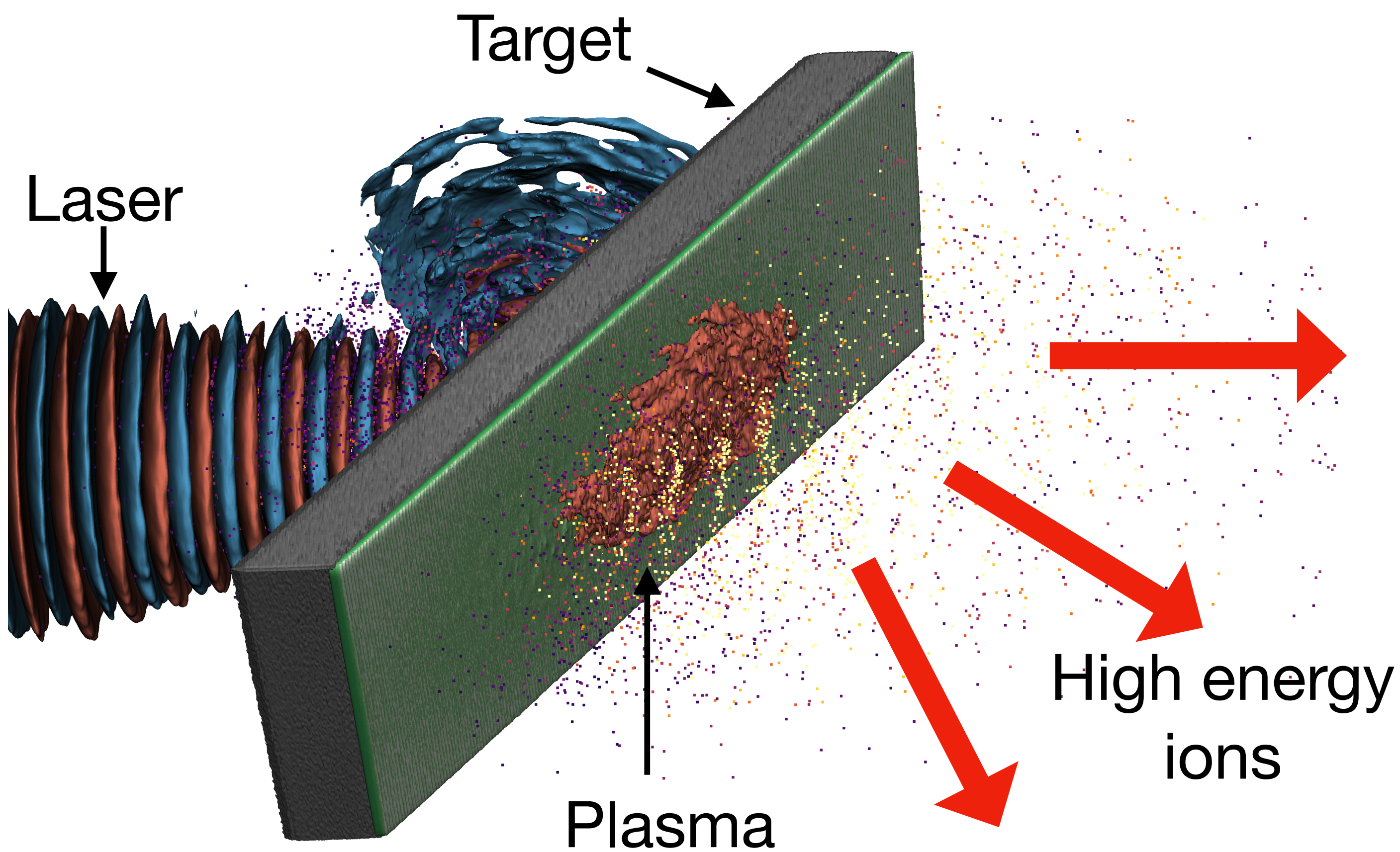
Laser-driven source (WPB): Progress review and future outlook

R. Gray (Strathclyde), N.Dover (Imperial) on behalf of all WP2 contributors

LhARA Collaboration Meeting #7, 7th April 2025

Laser driven ion source for LhARA



- High energy (e.g. ~15 MeV p+, 4 MeV/u C6+) from source
- Needs to operate at 10 Hz for long periods
- Aiming to deliver 10^9 protons or 10^8 carbon ions per shot, eventually other ions

Overview of aims

Source demonstration

What laser do we need? What targets? What diagnostics?

Technical R&D

How can we run our source stably at 10 Hz for long periods?

Simulations

How do we optimise source without costly experiments?

Overview of aims

Source demonstration

What laser do we need? What targets? What diagnostics?

Technical R&D

How can we run our source stably at 10 Hz for long periods?

Simulations

How do we optimise source without costly experiments?

ITRF/LhARA milestone M2.2 report

First SCAPA Ion Source Simulations and Experiments

Work Package 1.2

T.S. Dascalu[1], N.P. Dover[3], R.J. Gray[2,4]

ITRF/LhARA milestone M2.1 report

Baseline simulations of the future LhARA proton and ion source

Work Package 1.2

T.S. Dascalu[1], E. Boella[1,2], N.P. Dover[3], R.J. Gray[2,4]

Updated laser parameters - more energy!

Old specification (Aymar et al.)

TABLE 1 | Design parameters of the components of the LhARA facility.

Parameter	Value or range	Unit
Laser driven proton and ion source		
Laser power	100	TW
Laser energy	2.5	J
Laser pulse length	25	fs
Laser rep. rate	10	Hz
Required maximum proton energy	15	MeV

Updated laser parameters - more energy!

Old specification (Aymar et al.)

TABLE 1 | Design parameters of the components of the LhARA facility.

Parameter	Value or range	Unit
Laser driven proton and ion source		
Laser power	100	TW
Laser energy	2.5	J
Laser pulse length	25	fs
Laser rep. rate	10	Hz
Required maximum proton energy	15	MeV

- Initial specification over-optimistic for ion production
- We updated it for the CDR - big increase in laser energy

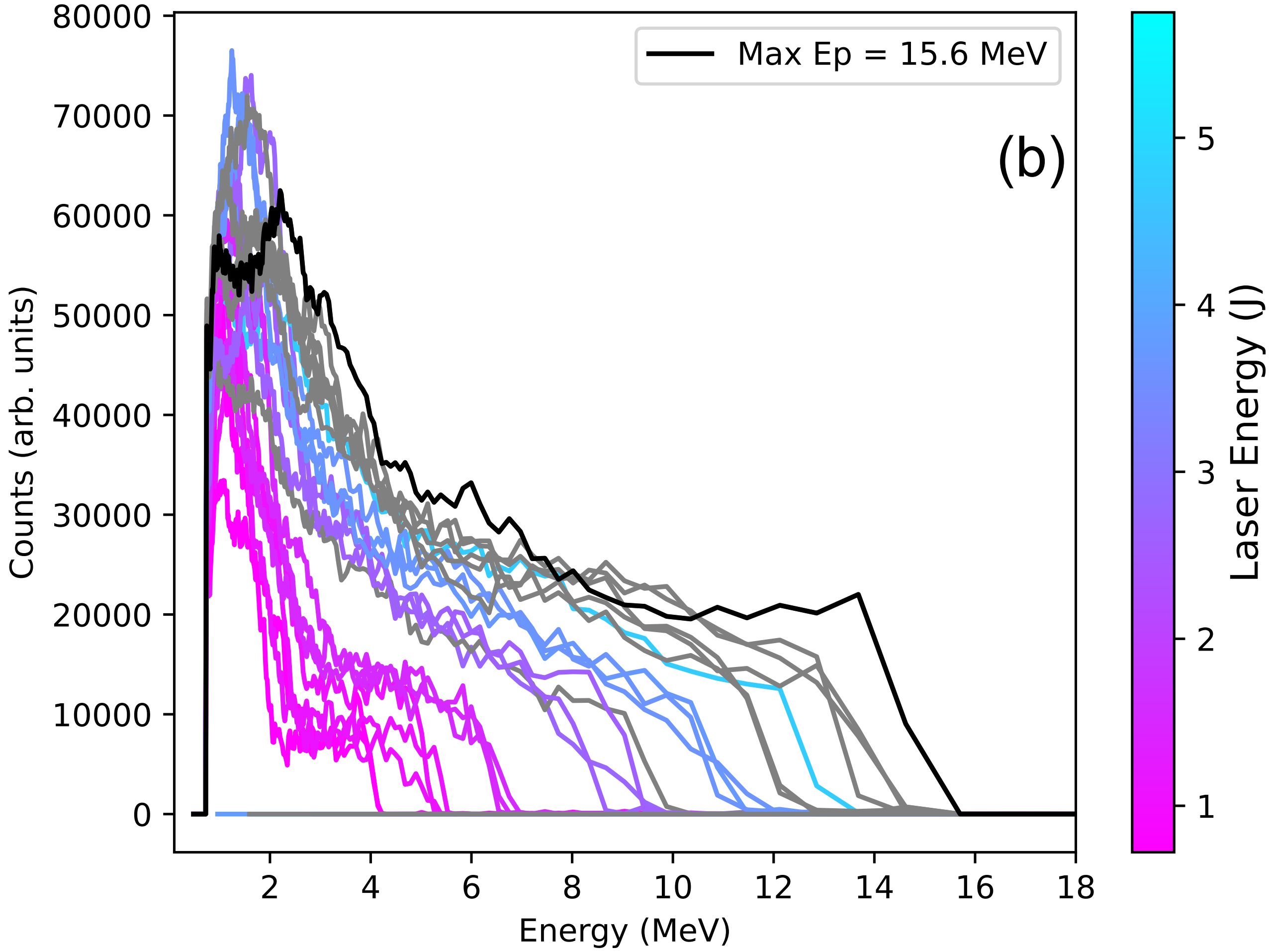
New specification (CDR)

Parameter	Value	Unit
Laser Parameters		
Central wavelength	800	nm
Energy before compressor	> 18	J
Energy stability (RMS)	< 2	%
Energy stability (RMS over 12 hours)	< 5	%
Pulse Length (FWHM)	< 50	fs
Pulse length stability (RMS)	< 5	%
Rep. rate	10	Hz
Contrast at 5 ps	10^{-8}	
Contrast at 10 ps	10^{-9}	
Contrast at 100 ps	10^{-10}	
Laser delivery parameters		
Energy on target	> 10	J
Focal spot size (FWHM)	< 3	μm
Strehl ratio (Measured)	> 0.5	
Angle of incidence	30	$^\circ$
Pointing stability	< 5	μrad

Table 1.1: Envisioned laser specification for ITRF.

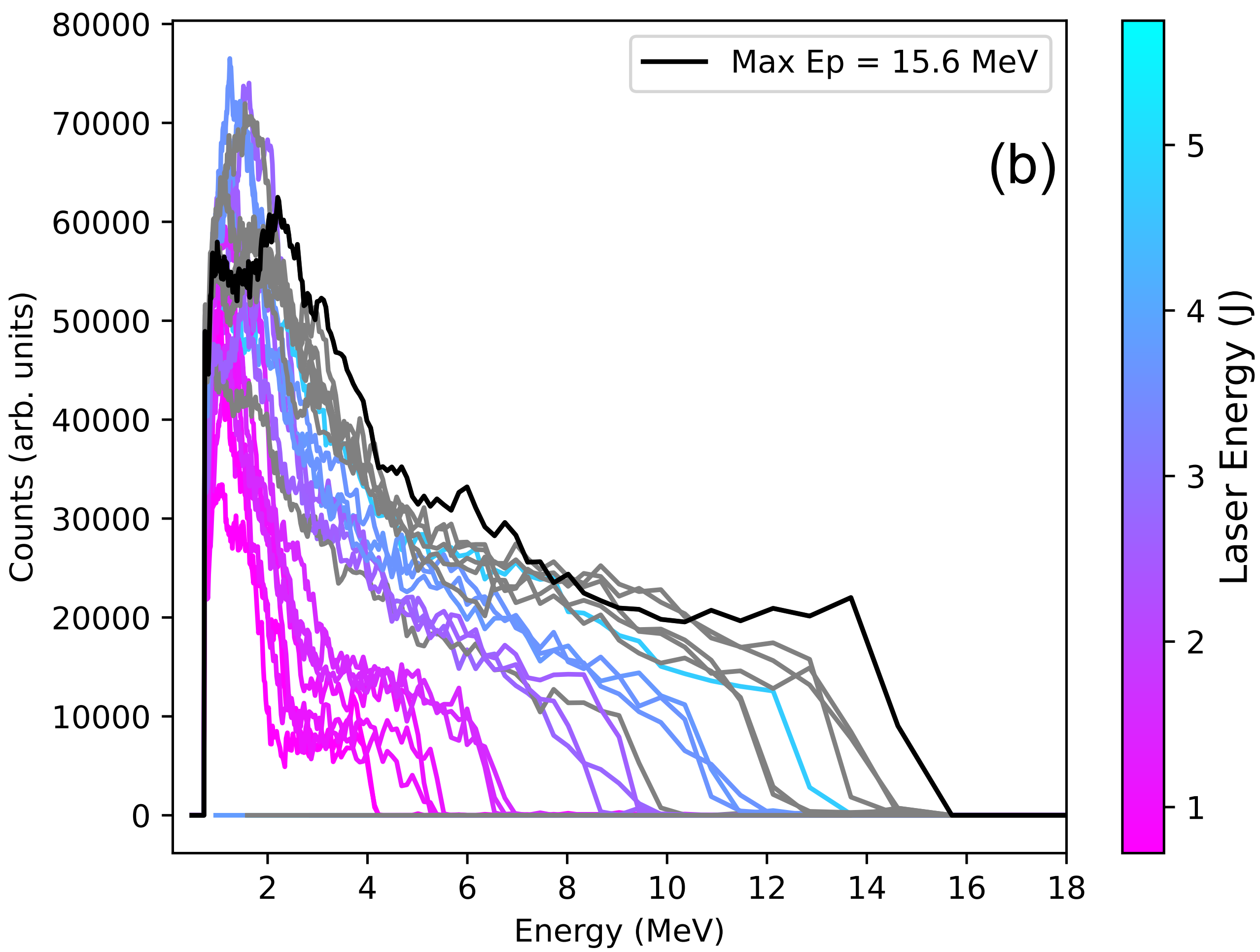
Importance of higher laser energy

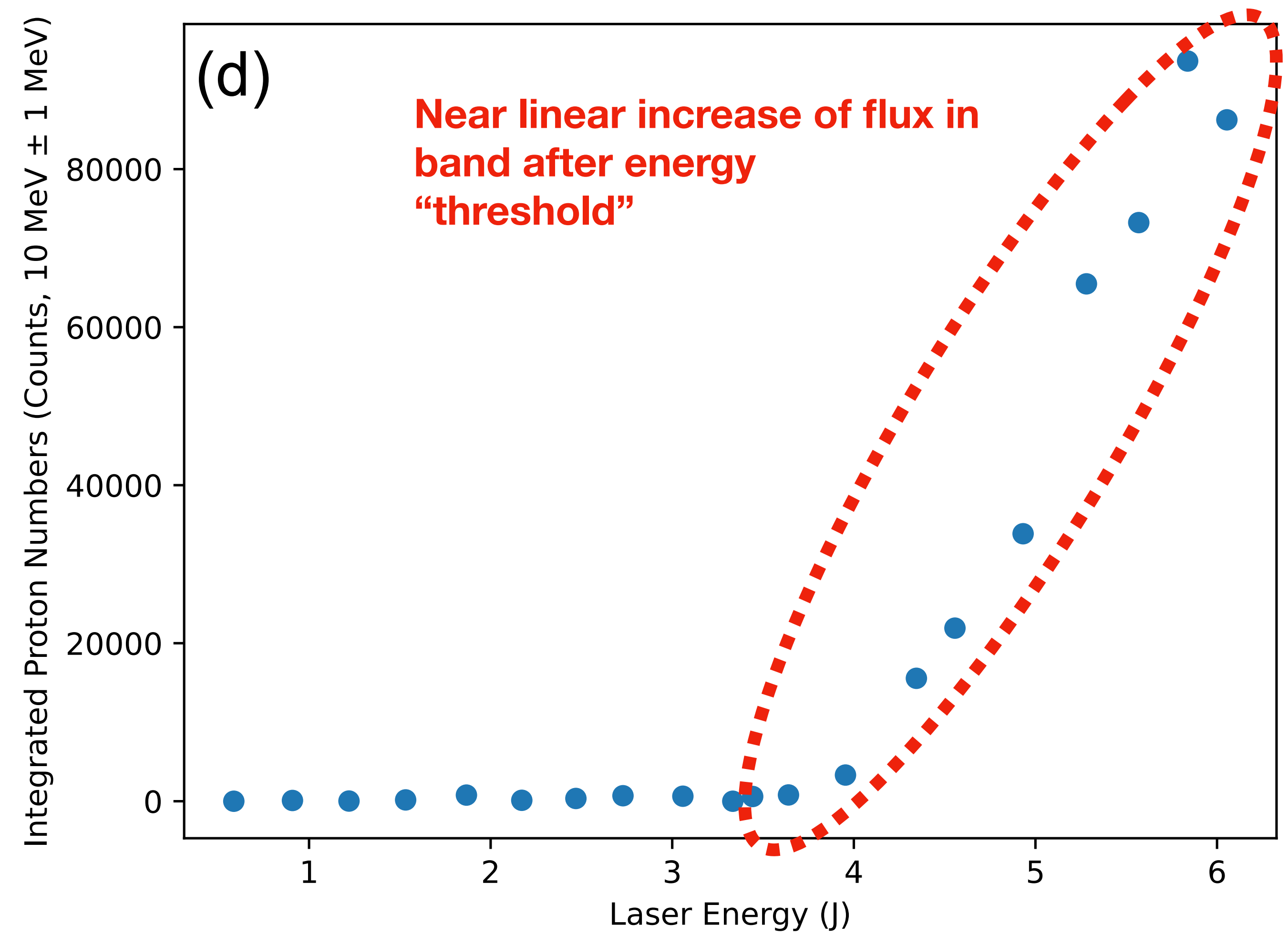
From R. Gray - SCAPA results



Importance of higher laser energy

From R. Gray -
SCAPA results





Initial specification - insufficient particle number

From Milestone Report 2:1 - from simulations performed by T. Dascalu

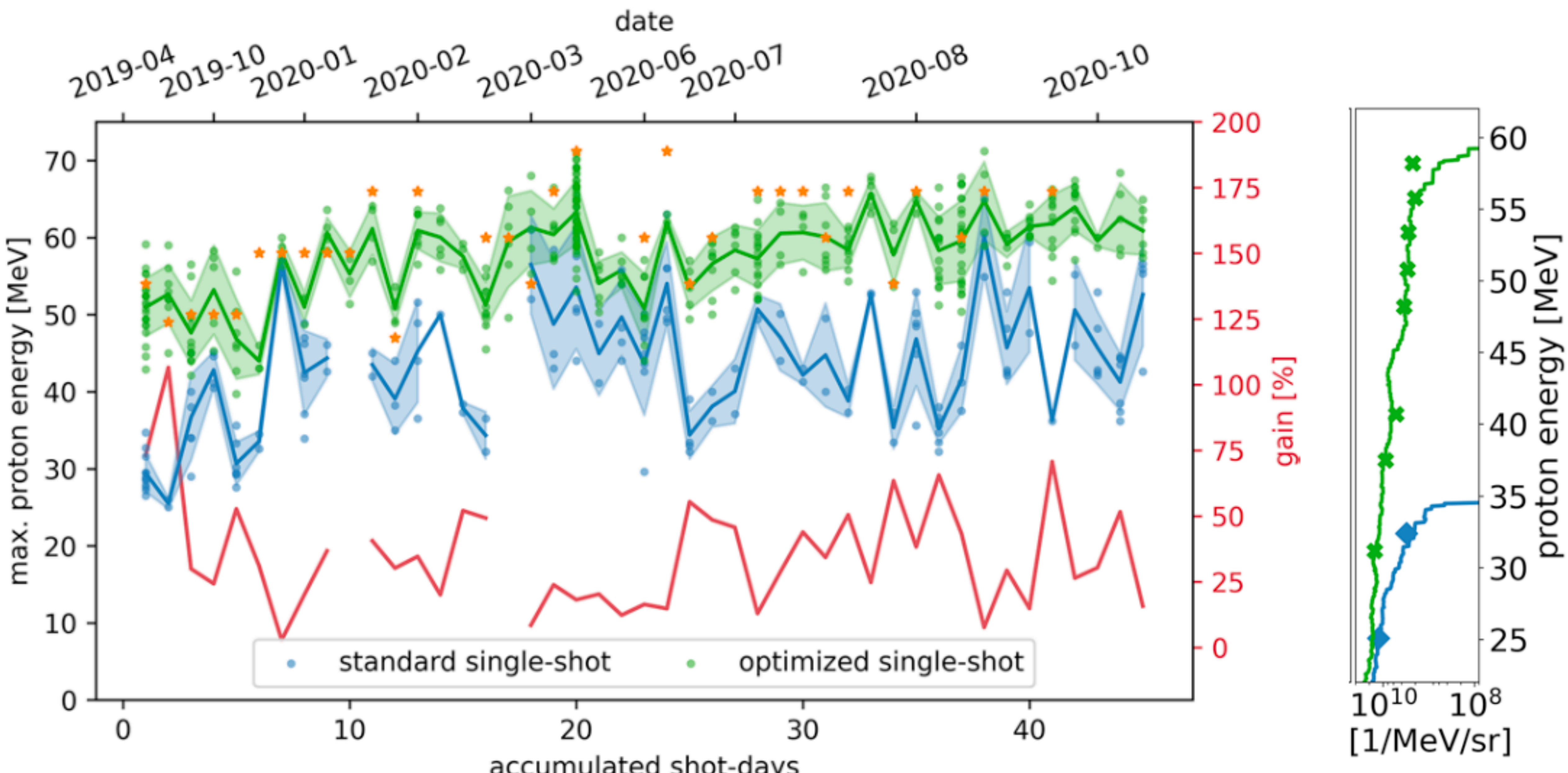
Table 3: Summary of the baseline parameters for the LhARA proton source as predicted by high-fidelity hydrodynamic and 3-D kinetic simulations (at normal laser incidence).

	Parameter	Value	Unit
Realistic conditions	Cutoff energy	21.5	MeV
	Particle number per pulse (15.0 ± 0.5 MeV)	3.1×10^8	
	RMS beam divergence (>1 MeV)	52	mrad
	RMS beam divergence (15.0 ± 0.5 MeV)	32	mrad
	Max. emission half opening angle (15.0 ± 0.5 MeV)	141	mrad
	Emittance‡	0.133	mm-mrad

- Particle number far too low!
  - Current spec E=15 MeV +- 2%, angular acceptance 15 mrad
  - Particles going into capture <10^8 !
  - Need to boost numbers -> increase laser energy significantly
  - (Would help if bandwidth & angular acceptance increased)

Going to even higher laser energy?

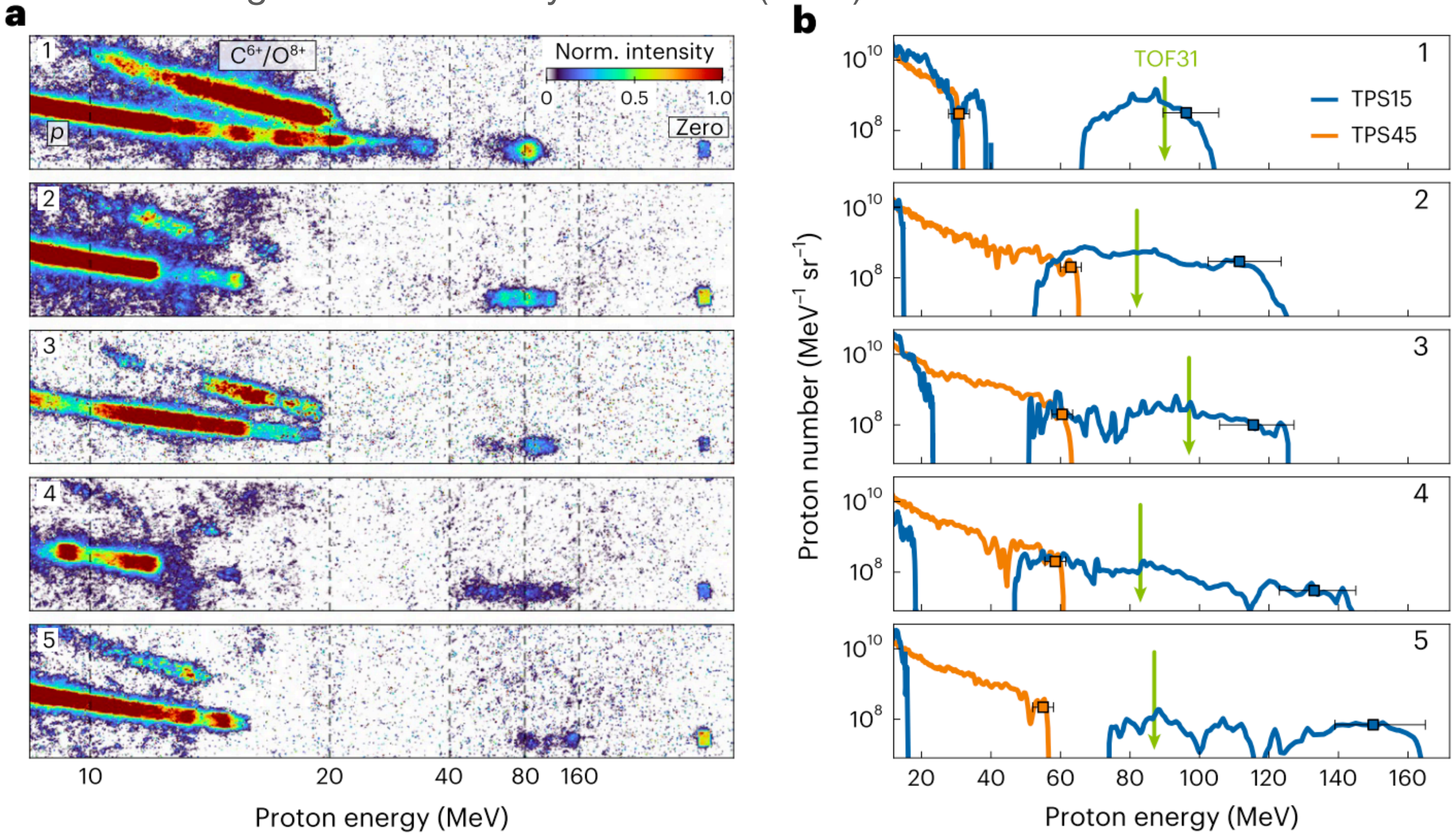
From Ziegler et al. Sci. Rep. 11:7338 (2021)

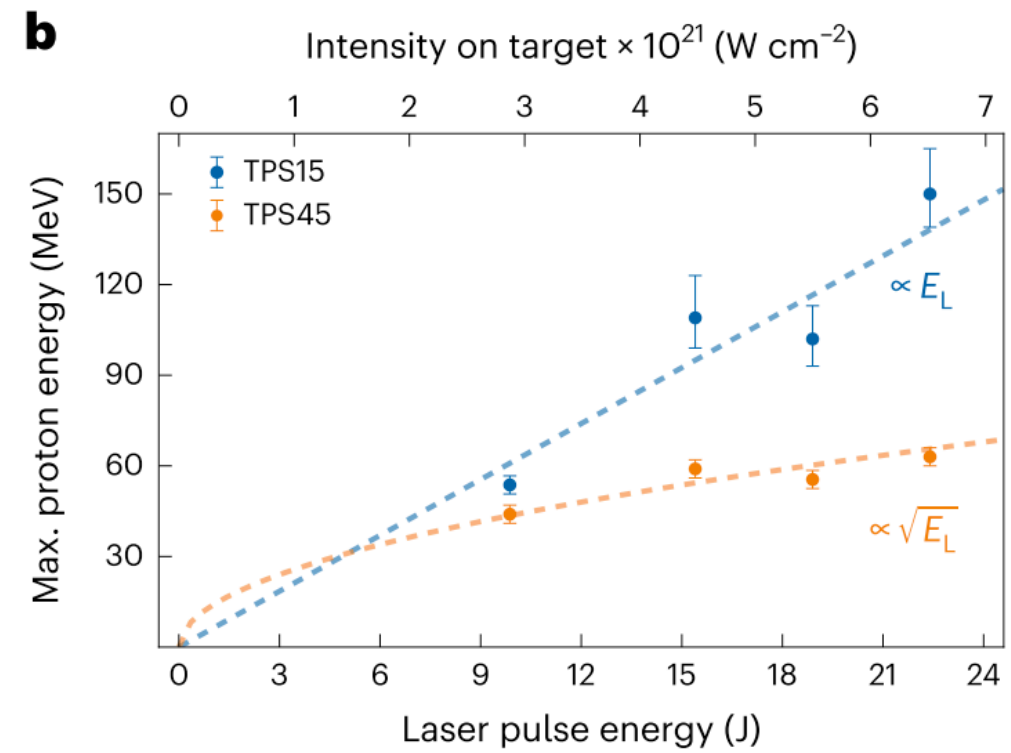


- 18 J on target -> DRACO laser
- Reliable generation of maximum energies up > 50 MeV using TNSA
- >10^{10} protons per MeV sr up to ~30 MeV
    - (Although still <10^{9} protons for LhARA capture parameters!)

Or stabilising advanced acceleration mechanisms?

From Ziegler et al. Nat. Phys. 20:1211 (2024)

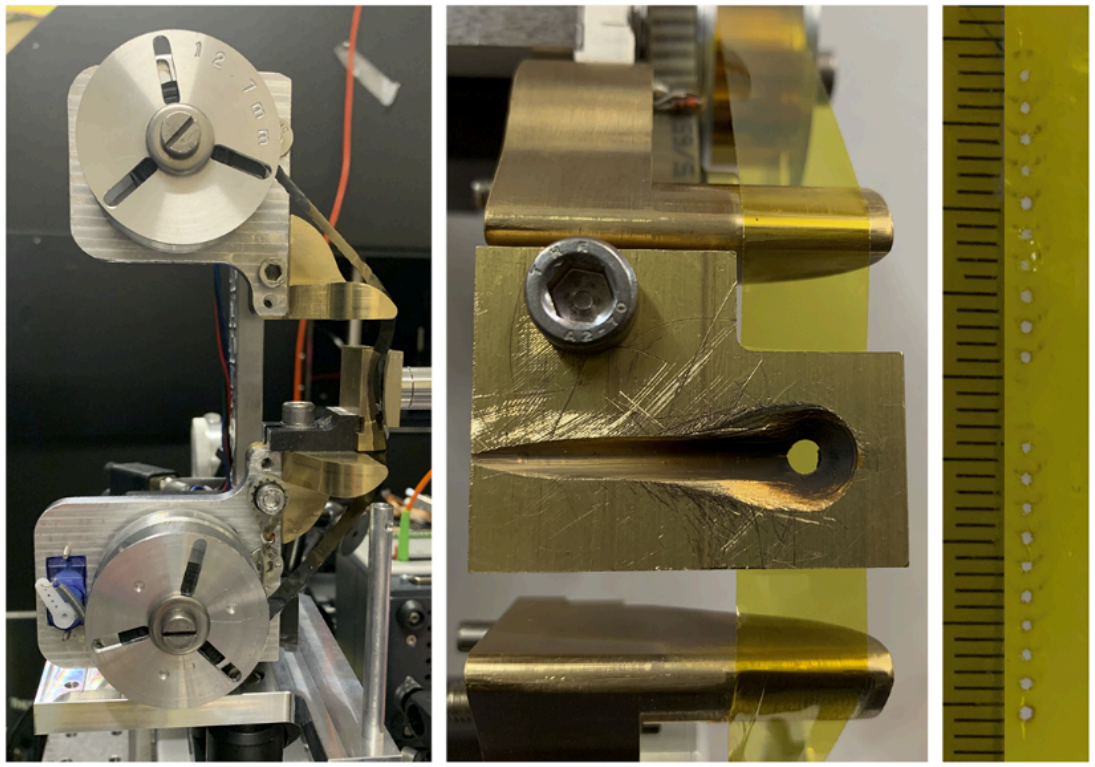


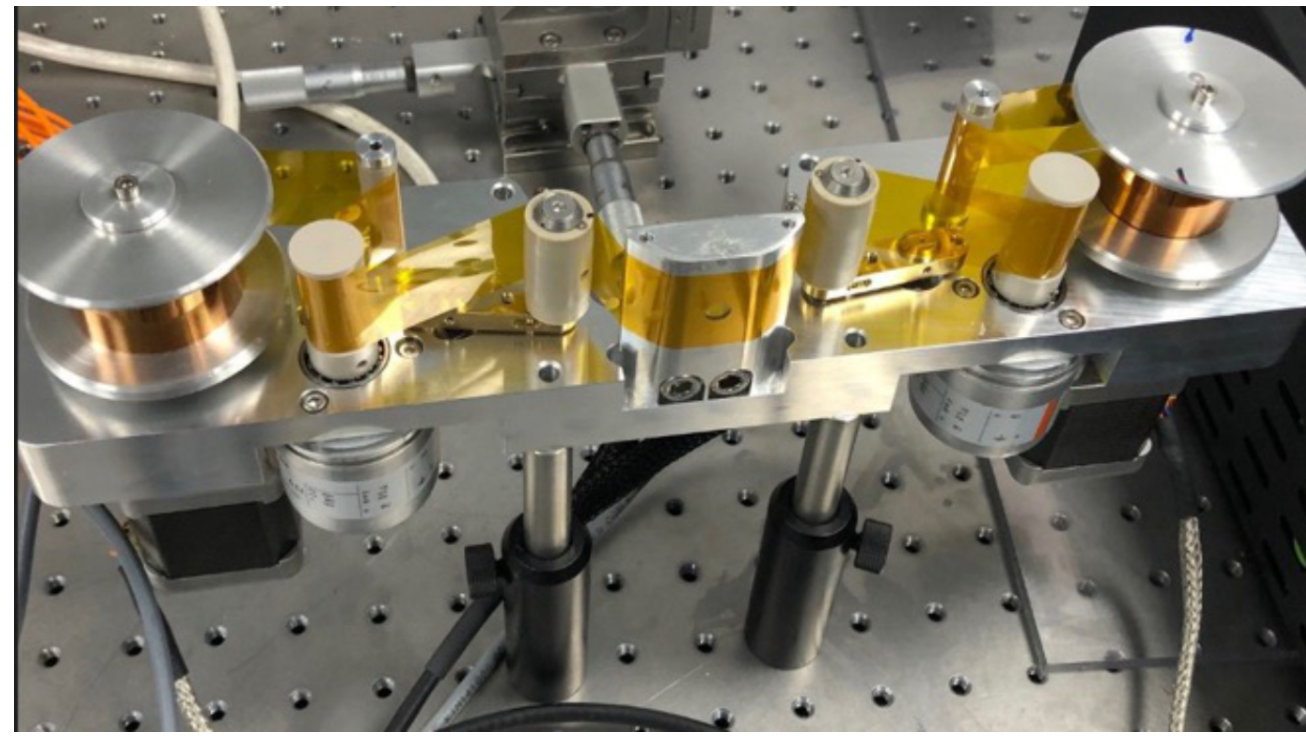


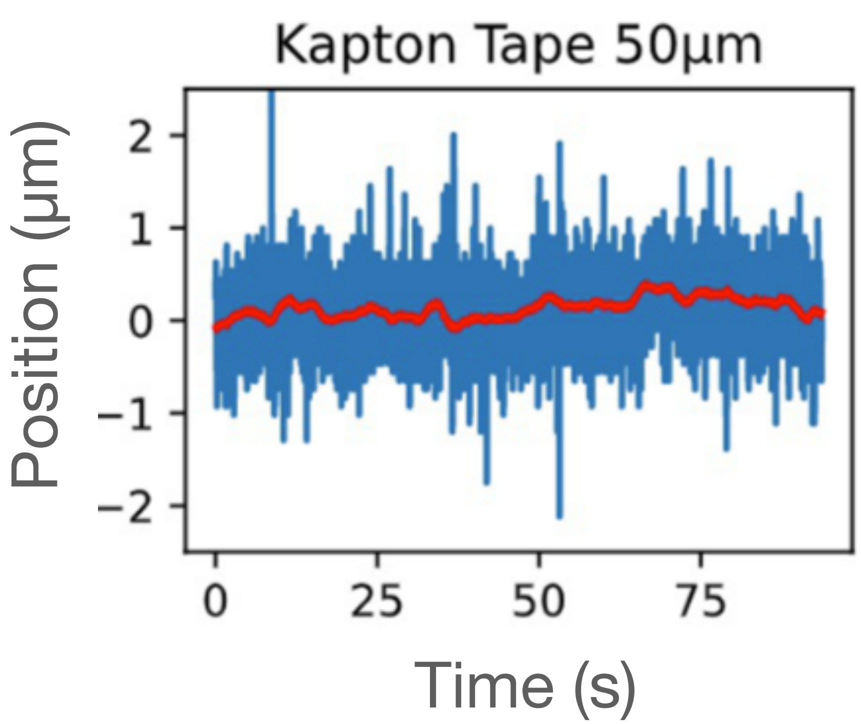
- Same laser - even higher proton energies
- Going beyond TNSA
  - Stability is an outstanding issue?
  - Targetry also more complex!
- But, could enable in-vivo studies even without a stage 2 - if the flux is high enough!

High repetition targets for ion sources

Tape drives:





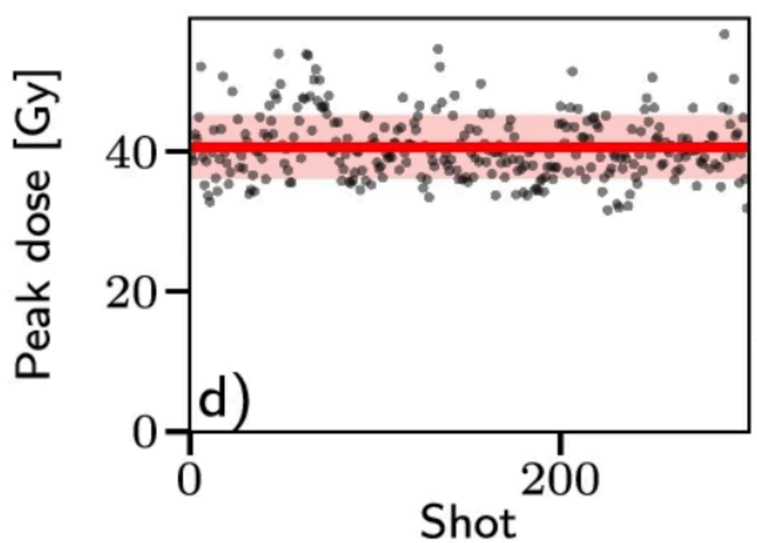


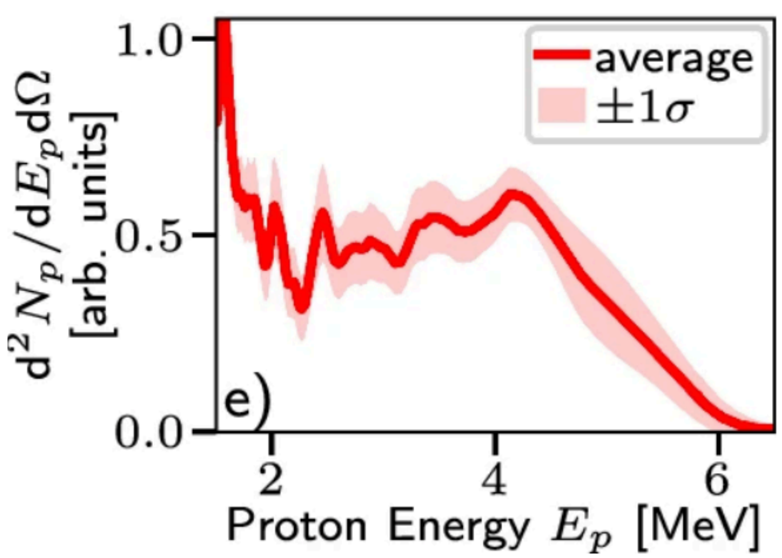
- Significant experience with tape drives
- Should be suitable for 10 Hz operation for short periods
- Debris and target replacement will be problems for long term operation

High repetition targets for ion sources

Liquid jets

Kim+, Nature Comms 14:2328 (2023)
Streeter+, Nature Comms 16:1004 (2025)

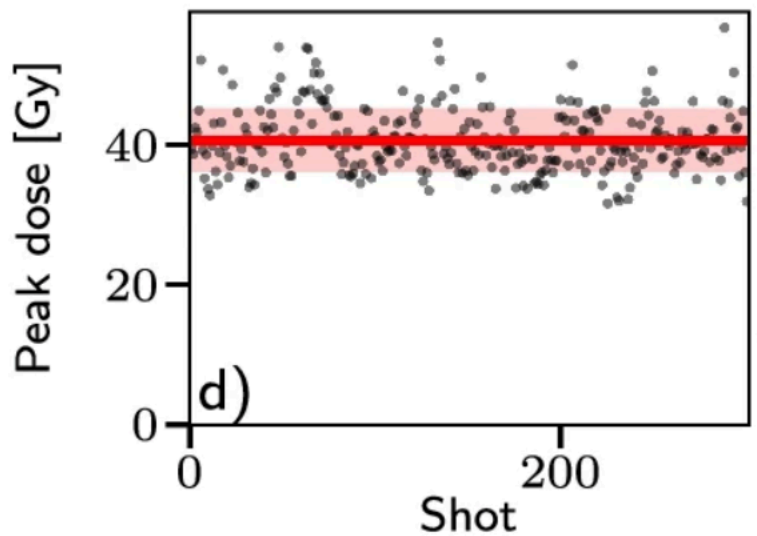


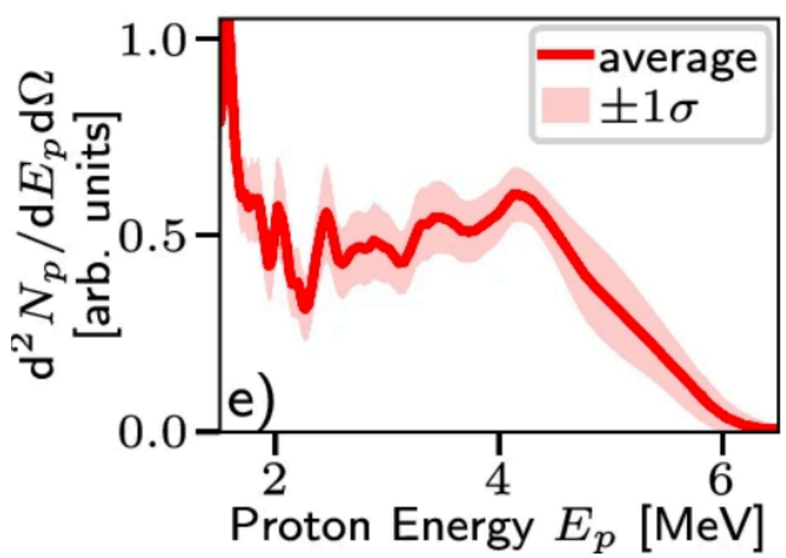


High repetition targets for ion sources

Liquid jets

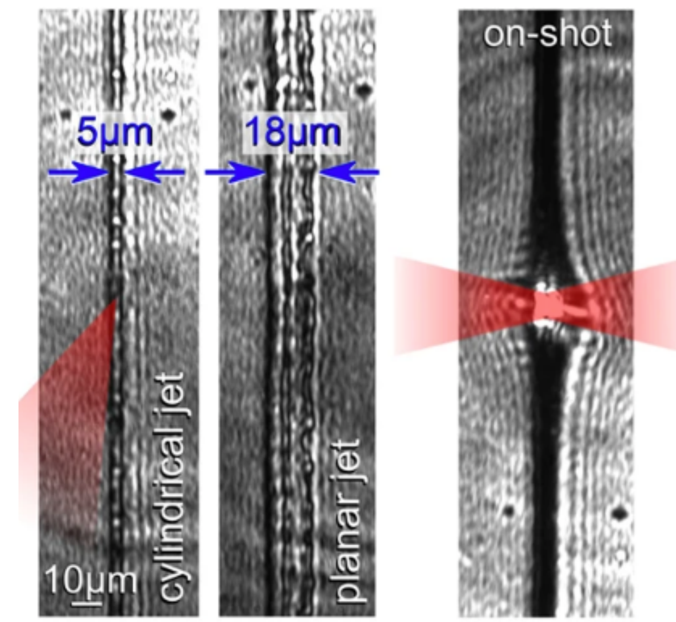
Kim+, Nature Comms 14:2328 (2023)
Streeter+, Nature Comms 16:1004 (2025)

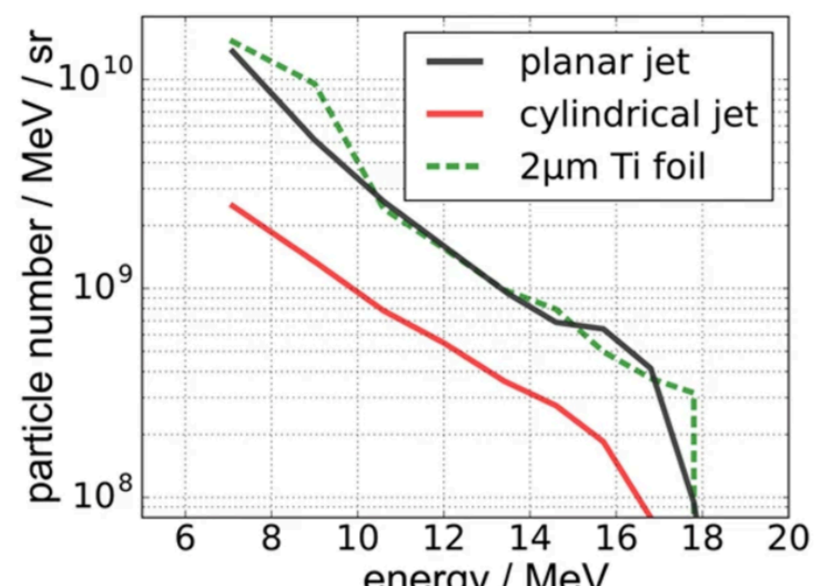




Cryogenic targets

Obst+, Scientific Reports 7:10248 (2017)





Diagnostics for high repetition operation

Single shot diagnostics capable of 10 Hz operation

- Proton energy / flux, spatial variation (particularly 10-15 MeV)
- Heavier ion energy / flux, spatial variation (few MeV/u)
- Auxiliary diagnostics (electrons, plasma, x-ray, laser)

Diagnostics for high repetition operation

Single shot diagnostics capable of 10 Hz operation

- Proton energy / flux, spatial variation (particularly 10-15 MeV)
- Heavier ion energy / flux, spatial variation (few MeV/u)
- Auxiliary diagnostics (electrons, plasma, x-ray, laser)

Techniques

- Thomson parabola spectometers
- Beam profilers / PROBIES
- Time-of-flight spectrometry
- Laser metrology, spatial & temporal
- Target/debris monitoring

Diagnostics for high repetition operation

Single shot diagnostics capable of 10 Hz operation

- Proton energy / flux, spatial variation (particularly 10-15 MeV)
- Heavier ion energy / flux, spatial variation (few MeV/u)
- Auxiliary diagnostics (electrons, plasma, x-ray, laser)

Techniques

- Thomson parabola spectometers
- Beam profilers / PROBIES
- Time-of-flight spectrometry
- Laser metrology, spatial & temporal
- Target/debris monitoring

Detectors/calibration

- Scintillators
- CCD/CMOS
- Cross calibration with at reference beam lines or calibrated sources
- Long term operation/radiation damage

Diagnostics for high repetition operation

Single shot diagnostics capable of 10 Hz operation

- Proton energy / flux, spatial variation (particularly 10-15 MeV)
- Heavier ion energy / flux, spatial variation (few MeV/u)
- Auxiliary diagnostics (electrons, plasma, x-ray, laser)

Techniques

- Thomson parabola spectometers
- Beam profilers / PROBIES
- Time-of-flight spectrometry
- Laser metrology, spatial & temporal
- Target/debris monitoring

Detectors/calibration

- Scintillators
- CCD/CMOS
- Cross calibration with at reference beam lines or calibrated sources
- Long term operation/radiation damage

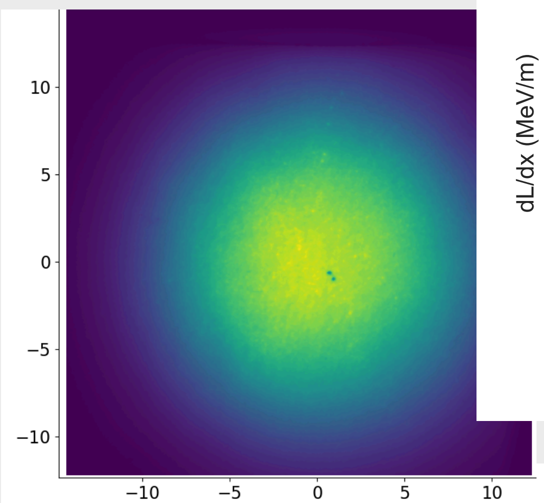
Analysis

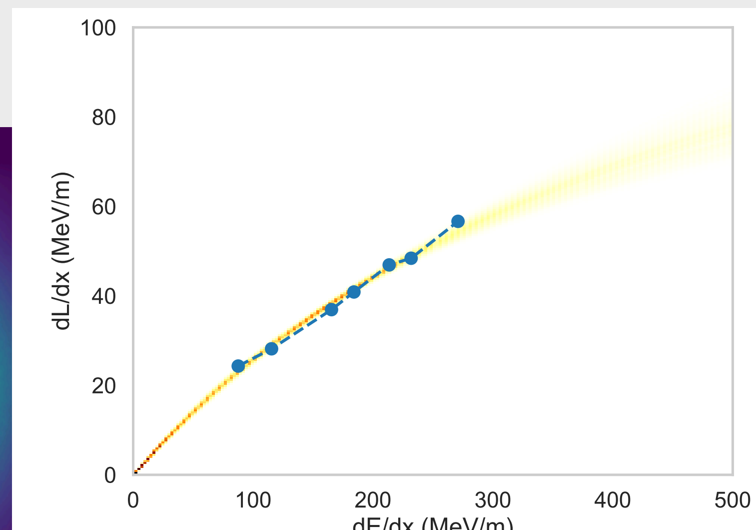
- Fast analysis techniques
- Integration into control systems for stabilisation & optimisation

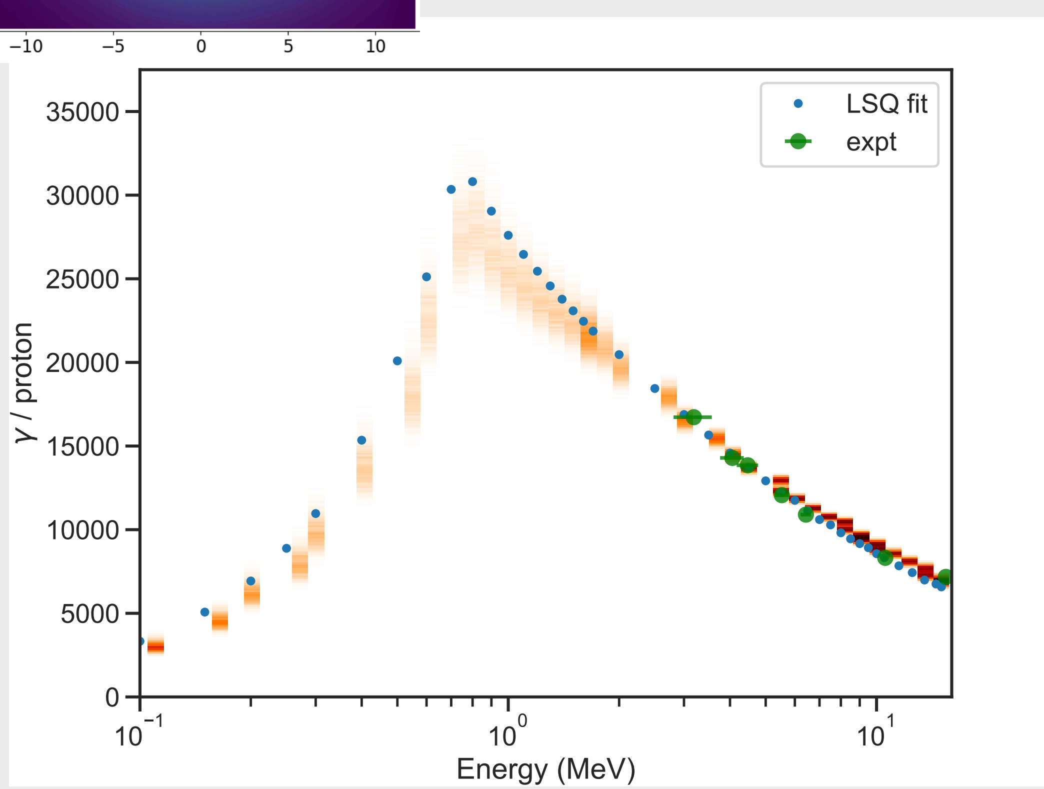
Current R&D examples

Scintillator calibration

- SCAPA & MC40



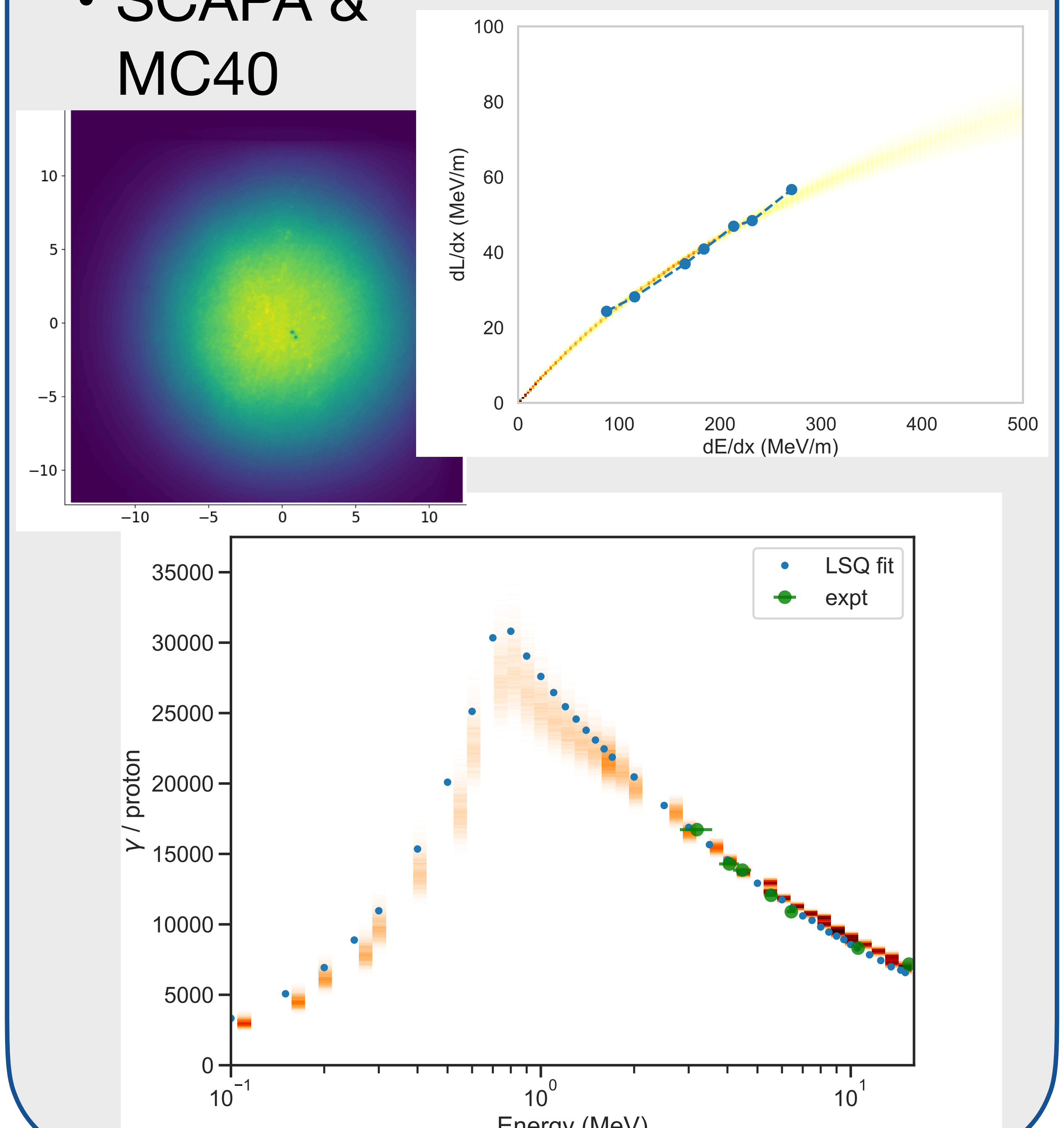




Current R&D examples

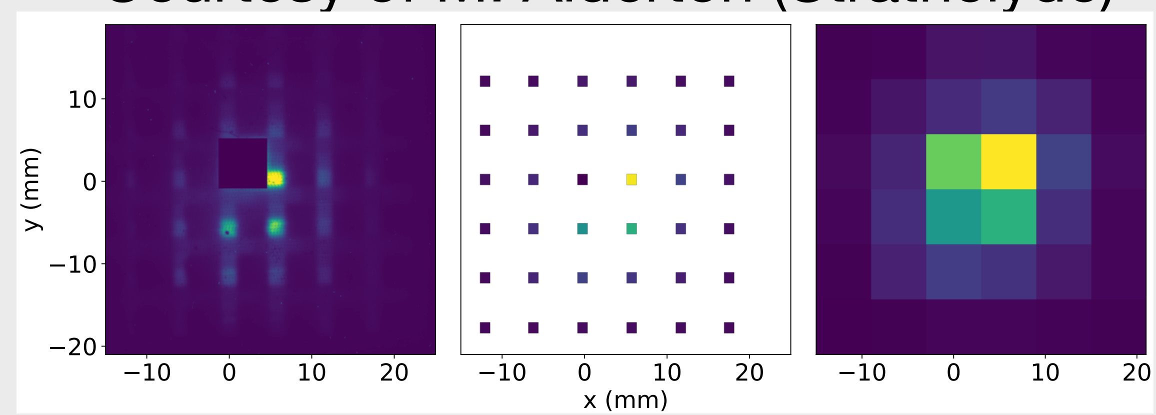
Scintillator calibration

- SCAPA & MC40



“PROBIES” type diagnostics

Courtesy of M. Alderton (Strathclyde)

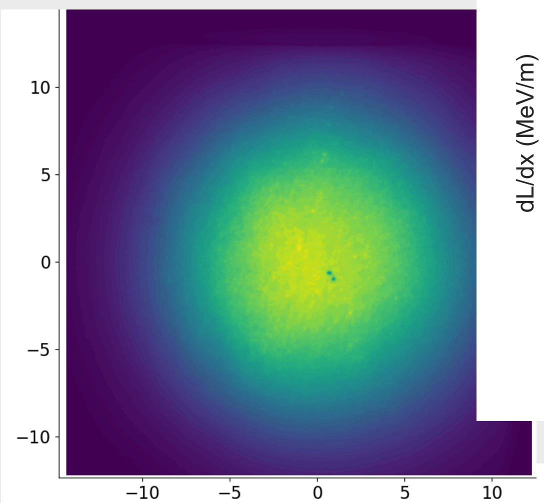


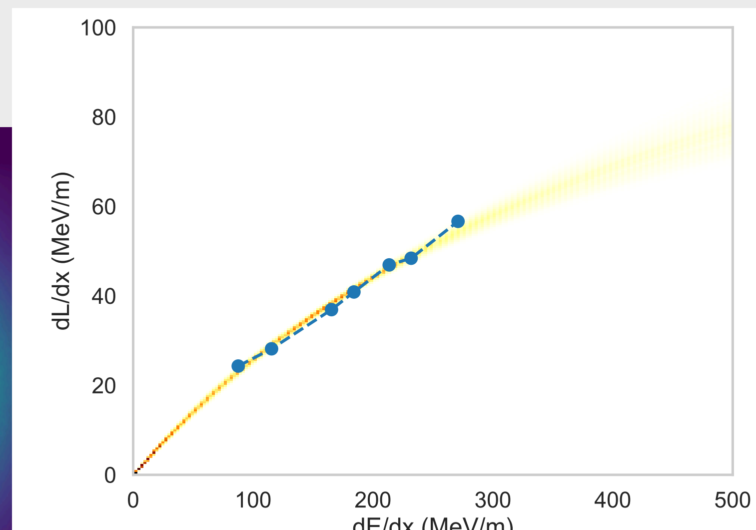
- RCF stack replacement
- Developing ML-aided fast analysis algorithms

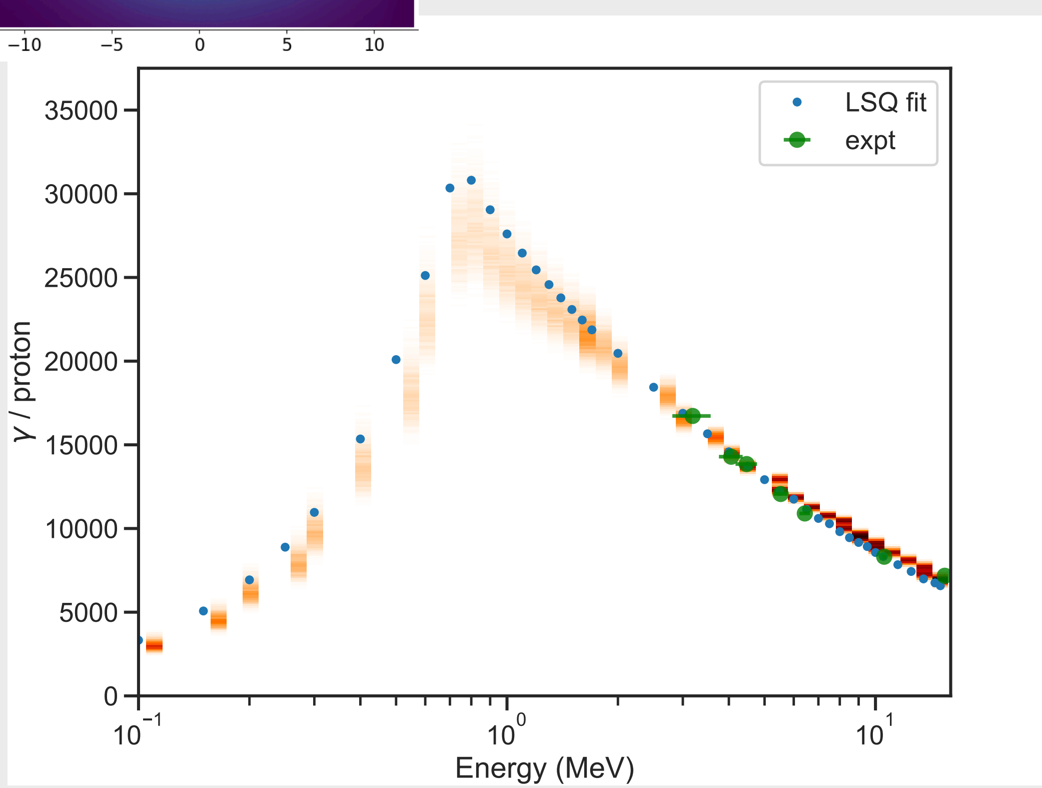
Current R&D examples

Scintillator calibration

- SCAPA & MC40

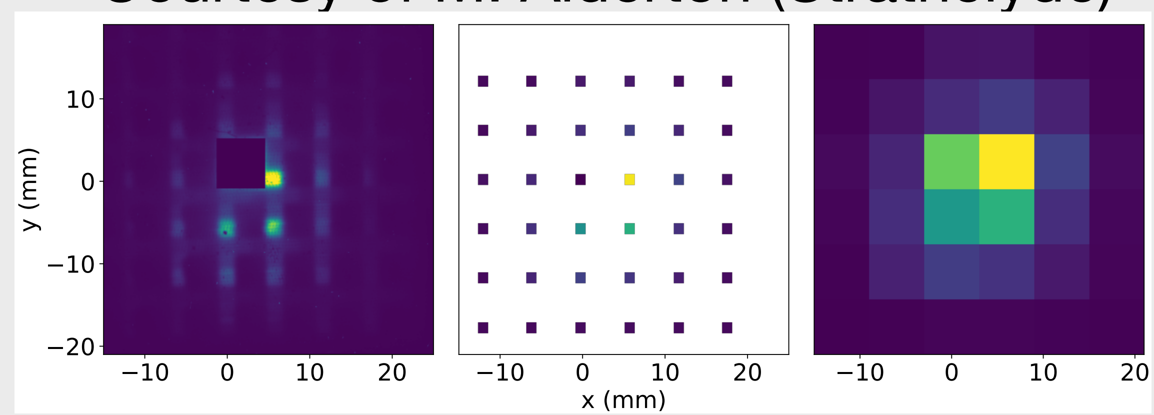






"PROBIES" type diagnostics

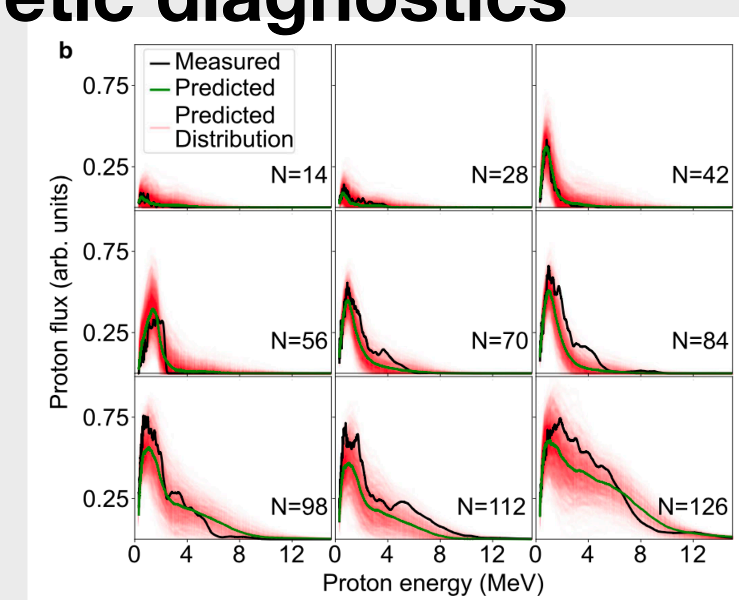
Courtesy of M. Alderton (Strathclyde)



- RCF stack replacement
- Developing ML-aided fast analysis algorithms

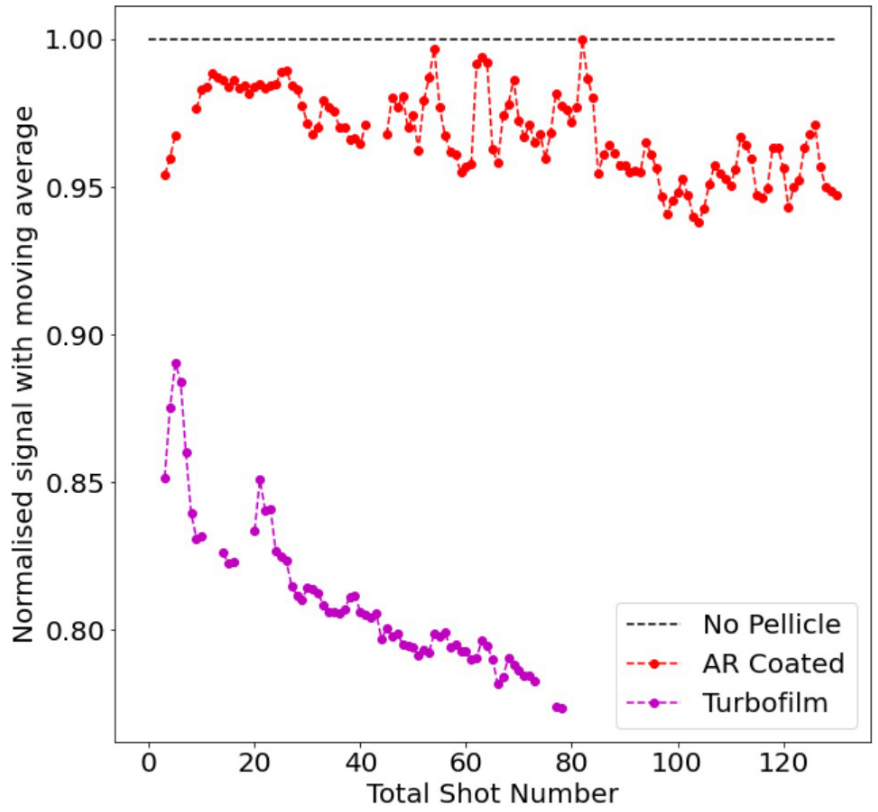
Synthetic diagnostics

McQueen+ Comm. Phys. 8:66 (2025)



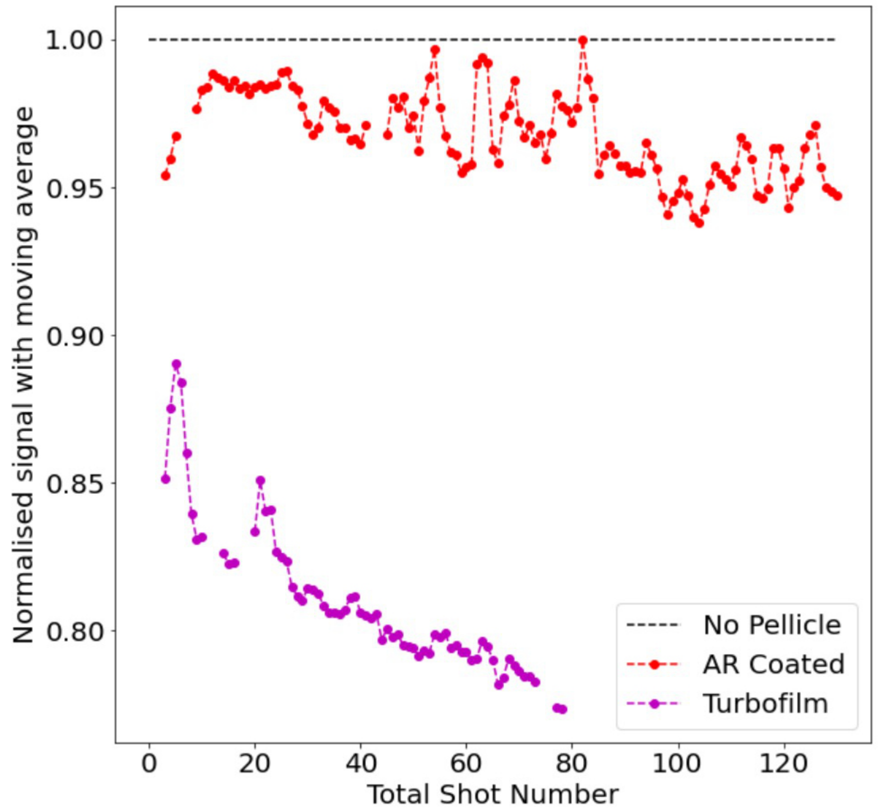
Can we run long term with high stability?

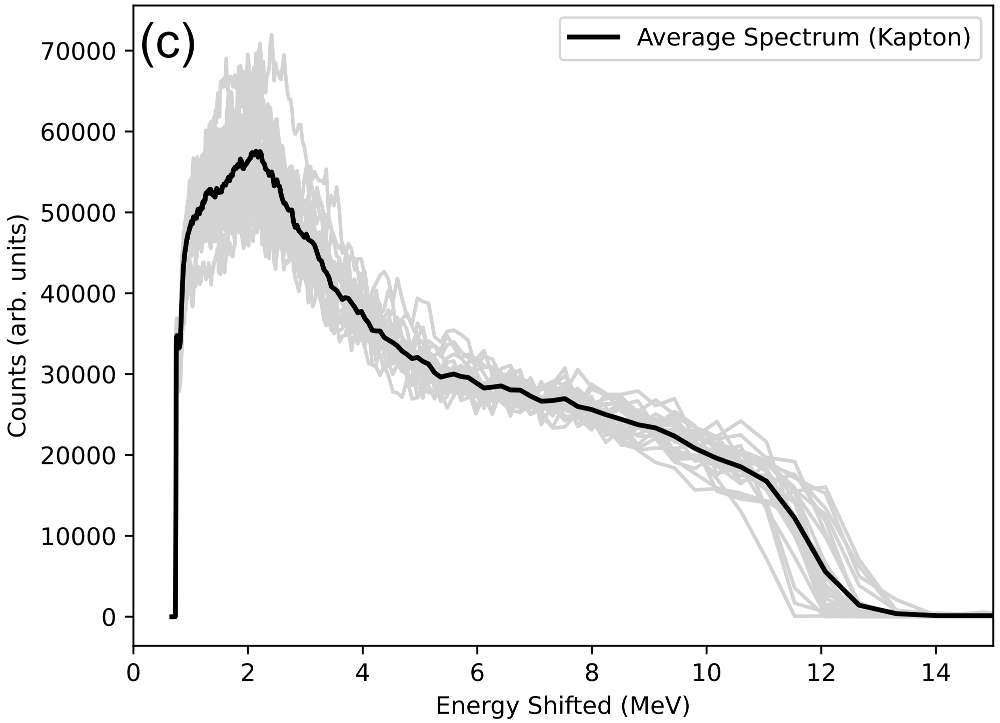
From R. Gray - SCAPA results



Can we run long term with high stability?

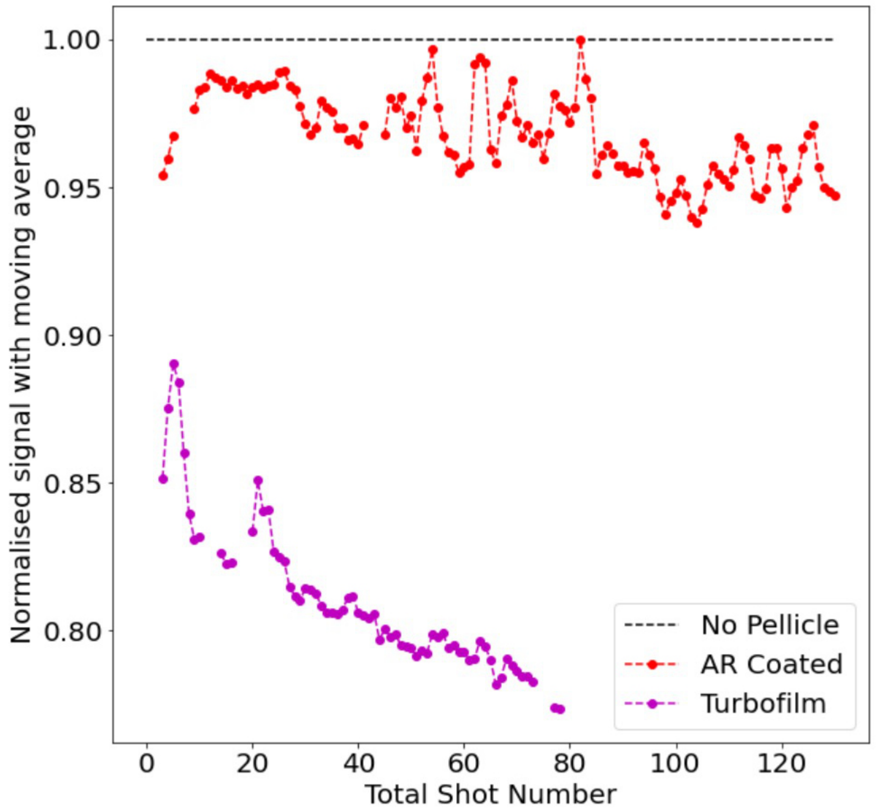
From R. Gray - SCAPA results

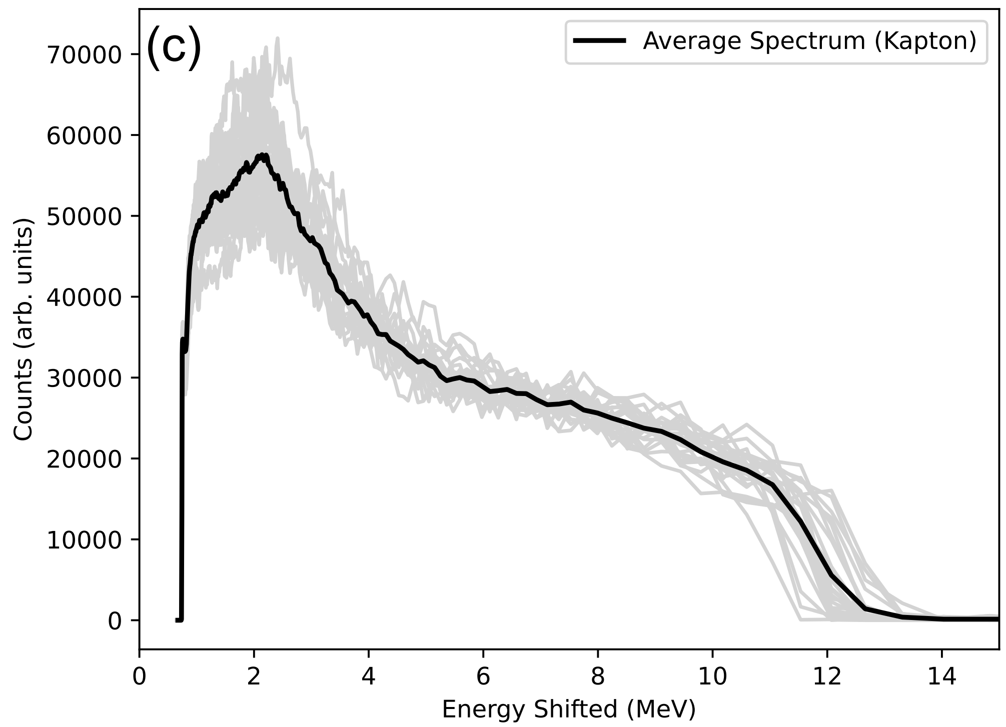


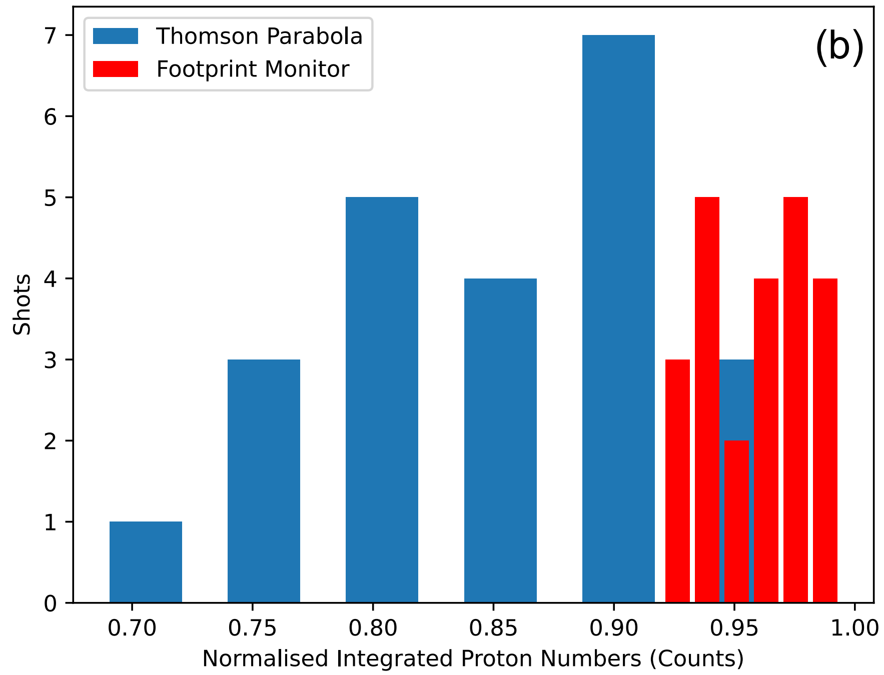


Can we run long term with high stability?

From R. Gray - SCAPA results

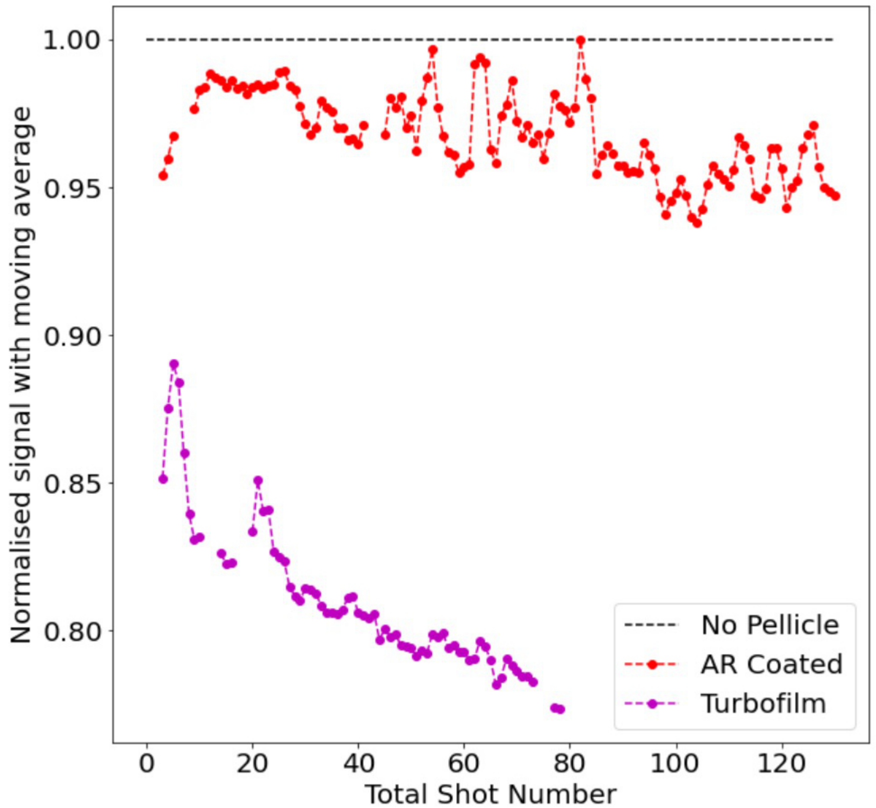


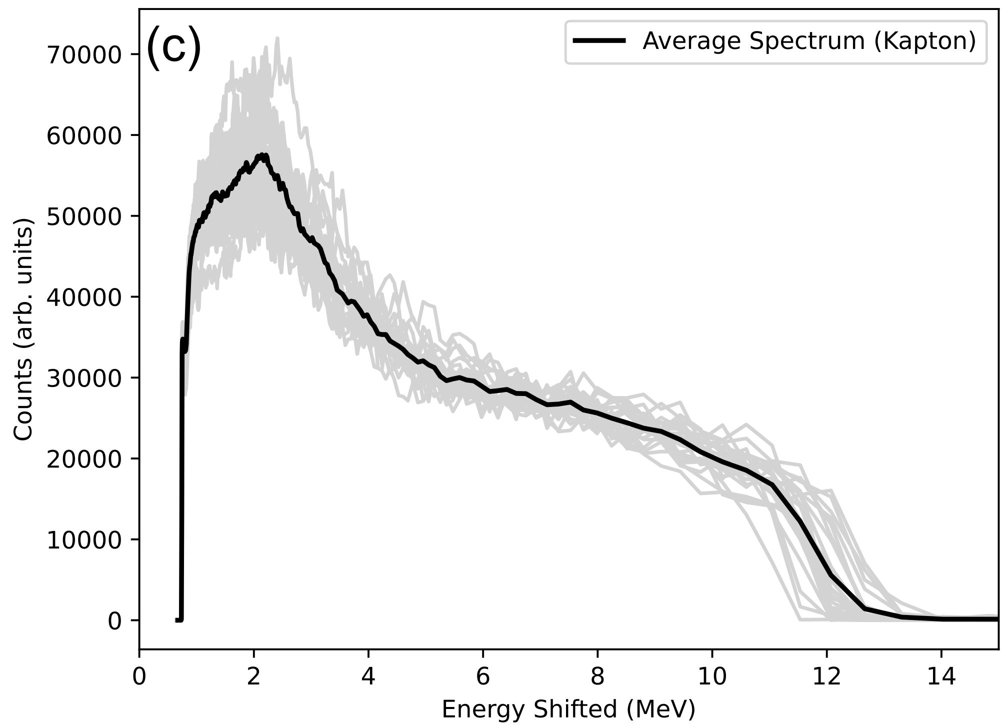


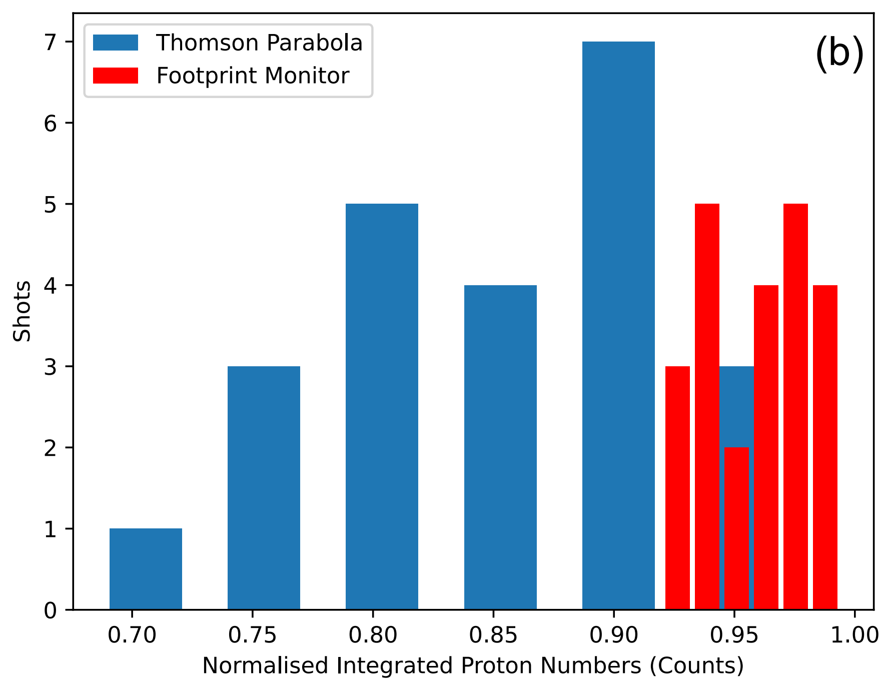


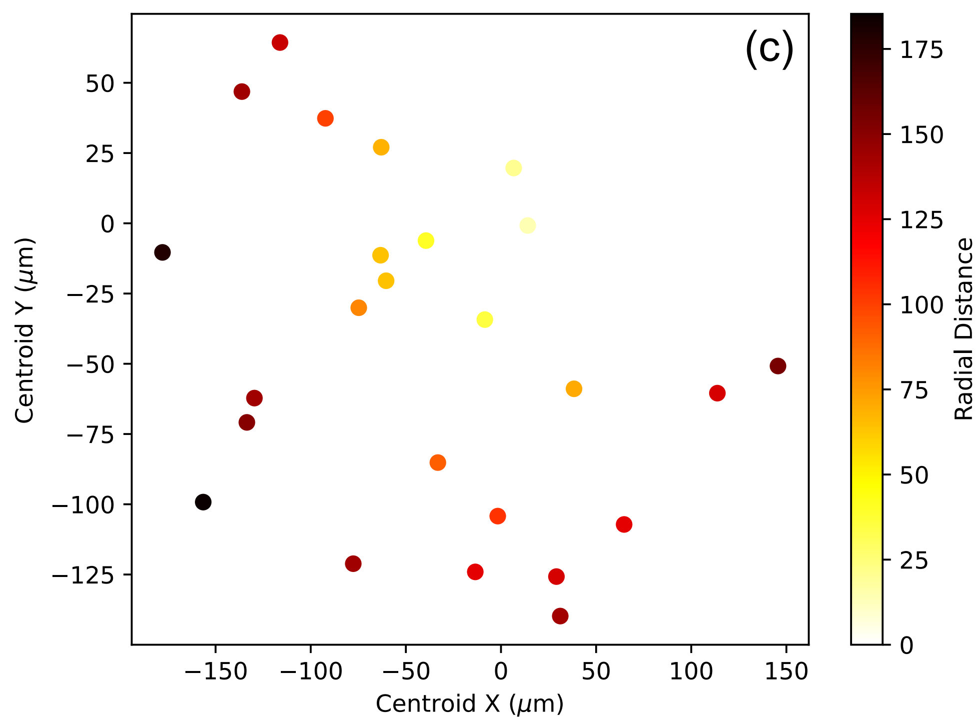
Can we run long term with high stability?

From R. Gray - SCAPA results





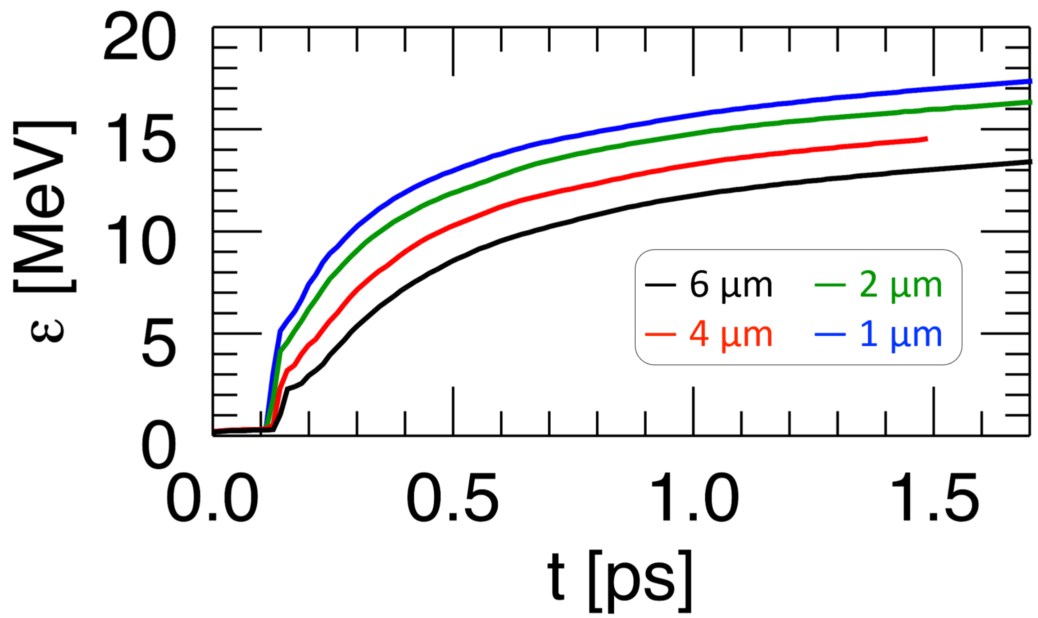




Strategies for source optimisation

See more details in Milestone Report 2:1 - from simulations performed by T. Dascalu

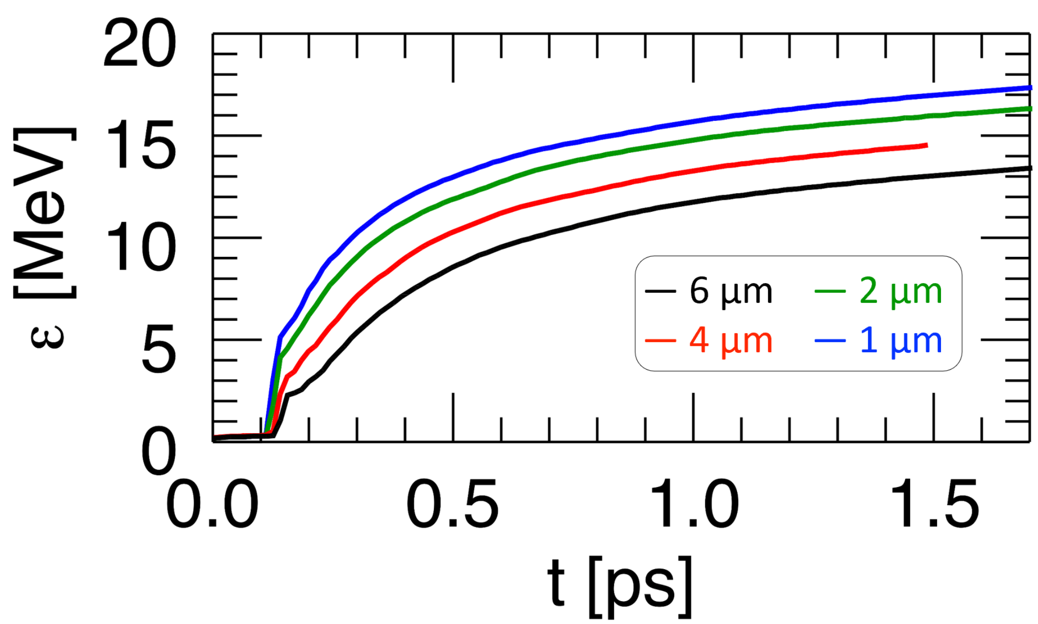
Thickness control



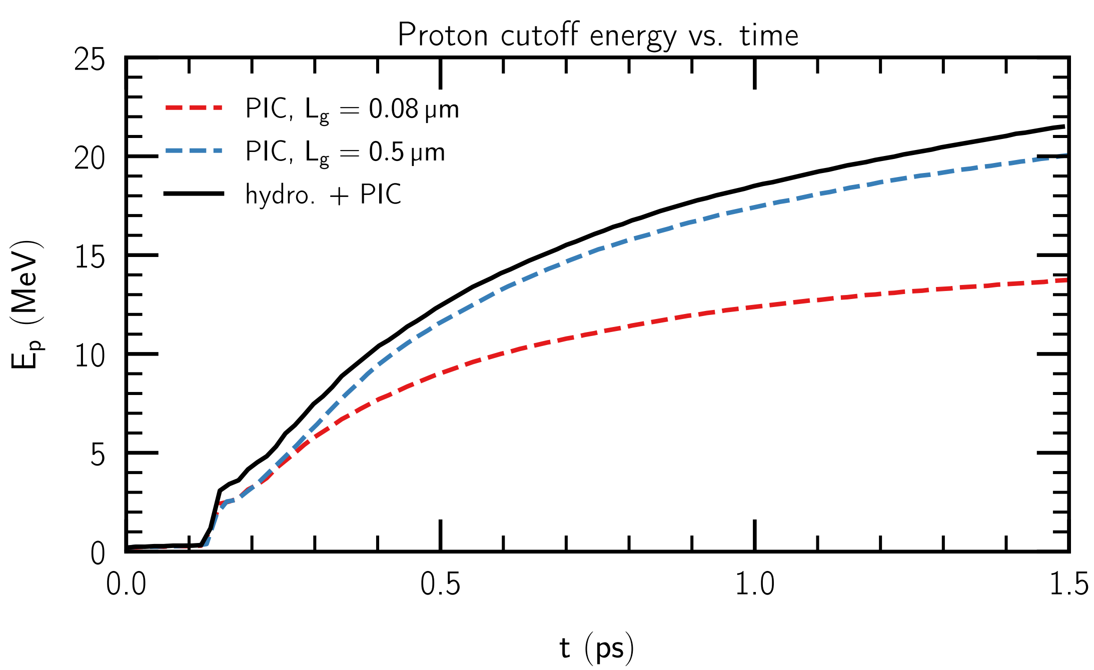
Strategies for source optimisation

See more details in Milestone Report 2:1 - from simulations performed by T. Dascalu

Thickness control



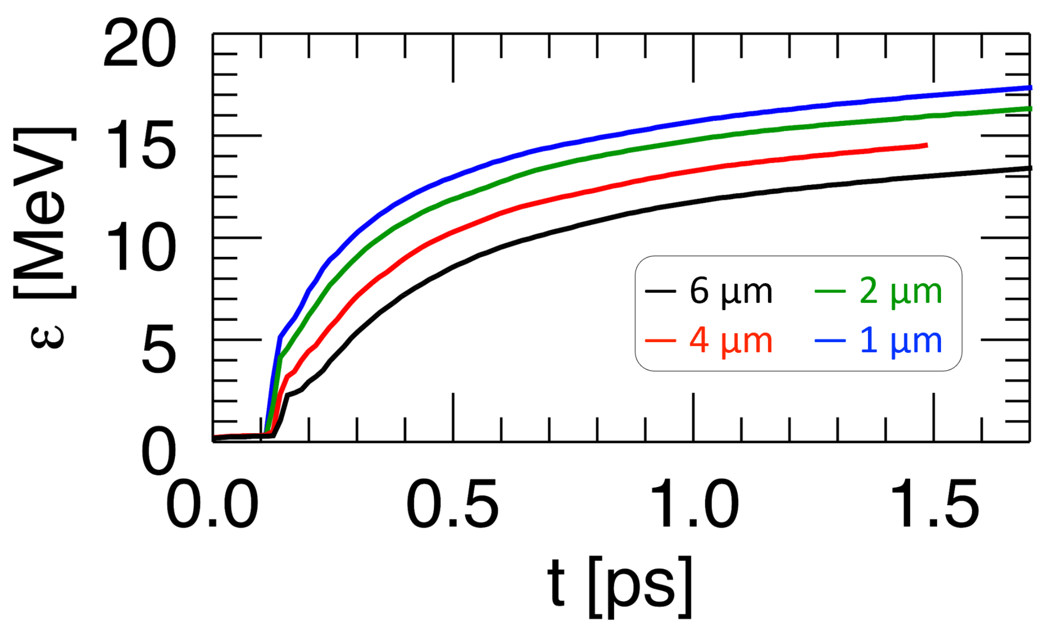
Prepulse control



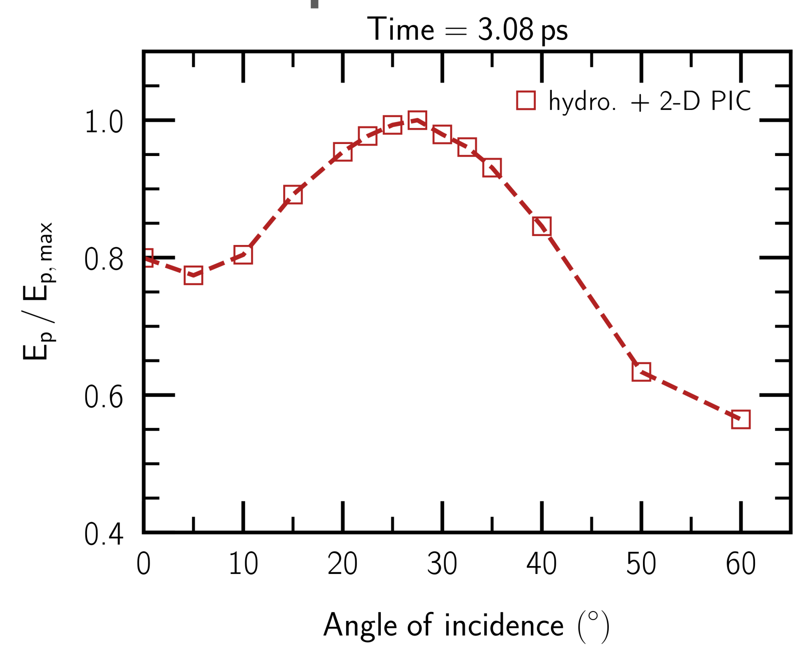
Strategies for source optimisation

See more details in Milestone Report 2:1 - from simulations performed by T. Dascalu

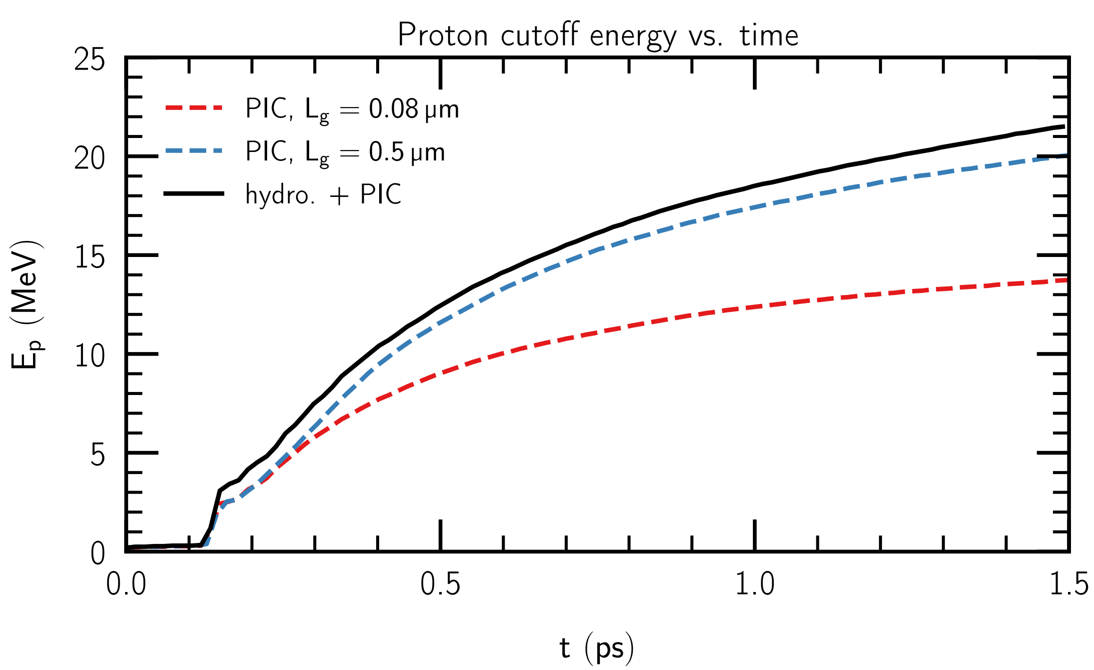
Thickness control

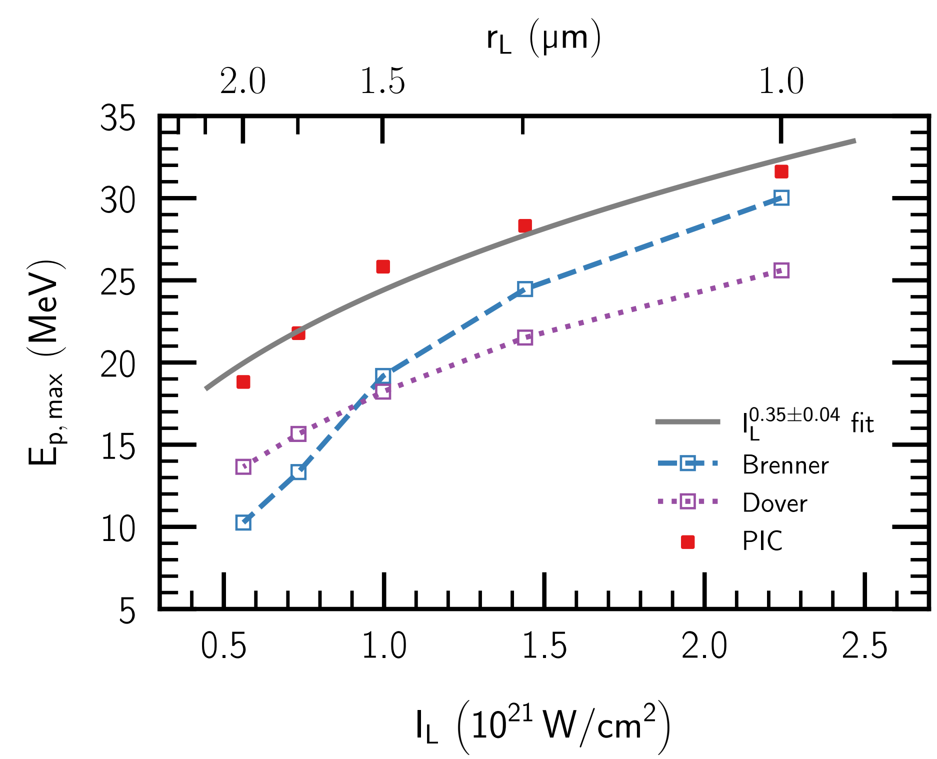


Laser parameter control



Prepulse control





Where next?

- Ongoing work domestically and overseas to develop source
  - High rep laser
  - Novel targets
  - Fast single shot diagnostics
  - New acceleration regimes

- Existing and upcoming UK facilities offer opportunities for future projects
  - SCAPA
  - EPAC
  - Smaller university based systems at QUB, Imperial, etc

- Many overseas user facilities open to proposals for source related applications
  - ELI facilities (especially ELIMAIA / ELIMED at ELI-Beamlines)
  - BELLA (LBNL)
  - ZEUS (Michigan)
  - And others…