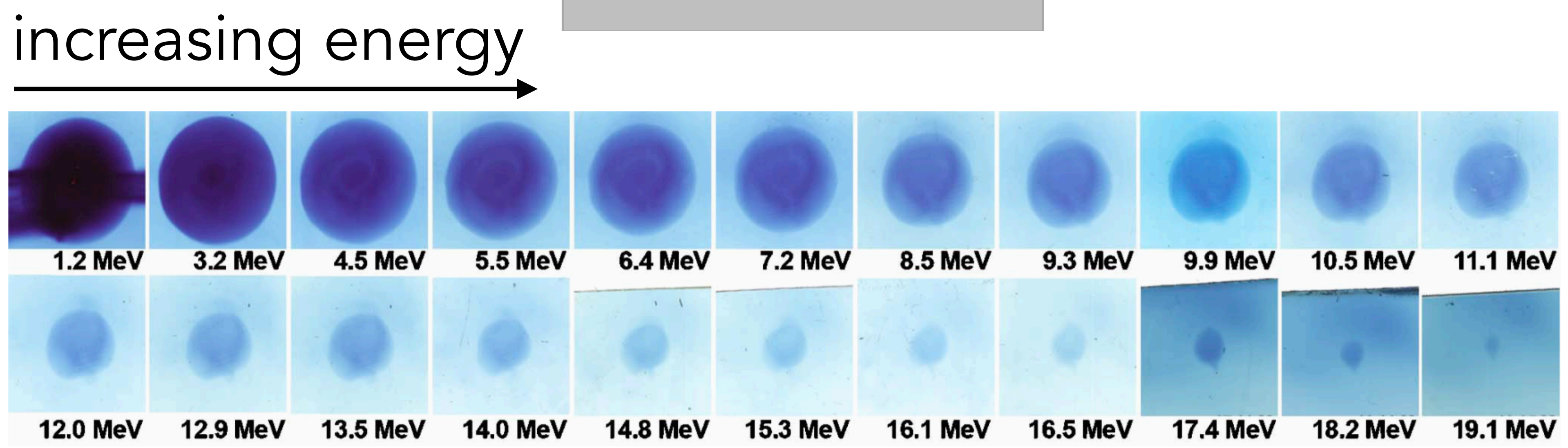


Overview:

- Brief introduction to TNSA
- Multi-Hz proton acceleration
- Experimental results from recent experiments using liquid sheet targets

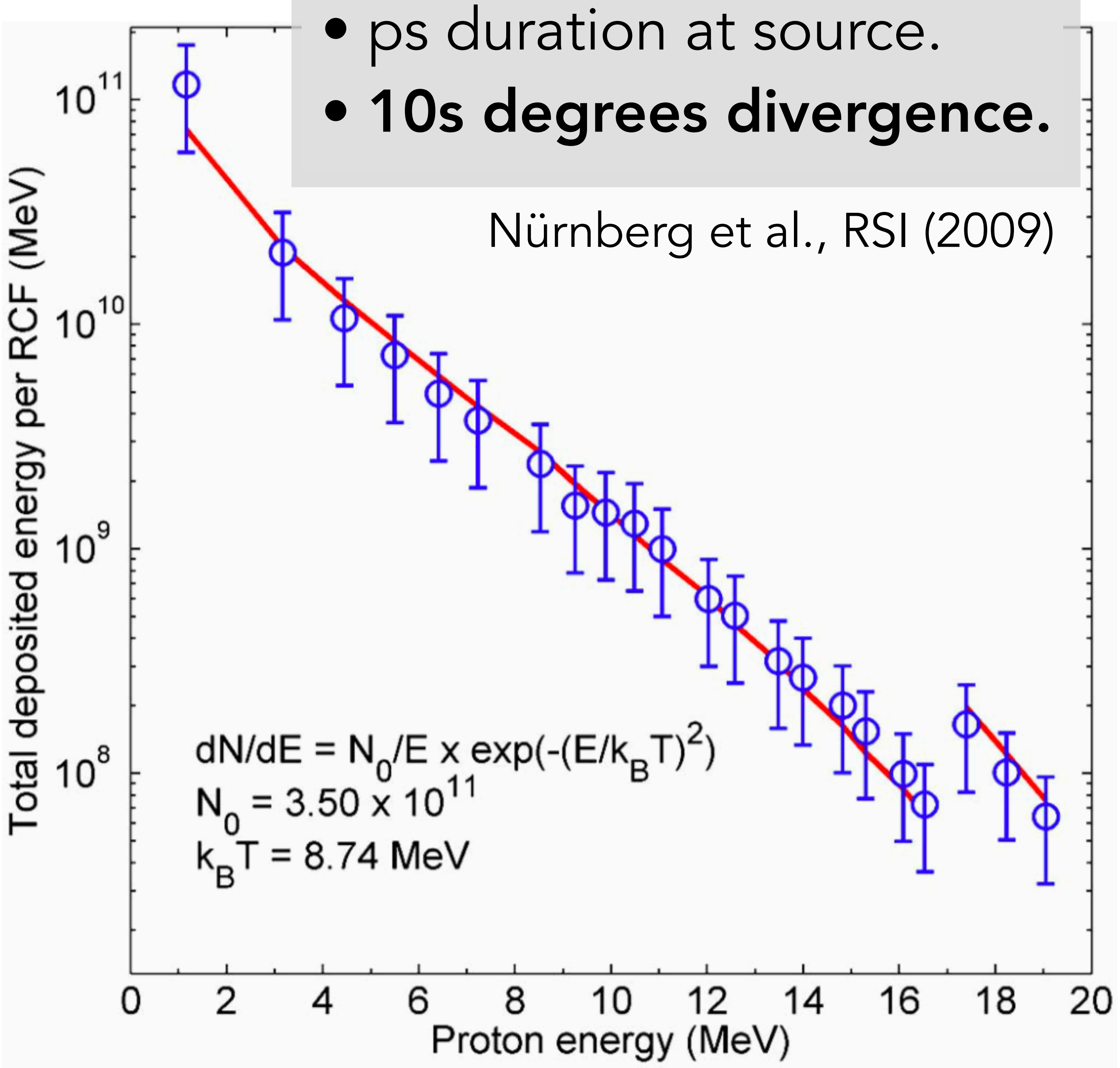
Target Normal Sheath Acceleration

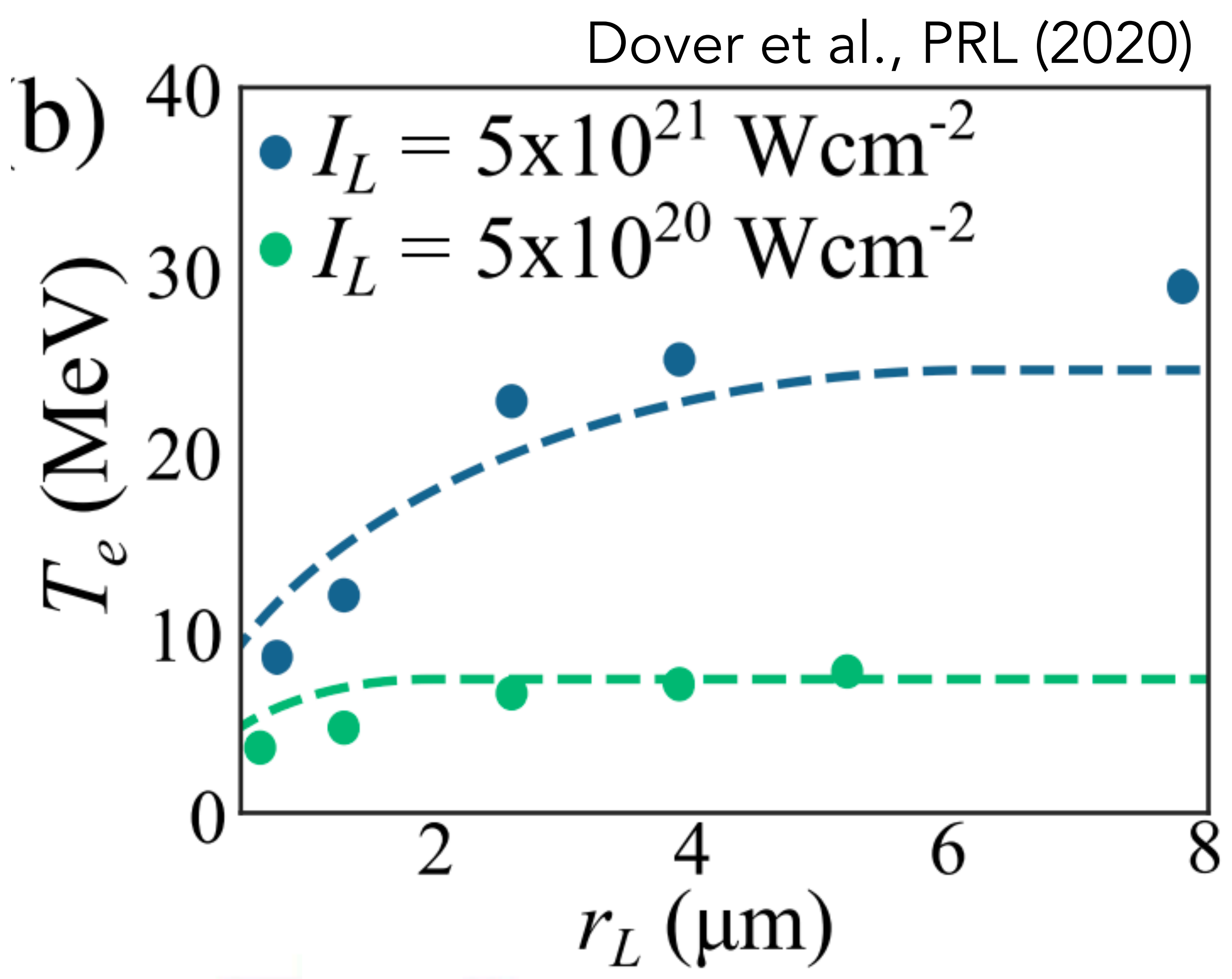


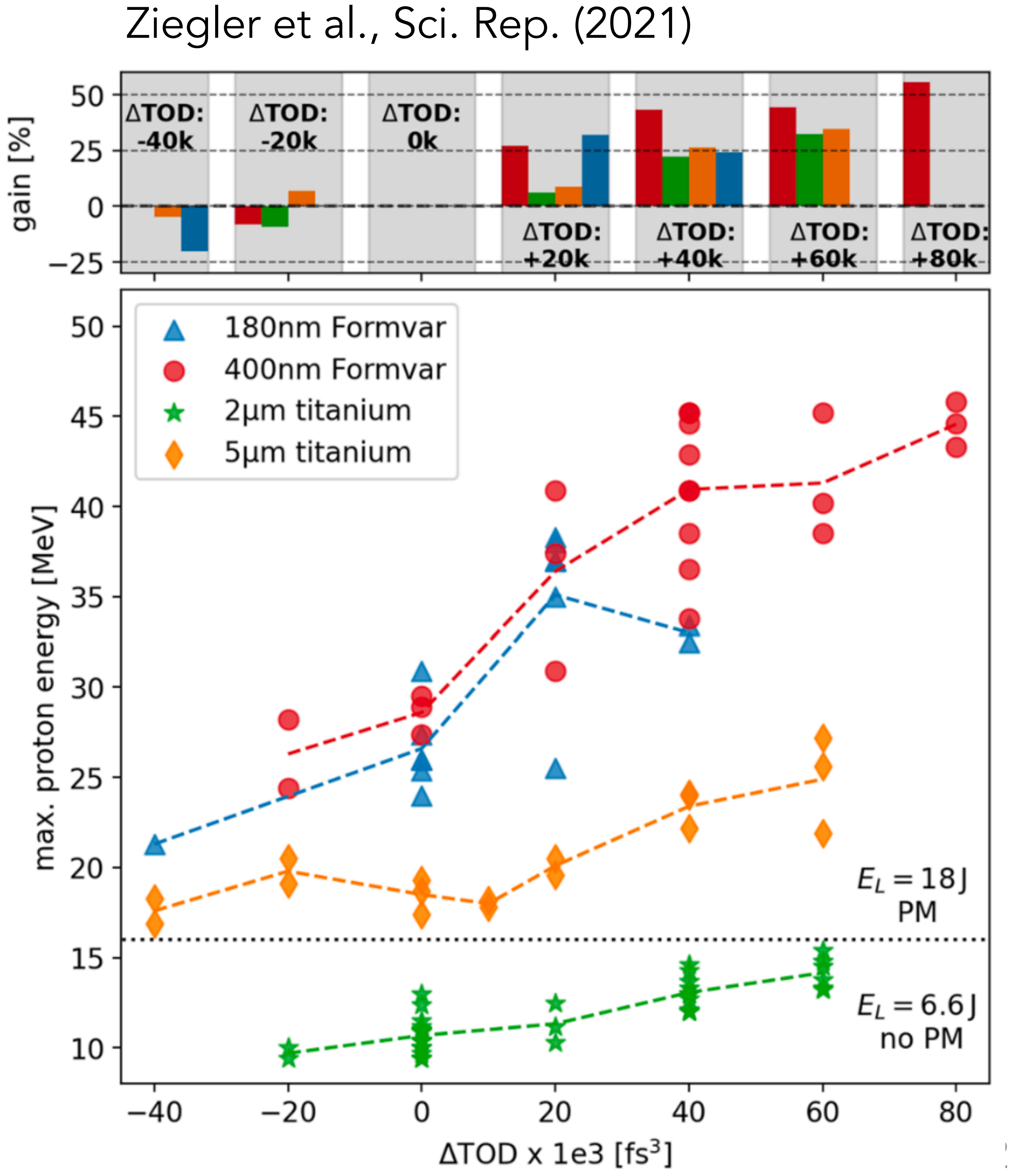


TNSA proton beams

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







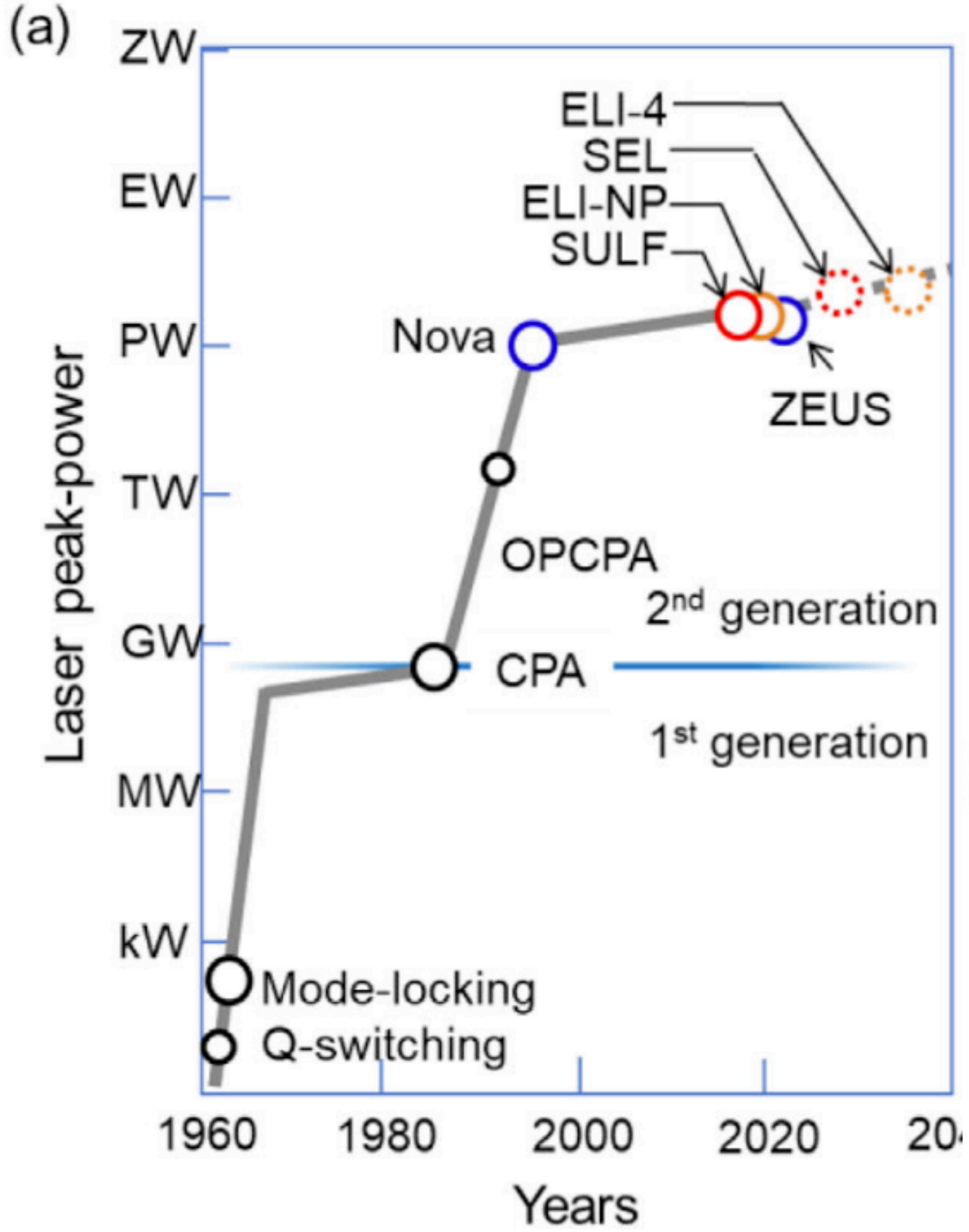
TNSA trends:

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

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

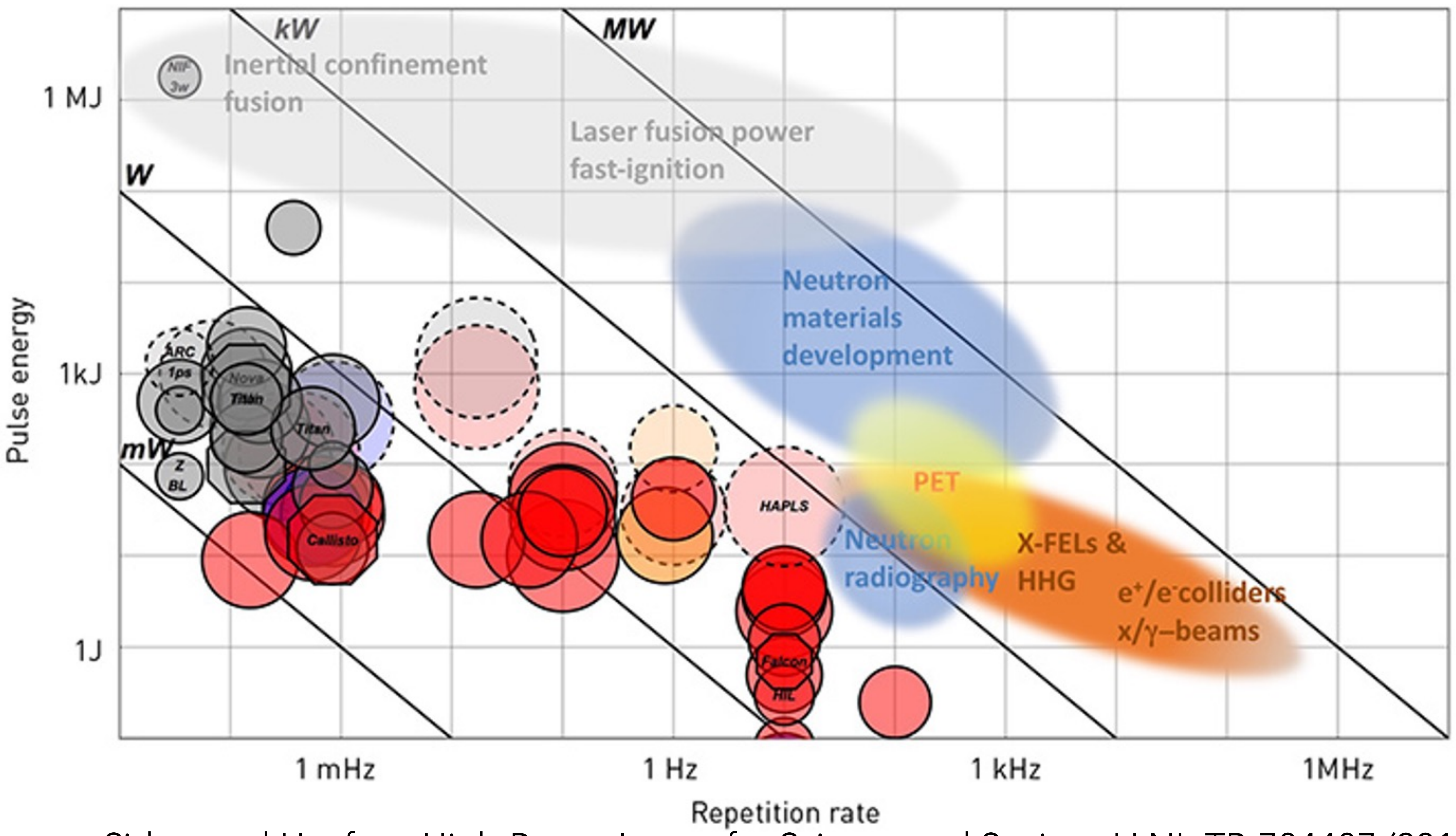
Proliferation of multi-Hz high-power lasers

Huge advances in last decade leading to increased repetition rate of high power and high intensity lasers and production as commercial products.



Li et al., Laser & Photonics Reviews (2023)

Ti:Sa lasers offer high peak intensity and high average power.



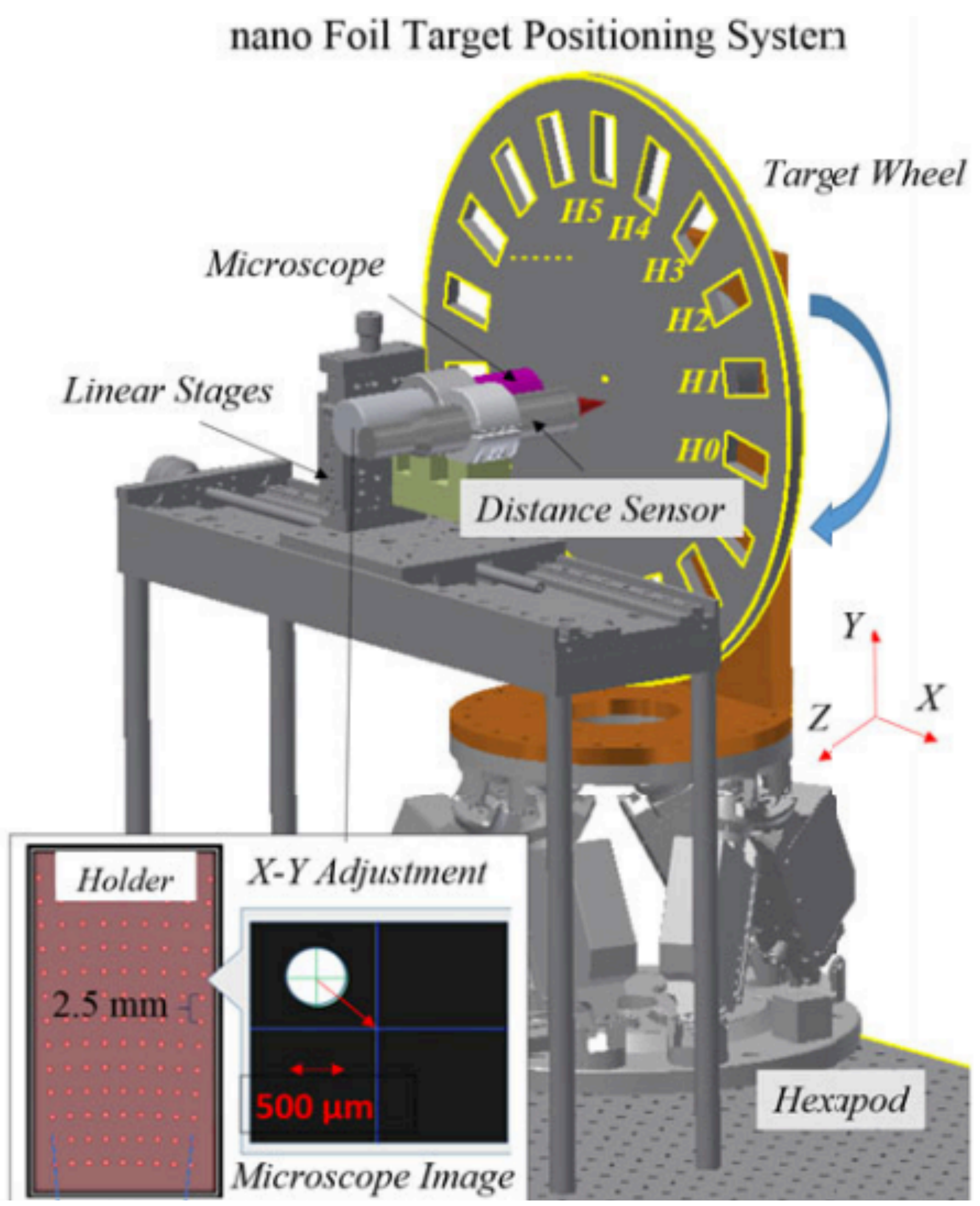
Siders and Haefner, High-Power Lasers for Science and Society, LLNL-TR-704407 (2016)

UK's CLF EPAC (due soon):

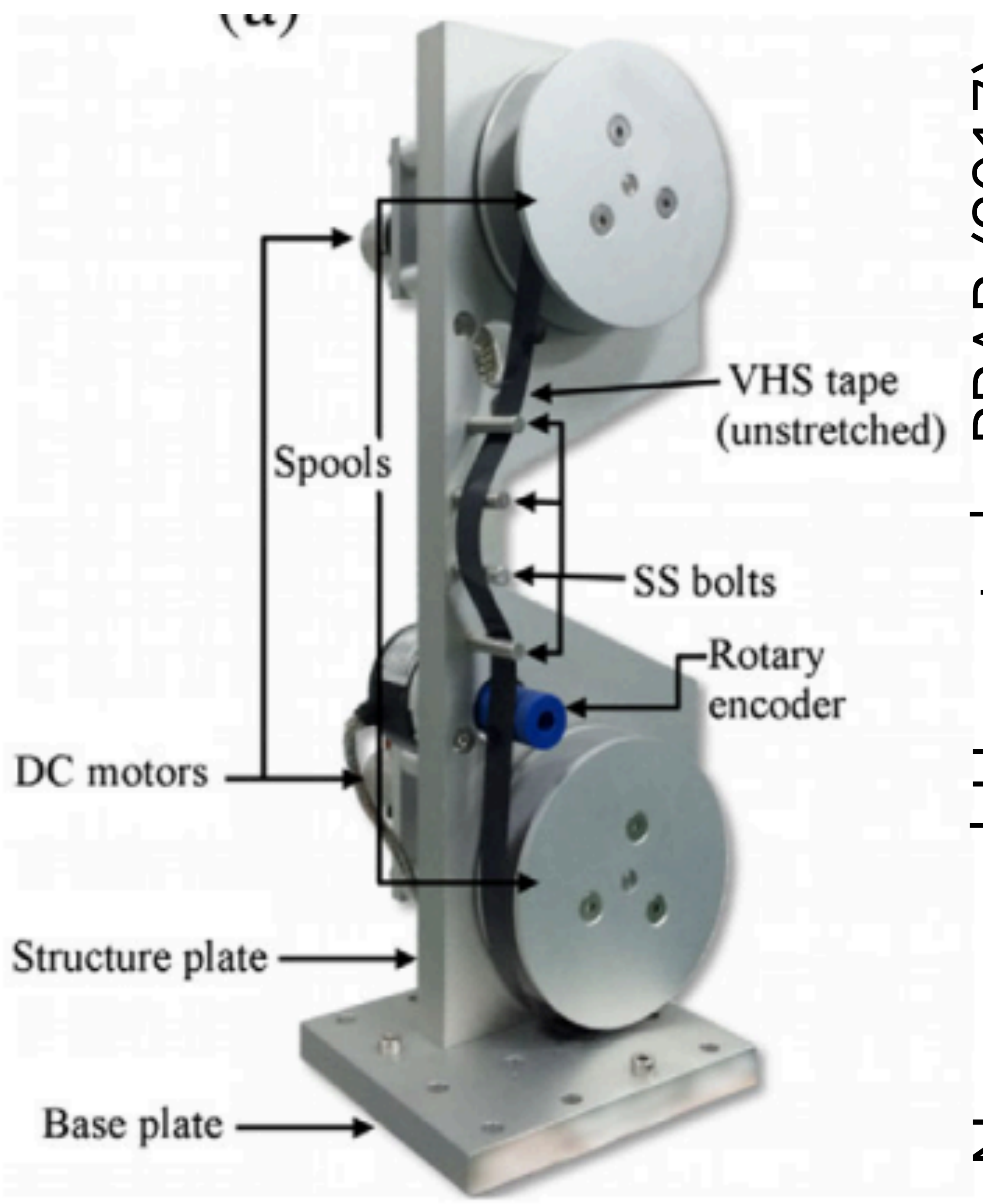
- 30 J in 30 fs
- 10 Hz
- 2 expt. halls
  - f/65
  - f/35 or f/3
- Additional beams

Multi-Hz targets

Tape drives and spinning disks:

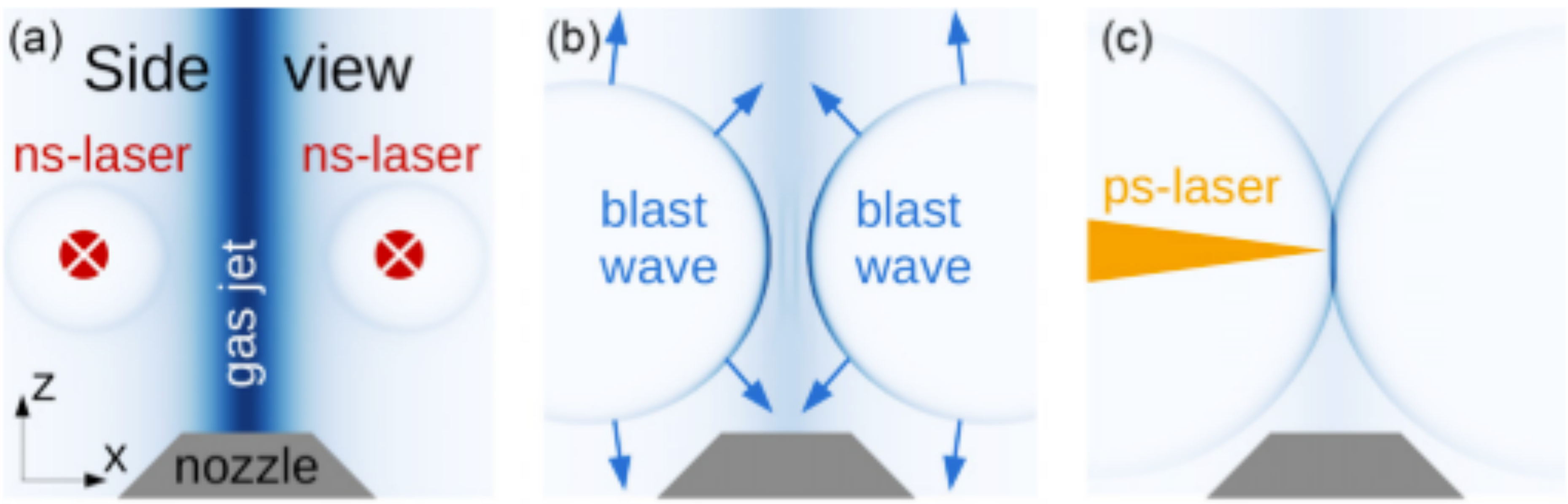


Gao et al., HPLSE (2017)



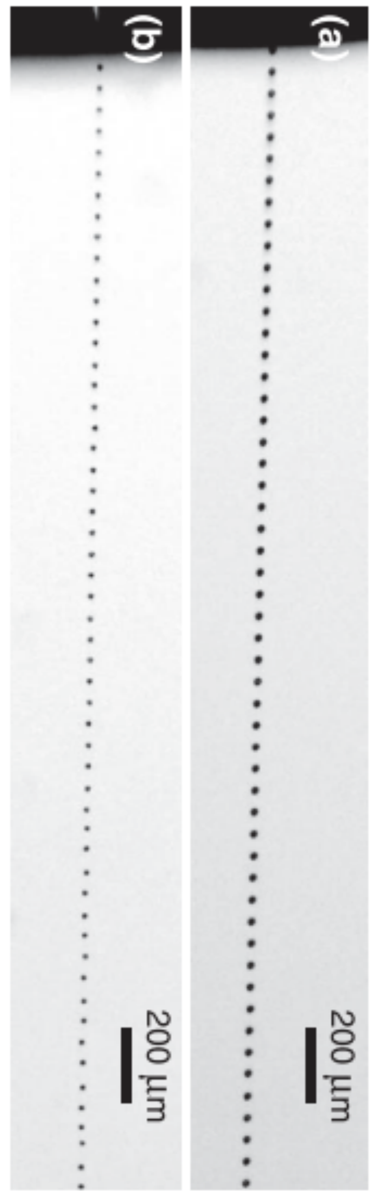
Noaman-ul-Haq et al., PRAB (2017)

High density gas targets:

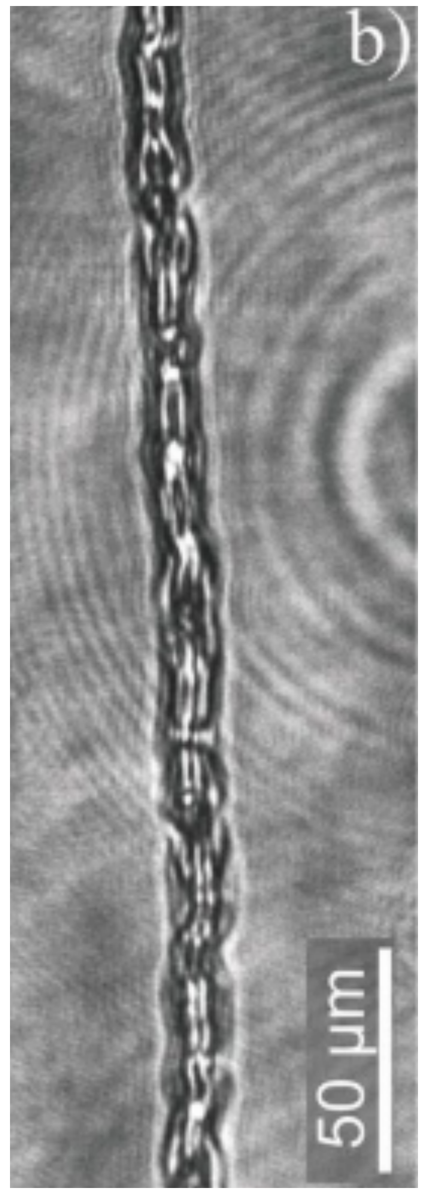


Marquès et al., PoP (2021)

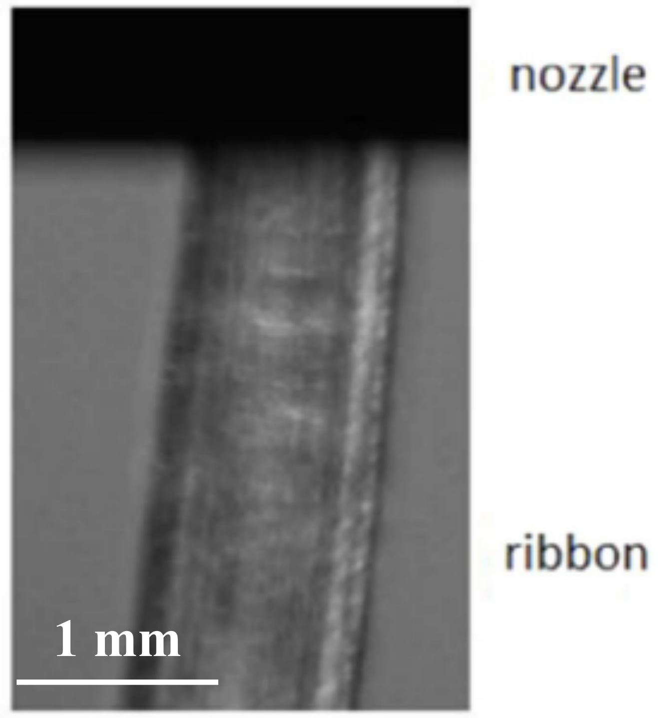
Cryogenic targets:



Propp et al., SLAC. Rep. (2015)



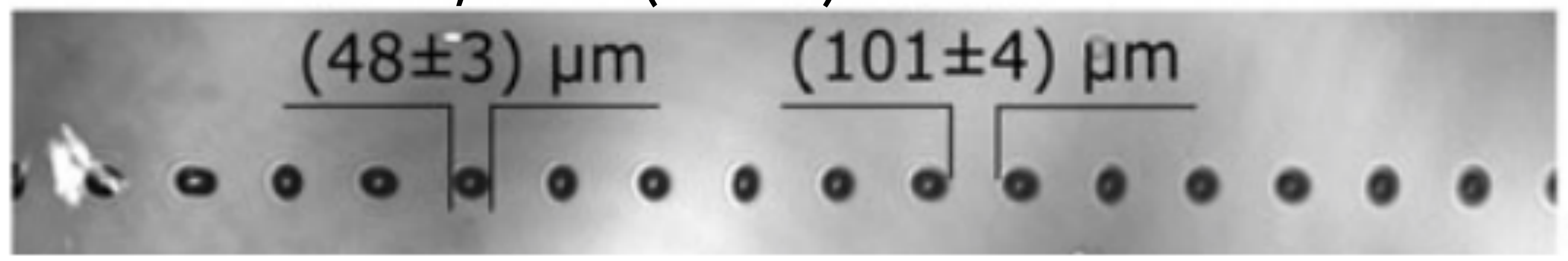
Polz et al., Sci. Rep. (2019)



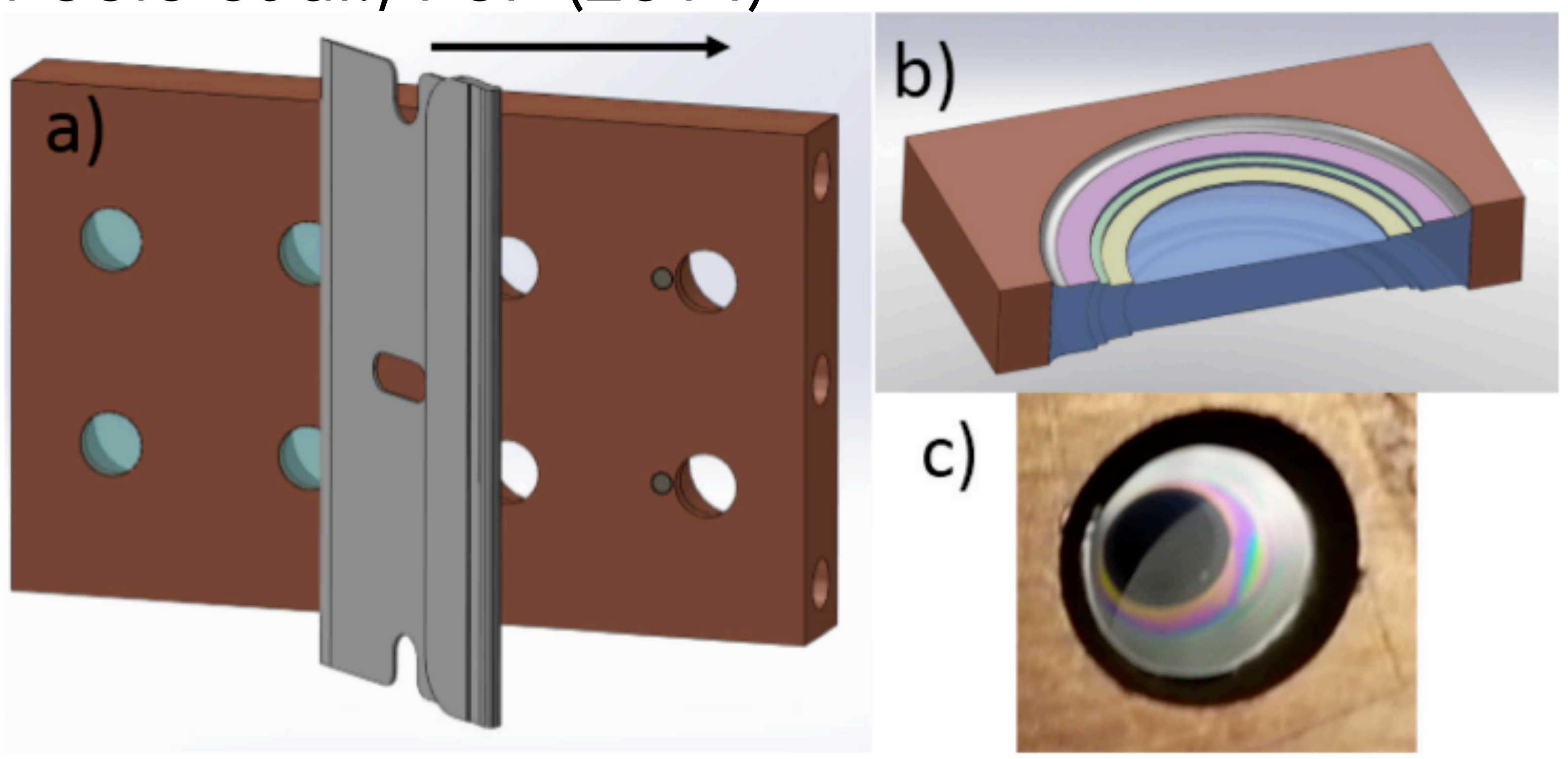
Kraft et al., PPCF (2018)

Liquid targets:

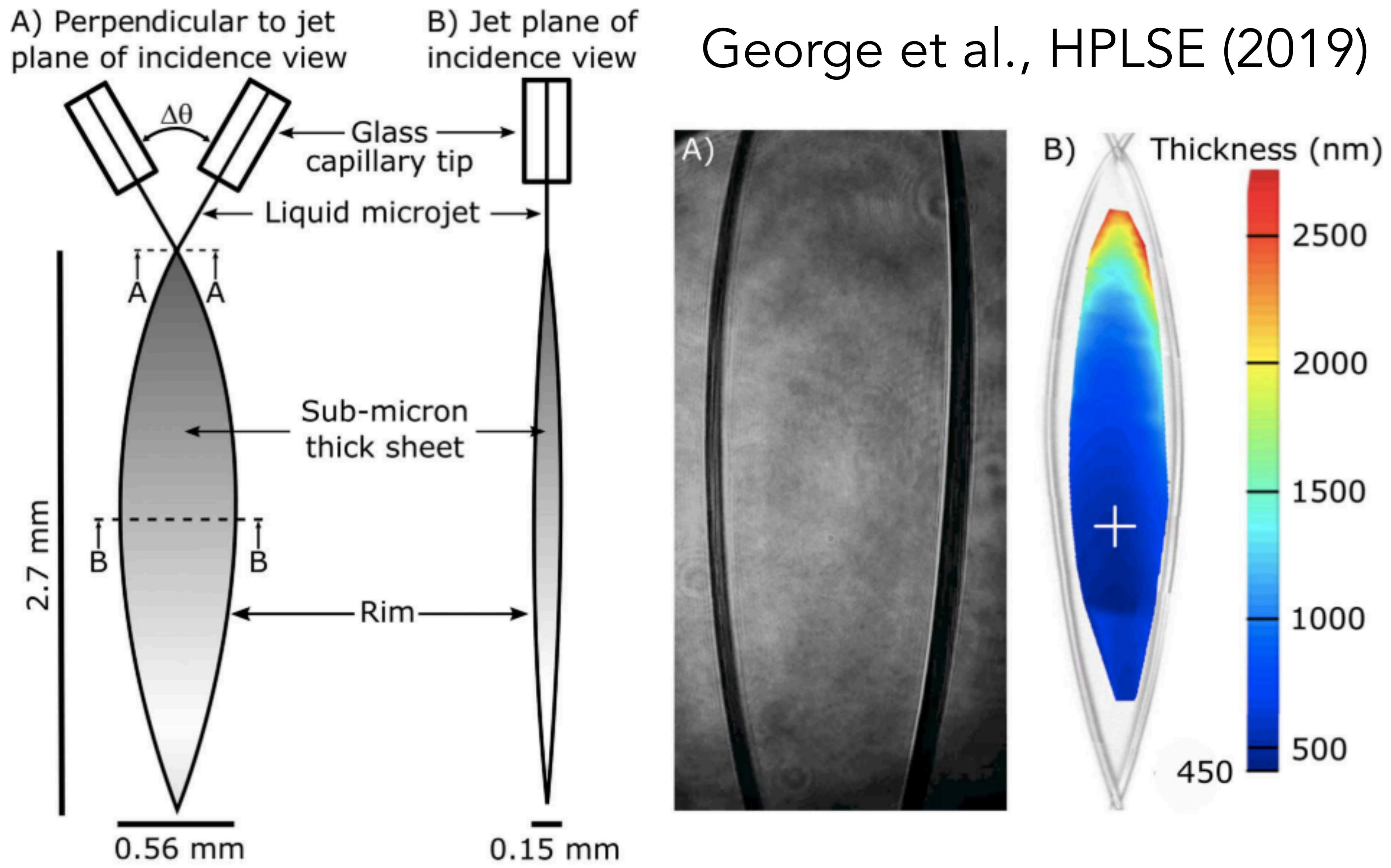
Aurand et al., LPB (2020)



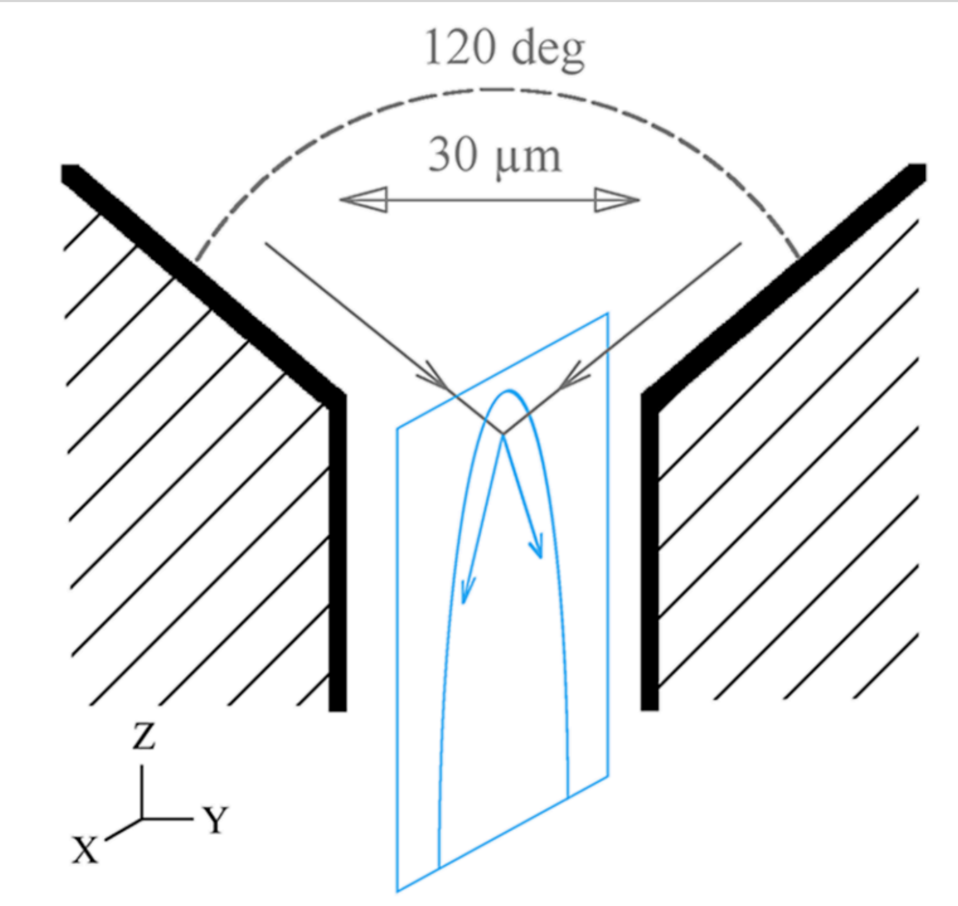
Poole et al., PoP (2014)



George et al., HPLSE (2019)



Liquid sheet formation and use

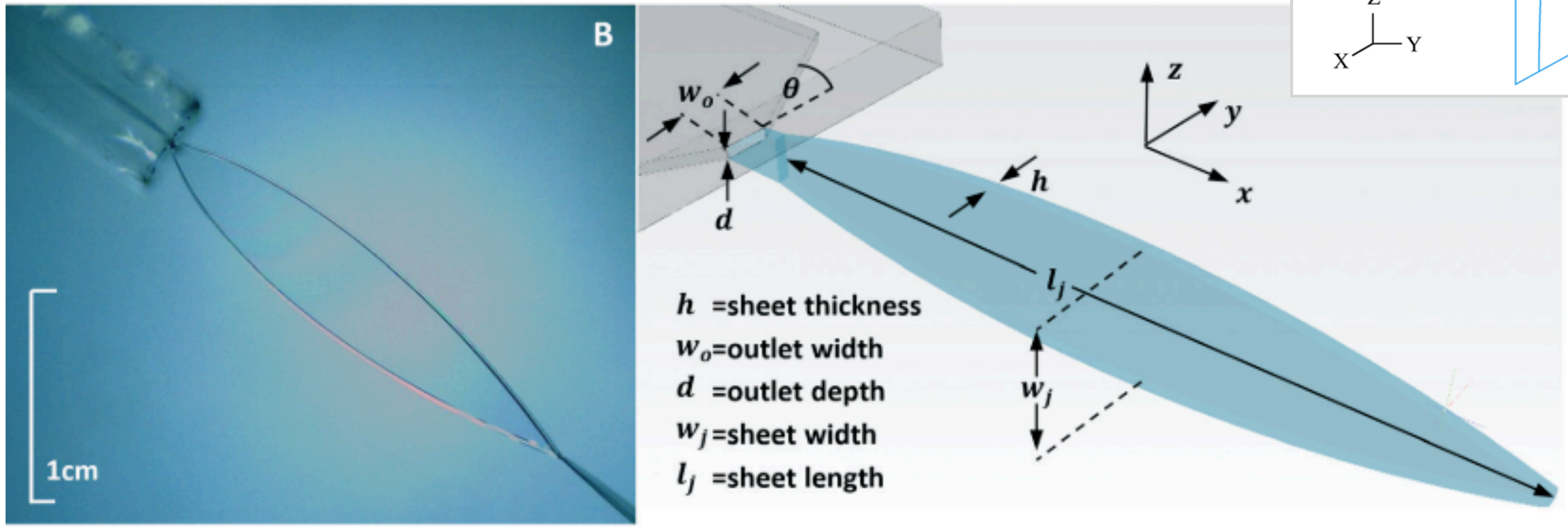


Galinis et al. RSI 2017

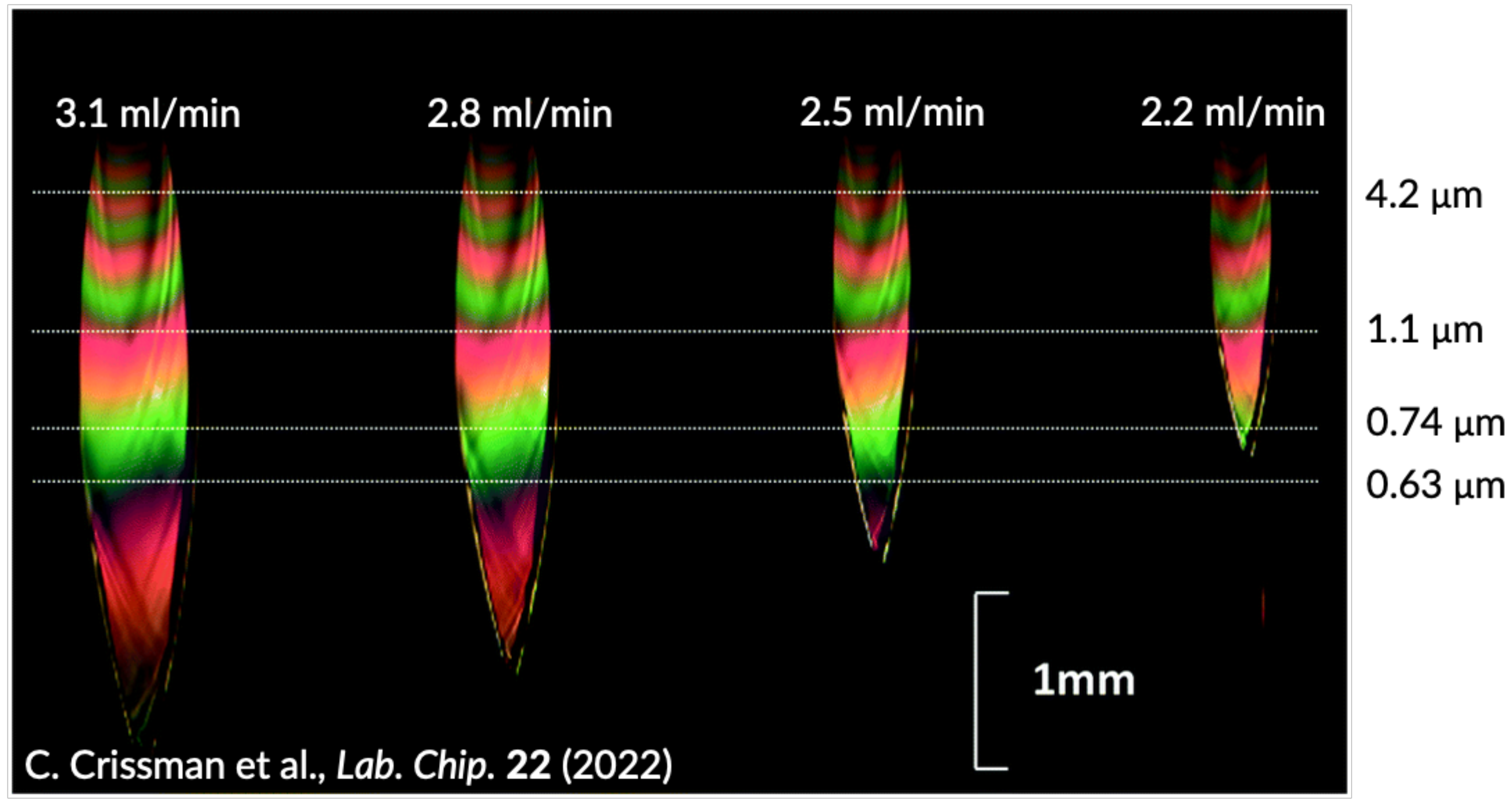
Use of liquid sheets with in high-intensity laser-plasma interactions

Example of a liquid sheet for converging nozzle geometry:

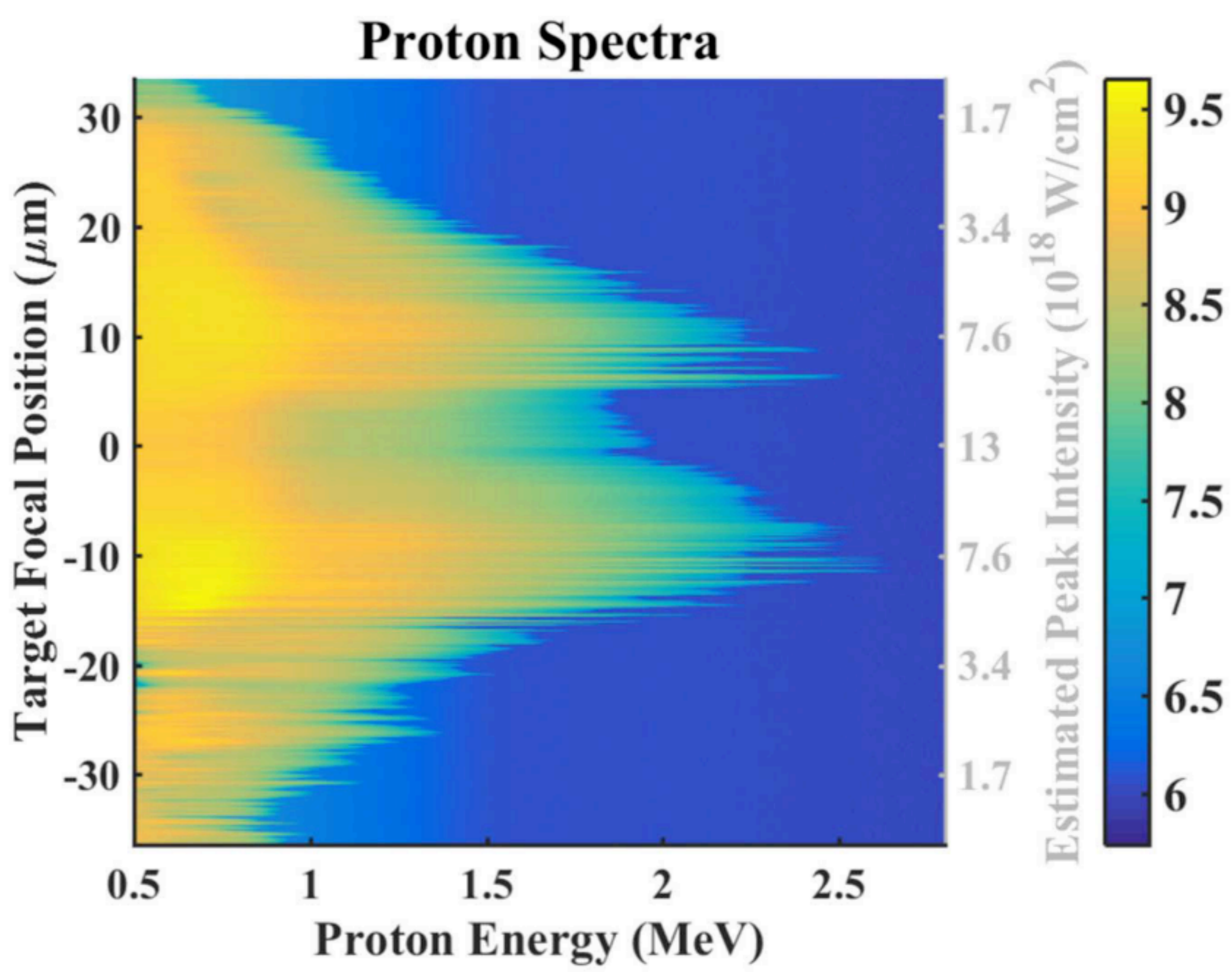
Crissman et al. Lab Chip 2022



Thickness mapped using thin film interferometry

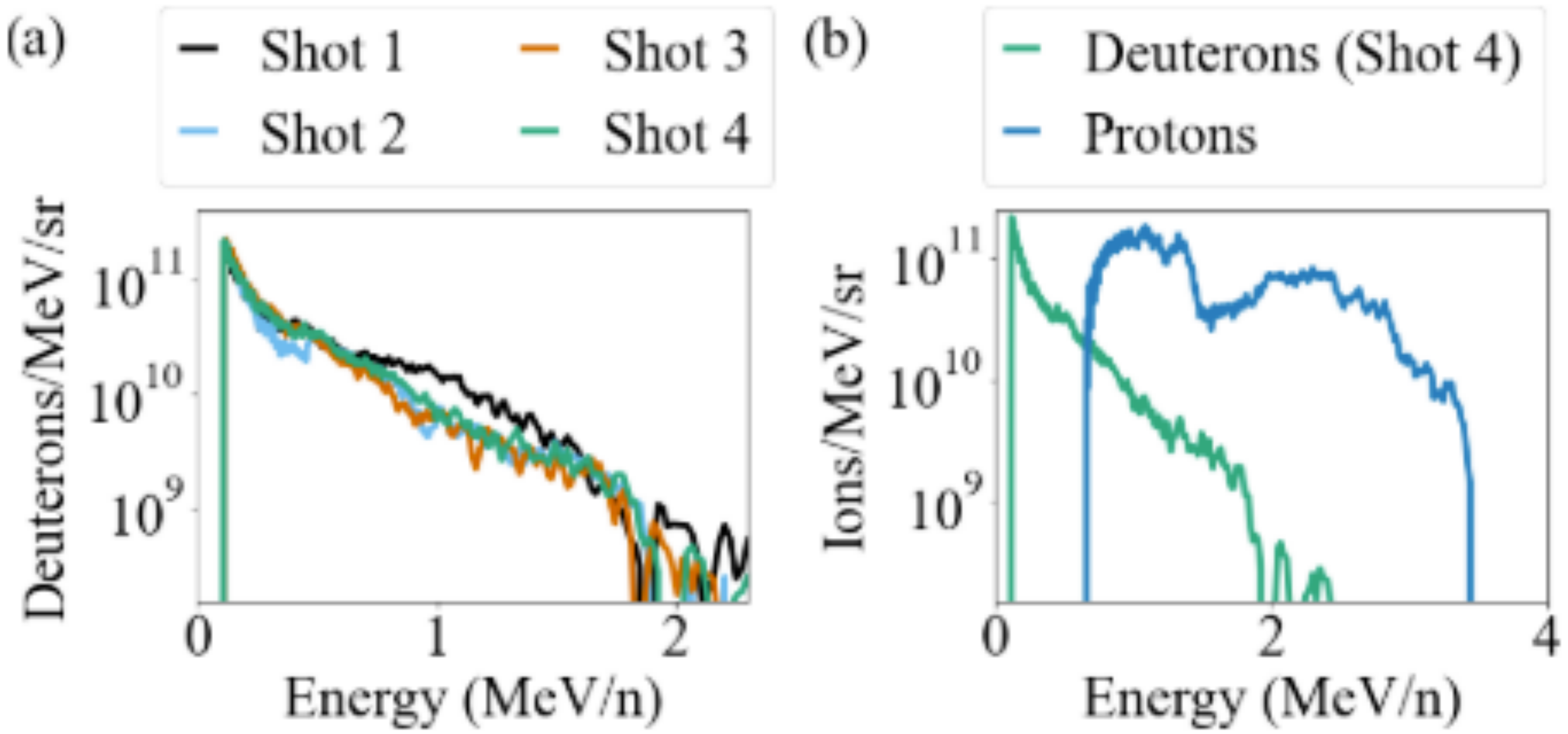


MeV proton acceleration at 1 kHz



Morrison et al. NJP 2018

Deuteron acceleration for MeV neutron generation



Treffert et al. PoP 2022

Addressing challenges for ion acceleration

Liquid evaporation in vacuum

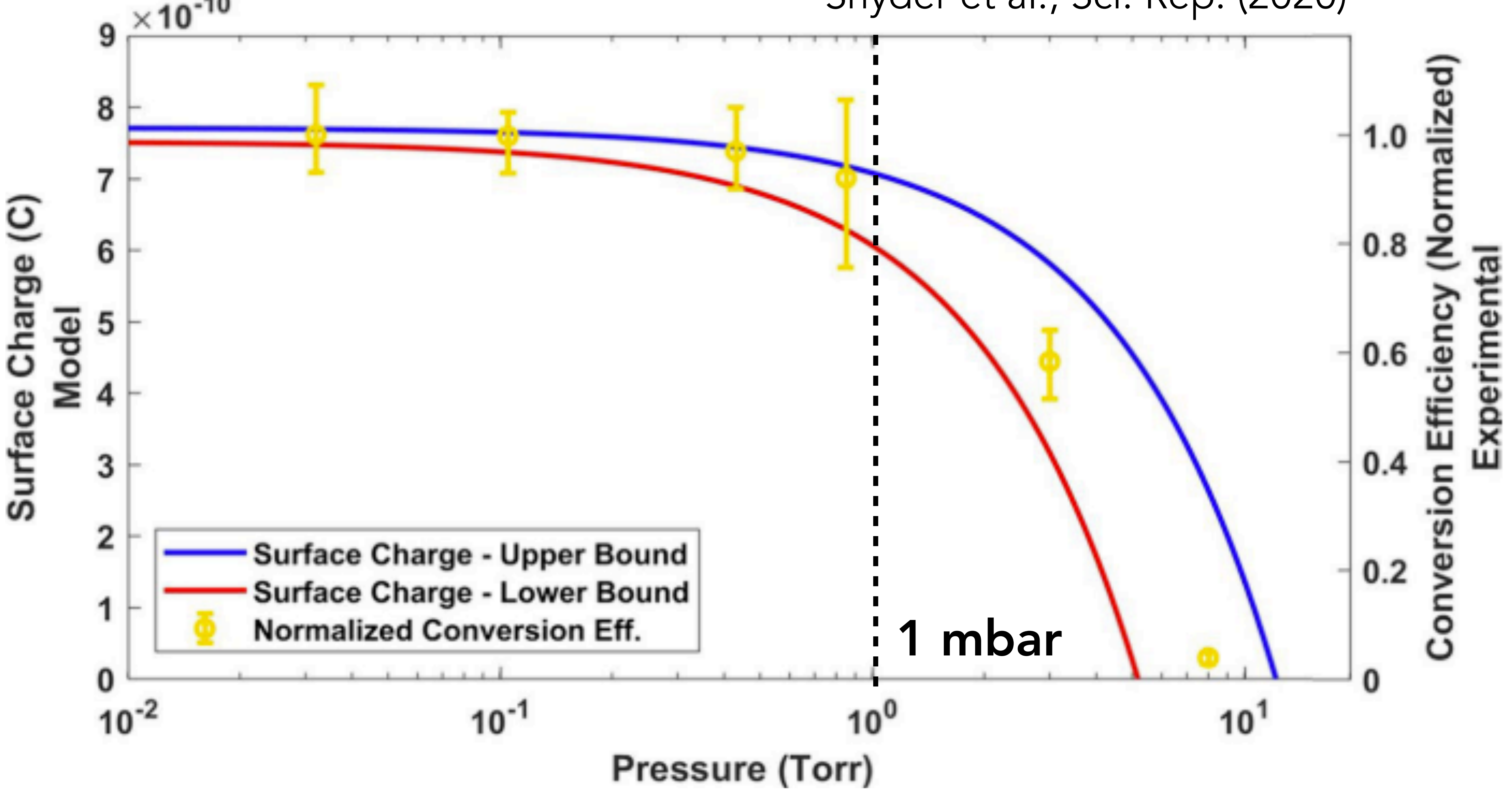
At low pressures, liquid will evaporate forming a vapour cloud and rapidly cooling the sheet.

Primary mitigation strategies:

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

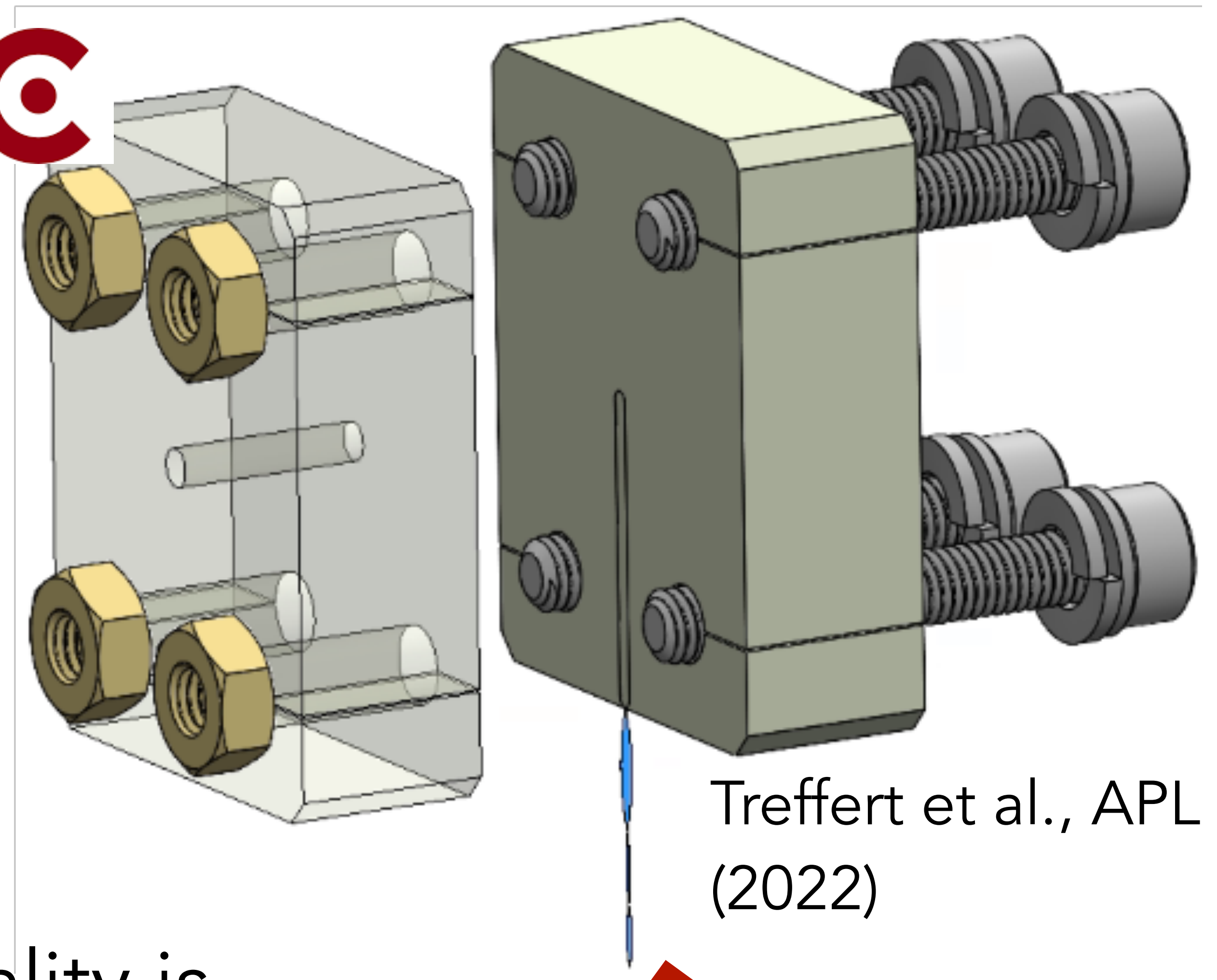
Vacuum pressures of 10^{-5} mbar have been achieved.

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



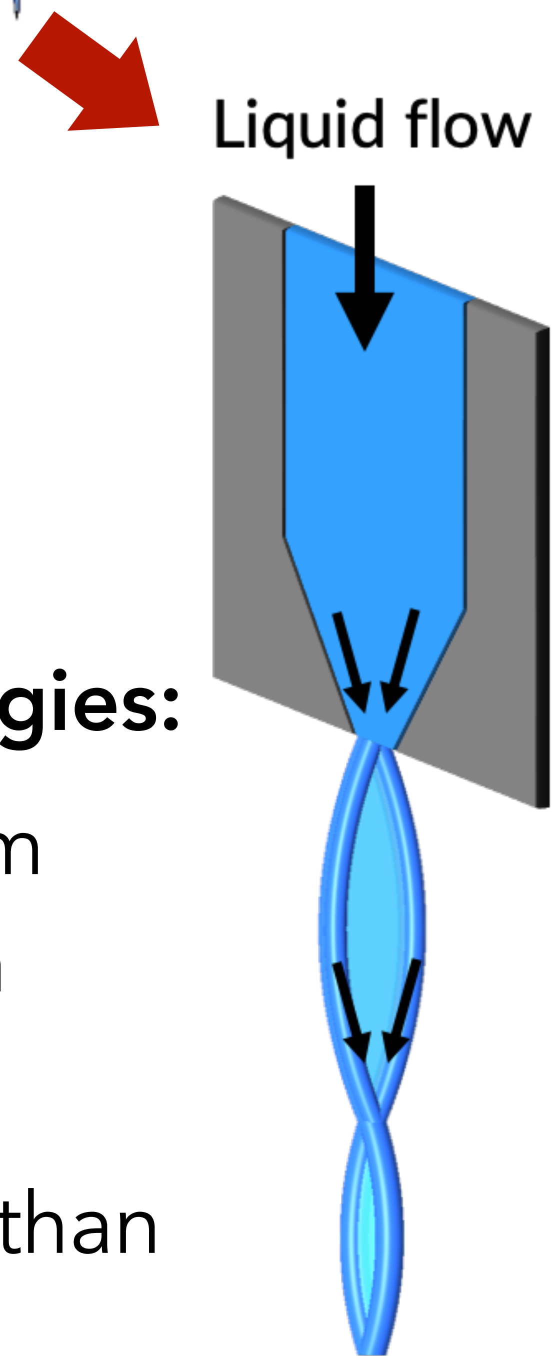
SLAC

Nozzle damage



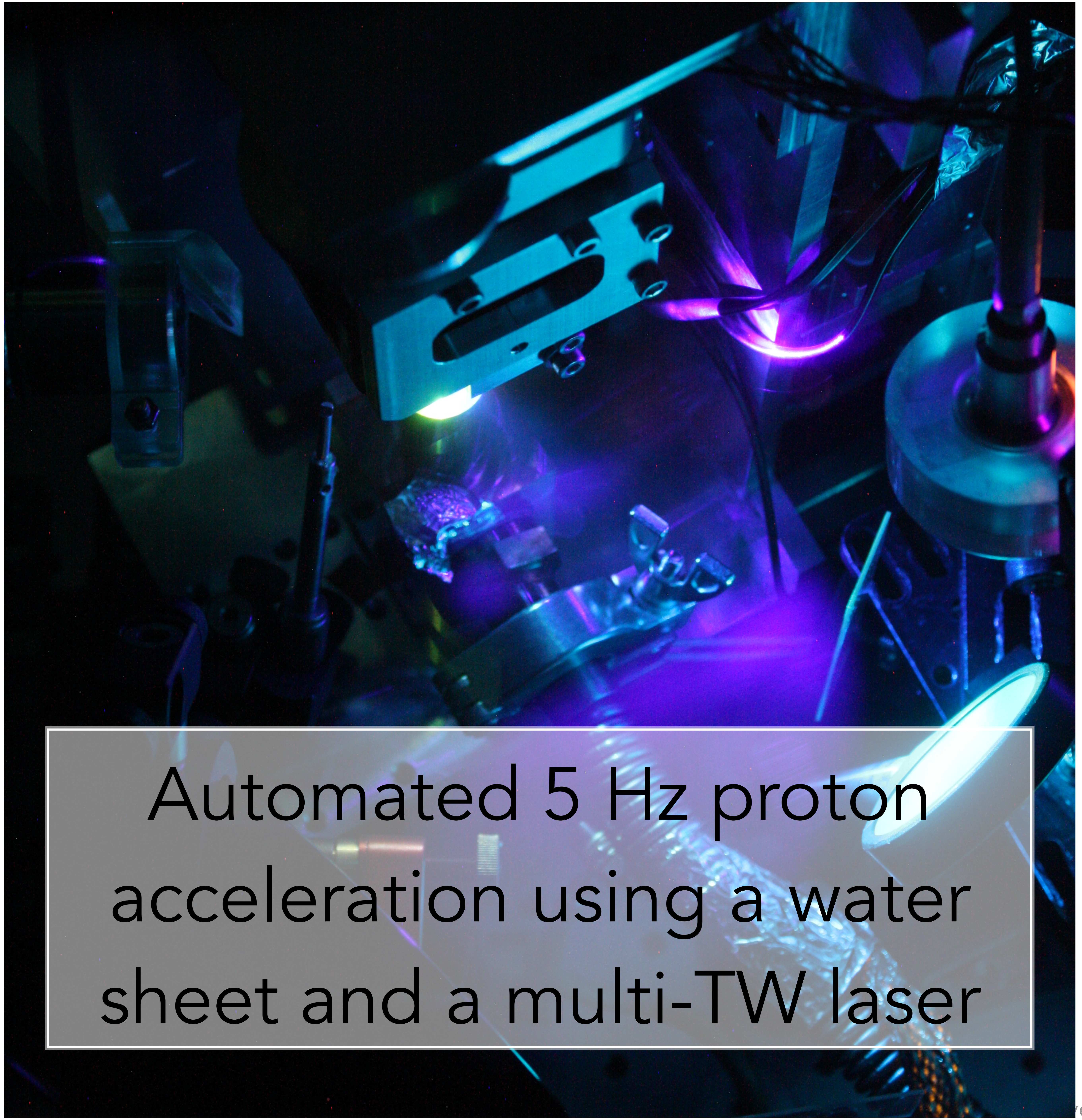
Treffert et al., APL (2022)

Sheet quality is dependent on the smoothness of the channels so laser damage leads to target instability.



Primary mitigation strategies:

- Increasing distance from nozzle outlets to collision point.
- Using harder materials than glass such as Tungsten.



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

Experimental overview

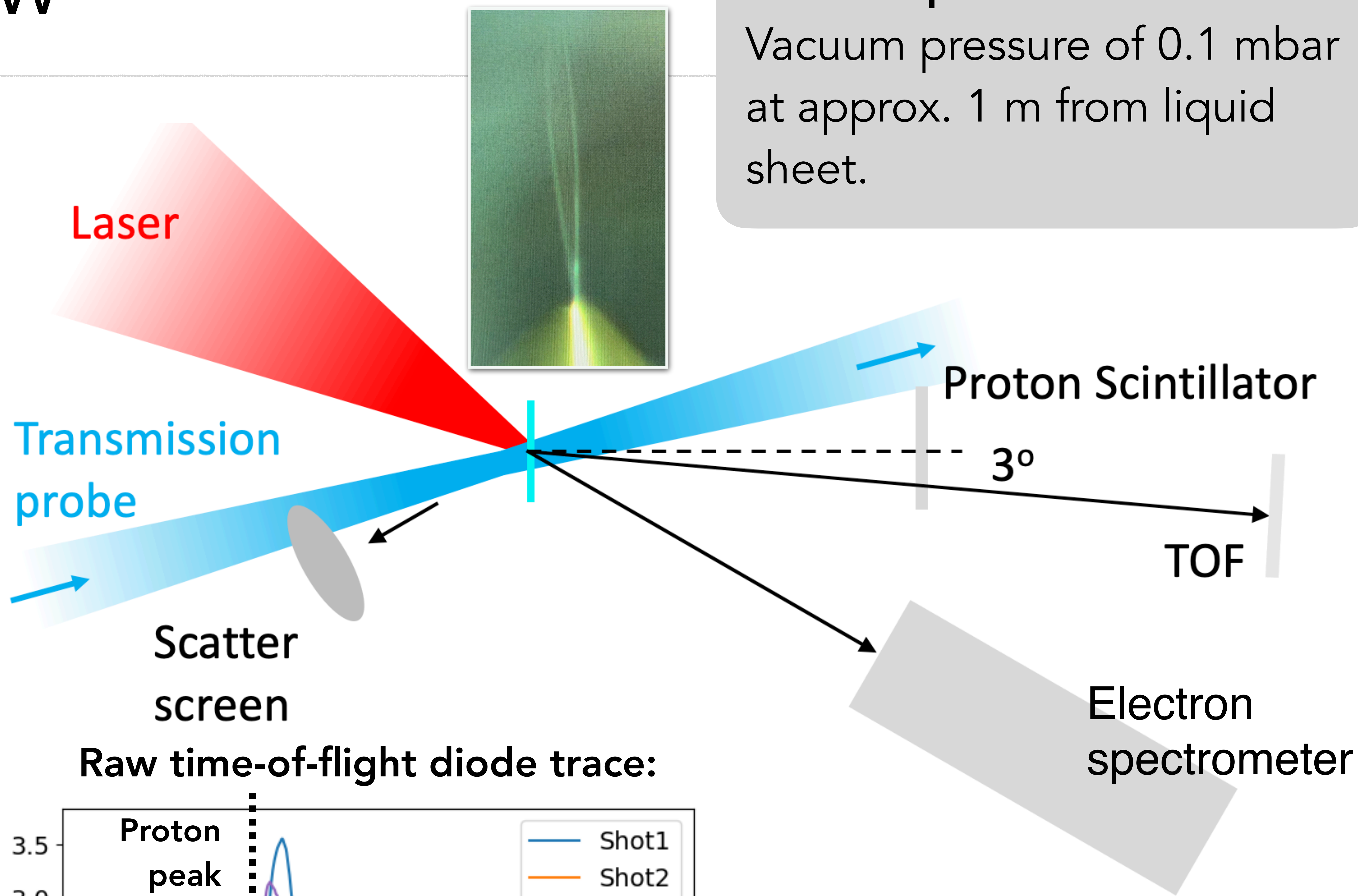
Loughran et al., HPLSE 11, e35 (2023)

Laser parameters: Up to 200 mJ on target in 60 fs focused with F/2.5 OAP (Rayleigh length ~ 15 μm)

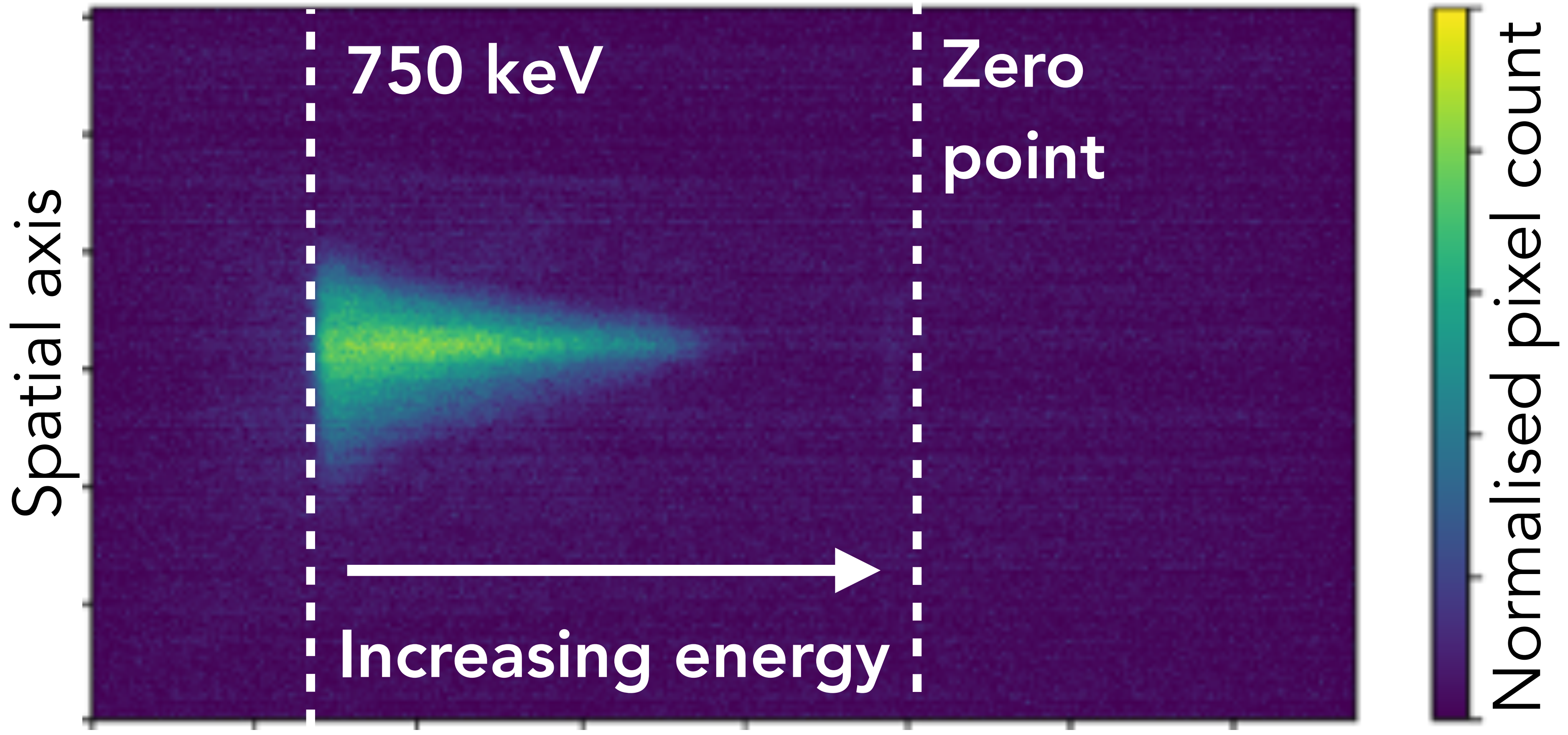
Target parameters: Ultra-pure water with (600 ± 100) nm thickness at 2.8 mm below nozzle outlet.

Results compared with 13 μm Kapton tape.

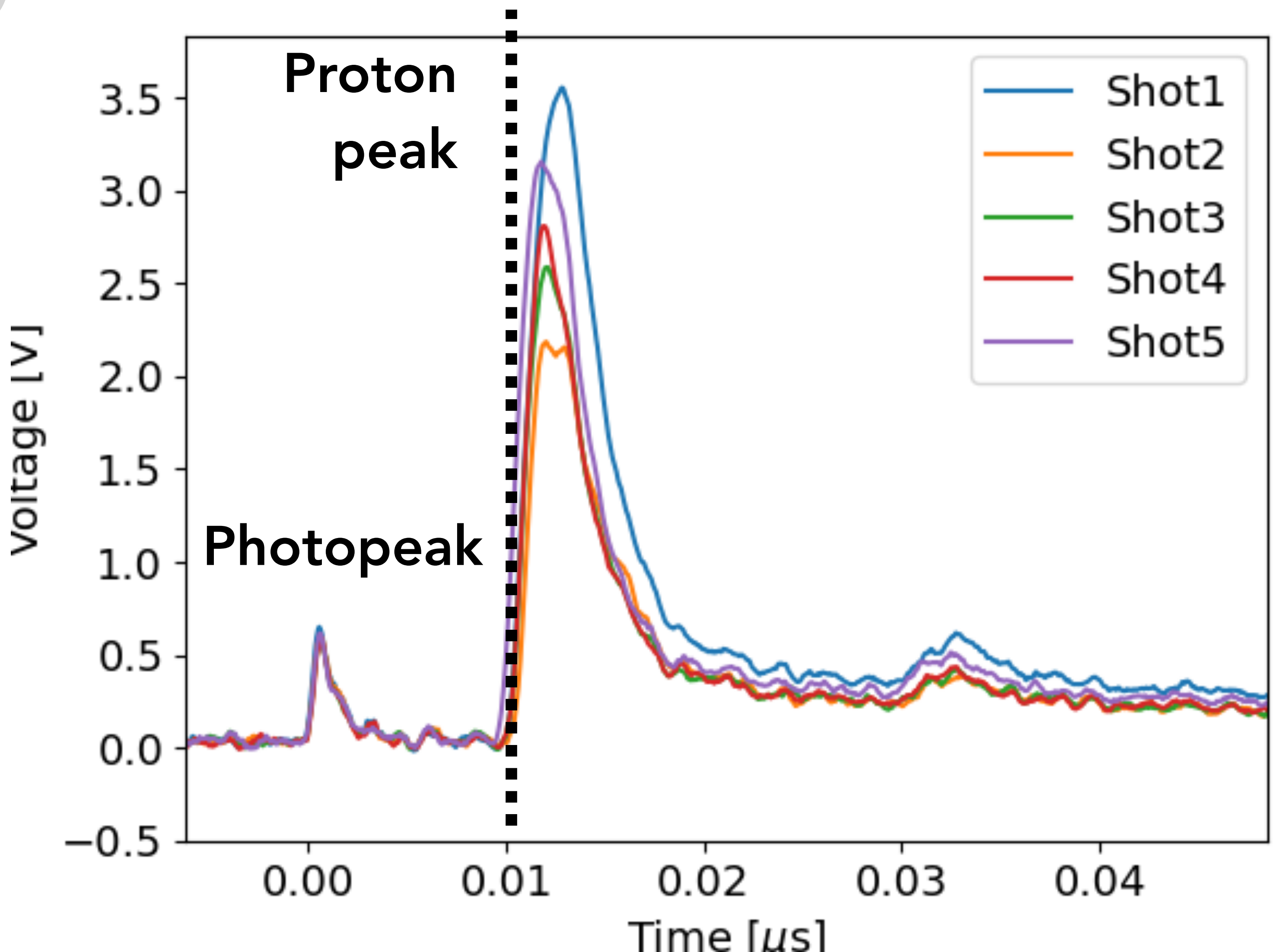
Vacuum parameters: Vacuum pressure of 0.1 mbar at approx. 1 m from liquid sheet.



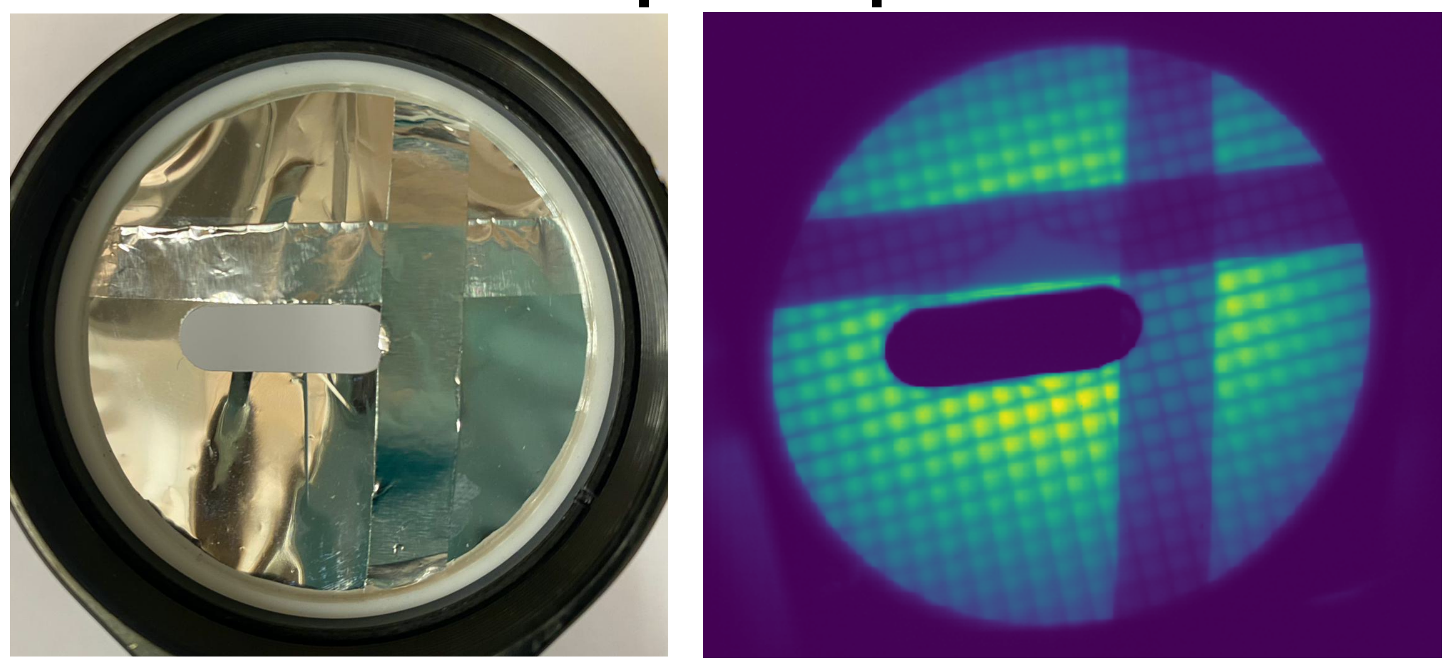
Electron spectrometer signal:



Raw time-of-flight diode trace:

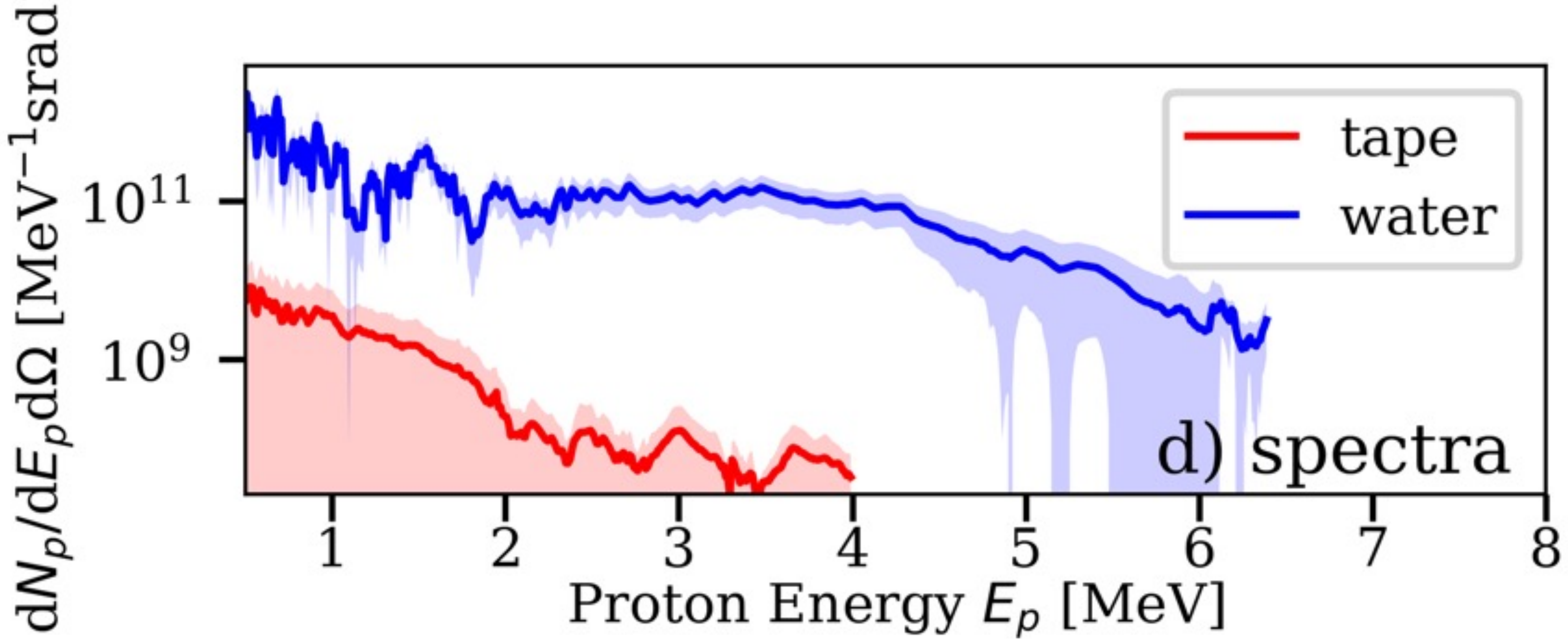


Proton spatial profile:



High flux MeV proton beams from the liquid sheet

Average proton energy spectrum:



- Proton spectra flux (blue) two orders of magnitude higher than reference 13 micron Kapton tape (red) with measured protons cut-off energy of 4-6 MeV.
- Slightly higher energies and flux than experiments with 500 nm targets and comparative laser conditions.

Comparative thin foil experiments:

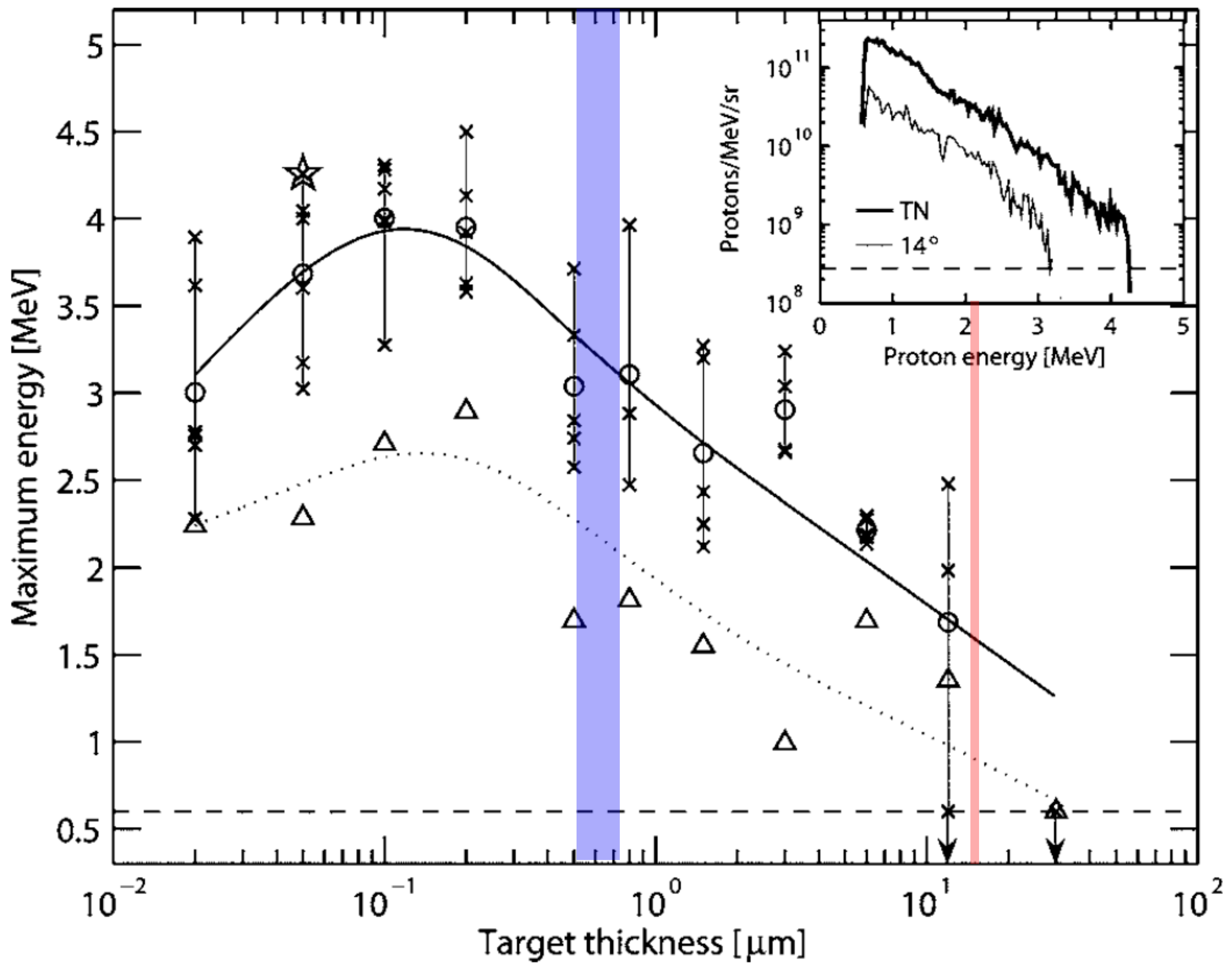
Targets:

- 20 nm - 30 micron Al

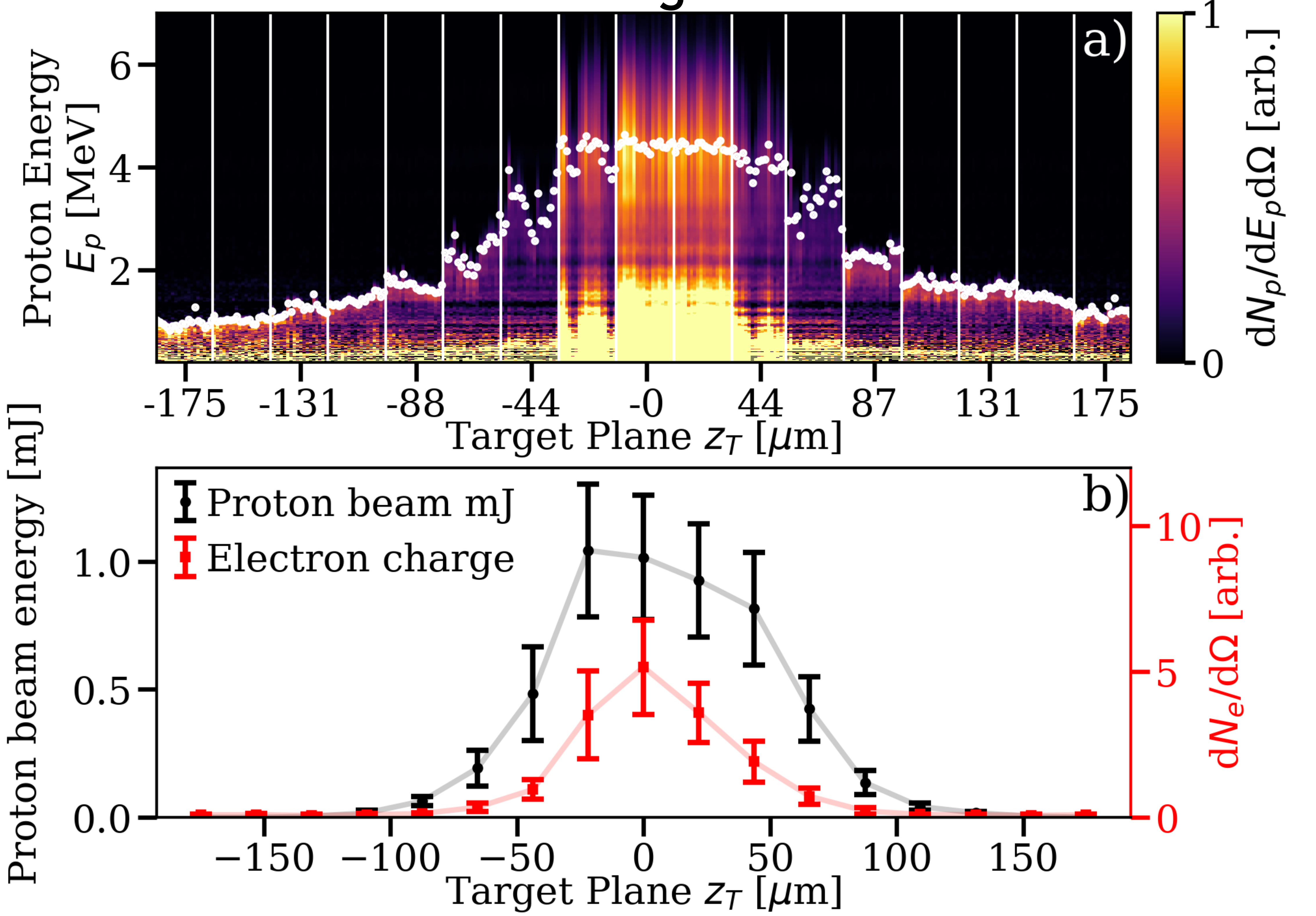
Laser parameters:

- 300 mJ
- 33 fs
- 10^{19} W/cm^2

Neely et al., APL (2006)

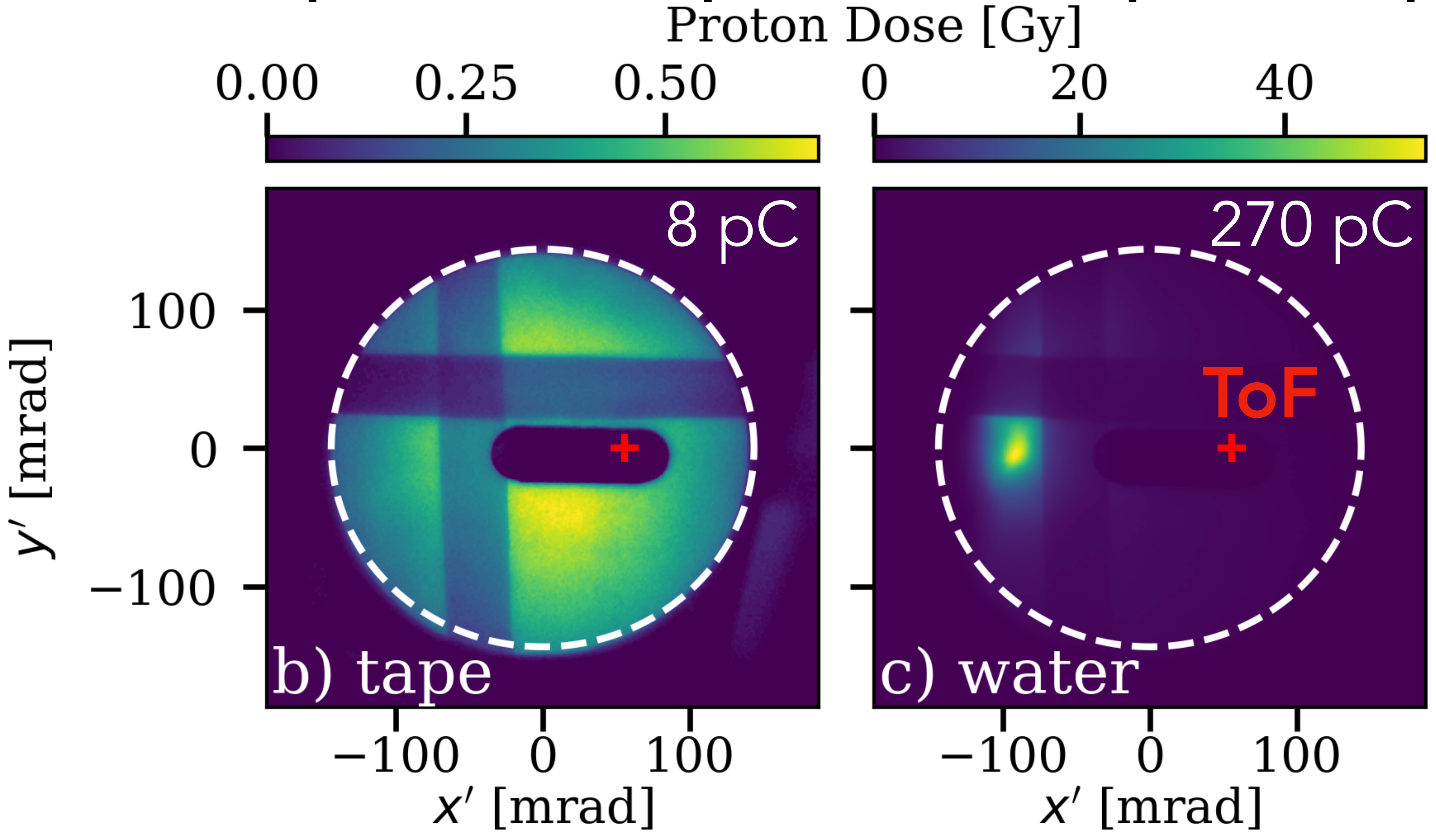


Variation in proton spectrum as target is scanned through focus:

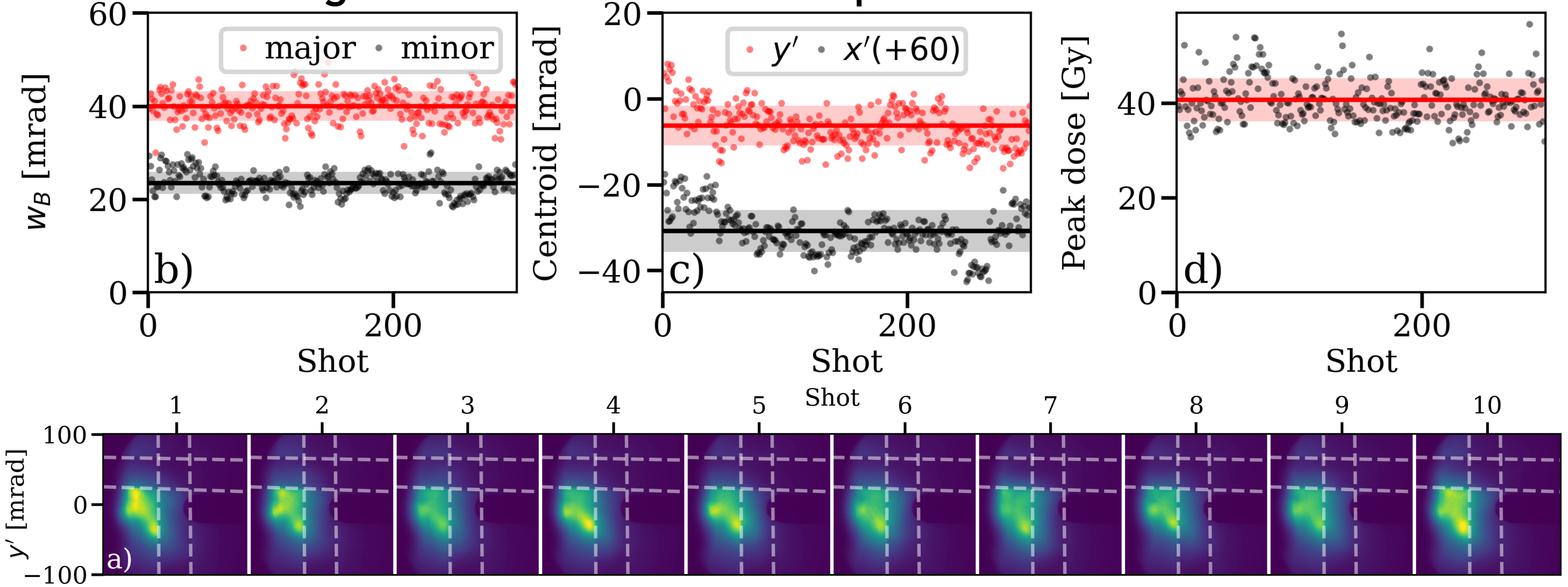


High stability and low proton beam divergence

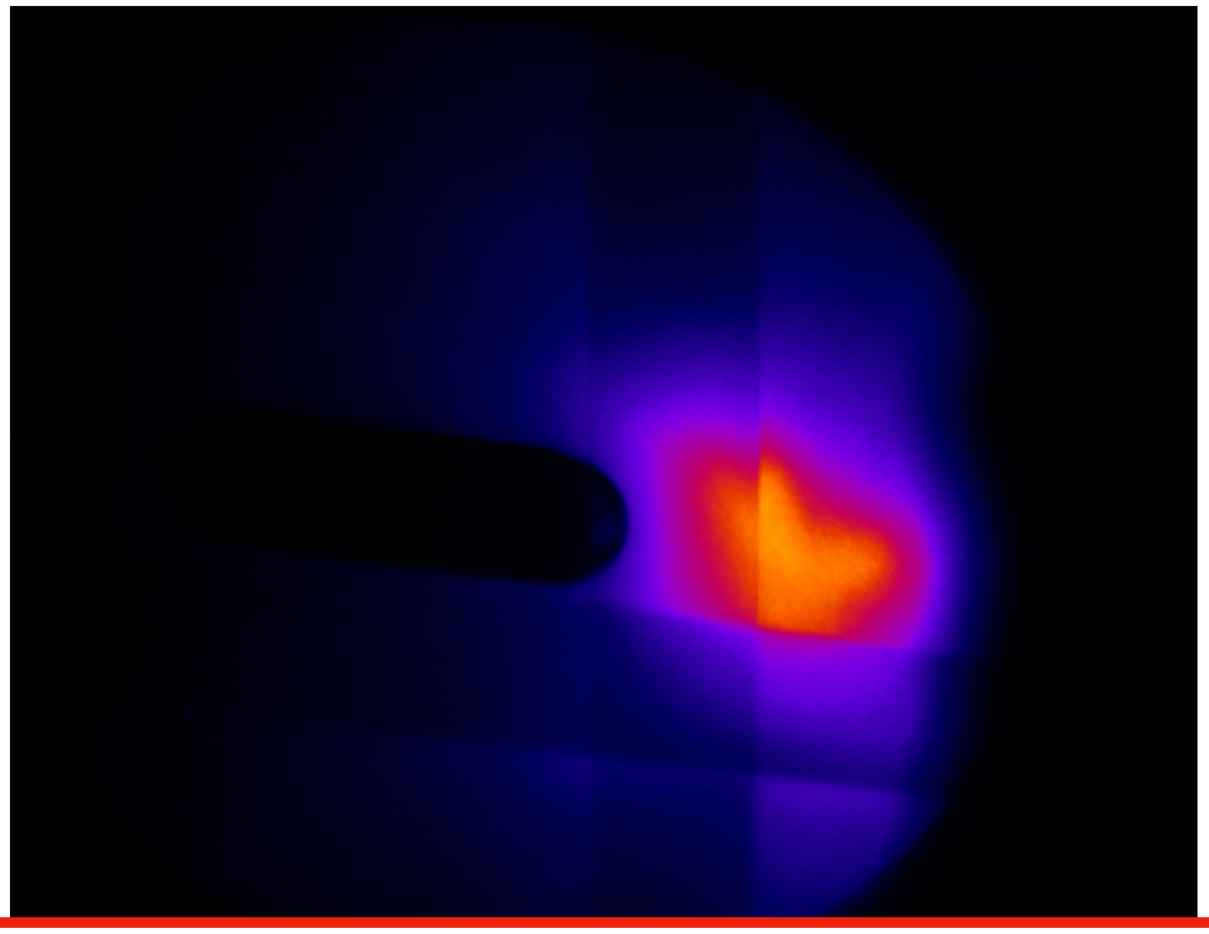
Comparison dose profile from tape and liquid:



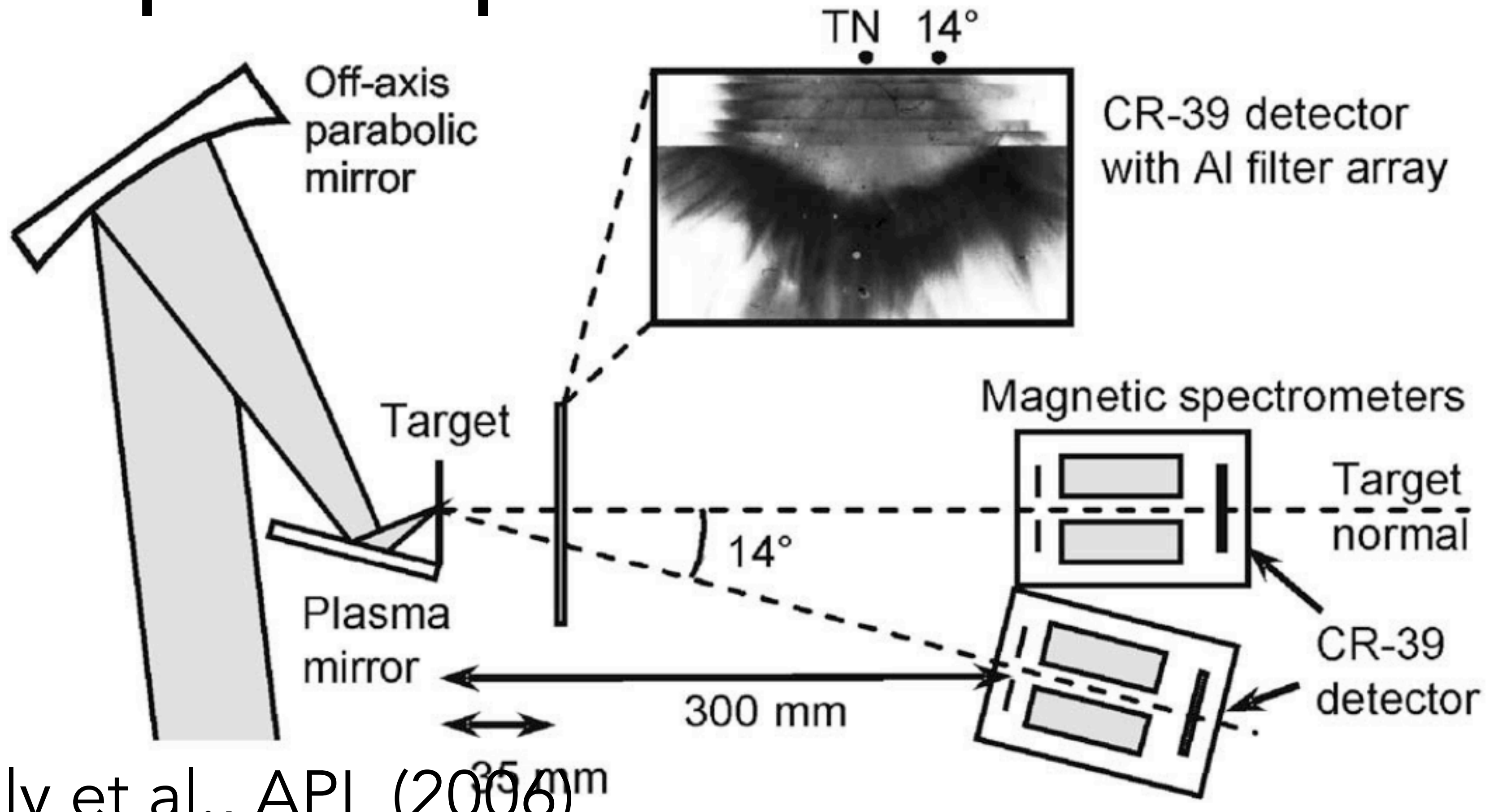
Divergence: **Centroid position:** **Dose:**



Raw proton spatial profile:



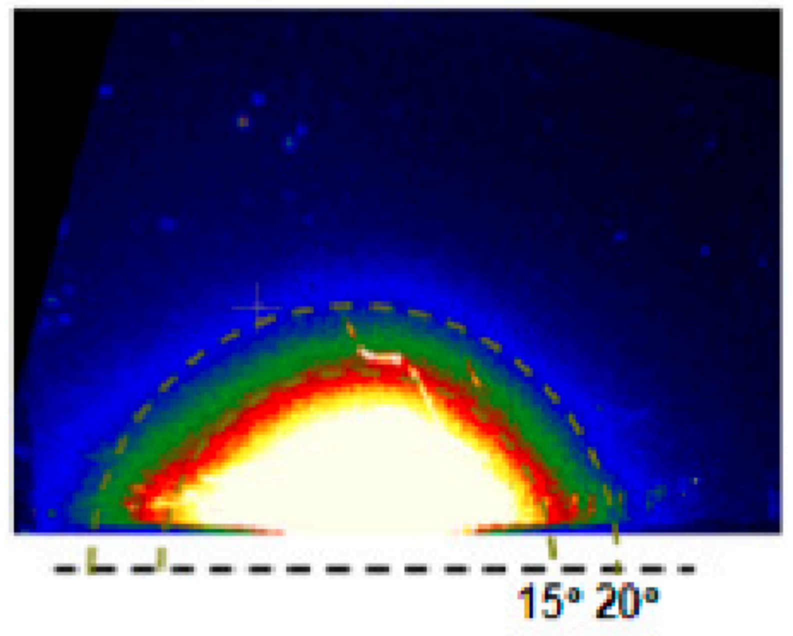
Comparative profiles from thin foils: Proton profiles from 50 nm foils



Neely et al., APL (2006)

Green et al., APL (2006)

Best focus

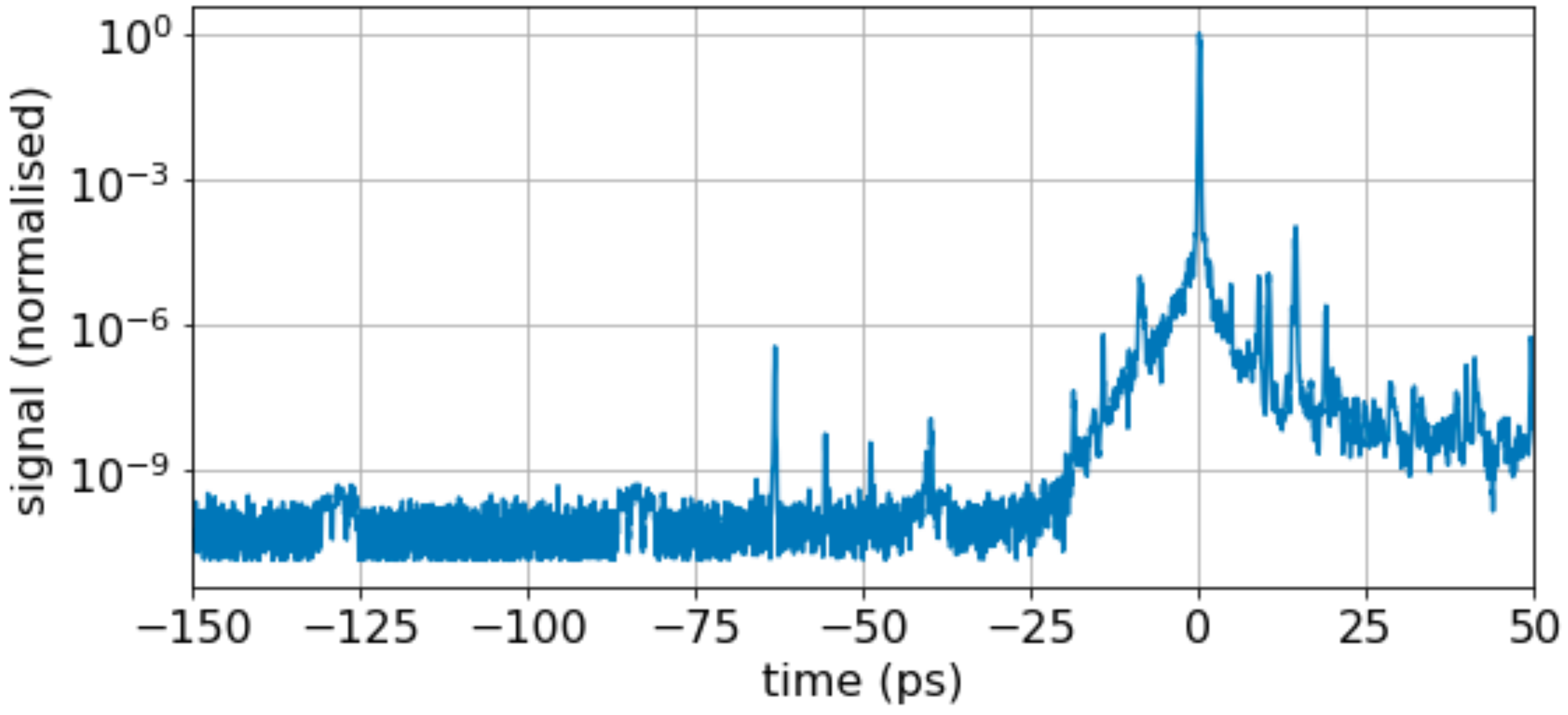


Streeter et al., Nat. Comms. 16, 1004 (2025)

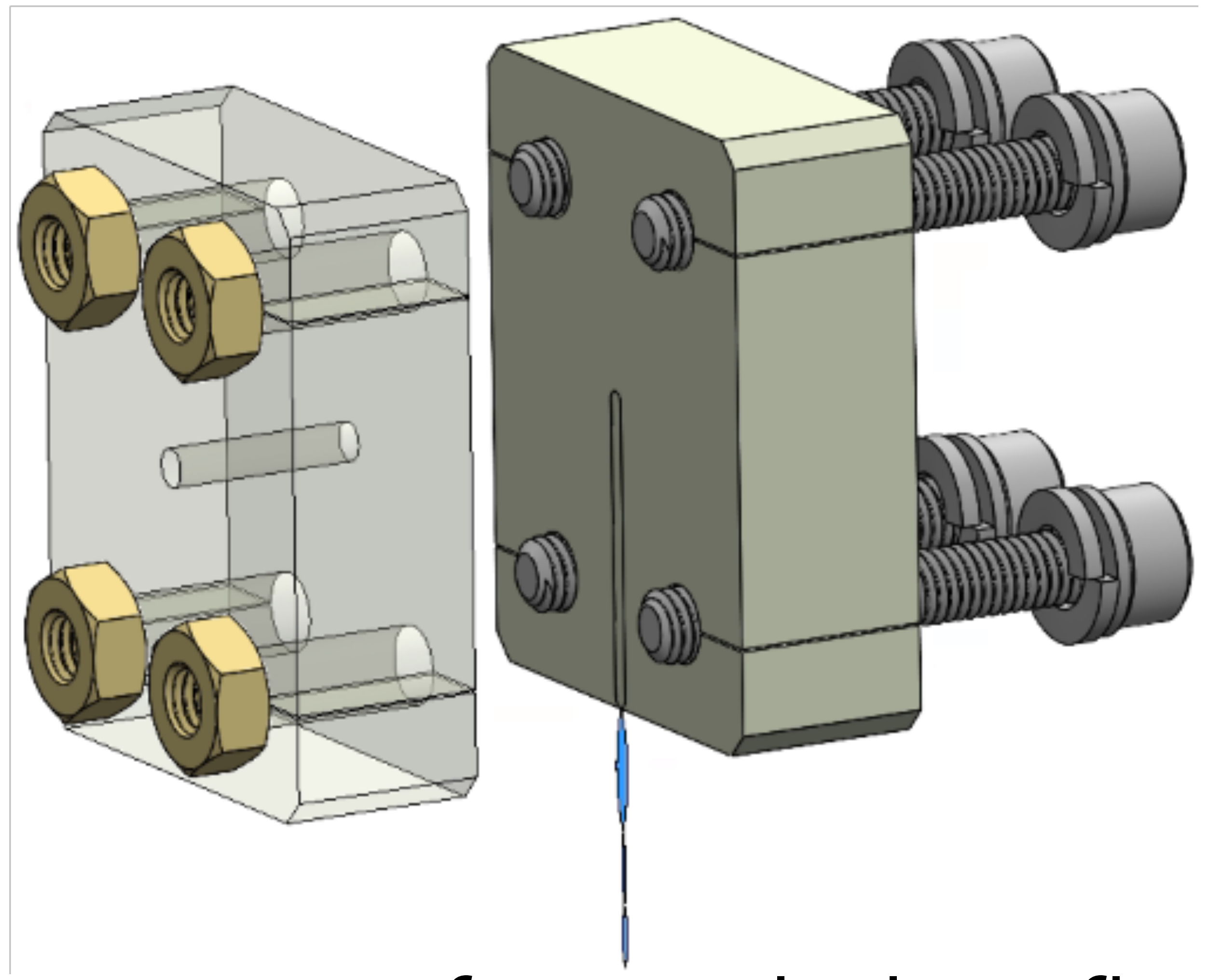
What is driving our high brightness, low-divergence proton beams?

Radiation hydrodynamic simulations using the measured laser contrast indicate target rear surface remains undisturbed until the arrival of the peak of the laser pulse.

Laser contrast measured with Sequoia

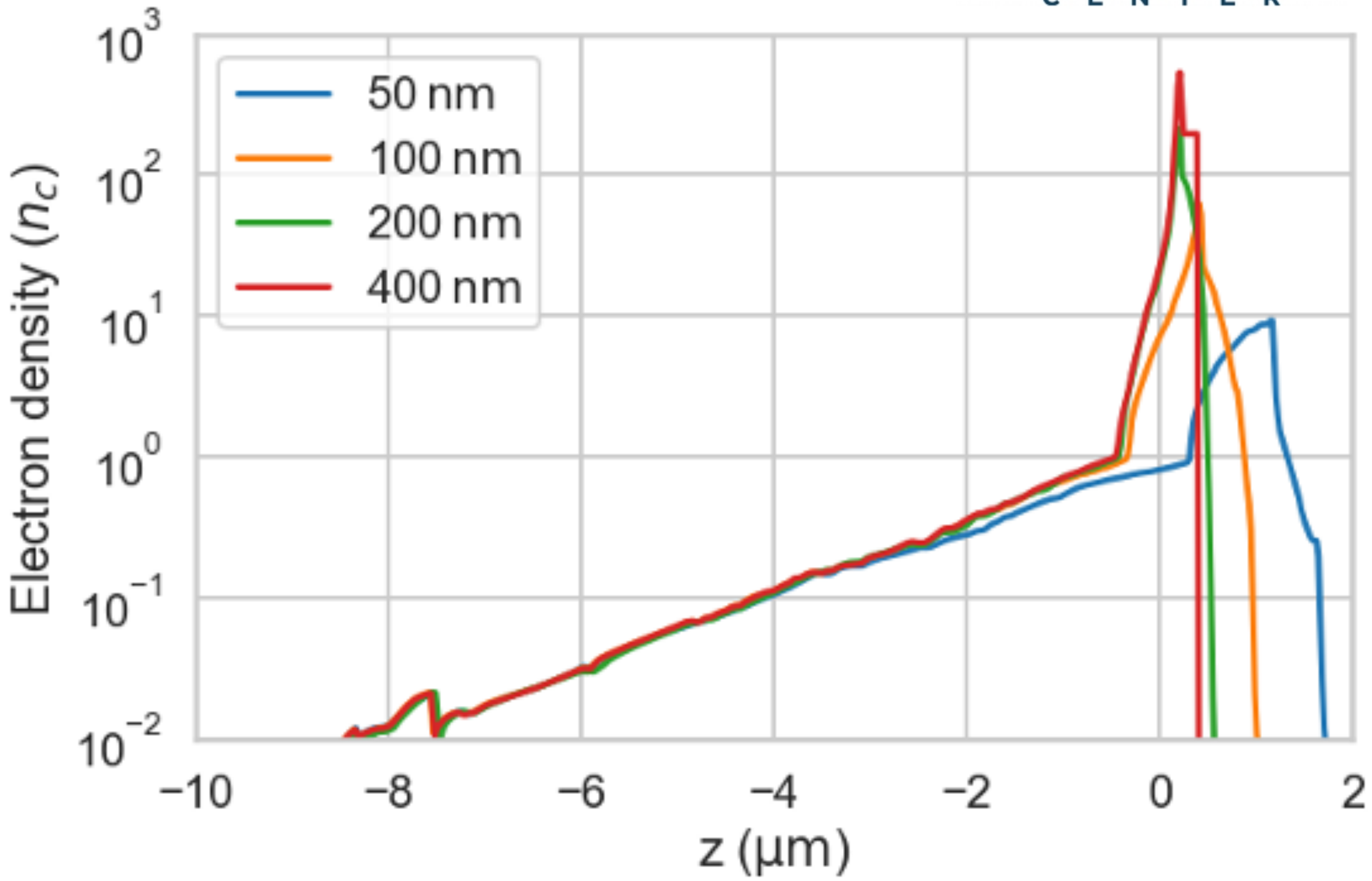


Target thickness at interaction point measured to be (600 ± 100) **nm**



Imperial College London

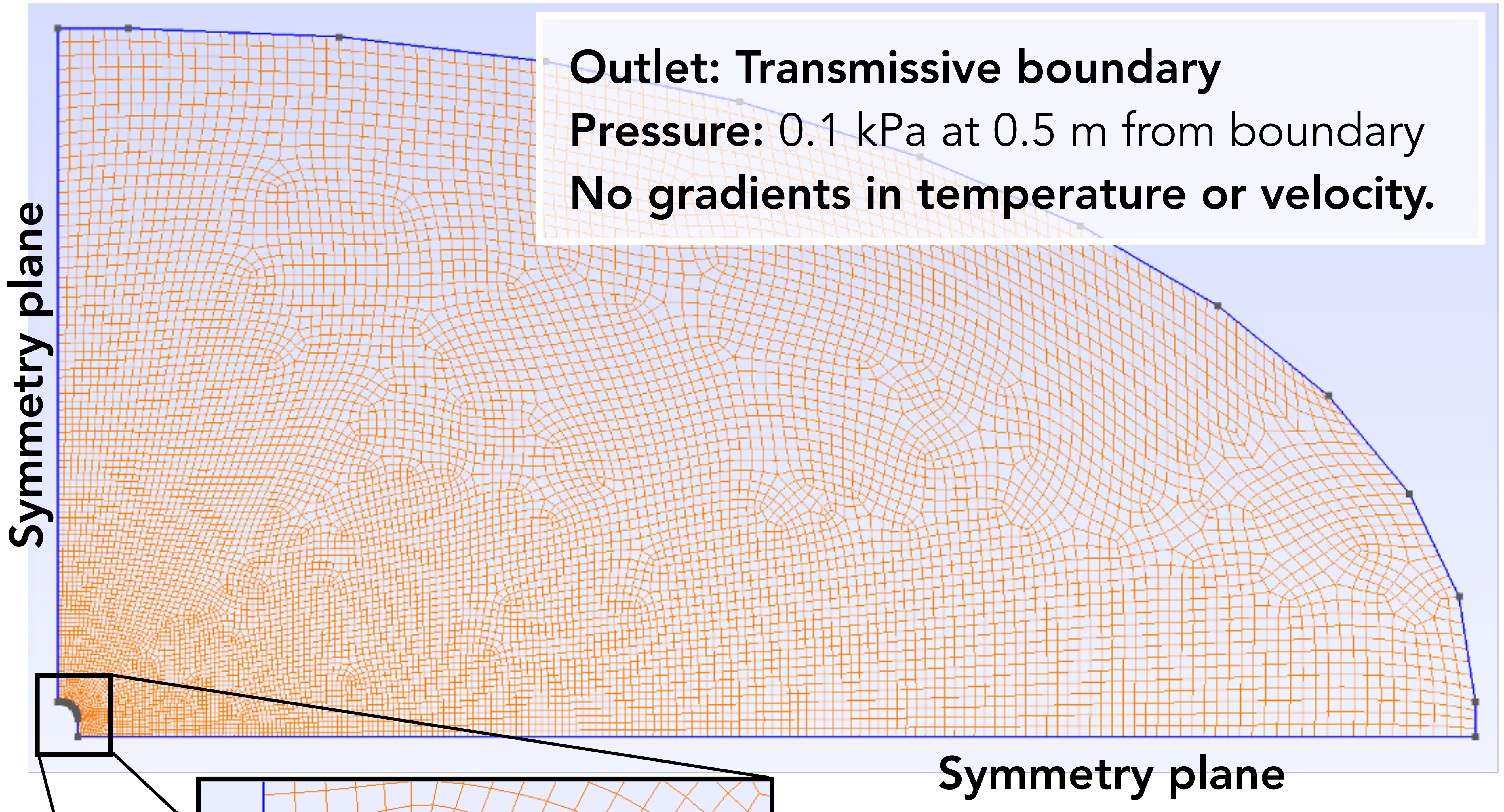
FLASH CENTER



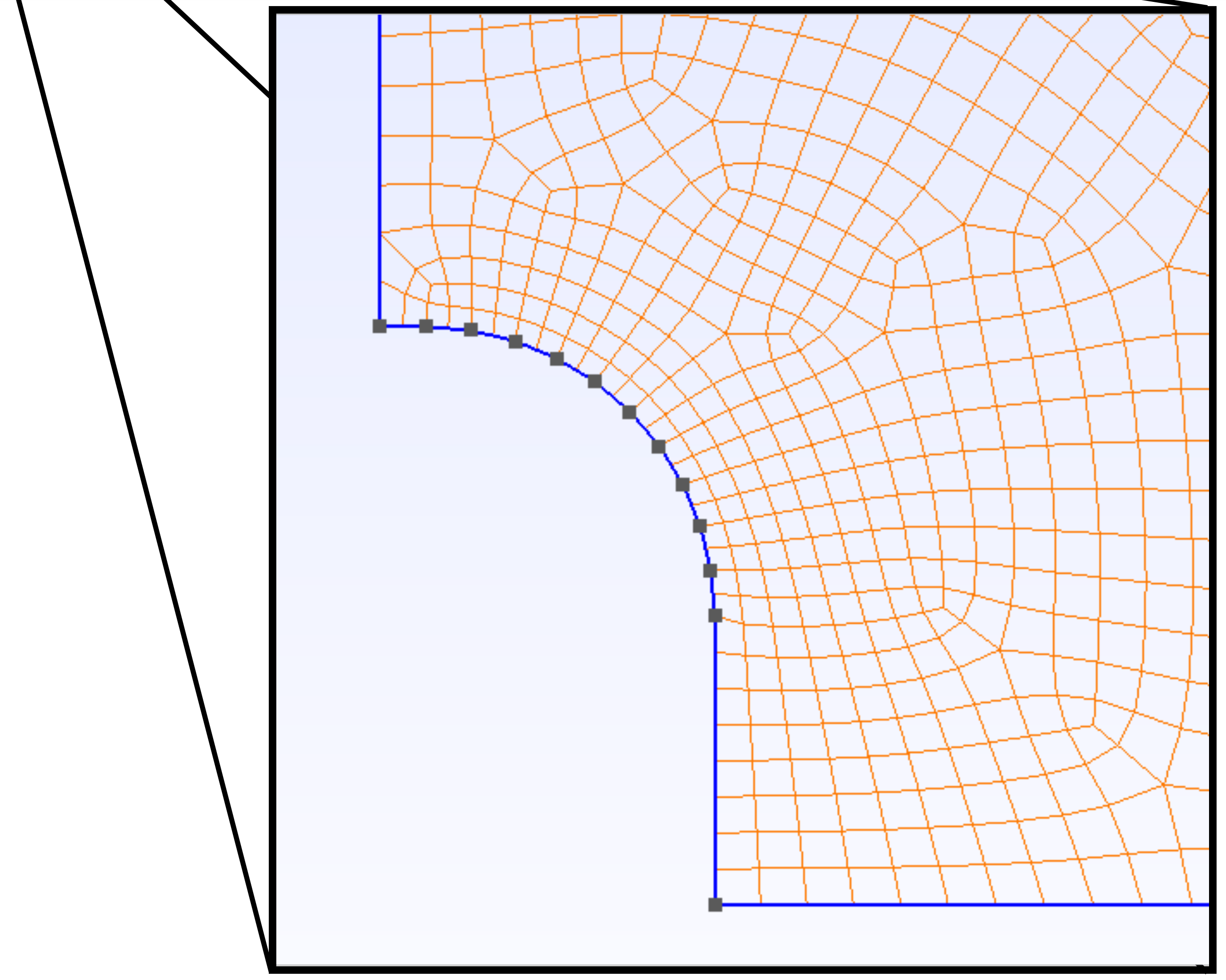
Courtesy of N. Dover

Consistent with measurements of specularly reflected laser profile and direction of proton beam along target normal.

Modelling of neutral gas profile



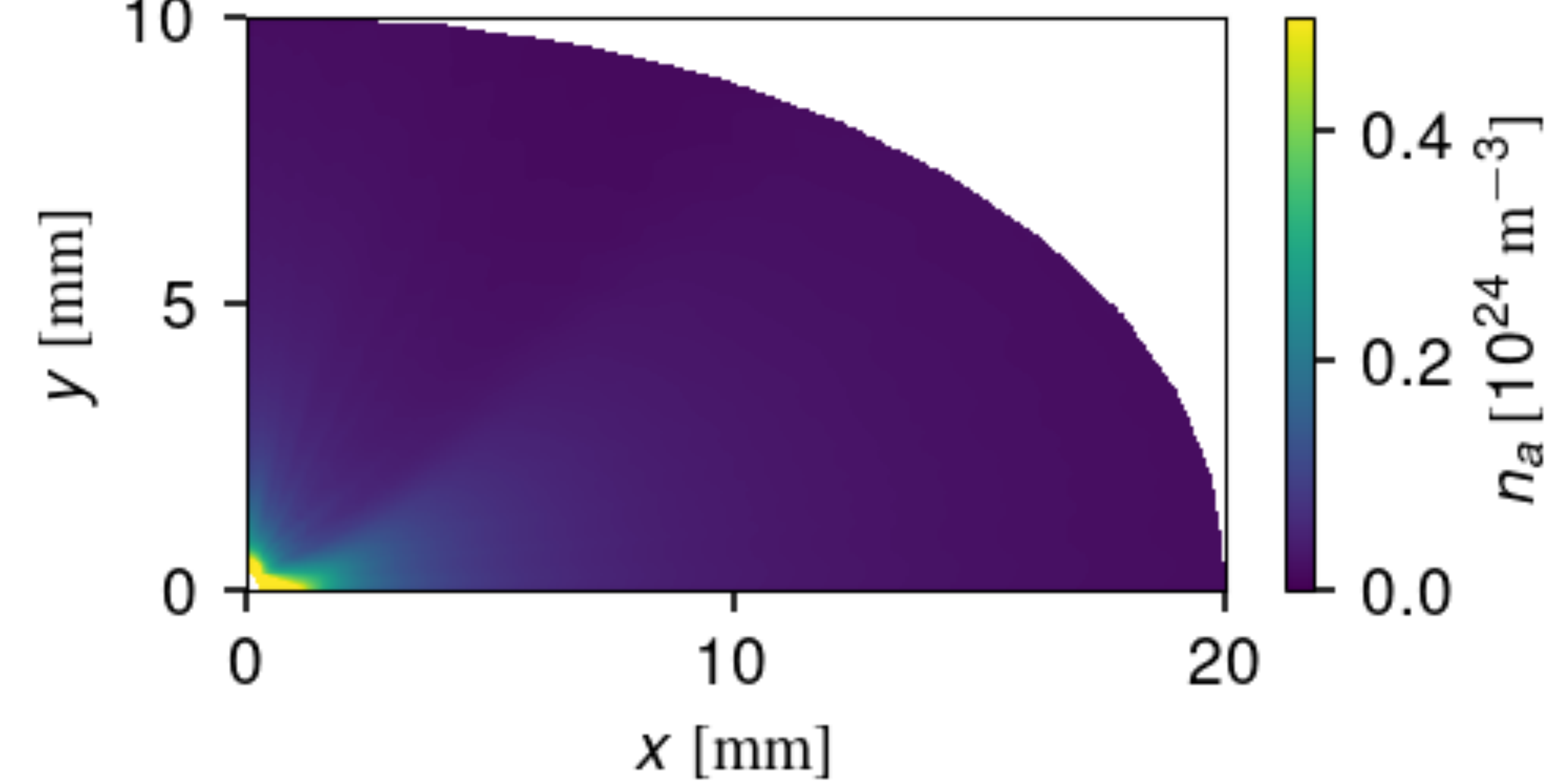
Outlet: Transmissive boundary
Pressure: 0.1 kPa at 0.5 m from boundary
No gradients in temperature or velocity.



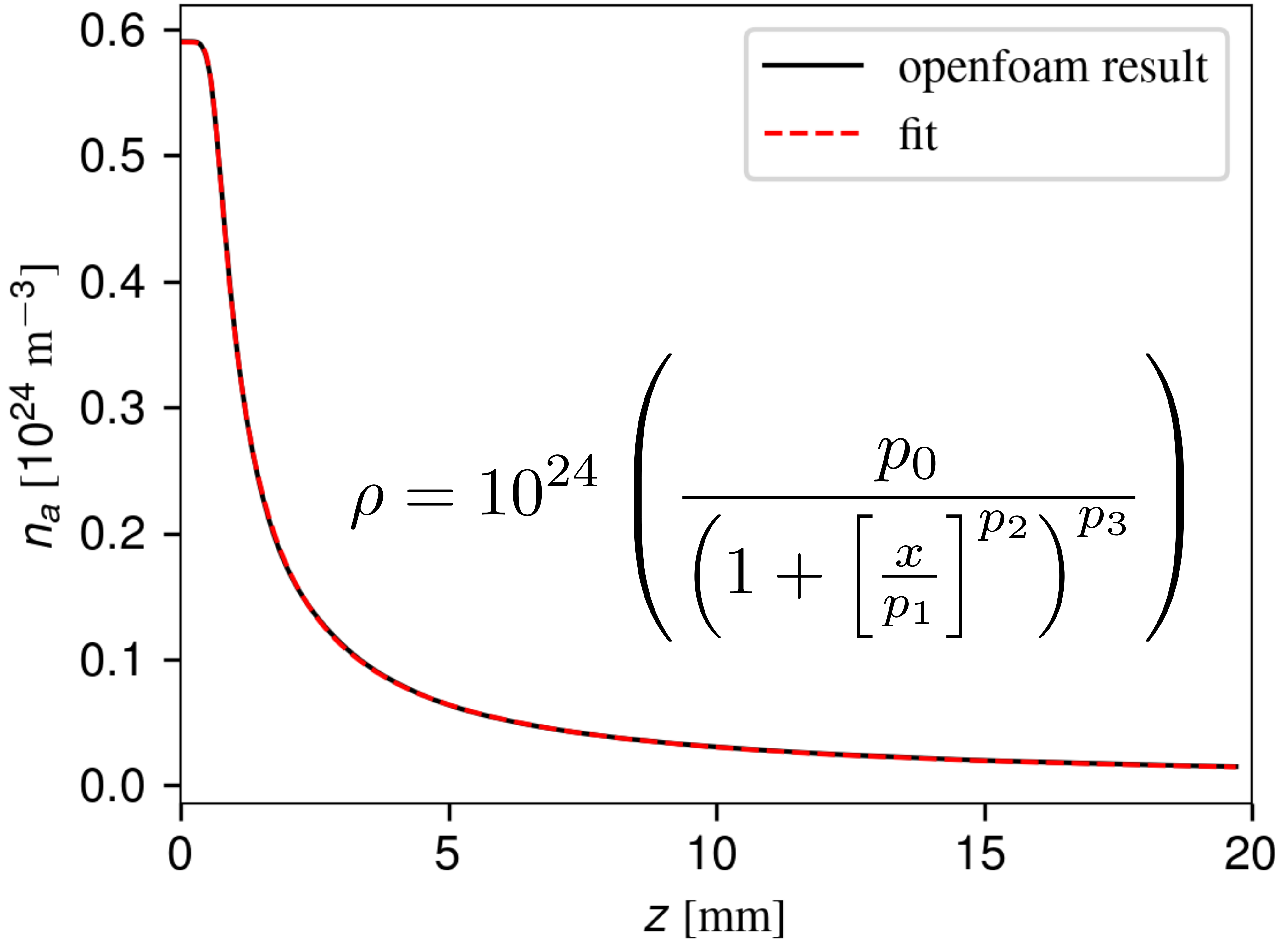
Inlet: Pressure driven flow
Pressure: 2 kPa
Temperature: 293 K
Width: 250 microns with rounded edges

OpenFOAM®

Neutral gas density map



Axial line out of gas density with analytic fit



$$\rho = 10^{24}\left(\frac{p_0}{\left(1+\left[\frac{x}{p_1}\right]^{p_2}\right)^{p_3}}\right)$$

Simulations of proton bunch propagation through vapour

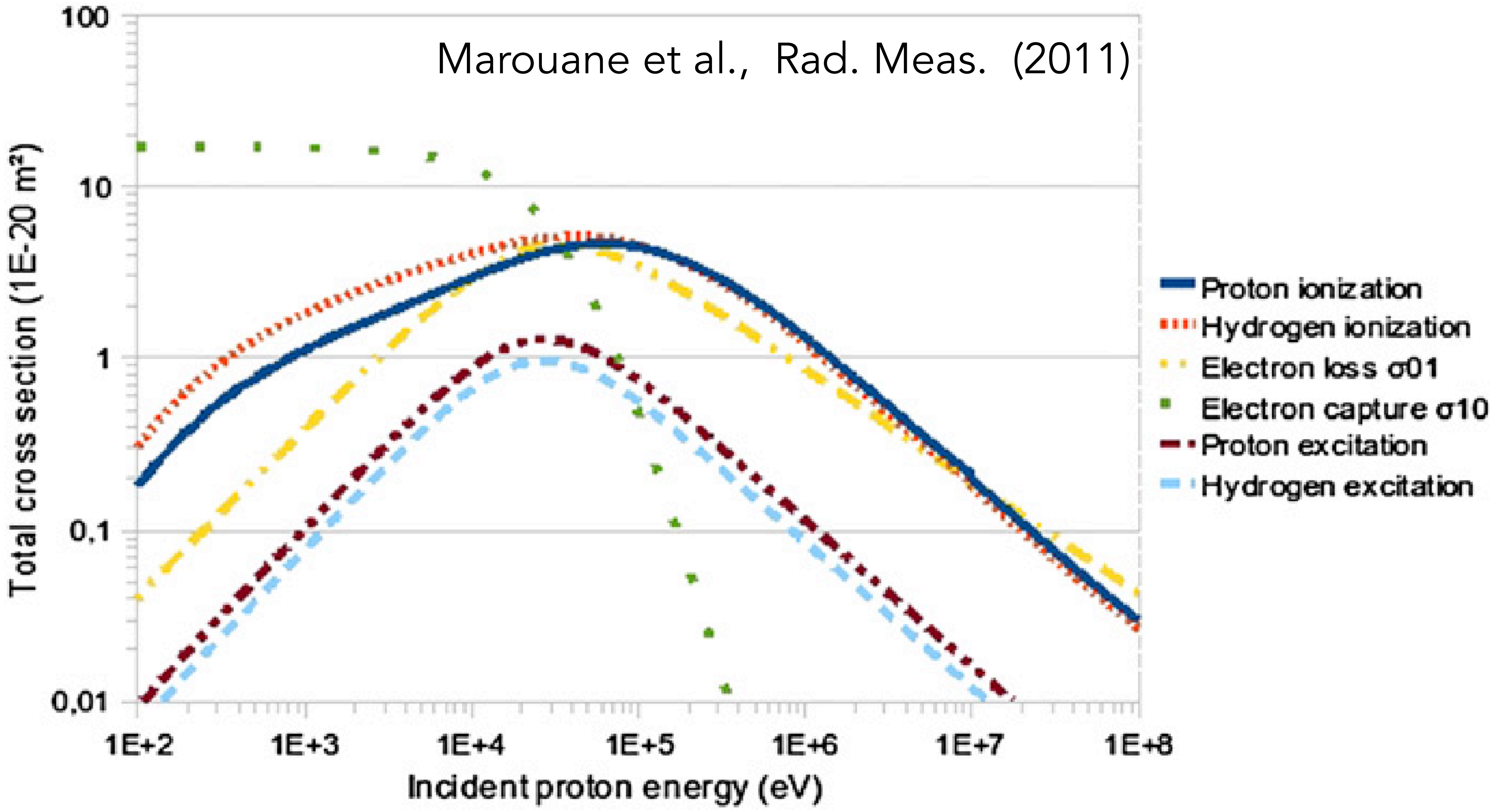
- 2D3v Particle-in-cell simulations used to explore the propagation of charge-neutral particle bunch of electrons and protons through a neutral water vapour.
- Custom impact ionisation model developed at Uni. Michigan for the ionisation of the neutral vapour by MeV protons. Plasma collisions not modelled.

Osiris

Simulation parameters:

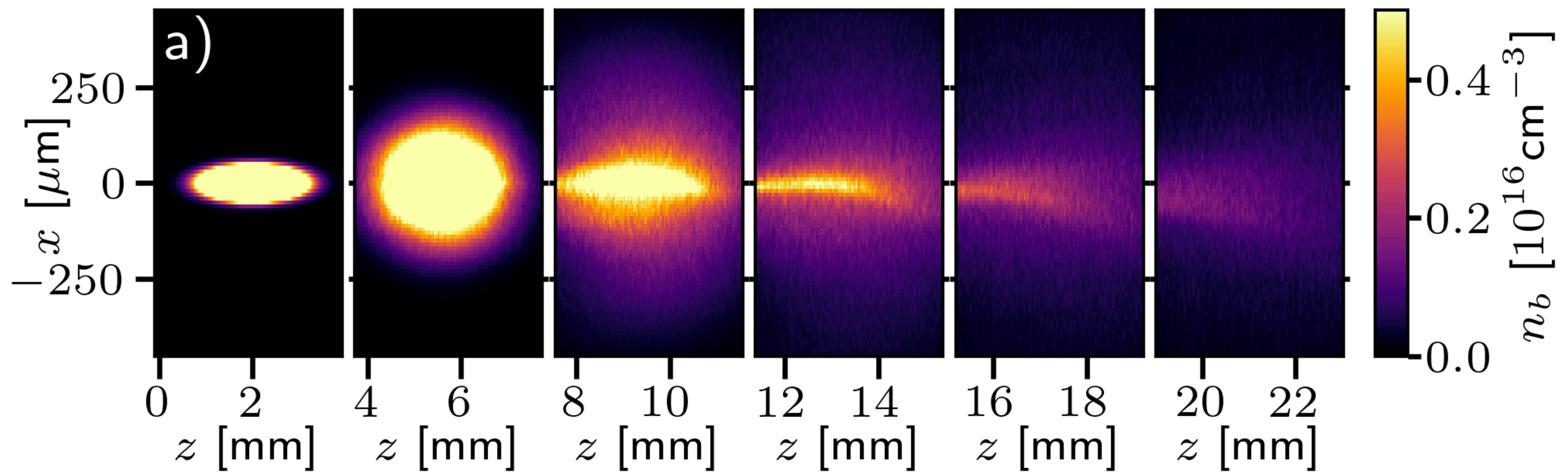
Box size	1.2 x 26 mm
Grid size	240 x 1300
Timestep	30 fs
Macroparticles /cell	Beam: 1296 protons, 36 electrons. Vapour: up to 900 for $Z_{max} = +1$.
Initial energetic electron-proton beam	2D Gaussian($w_z = 500\ \mu m$; $w_x = 20\ \mu m$) with peak density $1.1 \times 10^{17}\ cm^{-3}$. Divergence 20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

Impact ionisation cross sections:

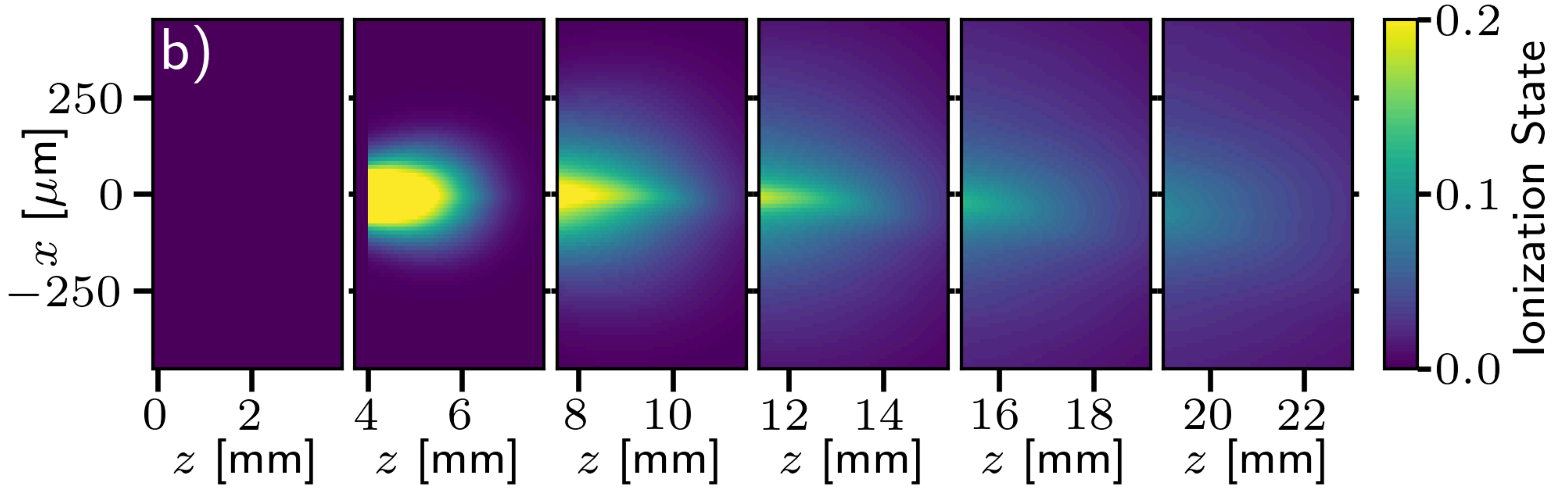


Simulations using simulated neutral vapour density profile

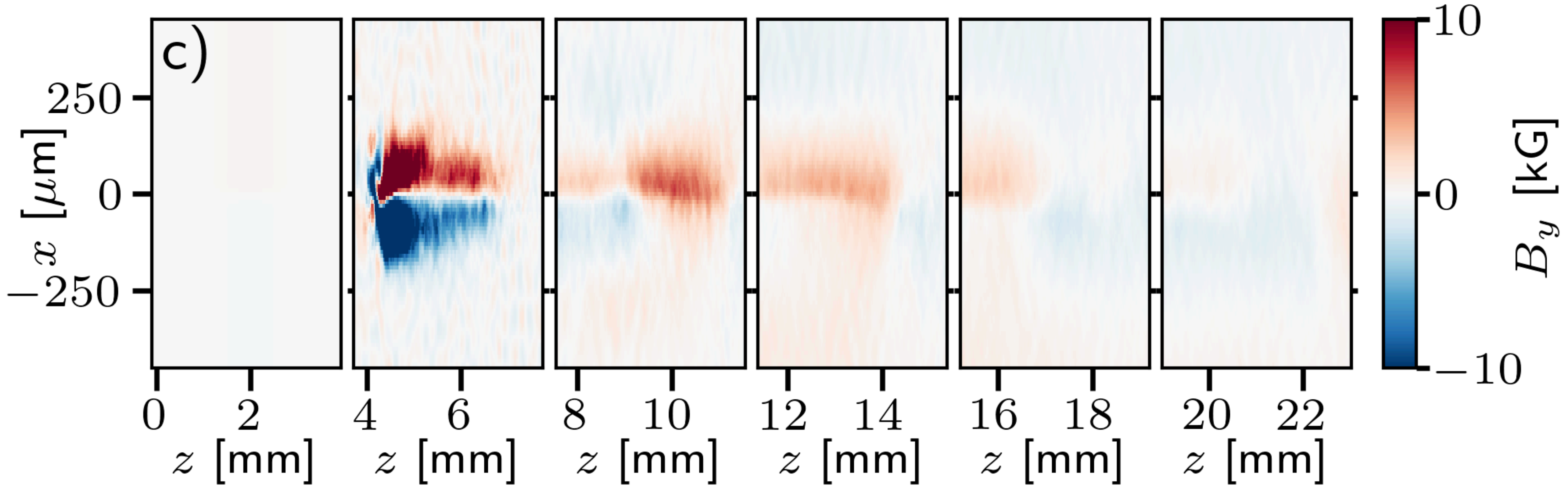
1) Central region of proton bunch pinches onto the axis.



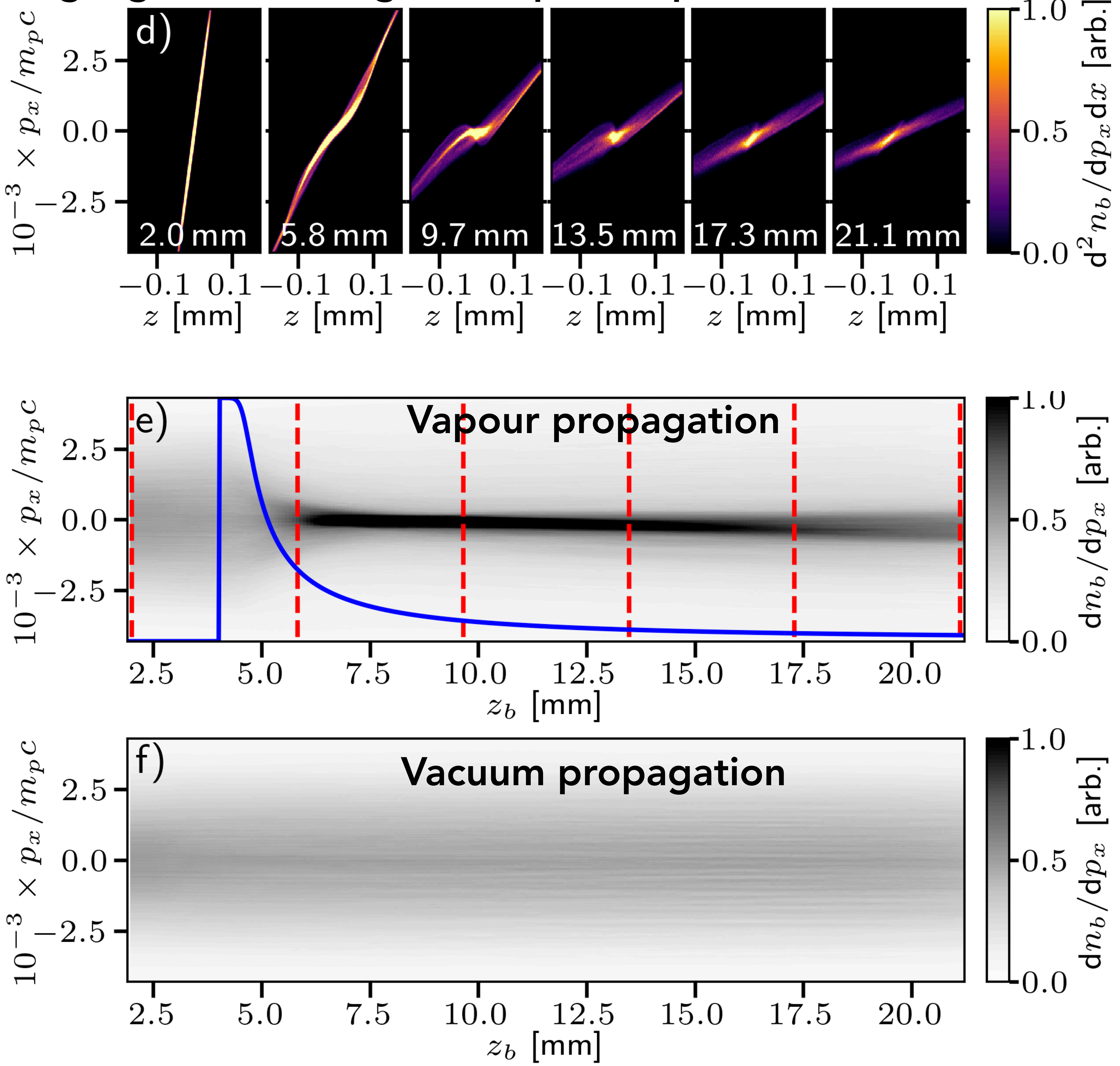
2) Ionisation of background vapour by proton impact.



3) Magnetic field grows around energetic proton bunch.



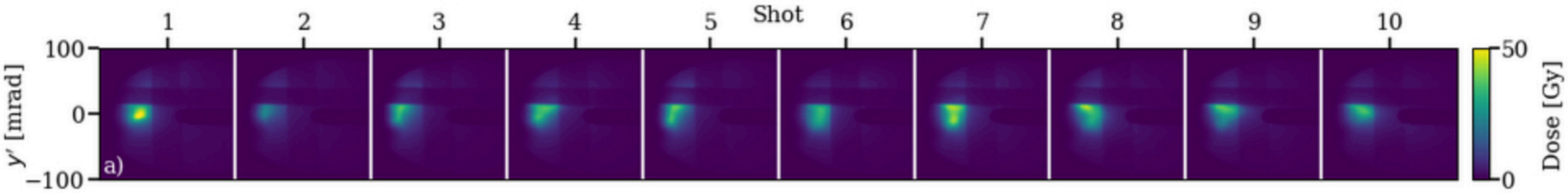
4) Phase space of proton bunch in vapour and vacuum highlights flattening of the phase space at the bunch centre.



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

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.

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ELI Beamlines: V. Istokskaiia, L. Giuffrida.

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