Acceleration of stable, low-divergence proton beams from novel liquid sheet targets

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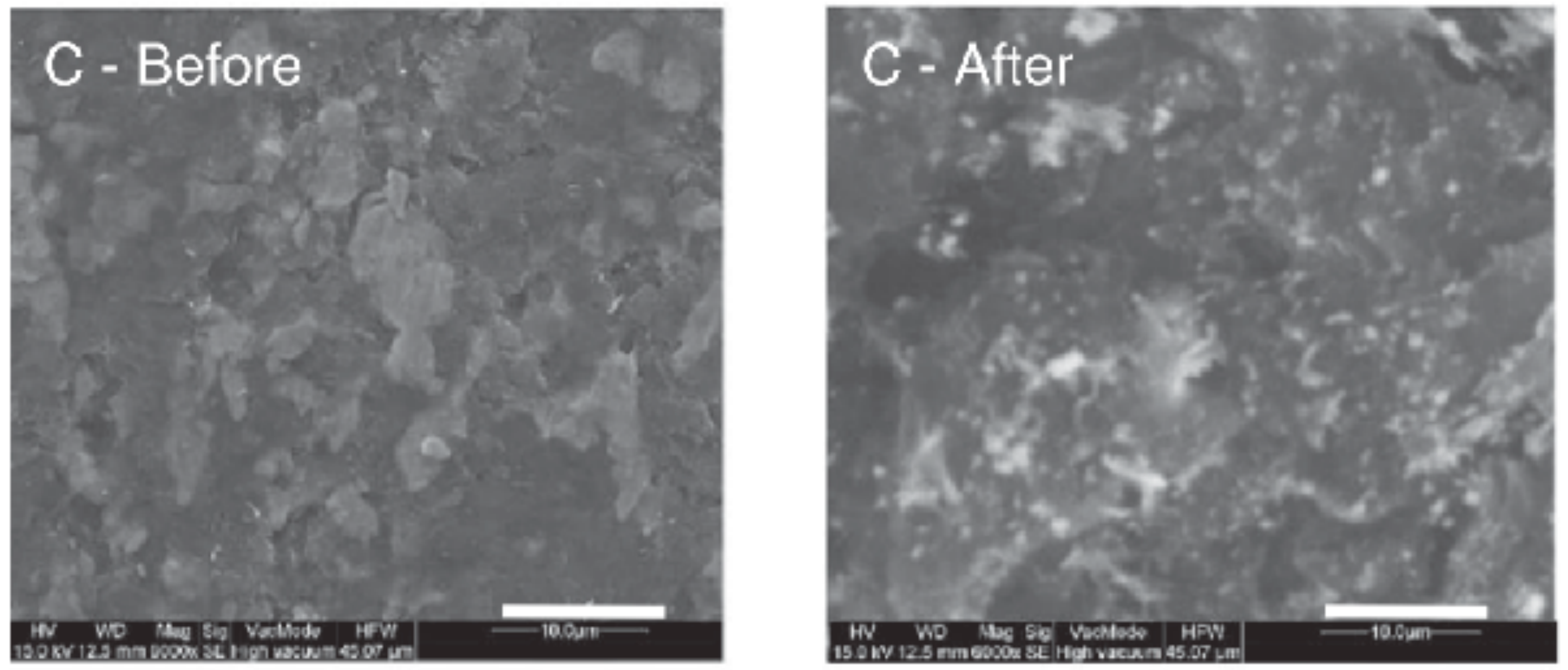
Target normal sheath acceleration (TNSA)

Applications (e.g Damage testing)



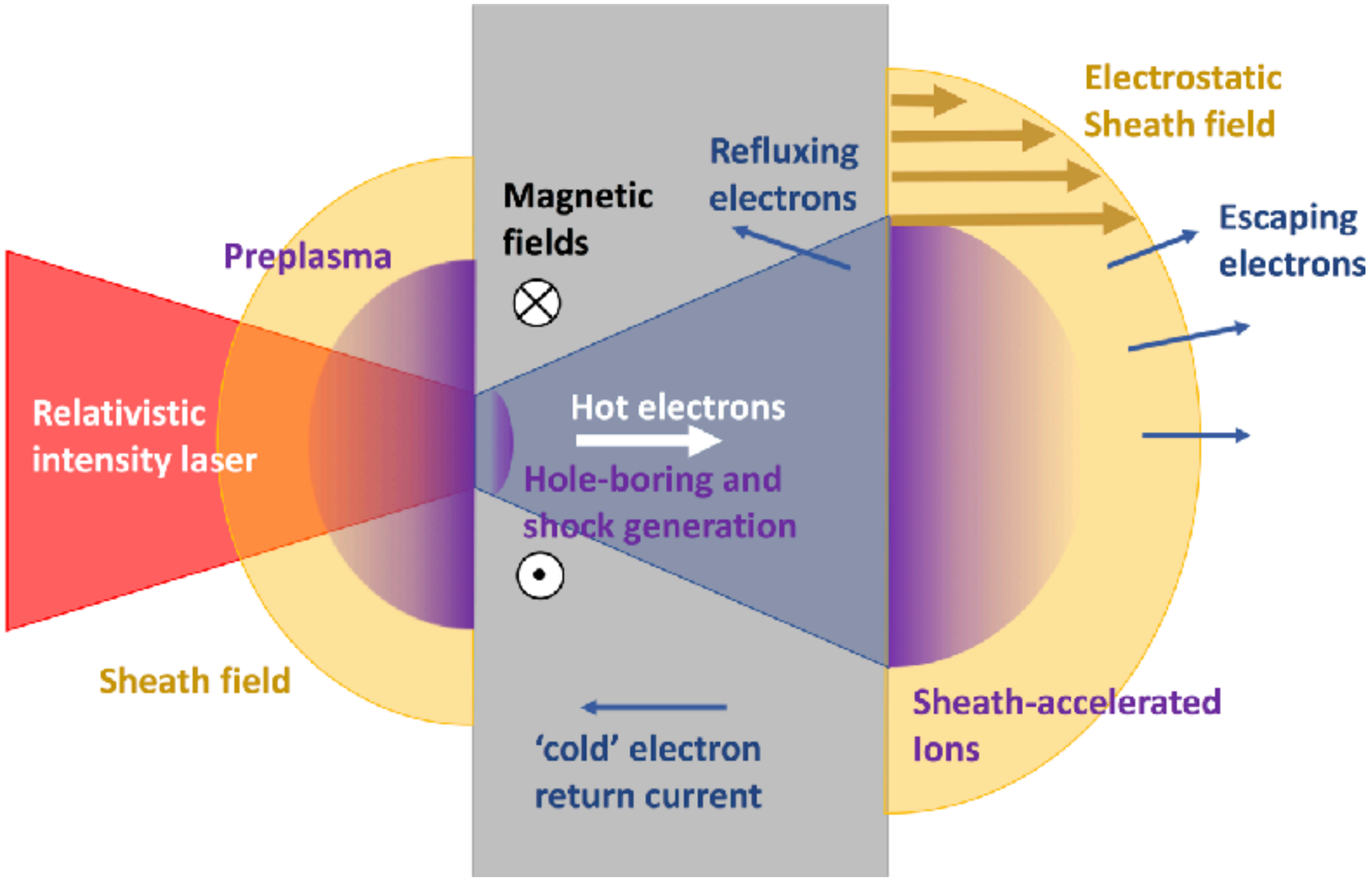
Barberio et al., Nat. Comms. (2018)

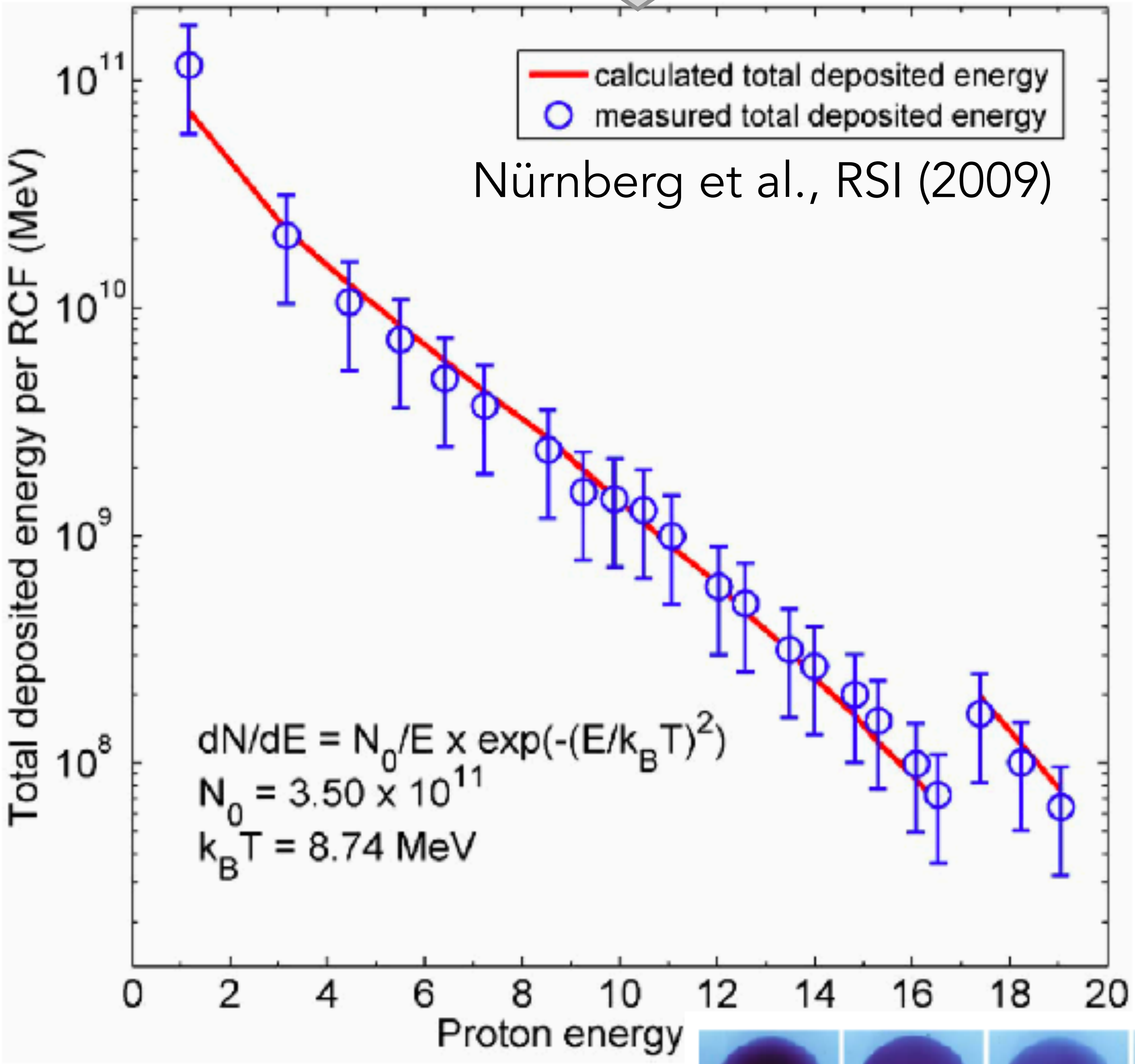
TNSA proton beams

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

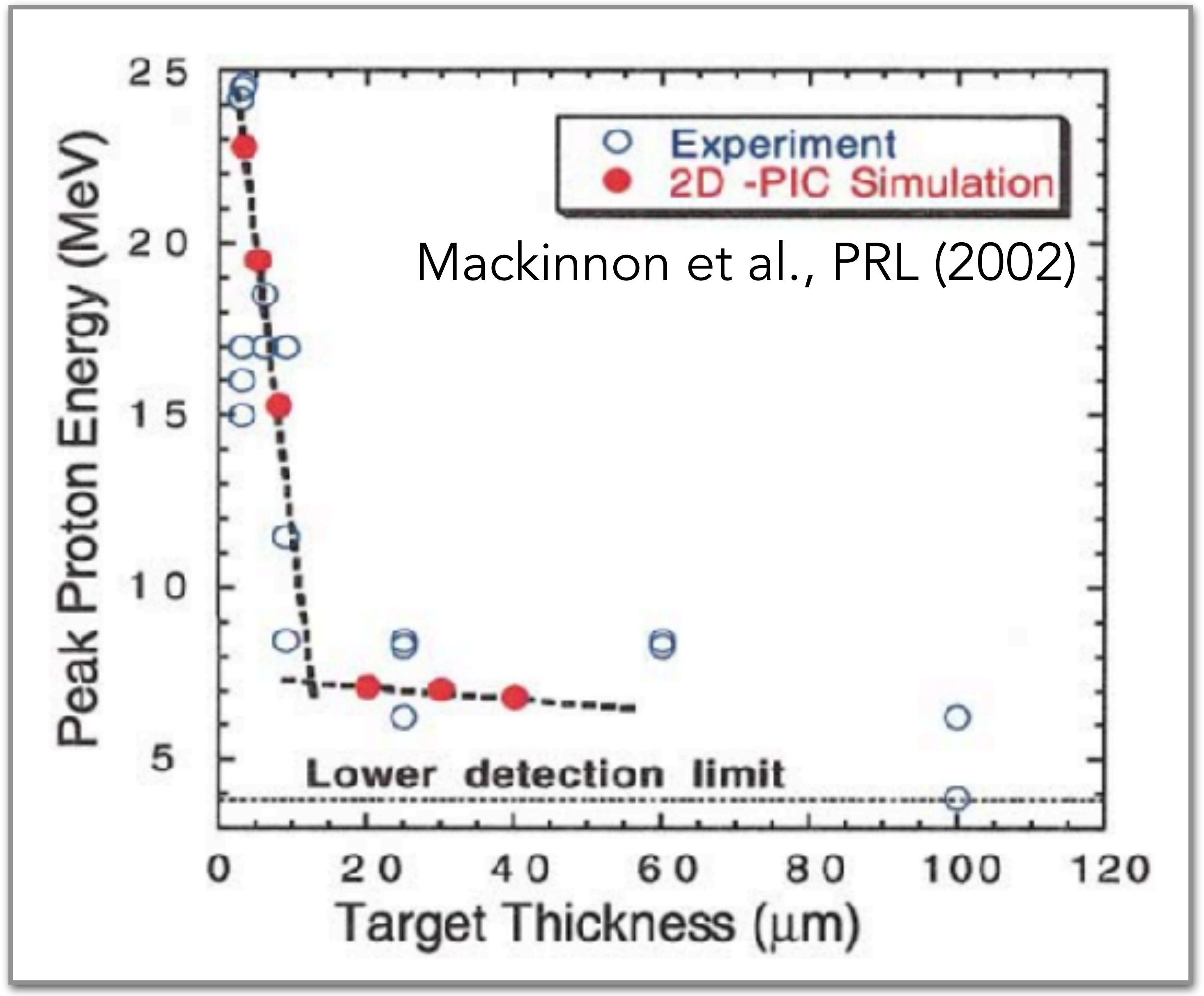
TNSA trends:

- Higher energy → higher proton flux
- Higher intensity → higher max proton energy
- Thinner targets → higher max proton energy





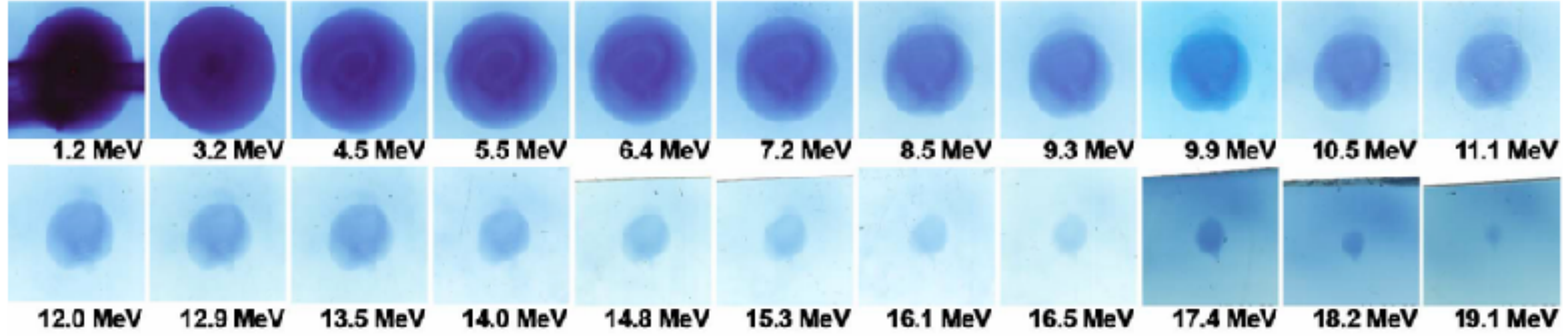
Nürnberg et al., RSI (2009)



Mackinnon et al., PRL (2002)

increasing energy

Slices of proton beam profile for increasing proton energy:



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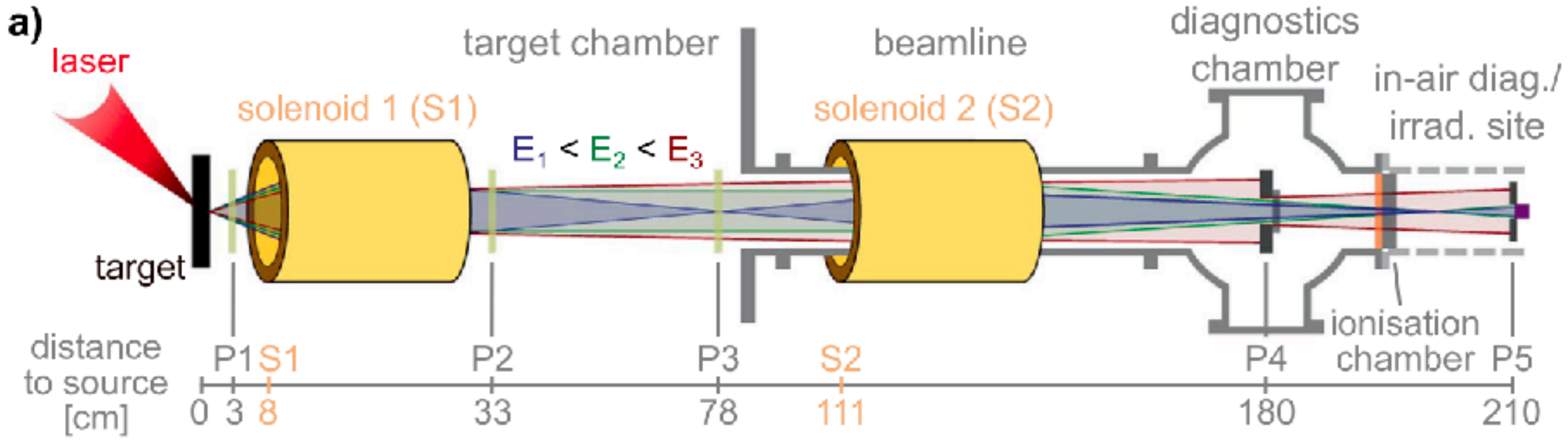
Developing sources for applications:

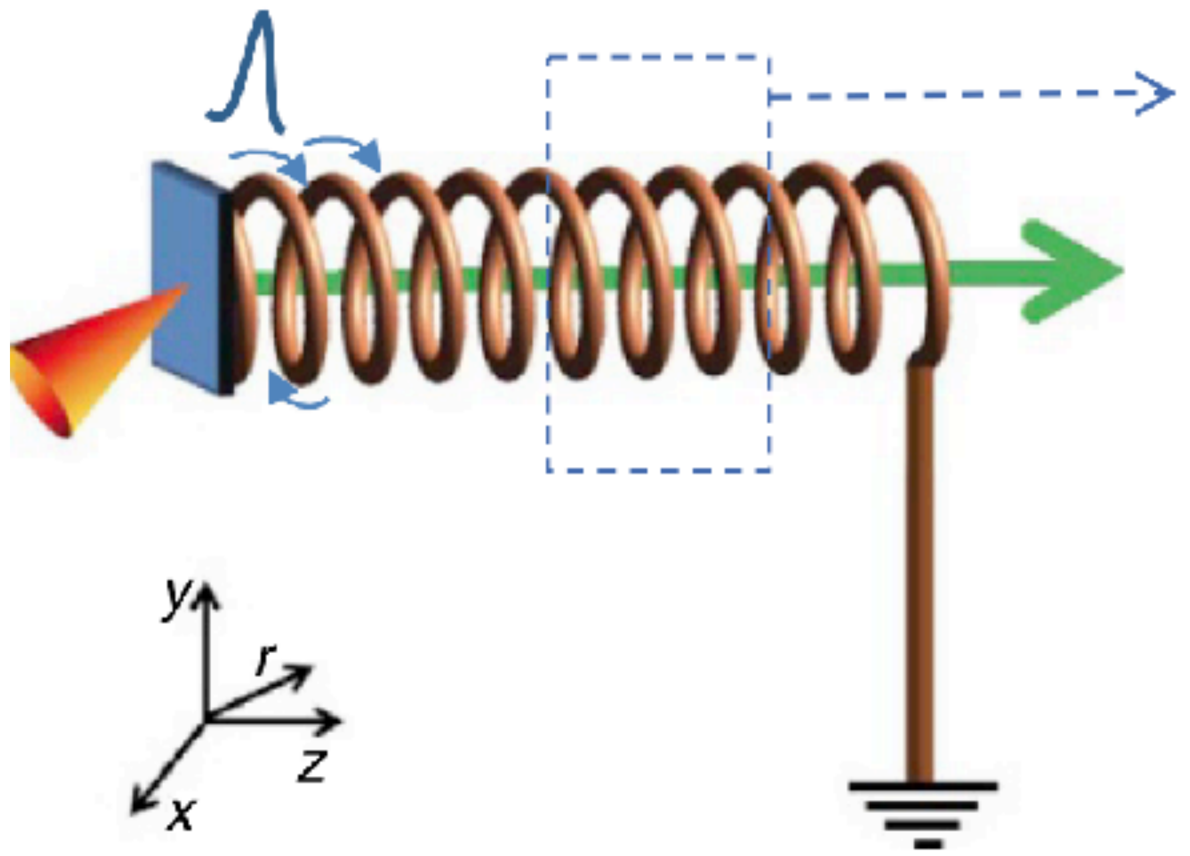
Divergence reduction:

RF or plasma beam optics



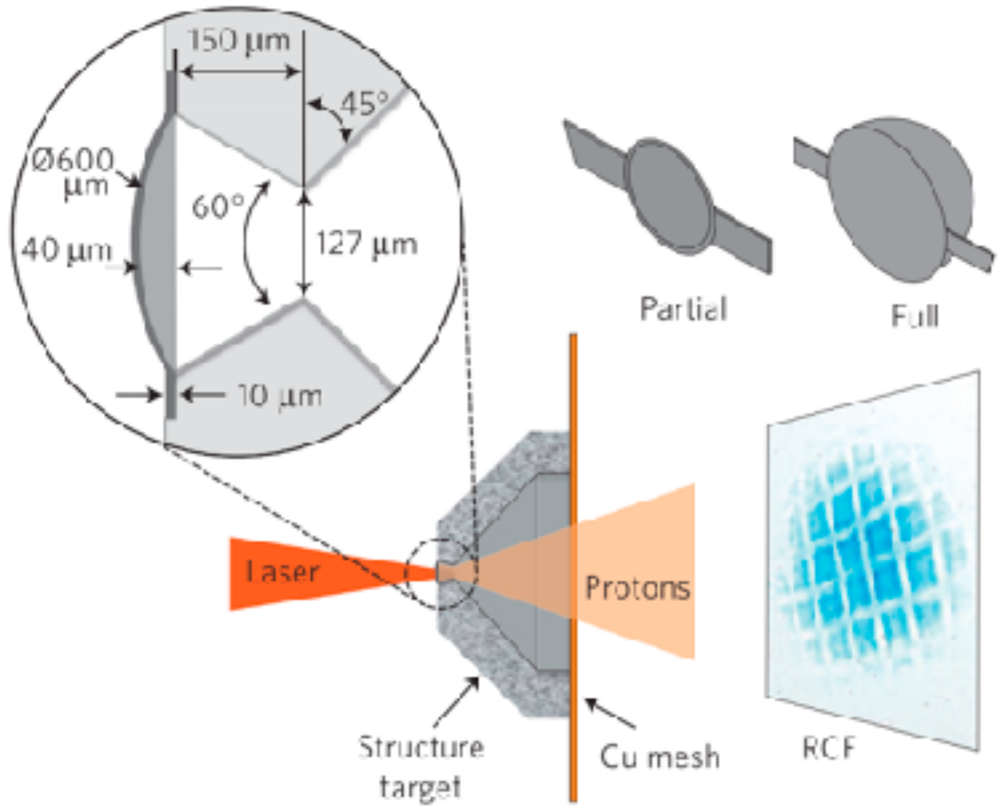
Brack et al., Sci. Rep. (2020)

Self-generated focusing fields



Kar et al., Nat Comms (2016)

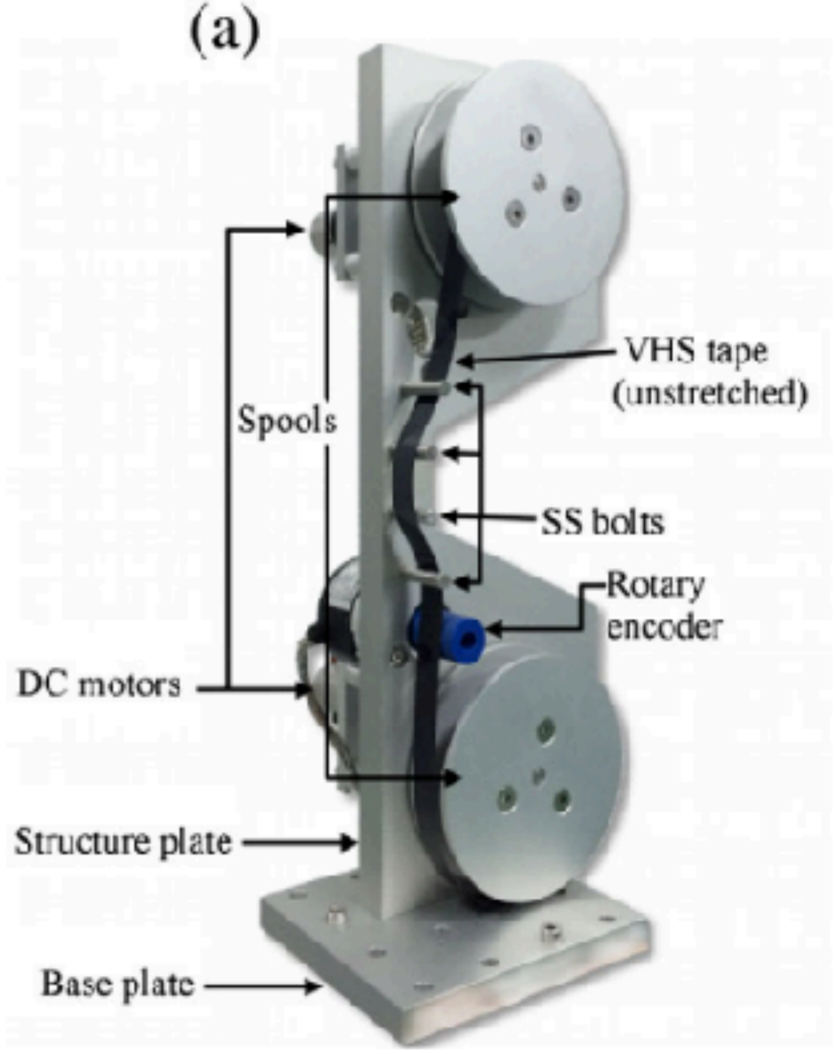
Shaped targets



Bartel et al., Nat Phys (2011)

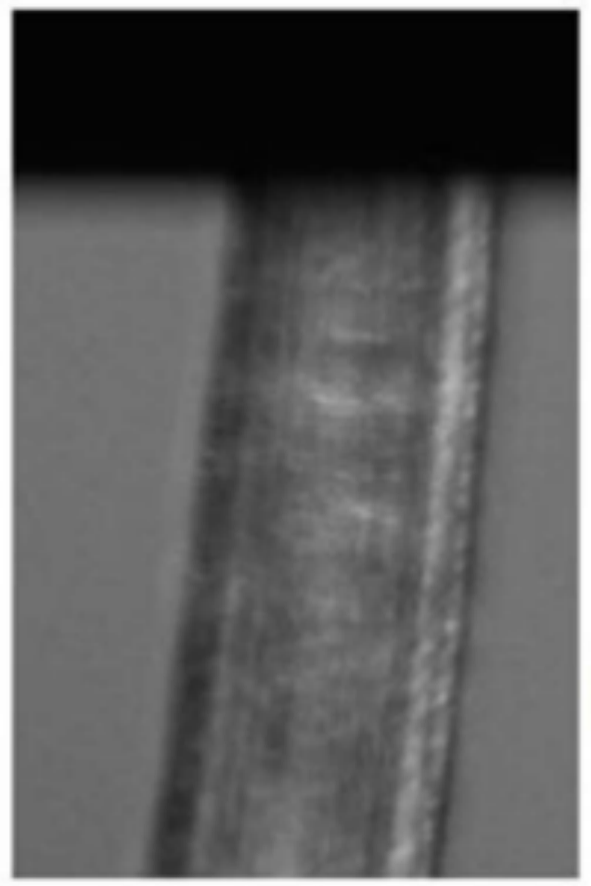
High-rep targets and diagnostics:

Tape-drives



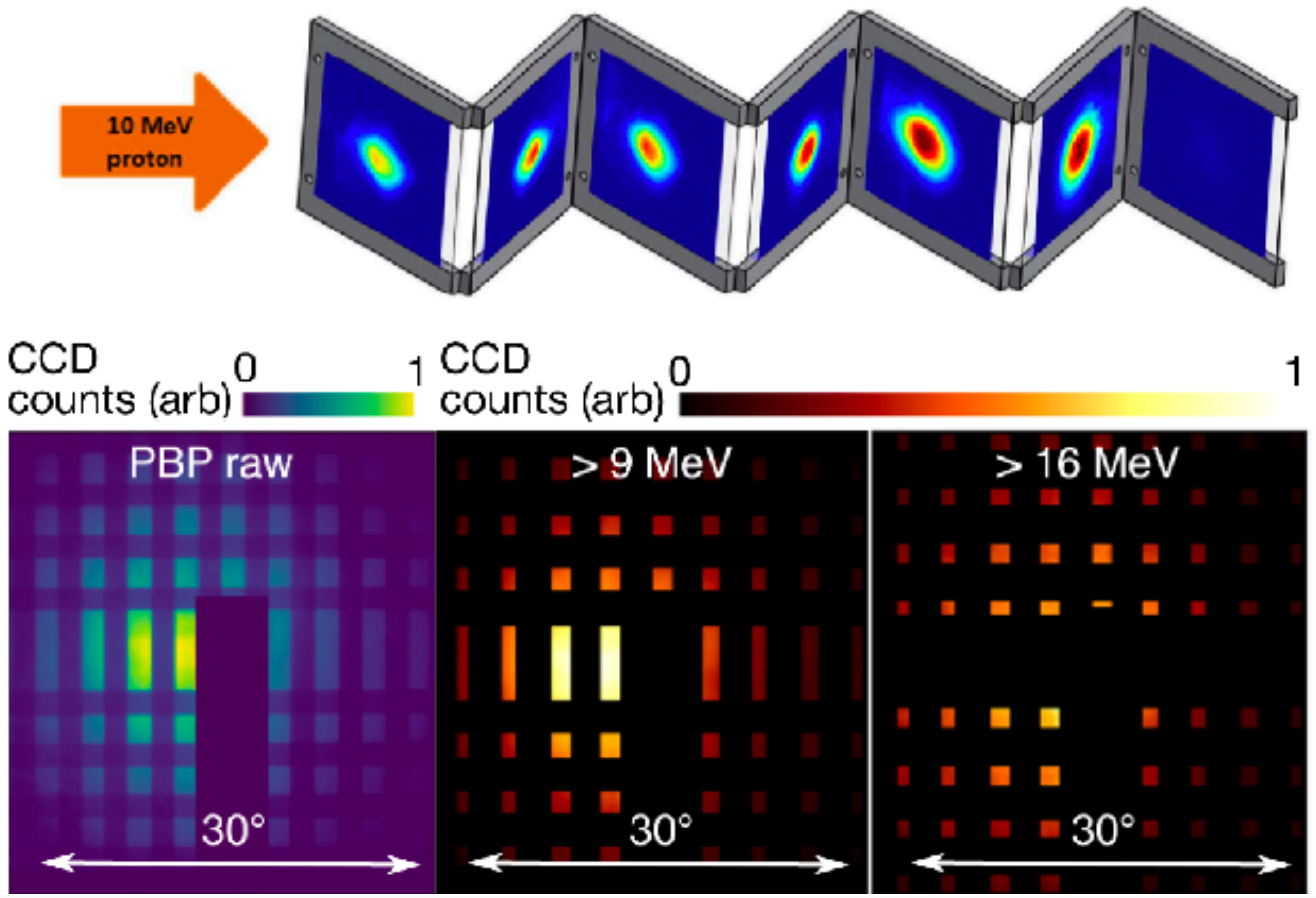
M. Noaman-ul-Haq et al., PRAB (2017)

Cryogenic ribbon



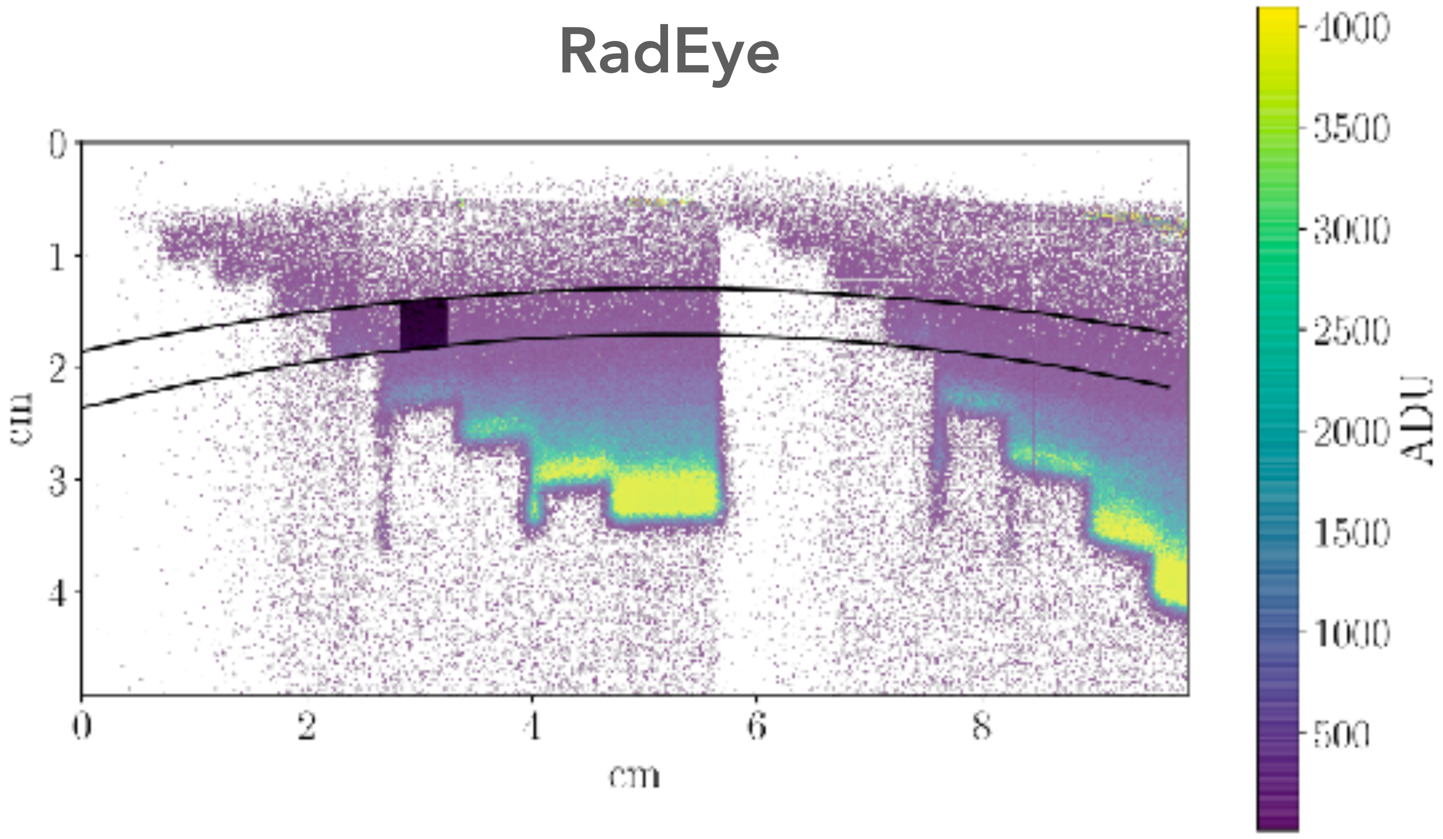
Kraft et al. PPCF (2018)

Scintillators



Direct detectors

RadEye

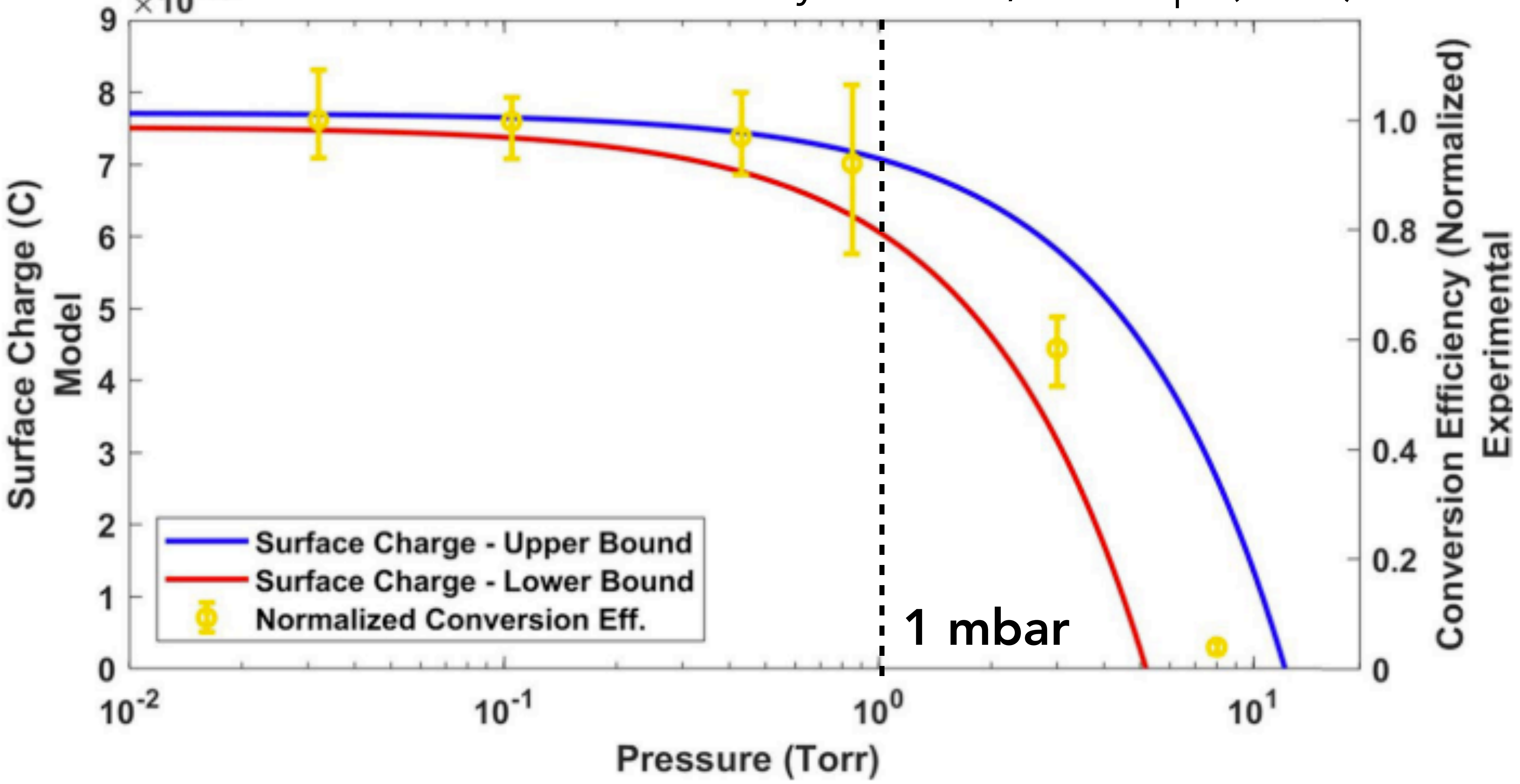


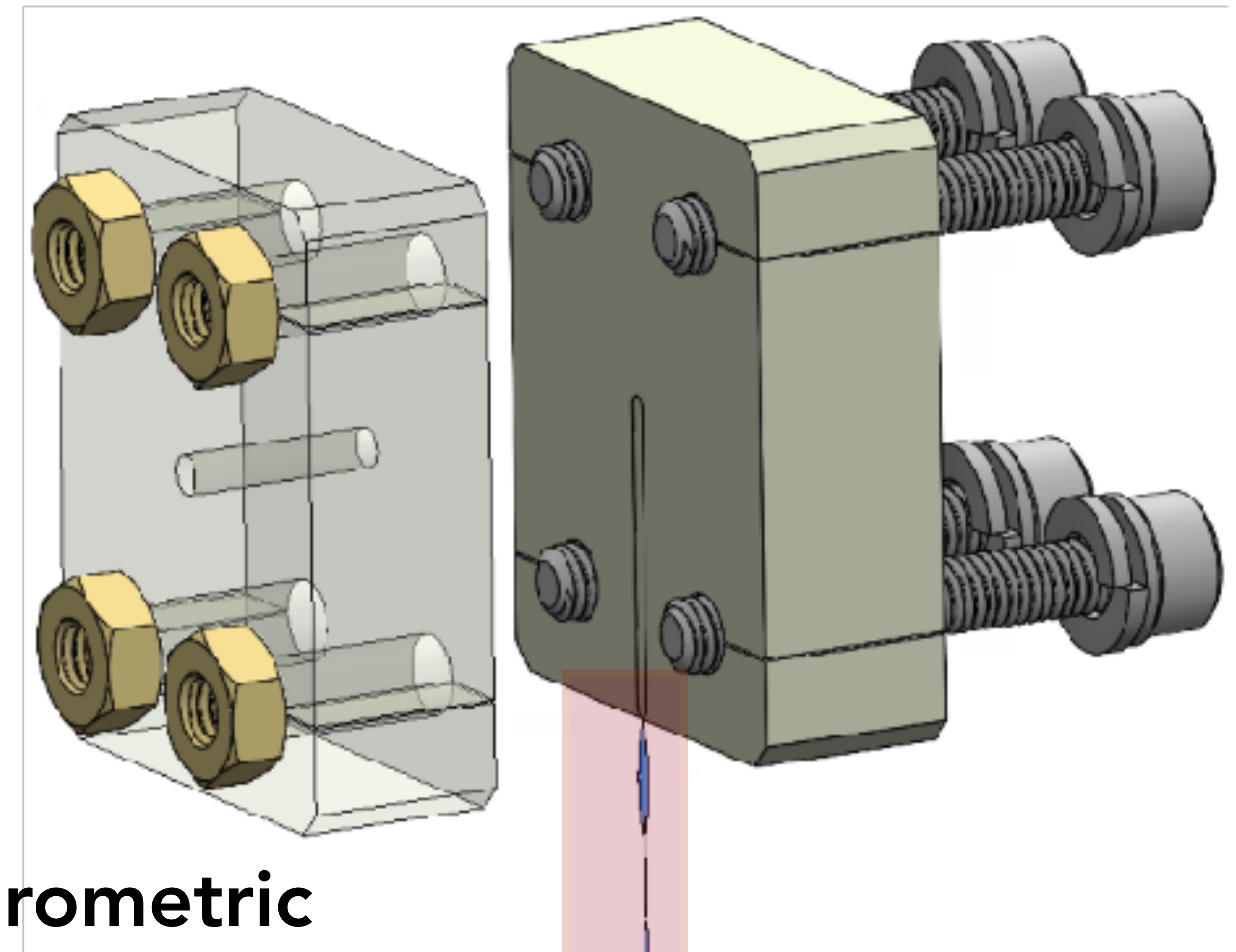
Dover et al., Rev. Sci. Instr. (2017), Huault et al., HPLSE (2019),
Hartmann et al., arXiv:2111.08461v1 (2021),

Liquid sheets as thin, high-rep targetry

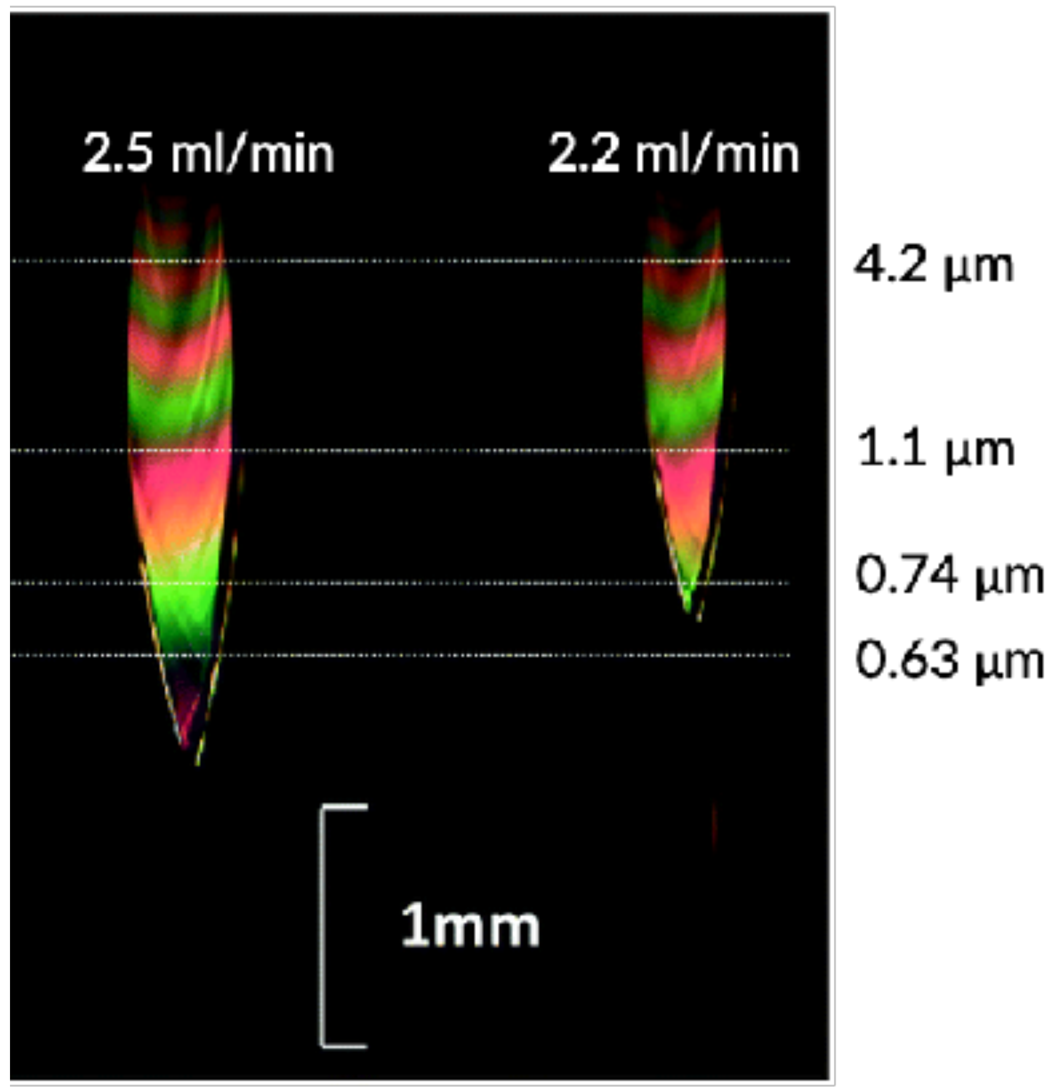
- High-purity mm-scale liquid sheet with variable thickness along sheet compatible with kHz operation (Morrison et al., NJP (2018)) and Joule-class lasers.
- **Challenges:** Evaporation of liquid in vacuum leads to low-density vapour around target and freezing of liquid.
- **Mitigation:** Choice of liquids which have low vapour pressure and heated 'catchers' which help to maintain typical vacuum.

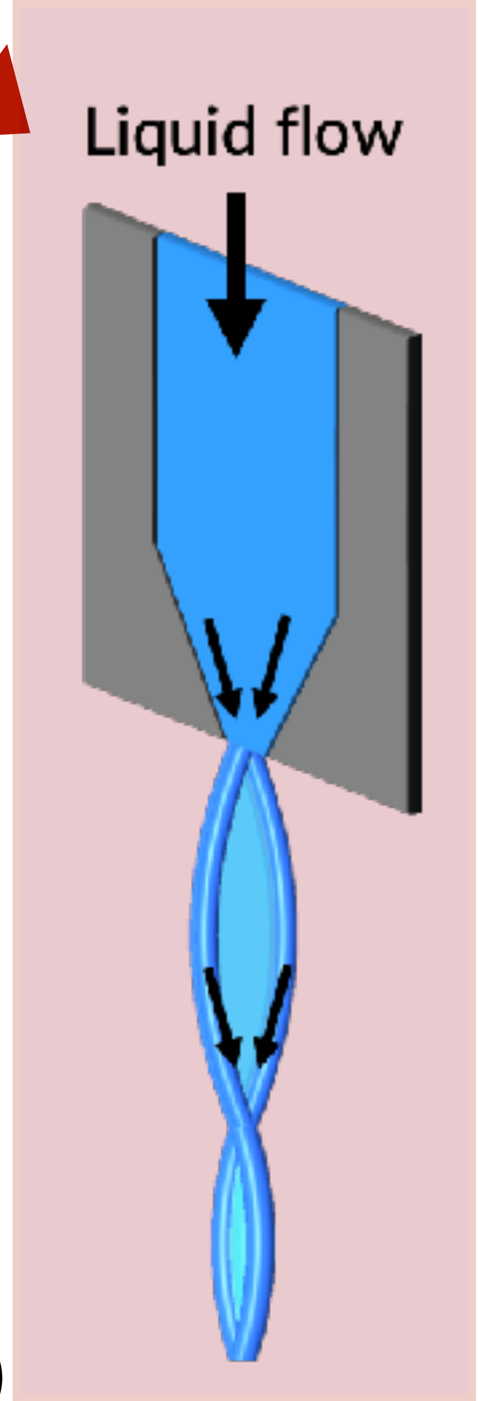
Snyder et al., Sci. Rep. (2020)





Interferometric thickness measurement





Treffert et al., APL (2022)
Crissmann et al. Lab Chip (2022)

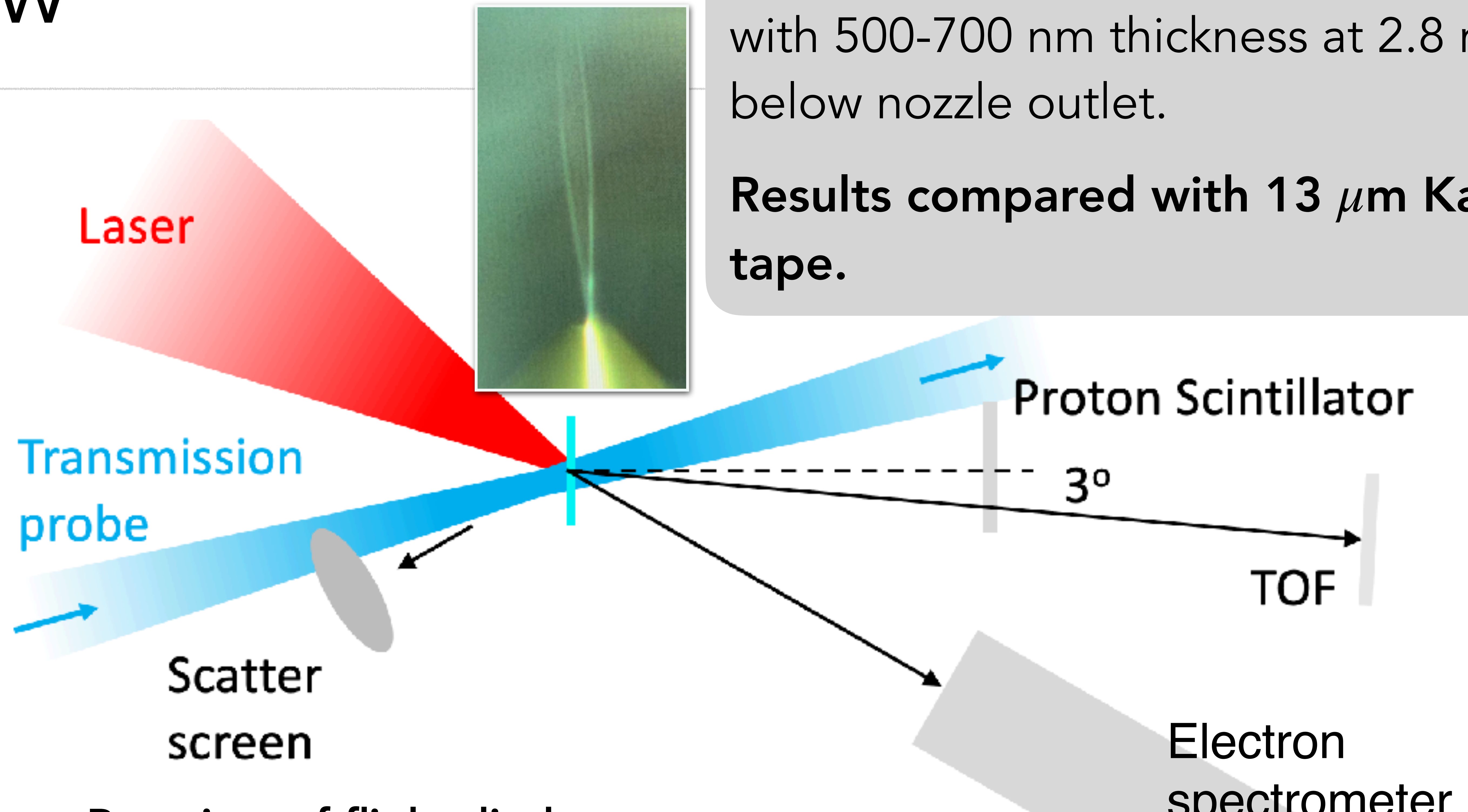
Experimental overview

Laser parameters: Up to 200 mJ on target in 40 fs (best compression) focused with F/2.5 OAP (Rayleigh length ~ 15 μm) with a contrast of 10^{-7} at 20 ps before peak.

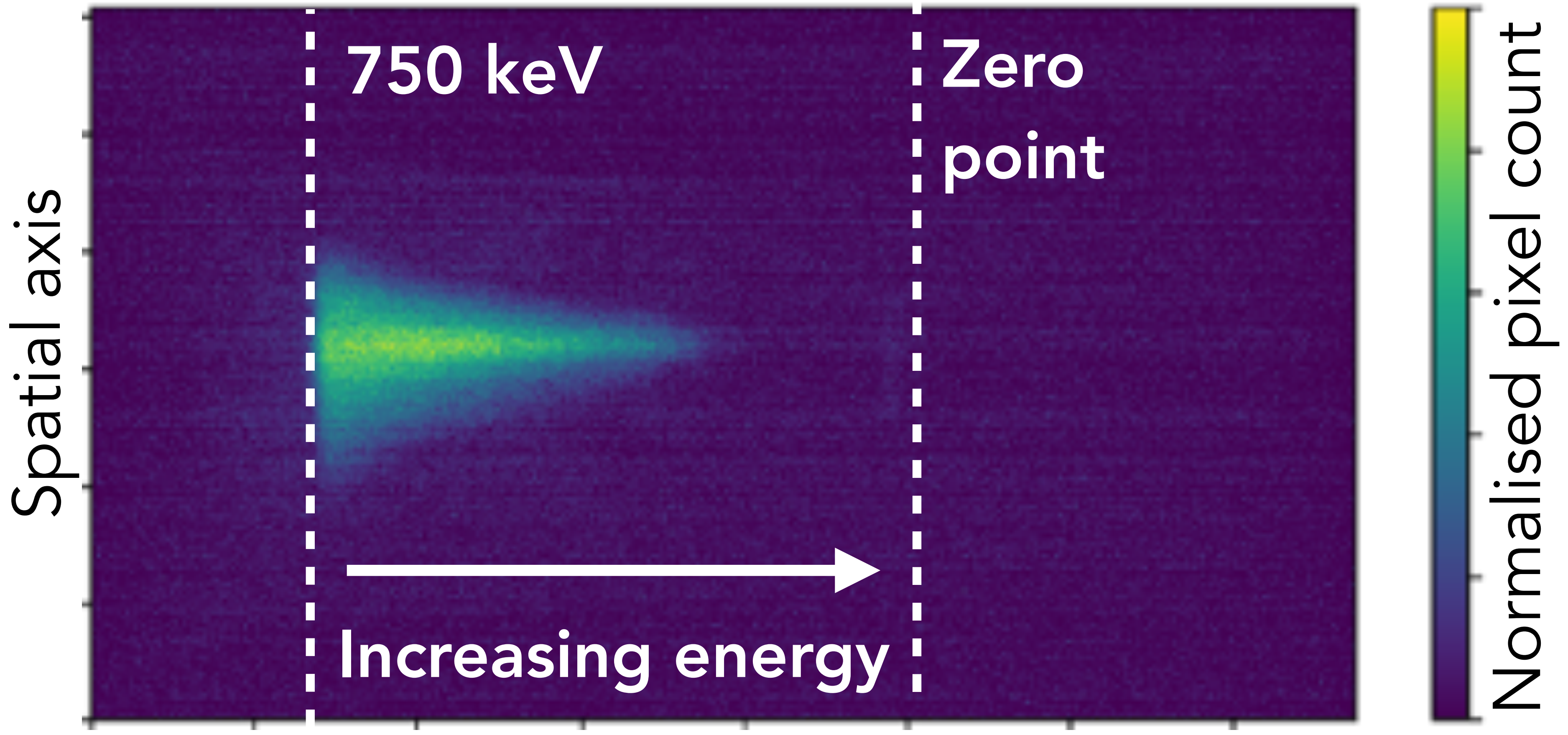
Vacuum parameters:
Vacuum pressure of 0.1 mbar at approx. 1 m from liquid sheet.

Target parameters: Ultra-pure water with 500-700 nm thickness at 2.8 mm below nozzle outlet.

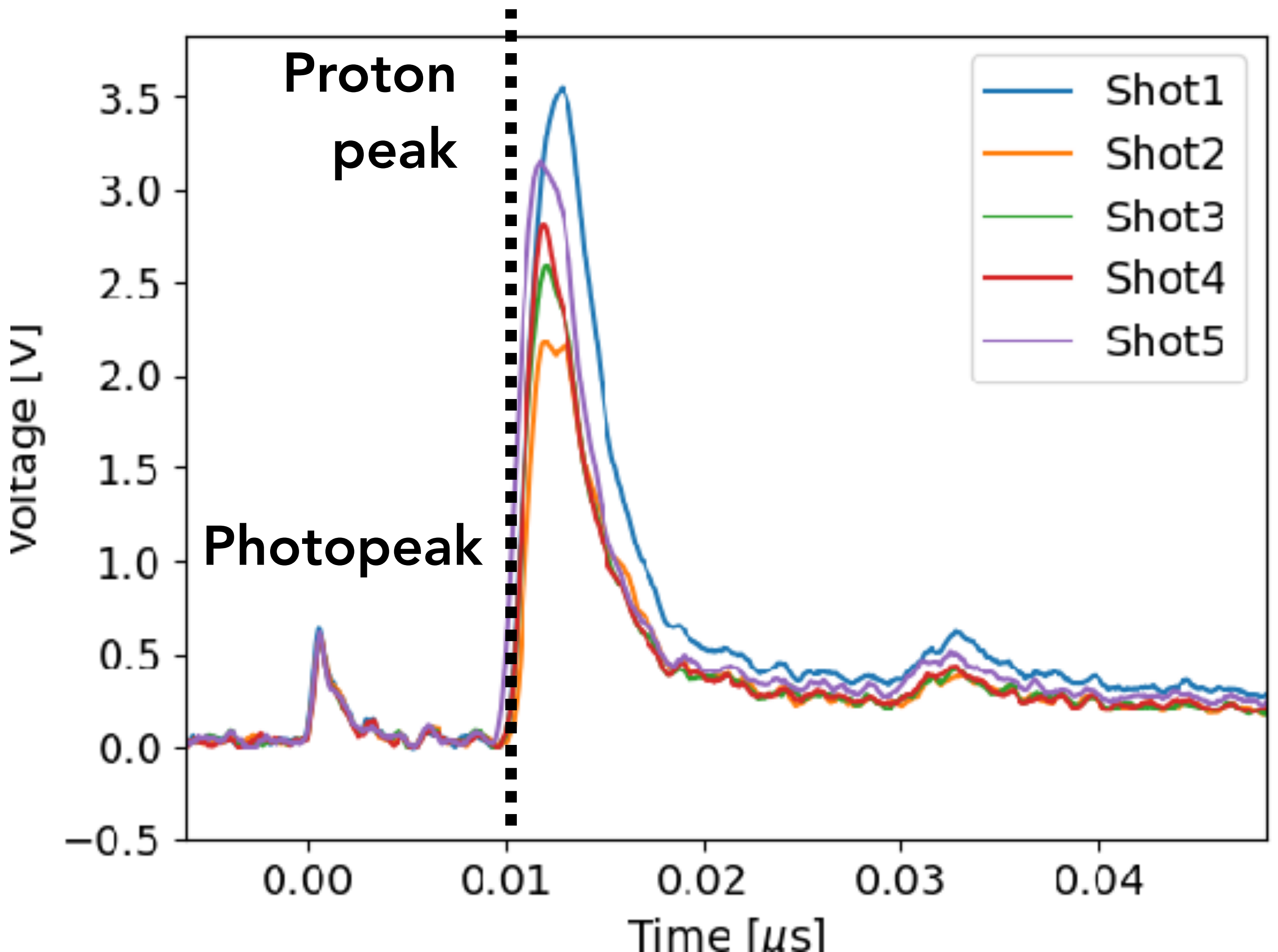
Results compared with 13 μm Kapton tape.



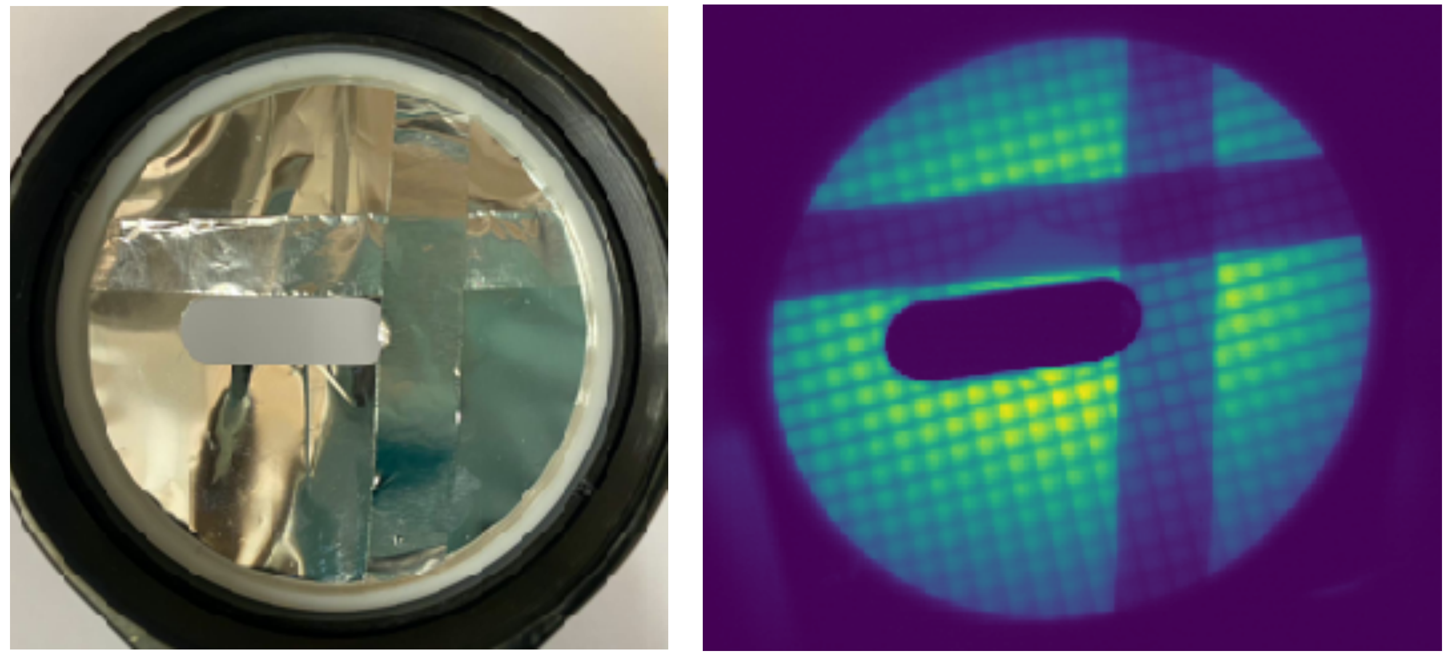
Electron spectrometer signal:



Raw time-of-flight diode trace:



Proton spatial profile:



High flux MeV proton beams from the liquid sheet

- 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:

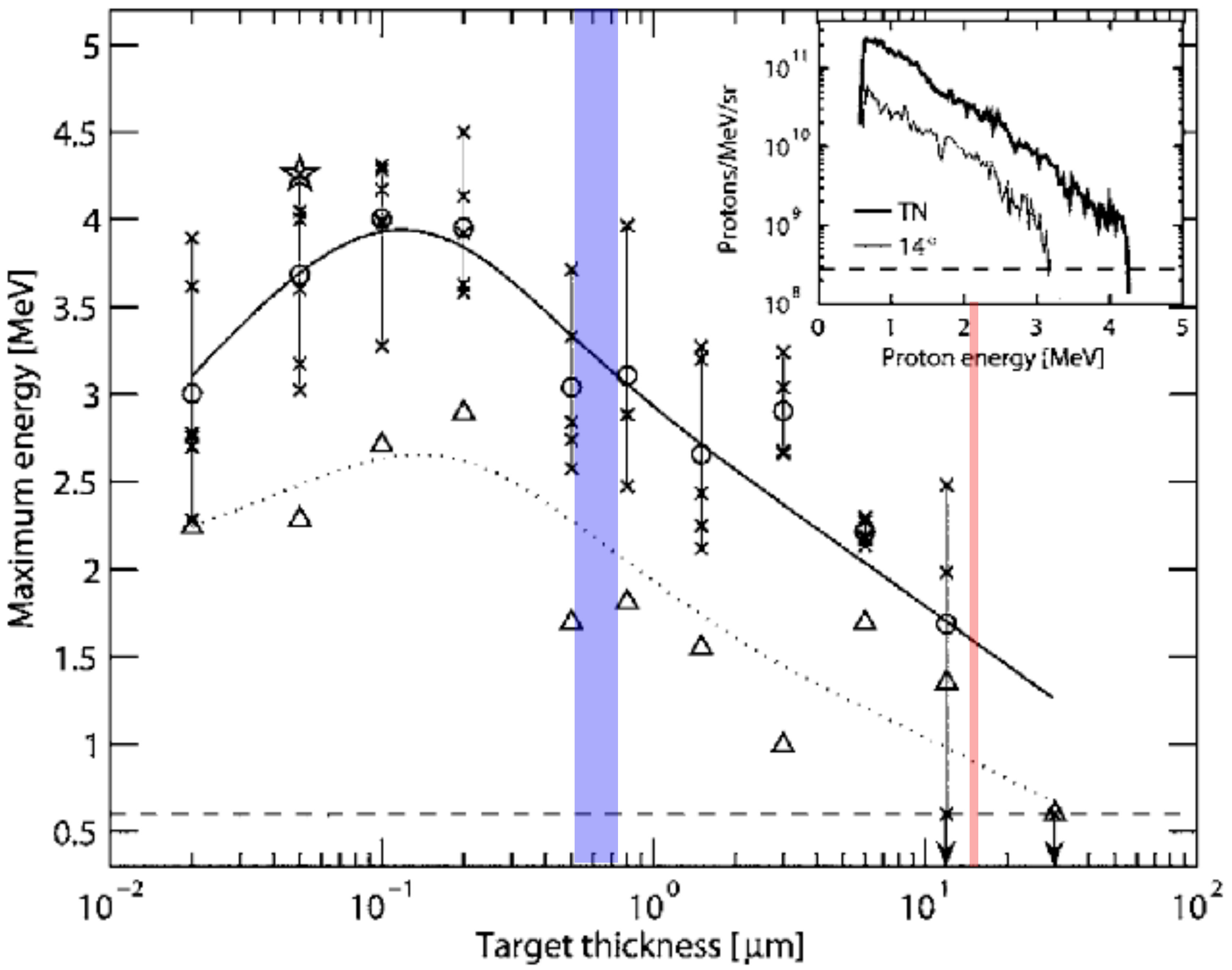
Targets:

- 20 nm - 30 micron Al

Laser parameters:

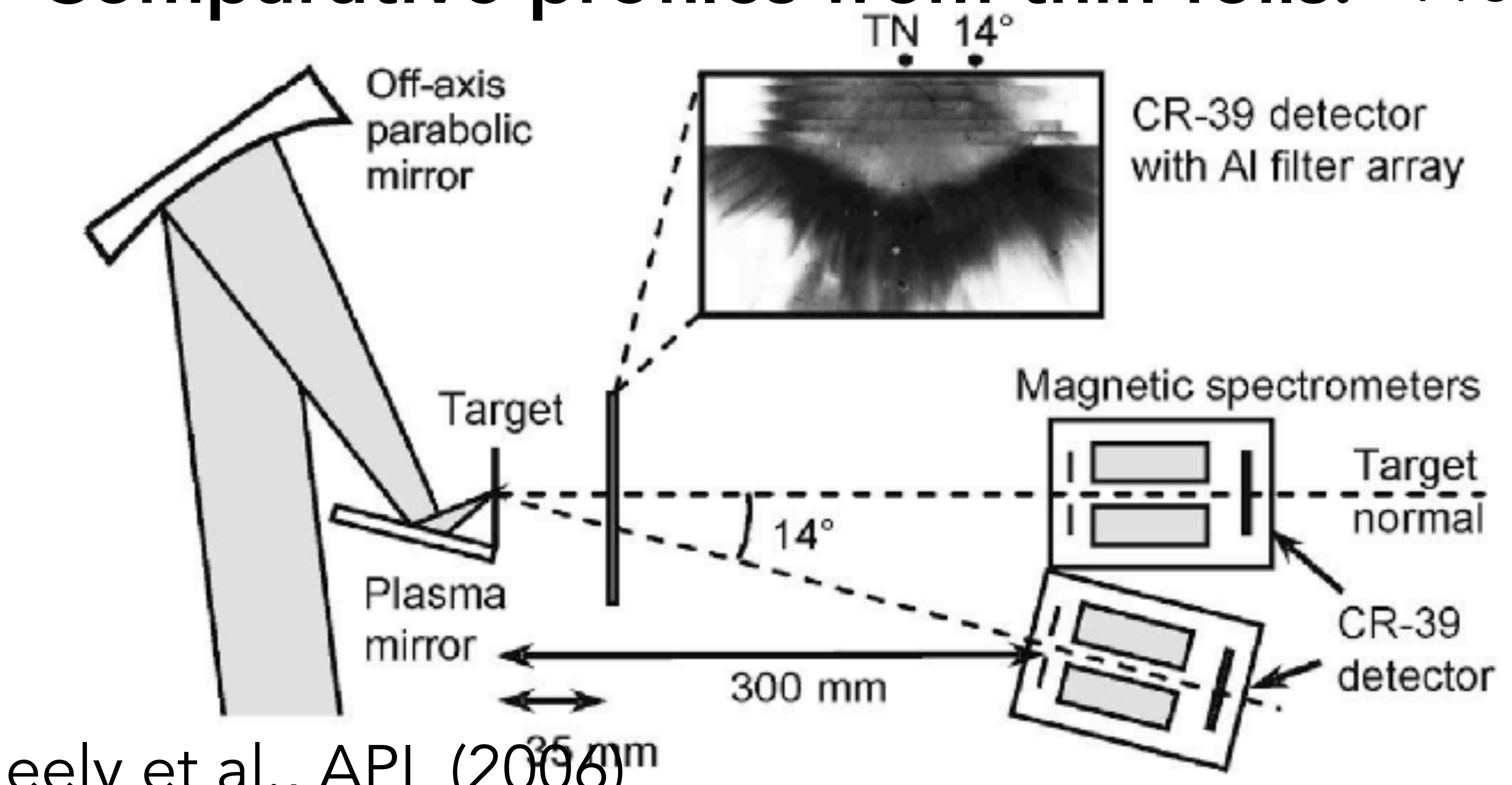
- 300 mJ
- 33 fs
- 10^{19} W/cm^2

Neely et al., APL (2006)



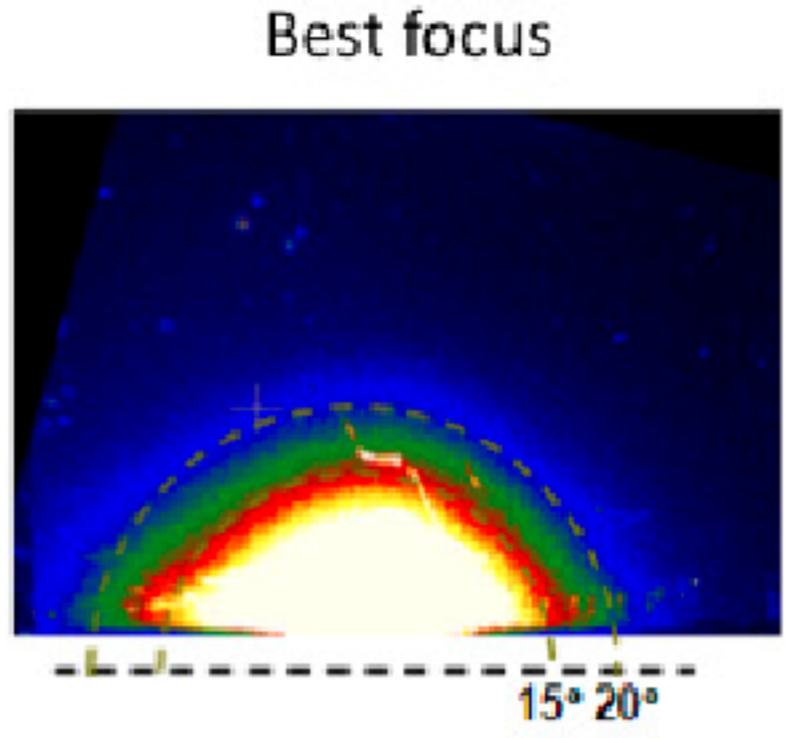
High stability and low proton beam divergence

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



Neely et al., APL (2006)

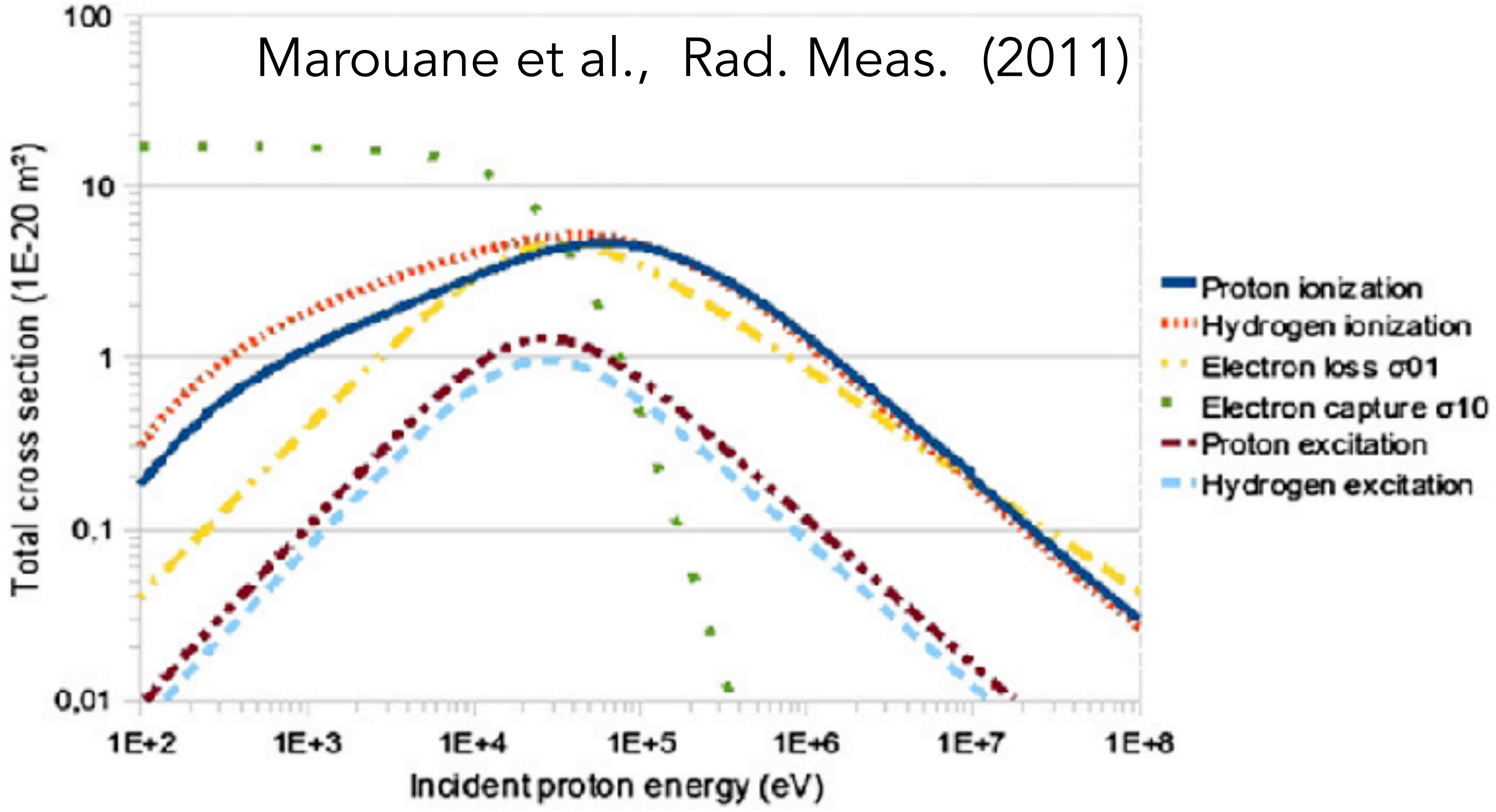
Green et al., APL (2006)



Simulations of proton bunch evolution

- 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

Impact ionisation cross sections:


Marouane et al., Rad. Meas. (2011)

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.

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**.

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. Dilorio, M. Balcazar, A. G. R. Thomas.