Automated control of laser-solid interactions for high-repetition rate ion acceleration

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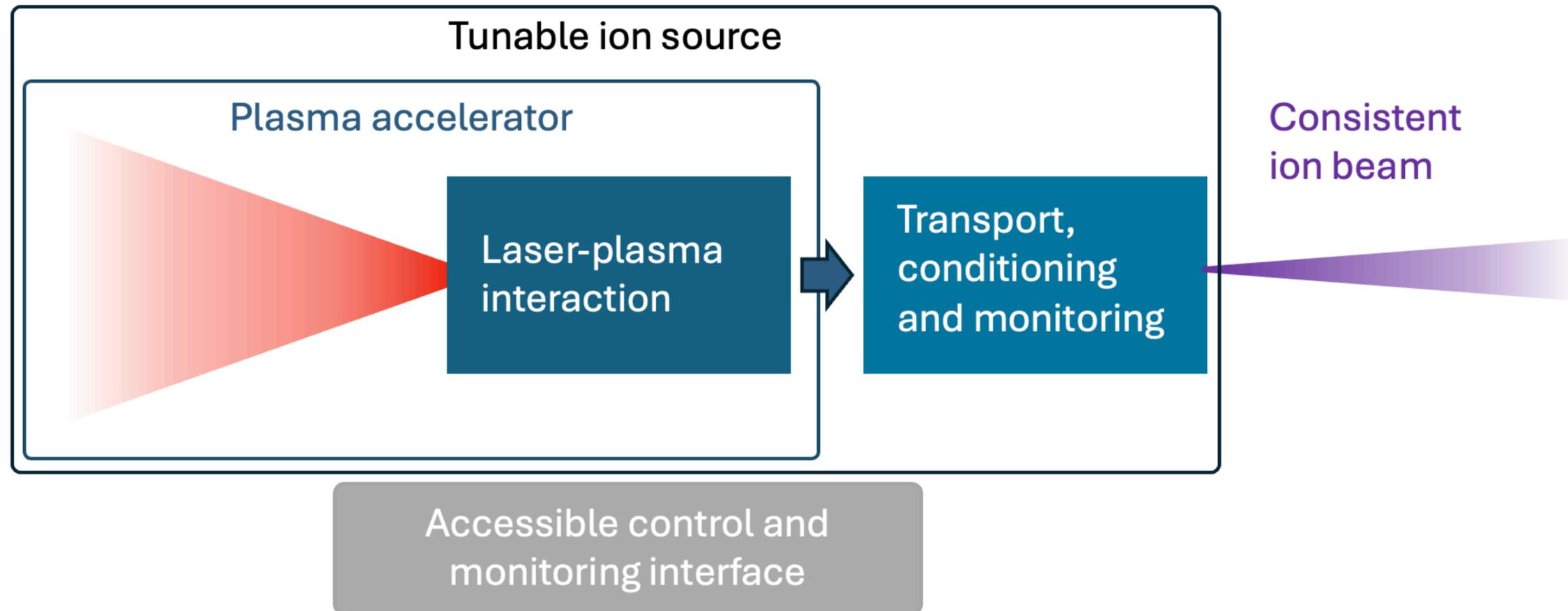
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Happy St. Patrick's Day

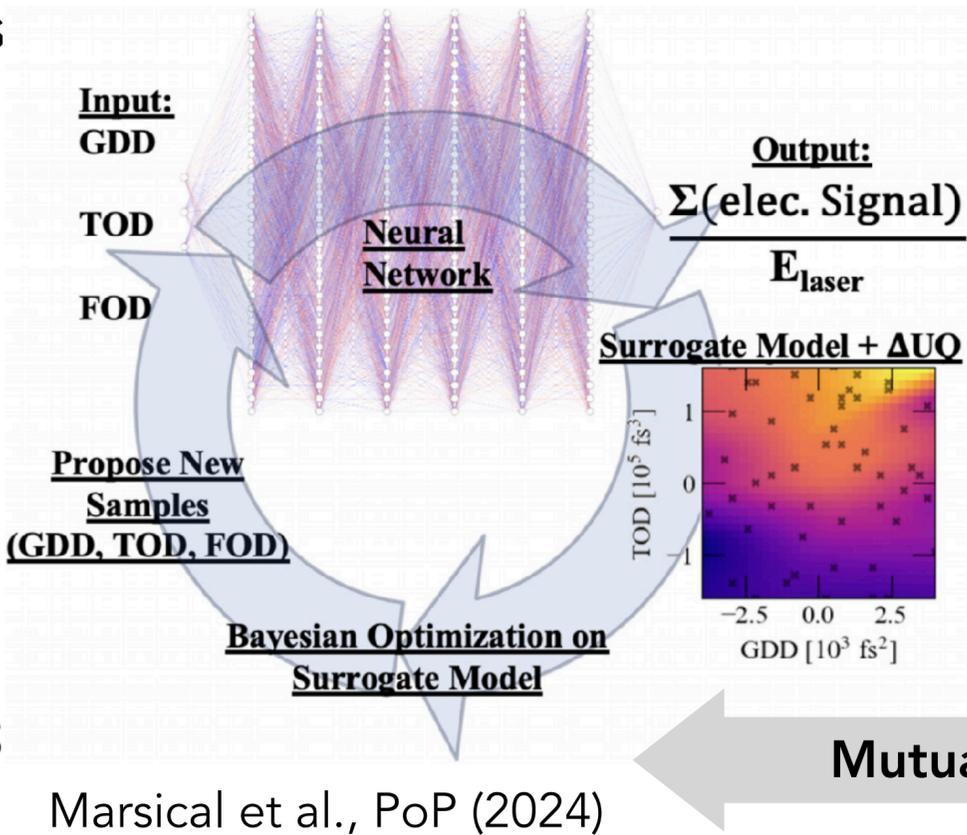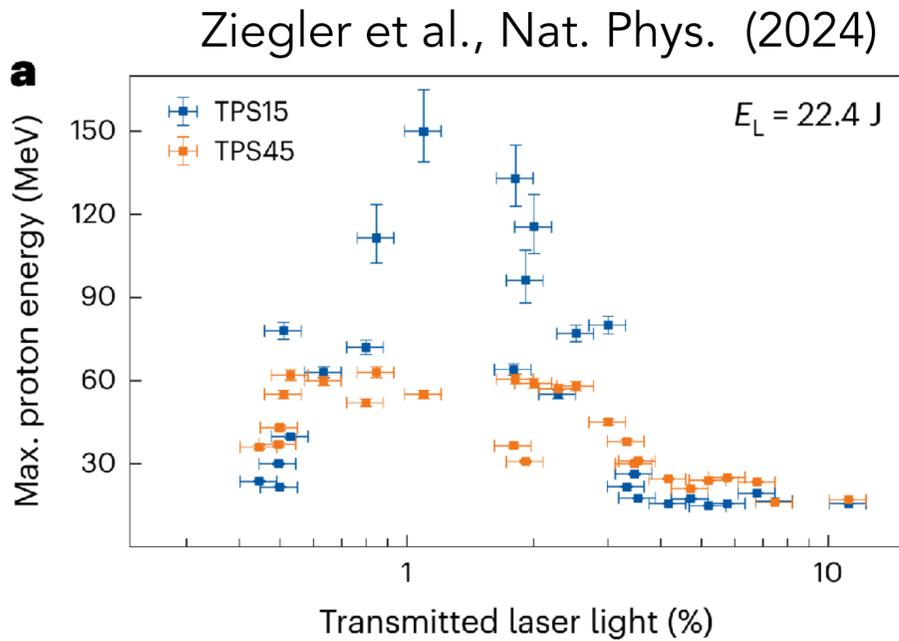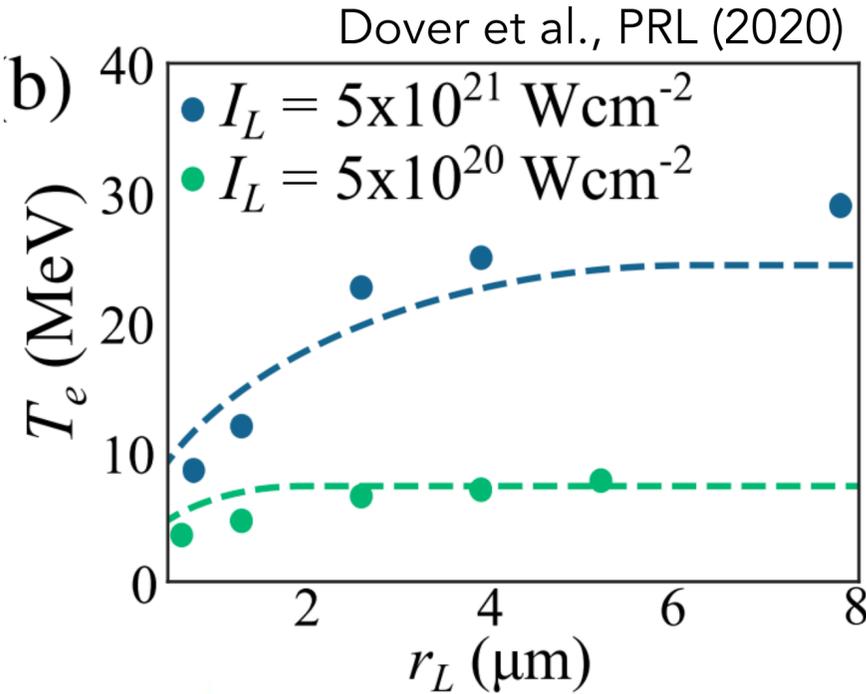# What is required by applications?

- Tuneable beam parameters with predictable performance.

- Stable operation at multi-Hz over long durations of delivery with minimal down time and on-shot monitoring.

Required development

Scientific advances

- Exploring novel acceleration schemes.

- Deeper understanding of the processes underpinning laser-driven ion acceleration.

- Locating optimal conditions

Ziegler et al., Nat. Phys. (2024)

E_L = 22.4 J

TPS15
TPS45

Max. proton energy (MeV)
Transmitted laser light (%)

Dover et al., PRL (2020)

$I_L = 5 \times 10^{21}$ Wcm^{-2}
$I_L = 5 \times 10^{20}$ Wcm^{-2}

T_e (MeV)
r_L (μm)

Input:
GDD
TOD
FOD

Neural Network

Output:
$\frac{\Sigma(\text{elec. Signal})}{E_{laser}}$

Surrogate Model + ΔUQ

TOD [10^5 fs^3]
GDD [10^3 fs^2]

Propose New Samples (GDD, TOD, FOD)

Bayesian Optimization on Surrogate Model

Marsical et al., PoP (2024)

Technological advances

- Multi-Hz targets

- Novel interaction diagnostics

- Interaction stabilisation/optimisation

- Non-destructive and synthetic diagnostics

- Beam capture and conditioning

Kraft et al., PPCF (2018)

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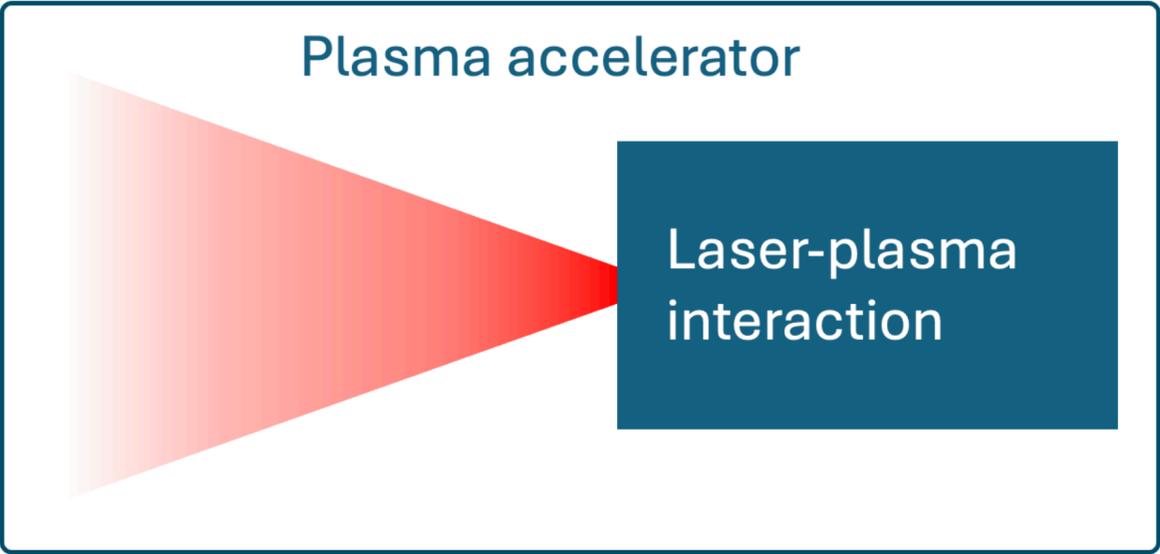
Propp et al., SLAC. Rep. (2015)

ICT
Magnet
Ion beam

Geulig et al. RSI (2022)

Mutual benefit

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

Experiment to demonstrate automated laser-ion accelerator

Plasma accelerator

Laser-plasma
interaction

Experiment goal was to demonstrate:

- multi-Hz operation of planar targets
- online diagnostics
- feedback from diagnostics to laser controls.

Exploited Target Normal Sheath
Acceleration (TNSA) as 'simplest' scheme.

TNSA trends:
- Higher energy $\longrightarrow$ higher proton flux
- Higher intensity $\longrightarrow$ higher max proton energy
- Thinner targets $\longrightarrow$ higher max proton energy
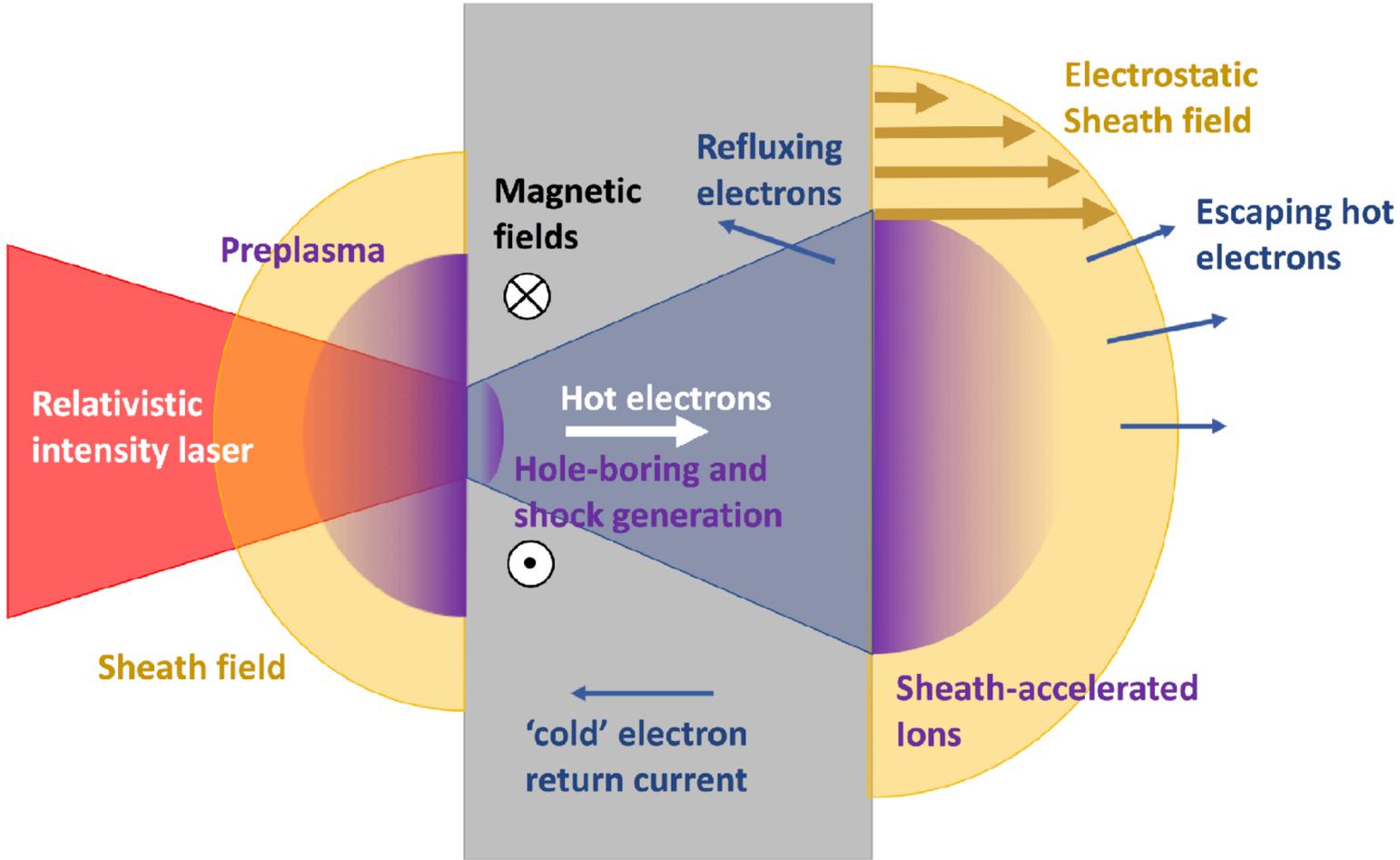
High-rep. targets exploited in TA2

SLAC : **Liquid sheet**

Treffert et al., APL (2022)

Imperial College London : **Tape drive**

Xu et al., HPLSE (2023)
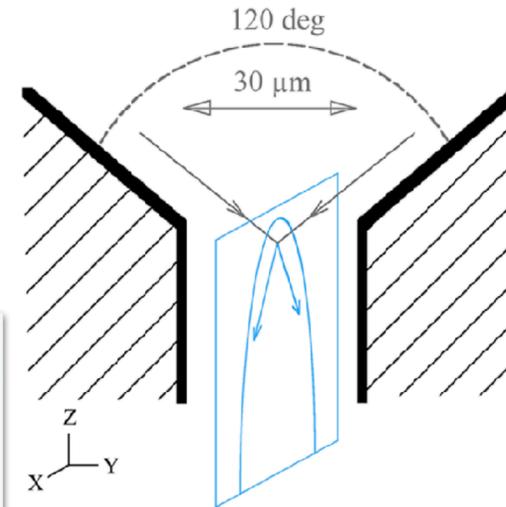
Example shot tape:

Tape position

50 μm Kapton

Galinis et al. RSI 2017

120 deg
30 μm

Crissman et al. Lab. Chip 2022

h = sheet thickness
w_o = outlet width
d = outlet depth
w_j = sheet width
l_j = sheet length

3.1 ml/min   2.8 ml/min   2.5 ml/min   2.2 ml/min

4.2 μm
1.1 μm
0.74 μm
0.63 μm

1mm

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

Liquid flow
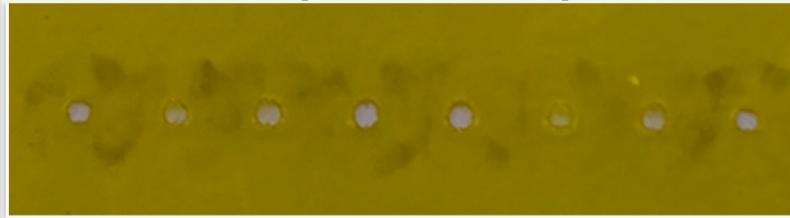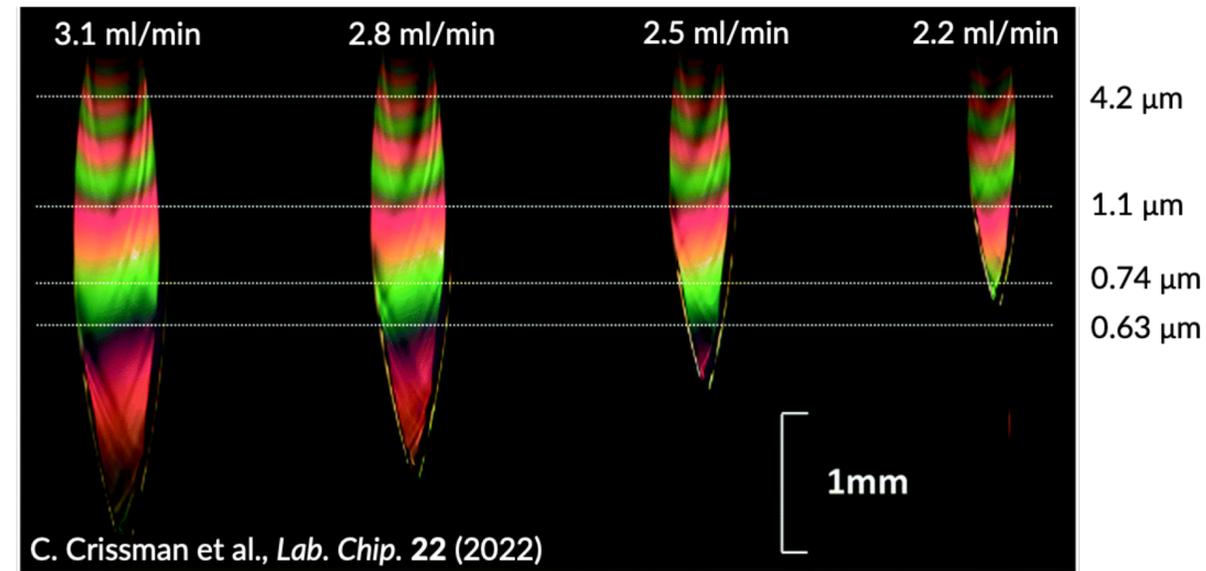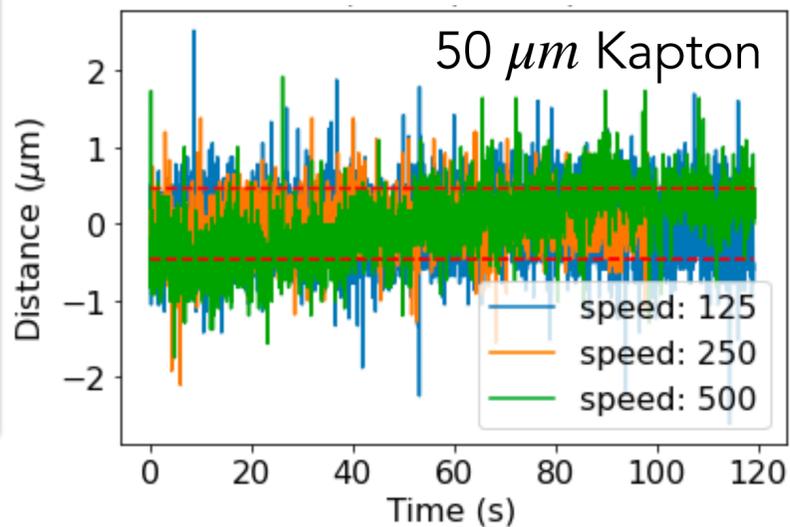
- Compact with excellent rear surface access.

- Used mainly 12.7 or 50 μm Kapton tape.

- Few microns short-term stability.

- High-purity mm-scale water sheet with variable thickness along sheet (< 100 nm).

- Position stability < 5 μm based on optical probing.

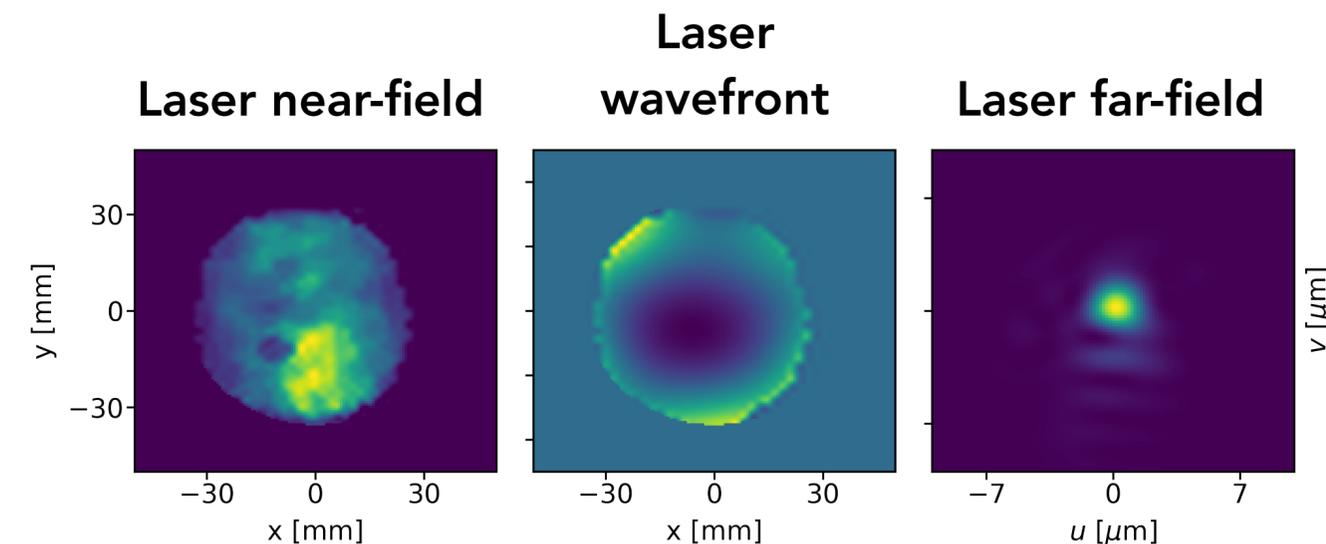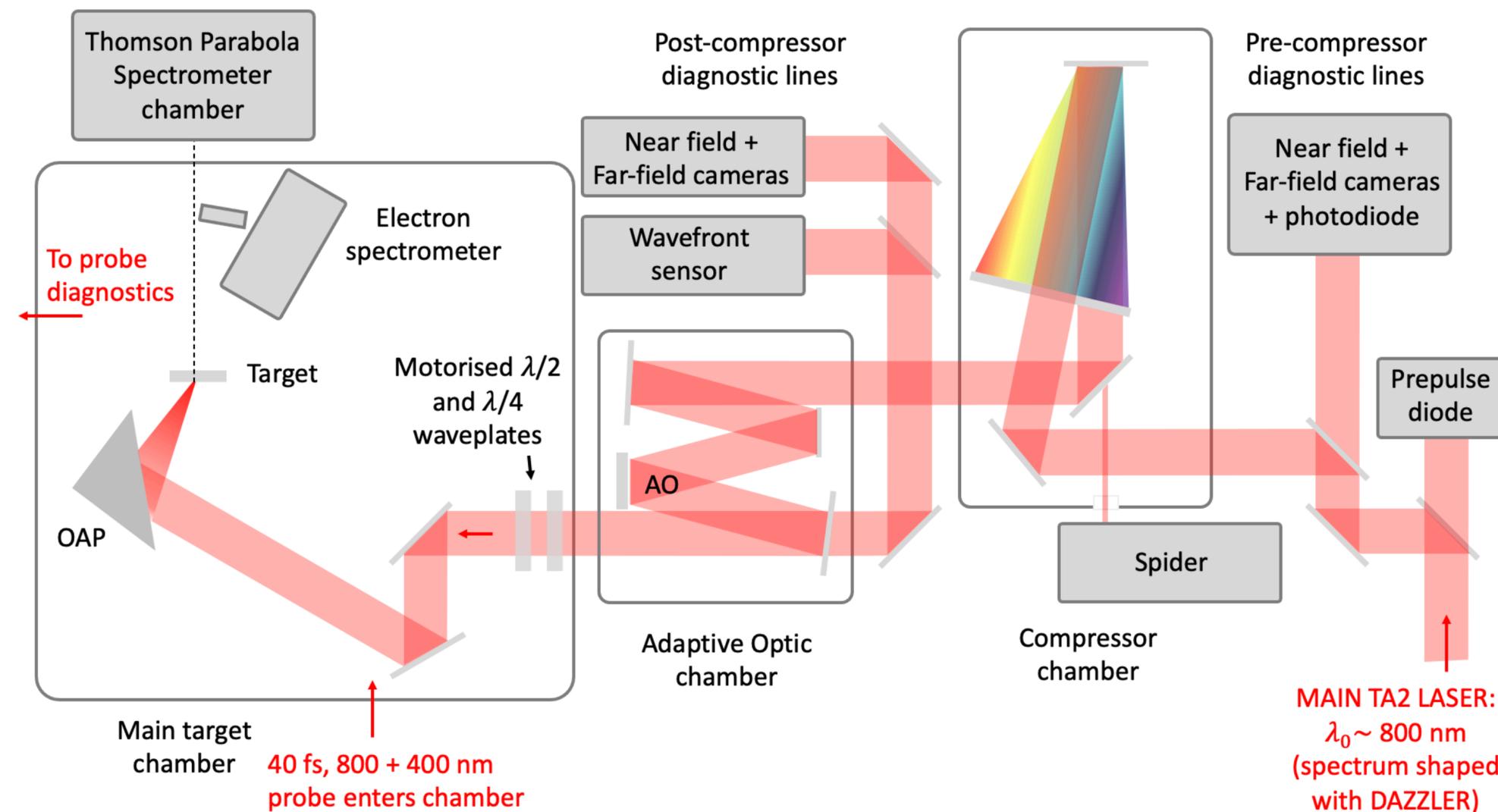- Exhausted via heated catcher.

TA2 Laser and experiment controls

Laser parameters: 5 Hz Ti:Sa with up to 500 mJ on target in 40 fs (best compression) focused with f/2.5 OAP (Rayleigh length ~ 15 μm)

Experiment controls:

- Pulse energy and polarisation controlled via motorised waveplates,

- Wavefront shaping with adaptive optic (via Zernick polynomials),

- Temporal shaping with DAZZLER,

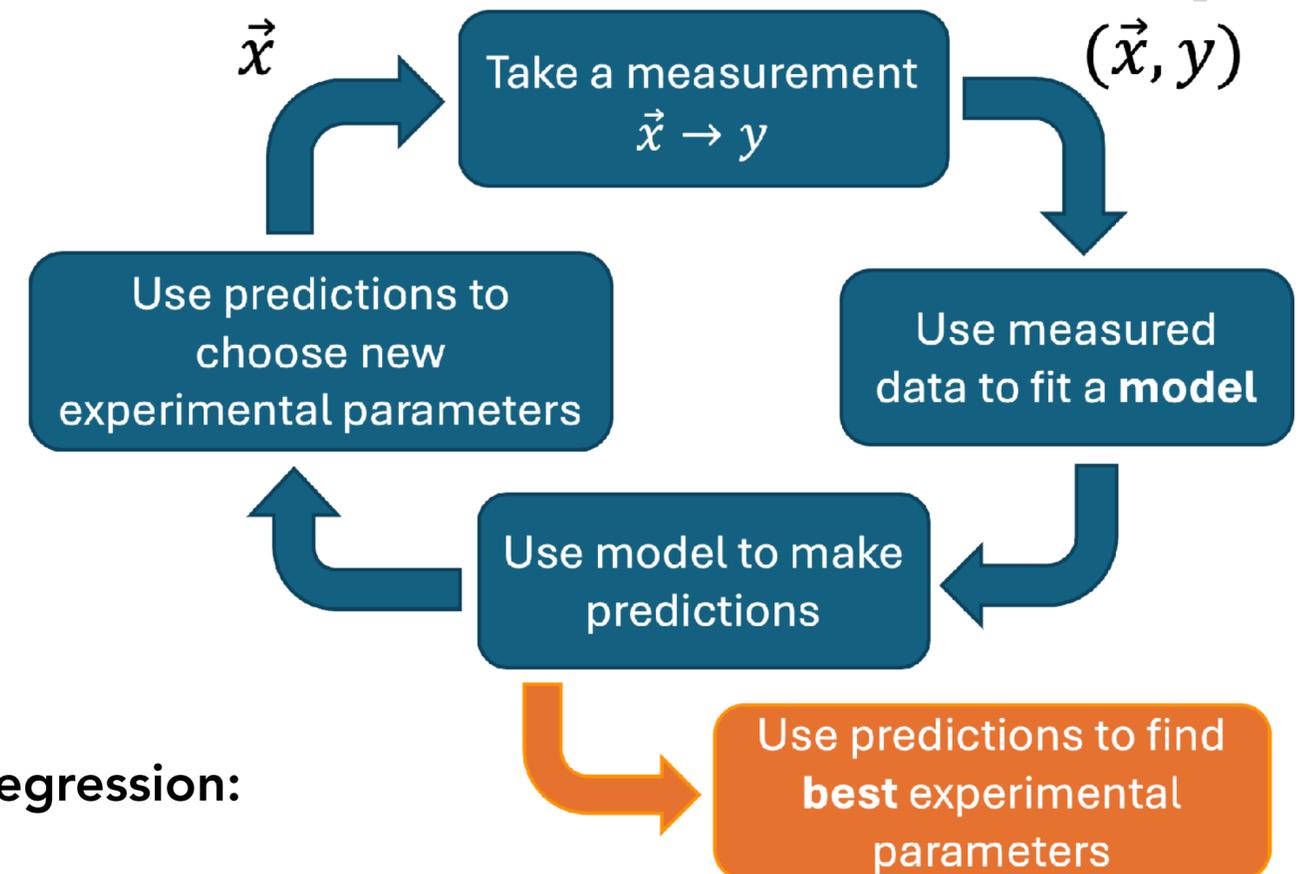- Target position with motorised stages

Control of laser wavefront using adaptive optic and wavefront sensor

Thomson Parabola Spectrometer chamber

Electron spectrometer

To probe diagnostics

Target

Motorised λ/2 and λ/4 waveplates

OAP

Main target chamber

40 fs, 800 + 400 nm probe enters chamber

Post-compressor diagnostic lines

Near field + Far-field cameras

Wavefront sensor

AO

Adaptive Optic chamber

Spider

Compressor chamber

Pre-compressor diagnostic lines

Near field + Far-field cameras + photodiode

Prepulse diode

MAIN TA2 LASER: λ_0 ~ 800 nm (spectrum shaped with DAZZLER)

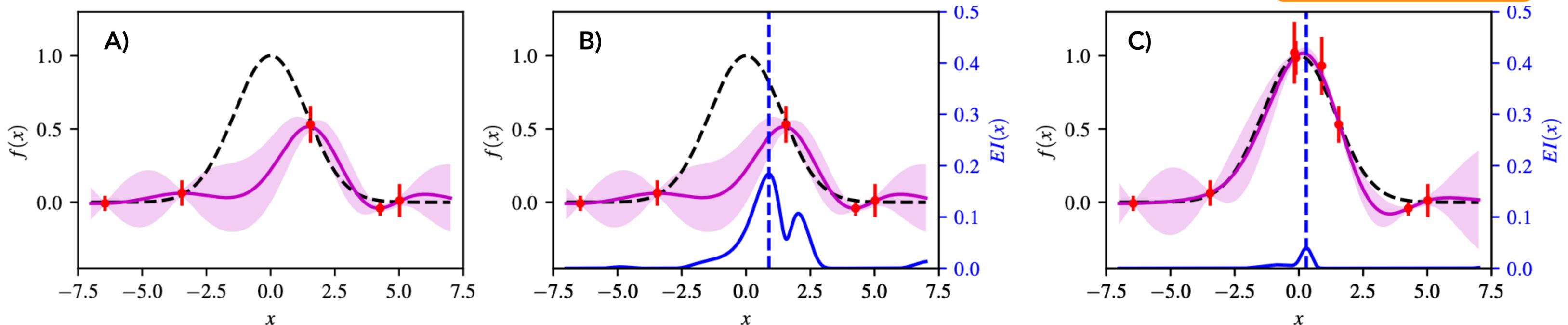Laser near-field

Laser wavefront

Laser far-field

Bayesian optimisation using Gaussian process regression

A Bayesian optimizer (BO) using Gaussian processes regression (GPR)

- Builds a multi-D parameter space model from noisy measurements where additional measurements are costly and tracks uncertainty in the model.

- Optimises a fitness parameter which defines a desirable outcome e.g. high proton flux or peak energy.

$\vec{x}$

Take a measurement
$\vec{x} \rightarrow y$

$(\vec{x}, y)$

Use predictions to choose new experimental parameters

Use measured data to fit a **model**

Use model to make predictions

Use predictions to find **best** experimental parameters

Cartoon of Bayesian Optimisation using Gaussian Process Regression:

Courtesy of M. J. V. Streeter - Optimiser details: Shalloo et al, Nat. Comms. (2020)
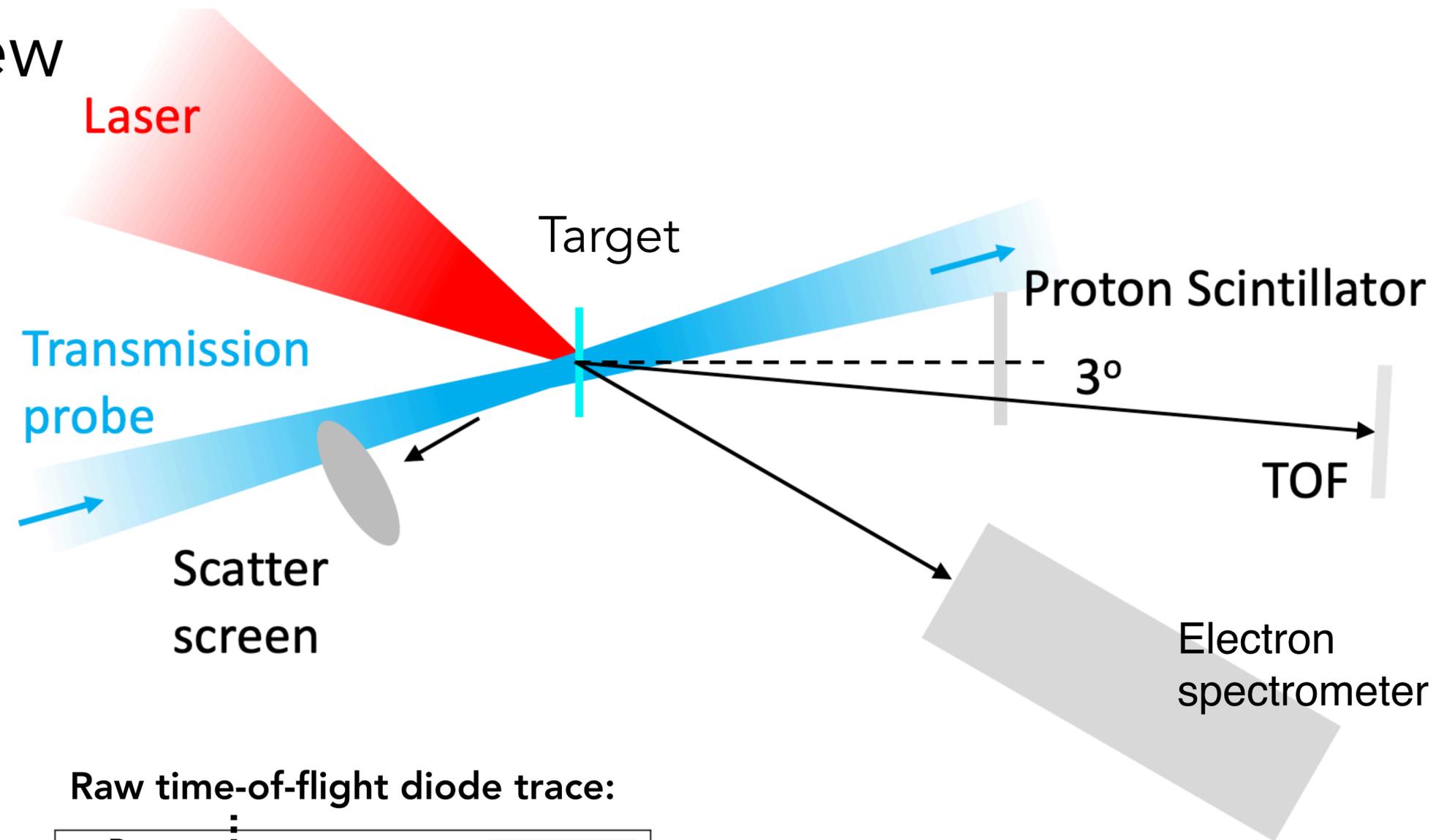
TA2 Experimental overview

Target parameters:

12.7 μm or 50 μm Kapton tape

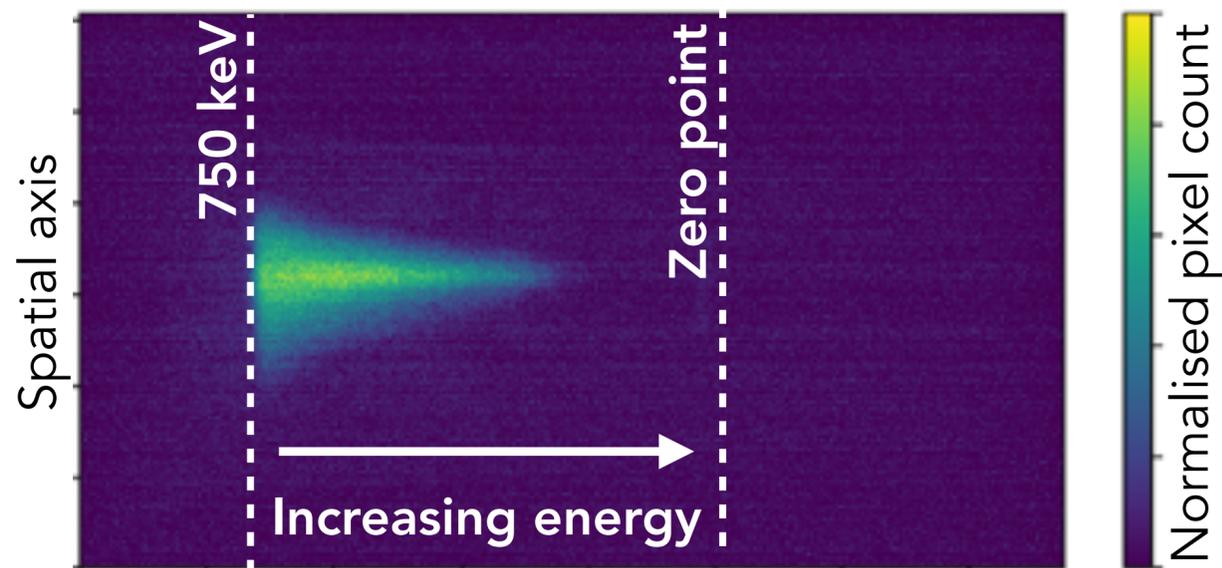Ultra-pure water with (600 ± 100) nm thickness at 2.8 mm below nozzle outlet.

Vacuum parameters:
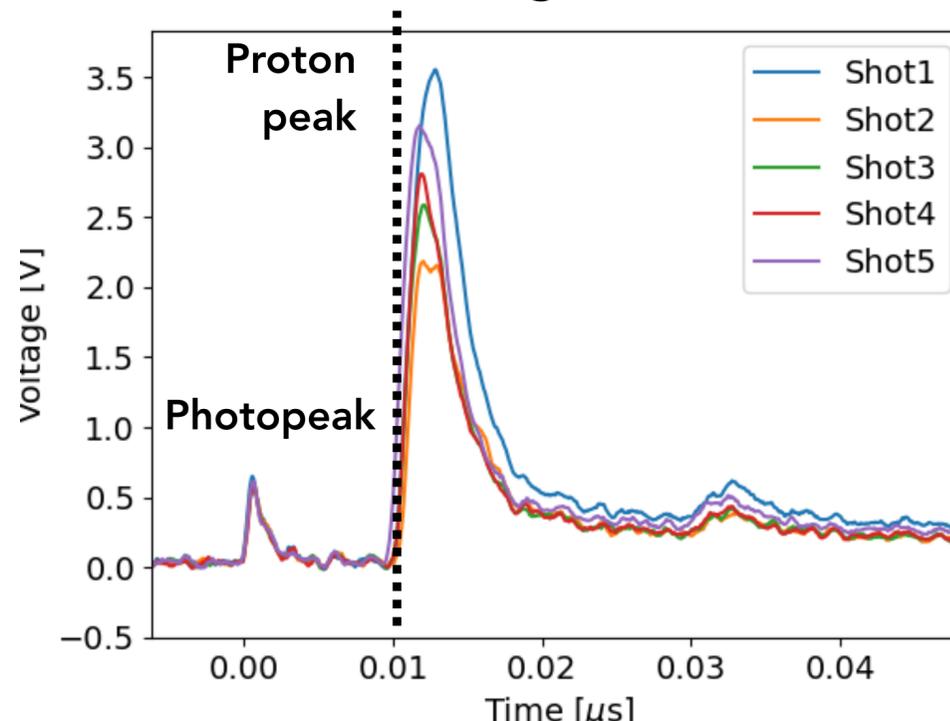
Typically vacuum pressure 1×10^{-4} mbar

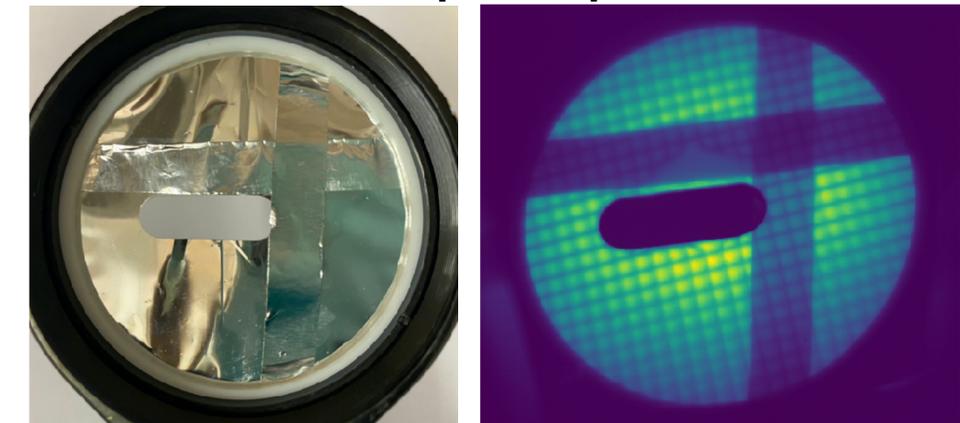With liquid jet - vacuum pressure of 0.1 mbar at approx. 1 m from liquid sheet.

Laser

Target

Transmission probe

Proton Scintillator

3°

TOF

Scatter screen

Electron spectrometer

Electron spectrometer signal:

Spatial axis

750 keV

Zero point

Increasing energy

Normalised pixel count

Raw time-of-flight diode trace:

Proton peak

Photopeak

Shot1
Shot2
Shot3
Shot4
Shot5

voltage [V]

Time [μs]

Proton spatial profile:

Variation in proton beam performance with target position/peak laser intensity

- Proton beam energy and flux are very dependent on position relative to laser best focus.
- Quick scanning of parameters with multiple shots per setting allowed characterisation of stability.

High-resolution 1D scan of target position along laser propagation axis.

Degradation in performance of proton with highest intensity on target, in contrast to simple TNSA models.

Average diagnostic flux

Particle energy spectra
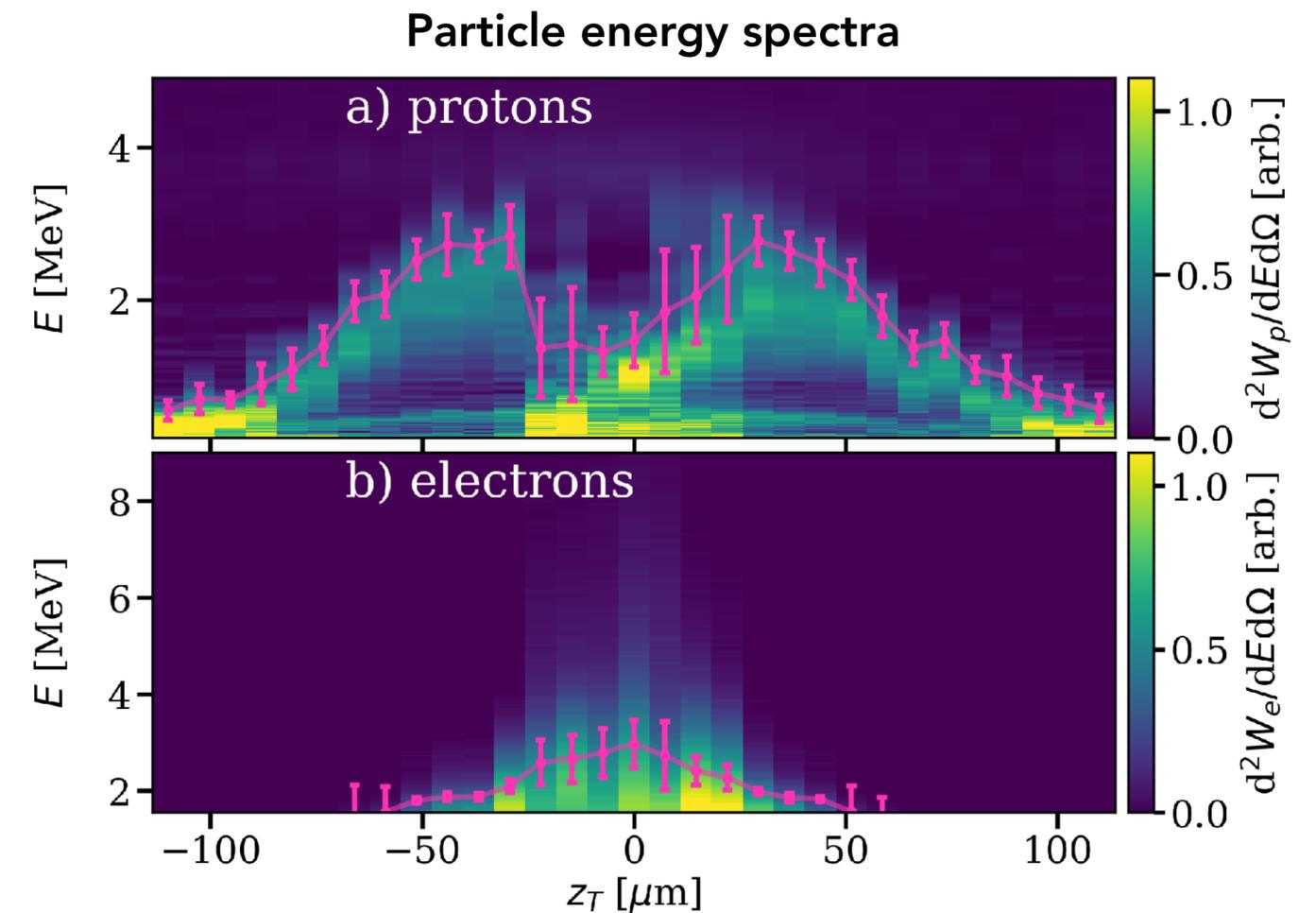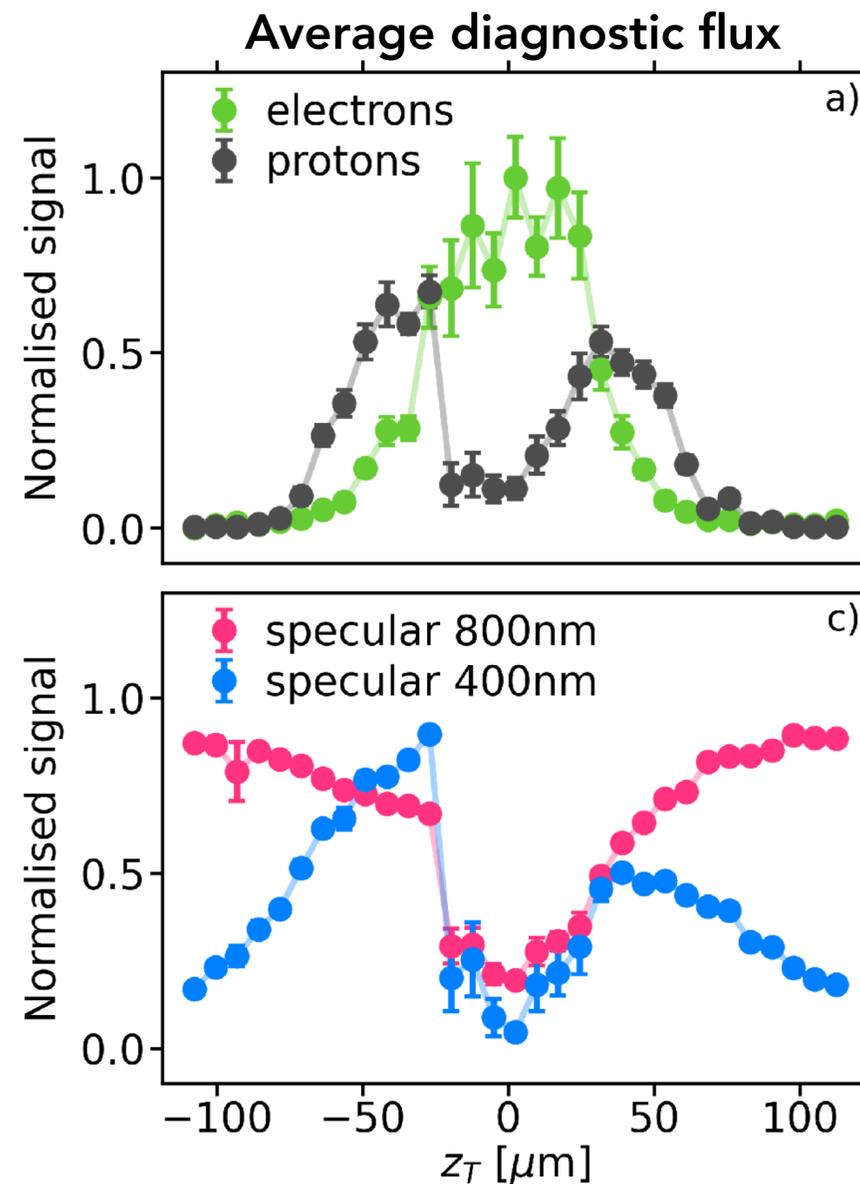
Target: 13 μm Kapton   **Laser energy: 438 ± 32 mJ**

Variation in proton beam performance with laser intensity distribution

- Same 'dip' observed when varying intensity via manipulation of laser intensity profile via wavefront control.

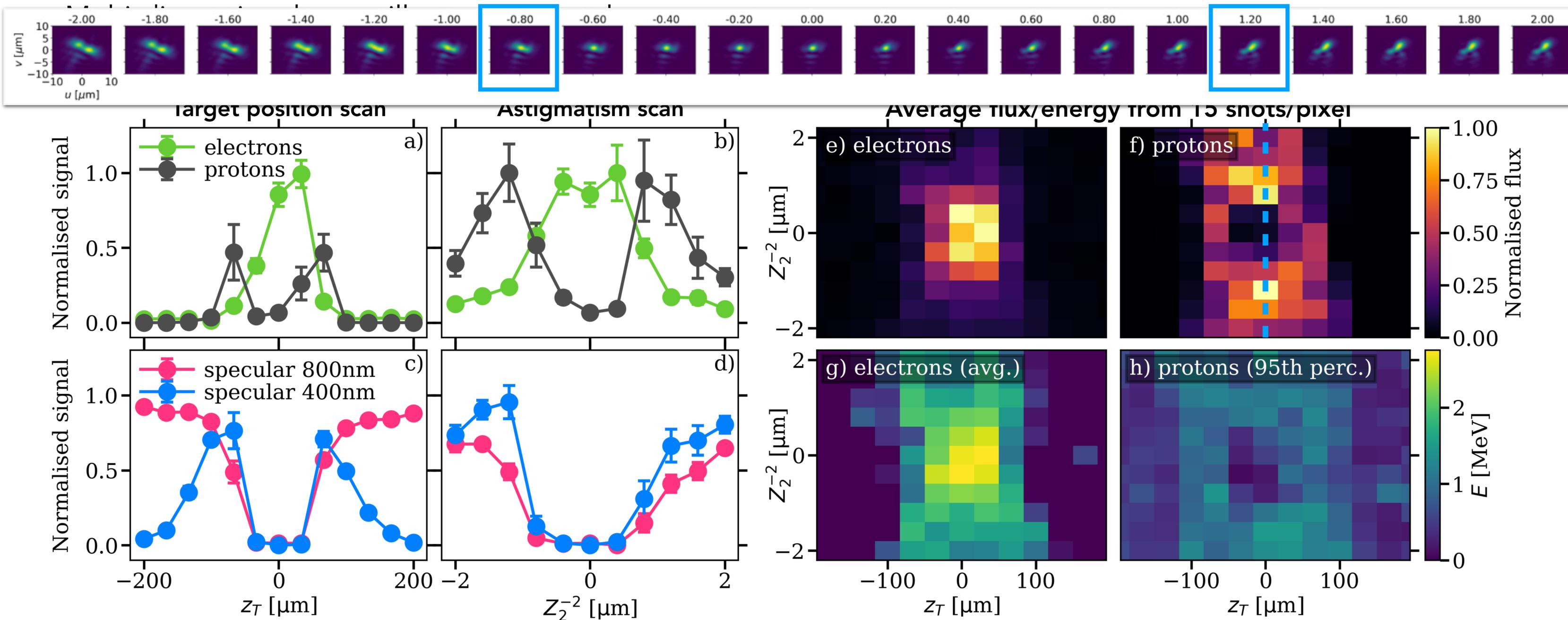- Multi-dimensional scans illustrate a complex parameter space.
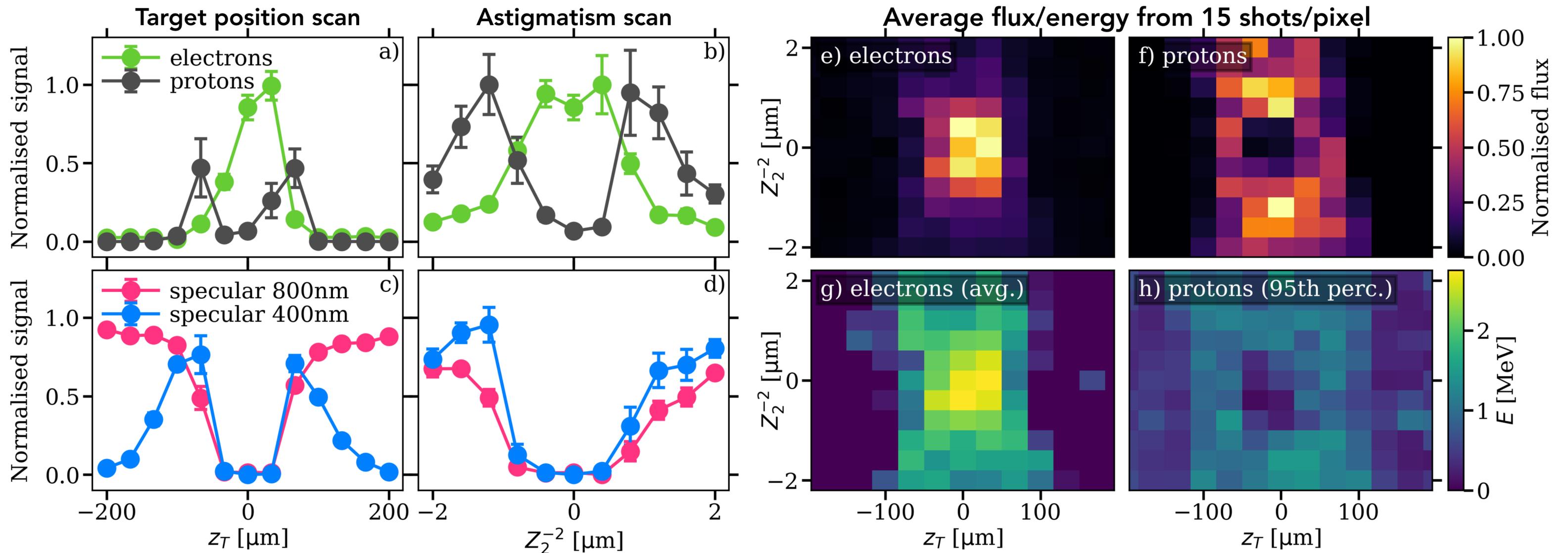
Target: 13 μm Kapton   Laser energy: 453 ± 40 mJ

Variation in proton beam performance with laser intensity distribution

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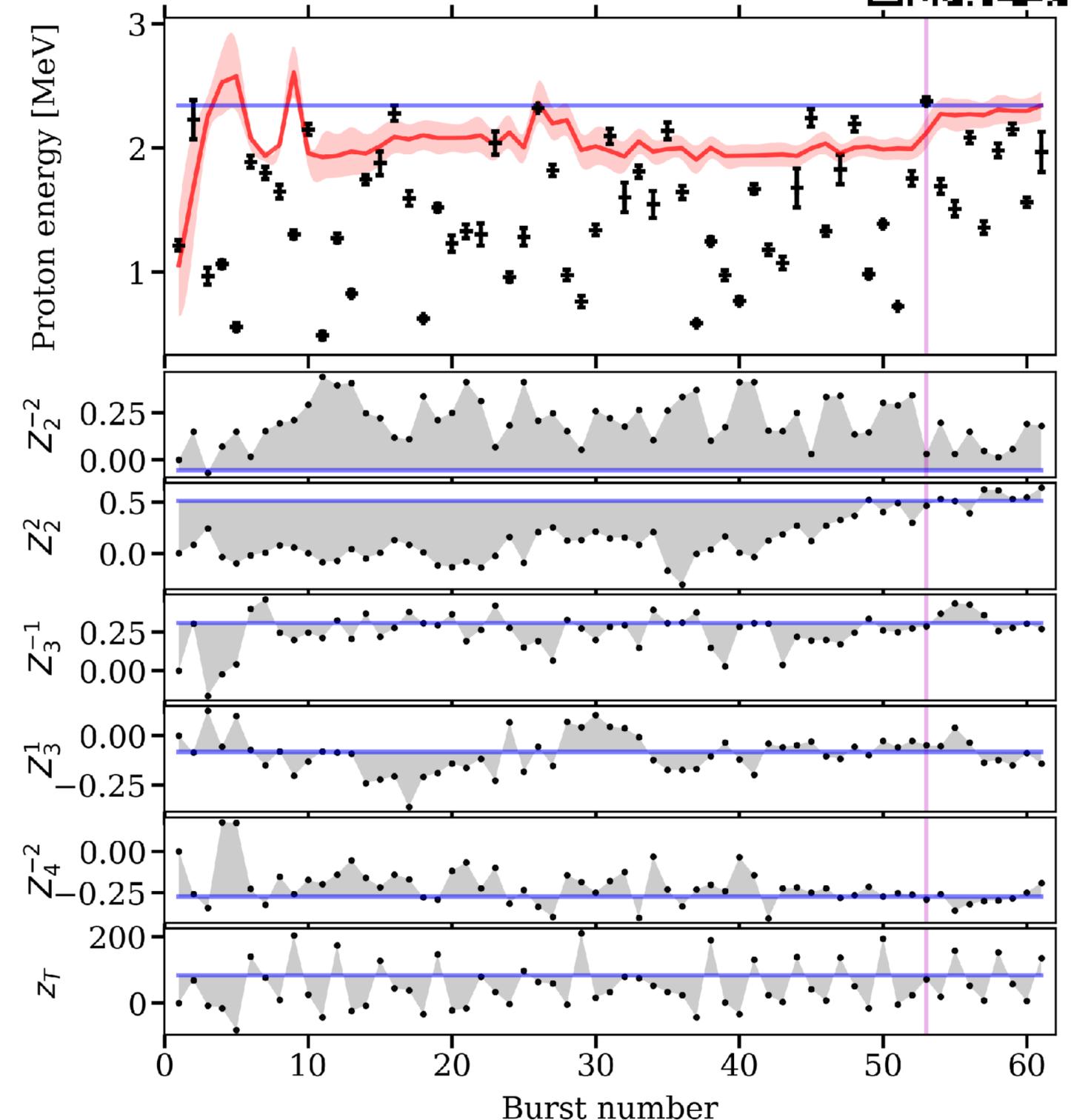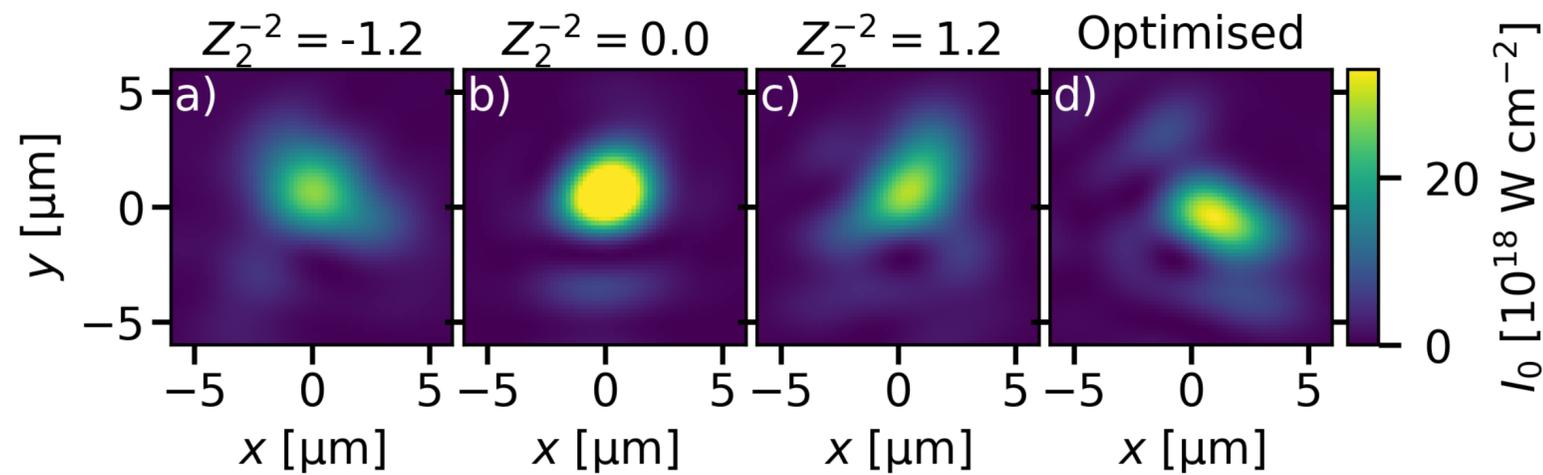**Target: 13 μm Kapton** **Laser energy:** 453 ± 40 **mJ**

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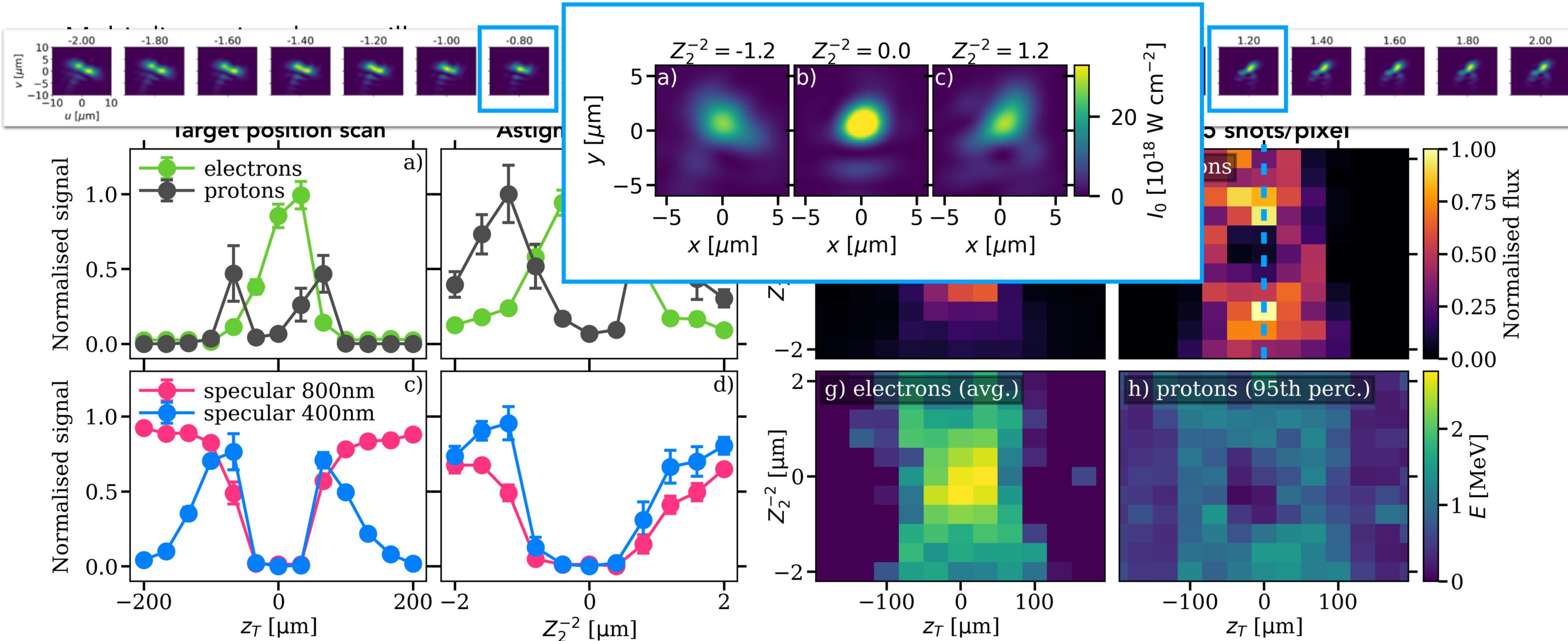
Target: 13 μm Kapton   Laser energy: 453 ± 40 mJ

Bayesian Optimisation of intensity distribution

- Scanning more than 2 parameters is prohibitively time consuming.

- Bayesian optimisation of laser wavefront and target position with goal of increase the maximum energy recorded from the Time-of-flight diode.

- Optimised spot is comparable to astigmatic pulses where we saw peak proton signal from the 2D scan.
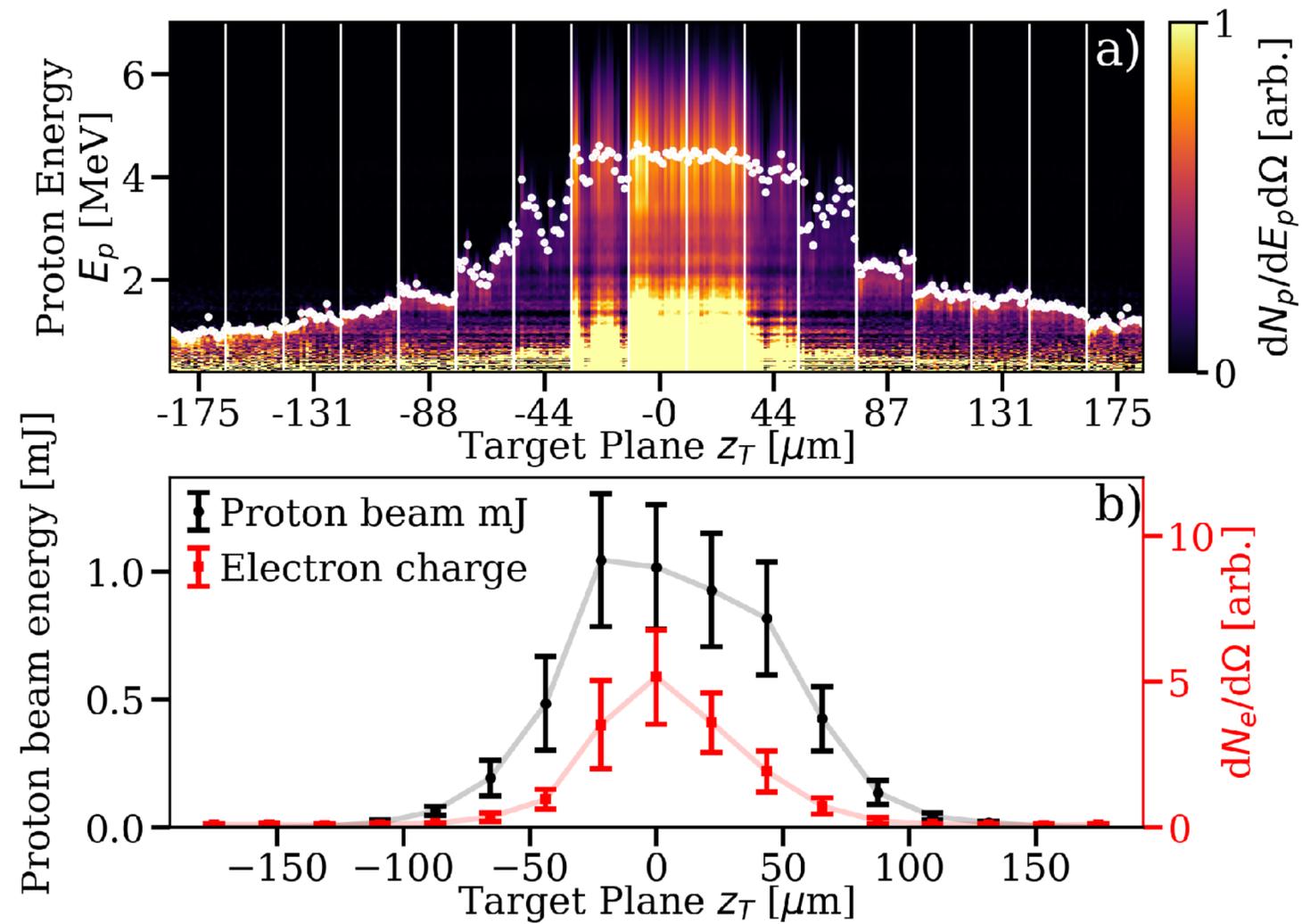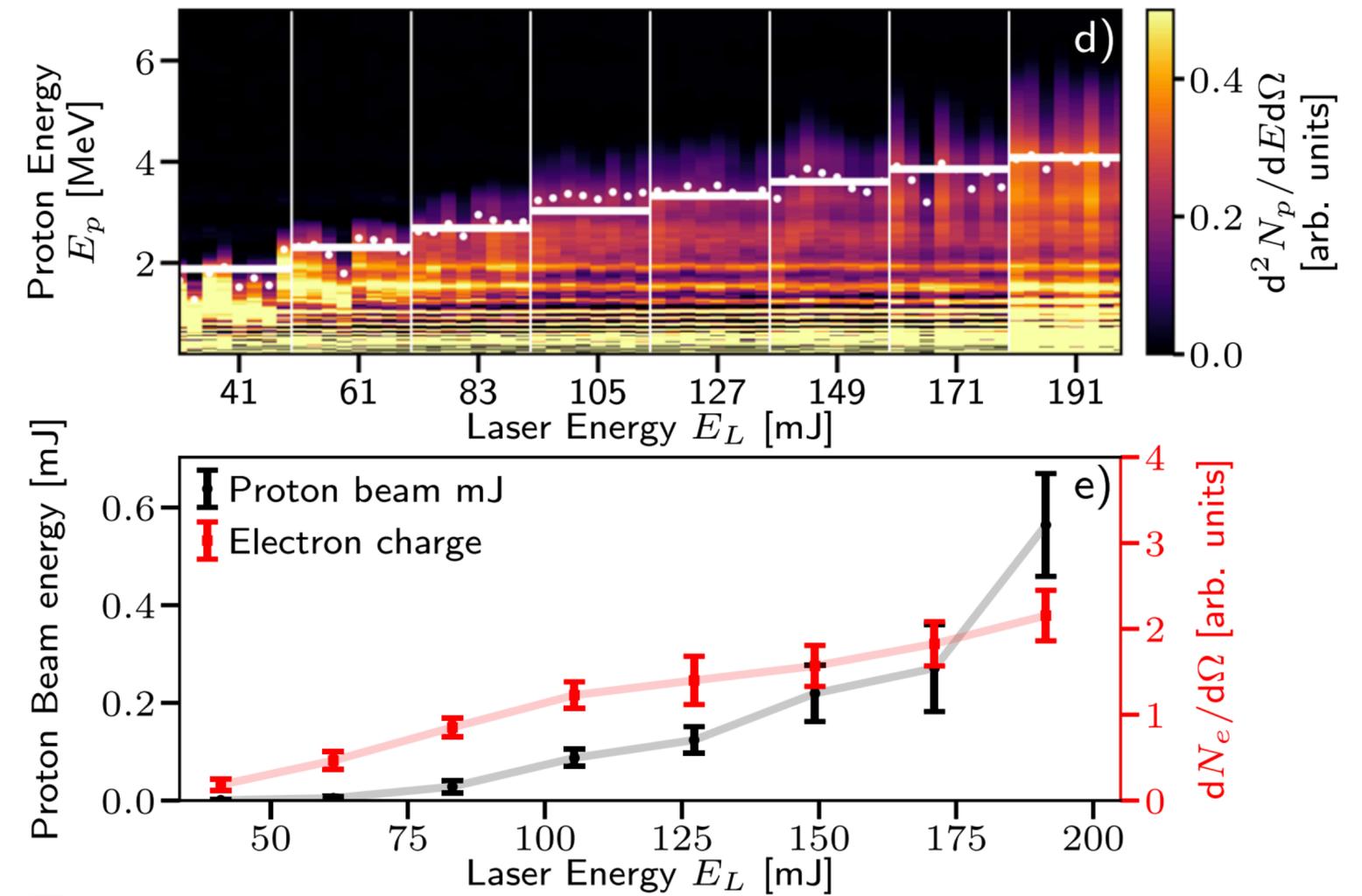

Target: 13 μm Kapton   **Laser energy: 258 ± 22 mJ**

Different interaction conditions provide different performance

Variation in proton spectrum as target is scanned through focus:

Variation in proton spectrum with incident laser energy:

- Laser energy reduced due to pump failure.

- Proton beam performance very stable across focus without dip in proton flux or energy.

Target: 600 nm Water   **Laser energy: 190 mJ**

# Bayesian Optimisation of intensity distribution

- Bayesian optimisation of laser wavefront with goal of increase the maximum energy recorded from the ToF.

- While fitness focused on maximum proton energy, integrated charge on ToF also increased.

- Optimised spot has improved energy concentration to achieve higher peak intensity.
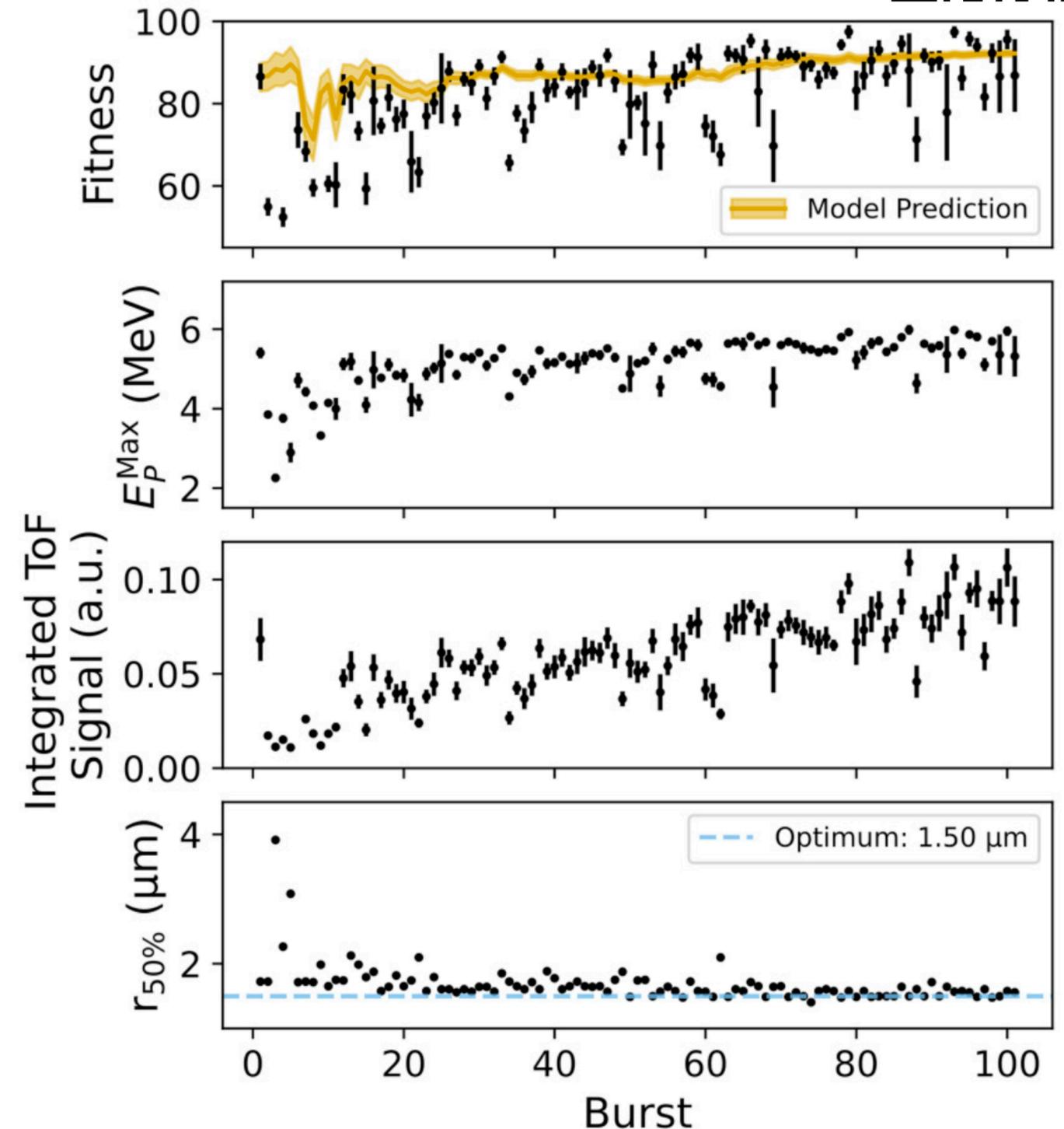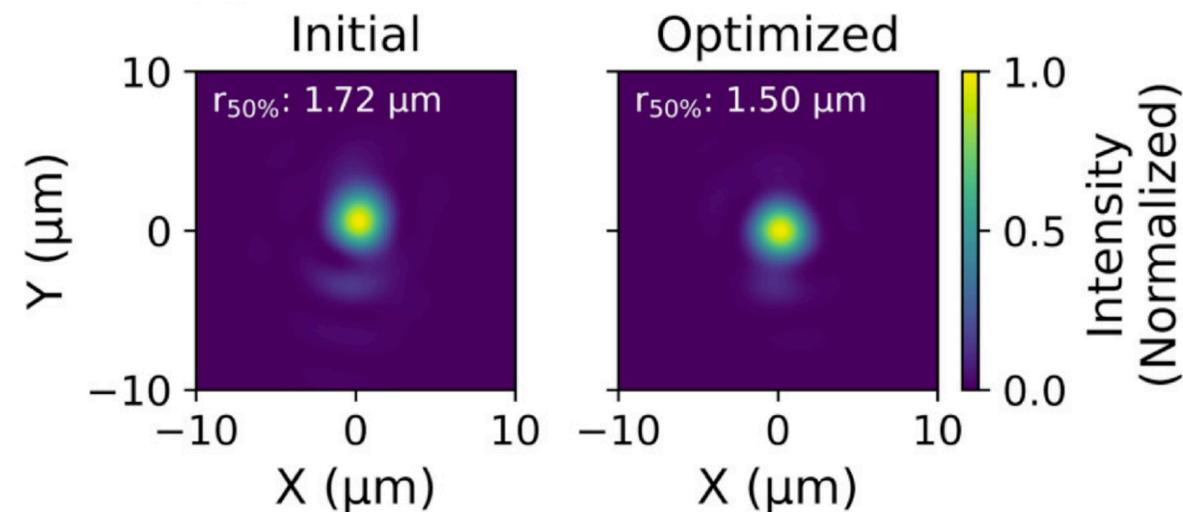
# Proton beams from liquid leaf exhibit low-divergence
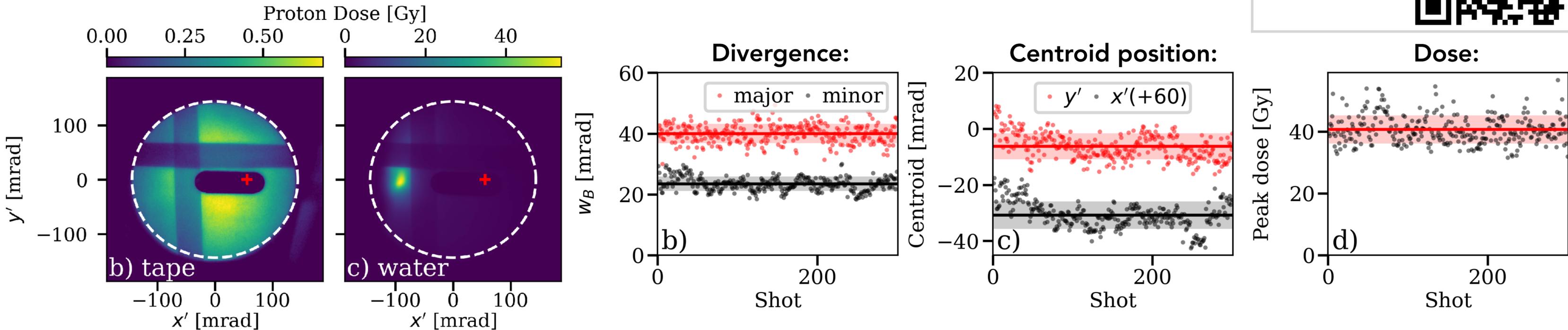
Observation repeated using foil target and gas volume
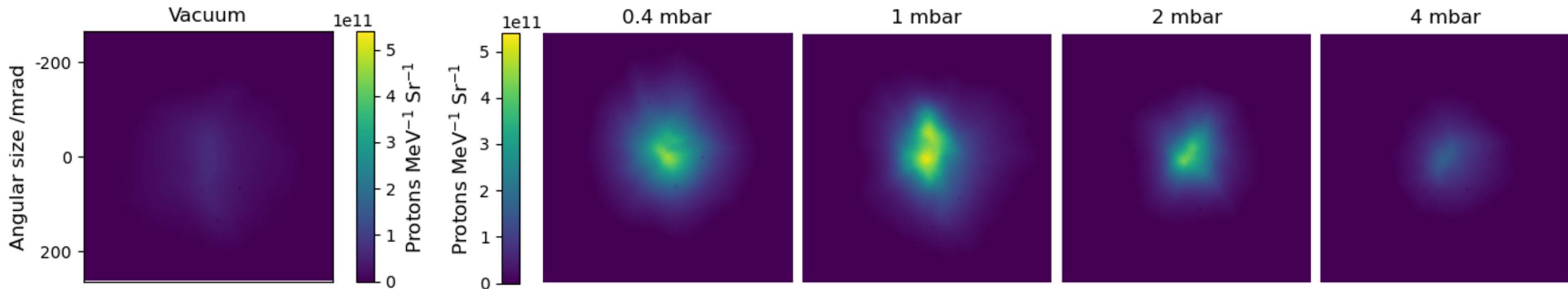
Summary

- Automation of experiments is a necessary step to prepare laser-driven secondary sources for realistic applications.

- Automation enables incorporation of computer guided data-acquisition for efficient mapping of multi-dimensional parameter spaces and non-specialise optimisation.

- Liquid sheet targets present an exciting, versatile opportunity for high-repetition-rate proton acceleration with high shot-to-shot stability and low divergence.

- The presence of a background gas influences proton beam propagation and can be tuned by vapour composition and density potentially allowing tailoring energetic proton propagation.
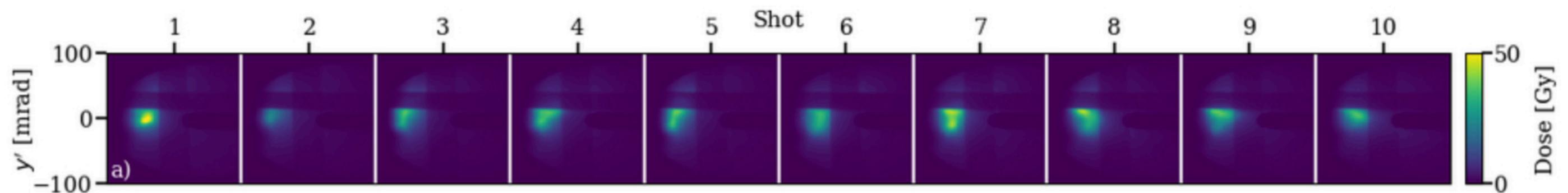
Thank you again to our collaborators
and to you for your attention

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

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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,

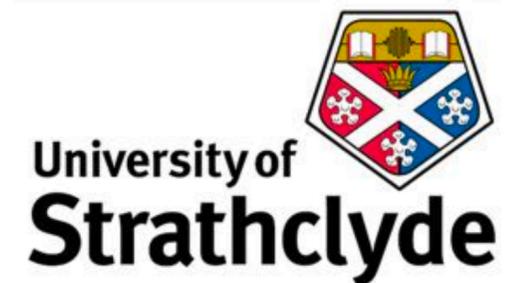**Strathclyde University:** R. Gray, M. King, P. McKenna.

ELI Beamlines: V. Istokskaiia, L. Giuffrida.

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