Advanced Acceleration

Zulfikar Najmudin

The John Adams Institute for Accelerator Science, Imperial College London

JAI Advisory Board
Thursday 7 April 2022

http://www.adams-institute.ac.uk http://www3.imperial.ac.uk/johnadamsinstitute

JAI *Advanced Acceleration* Effort

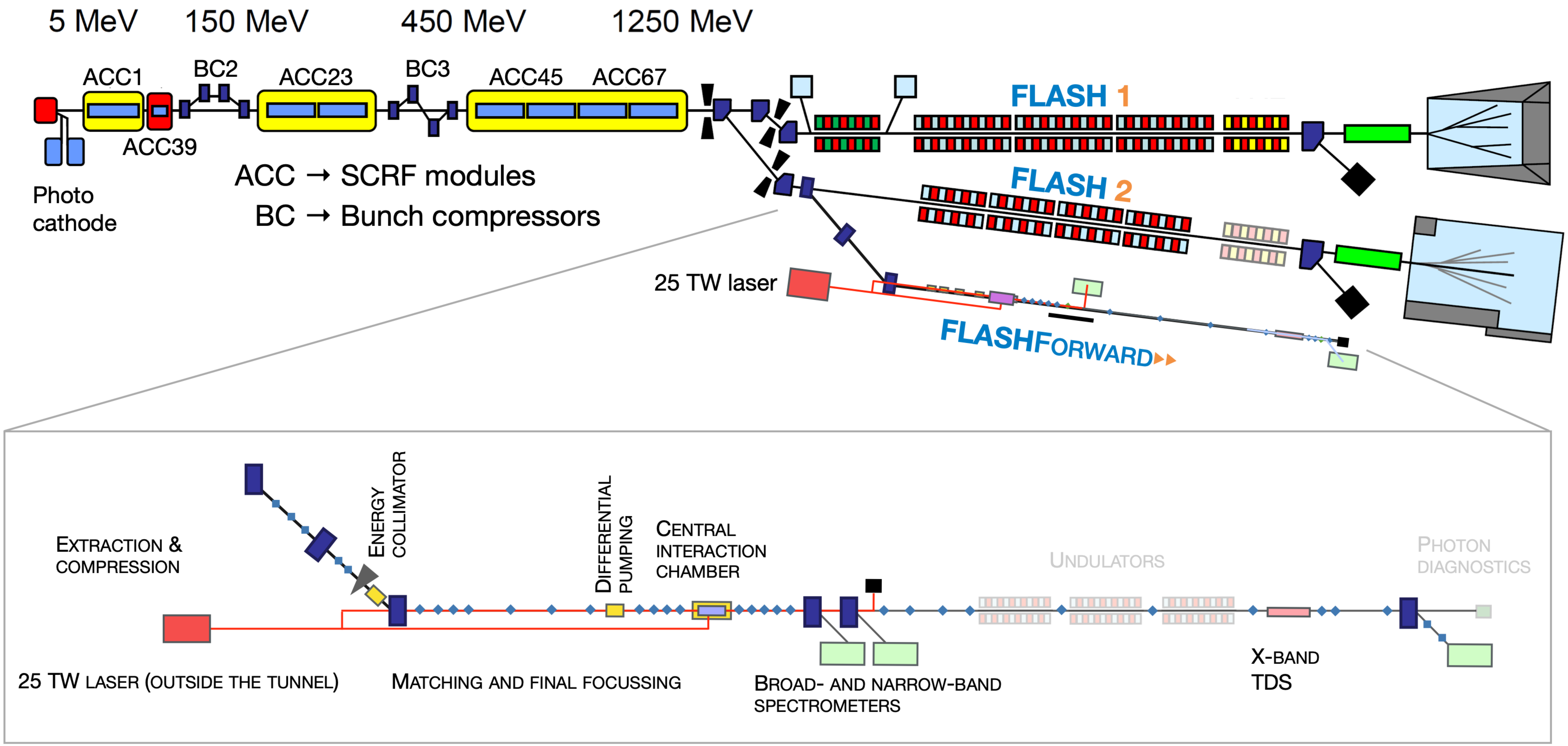
Institute	Staff	Projects
Imperial	Ken Long, Stuart Mangles, Zulfikar Najmudin, Jaroslaw Pasternak, Juergen Pozimski, Steve Rose	Wakefield Acceleration, Ion Acceleration, Betatron radiation, High-Field Physics, HEDP Lhara, AWAKE, ELI-ALPS, EuPRAXIA, J-Karen, CALA
Oxford	Phil Burrows, Brian Foster, Simon Hooker, Peter Norreys, Roman Walczak	Wakefield Acceleration, AWAKE, EuPRAXIA, FlashForward, CALA, LaserNet
Royal Holloway	Pavel Karataev	Wakefield Acceleration, AWAKE


CUOS
LUND
DESY
HZDR
CERN
KANSAI
SLAC
BNL
CALA
ELI-ALPS

Repetition rate of plasma accelerators

FLASHFORWARD▸▸ utilises FLASH superconducting accelerator

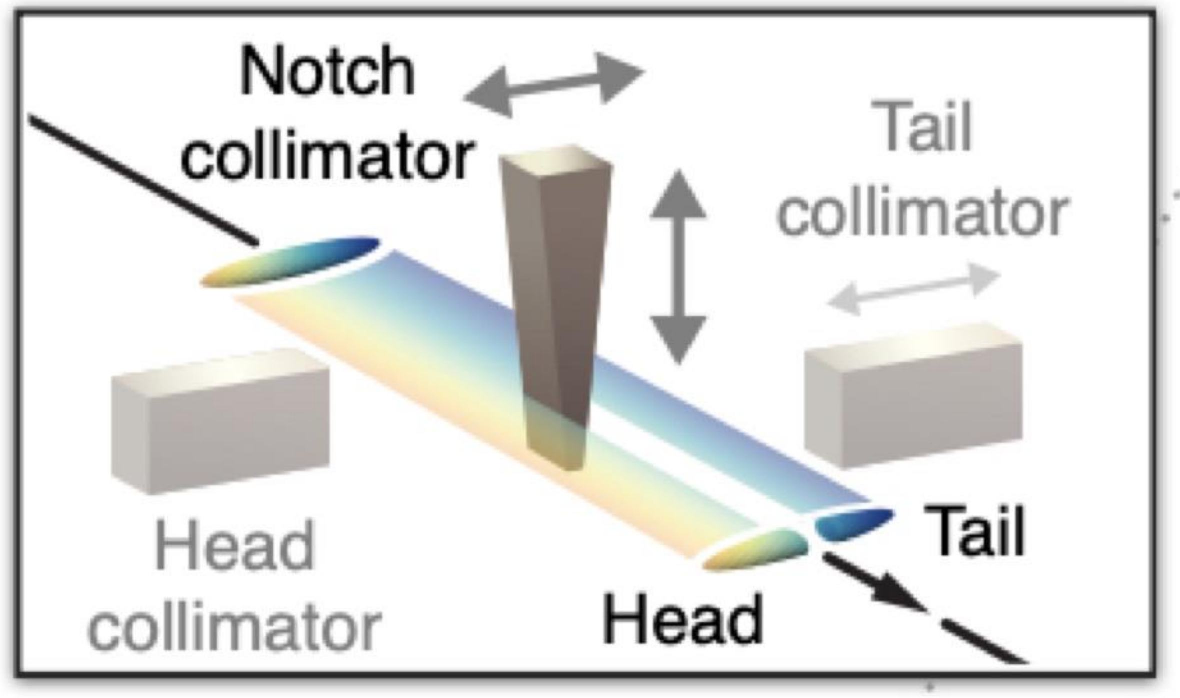
Plasma accelerator tightly integrated into facility and benefits from Free-Electron Laser beam quality



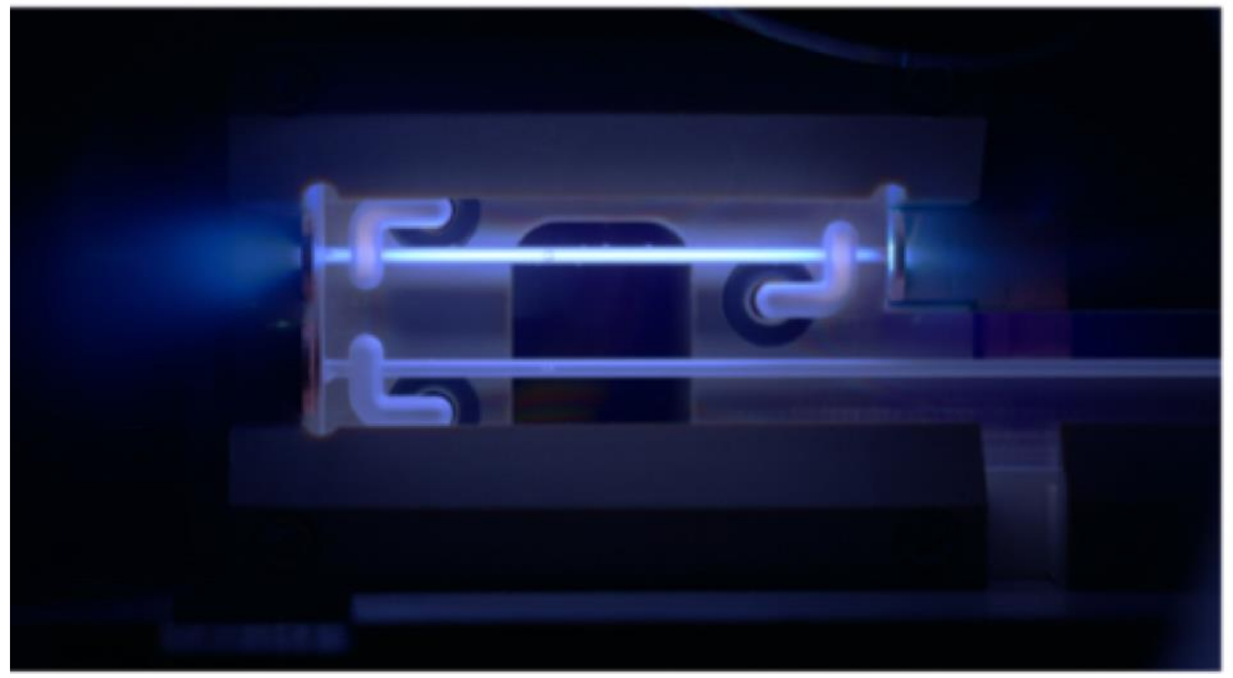
R. D'Arcy *et al.*, Phil. Trans. R. Soc. A **377**, 20180392 (2019)

FlashForward features:

Advanced collimator system for longitudinal bunch shaping



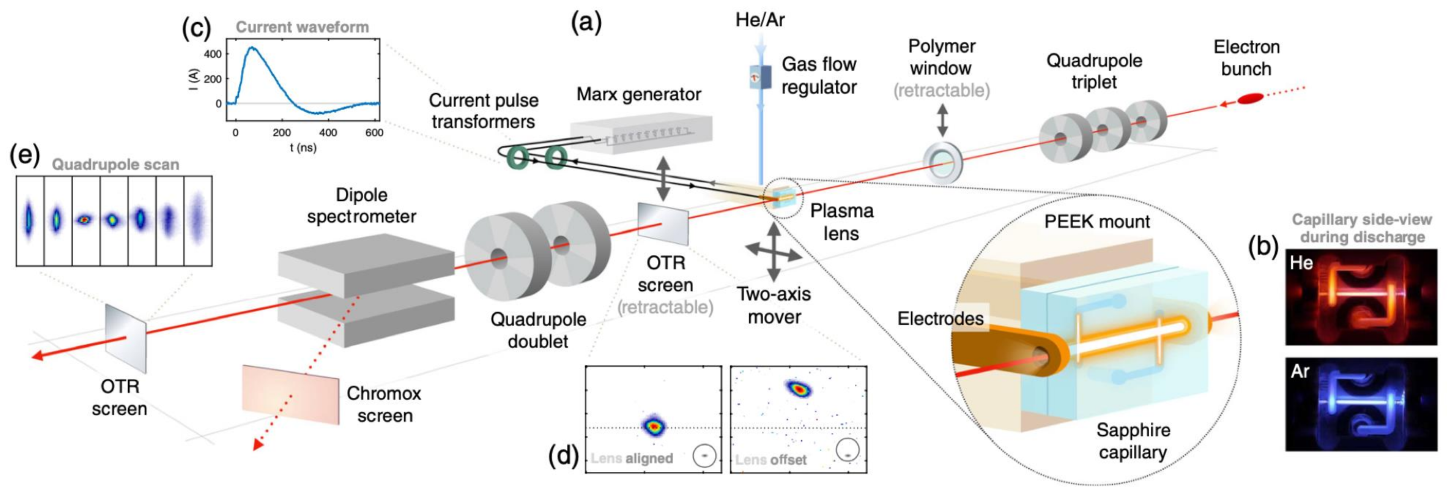
Two discharge capillaries provide density-controlled plasma

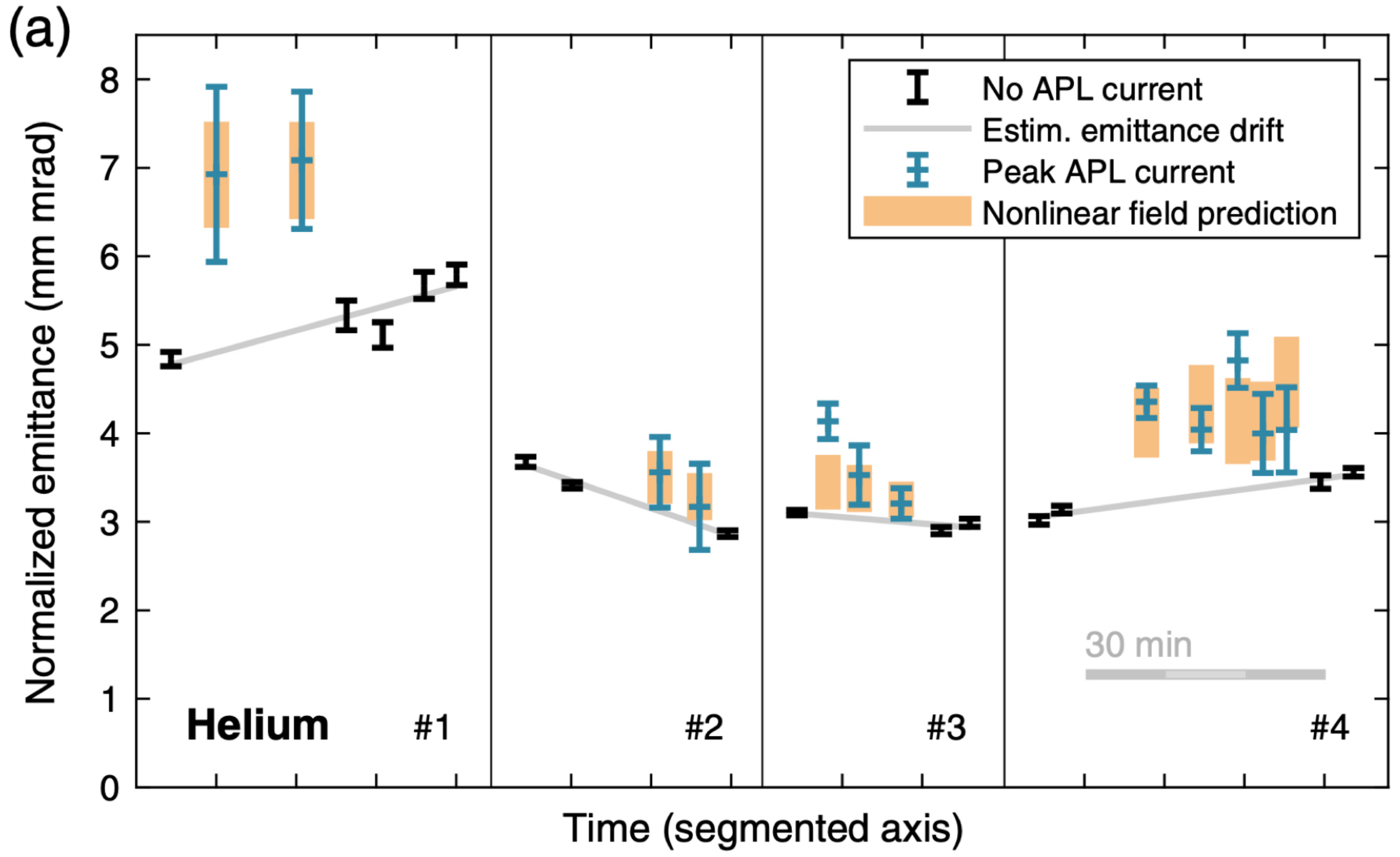


Two electron spectrometers used for diagnostic purposes

FLASHForward achievements:

FLASHForward now contributing to cutting edge research led by DESY group

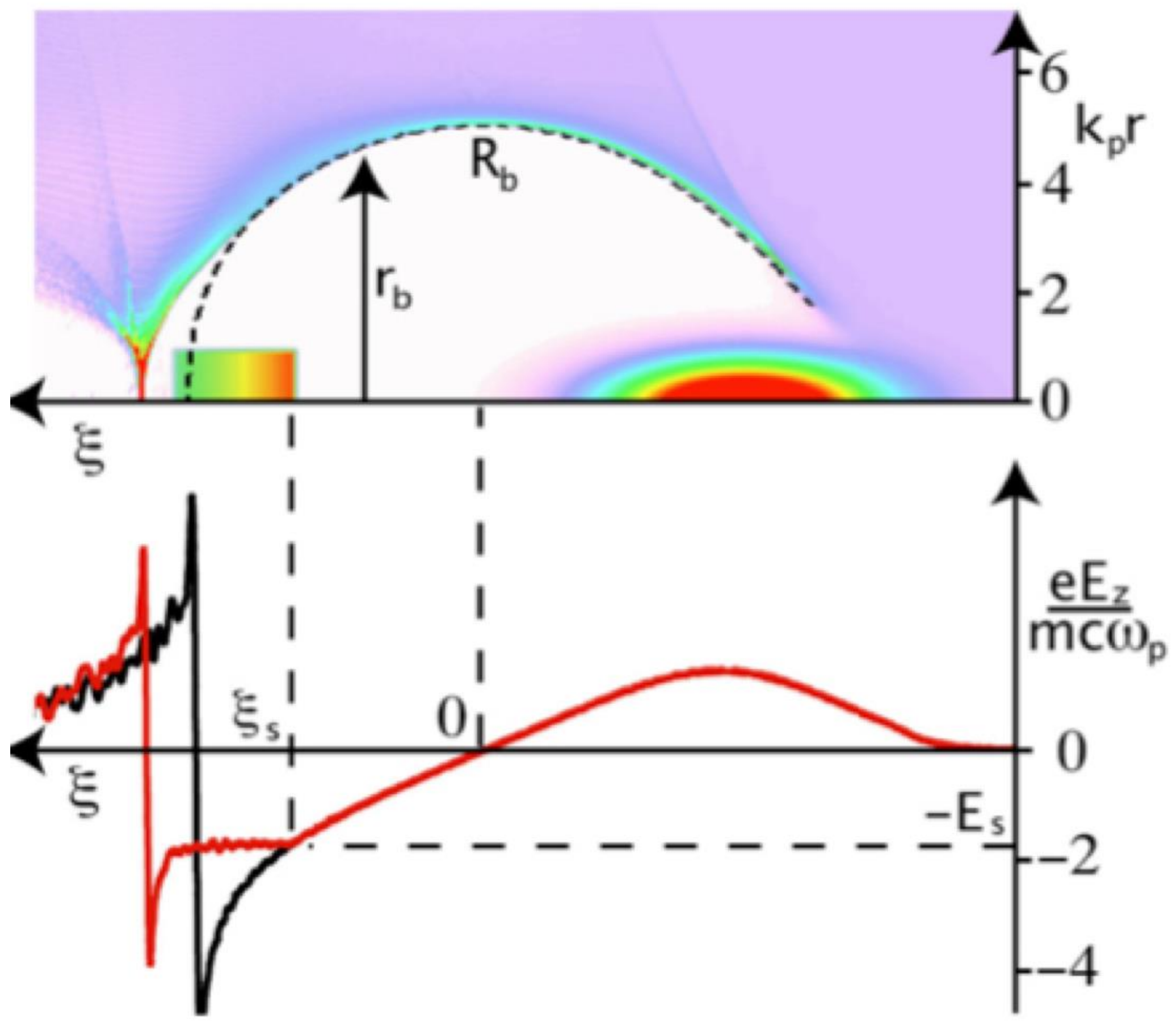




Emittance Preservation in an Aberration-Free Active Plasma Lens

C. A. Lindstrøm, E. Adli, G. Boyle, R. Corsini, A. E. Dyson, W. Farabolini, S. M. Hooker, M. Meisel, J. Osterhoff, J.-H. Röckemann, L. Schaper, and K. N. Sjobak

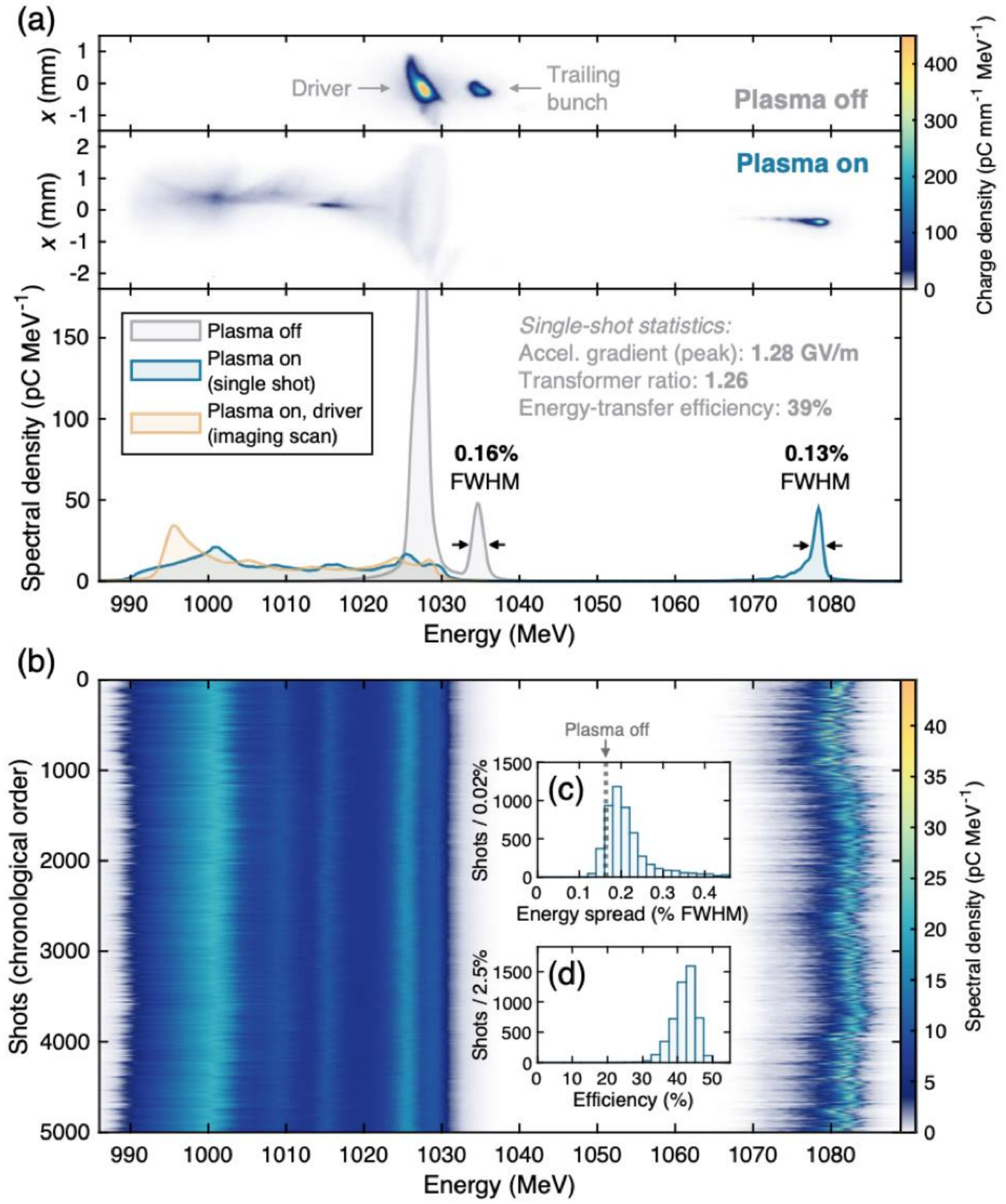
Phys. Rev. Lett. **121**, 194801 – Published 7 November 2018;
Erratum Phys. Rev. Lett. **122**, 129901 (2019)`



Tunable Plasma-Based Energy Dechirper

R. D'Arcy *et al.*

Phys. Rev. Lett. **122**, 034801 – Published 24 January 2019

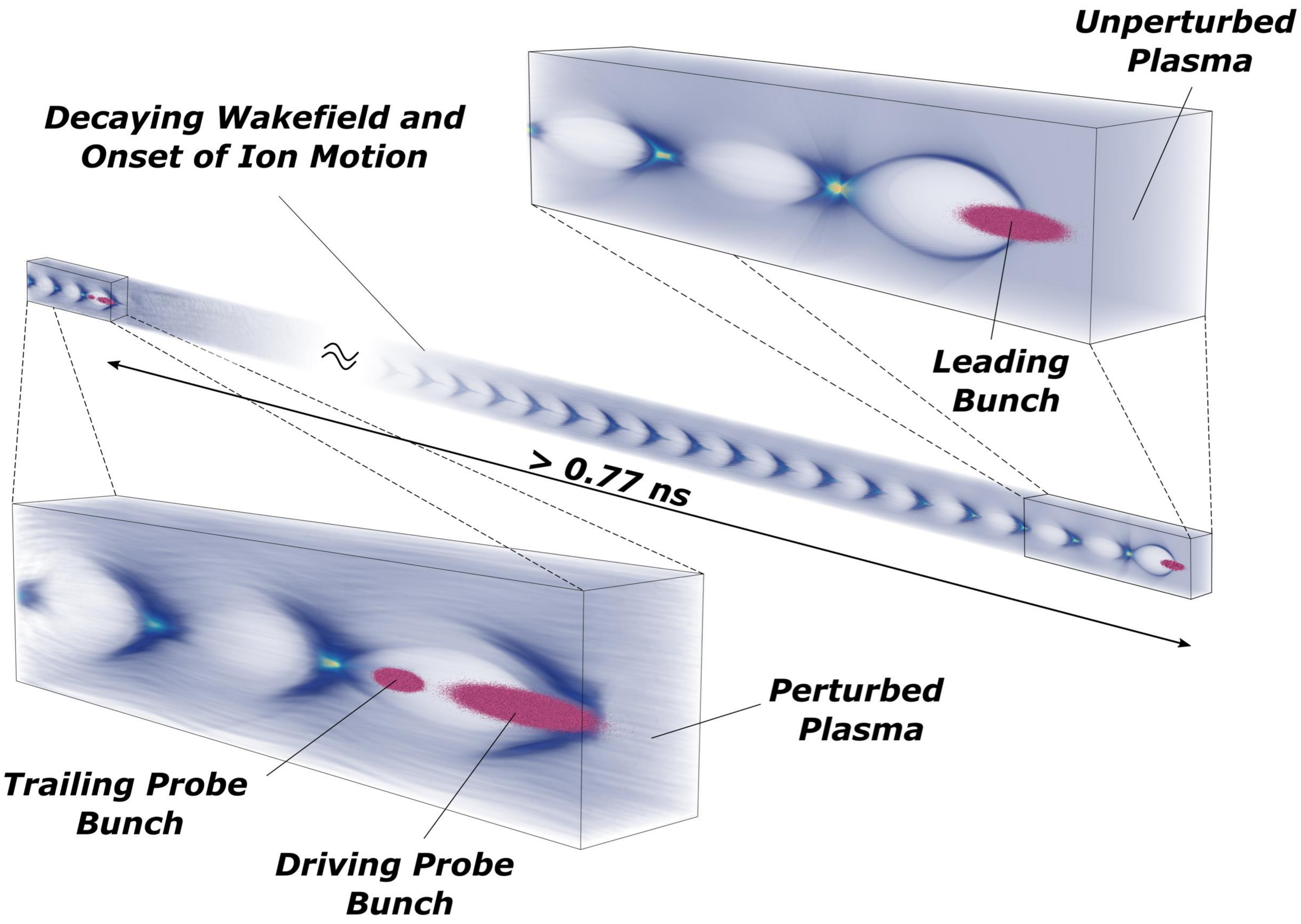


Ene
Efficiency in a Plasma-Wakefield Accelerator

C. A. Lindstrøm, J. M. Garland, S. Schröder, L. Boulton, G. Boyle, J. Chappell, R. D'Arcy, P. Gonzalez, A. Knetsch, V. Libov, G. Loisch, A. Martinez de la Ossa, P. Niknejadi, K. Põder, L. Schaper, B. Schmidt, B. Sheeran, S. Wesch, J. Wood, and J. Osterhoff

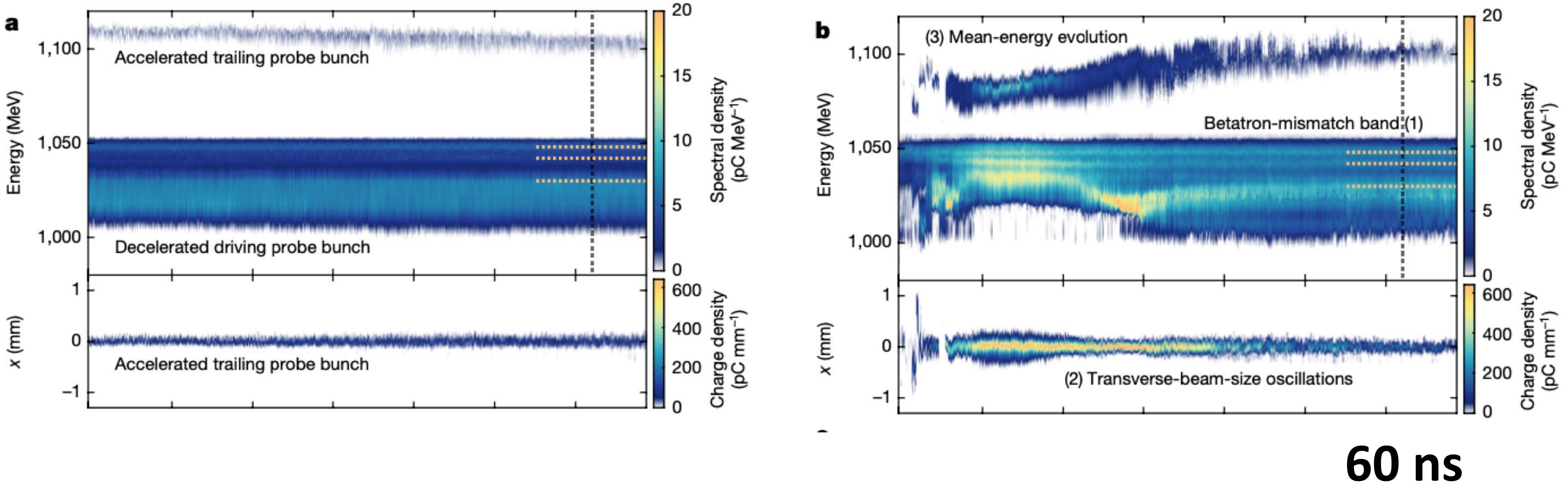
Phys. Rev. Lett. **126**, 014801 – Published 6 January 2021

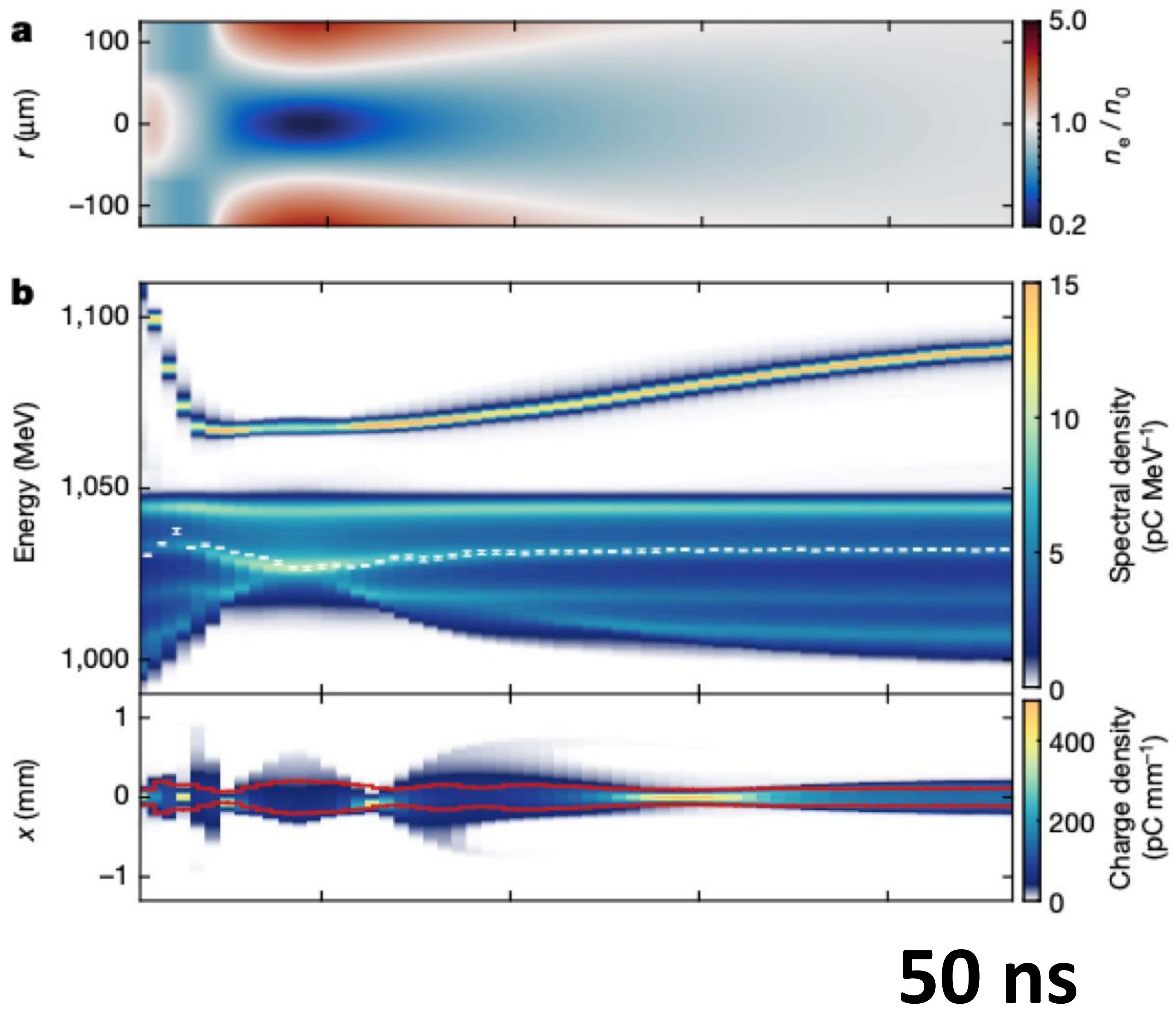
The recovery time of a plasma-wakefield accelerator



- A leading bunch perturbs the plasma by driving a wake
- A second probe-bunch pair arrives >0.77 ns behind the leading bunch and samples the plasma at that point in time
- The nature of the plasma can be inferred from the probe-bunch properties after driving its own wake
- The delay of the probe bunch can be changed in order to map out the evolution
- Analogous to pump-probe methodology in photon science

Recovery time of a plasma-wakefield accelerator





Equivalent to a repetition-rate upper limit of O(10 MHz)

Published: 02 March 2022

Recovery time of a plasma-wakefield accelerator

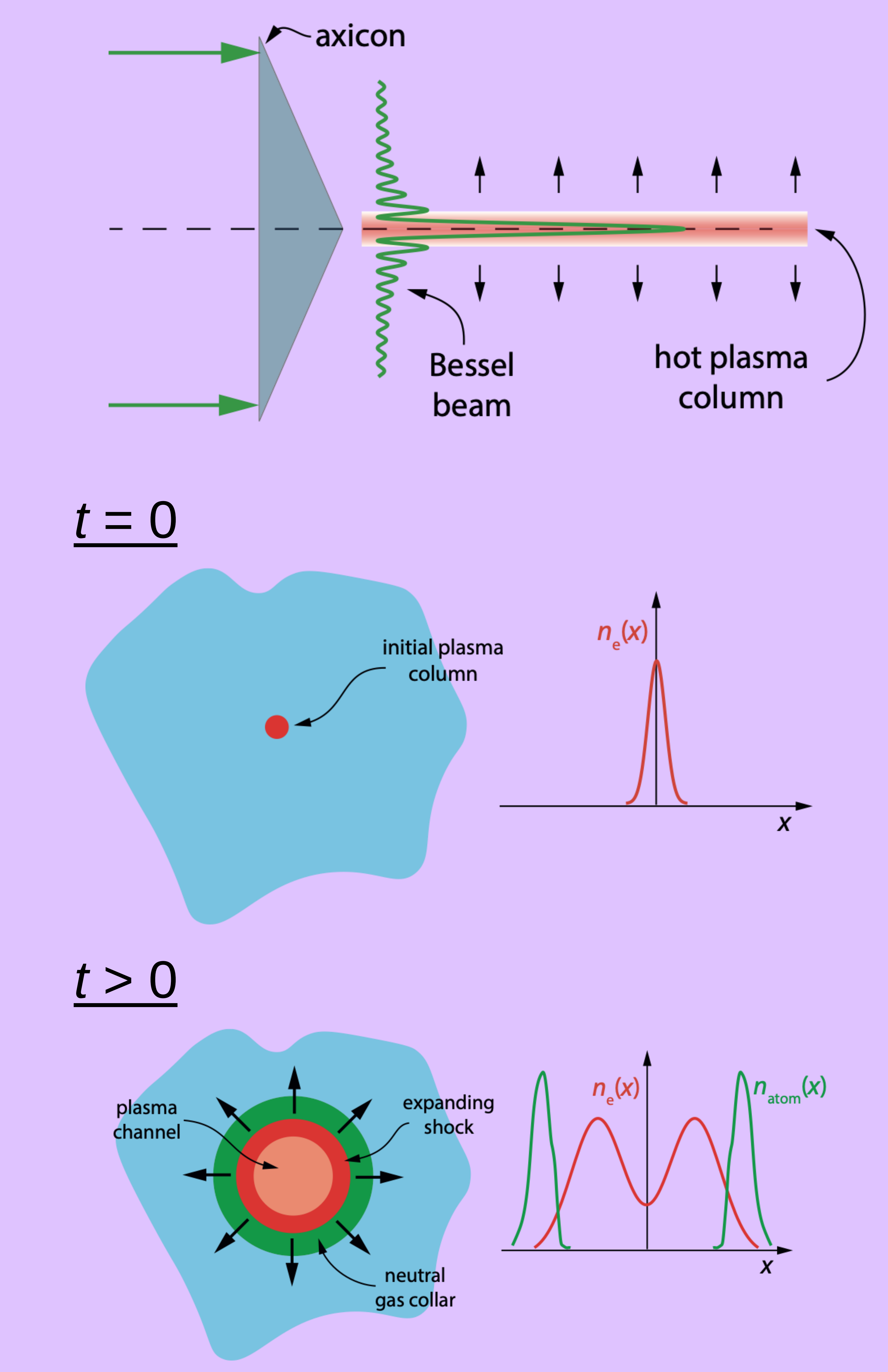
R. D’Arcy, J. Chappell, J. Beinortaite, S. Diederichs, G. Boyle, B. Foster, M. J. Garland, P. Gonzalez Caminal, C. A. Lindstrøm, G. Loisch, S. Schreiber, S. Schröder, R. J. Shalloo, M. Thévenet, S. W

Nature volume 603, pages 58–62 (2022)

Laser Wakefield Accelerators

All-optical plasma channels

- Multi-GeV stages require accelerator stages 100s mm long with densities ~ 10^{17} cm^{-3}:
- We have developed all-optical ("indestructible") plasma channels with properties ideal for high rep-rate, GeV-scale laser-plasma accelerators:
  - On-axis density ~ 10^{17} cm^{-3}
  - Attenuation length > 10 m



1. Axicon creates a long (> 100 mm) cylinder of plasma

2. This expands radially, driving a shock wave & forming a weak plasma channel.

3. Expansion pushes out a collar of neutral gas.

4. Ionization of collar by guided pulse creates a deeper, lower loss channel

Details in:

R.J. Shalloo *et al. Phys Rev E* **97** 053203 (2018)

A. Picksley *et al. Phys Rev Accel Beam* **23** 81303 (2020)

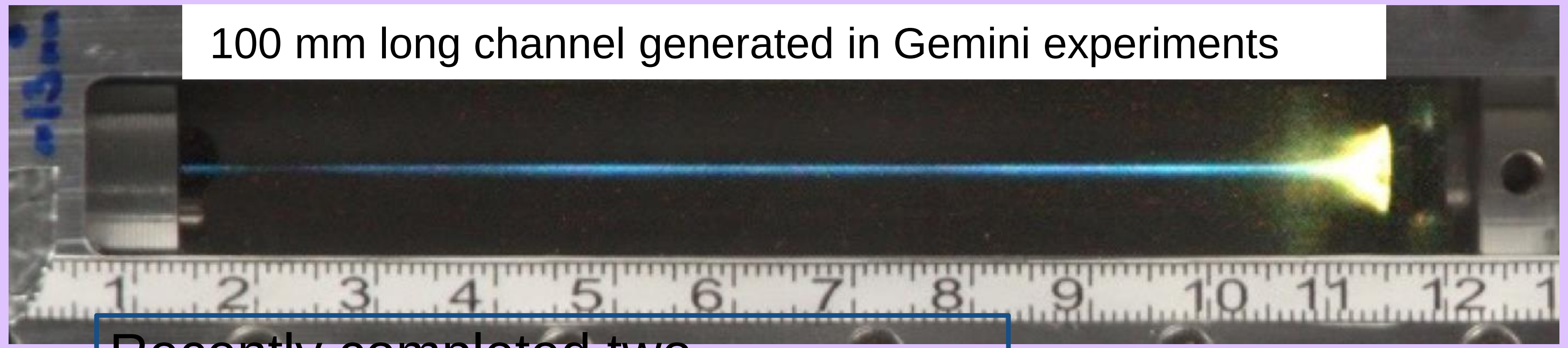
A. Picksley *et al. Phys Rev E* **102** 053201 (2020)

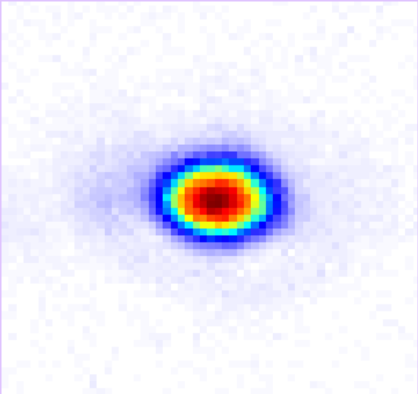
A. Alejo *et al. Phys Rev Accel Beam* **25** 011301 (2022)

All-optical plasma channels

Guiding in > 100 mm long channels

100 mm long channel generated in Gemini experiments





Warning! Preliminary analysis !

Recently completed two experiments with the Gemini laser at CLF.

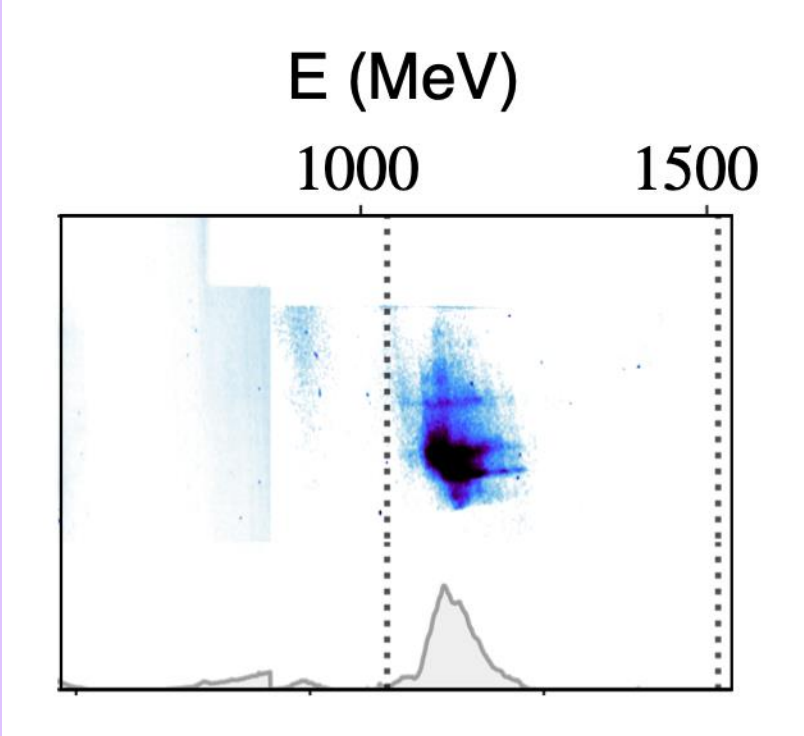
Preliminary analysis suggests:

High-quality guiding of 10^{18} W cm^{-2} pulses over 300 mm demonstrated

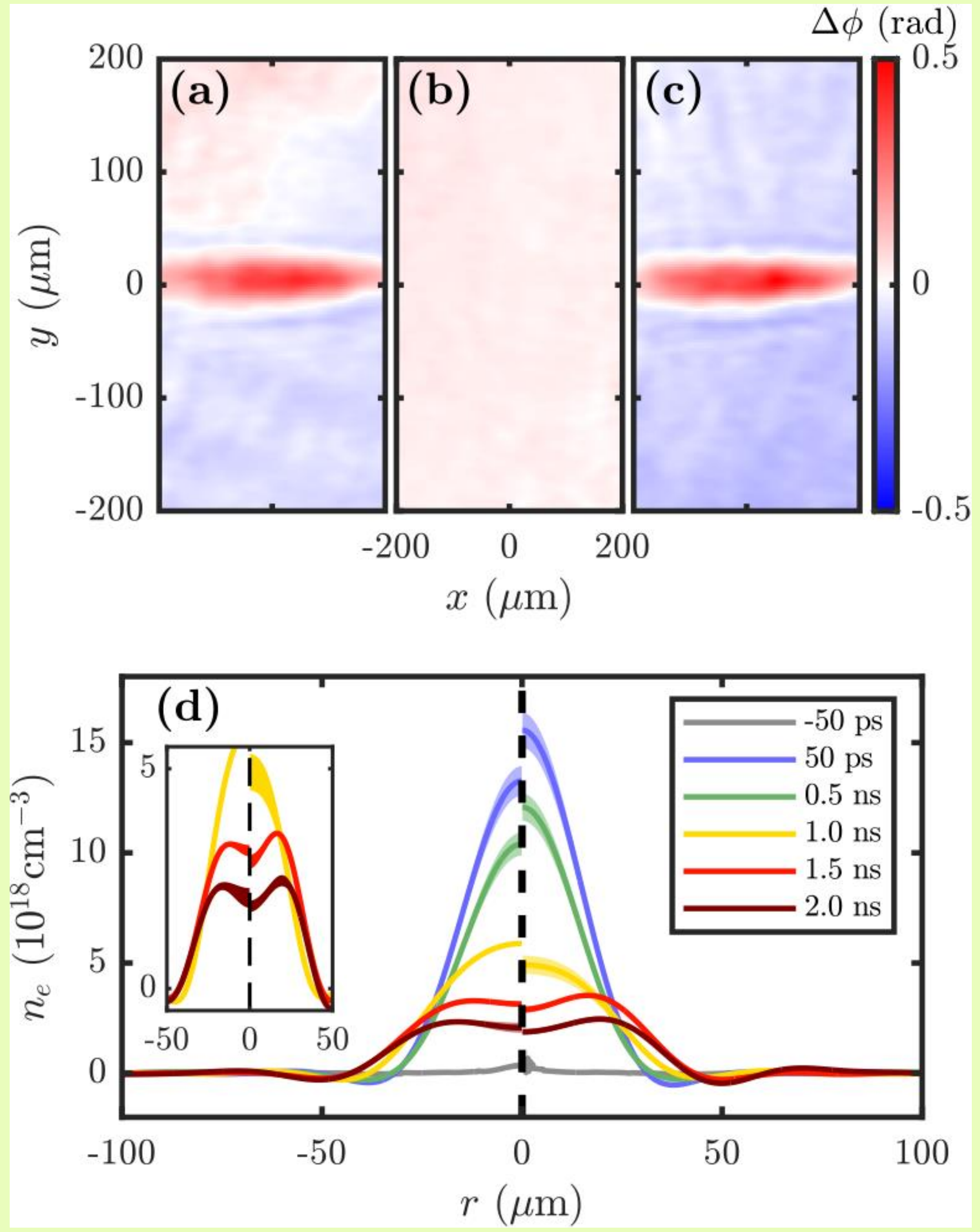
Electron acceleration in HOFI channels to > 1 GeV.

High-quality guiding of trains of ~ 10 pulses over 100 mm.

Resonant excitation of plasma wakefields by channel-guided pulse trains.



1 kHz channels demonstrated

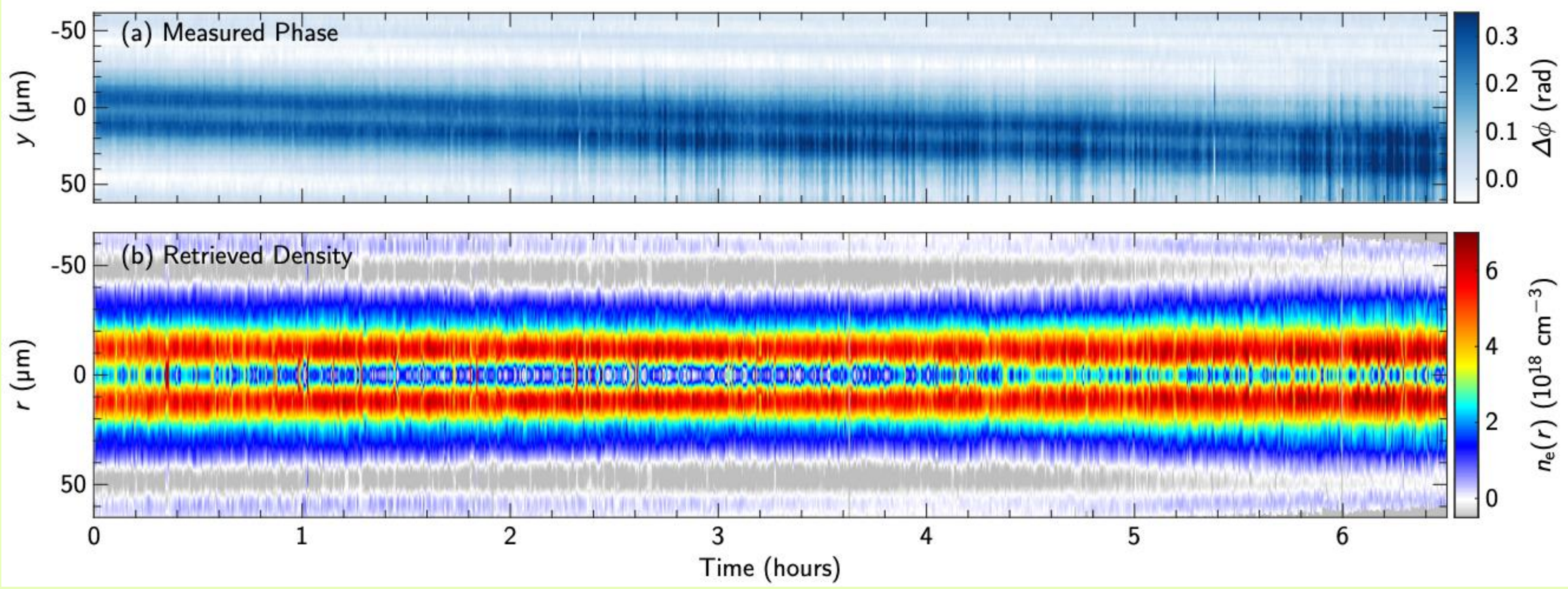


Short HOFI channels have been generated at f_{rep} = 1 kHz for the first time.

Interferometry shows: (a) channel formed by pulse 1; (b) plasma immediately before pulse 2, 1 ms after pulse 1; (c) channel formed by pulse 2; (d) temporal evolution of channels formed by pulse 1 (left) and pulse 2 (right)

Very stable channels generated at f_{rep} = 0.4 kHz **over 6 hour run**!

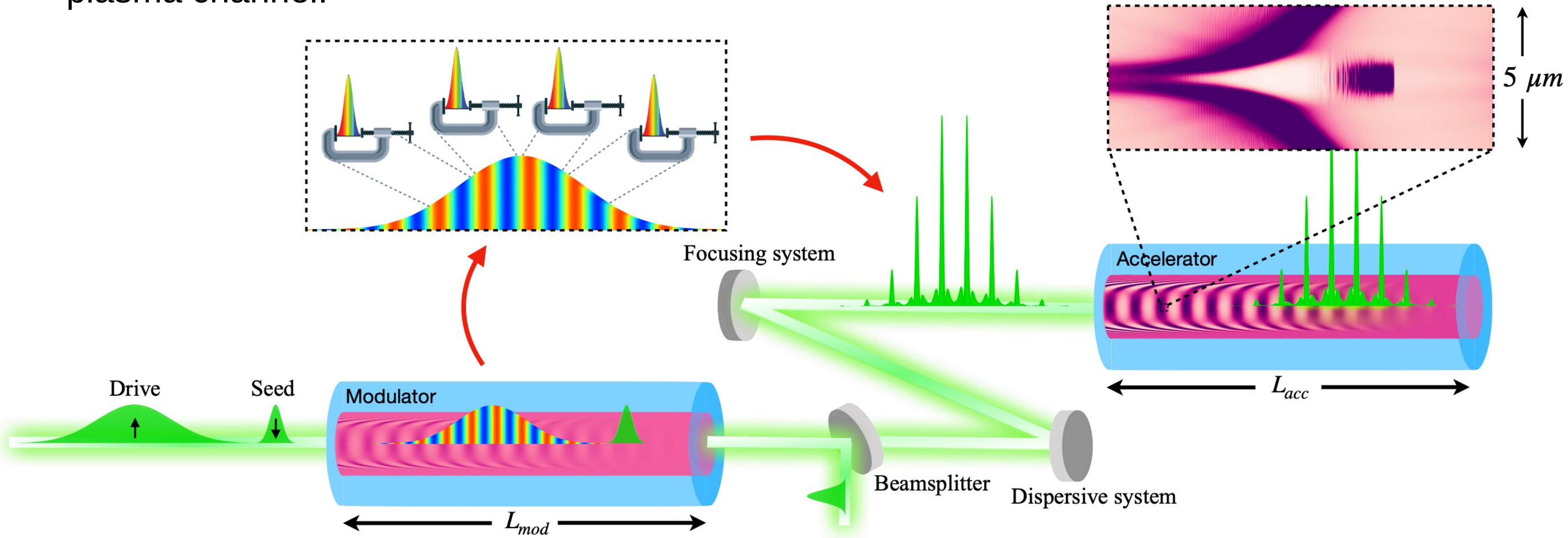
A. Alejo *et al.*, *PRAB* **25** 011301 (2022).



Towards GeV@kHz - Resonant LWFA using thin disk lasers

- Ti:Sa lasers are limited to few-Hz repetition rates at high pulse energies and low wall-plug efficiencies.
- **Commercially-available, high-efficiency** thin-disk lasers can deliver the **kW average power** and **kHz repetition rate** needed for GeV@kHz, but their ps-duration pulses are too long for LWFA.
- A novel scheme has been proposed to generate a train of fs-duration pulses to **resonantly** drive large-amplitude plasma wakes with 10s of GV/m acceleration gradients.

- Plasma wake driven by low-energy fs pulse spectrally modulates long pulse in plasma channel.
- Compression gives train of pulses separated by plasma wavelength.
- Acceleration of micrometer-sized pC electron bunches to GeV energies.



- Collaboration between Oxford University, CLF, LMU Munich and TRUMPF Scientific Lasers to develop this scheme.
- Joint PhD studentship at Oxford funded by CLF and TRUMPF.
- Aim for a proof-of-principle demonstration in new Oxford lab.
- Experimental demonstration of full scheme in Munich using 0.5 J, 1 ps, 1 kHz thin-disk laser
- Plan to apply for major (> £5M) research grants to support this new programme.

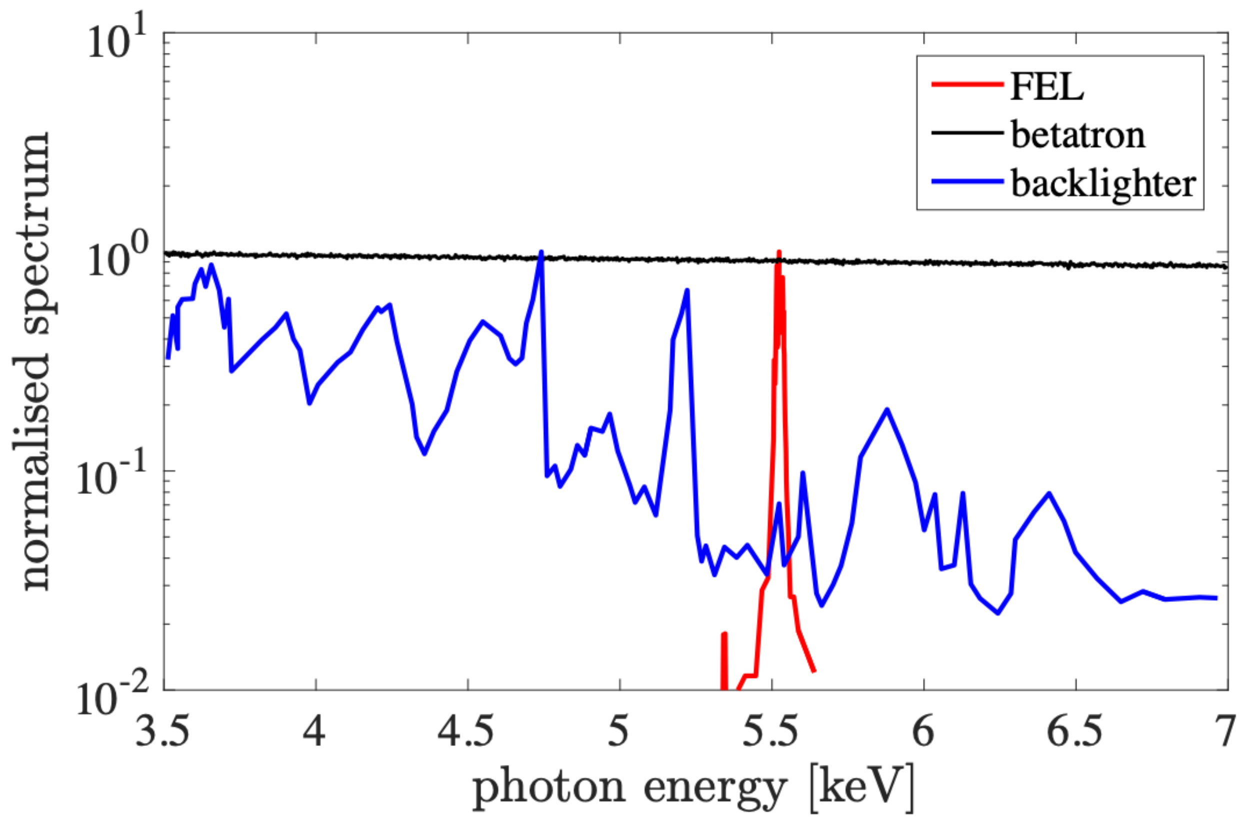
Details in:
O. Jakobsson et al. Phys. Rev. Lett. **127**, 184801 (2021)

Imperial College London · University of Oxford · Royal Holloway University of London

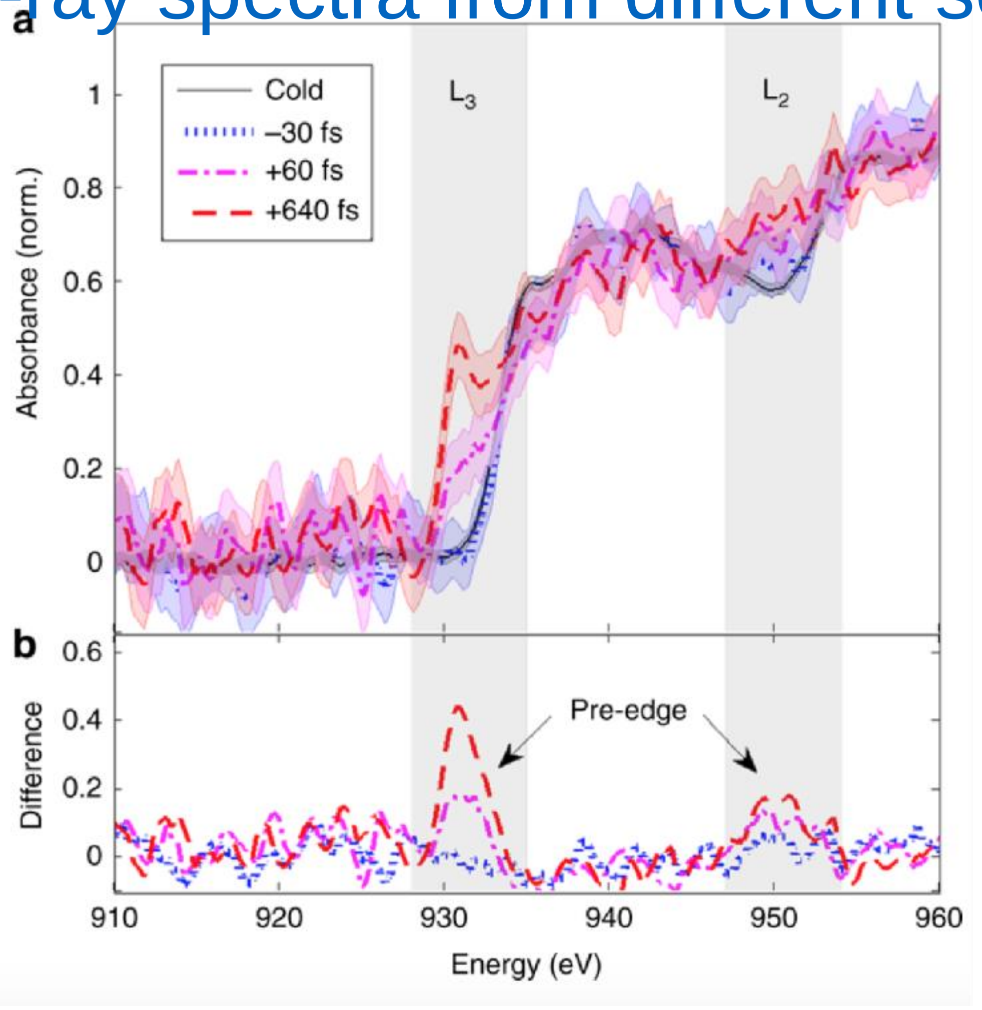
EXAFS with Betatron source

Ultrafast X-ray Absorption Spectroscopy Platform at Gemini

- X-rays produced by a LWFA are unique
  - broadband and ultra-fast
  - can be synchronised with other lasers
- Well-suited for pump probe X-ray absorption studies
  - XANES and EXAFS are standard XAS methods employed at synchrotrons
  - XANES: reveals details of electronic structure / temperature
  - EXAFS: reveals details of ion structure / temperature
  - Can we use a LWFA to do these?
- Experiments at with lower power lasers have suffered from:
  - low energy (< 1 keV): limits materials which can be probed
  - low flux: many shots needed for a single spectrum



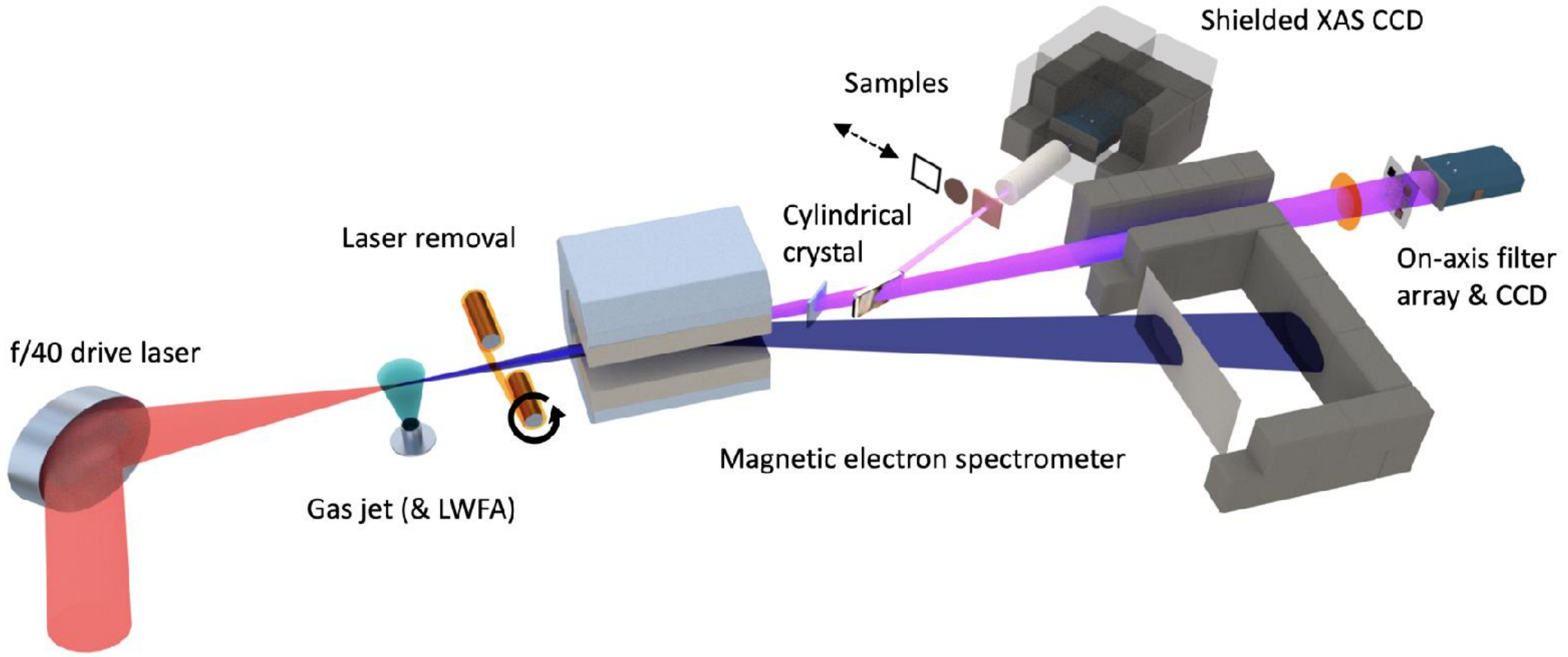
Ultra-fast X-ray spectra from different sources

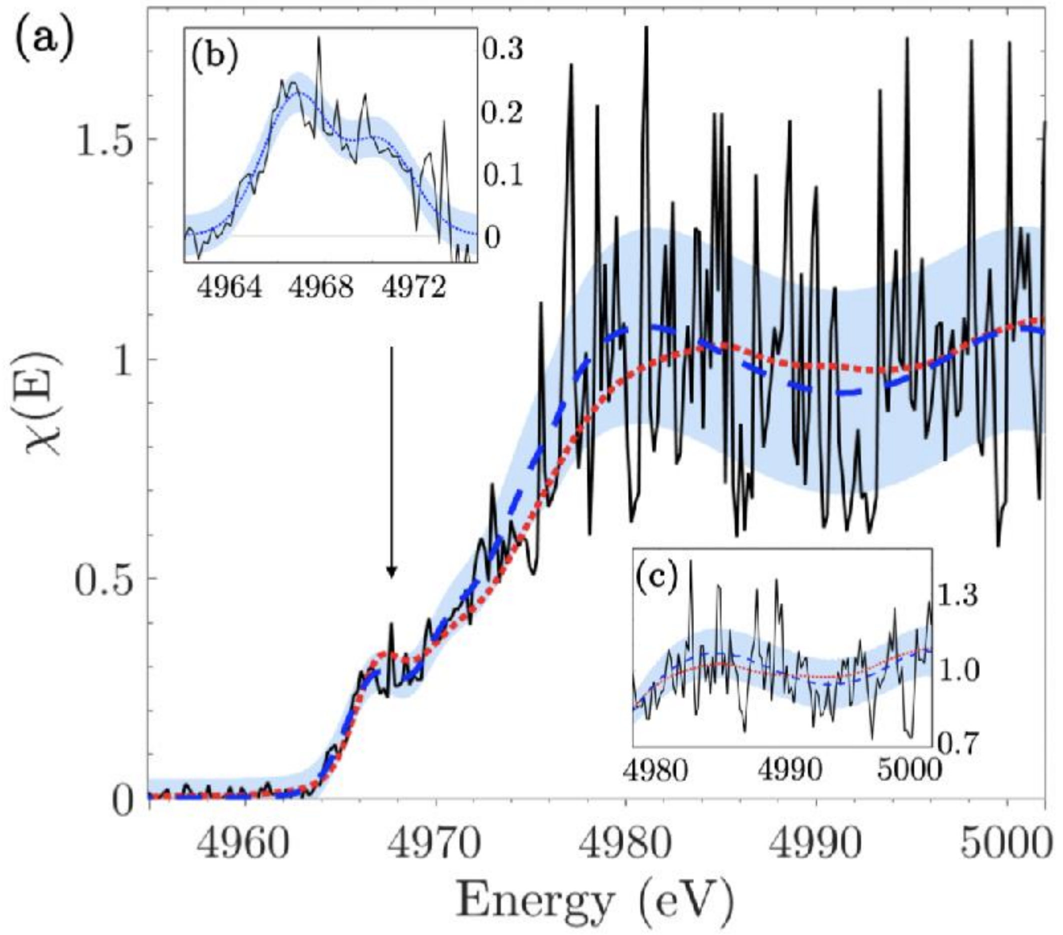


LOA group work: Mahieu Nature Communications 2018
50 TW laser: 50 shots per spectrum

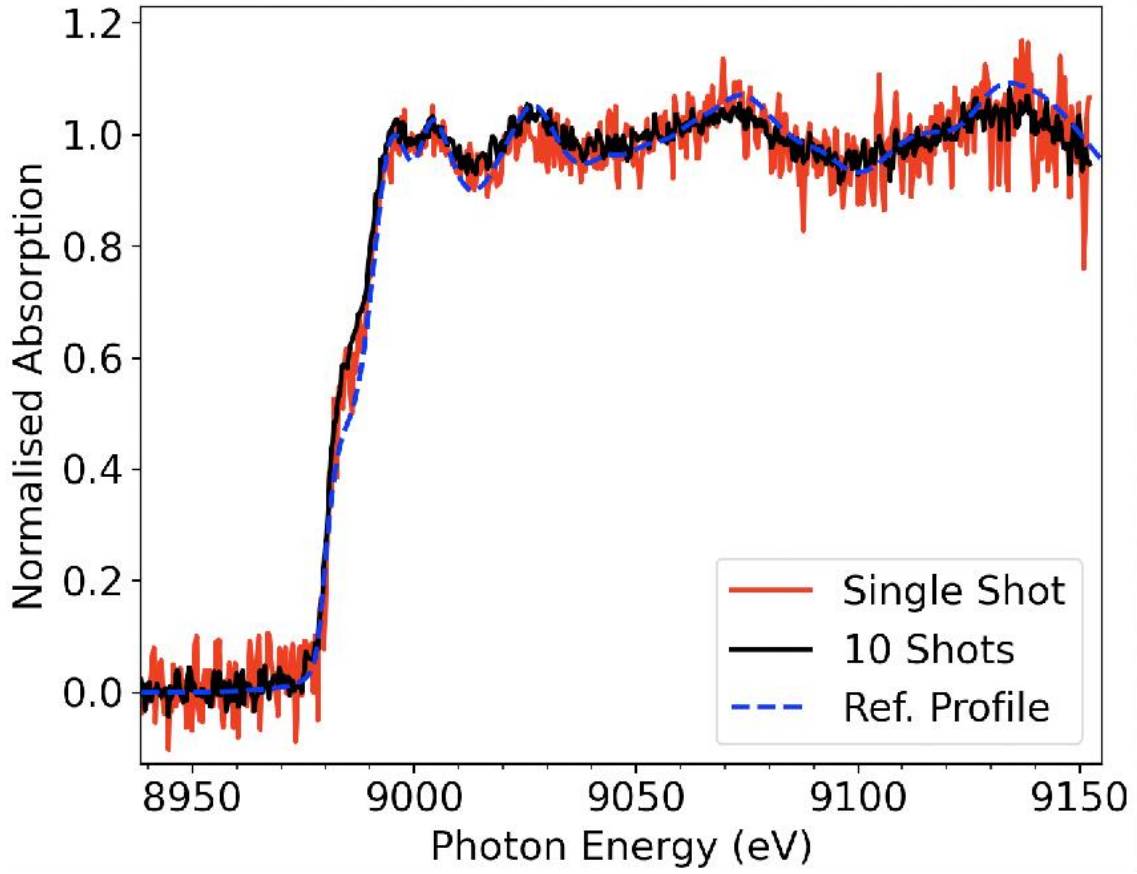
Realising single-shot XANES spectrum using betatron radiation from a LWFA

- In 2019 we showed first single-shot XANES spectrum using betatron radiation from a LWFA
  - Electron features (slope and pre edge) well resolved
  - ion features (EXAFS) still poorly resolved





B Kettle et al
PRL, 123, 254801 (2019)

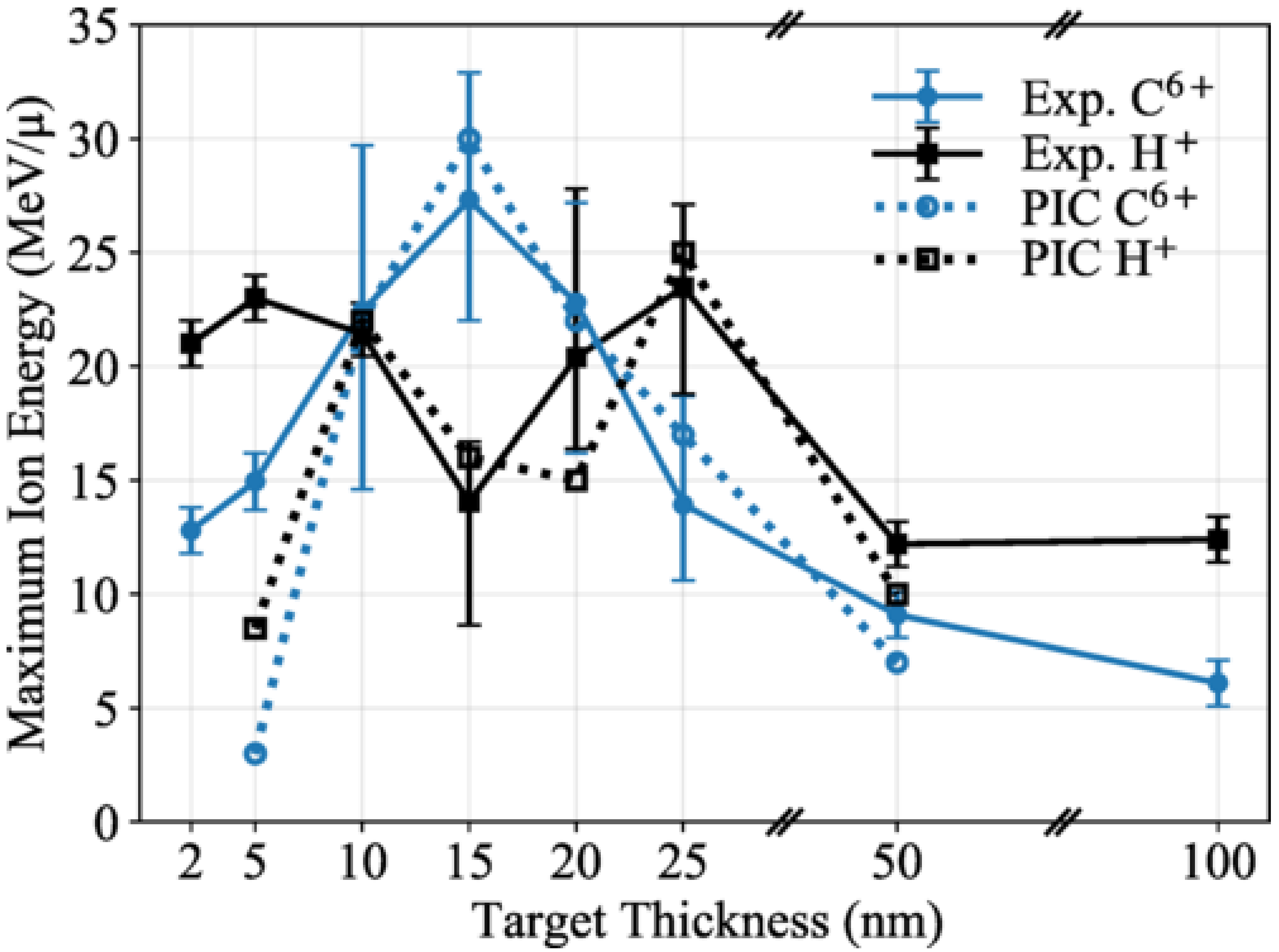


B Kettle et al
unpublished

- Experiment in 2020 First single-shot XANES+EXAFS spectrum using betatron radiation from a LWFA
  - Improvements to beam line: better shielding (noise ↓), focusing X-ray spectrometer (signal ↑)
  - Single shot EXAFS now achieved - electron and ion features now resolved in a single shot

Ion acceleration with lasers

Selective Ion Acceleration by Intense Radiation Pressure



Carbon ions selectively accelerated for right target thickness

A New Trick to Make Short-Pulse Ion Beam

November 1, 2021• *Physics* 14, 153

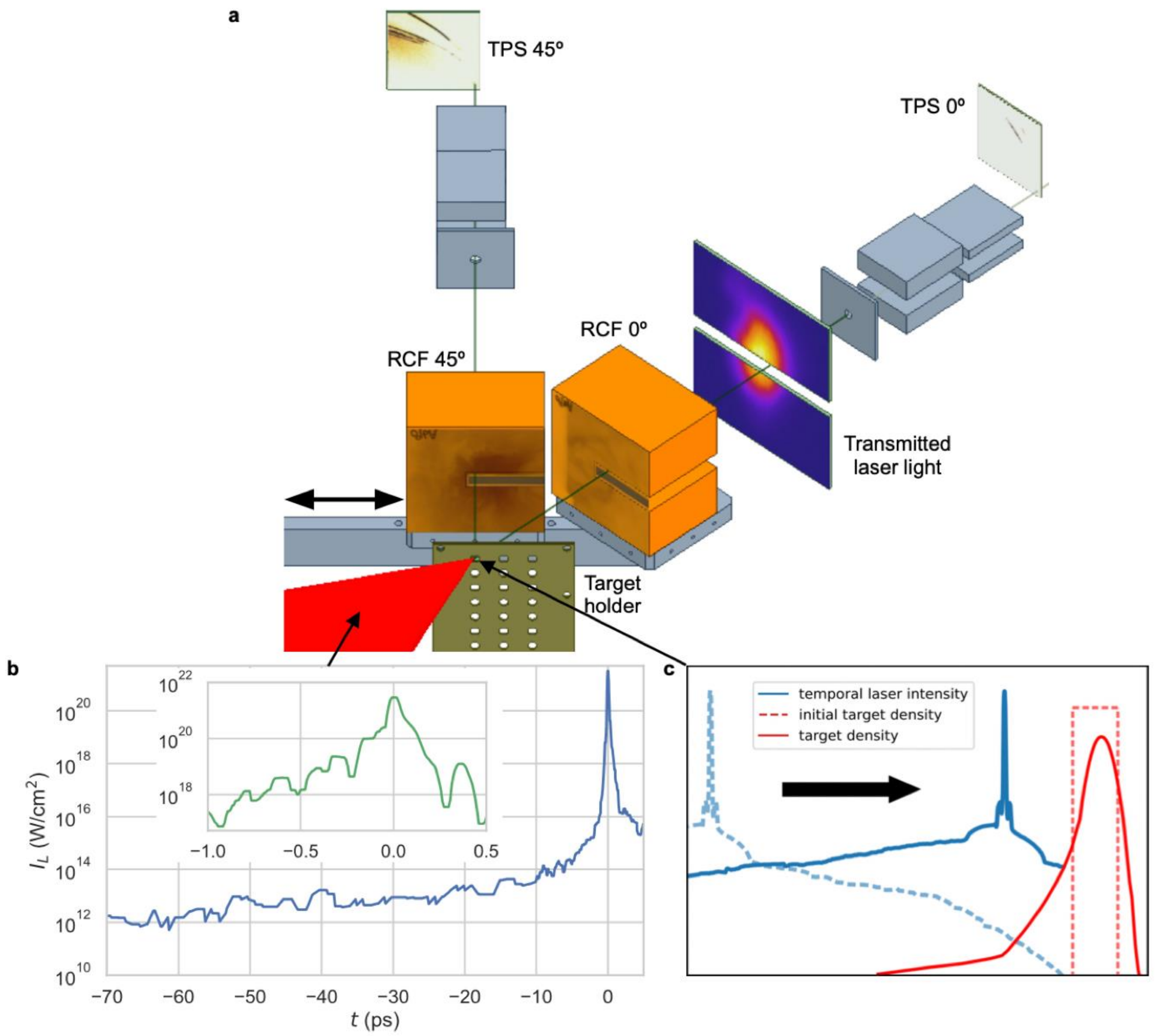
Selective Ion Acceleration by Intense Radiation Pressure

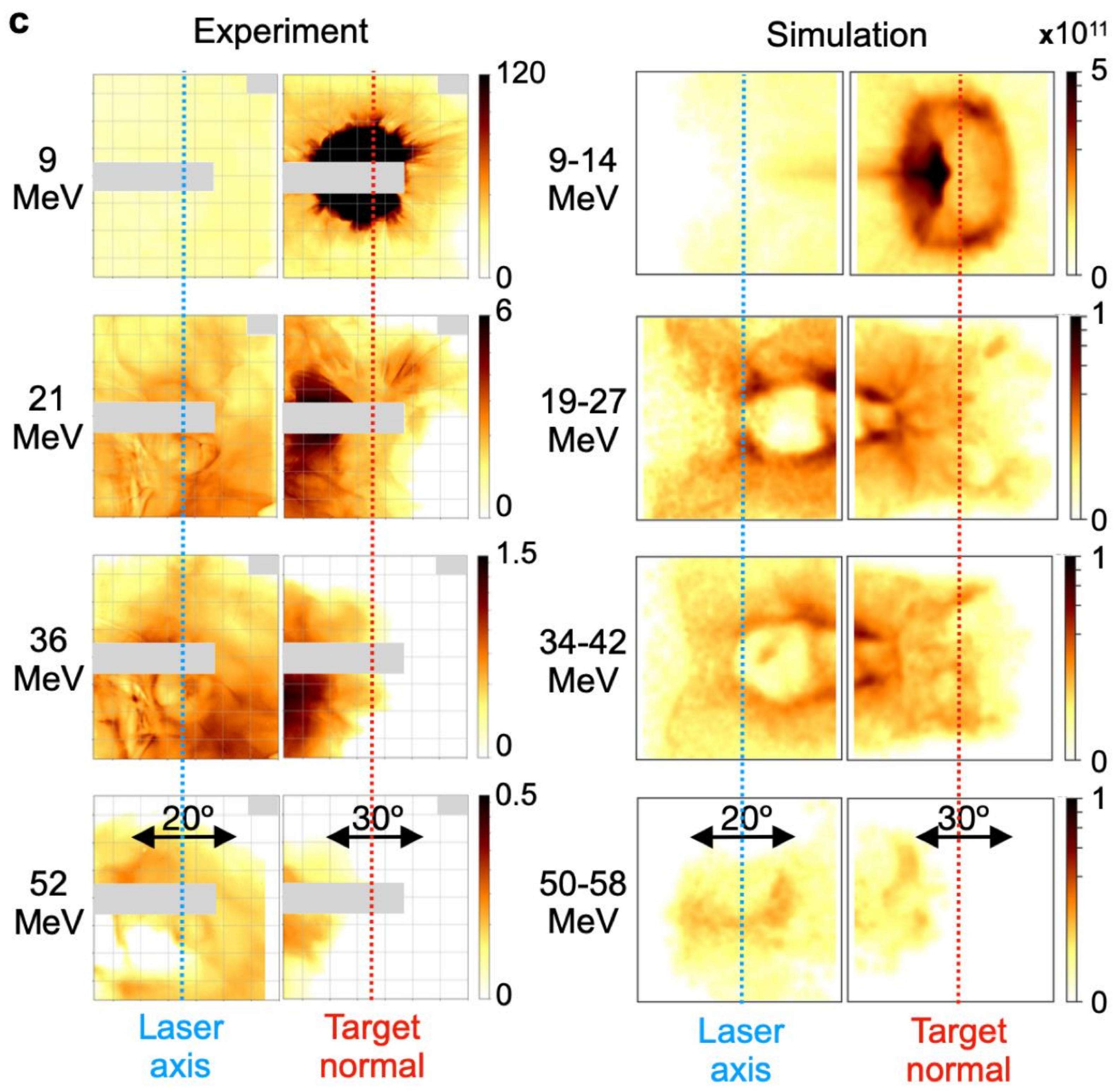
A. McIlvenny, D. Doria, L. Romagnani, H. Ahmed, N. Booth, E. J. Ditter, O. C. Ettlinger, G. S. Hicks, P. Martin, G. G. Scott, S. D. R. Williamson, A. Macchi, P. McKenna, Z. Najmudin, D. Neely, S. Kar, and M. Borghesi

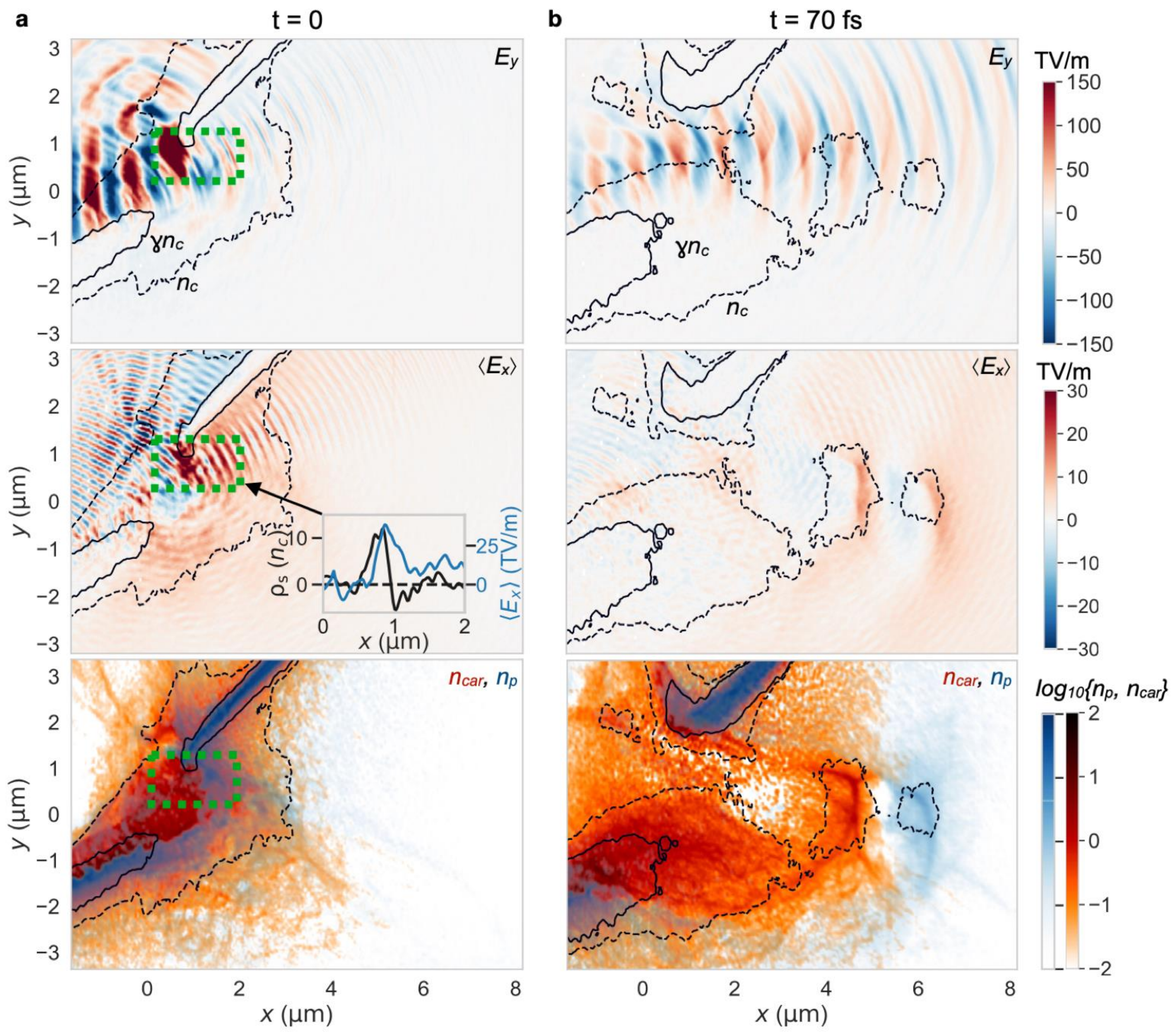
Phys. Rev. Lett. **127**, 194801 – Published 1 November 2021

Relativistically induced transparency

Proton energies exceeding 60 MeV





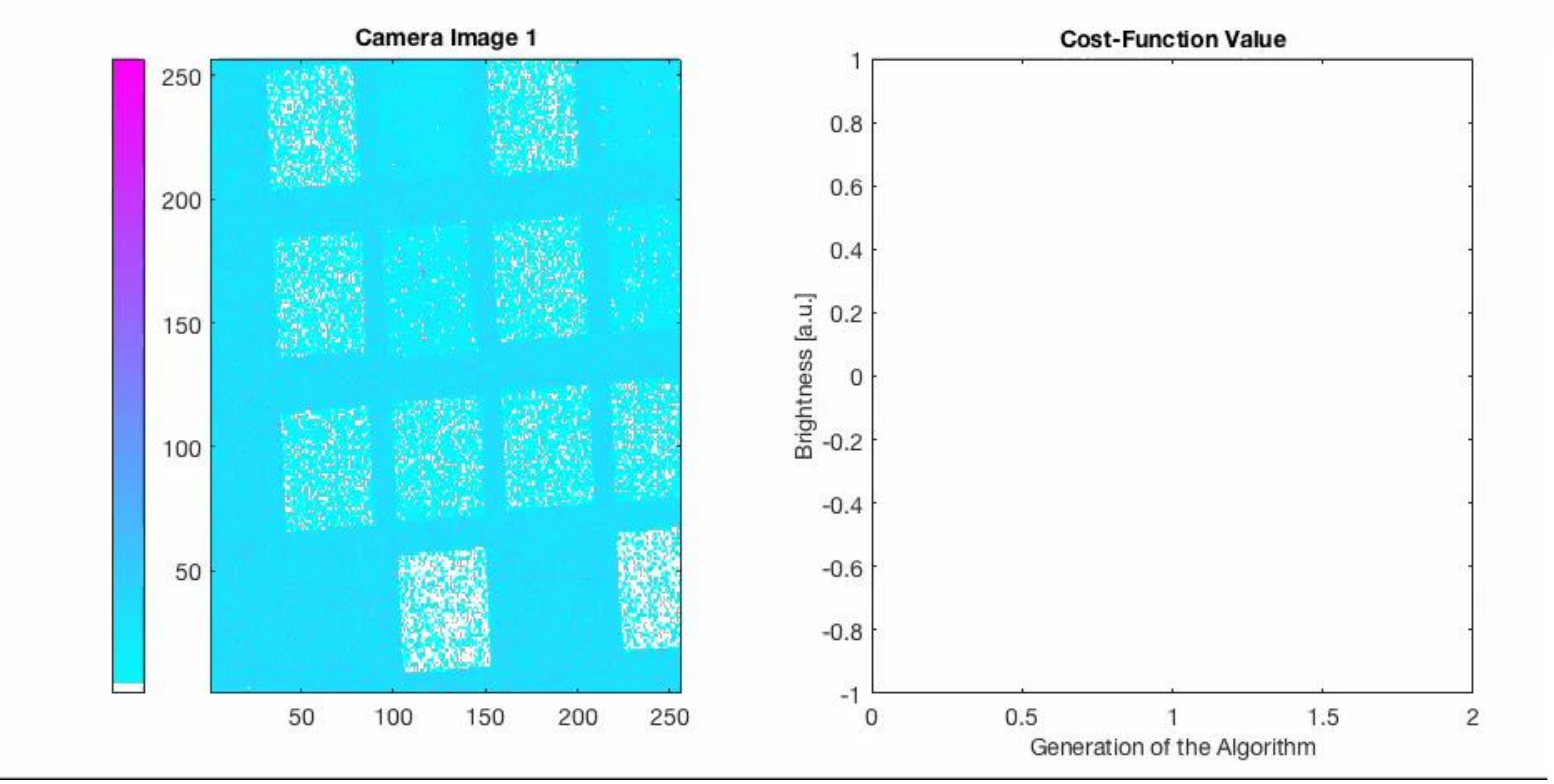


Similar effects seen in p-polarised interaction at oblique incidence. Compression of target

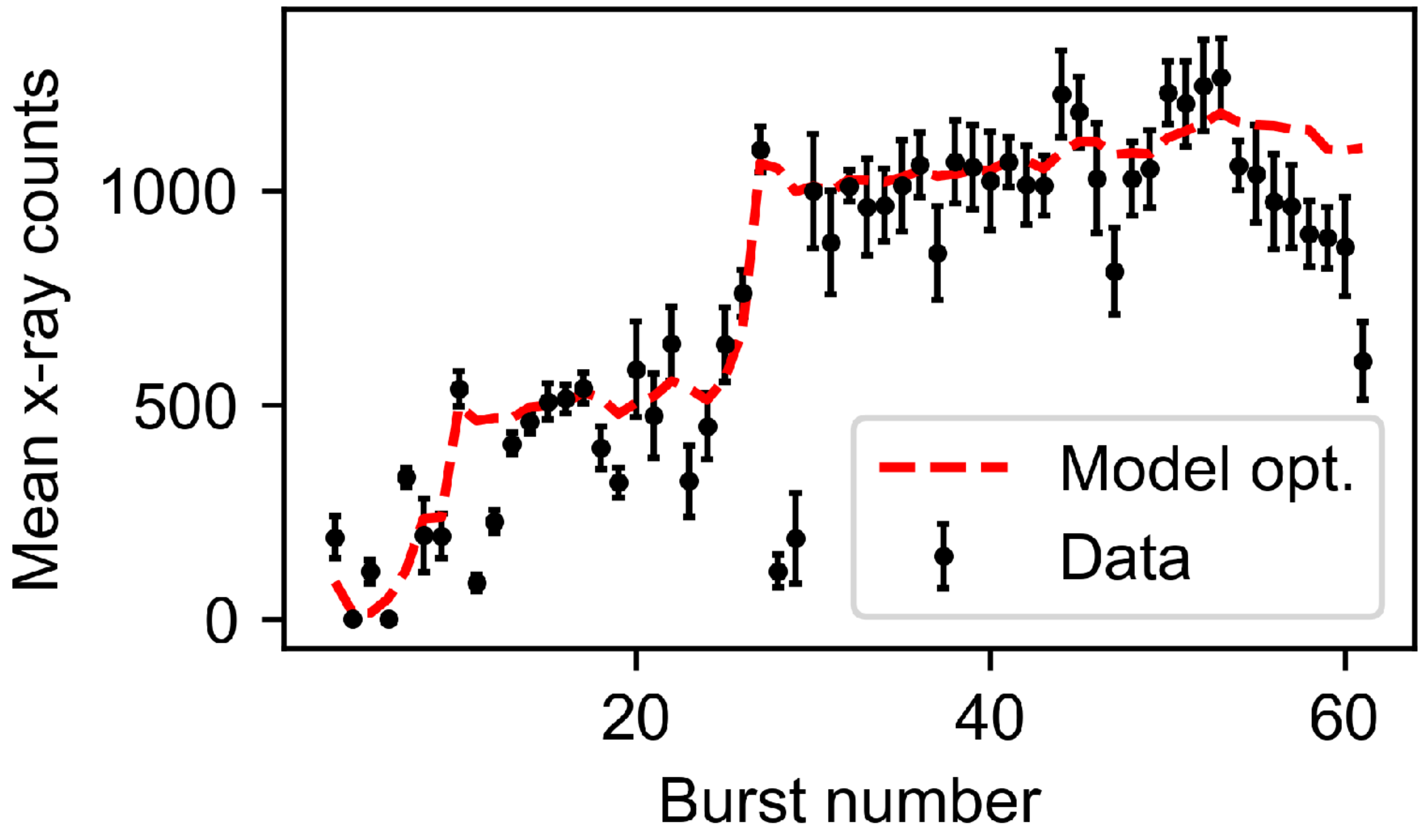
Energetic ion emission from prepulse-expanded relativistically transparent foils driven by ultra-intense femtosecond class lasers
N. Dover et al - in preparation

Automation of plasma accelerators

Machine Learning Applied to Plasma Accelerators



6D optimisation of mean x-ray CCD counts



- Optimisation of betatron source using genetic algorithm
- x-ray filter image from 5 TW source

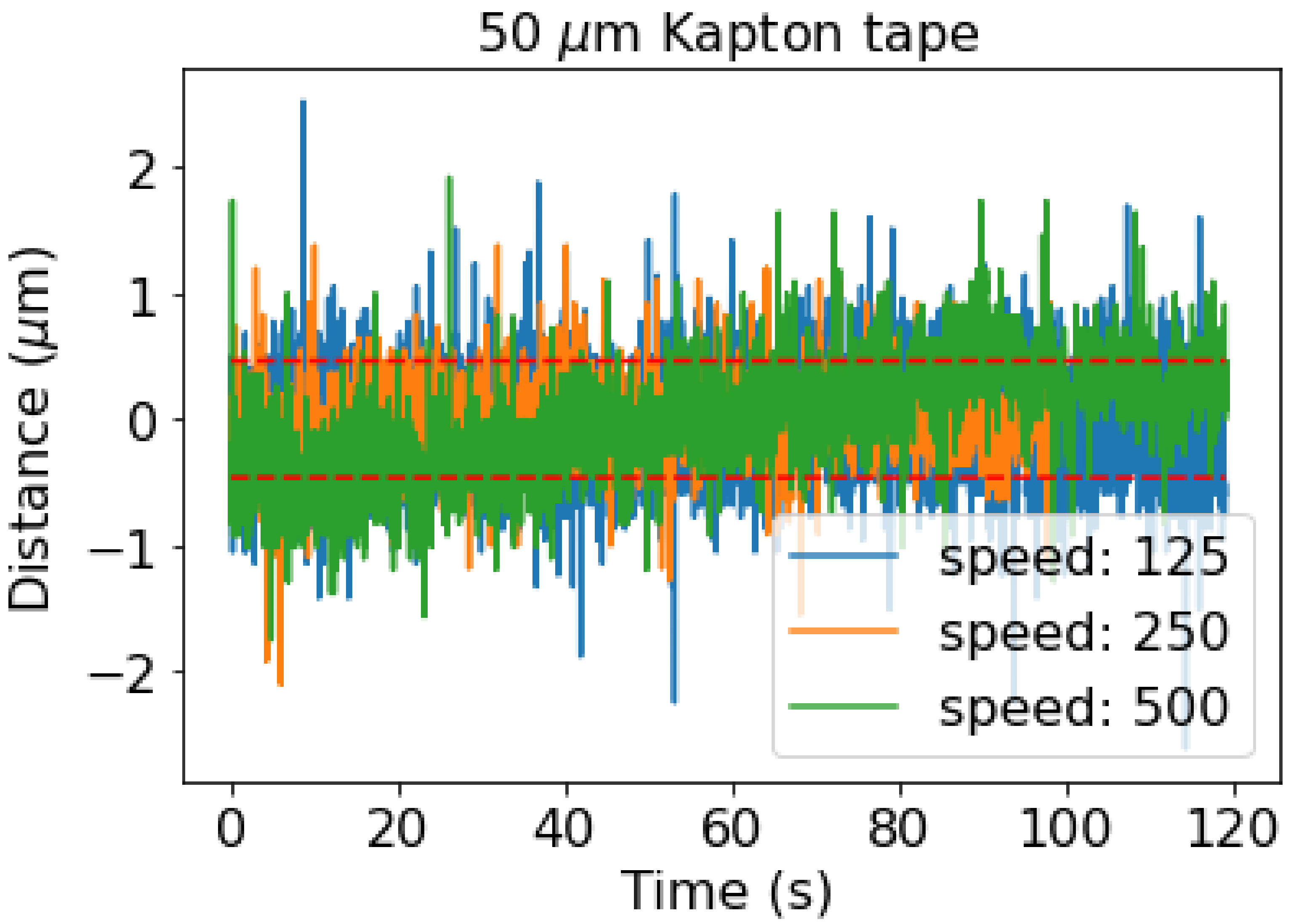
- Faster & Better Optimisations (BO: 20 minutes compared to 35 mins for 4 successive 1D scans)
- Optimisation algorithm makes morning start-up efficient and easy

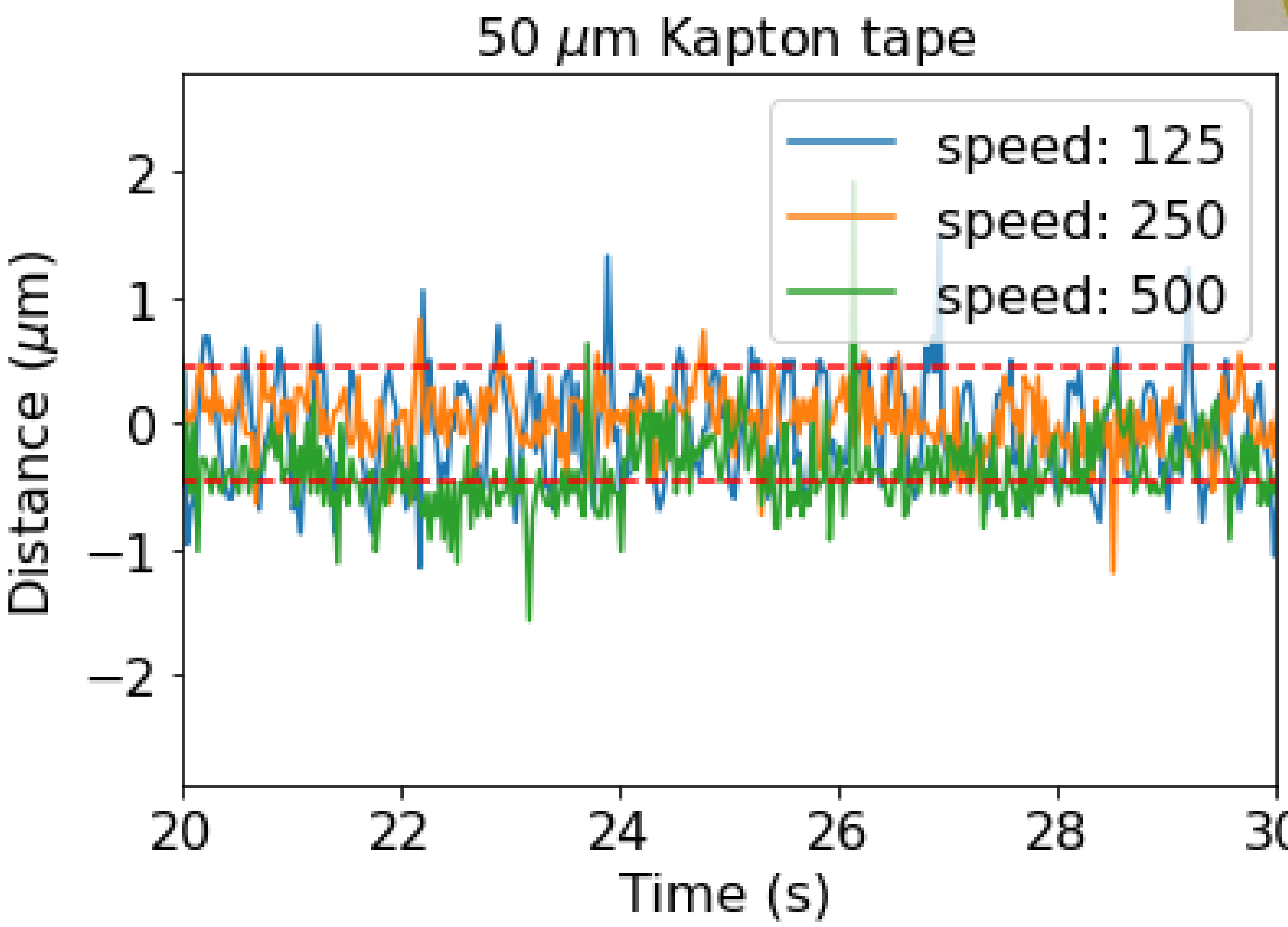
Streeter, M. J. V., et al. *APL*, *112*(24), 244101 (2018).
Dann, S. J. D. et al *PRAB*, *22*(4), 041303 (2019).

Shalloo, R. J., et al. "Automation and Control of Laser Wakefield Accelerators Using Bayesian Optimization." Nature Communications 11, no. 1 (2020): 6355.

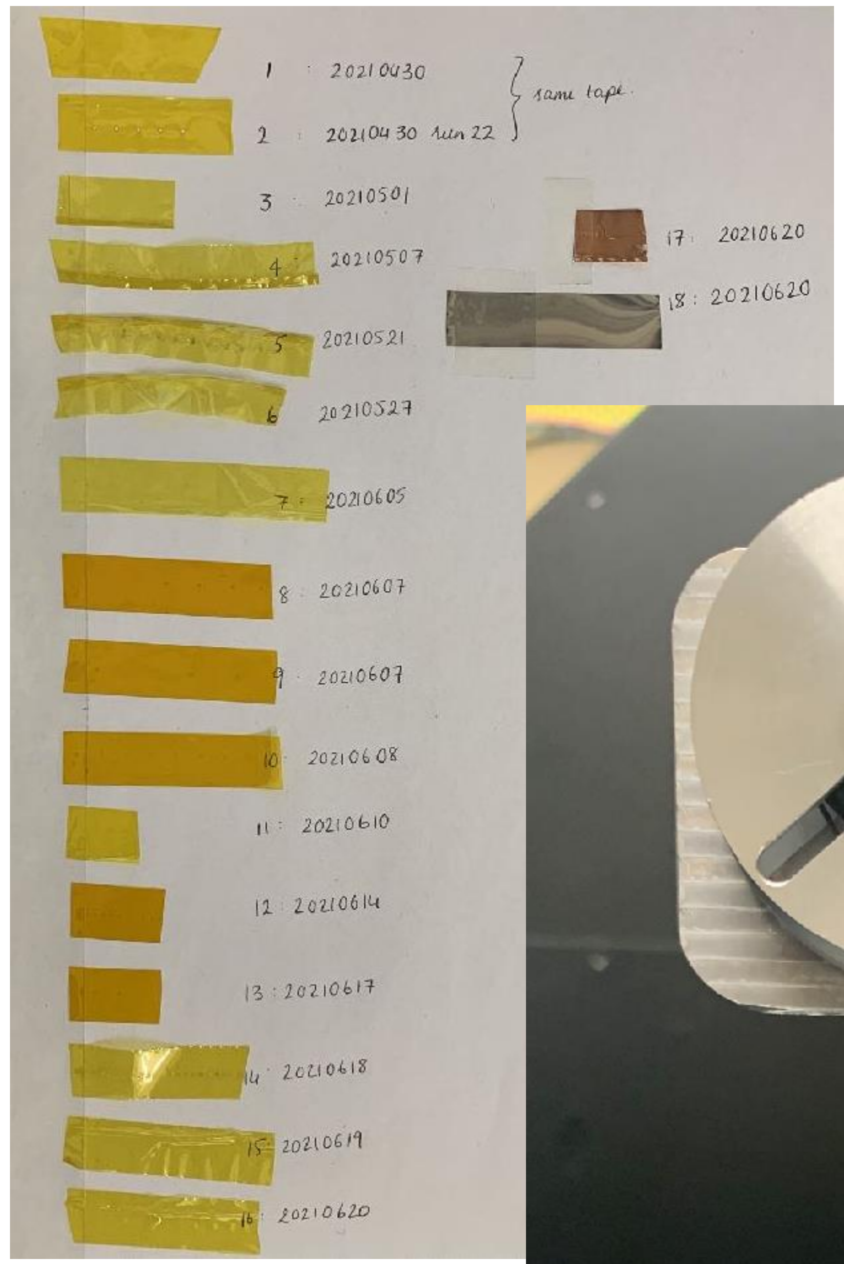
Automation applied to ion acceleration

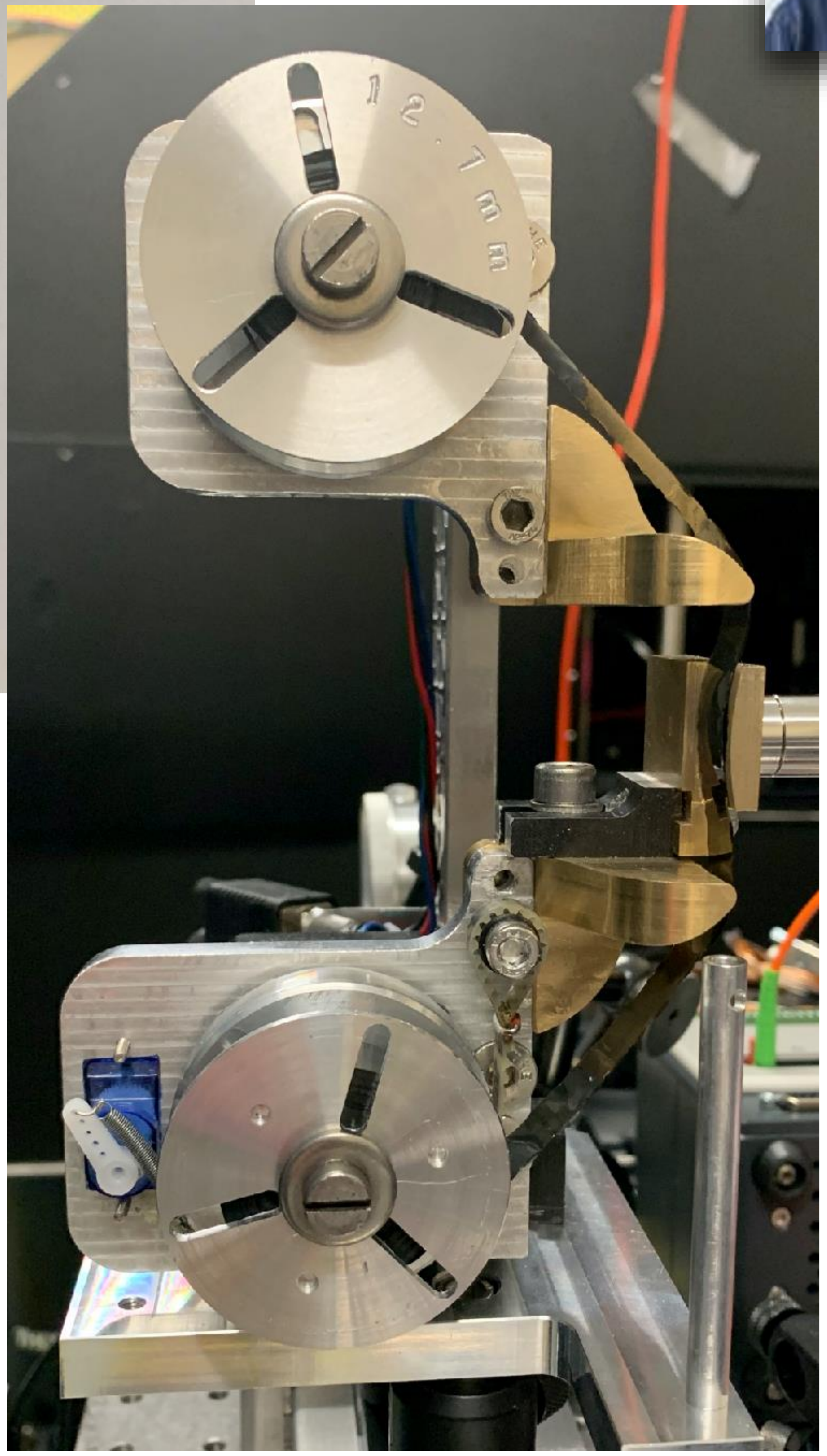
- Developed by Nuo Xu at Imperial College London
- Compact with excellent rear surface access and stability of a few microns.
- Supports variety of materials (we used kapton, copper and steel) with thicknesses 12.7 - 50 microns.





Tape samples:

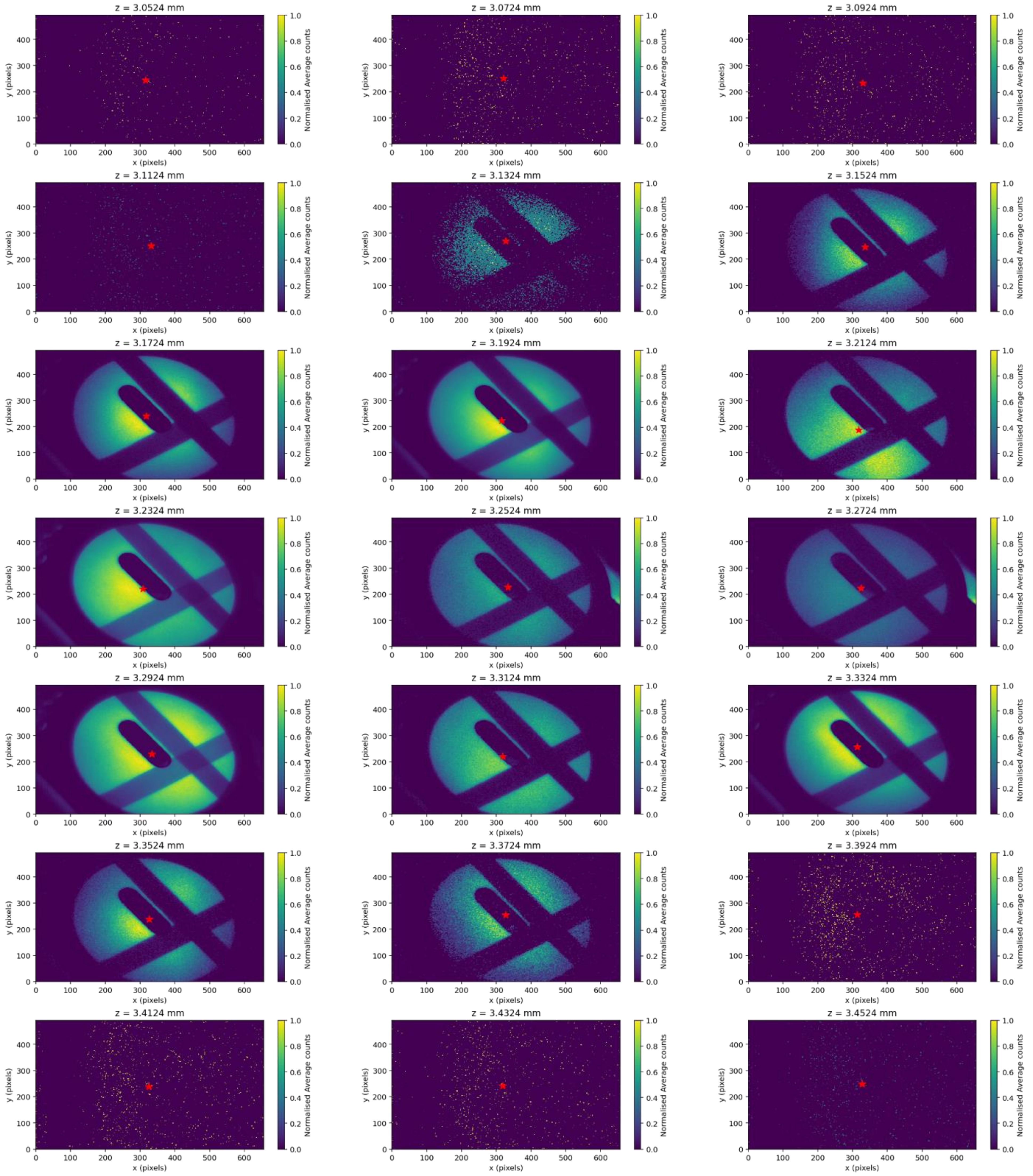




Dependence on target z: tape drive burst averaged 2D images

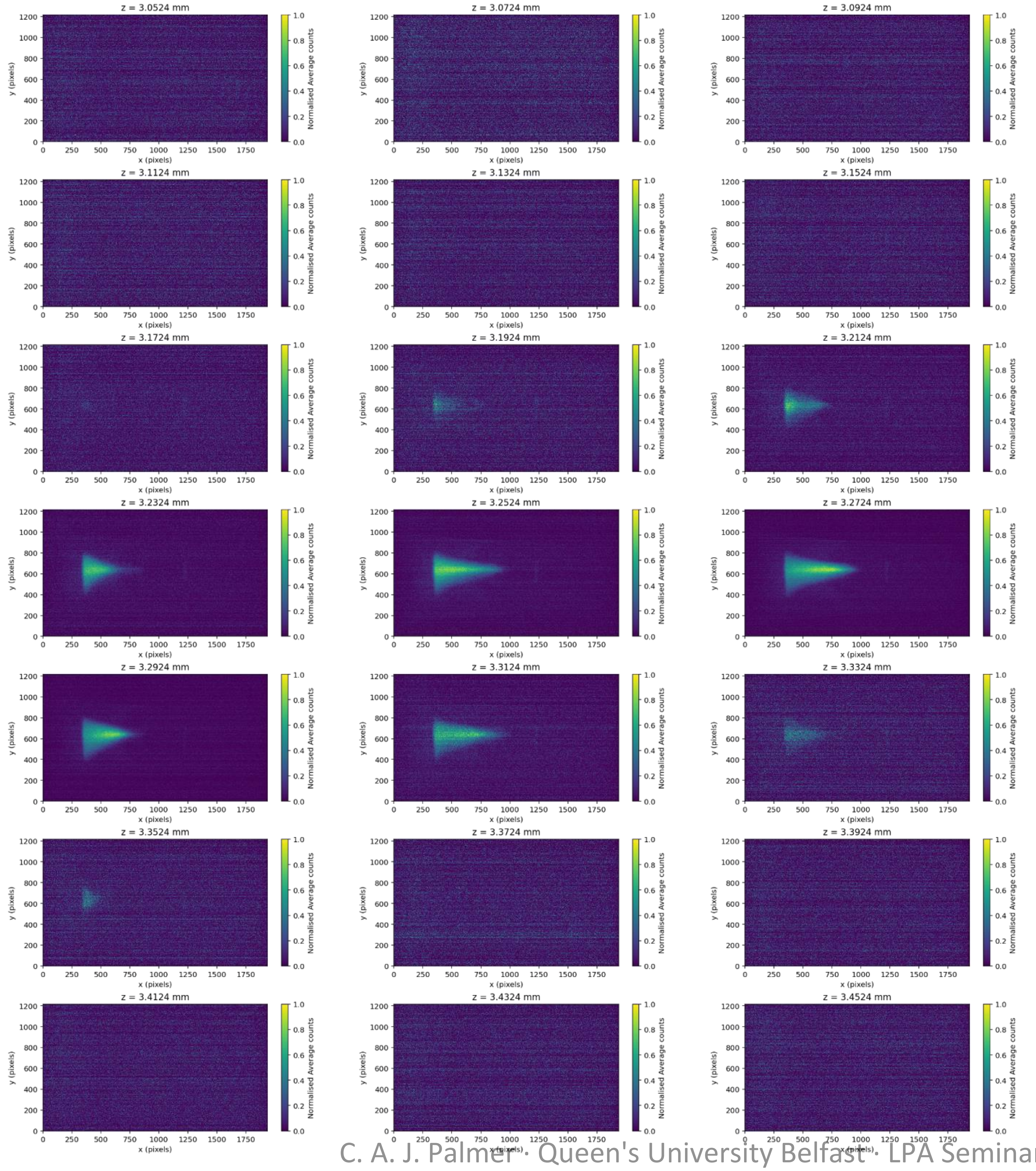
Typical Proton Spatial z-scan from tape drive:

Reduction in signal at best focus



Typical ESpec z-scan from tape drive:

Peak in signal at best focus

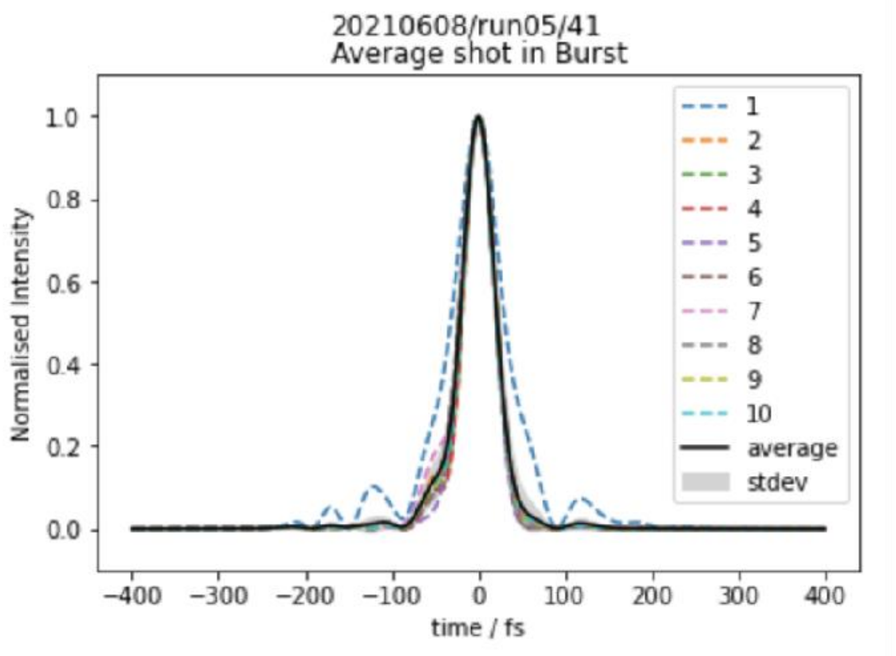


Effect of the pulse shape

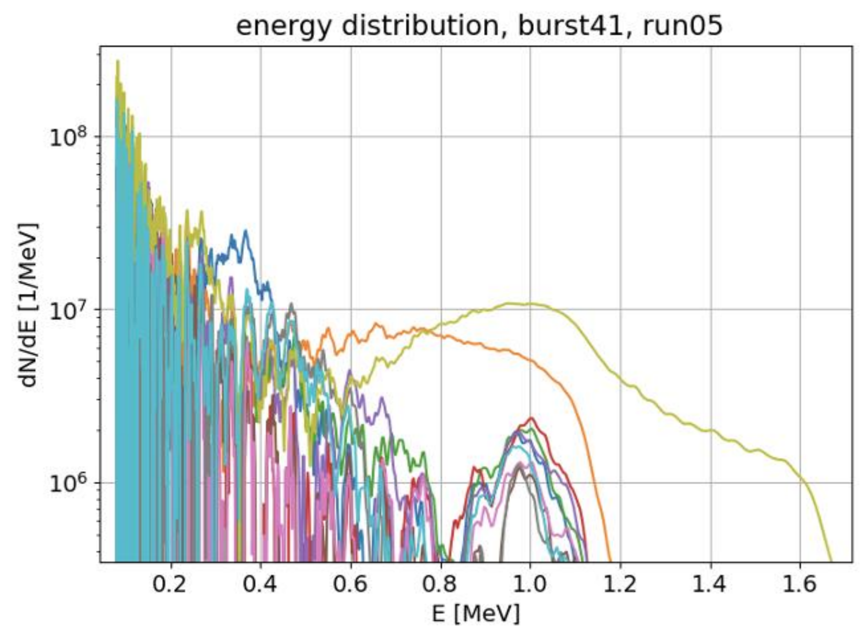
QUEEN'S UNIVERSITY BELFAST

courtesy of C. Palmer

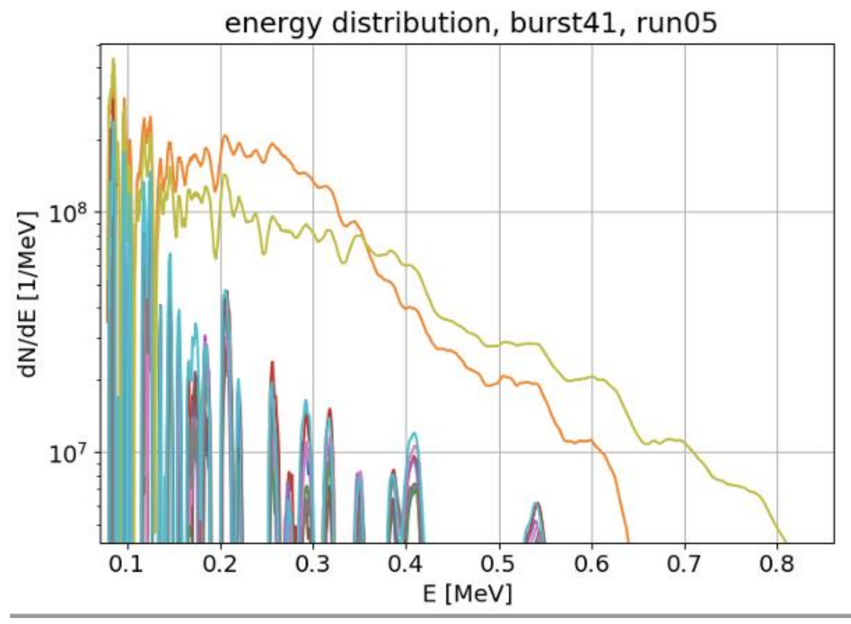
Pulse



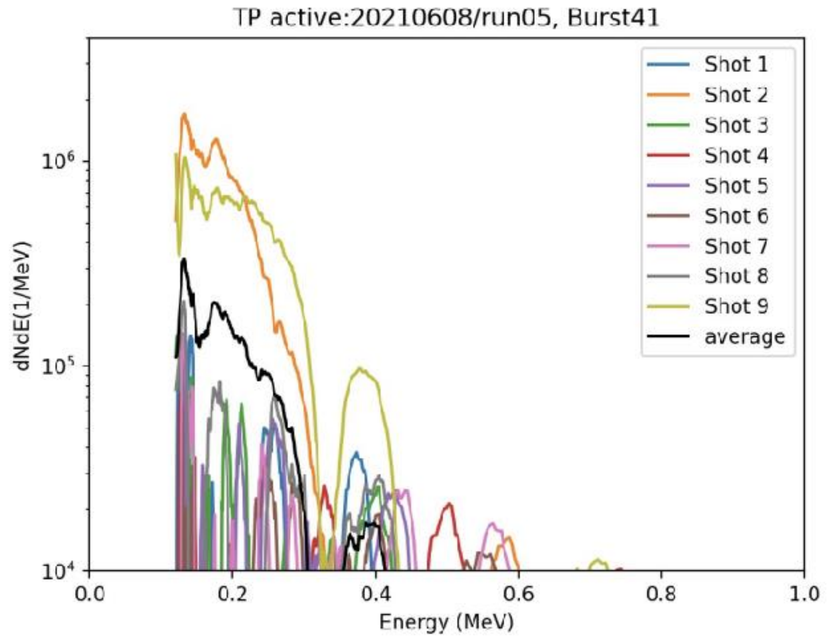
Front TOF



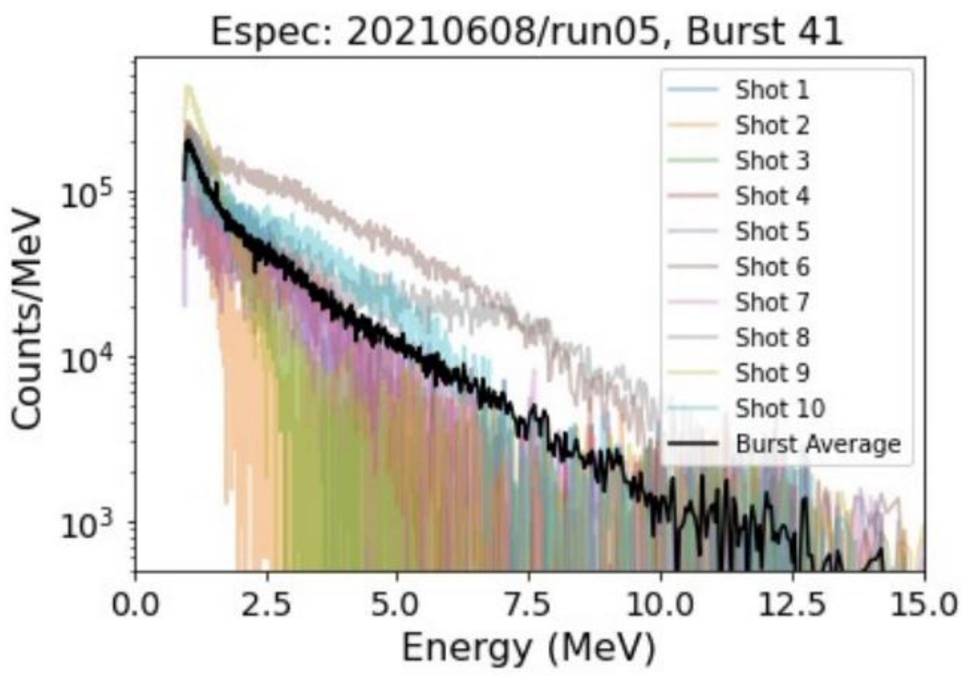
Rear TOF



TP

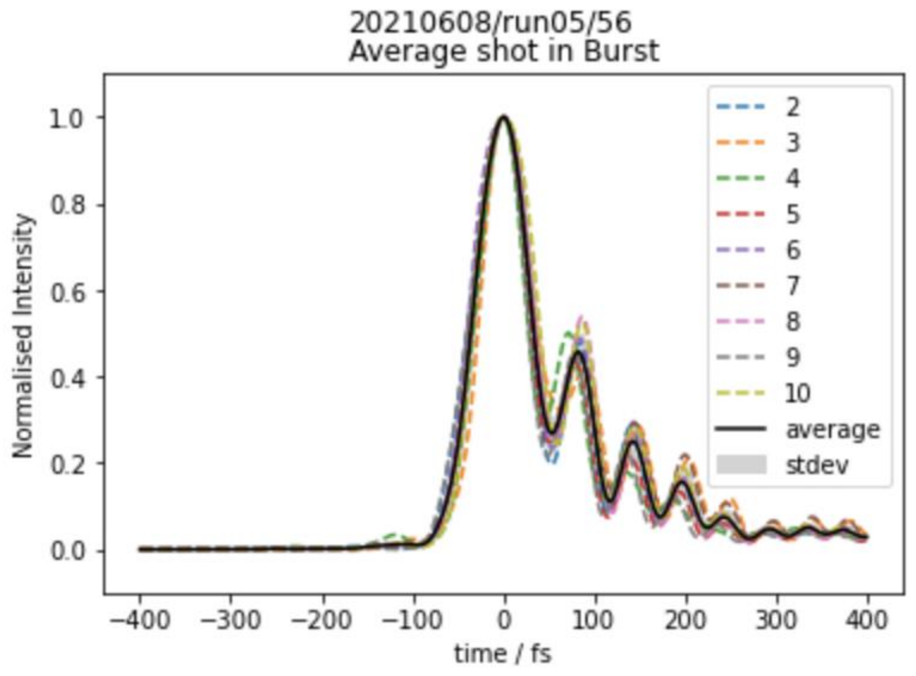


ESpec

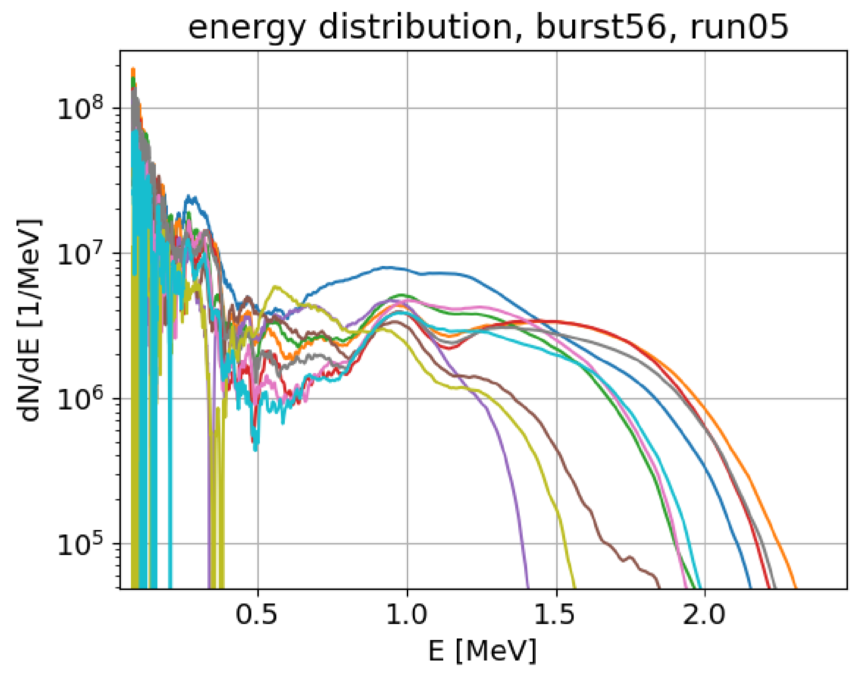


E_{Max}: 6.4 ± 3.2
T_e: 1.1 ± 0.58

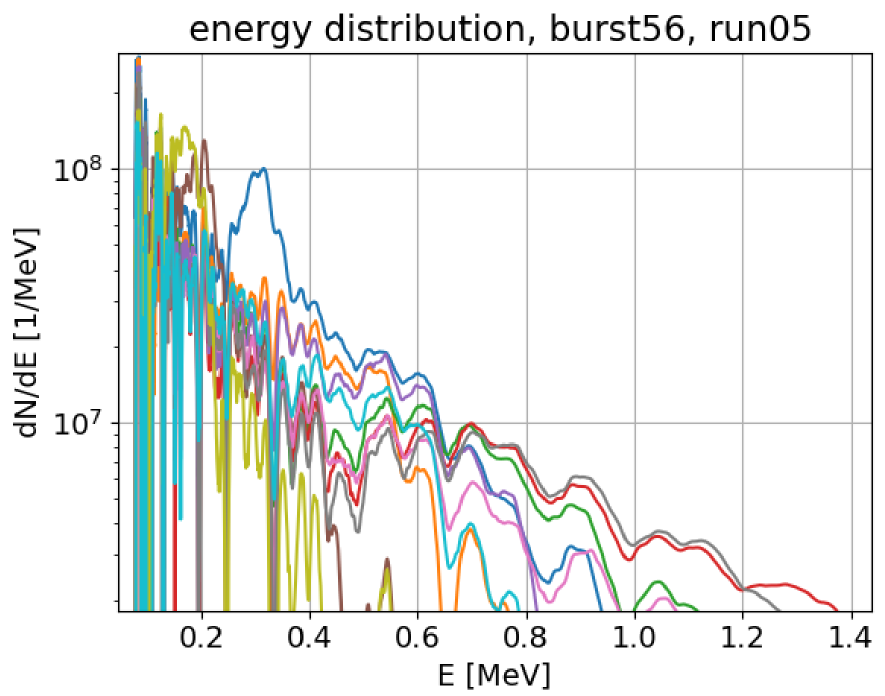
Pulse



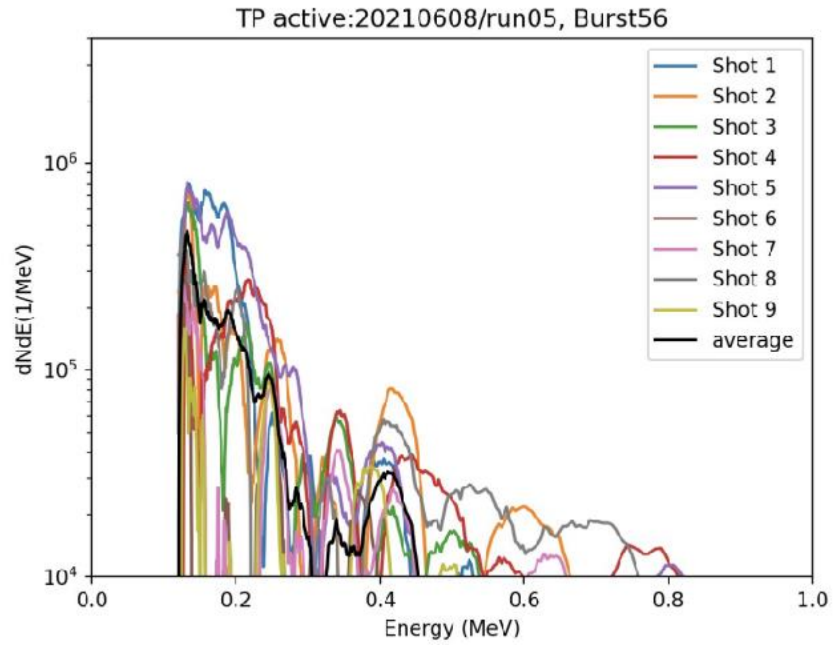
Front TOF



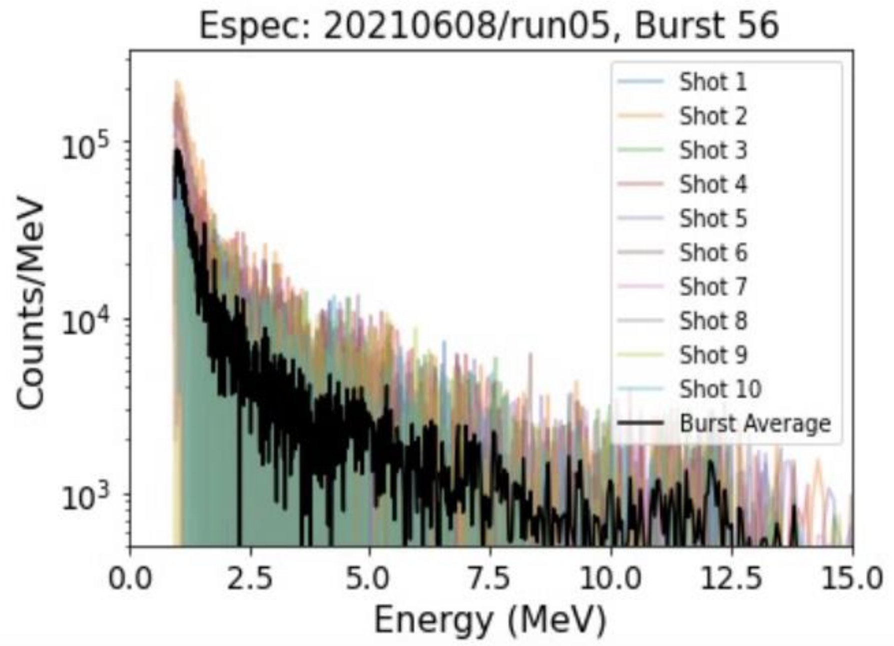
Rear TOF



TP



ESpec



E_{Max}: 0.28 ± 0.83
T_e: 0.038 ± 0.11

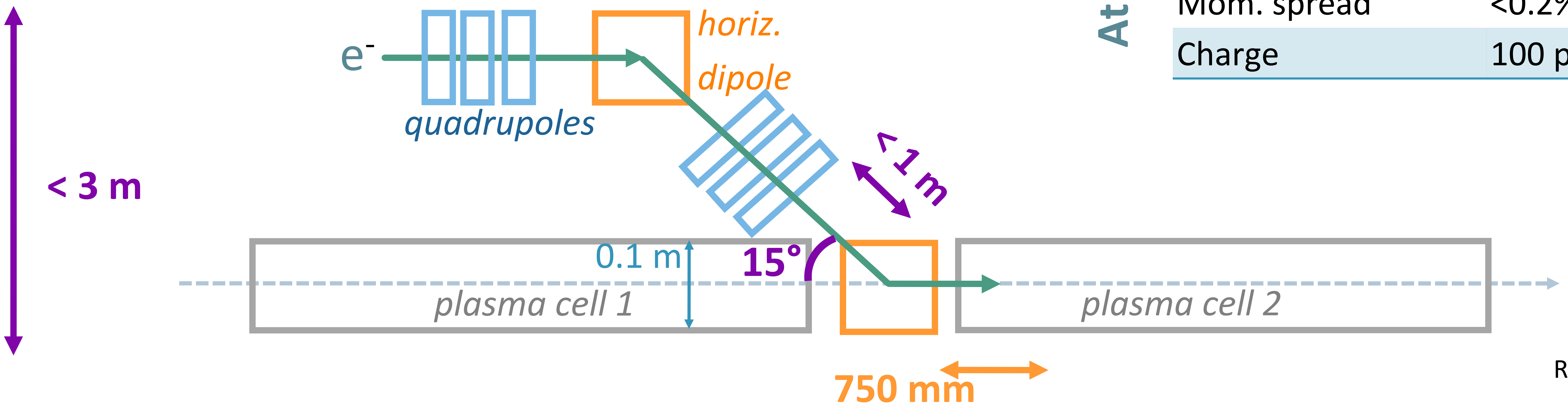
AWAKE

AWAKE-UK

- New AWAKE-UK grant approved by STFC
- £1.9m awarded (£0.6m JAI) with a gateway after two year to extend funding for another 3 years - supposed to lead until run-2 after next shutdown
  - Gateway step due later this year!
- 7 funded UK institutes including JAI-OX and JAI-IC (also UCL, Lancaster, Liverpool, Manchester, Strath)
- Aligned to AWAKE run-2:
  - Accelerate higher beam capture
  - Acceleratre over multiple cells
- Goal is to have an electron beam usable for HEP after run 2.

e^- injection to the 2nd plasma cell

- Requirement of $\sigma^* = \sqrt{4.8\ \text{mm} \times \epsilon}$ at injection to be "matched to the plasma" ⟶ for $\epsilon_{x,y} = 2\ \mu\text{m}$: $\boldsymbol{\sigma}^* = \mathbf{5.75\ \mu m}$.
- Gaussian bunch at injection.
- Transfer line should be achromatic, with no bunch lengthening.
- Spatial constraints shown below.

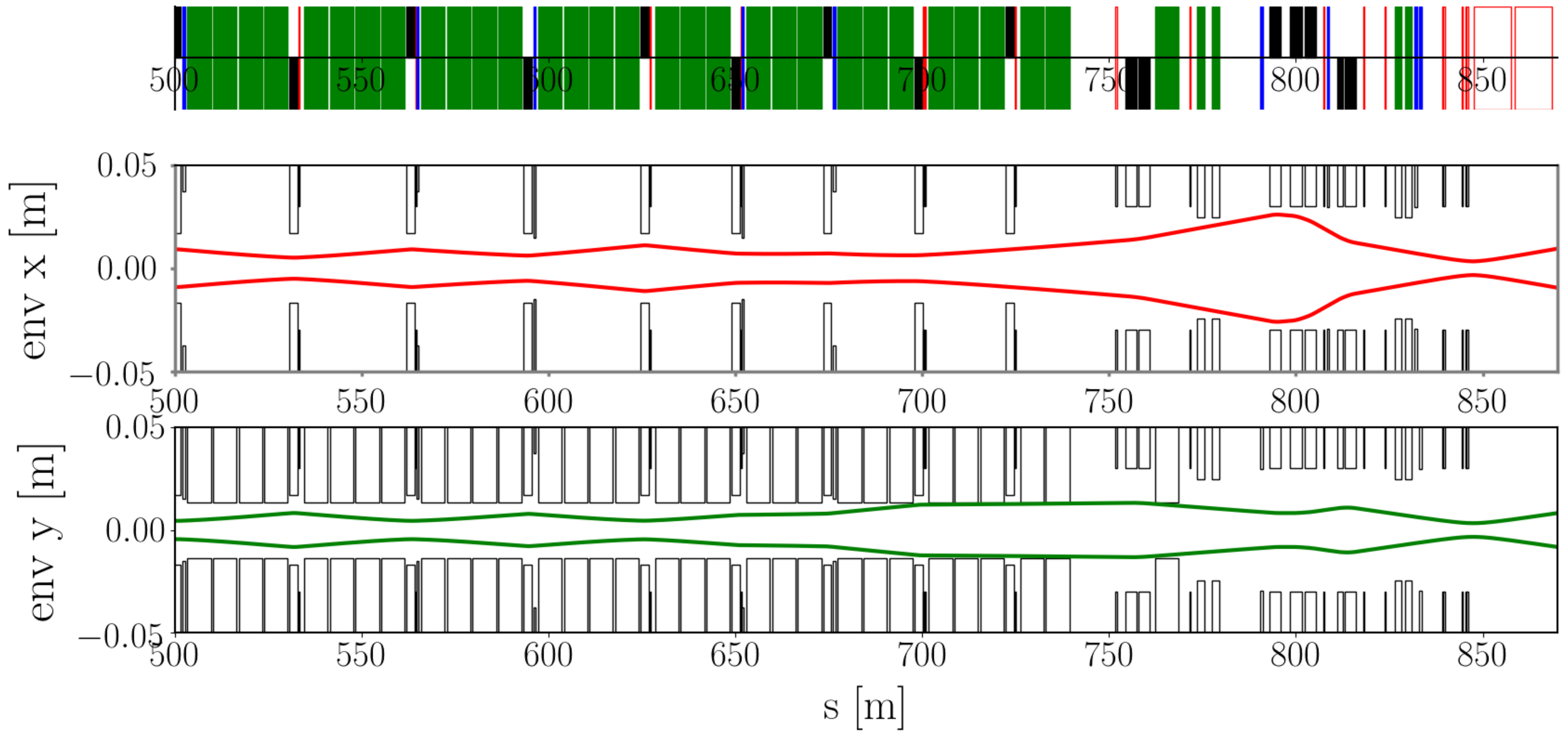


At injection point

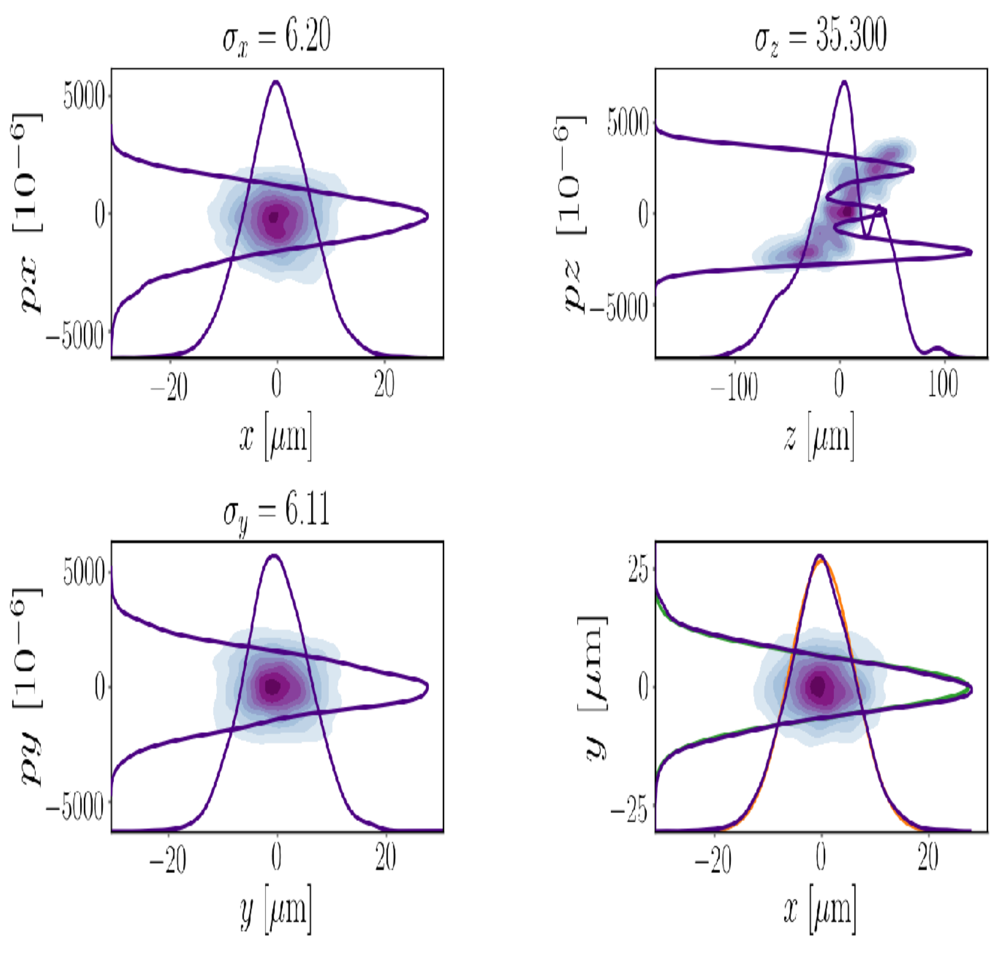
Parameter	Nominal value
Dispersion	0
	5.75 m
Bunch length	200 fs/60 m
Electron energy	150 MeV
	<2 mm mrad
Mom. spread	<0.2%
Charge	100 pC

R. Ramjiawan, F.M. Velotti

Summary of Aligment and Beam Size requirements



- For 2 µm emittance → $\sigma_{\text{matched}} = 5.75\ \mu\text{m}$
- To keep acceleration quality Q_t within 20% of maximum, we should try to keep beam size within **50% of matched value** $< 8.6\ \mu\text{m}$.



Beam distributions (no errors)

Alignment

- The shot-to-shot jitter of the proton beam challenges driver-witness alignment. Impossible to reduce without replacing the PCs.
- More studies will be done to characterise jitter.
- Studies to be done adjusting the optics to reduce β^*.

Beam size

- 85% of shots satisfying beam size requirements.
- Utilise BTV measurements (beam size resolution of 1 µm) at the injection-point help to quantify the alignment.
- Magnet specifications seem possible, but still to be confirmed.
- On-going discussions with (BI, PC, magnet) teams to determine the limits for hardware and the time and cost involved.

Visualising the density profile in plasma columns

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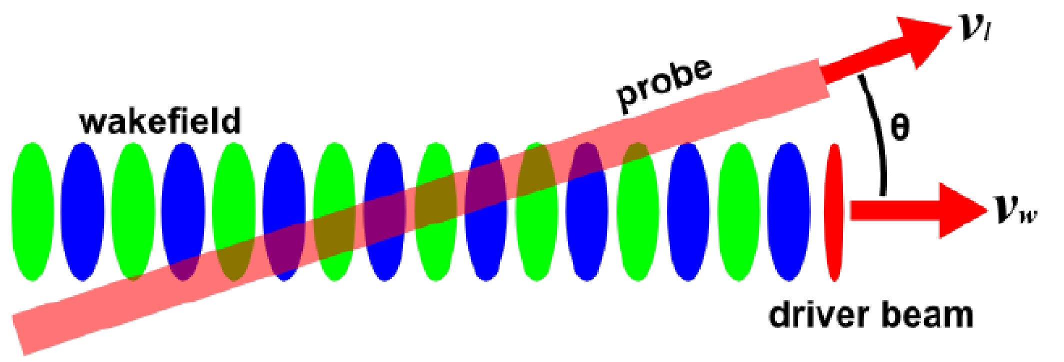
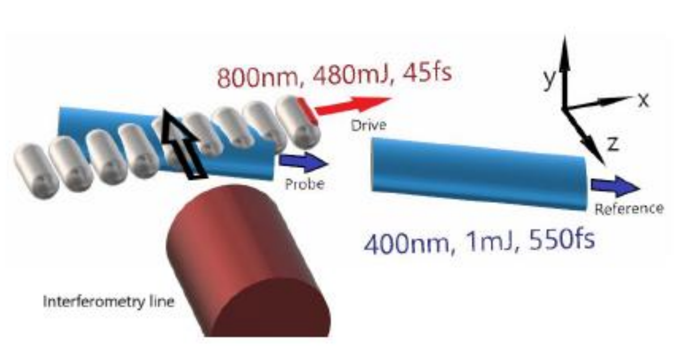
Oblique-angle Single-shot Frequency Domain Holography Diagnostic

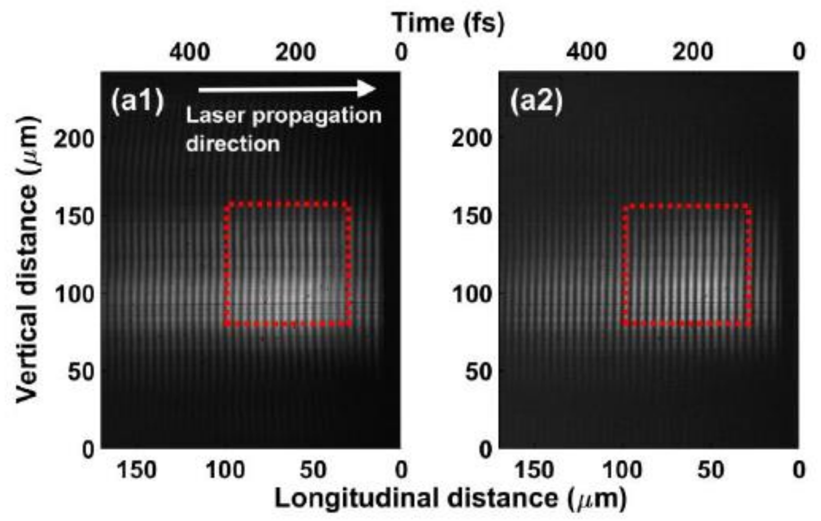


$$\frac{\Delta\omega}{\omega_0} \approx -\frac{\omega_p^2}{2\omega_0^2}\frac{1}{n_0}\int \frac{\partial n}{\partial \zeta}\,ds \Rightarrow \frac{\Delta\omega}{\omega_0} \approx -\frac{\omega_p^2}{2\omega_0^2}\frac{v_w}{v_l \sin\theta}\frac{1}{n_0}\int_y^\infty 2\frac{\partial n}{\partial \zeta}\frac{r\,dr}{\sqrt{r^2-y^2}}$$

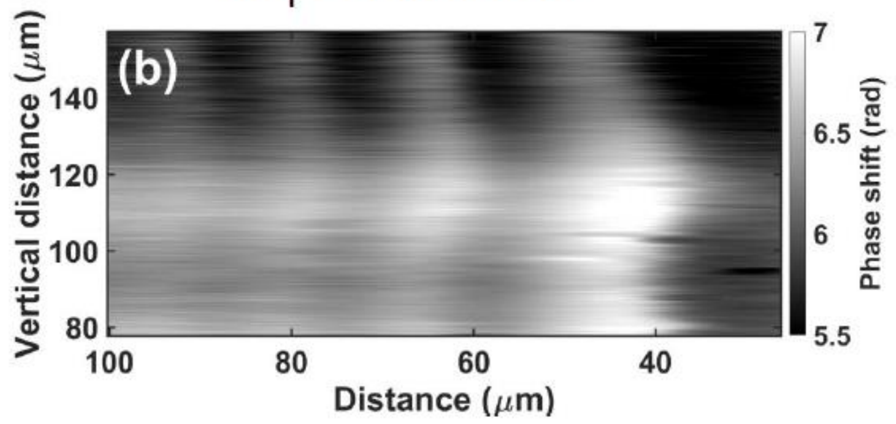
Astra experiment



Interferogram from spectrometer

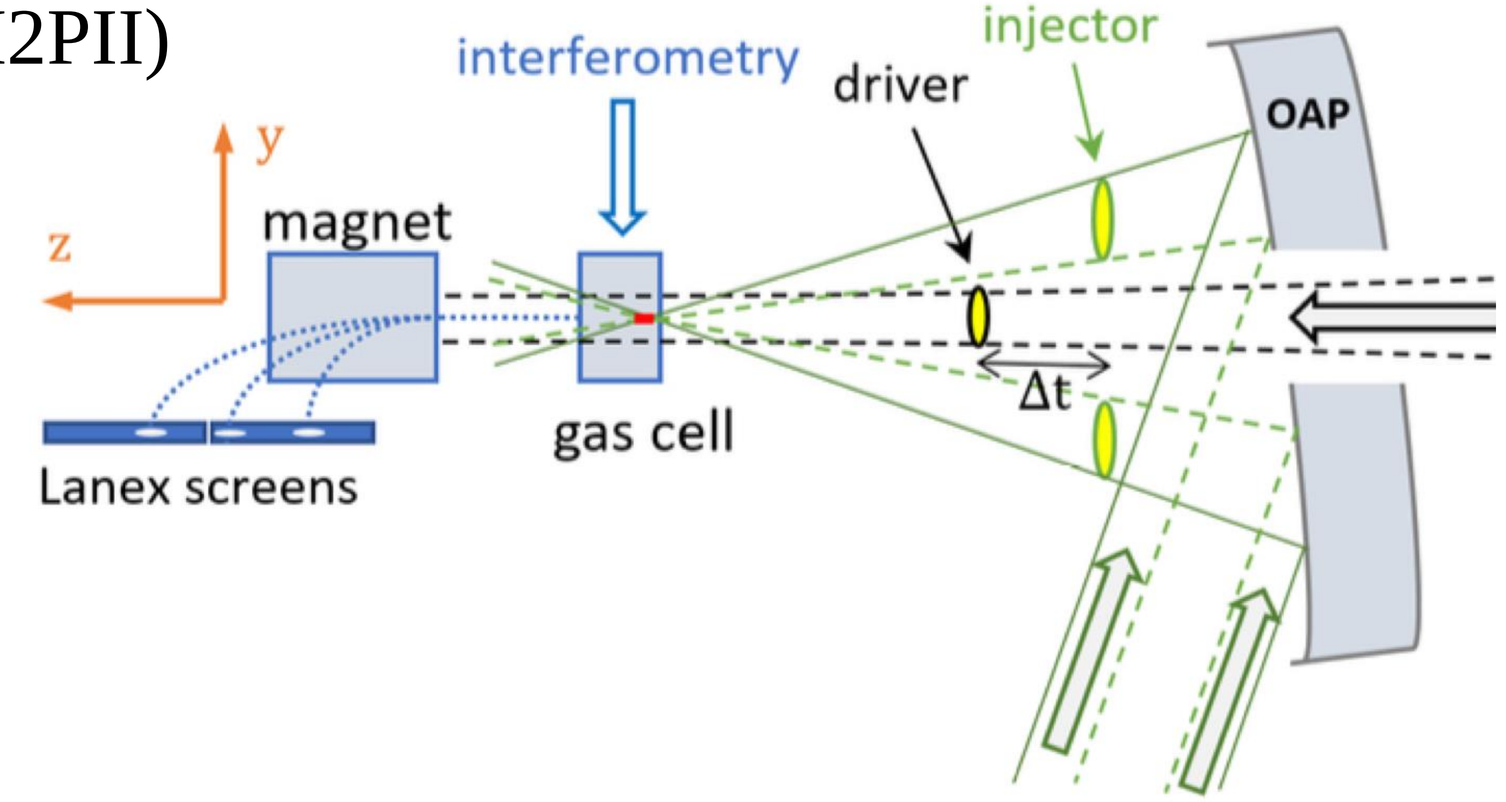


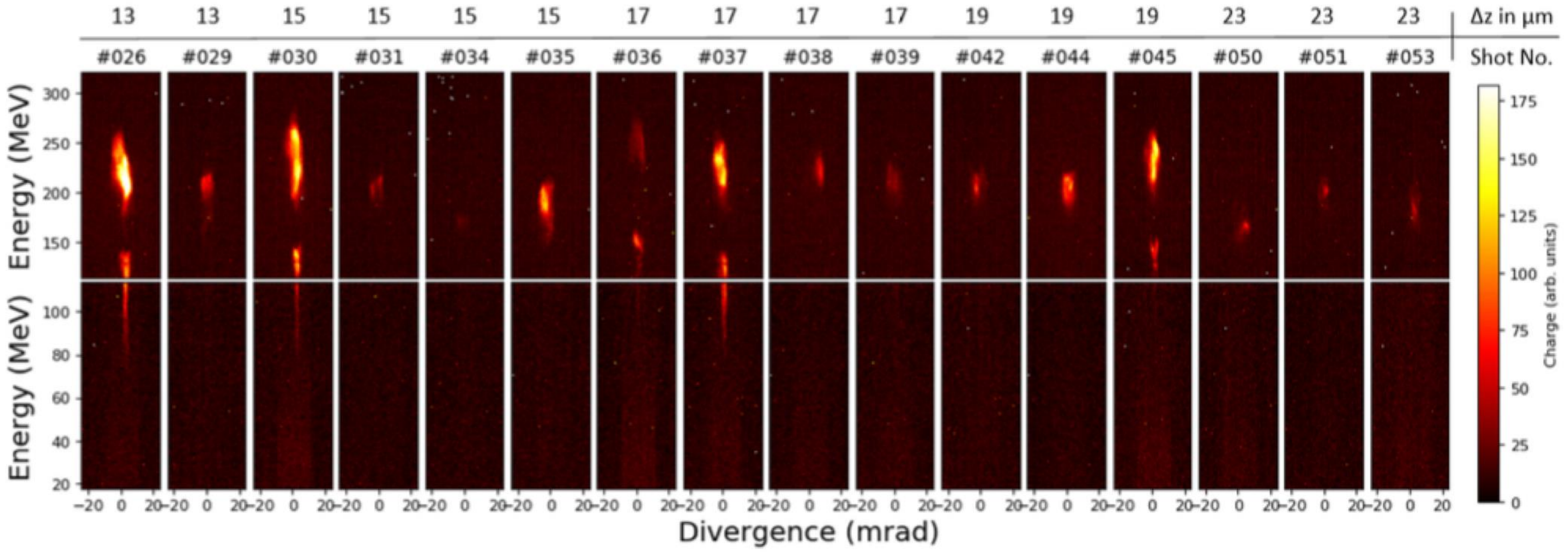
Shape of wakefield



- Frequency mapped to time
- Phase shift obtained after subtracting null-shot data
- Phase unwrapping necessary
- Interest was in shape rather than amplitude estimation

Alternative Electron Injection Scheme using Modified Two-Pulse Ionisation Injection (M2PII)

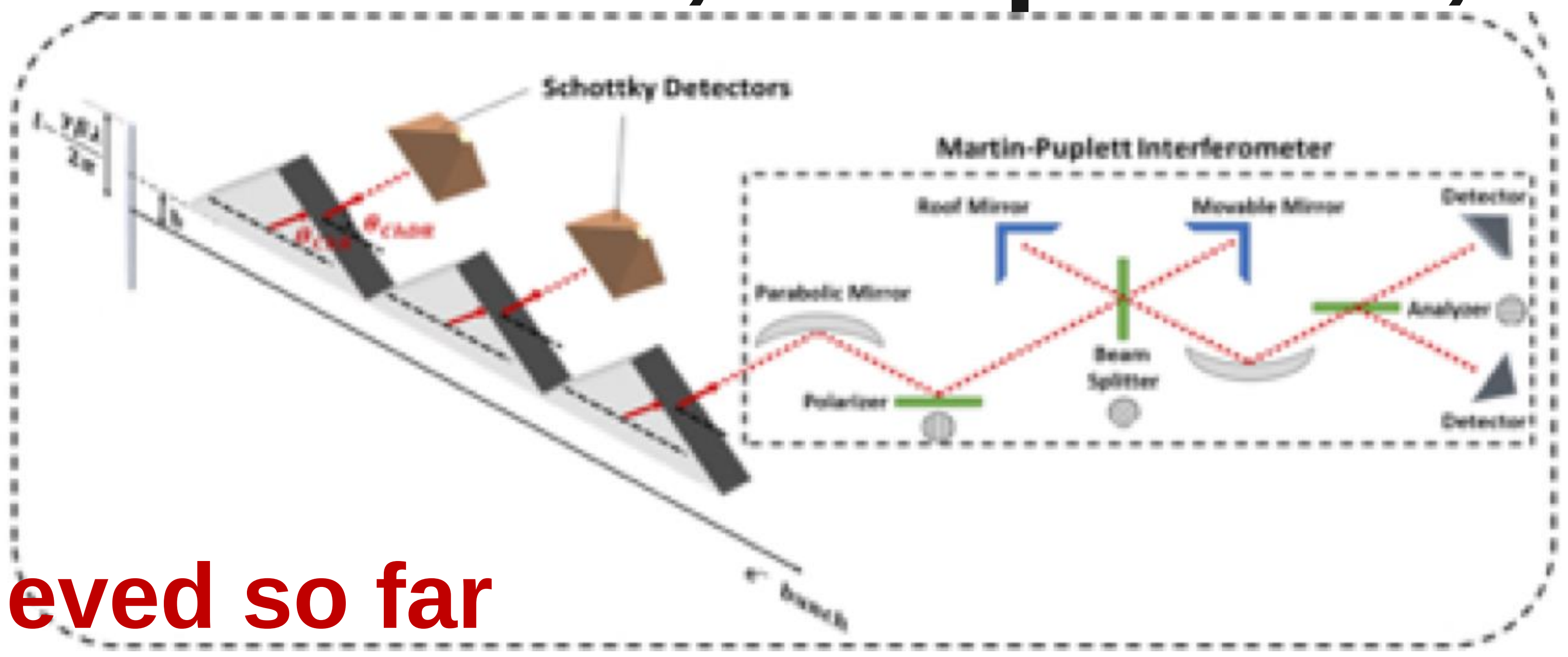




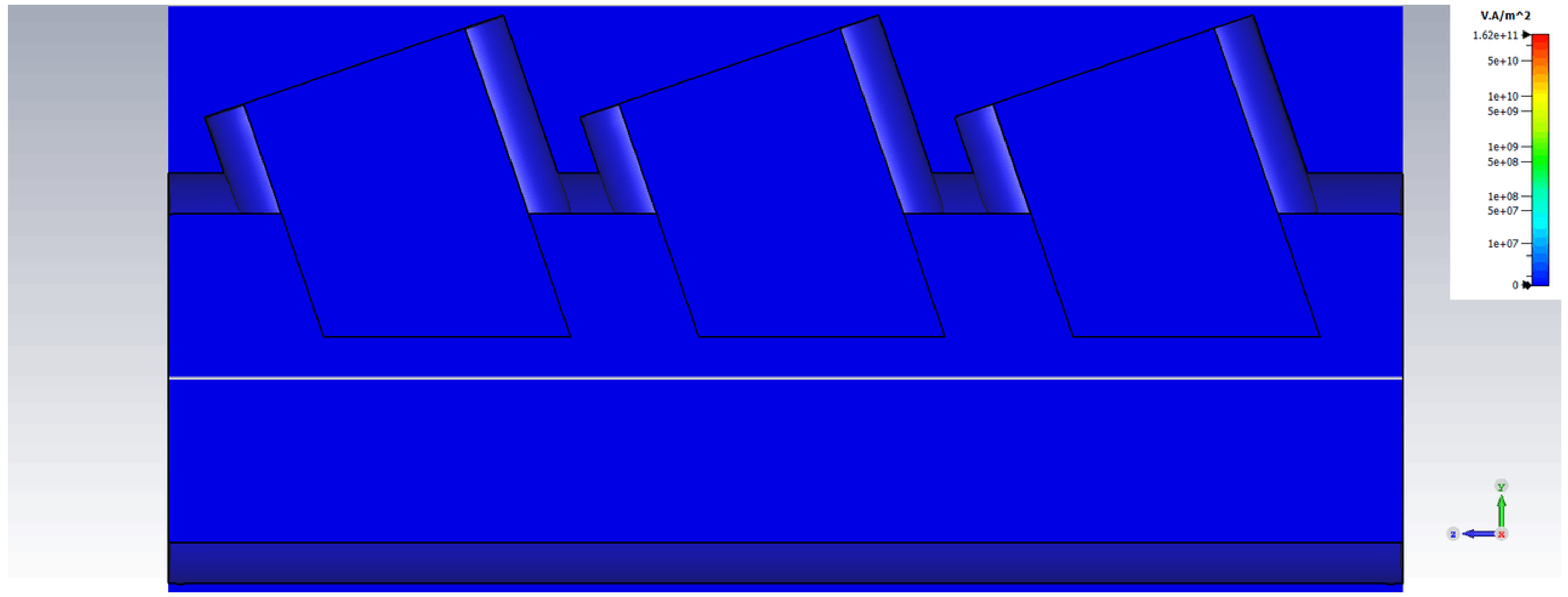
Successful implementation on CUOS laser system M. von der Leyen et al.

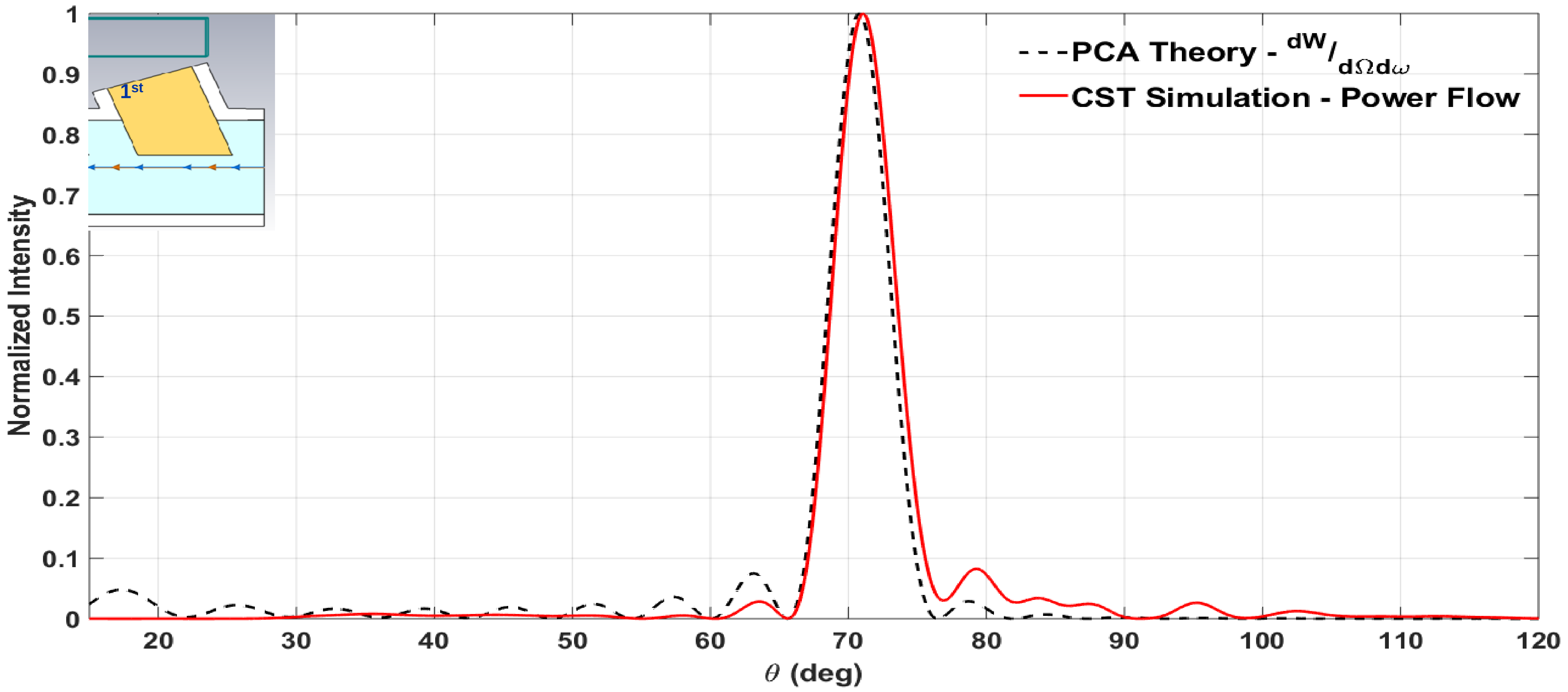
Coherent ChDR electron Bunch Length Monitor

C. Davut, O. Apsimon, P. Karataev, T. Lefevre, S. Mazzoni, G. Xia



To be implemented after first plasma cell





Achieved so far

- Bunch length prototype designed and being manufactured
- Analyzed using polarization current approach and CST Studio Suite;
- A shot-by-shot quick bunch length monitoring and a precise Martin-Pupplet Fourier spectrometer is foreseen.

Current Status

- All components ordered
- Vacuum vessel manufacturing completed
- Commissioning is scheduled for May-June 2022

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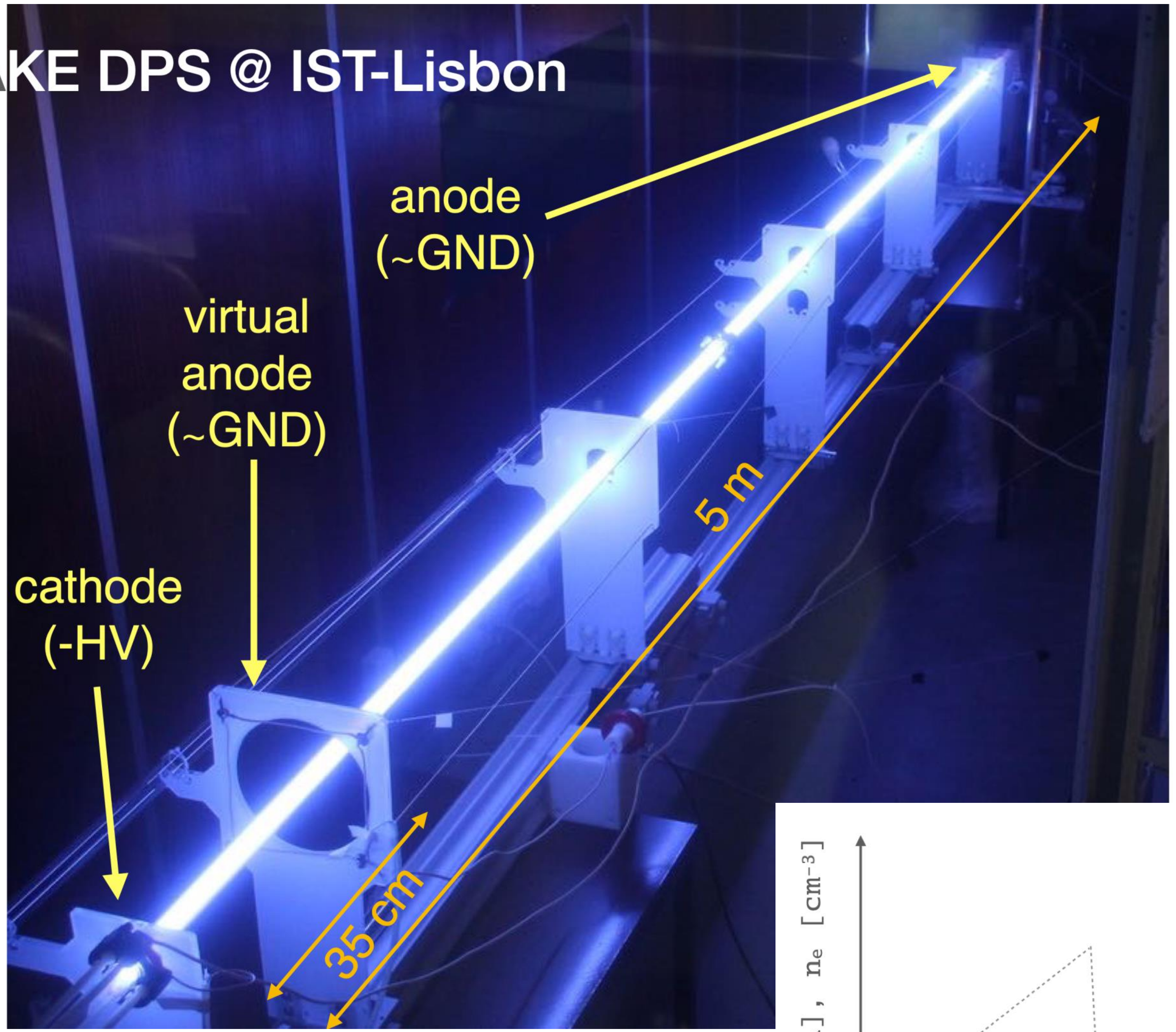
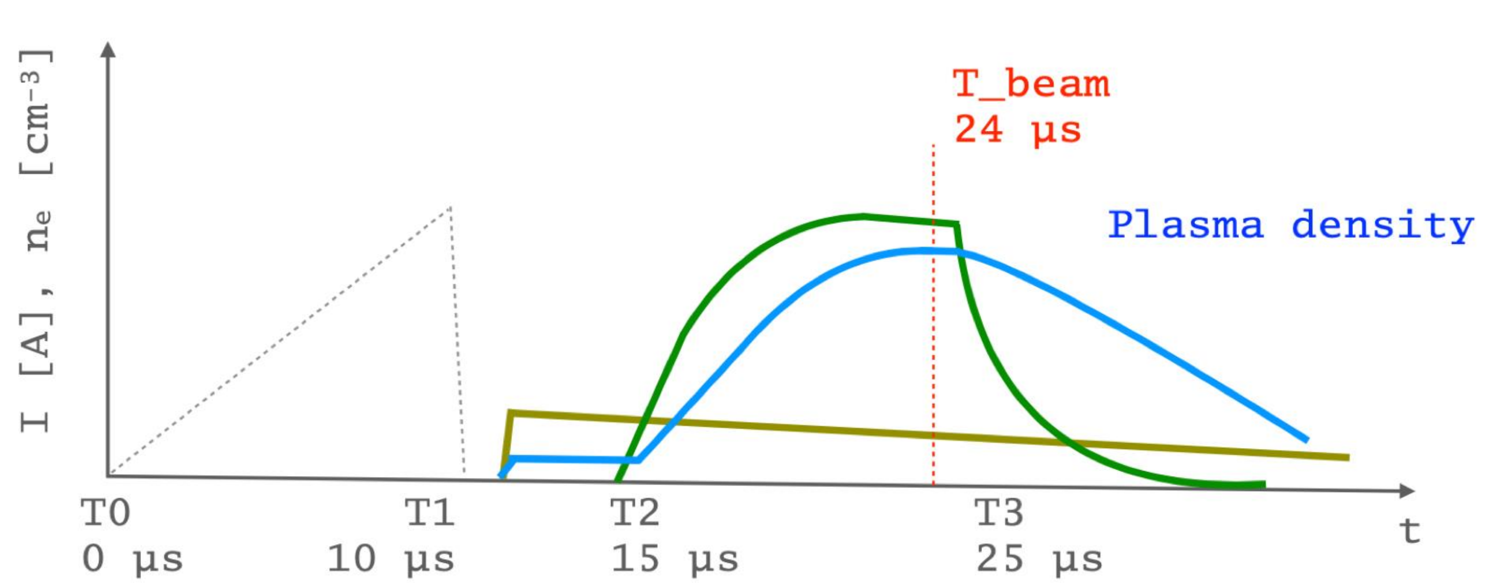
Plasma discharge being developed at CERN

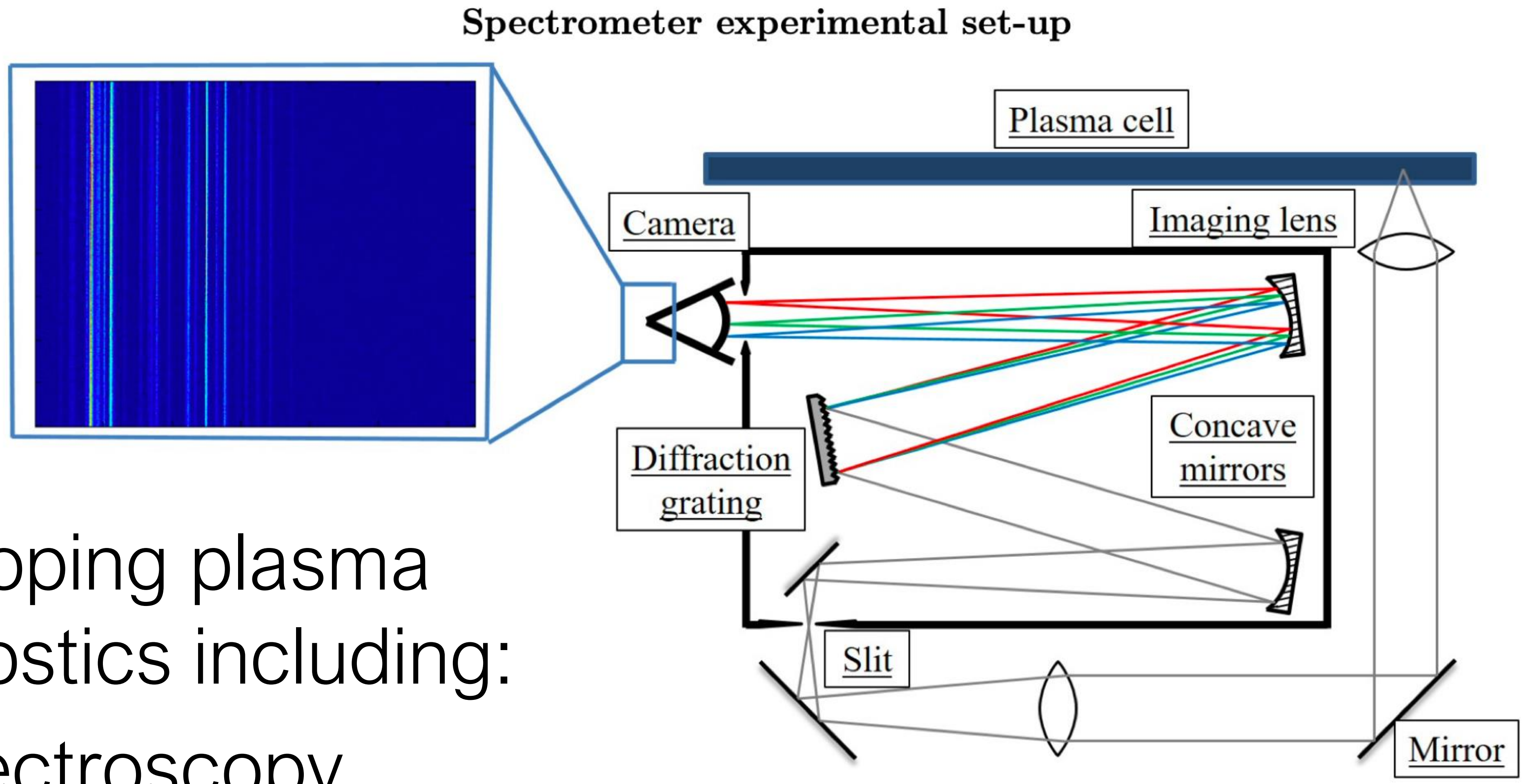
10 m Ar discharge plasma to developed by IST/CERN to be implemented later this year



L = 5m
D = 25 mm
P ~ 10 Pa (Argon…)
I ~ 500 A
τ ~ 10 μs

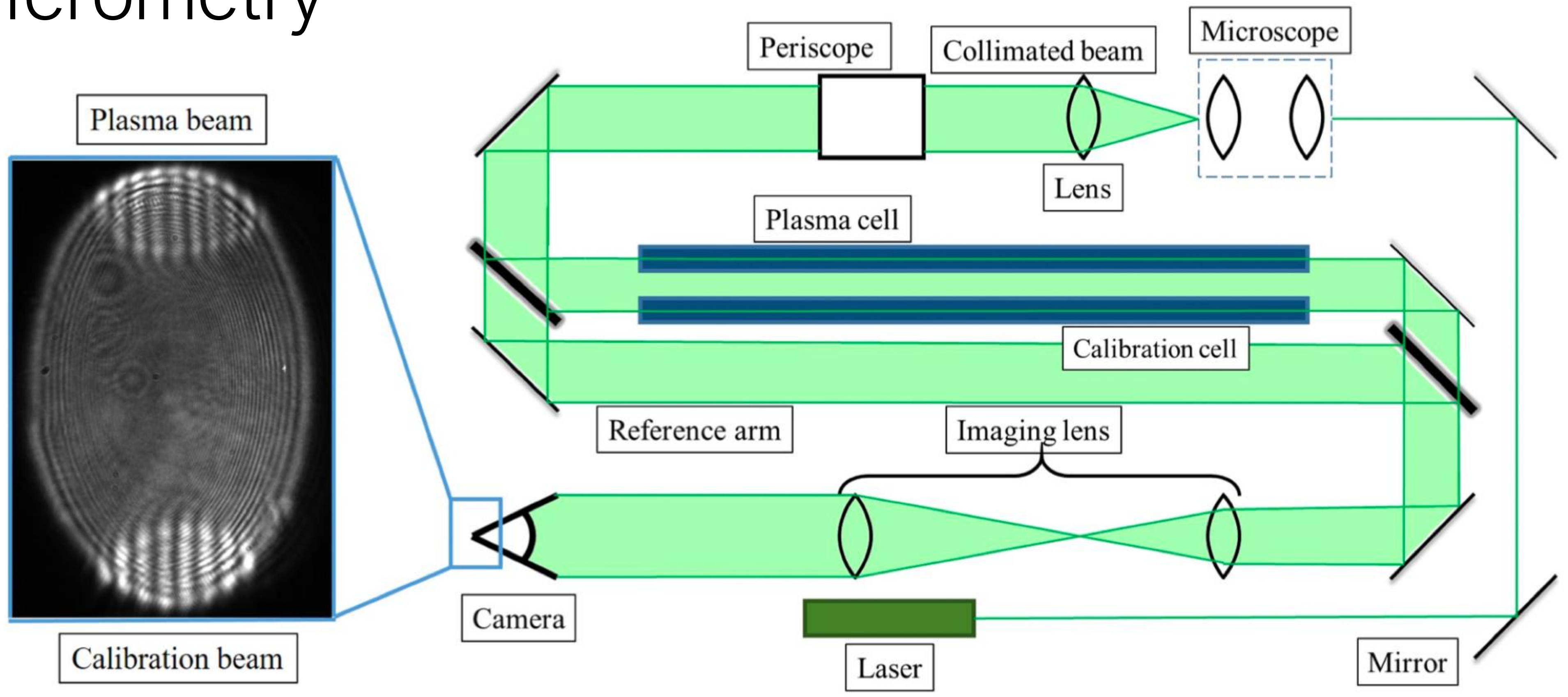
n_e ~ 1-10 e14 cm^{-3}
n_e/n_0 ~ 30% …



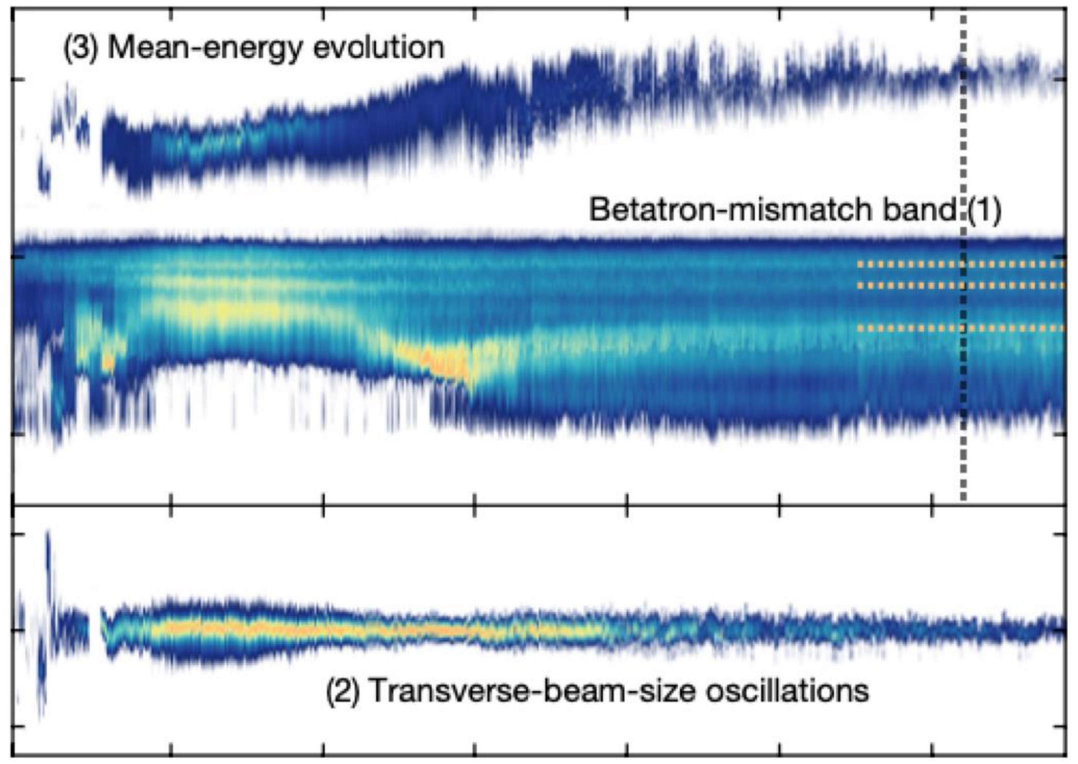


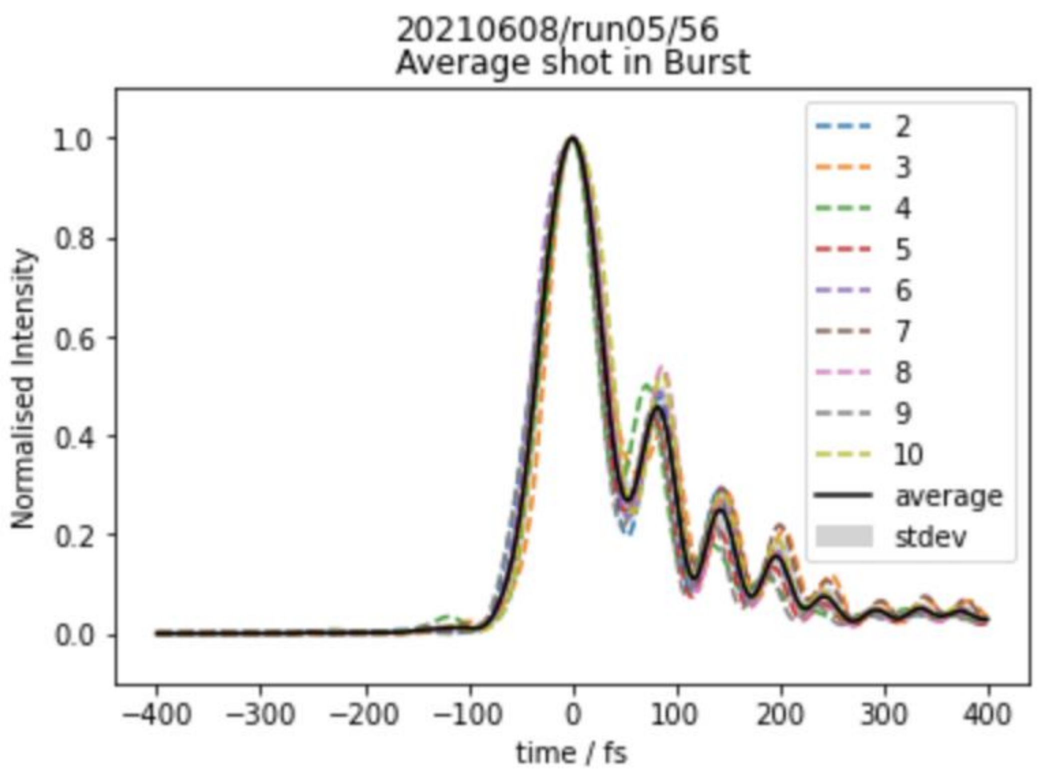
Developing plasma diagnostics including:

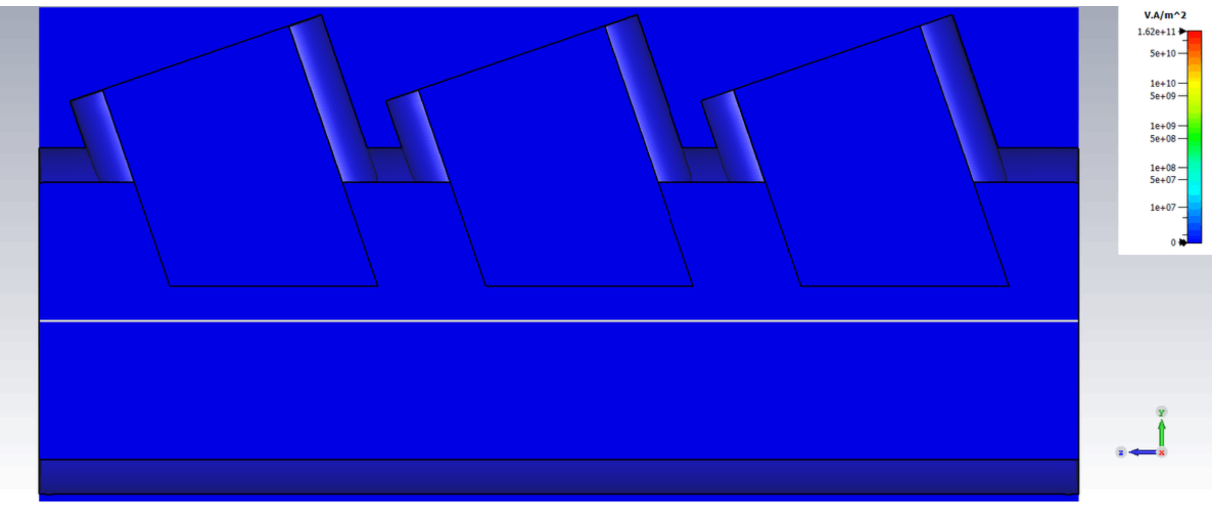
- Spectroscopy
- Interferometry



Summary







- Repeatability of plasma accelerators determined (10's MHz achievable)
- CHOFI waveguides demonstrated at kHz and up to 30 cm
- kHz MP-LWFA scheme developed
- Betatron Absorption Spectroscopy used for XANES in single shot
- Selective light sail acceleration of carbon ions observed
- Bayesian optimisation applied to laser ion acceleration
- AWAKE:
    - electron beamline designed and pointing and beam size variations assessed
    - New bunch length diagnostic based on coherent Cherenkov diffraction to be implemented
    - Discharge cell to be implemented at CERN