# High-repetition rate laser-solid interactions: Automation, optimisation, challenges

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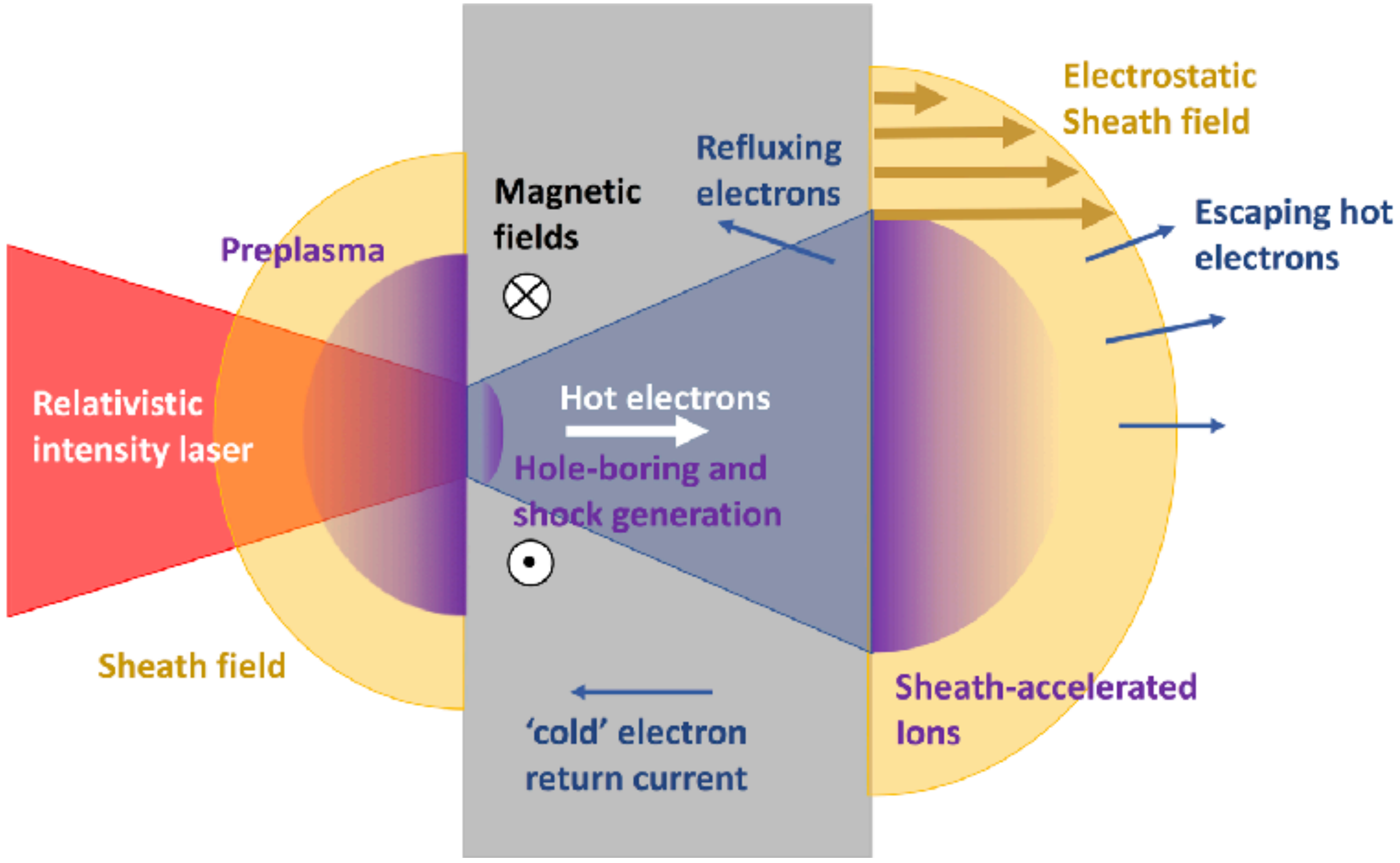
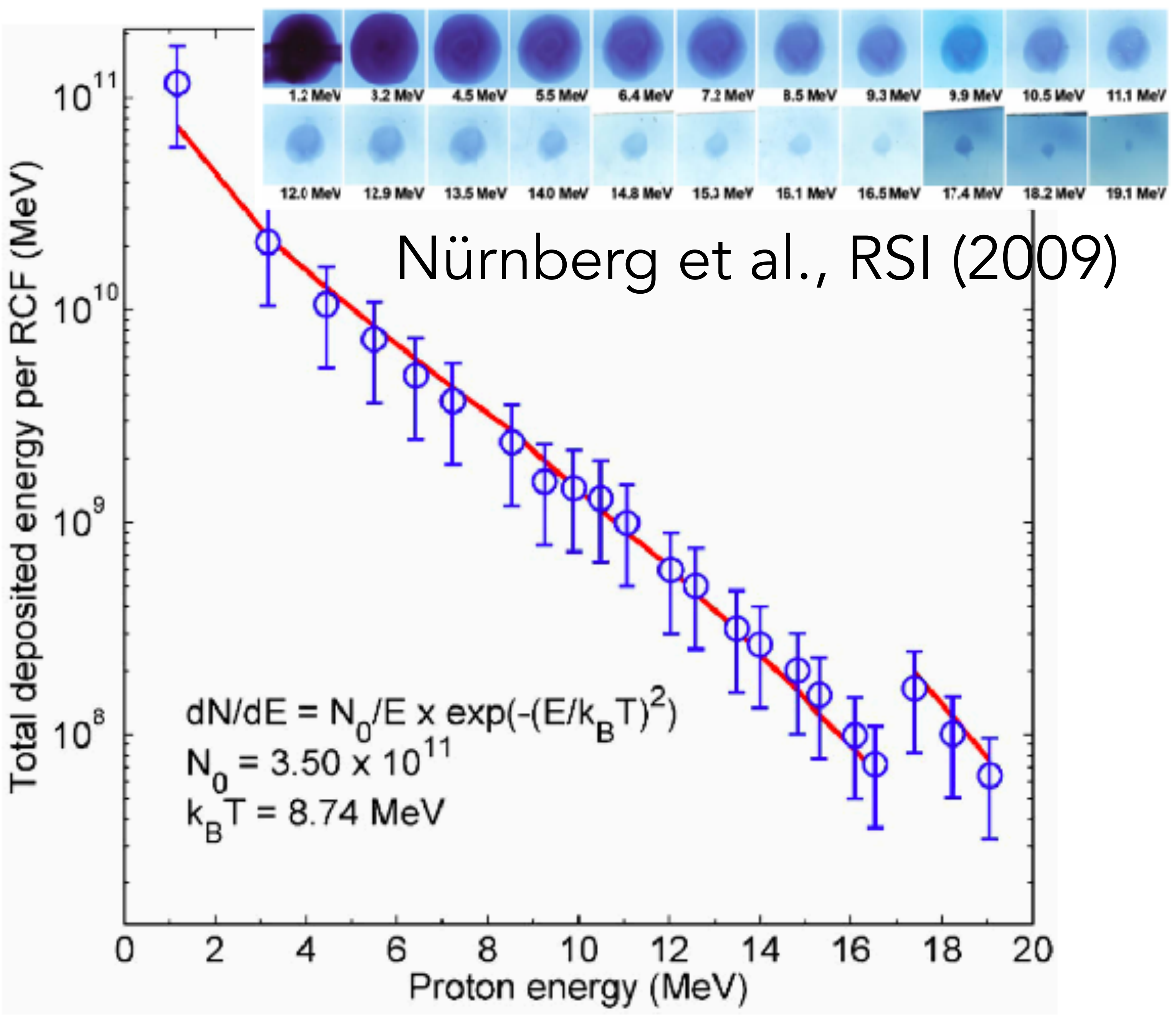
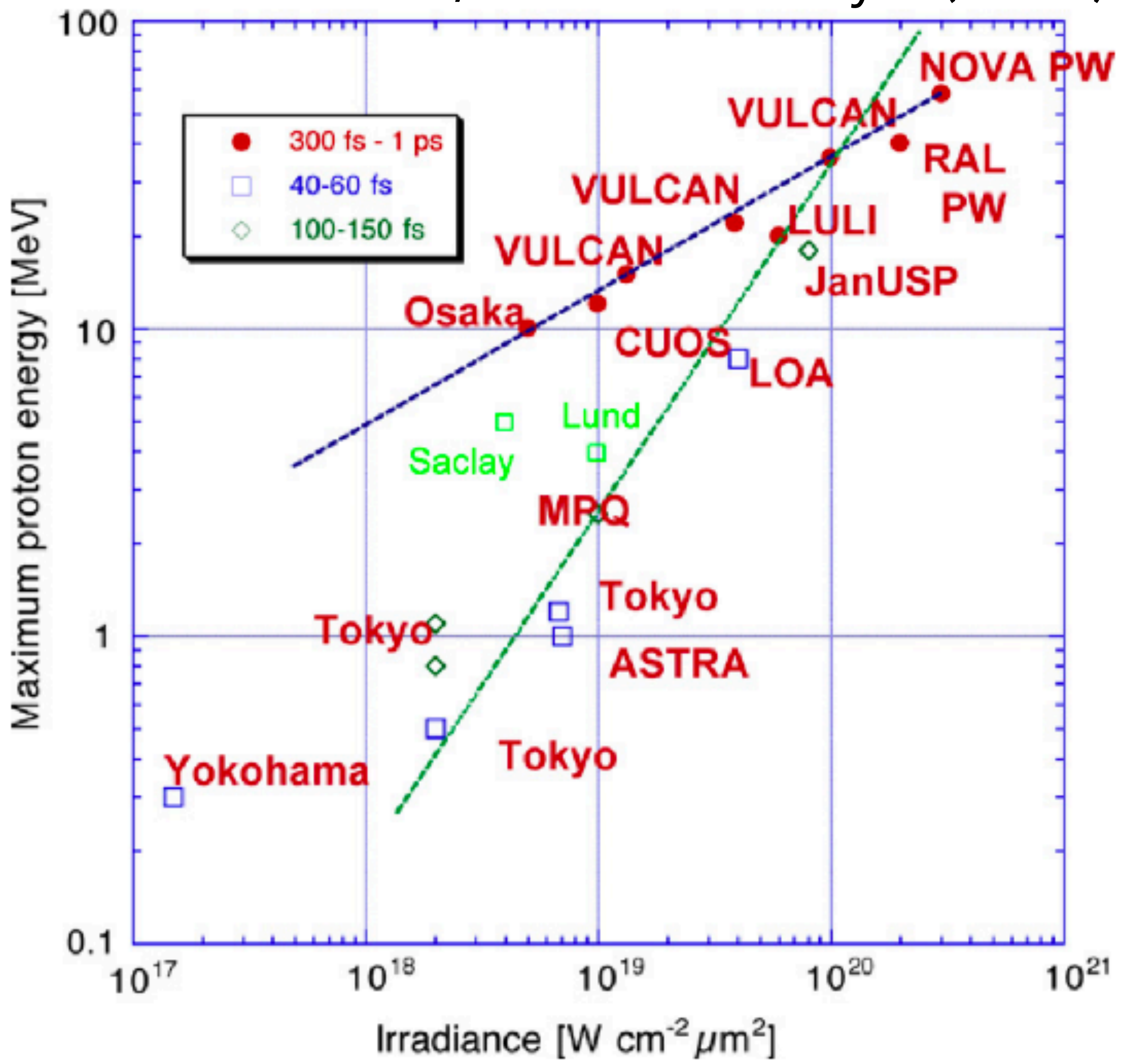
# Refresher on Target Normal Sheath Acceleration (TNSA)



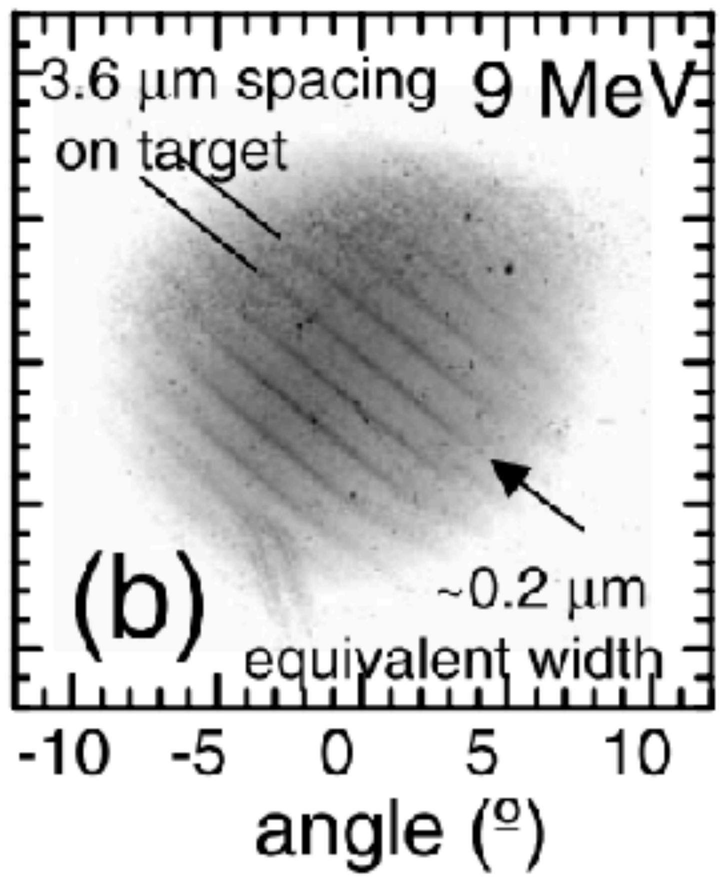

Nürnberg et al., RSI (2009)

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




**TNSA proton beam properties and trends:**

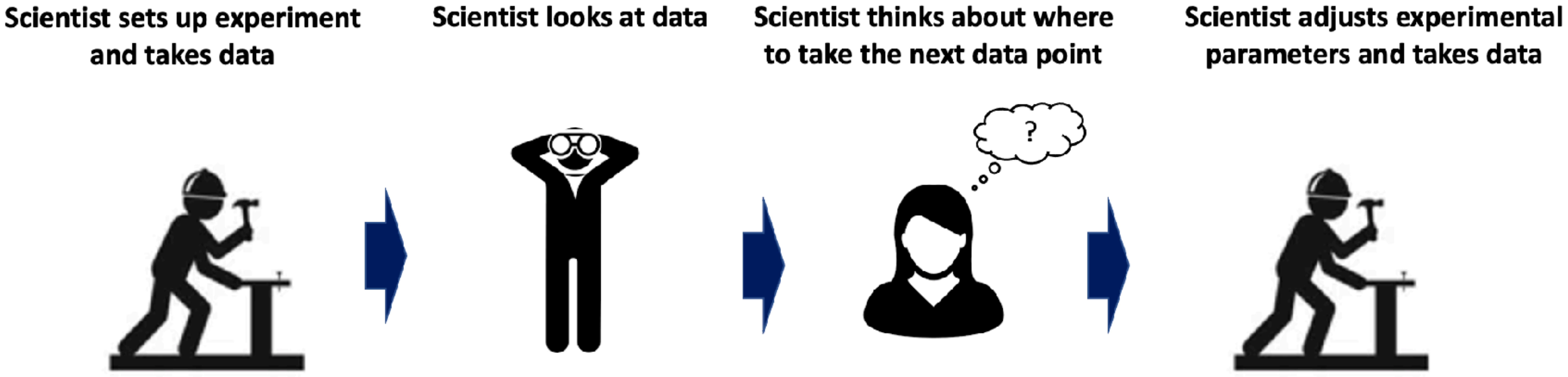
- Low emittance with point-like virtual source : nrad emittance
- Proton flux increasing with laser energy : nC bunch charges.
- Broadband energy distribution with exponentially decaying spectrum : MeV scale temperatures
- Decreasing divergence with increasing proton energy : 10s degrees.
- **High energy cut-off increasing with decreasing target thickness down to 100s nm.**
- **High energy cut-off increasing with intensity due to increasing hot electron temperature : 10s of MeV**




Cowan et al., PRL, (2004)

# Steps of traditional experiments

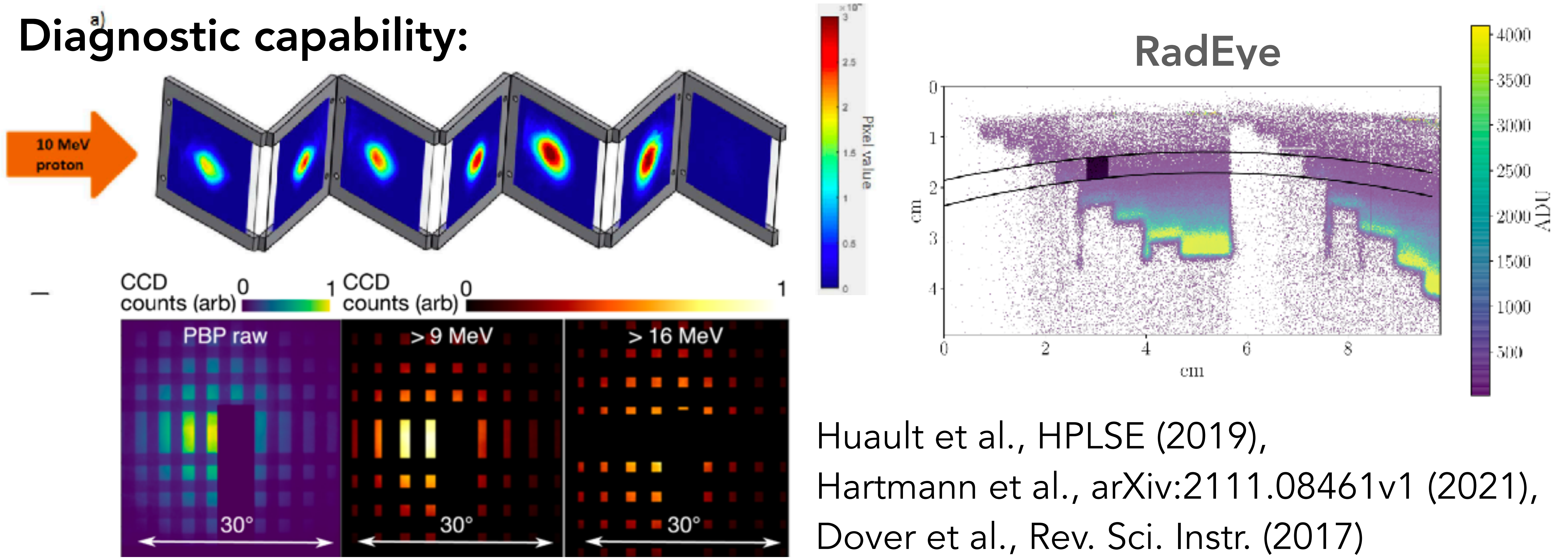
- Traditional experiments used facilities with very low shot rates due to laser rep rate, target replacement, diagnostics....
- Due to this experiments remained very manual with human involvement at every step.



# Proliferation of multi-Hz, joule-class, high-intensity lasers facilities and supporting technology

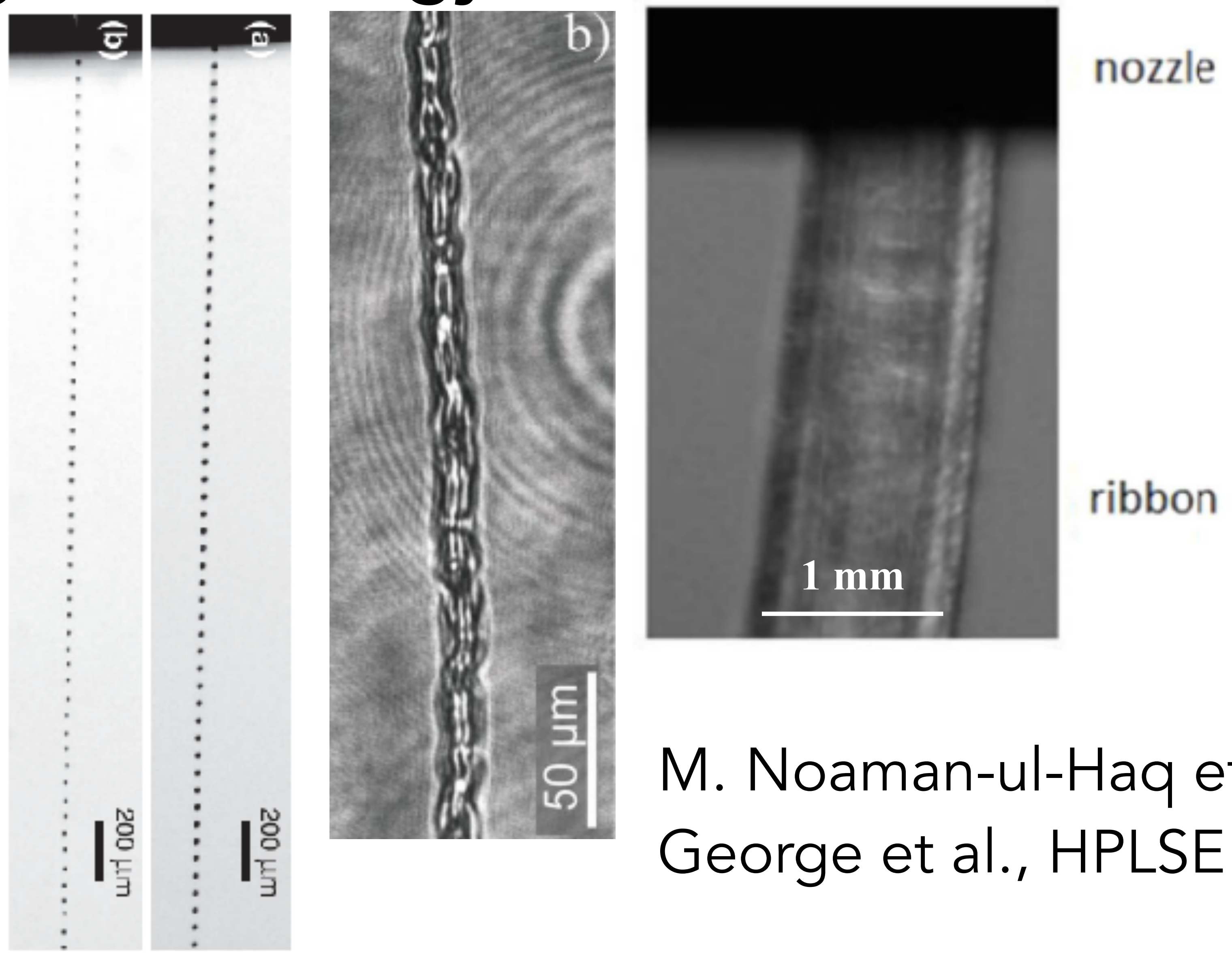
**Laser Facilities** e.g. EPAC, CLF

**Diagnostic capability:**

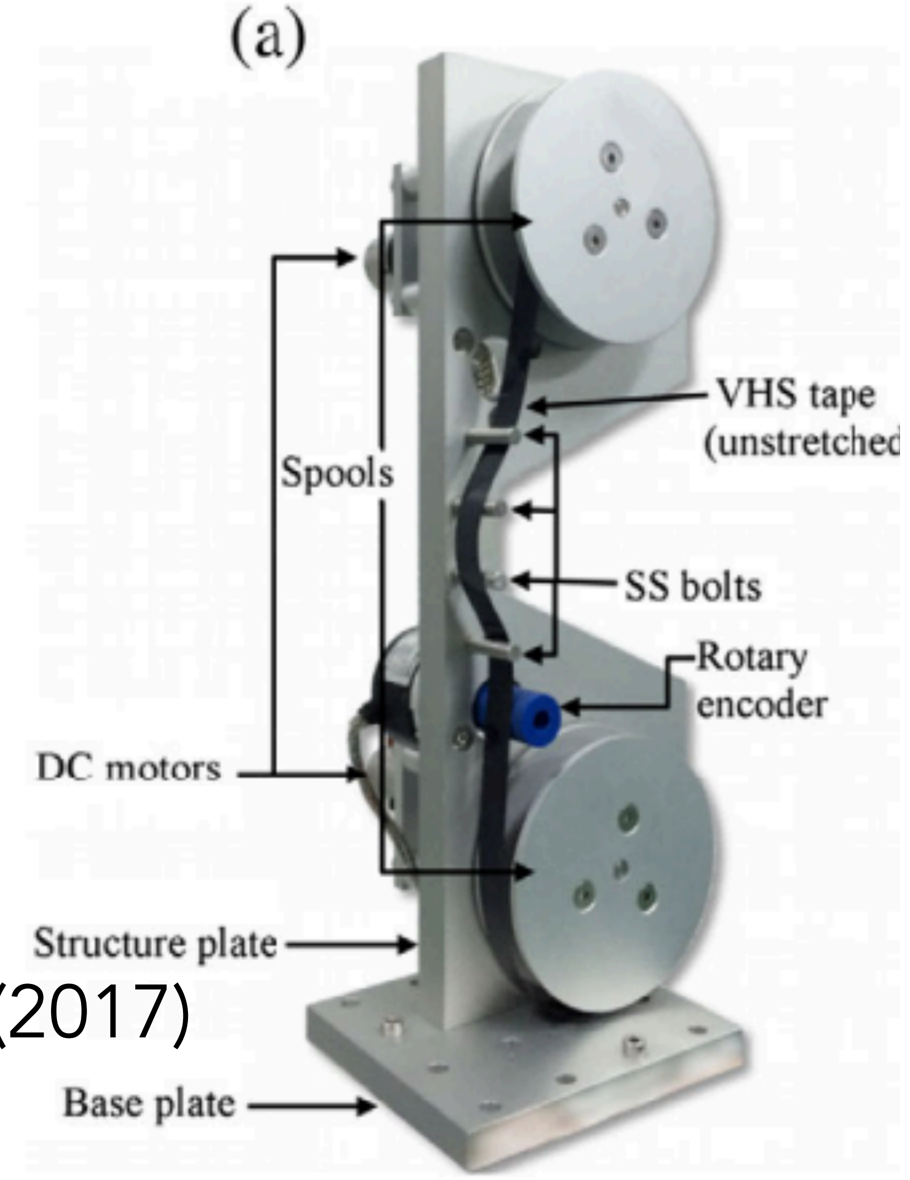


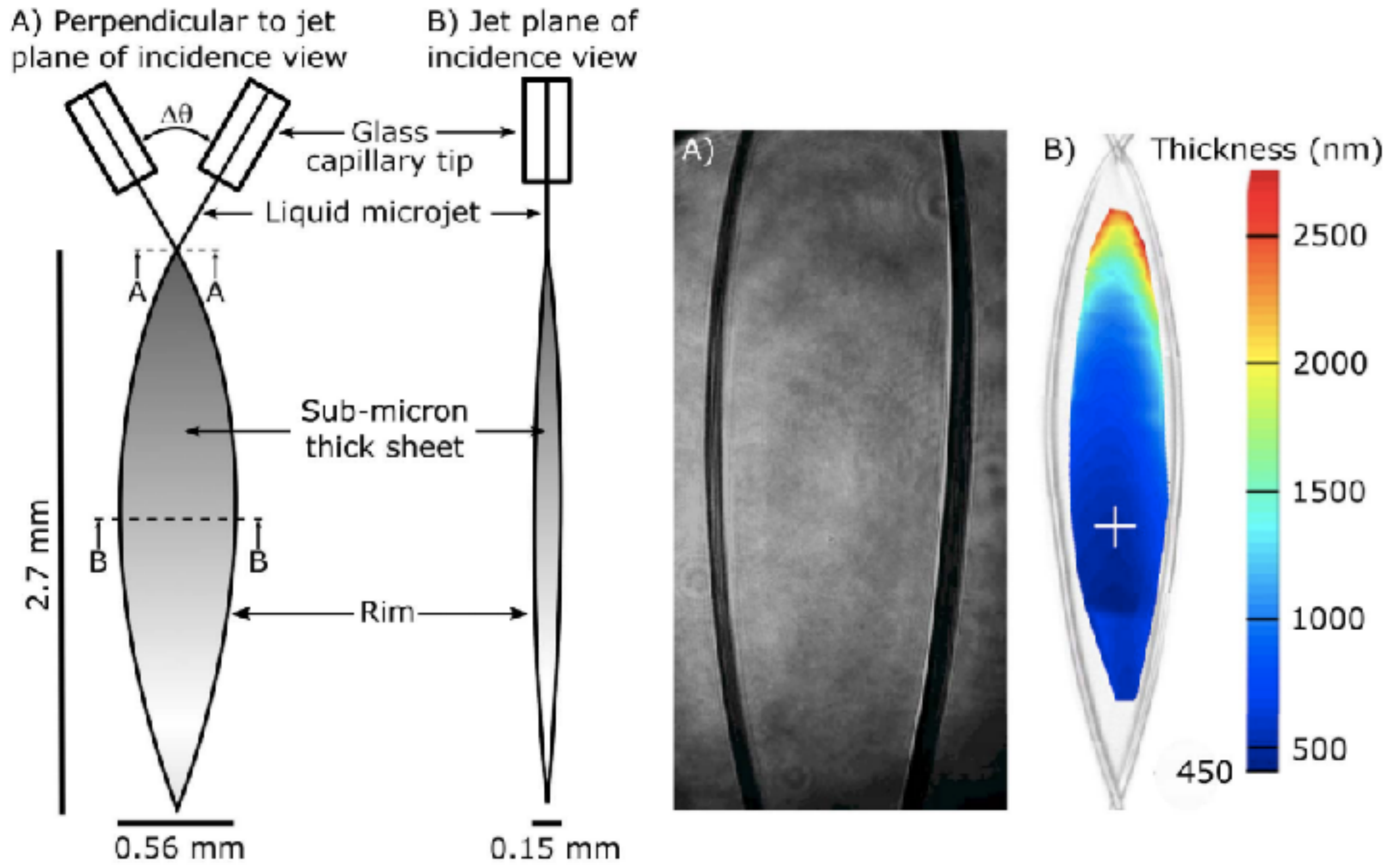

Huault et al., HPLSE (2019),
Hartmann et al., arXiv:2111.08461v1 (2021),
Dover et al., Rev. Sci. Instr. (2017)

**Target technology:**




M. Noaman-ul-Haq et al., PRAB (2017)
George et al., HPLSE (2019)

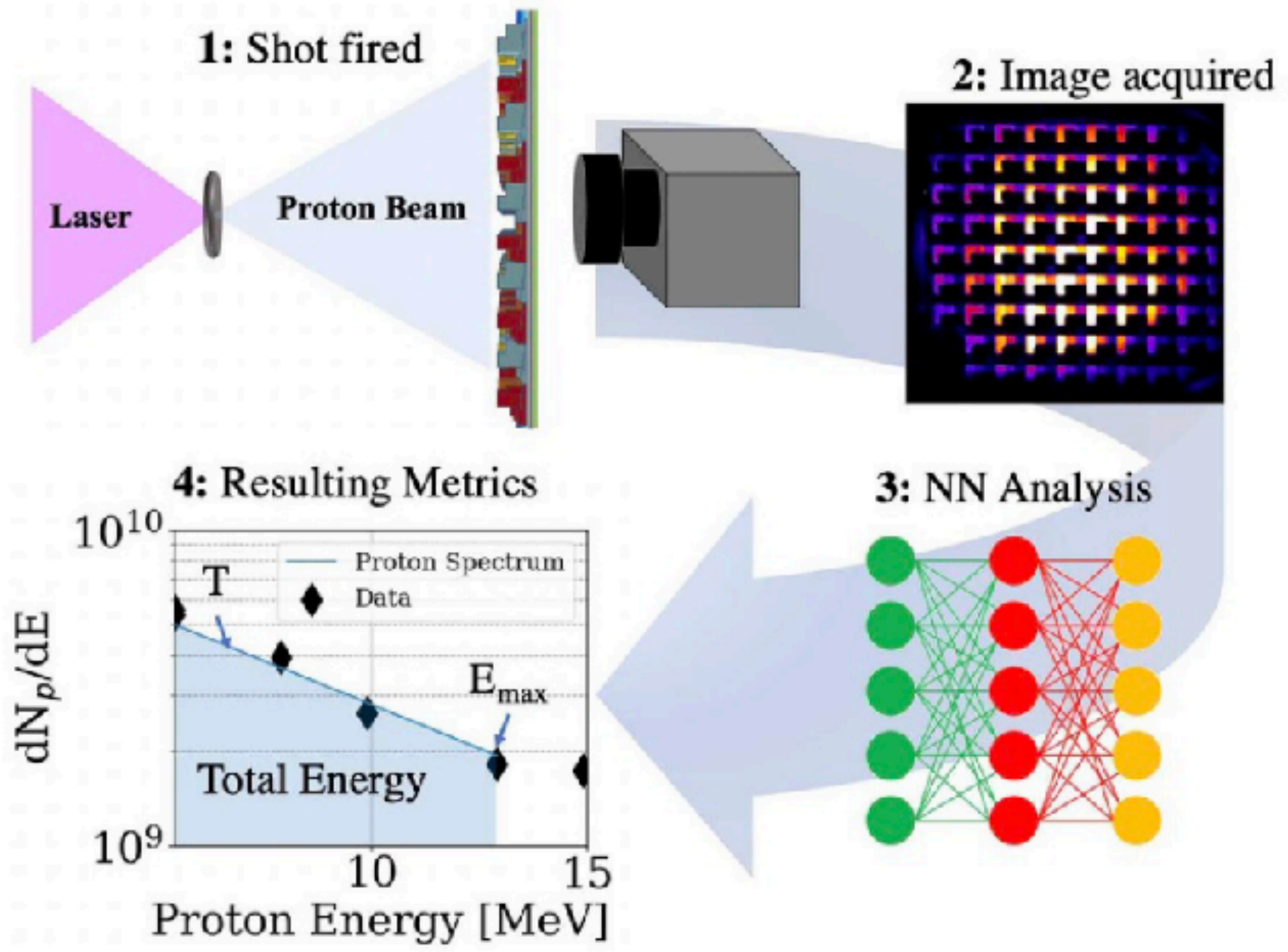


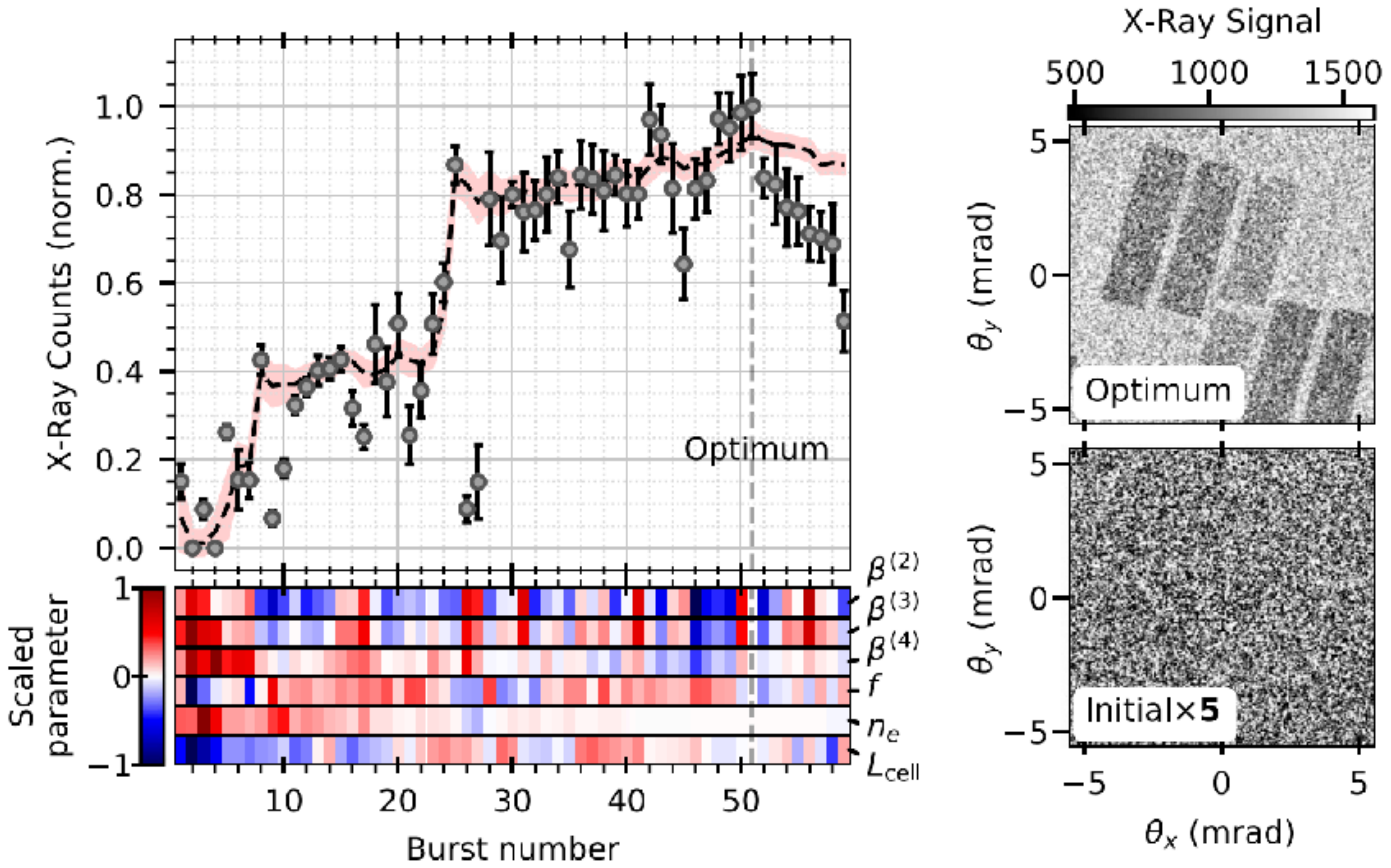
# Use of Machine Learning (ML) within plasma accelerator research

## Retrieving parameters from complex data

Mariscal et al., PPCF (2021)



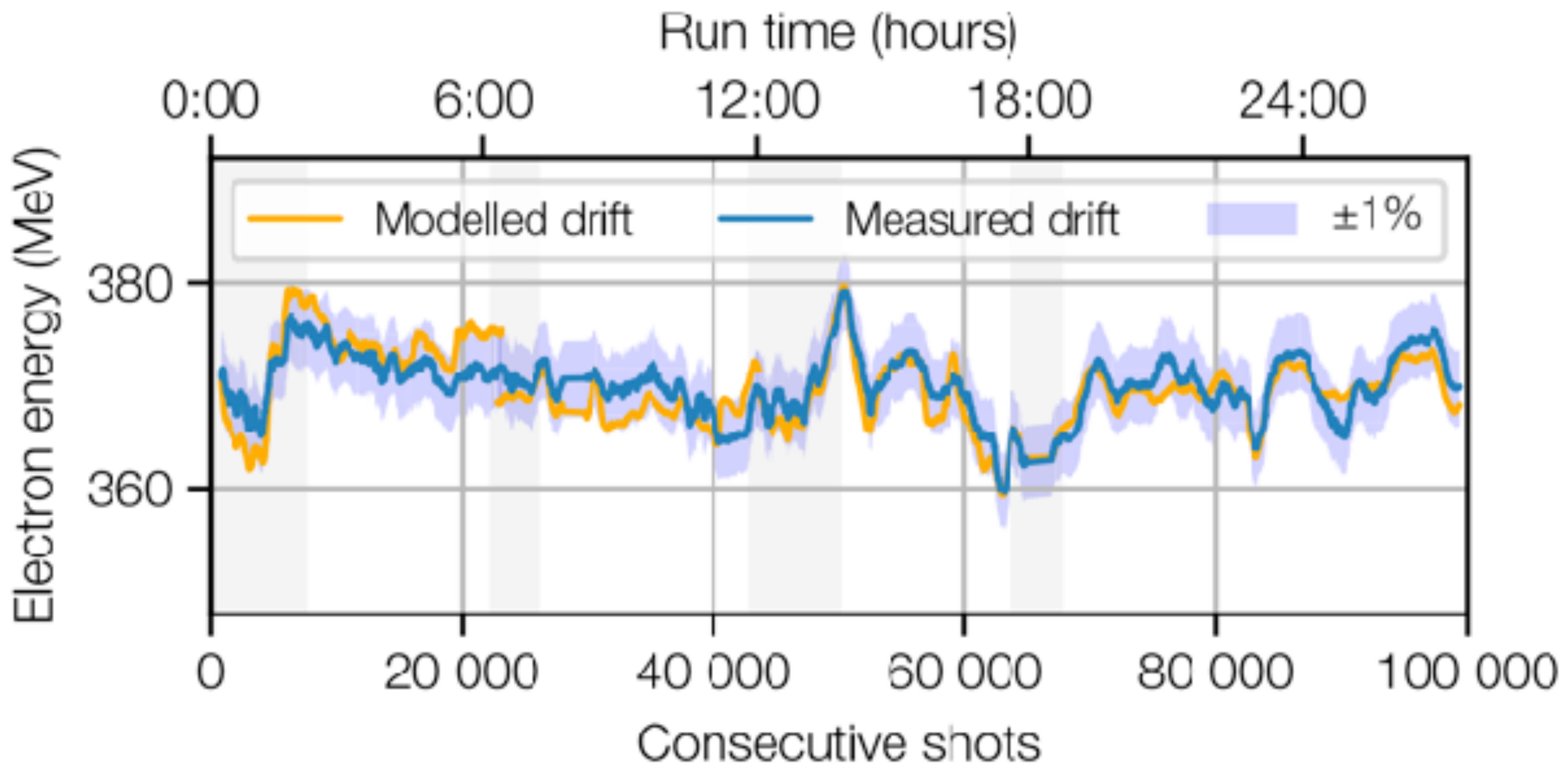

## Online optimisation of experimental outputs




Shalloo et al, Nat. Comms. (2020)

## Inferring correlations between parameters

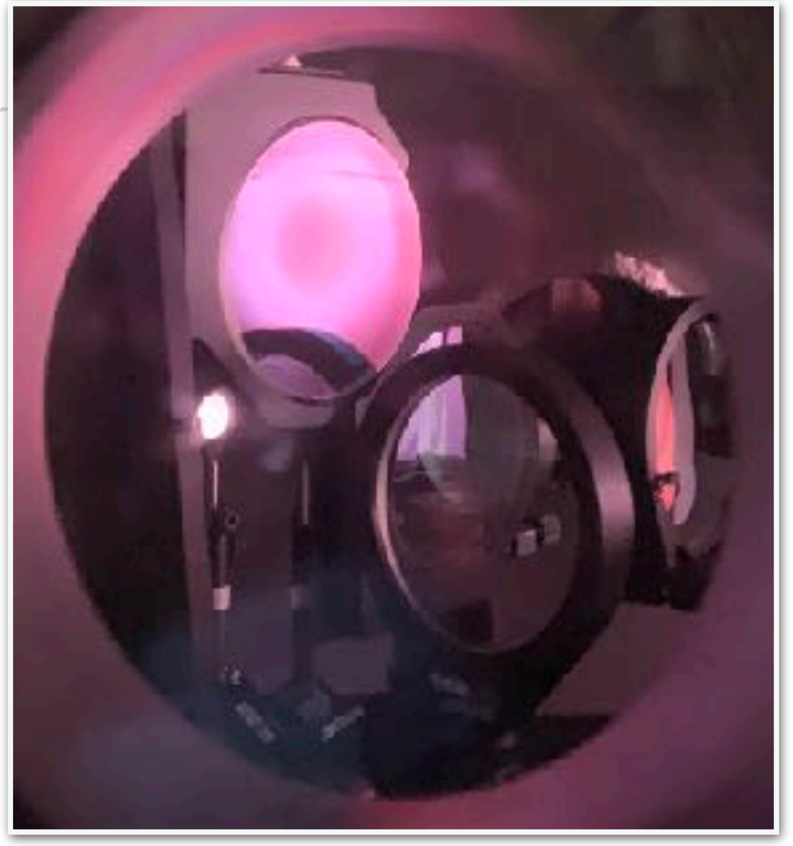
Maier et al, PRX (2020)




- **Extra Goal:** To build a multi-D parameter space model from noisy measurements where additional measurements are costly.
- **Soln:** A Bayesian optimizer (BO) using Gaussian processes regression (GPR) incorporating all data into the model and tracks uncertainties.

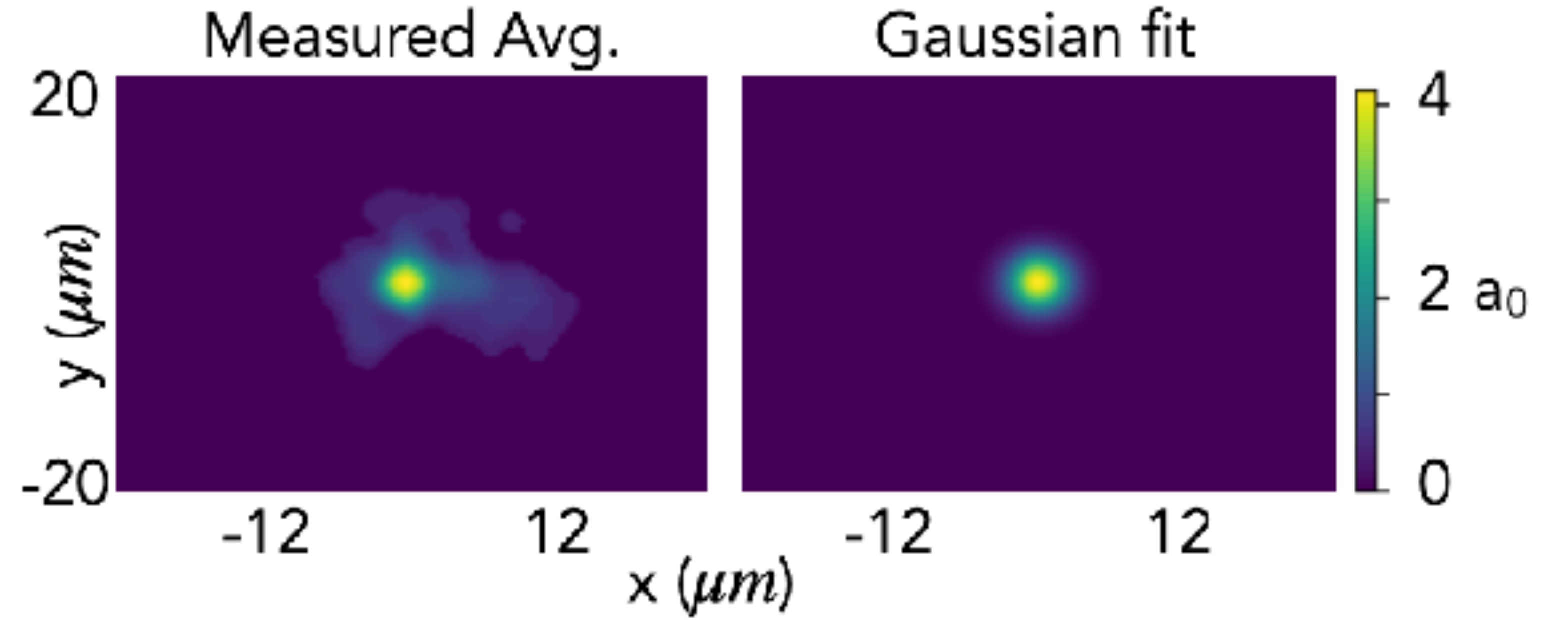
# Laser parameters, diagnostics and control

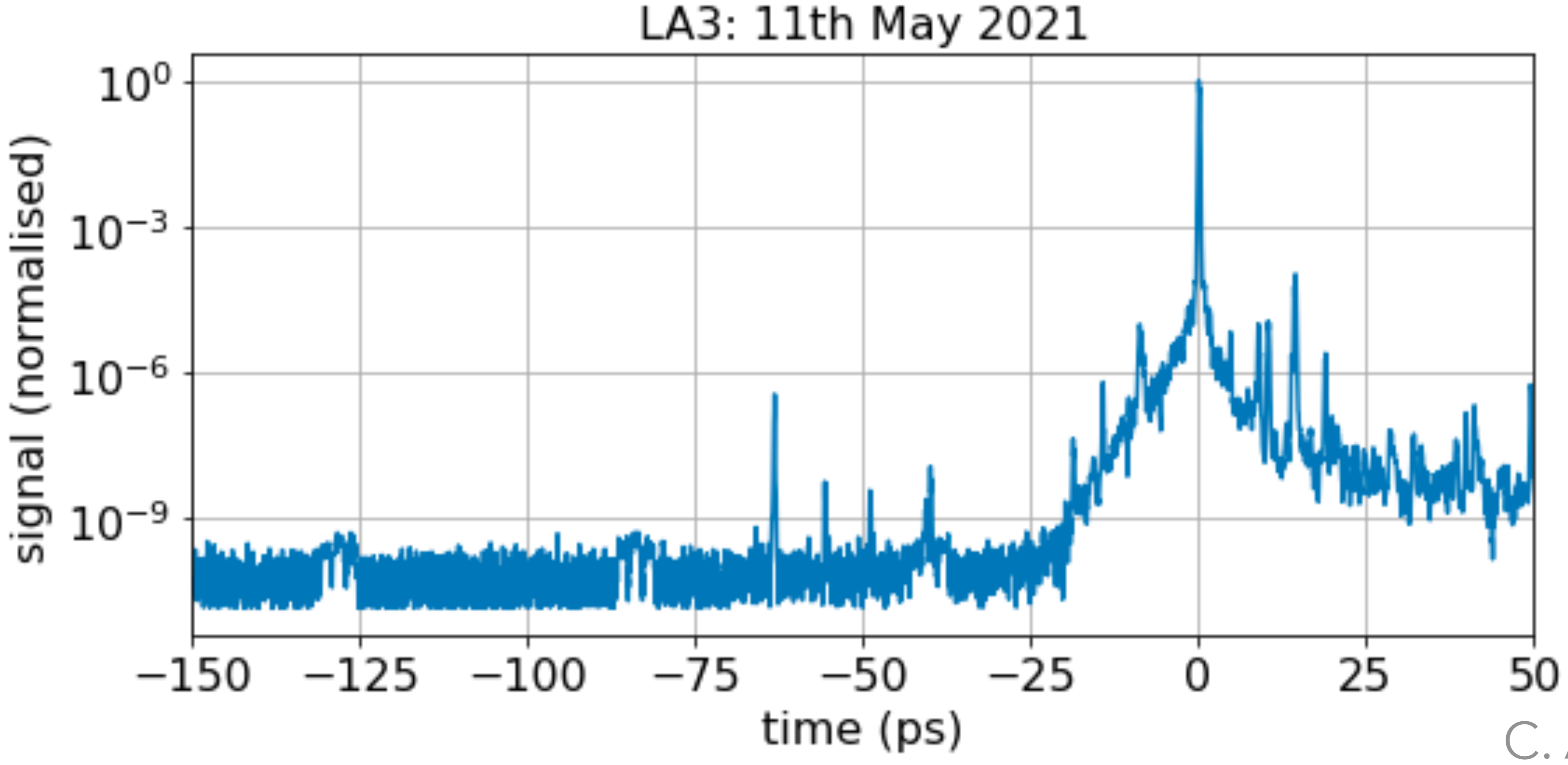
**RF cleaning of compressor daily**

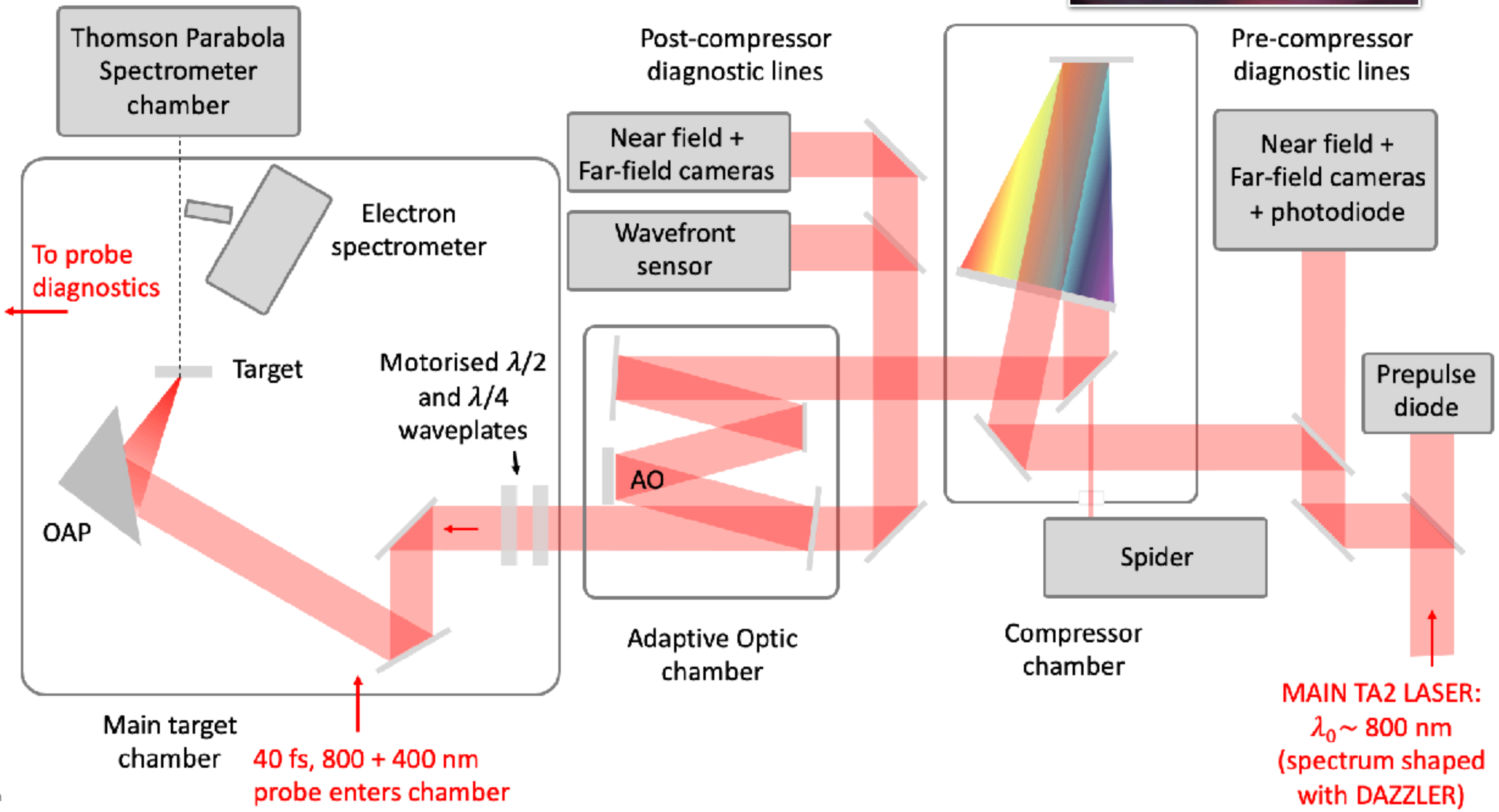



**Laser parameters:** Up to 500 mJ on target in 40 fs (best compression) focused with F/2.5 OAP (Rayleigh length ~ 15 $\mu$m)

**Control:** Wavefront shaping with adaptive optic and temporal shaping with DAZZLER.

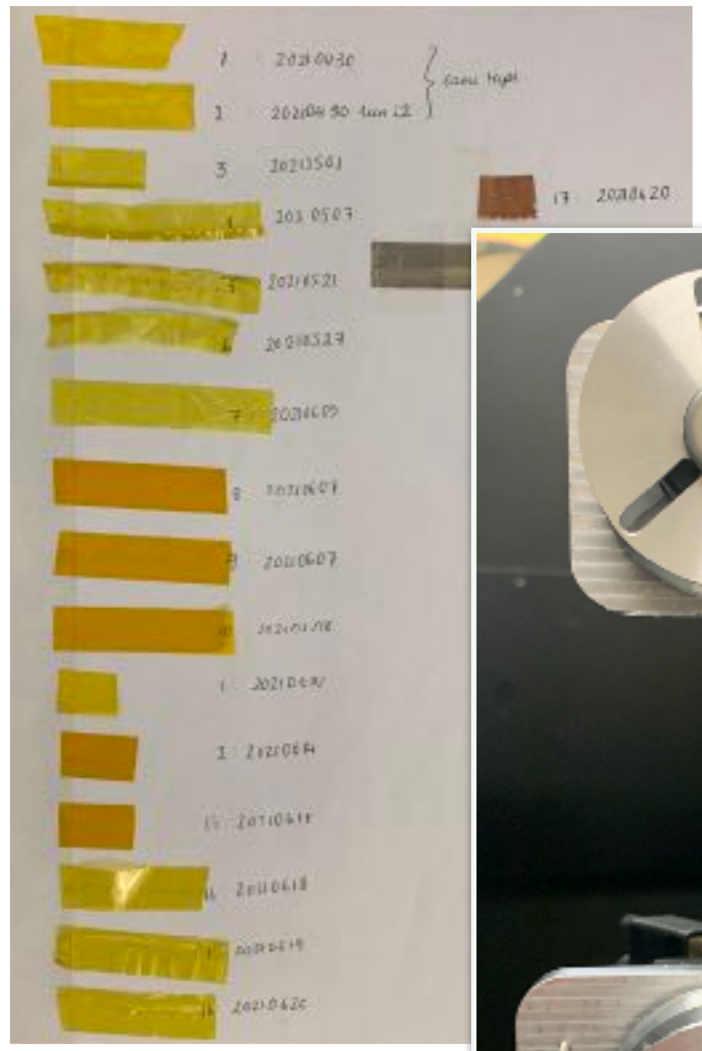


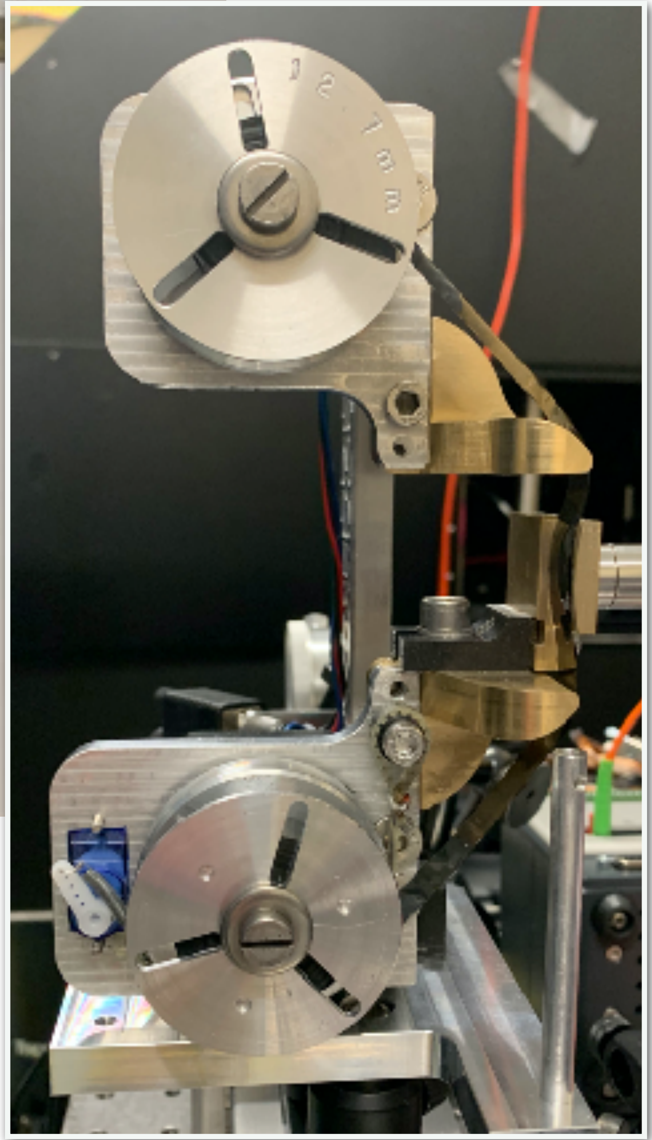



# High-rep. Targetry

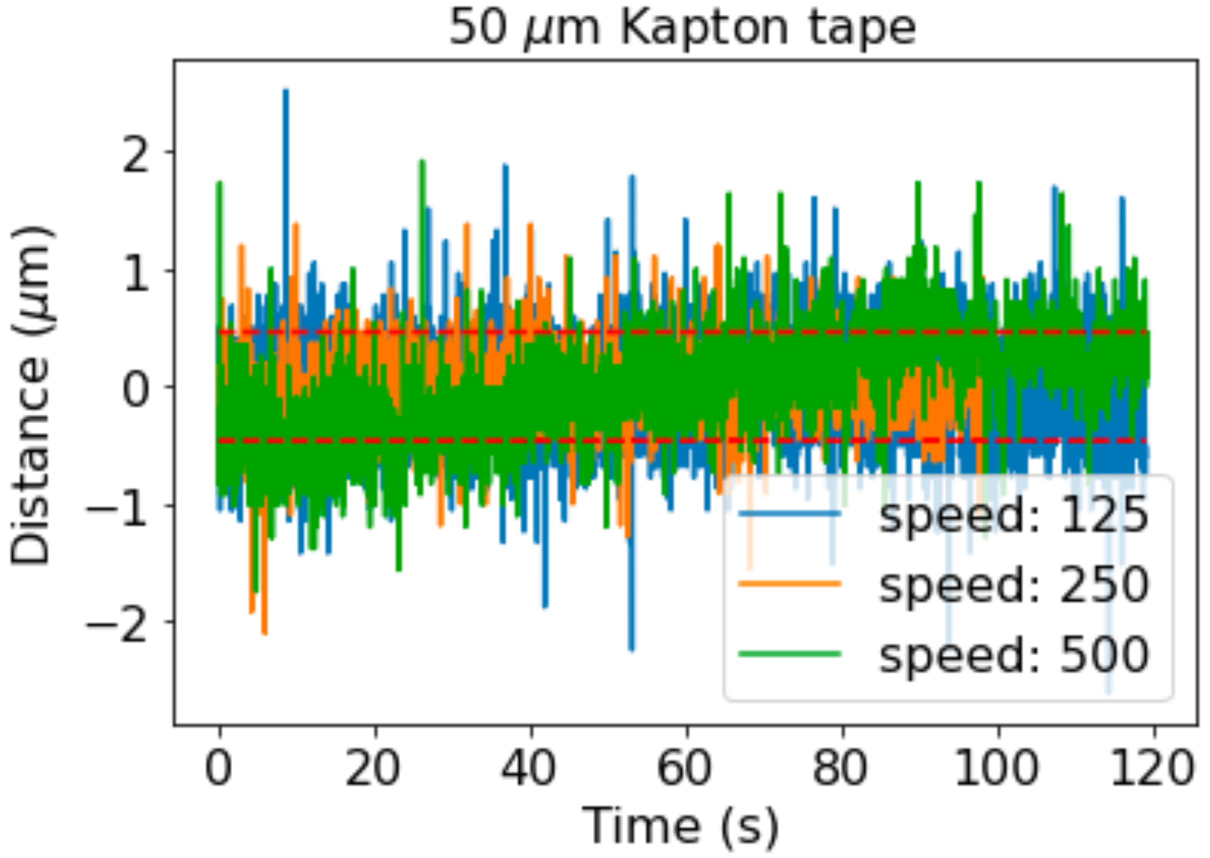
**Tape samples:**

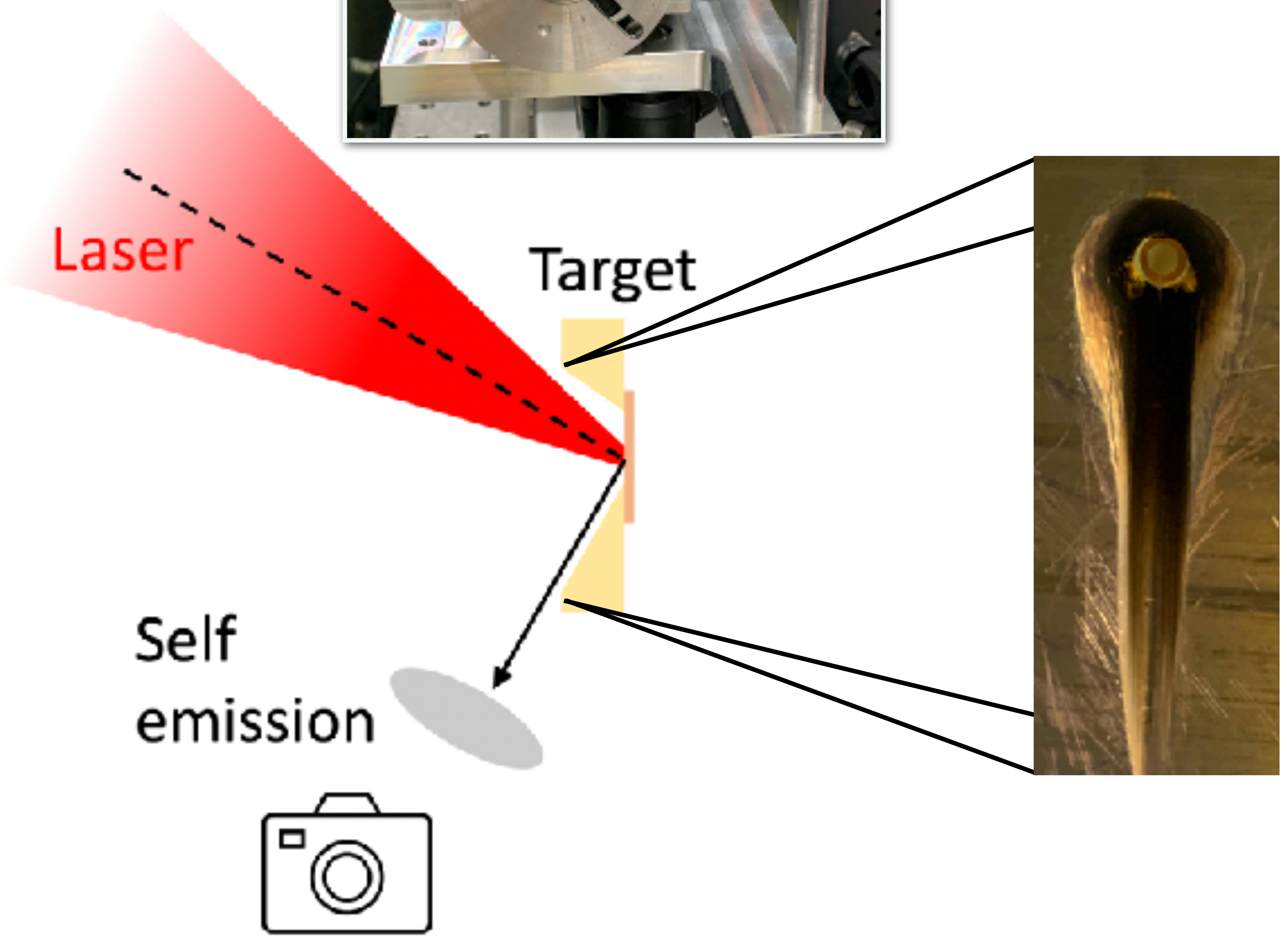


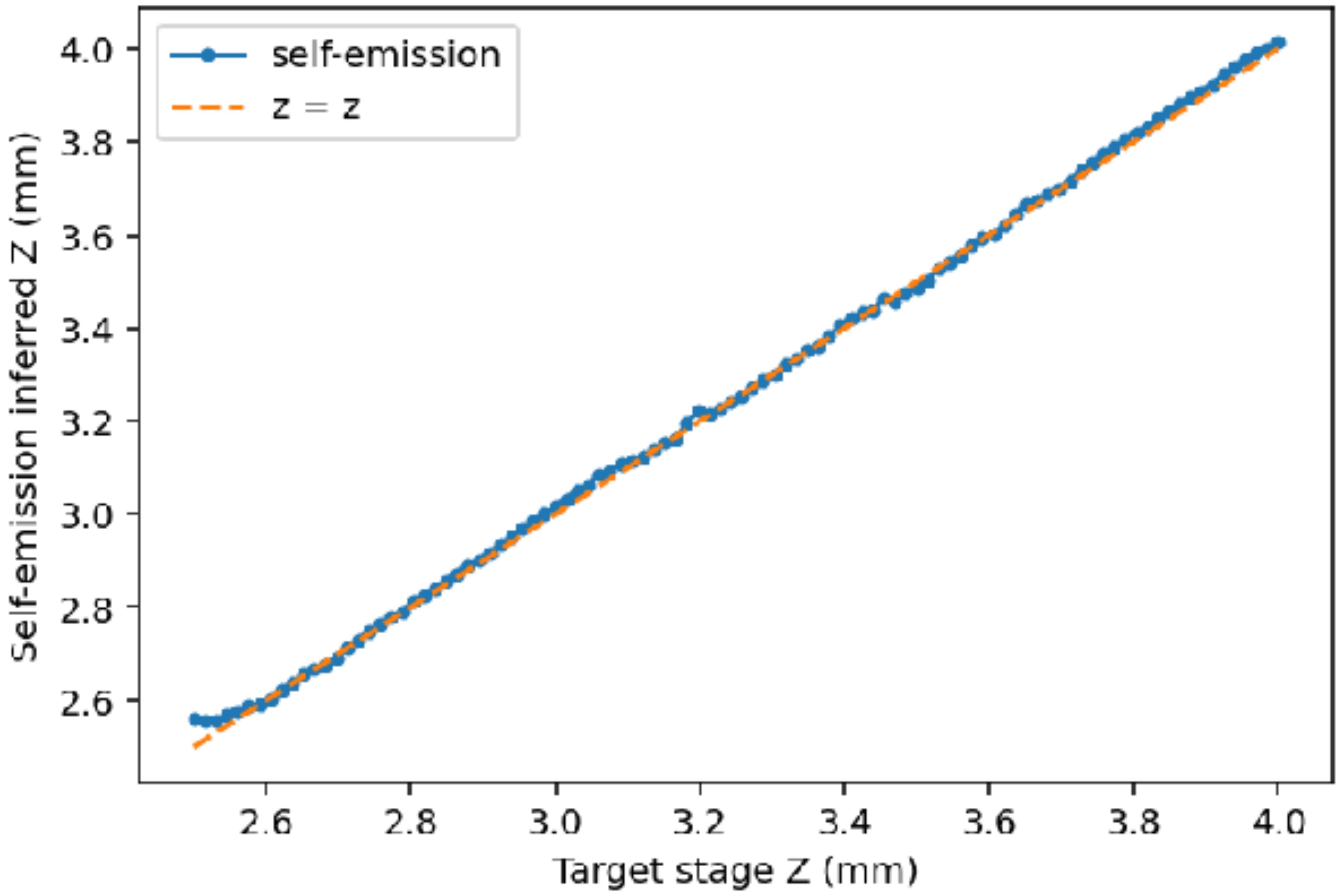
**Imperial College London: Tape drive**



- Compact with excellent rear surface access.
- Used mainly 12.7 or 50 $\mu m$ Kapton tape.
- Few microns short-term stability.
- On-shot position monitored using self-emission.

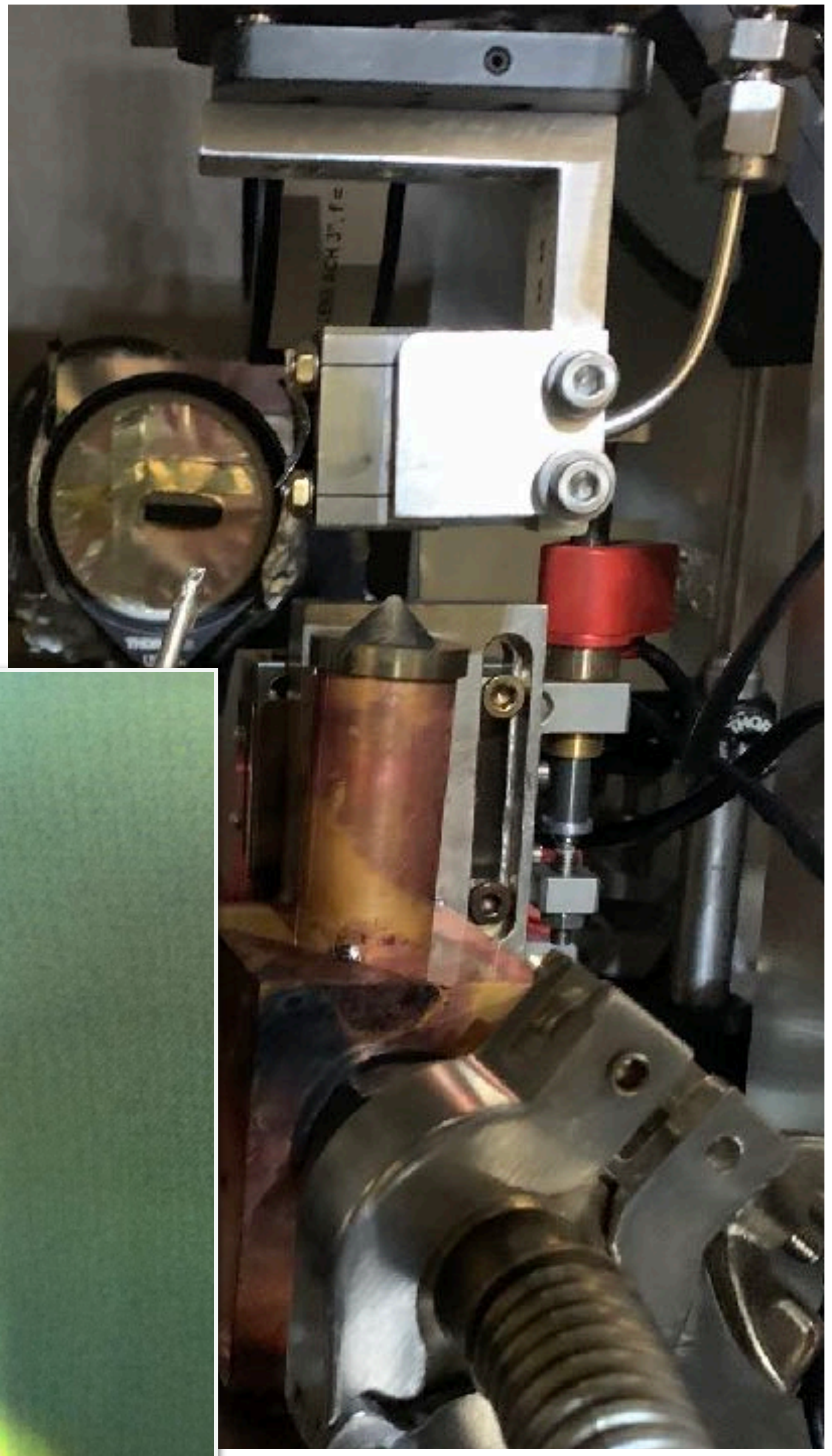


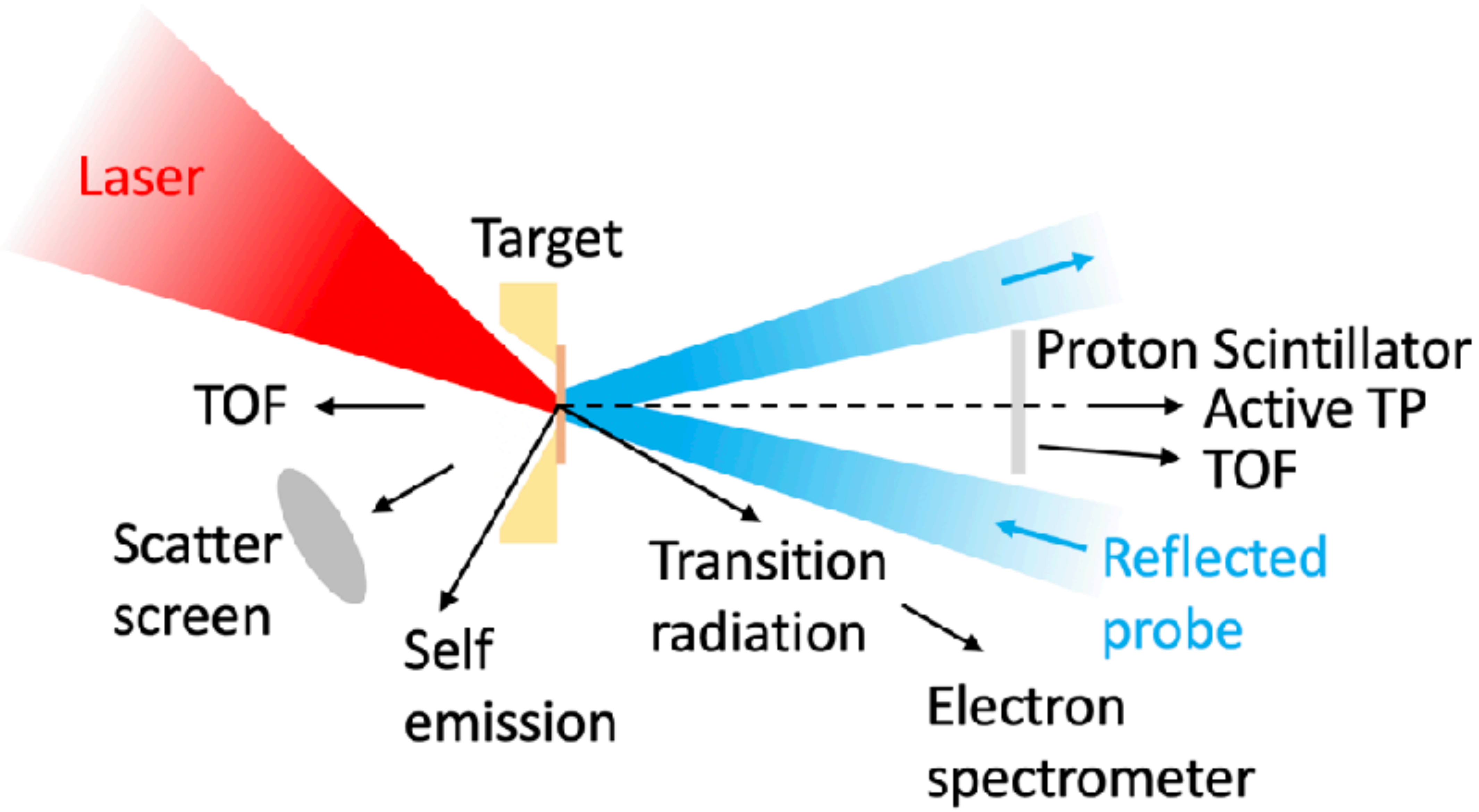




**SLAC: Liquid sheet**

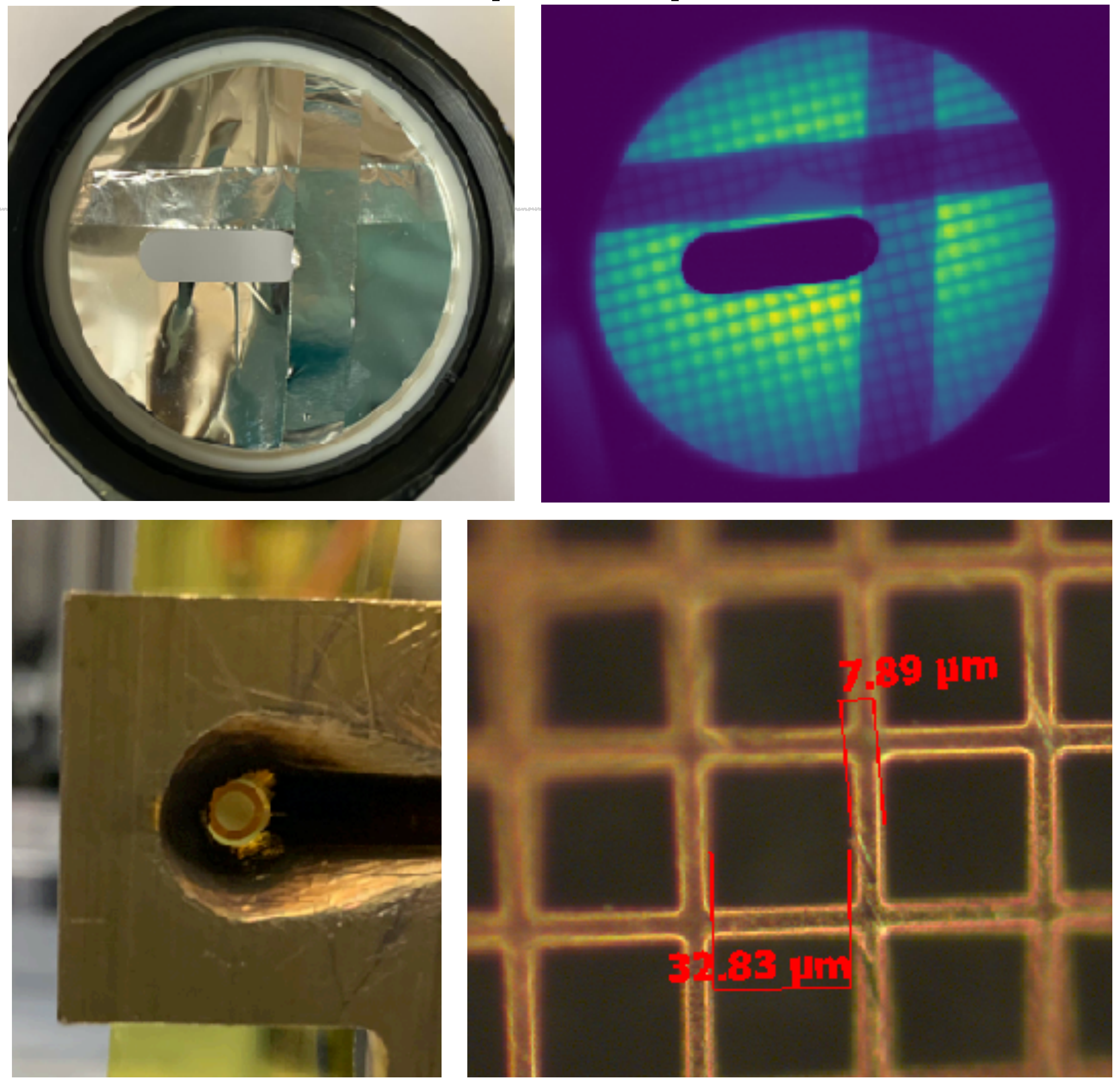
- High-purity mm-scale water sheet with variable thickness along sheet (down to 100 nm).
- Heater unit to prevent freezing.
- Vacuum maintained at 0.1 mbar using exhaust line (higher vacuum has been demonstrated elsewhere).



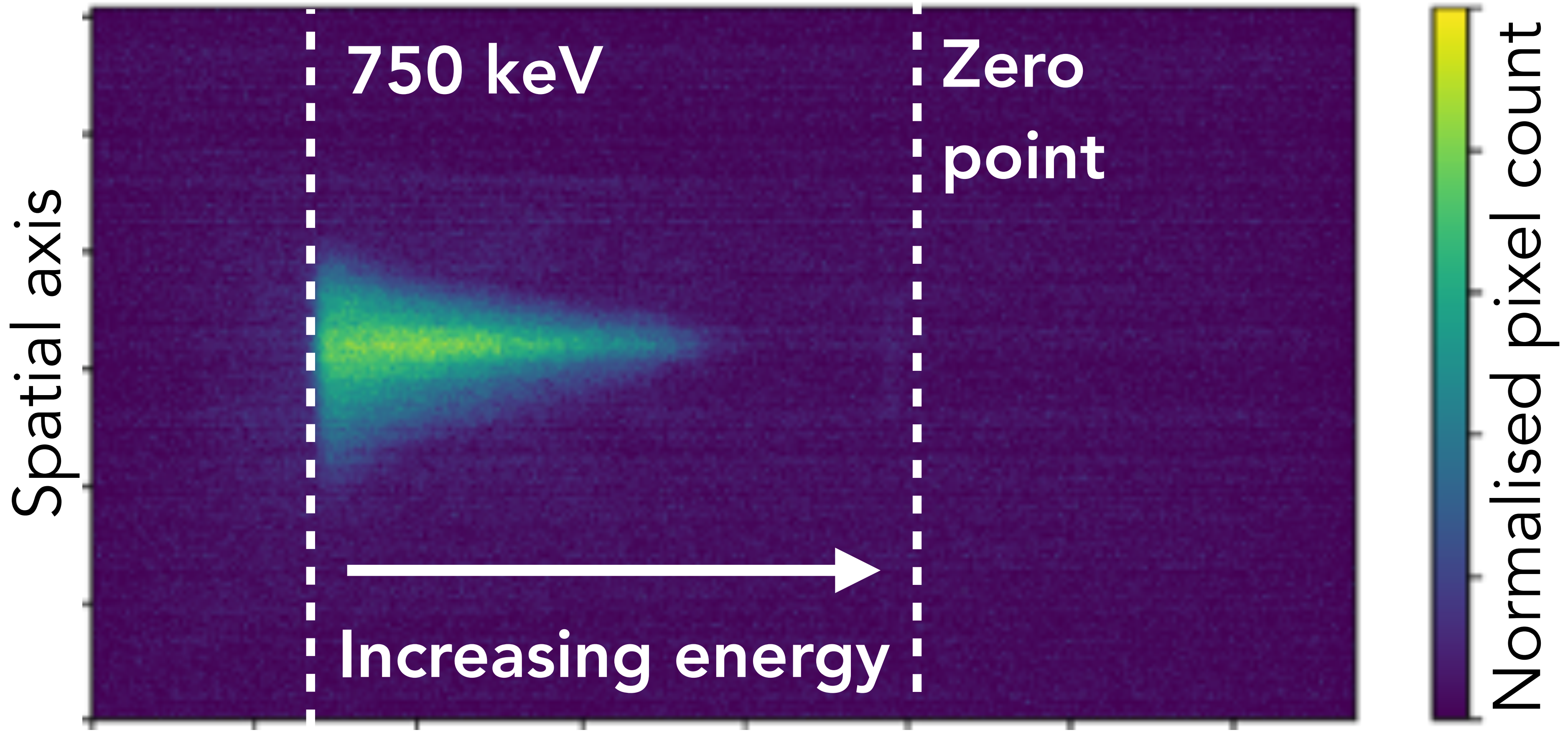
# TA2 experimental setup.

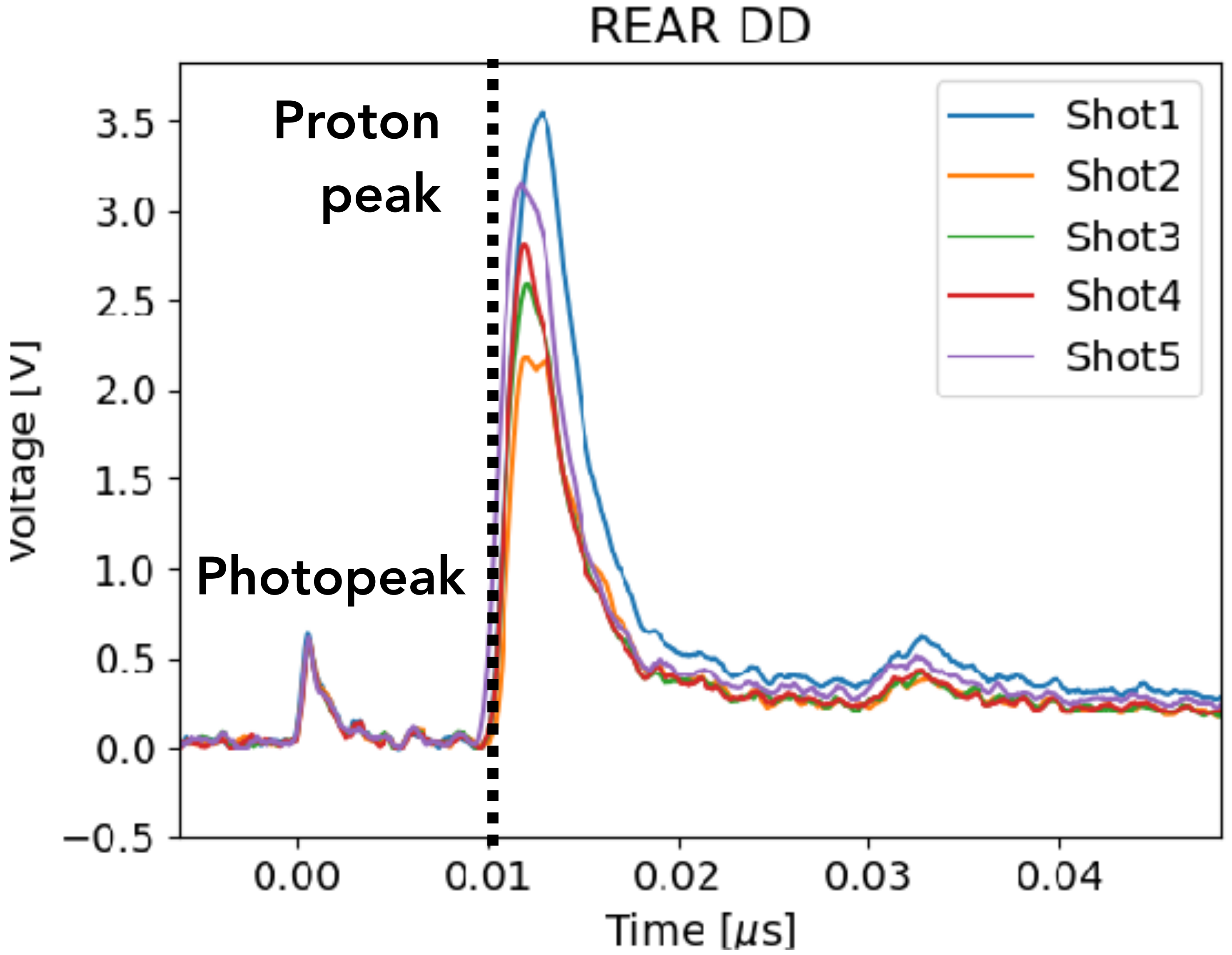



Proton spatial profile:

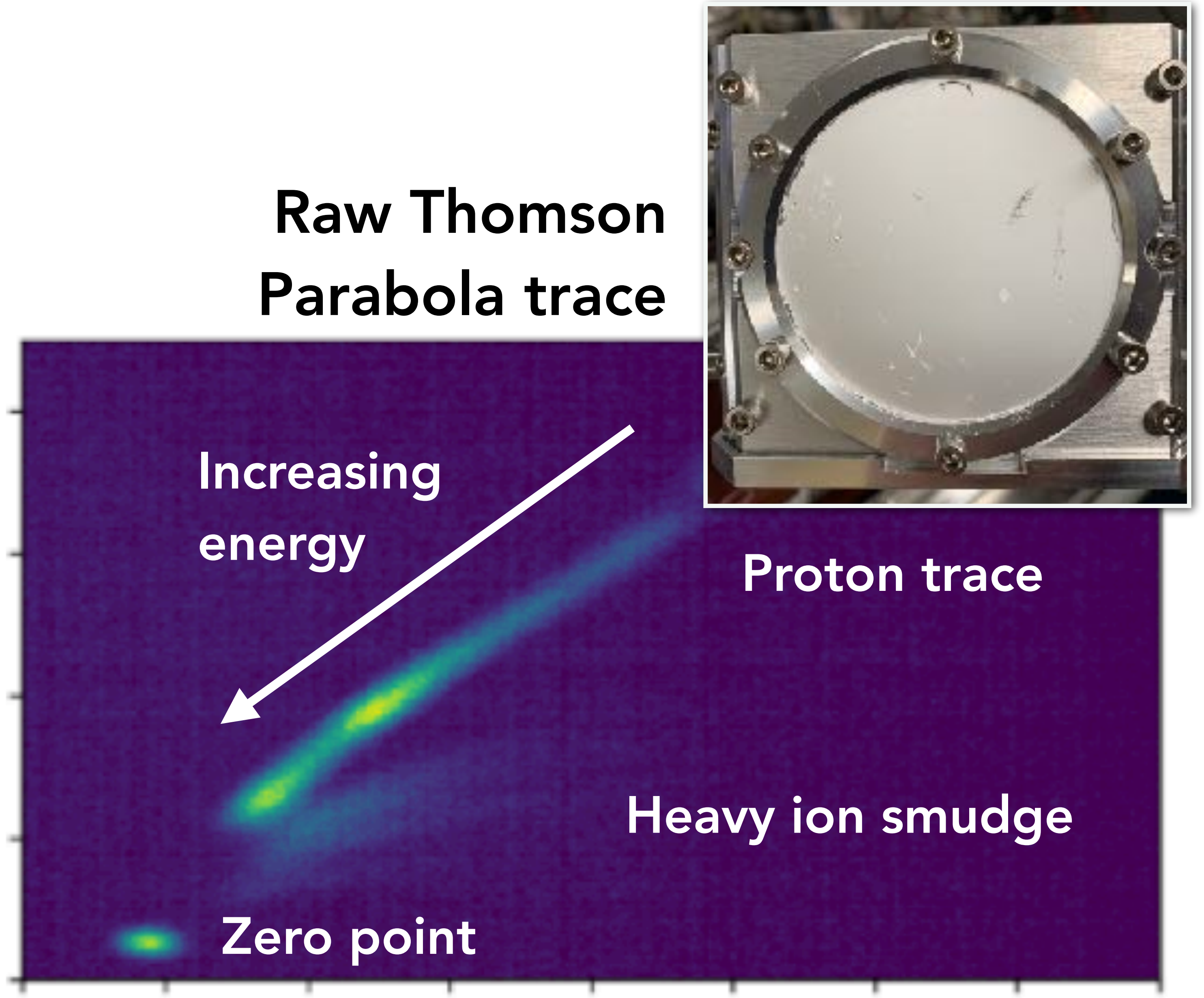



Burst averaged electron spectrometer signal




Raw Thomson Parabola trace



# Traditional experiments

**Scientist looks at data**

**Analysis often slow and complex with unique treatment of individual shots**

**Scientist thinks about where to take the next data point**


**Scientist adjusts experimental parameters and takes data**

**Machine safety limits**

**Laser focus shape via** adaptive optic

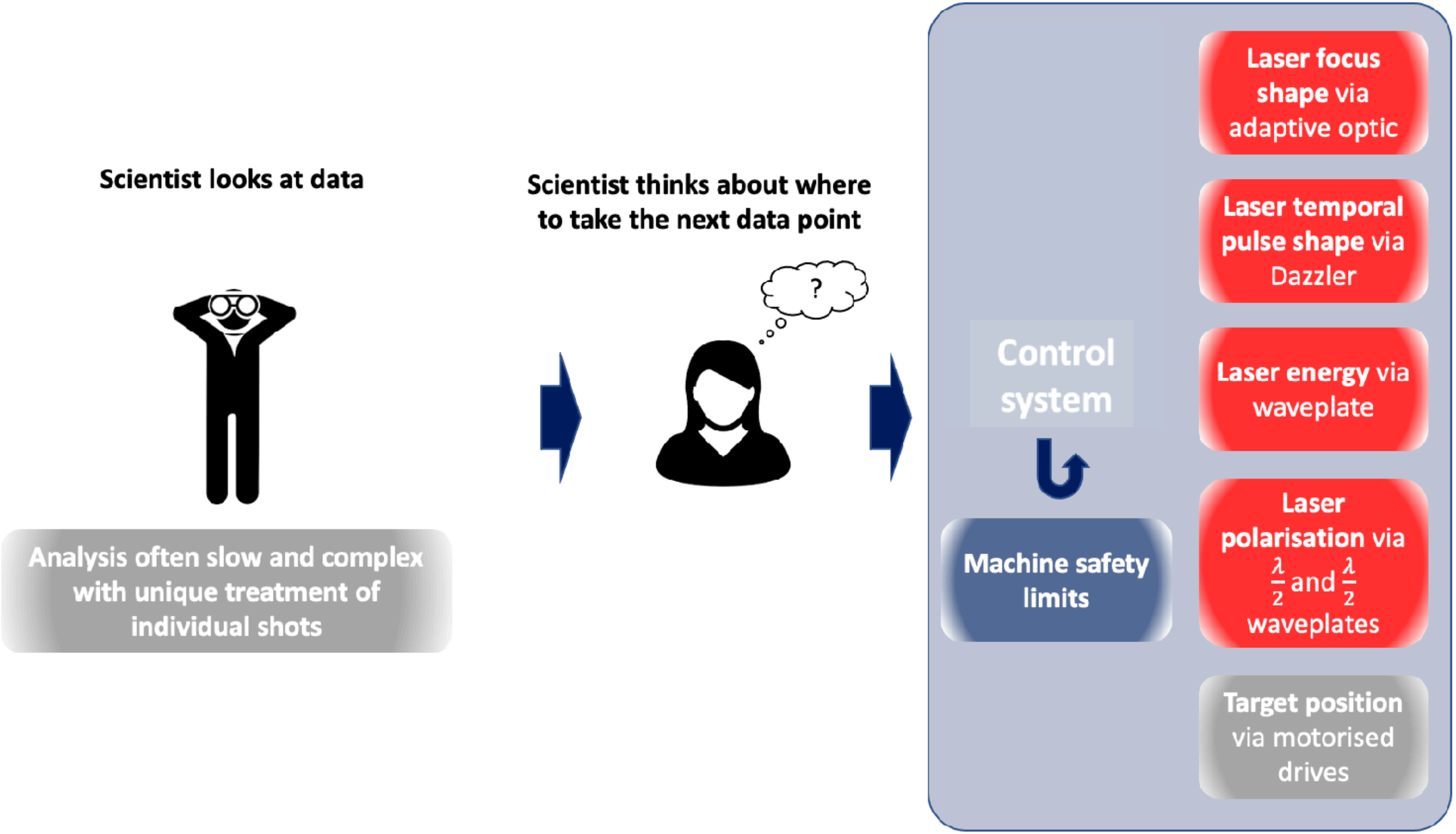
**Laser temporal pulse shape via** Dazzler

**Laser energy via** waveplate

**Laser polarisation via** $\frac{\lambda}{2}$ and $\frac{\lambda}{2}$ waveplates

**Target position** via motorised drives

# Traditional experiments



# Automation of analysis and control systems

Simple functions provide key values from online analysis of raw data that feed into the optimisation algorithm

**Proton flux and maximum energy** via:

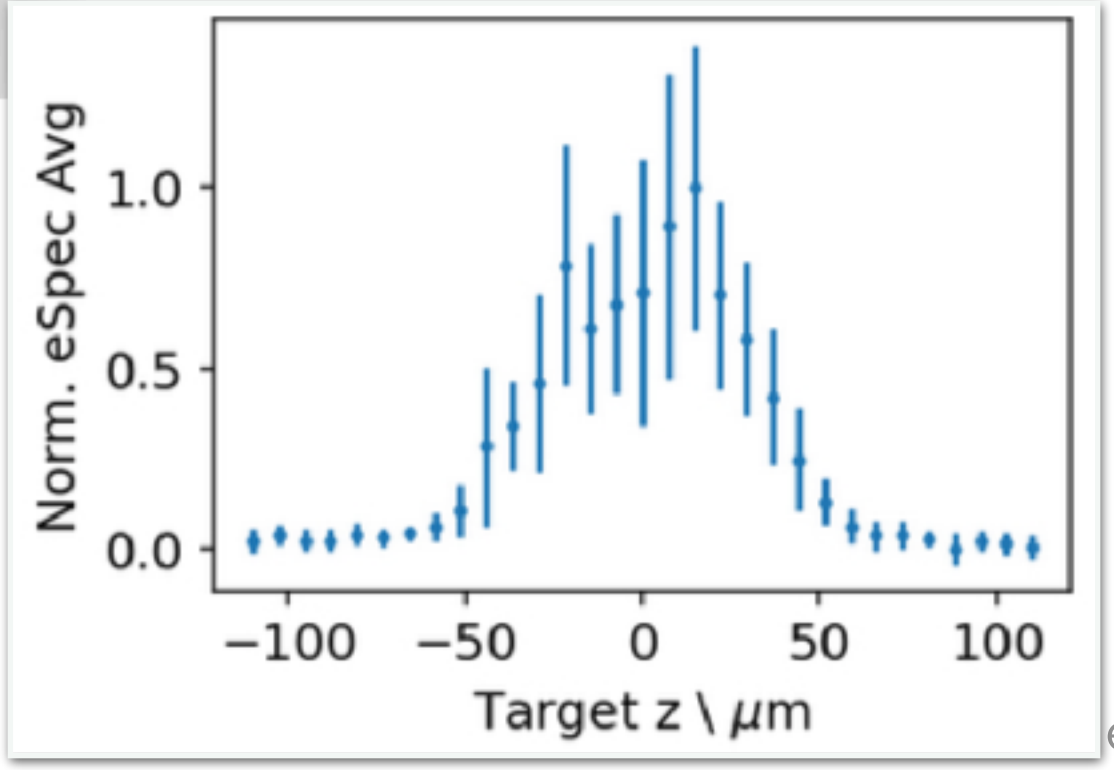
- Time-of-flight diodes
- Active Thomson parabola spectrometer
- Scintillator screen

**Electron flux and maximum energy** via CCD coupled electron spectrometer

**Target position** via diagnostic of plasma self-emission.

**Scientist thinks about where to take the next data point**


**E.g. Electron flux variation with target position scan**




**Control system**

**Machine safety limits**

**Laser focus shape via** adaptive optic

**Laser temporal pulse shape via** Dazzler

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# Automated Optimisation

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**Target position** via diagnostic of plasma self-emission.

**Machine learning algorithm**

Experimental data used to update model of parameter space and prediction of optimum. New test point in parameter space selected and passed to control system.

**Control system**

**Machine safety limits**

**Laser focus shape** via adaptive optic

**Laser temporal pulse shape** via Dazzler

**Laser energy** via waveplate

**Laser polarisation** via $\frac{\lambda}{2}$ and $\frac{\lambda}{2}$ waveplates

**Target position** via motorised drives

# Summary

- Recent developments in laser, target and diagnostic technology and the proliferation of ML tools and computing resources are enabling a shift in laser-solid experimental research.
- A Bayesian optimization based on Gaussian process regression was implemented within a high-repetition rate, high-intensity laser-solid experiment to tune the experimental parameters towards desirable outputs for the first time.
- Optimizations tuned laser wavefront, temporal pulse shape and target position, with on-shot measured target position fed back into the optimization.
- Optimizer was tuned over the experiment to improve it's capability to model the noisy, sharply varying parameter space of TA2 interaction.
- There's a lot to explore in the data-sets and prepare them as a resource for the community as potential training data/examples.

# Thank you again to our collaborators and to you for your attention

**QUB:**

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QUEEN'S UNIVERSITY BELFAST

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Imperial College London

SLAC NATIONAL ACCELERATOR LABORATORY

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eli beamlines

UNIVERSITY OF MICHIGAN