Advanced Acceleration

Zulfikar Najmudin

The John Adams Institute for Accelerator Science, Imperial College London

JAI Advisory Board
Monday 19 April 2021

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

John Adams Institute for Accelerator Science

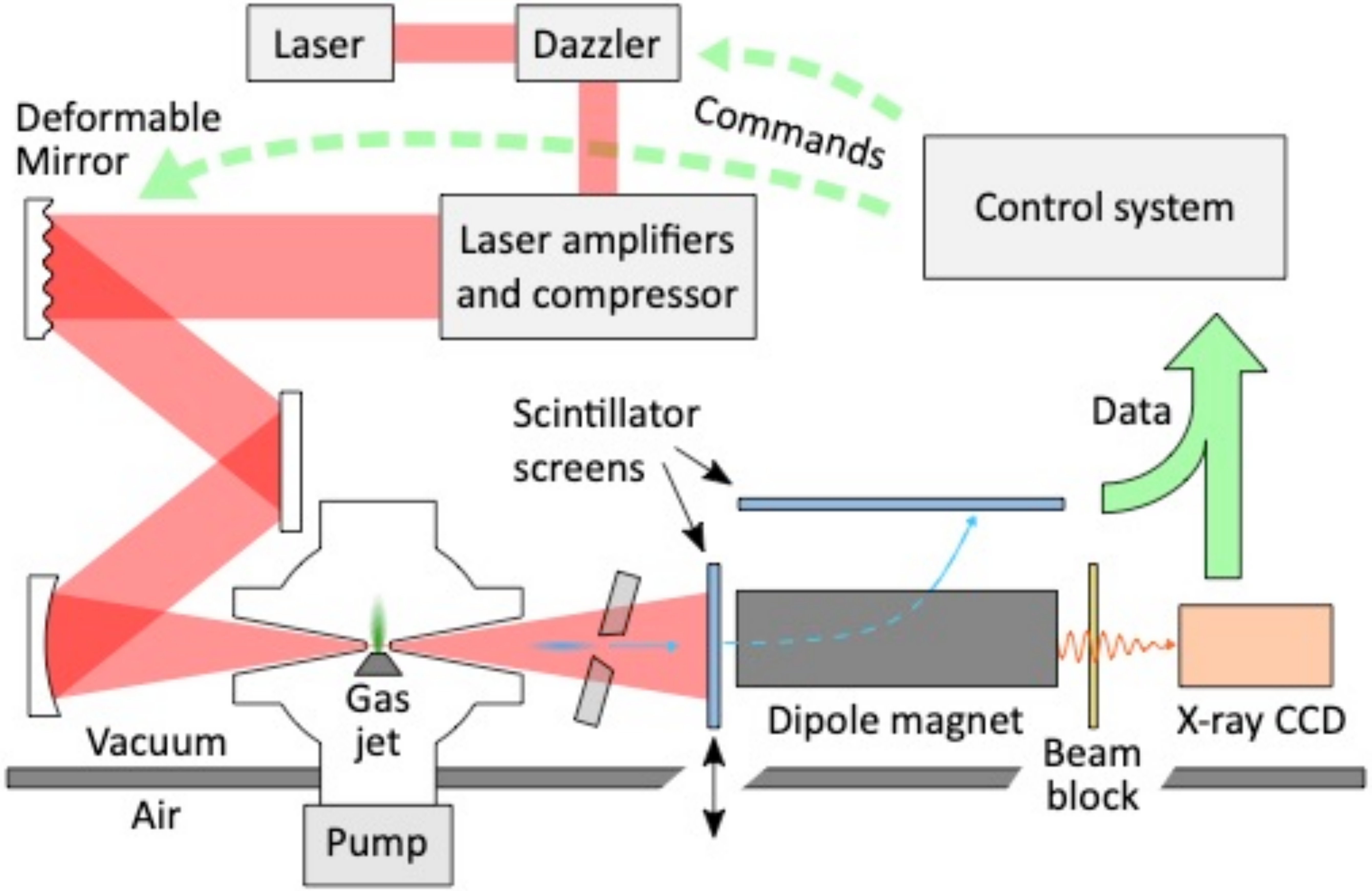
JAI *Advanced Acceleration* Effort

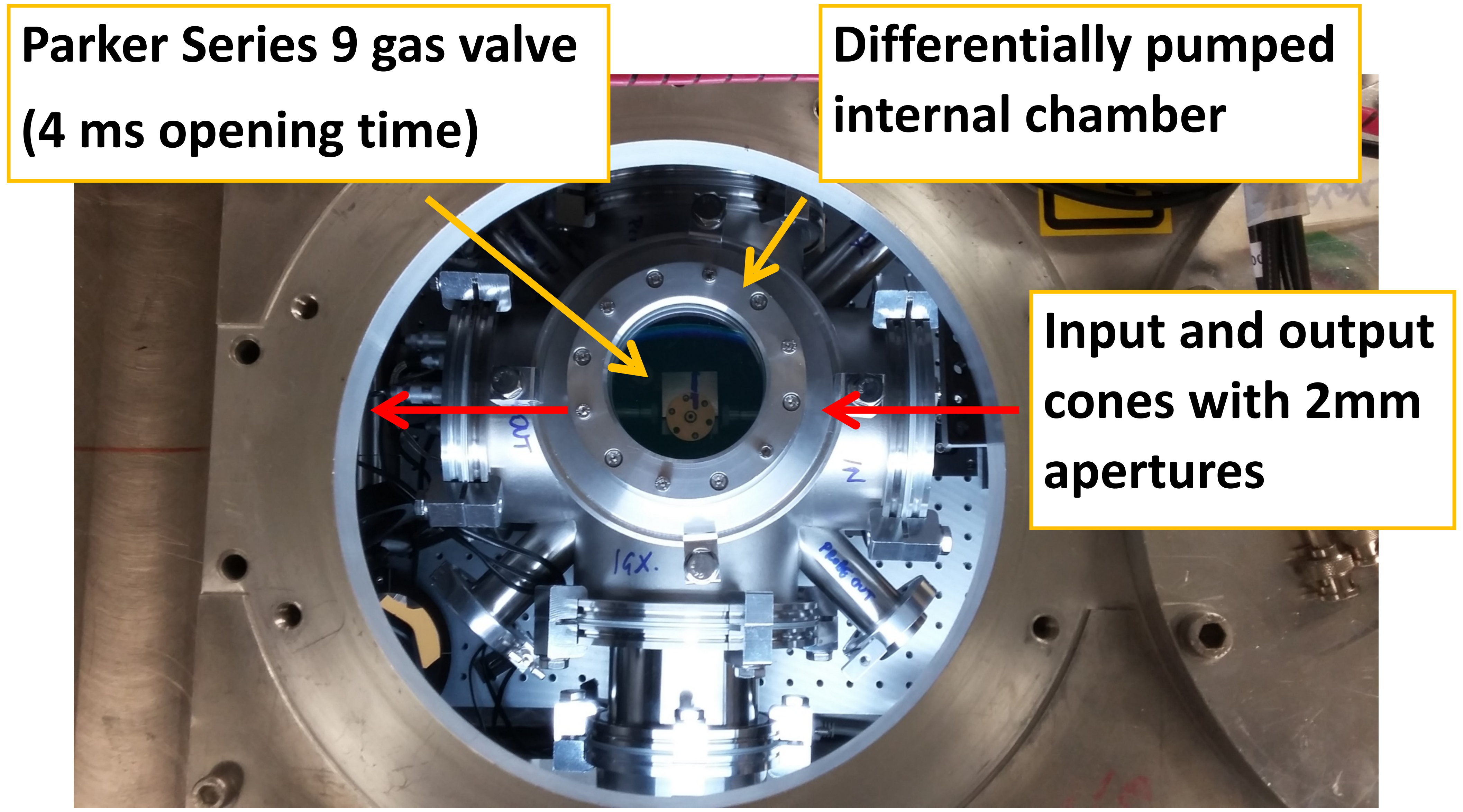
Staff	(Imperial) Ken Long, Stuart Mangles, Zulfikar Najmudin, Jaroslaw Paternak, Juergen Pozimski, Steve Rose (Oxford) Phil Burrows, Brian Foster, Simon Hooker, Peter Norreys, Roman Walczak	11
Fellows + Post-docs	(Imperial) Rory Bagott, Nick Dover, Oliver Ettlinger, George Hicks, Brendan Kettle + (incoming) Ben Chen, Rakesh Kumar (Oxford) James Cowley, Rebecca Ramjiawan, Marko Mayr + 2 TBA	12
Students	(Imperial) Robbie Watt, Cary Colgan, Michael Backhouse, Eva Los, Wei Wu, Toby Nonenmacher, HT Lau, Titus-Stefan Dascalu, Rebeca Taylor, Meriame Berboucha Adam Hughes, Nuo Xu, + (incoming) Annabel Gunn, Maria Maxouti (Oxford) Alexander von Boetticher, Jakob Jonnerby, Alex Picksley, Aimee Ross, Warren Wang, Emily Archer, Senes, Pakuza + 2 TBA (+ 2 students to join in October 2021	24
Recent leavers:	(Imperial) Emma-Jane Ditter, Jan-Niclas Gruse, Savio Rosario, Rob Shalloo, Matt Streeter (Oxford) Aarón Alejo, Jimmy Holloway	7


CUOS
DESY
LUND
CALA
ELI-ALPS
CERN
KANSAI
SLAC
BNL

Automation of plasma accelerators

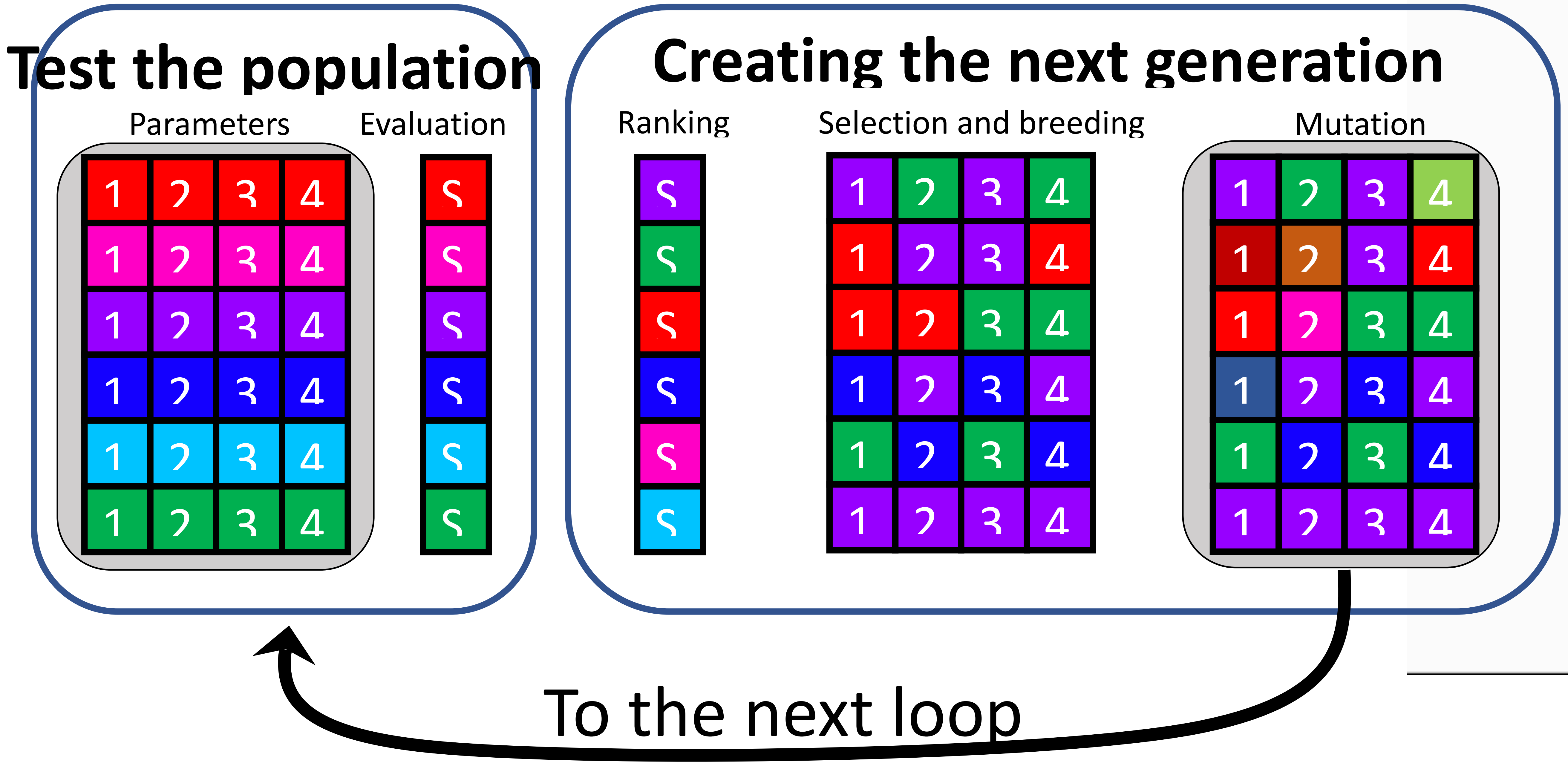
2017 Astra Gemini TA2 at the CLF

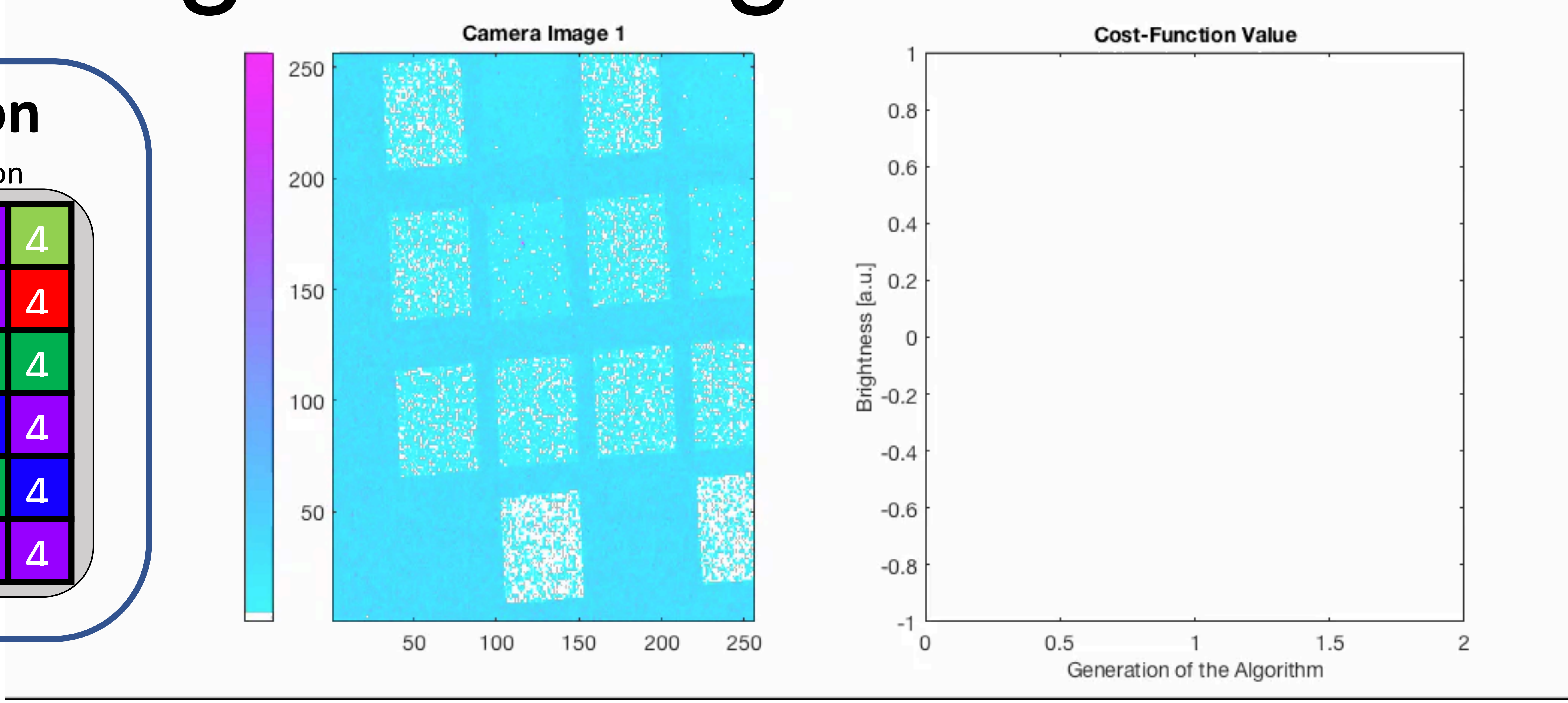




TA2 has less energy (unto ~ 500 mJ) but can be operated at up to 5 Hz

Optimisation with a genetic algorithm





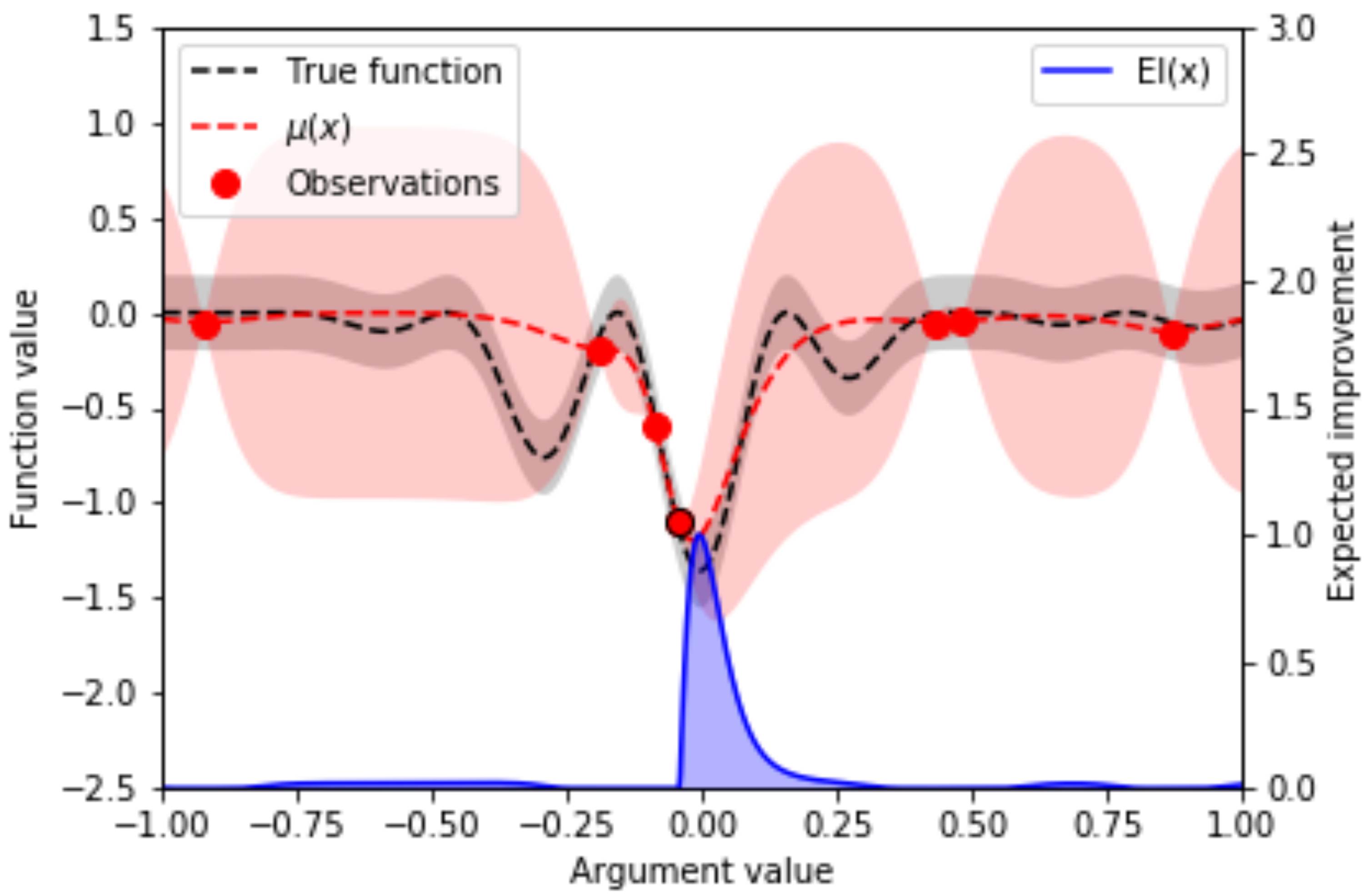
x-ray filter image from 5 TW source

- ✓ Started from 'flat' deformable mirror position with some random fluctuations
- ✓ Optimised the actuator voltages so no need for measurements or calibrations
- ✓ Equivalent level of performance when the spot was optimised manually
- ✳ No obvious stopping point, optimisation sensitive to noise

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

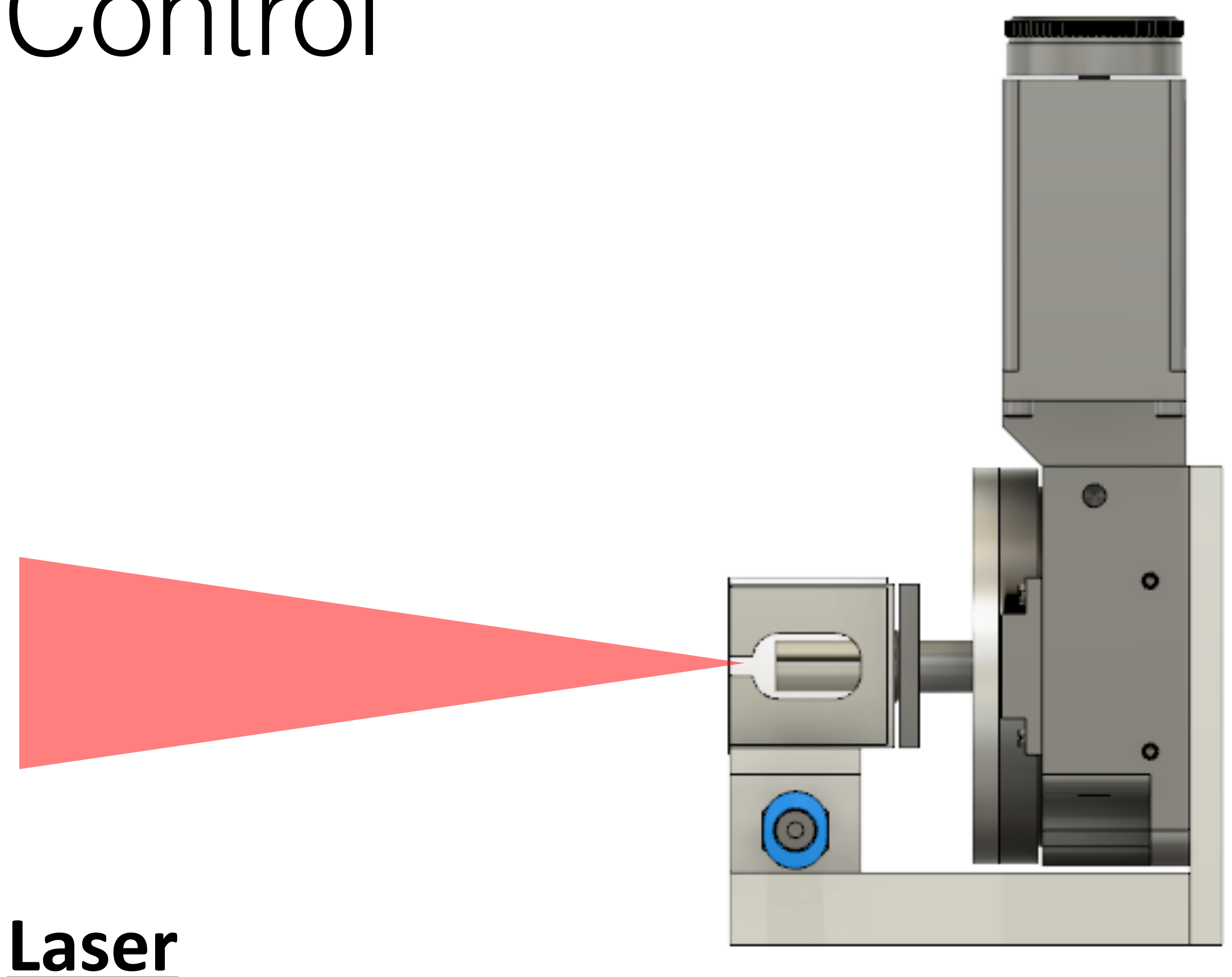
Bayesian Optimisation on Gemini TA2

Gaussian process regression



Measure at the position of greatest expected improvement and update model

Control



Laser

Energy

Spectral phase (temporal pulse shape)

Spatial phase (focal spot shape)

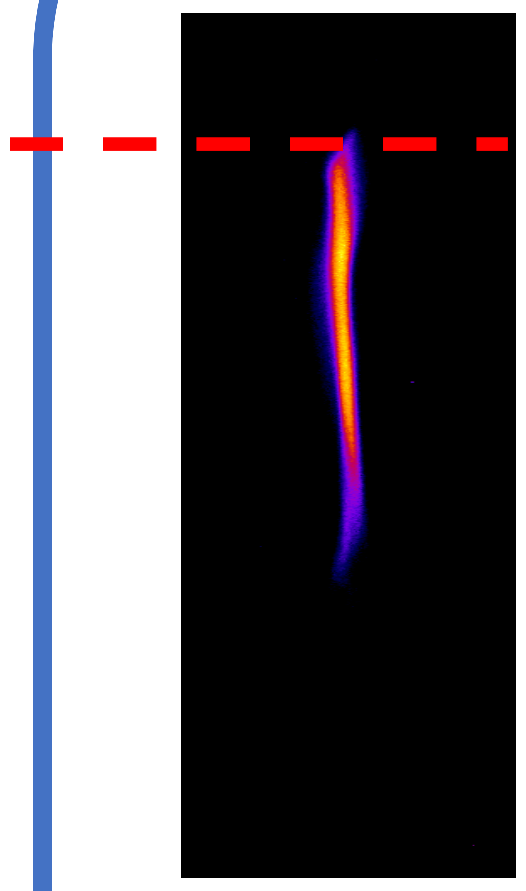
Plasma

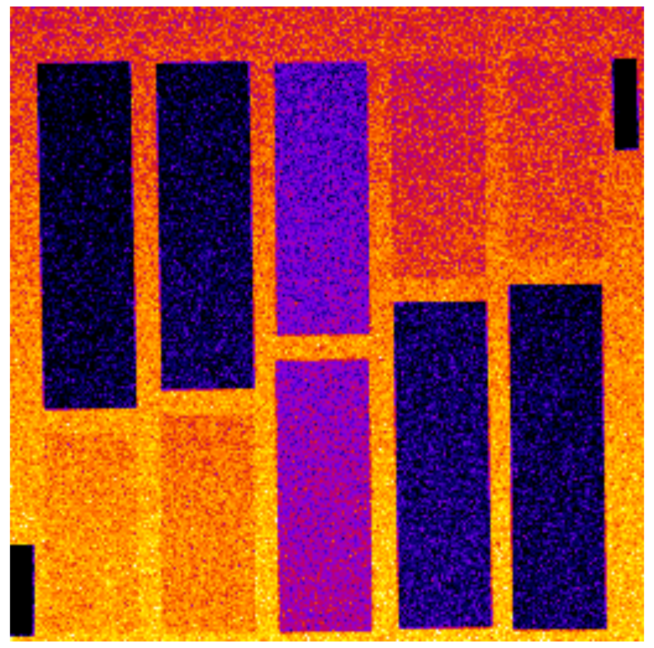
Density

Length

Longitudinal profile

Feedback





Electrons

Maximum energy

Charge

Spectrum

Divergence

X-rays

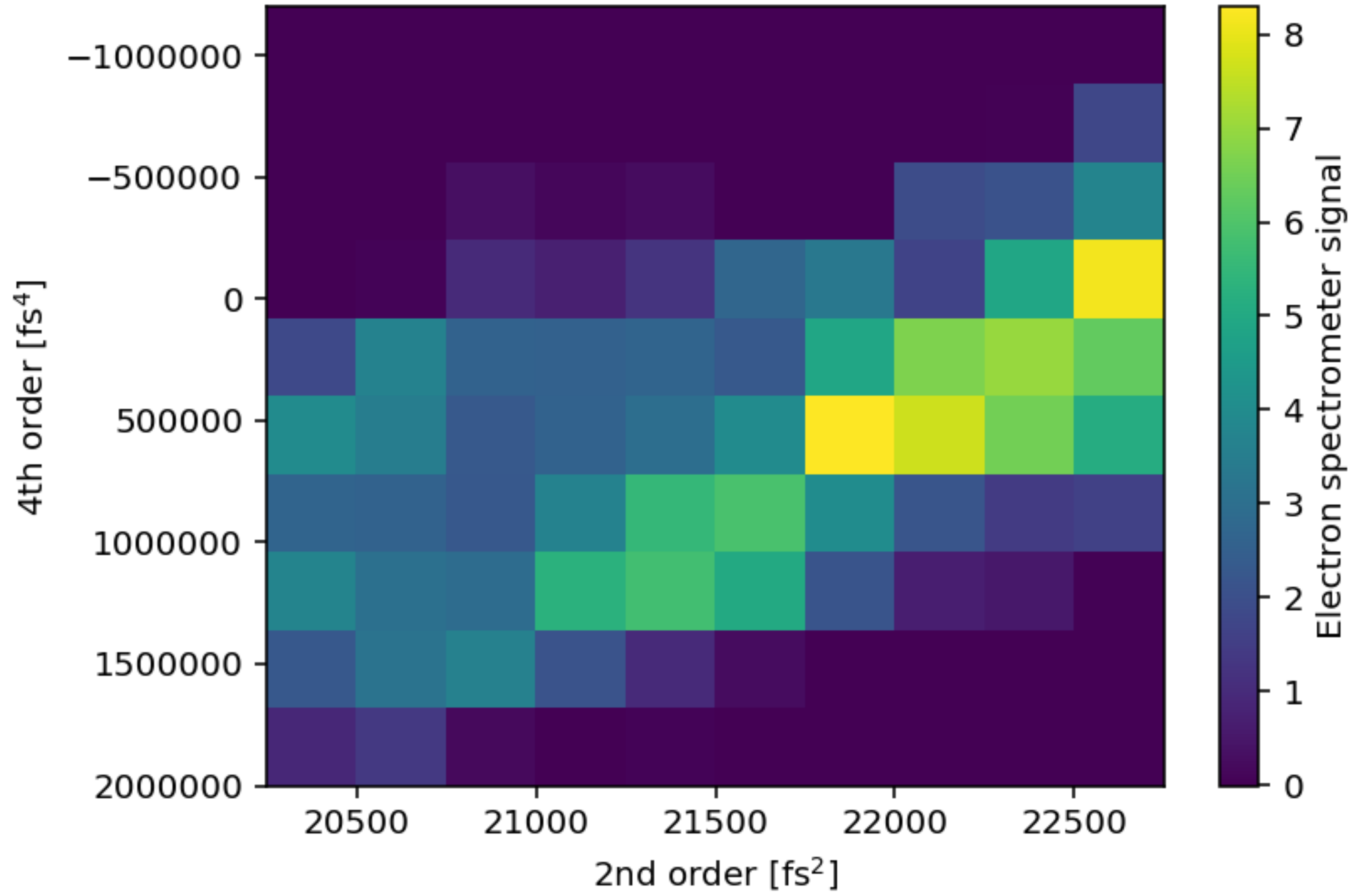
Flux

Critical energy

John Adams Institute for Accelerator Science

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

Bayesian optimisation of electron charge with 2nd and 4th order spectral phase



- Incomplete and course scan of parameter space taking- 20 minutes
- Due to correlated nature of the space, you could not just optimise by 2x 1D scans

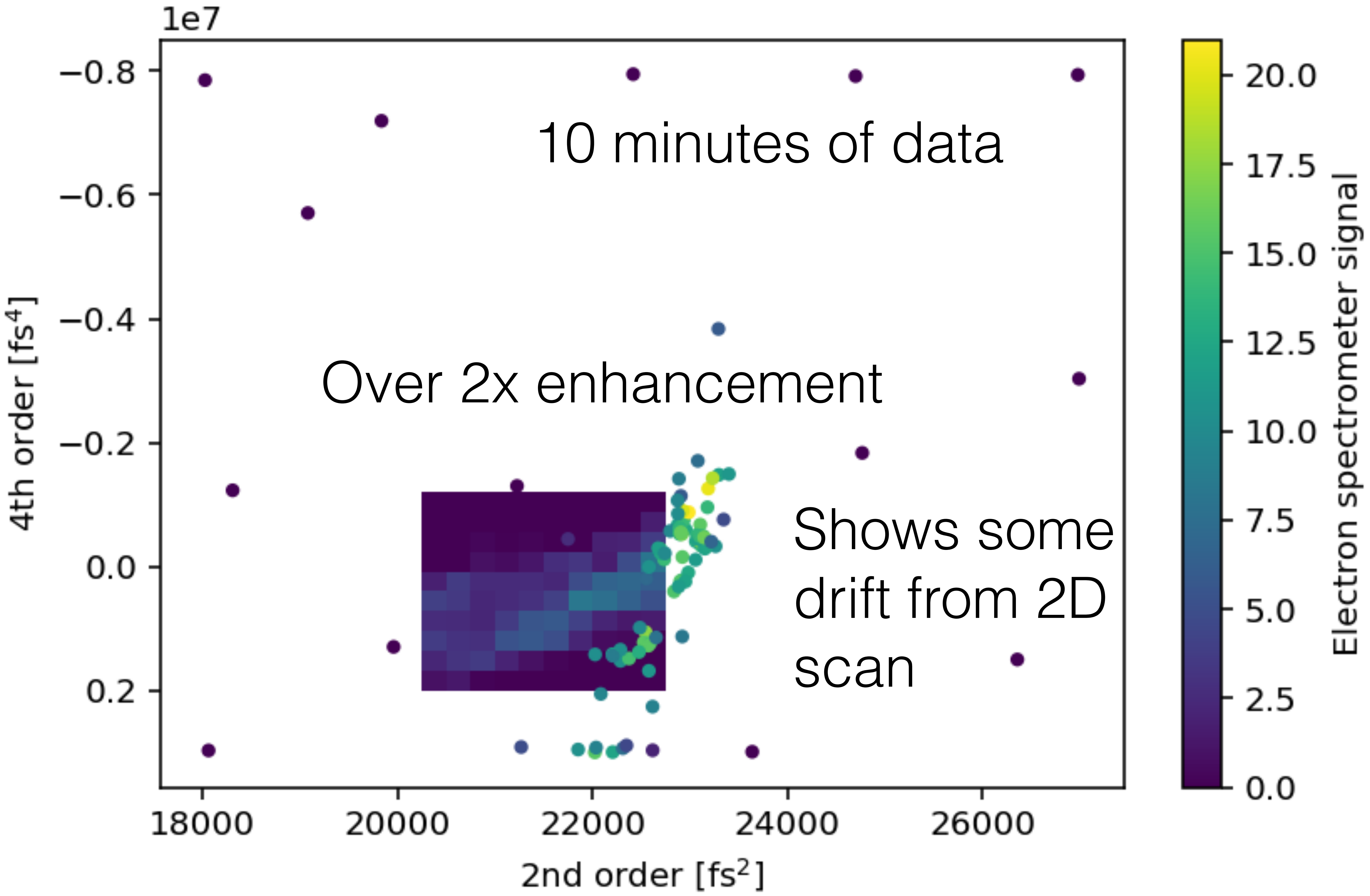
John Adams Institute for Accelerator Science

Imperial College London

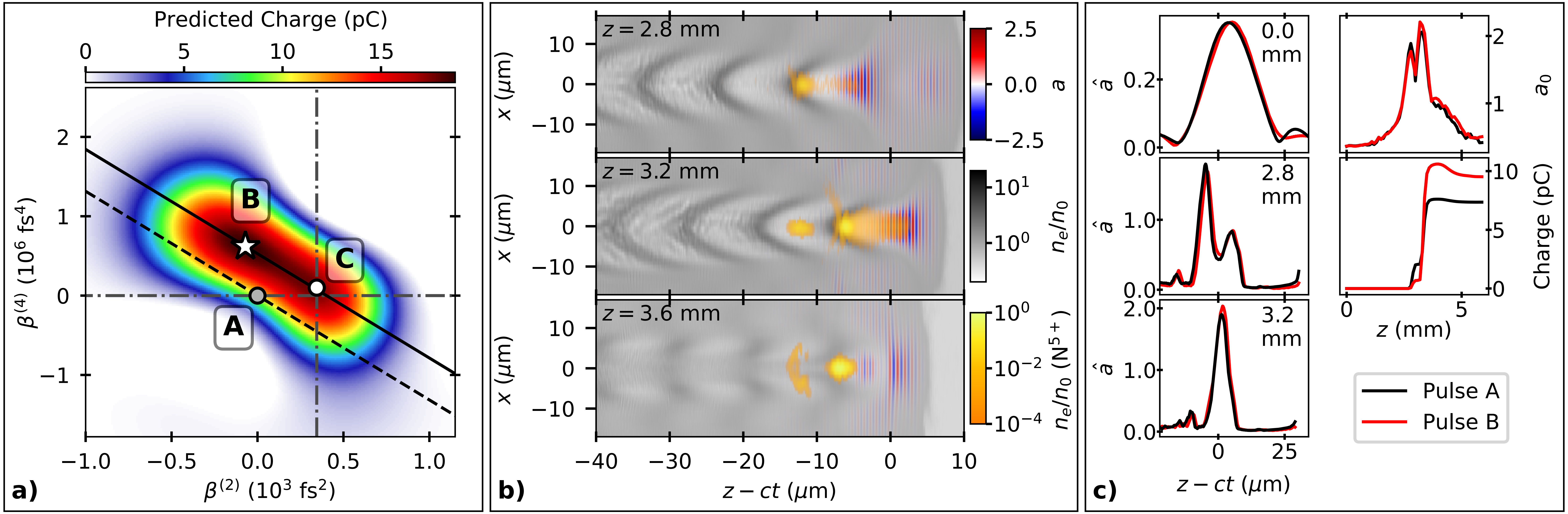
UNIVERSITY OF OXFORD

Royal Holloway University of London

Optimisation found a maximum outside of original scan region



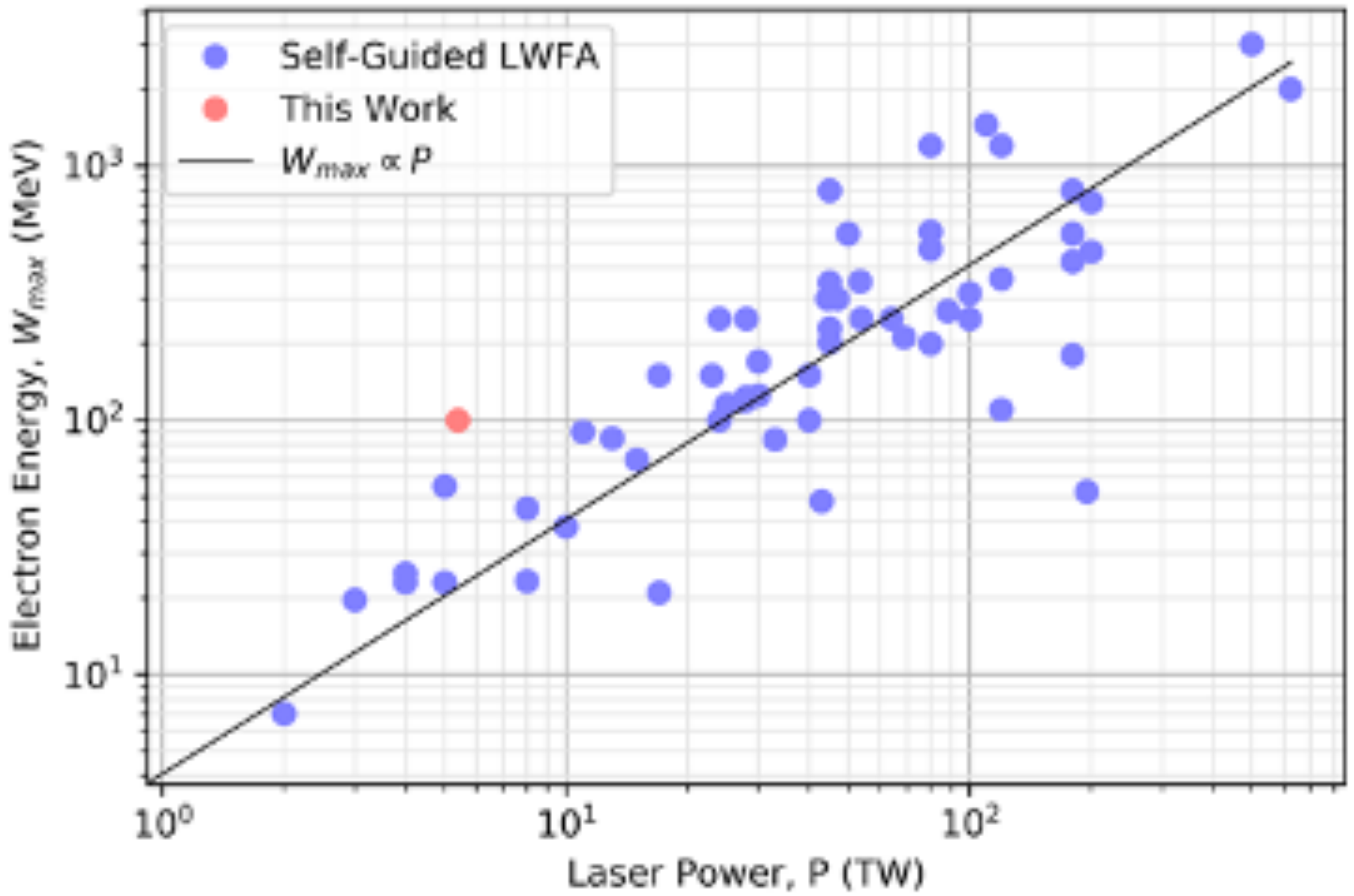
Optimisation demonstrates subtle physics effects

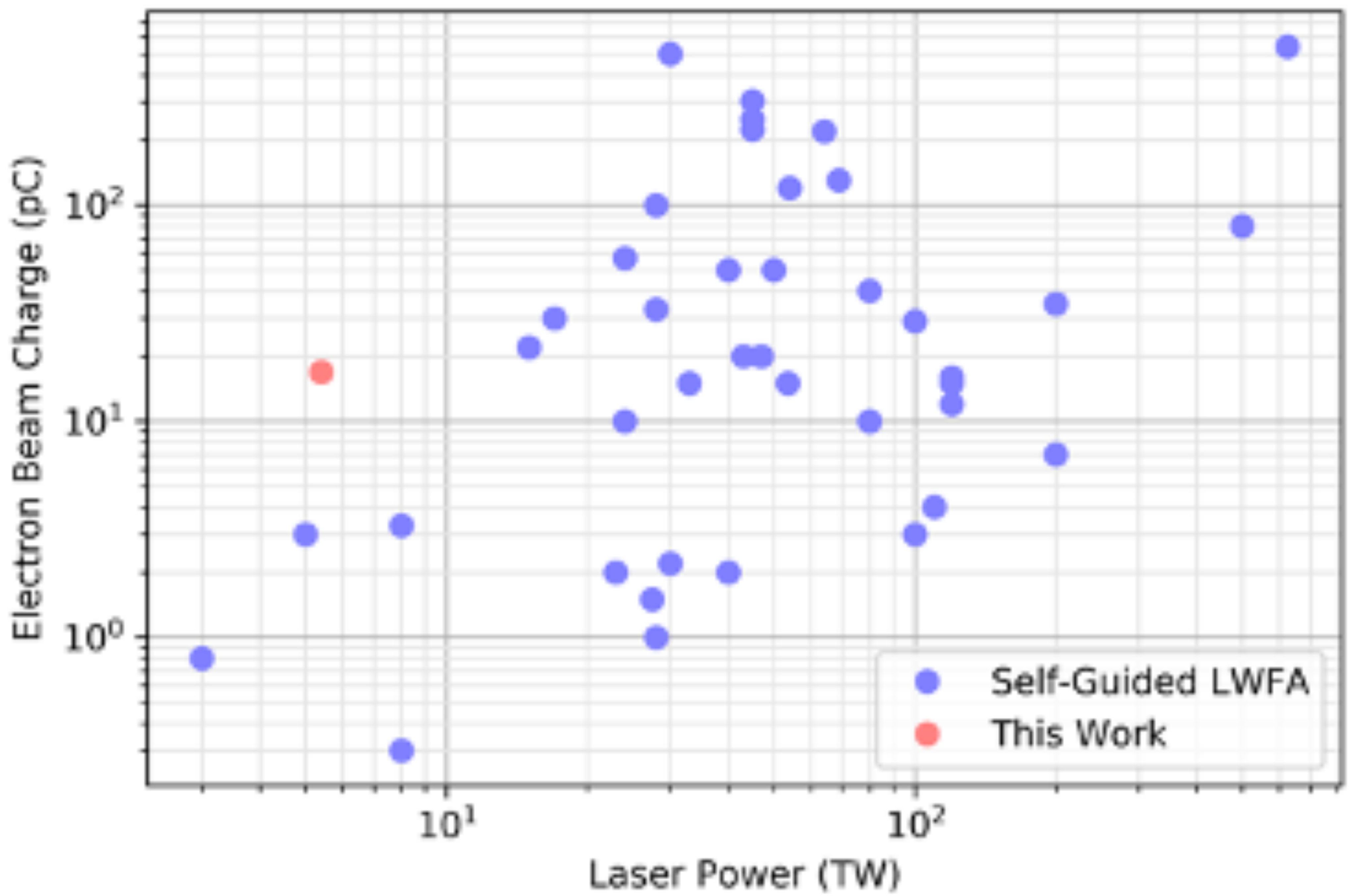


John Adams Institute for Accelerator Science

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

Comparison to previous studies





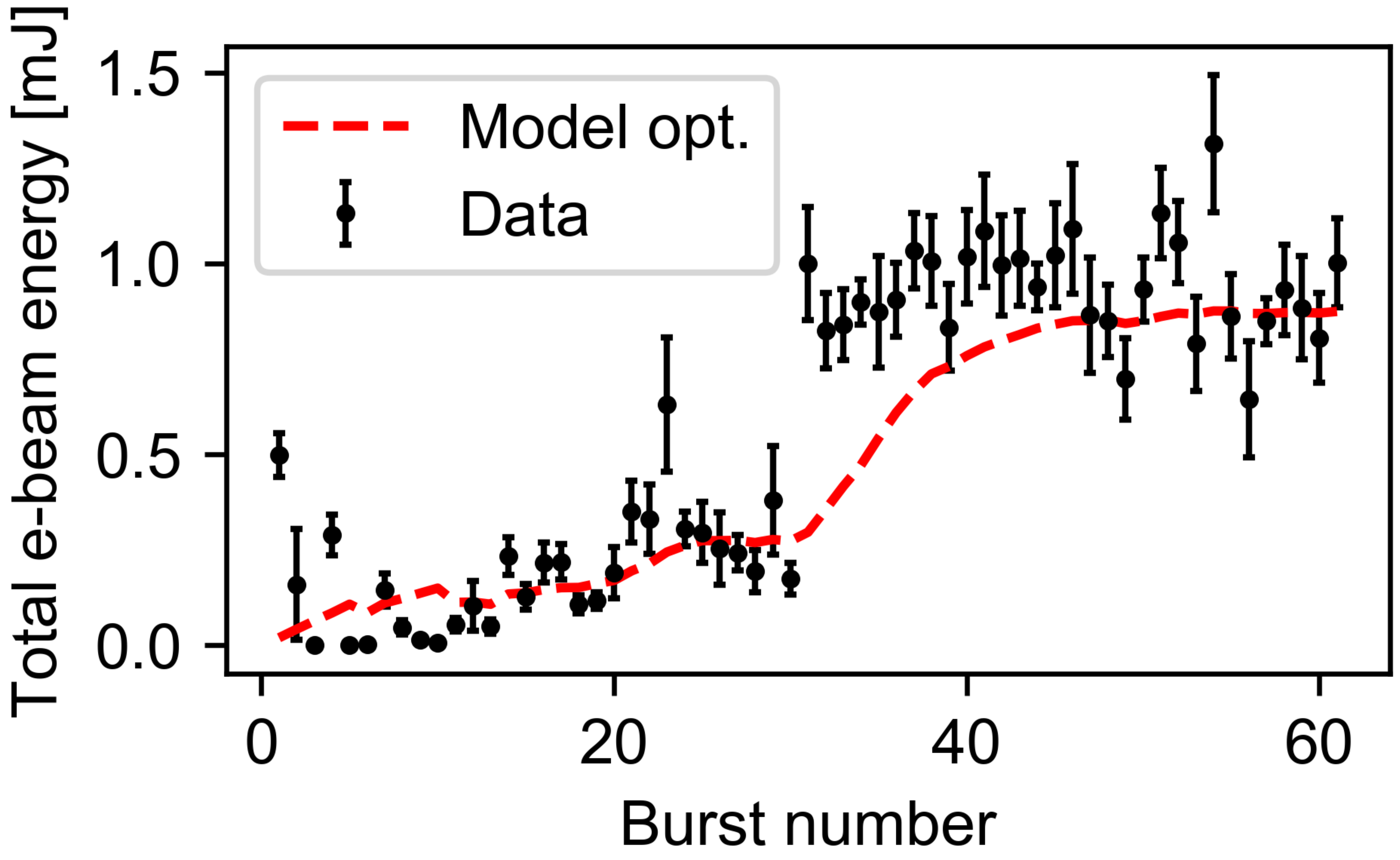
maximum energy exceeds other 5 TW systems by on average 5 times

maximum electron charge exceeds results with other 5 TW systems by on average an order of magnitude

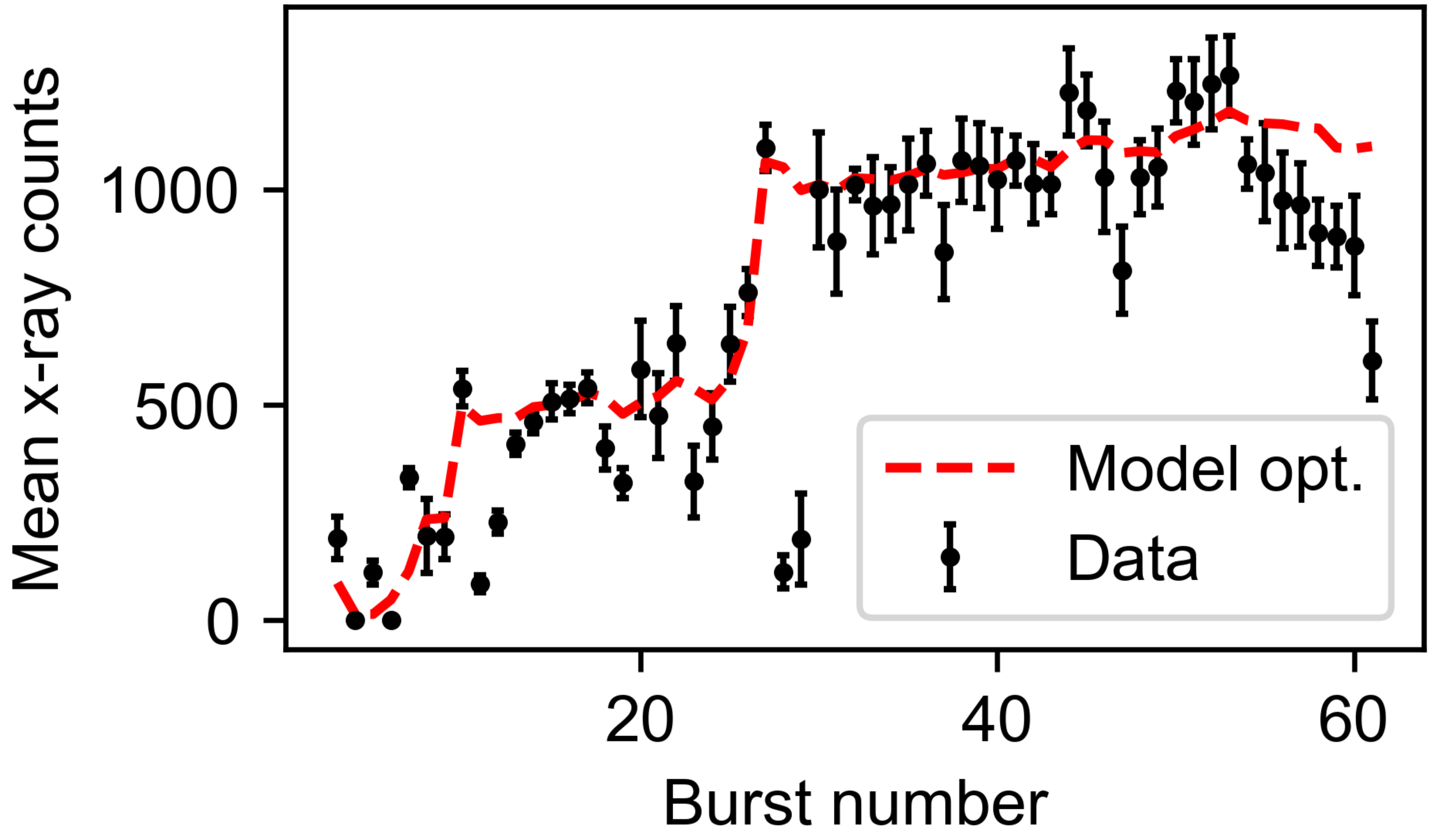
Shalloo, R. J., S. J.D. Dann, J. N. Gruse, C. I.D. Underwood, A. F. Antoine, C. Arran, M. Backhouse, et al. "Automation and Control of Laser Wakefield Accelerators Using Bayesian Optimization." Nature Communications 11, no. 1 (2020): 6355.

Algorithm allows automated optimisation

5D optimisation of total electron beam energy



6D optimisation of mean x-ray CCD counts



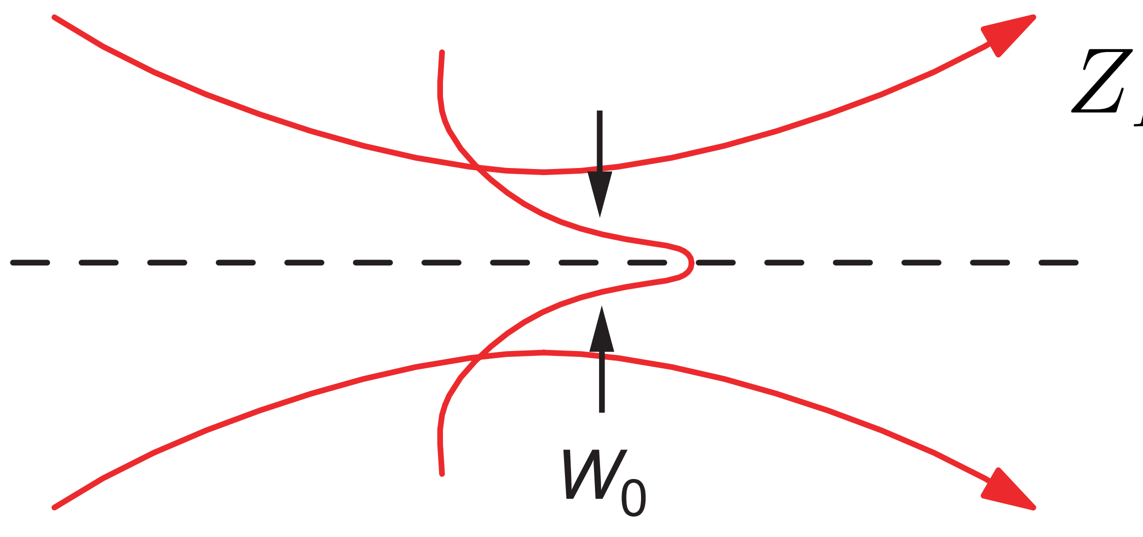
- Optimisations started from previously identified optimum positions
- Optimisations took 20 minutes compared to 35 mins for 4 successive 1D scans and found a better optimum
- Optimisation algorithm makes morning start-up efficient and easy

Development of low-density plasma waveguides

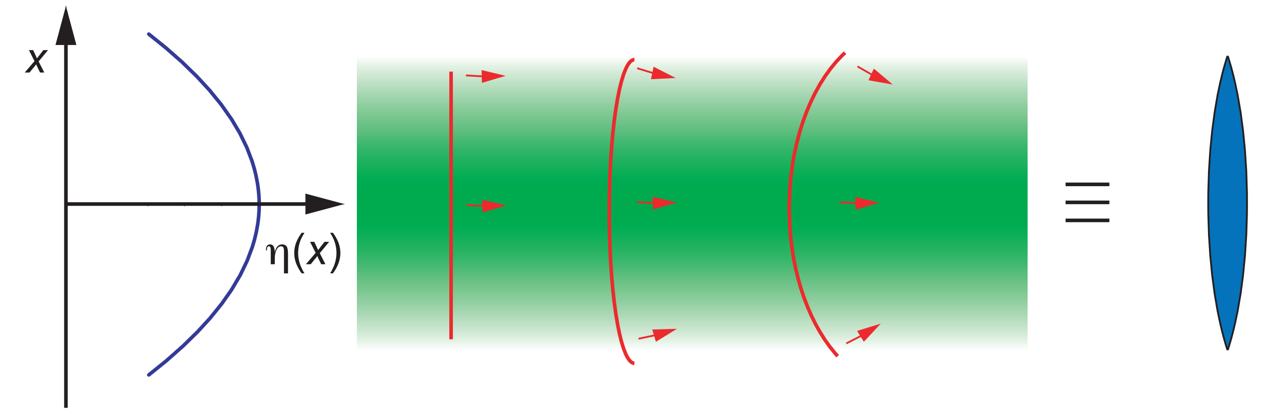
Motivation

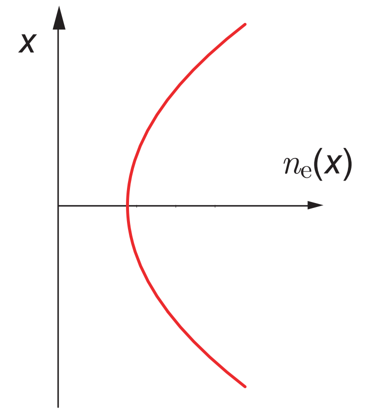
$$\Delta W \propto \frac{1}{n_e} \qquad L_d \approx \frac{\lambda_p^3}{\lambda^2} \propto \frac{1}{n_e^{3/2}}$$

- Multi-GeV stages require accelerator stages 100s mm long with densities ~ 10^{17} cm^{-3}:
  - EuPRAXIA n_e = 1.8 × 10^{17} cm^{-3}, L_{acc} = 118 mm [Cros et al. EuPRAXIA Milestone Report 3.1 (2017)]
  - BELLA n_e = 0.96 × 10^{17} cm^{-3}, L_{acc} = 600 mm [Leemans et al. Proc. PAC 1416 (2011)]
  - In addition, we would like to operate at high repetition rates (kHz) for extended periods



$$Z_R = \frac{\pi w_0^2}{\lambda}$$





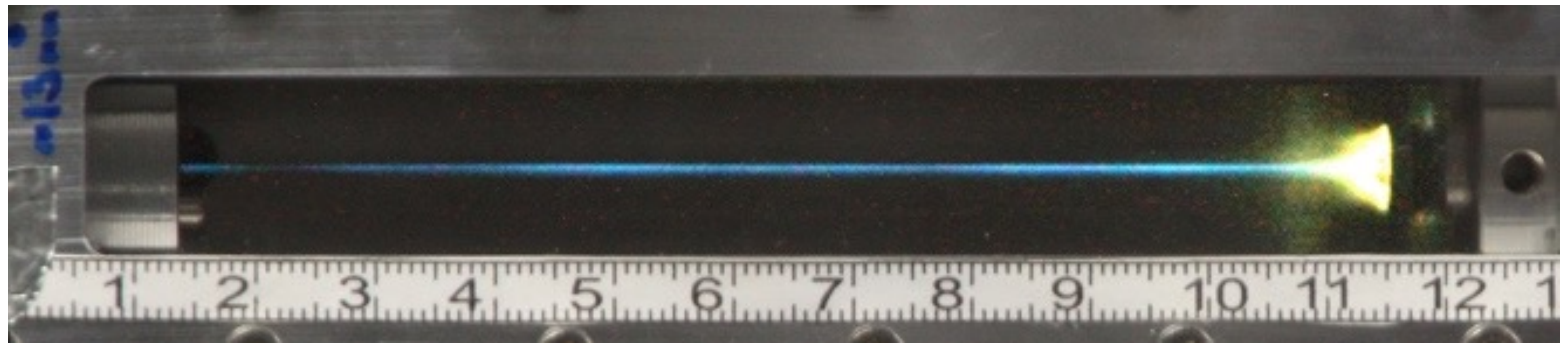
$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \epsilon_0 \omega^2}$$

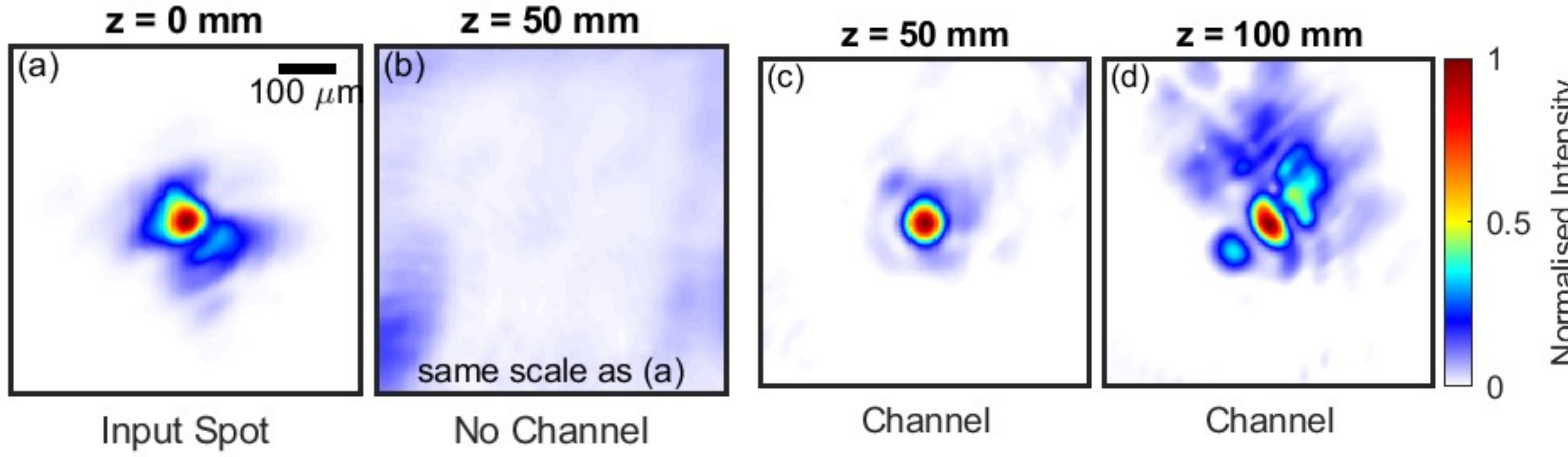
- There is a need for long (> 100 mm), low density (~ 10^{17} cm^{-3}) plasma channels capable of high-rep-rate operation

Hydrodynamic plasma waveguides

- There is a need for long (> 100 mm), low density (~ 10^{17} cm^{-3}) plasma channels capable of high-rep-rate operation

- Capillary discharge waveguide (developed by Oxford) used in many GeV-scale expts (e.g. BELLA) but prone to laser damage
- Hydrodynamic channels attractive for high rep rate since free-standing ⇒ “indestructible”
  - Create & heat column of hot plasma
  - Expansion into surrounding cold gas / plasma drives cylindrical blast wave
  - Plasma channel formed within expanding shell
- To date, plasma column has been **heated collisionally**:
- Requirement for fast heating limits axial density to ~ 10^{18} cm^{-3}





- Expts with Gemini laser demonstrated guiding of 6 × 10^{17} Wcm^{-2} pulses over 100 mm long channels with n_e ~ 10^{17} cm^{-3}

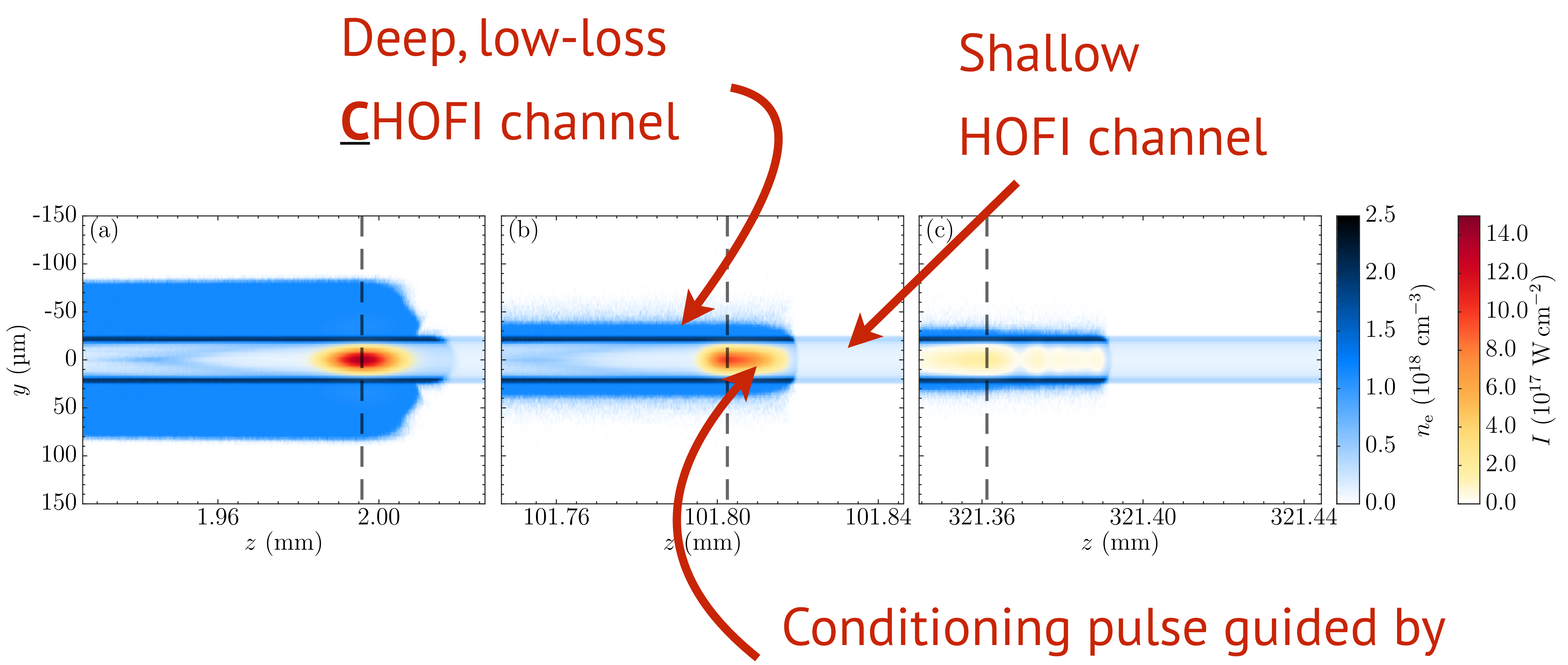
R.J. Shalloo *et al. Phys Rev E* **97** 053203 (2018)
A. Picksley et al. Phys Rev Accel Beam 23 81303 (2020)

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

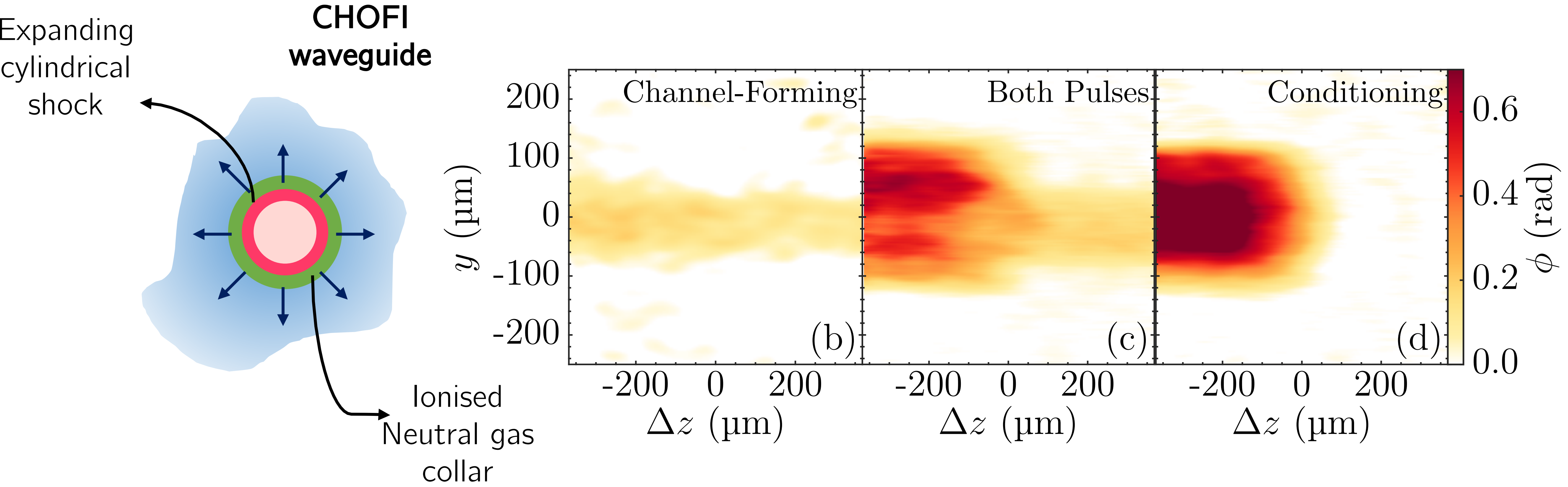
Conditioned HOFI (CHOFI) plasma waveguides

John Adams Institute for Accelerator Science

- Expts with Astra TA2 laser showed additional ionization of channel wall by guided pulse
- Analysis shows:
  - Collar of neutral gas pushed out by shock
  - Collar ionized by guided / "conditioning" pulse to form a <u>conditioned</u> HOFI channel which has **very low losses**



- FBPIC simulations using electron & neutral density profiles from FLASH simulations
- matched to 2018 Astra experiment
- Power attenuation of CHOFI channel 2.5 m!
- Metre-scale channels possible!
- Only ~ 1 J of laser energy per metre of channel



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

R.J. Shalloo et al. Phys Rev Accel. Beam 22 41302 (2019)
A. Picksley et al. Phys Rev E 102 053201 (2020)

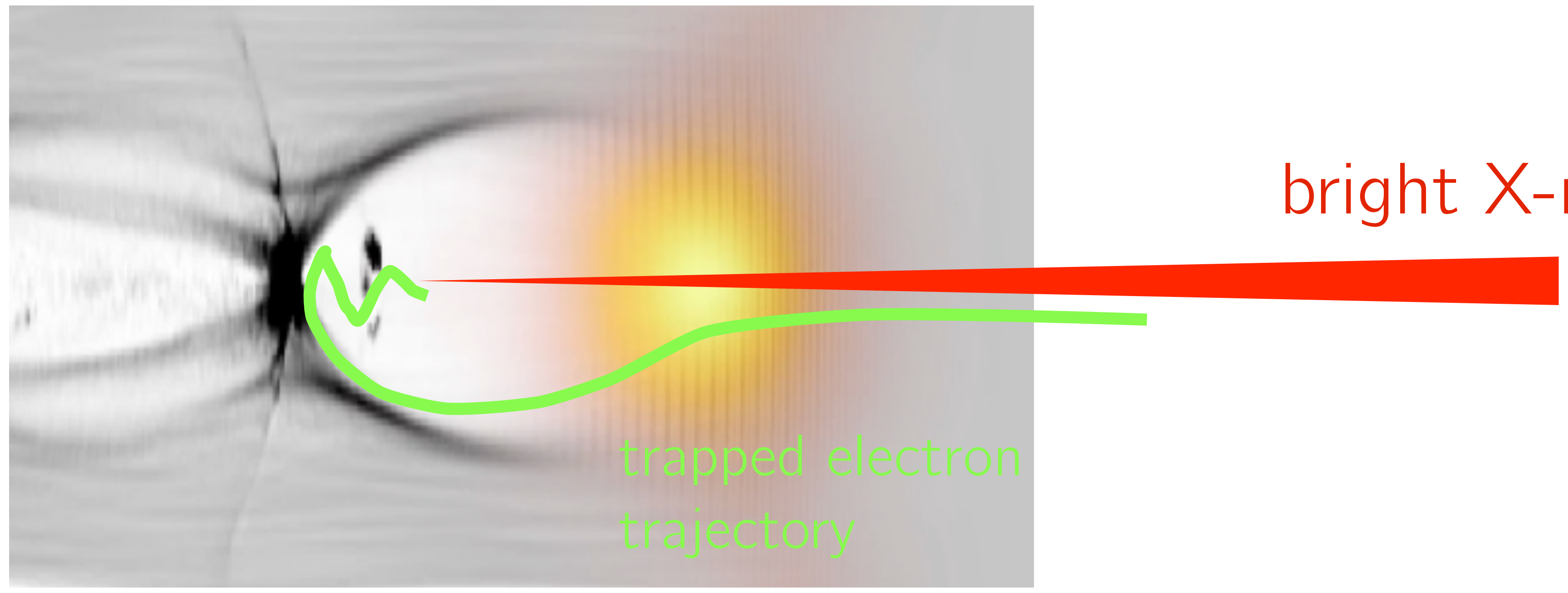
Imperial College London | University of Oxford | Royal Holloway University of London

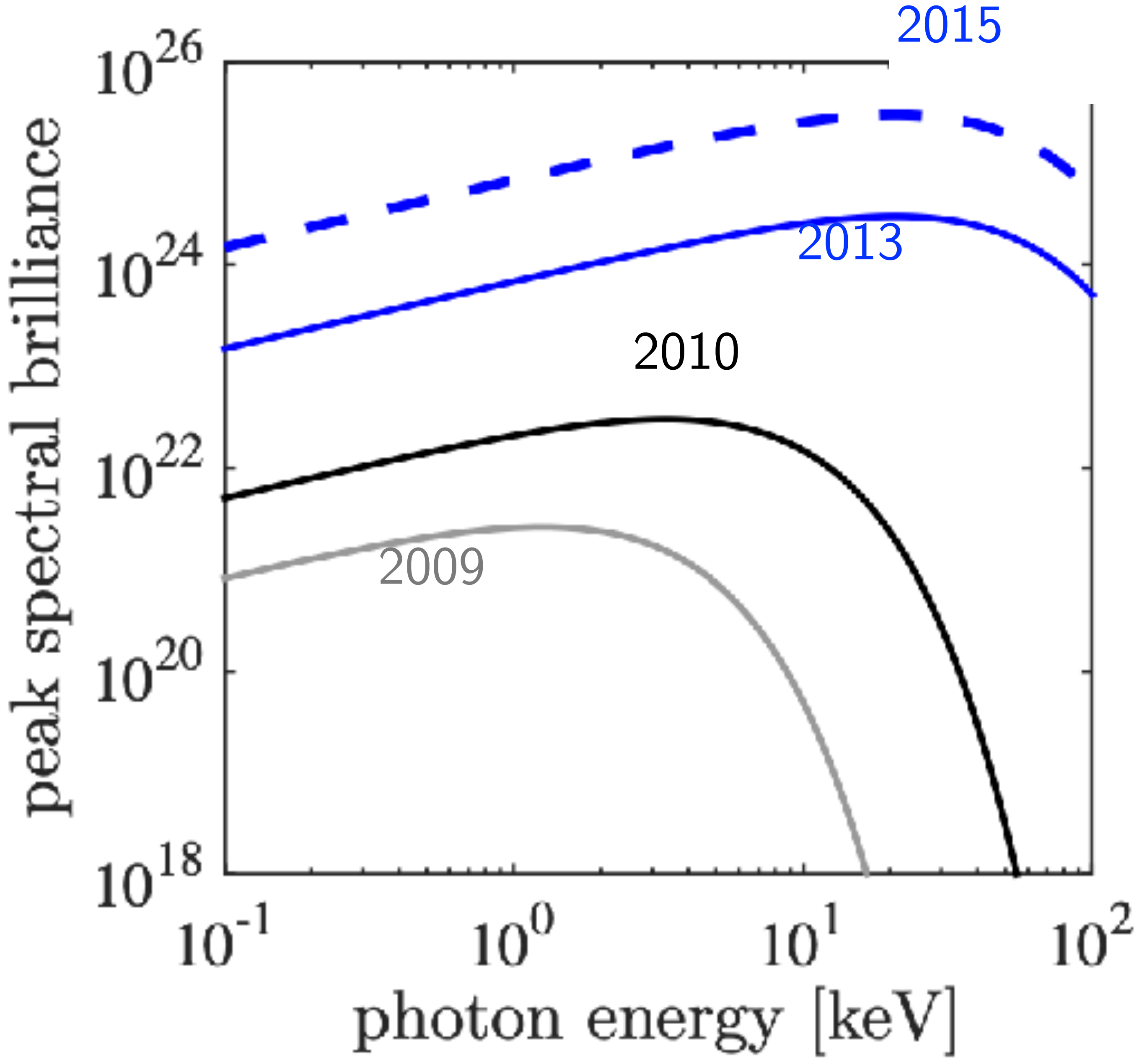
EXAFS with Betatron source

Laser Wakefield Accelerators for x-ray absorption spectroscopy

- x-ray absorption spectroscopy (XAS) is a powerful technique for studying the structure of matter
  - XANES and EXAFS developed at synchrotrons to study ***static*** systems
- Laser wakefield accelerators are ideal facilities to use XAS to study rapid evolution of ***dynamic*** systems
  - LWFAs produce broadband femtosecond duration x-rays
  - LWFAs are co-located and readily synchronised with other high power lasers used to drive dynamic experiments
  - Previous attempts have required accumulation of many shots to produce one spectrum - severely limiting applicability

Betatron oscillations of electrons in a laser wakefield accelerator generate ultrafast, broadband X-rays

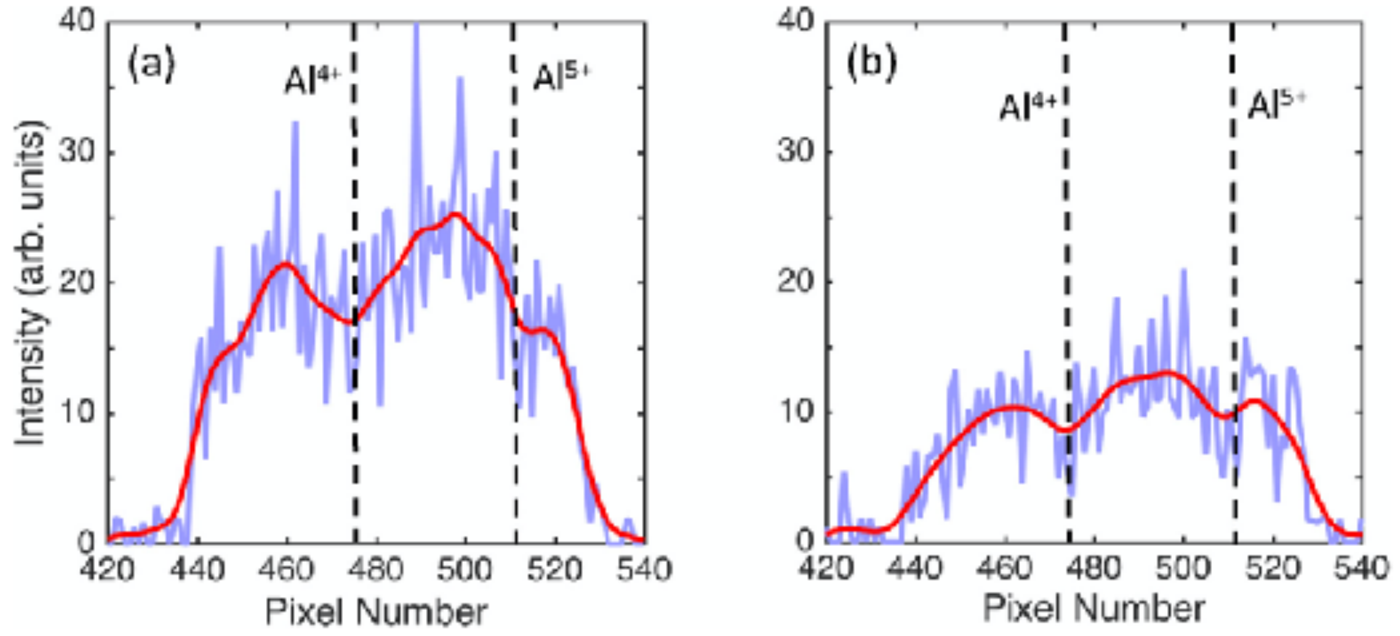




JAI group at Imperial have pioneered development of betatron on Gemini laser at CLF

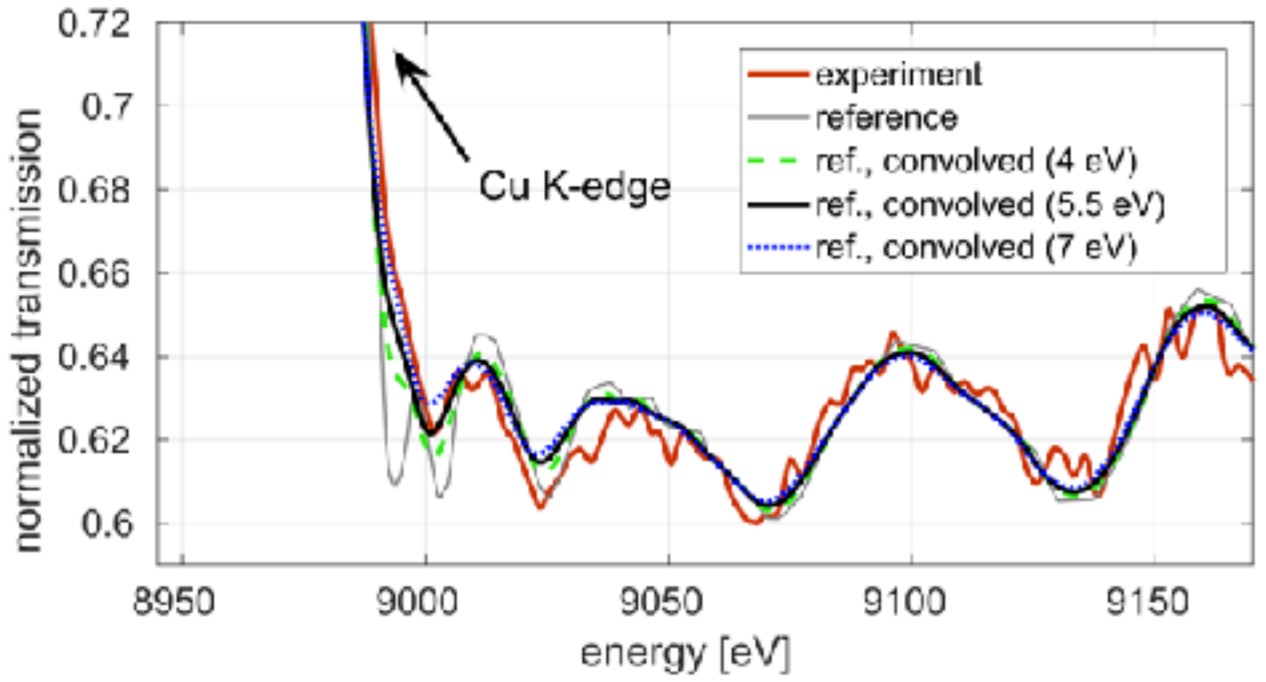
x-ray absorption spectroscopy with LWFAs

- Previous attempts by various groups (* indicates JAI involvement) needed many laser shots to accumulate a spectrum
  - Limits use in pump probe experiments, especially for experiments needing high-energy (low rep rate) pump pulses.



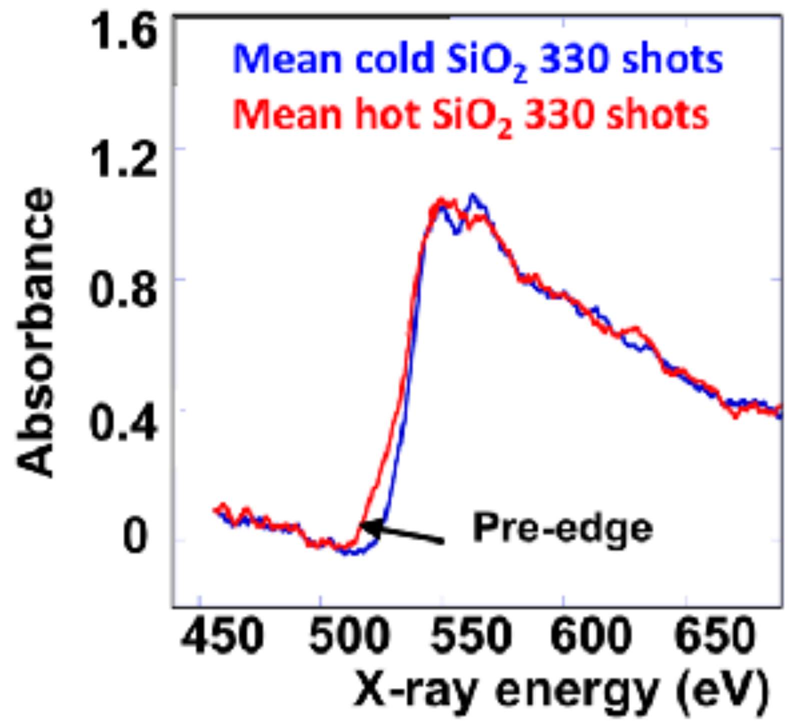
MZ Mo PRE 2017

150 shots per spectrum



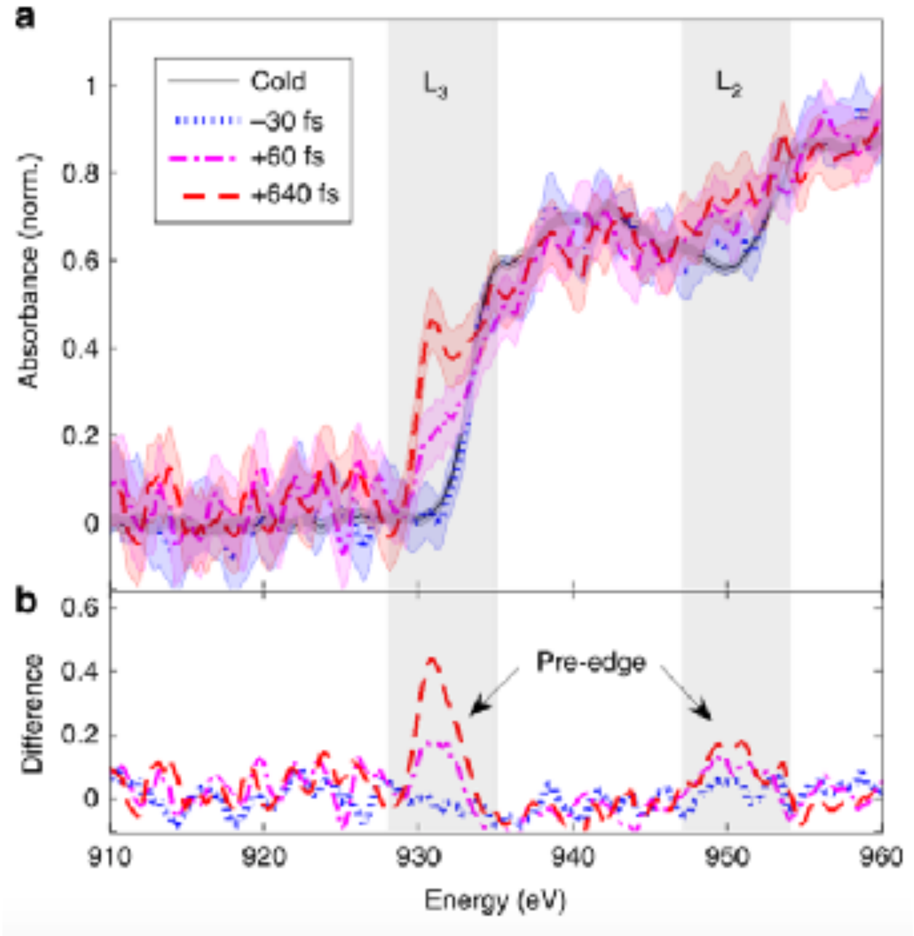
*M Smid et al RSI 2017

150 shots per spectrum



*F Albert, IPAC 2018

330 shots per spectrum

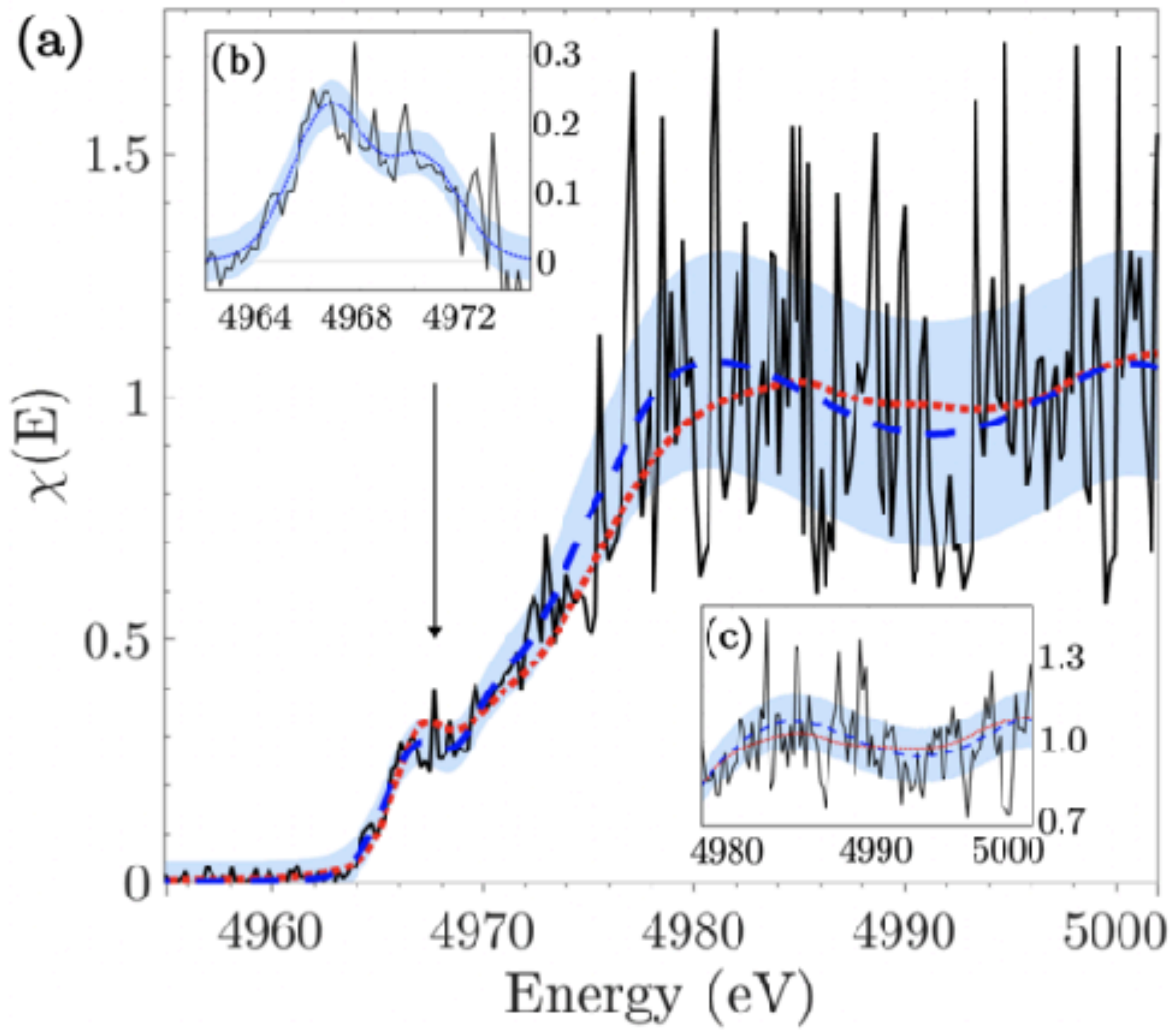


Mahieu Nature Communications 2018

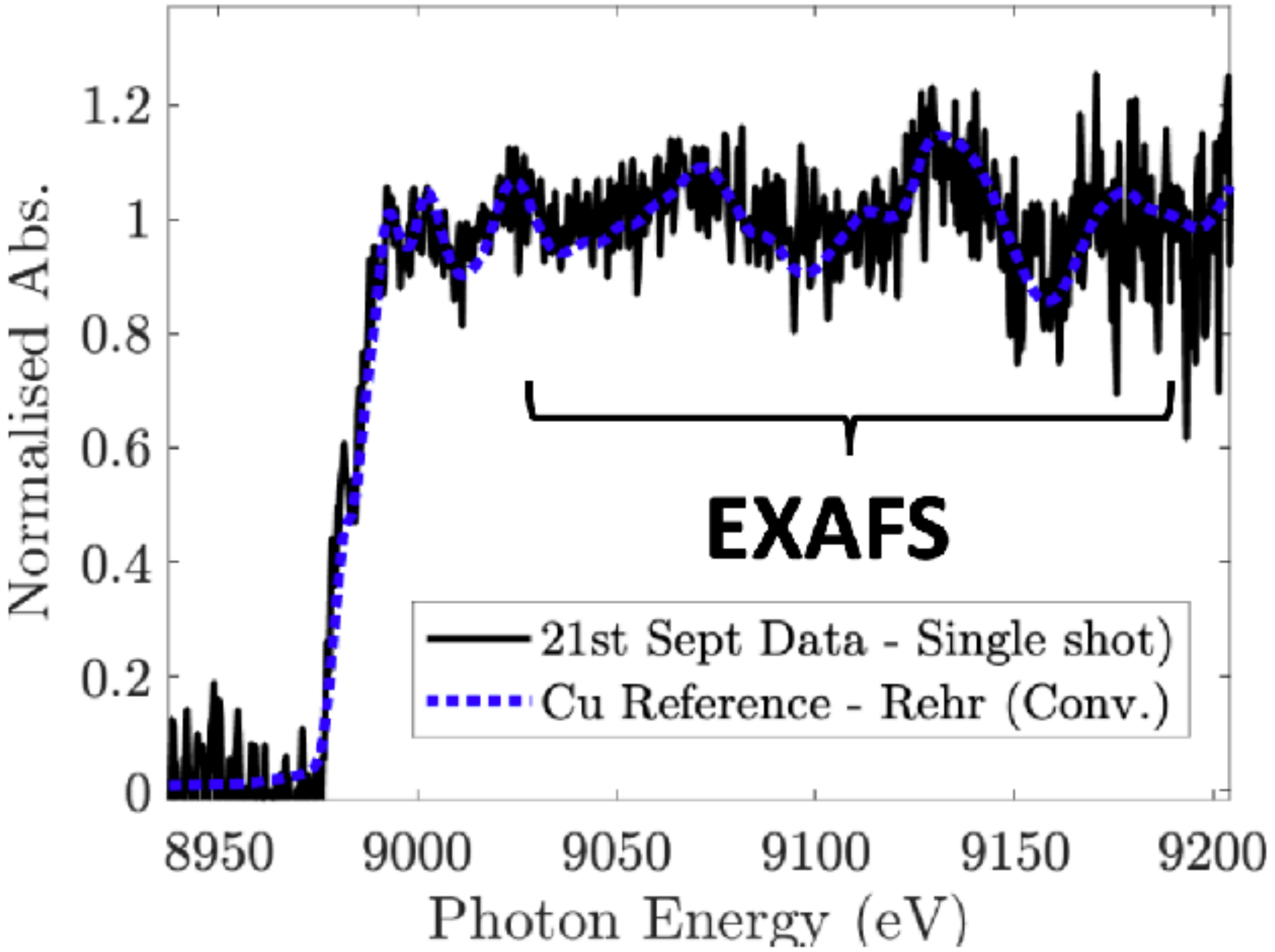
50 shots per spectrum

Experiments on Gemini have now achieved single shot XANES and EXAFS

B Kettle PRL, 123, 254801 (2019)



2020 results (unpublished)



- Single shot near edge spectroscopy (XANES) published in PRL in 2019
  - XANES provides information about electron population (e.g. temperature, ionisation state)
- 2020 experiment achieved single shots EXAFS
  - EXAFS provides information about ion population (e.g. temperature, crystal structure)
- Simultaneous XANES + EXAFS will allow key dynamics of electron-ion equilibration in warm dense matter to be studied (data analysis of pump probe experiments underway)

AWAKE

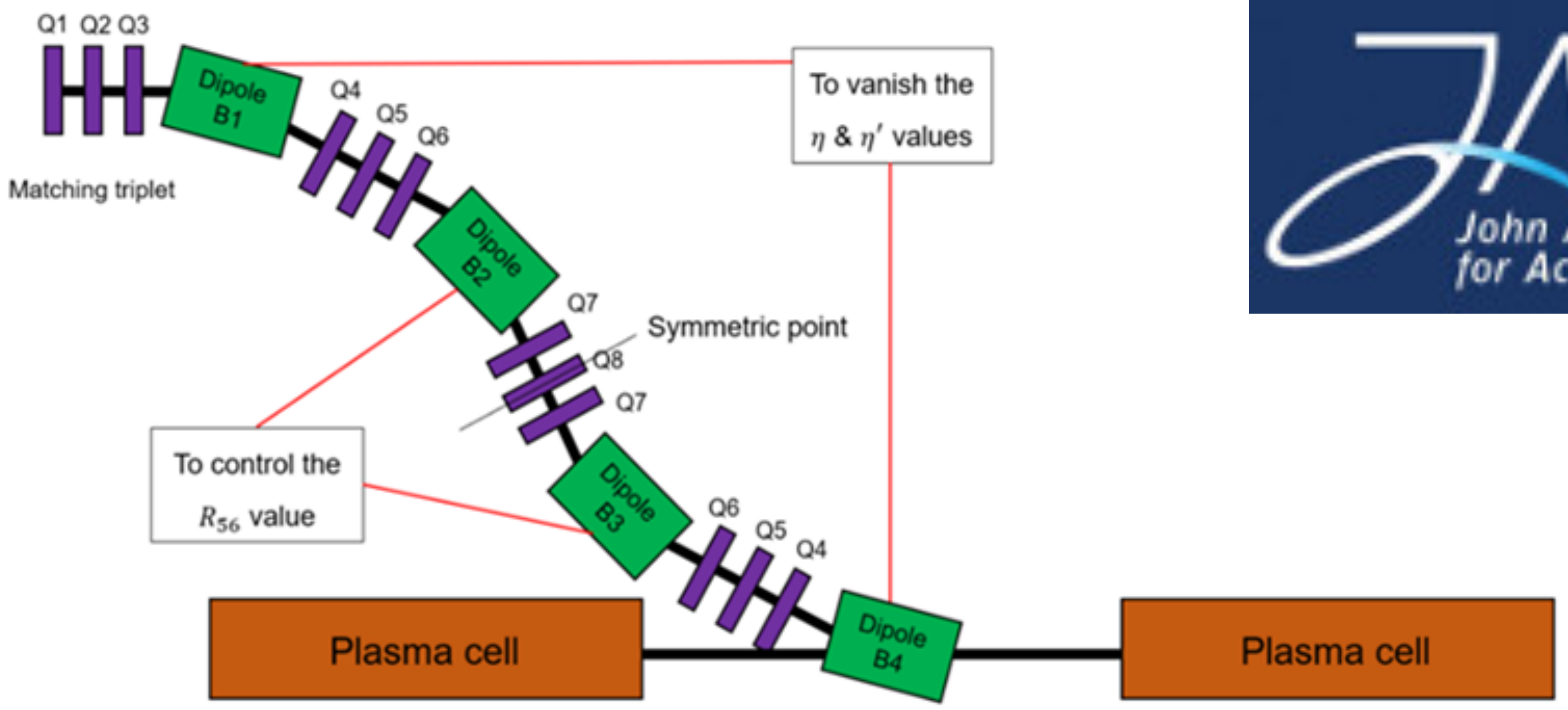
AWAKE-UK

- 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 in 1 years time!
- 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.

AWAKE Run 2: e-/p BPM

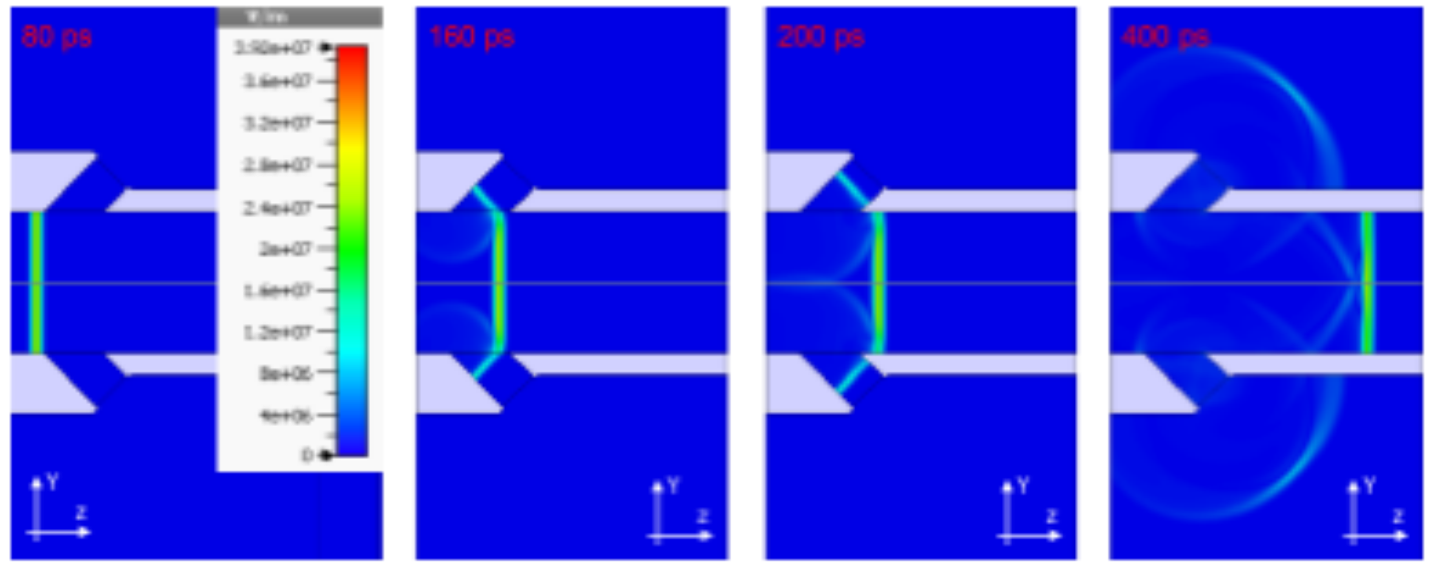
Major new initiative in Oxford Particle Physics

design of witness e- beamline for split plasma cell;
design/prototyping/testing of e-/p BPMs

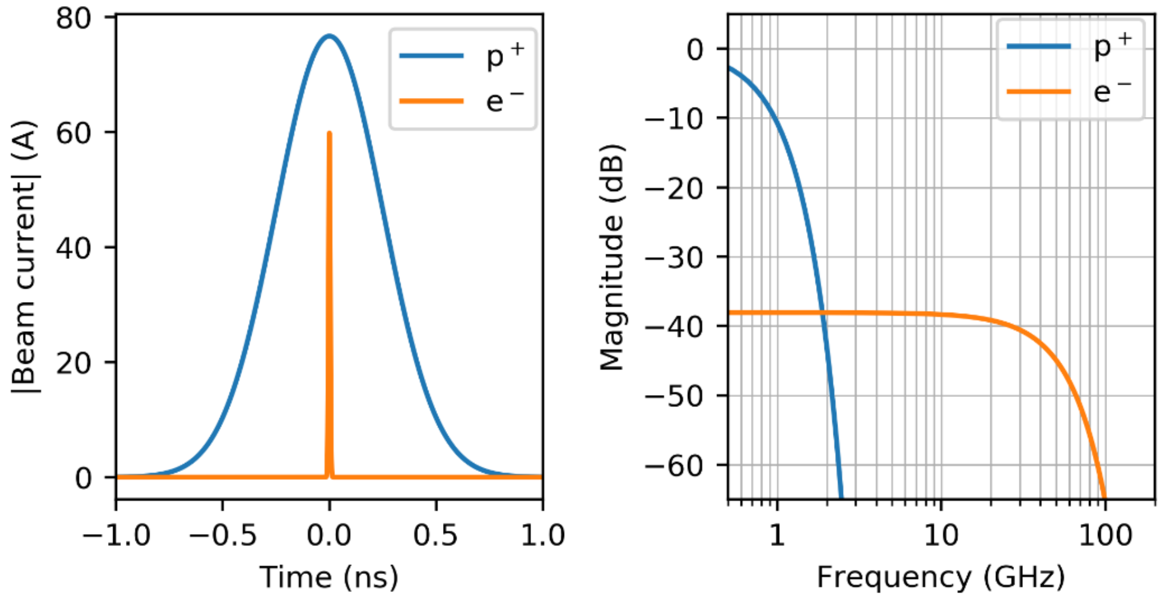


Strong synergy with CLIC/CLEAR diagnostics

BPM based on Coherent Cherenkov Diffraction Radiation



(a) t = 80 ps (b) t = 160 ps (c) t = 200 ps (d) t = 400 ps



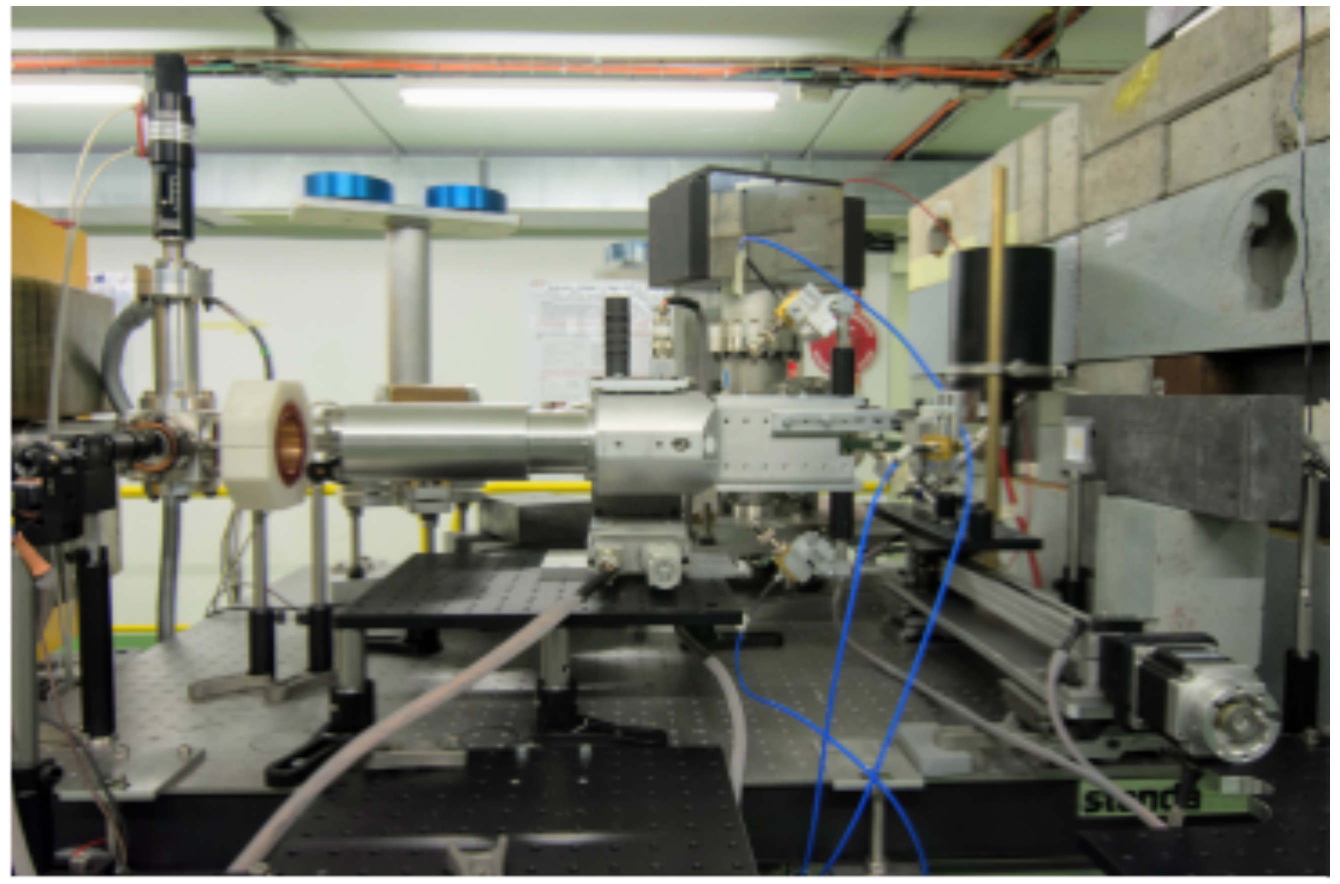
Development of a beam position monitor for co-propagating electron and proton beams

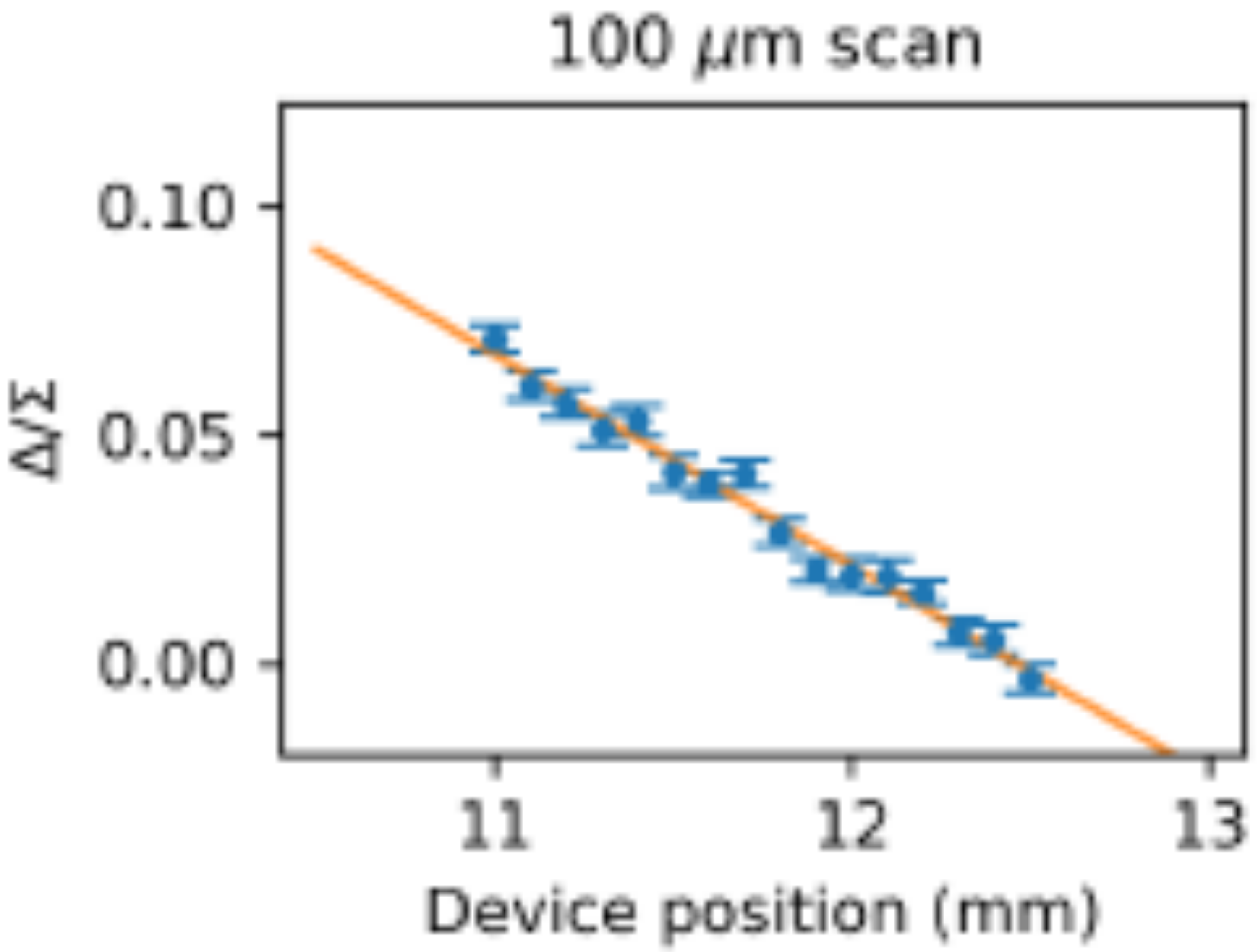
Eugenio Senes
Jesus College, Oxford

Thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy at the University of Oxford

Trinity Term 2020

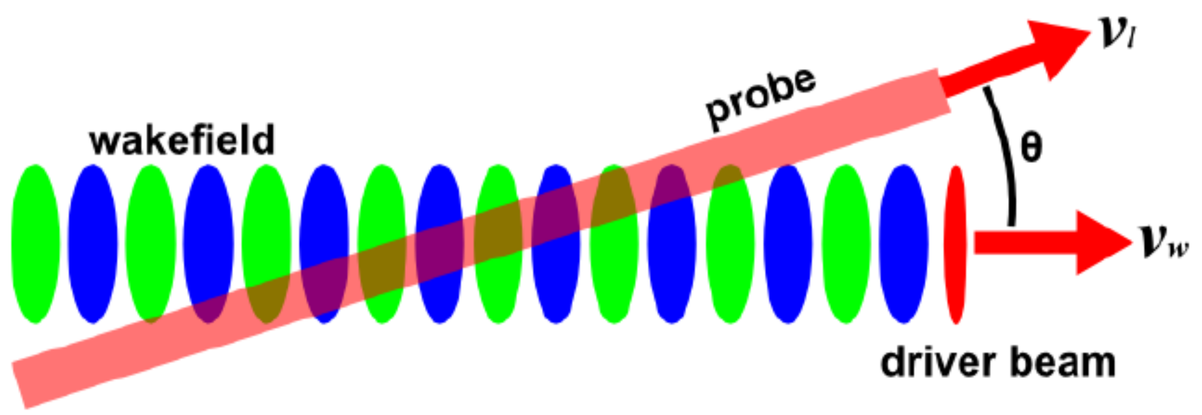
Prototype built, and tested at CLEAR:





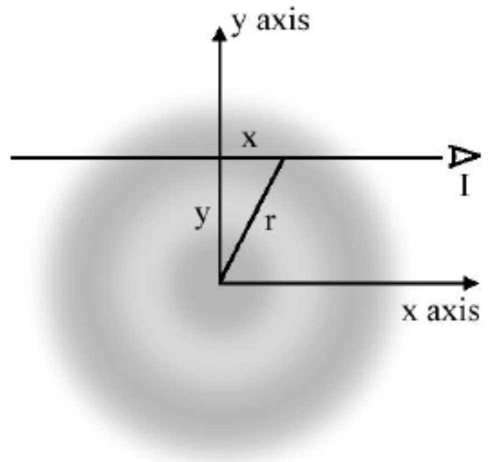
UNIVERSITY OF OXFORD

Visualising the density profile in plasma columns

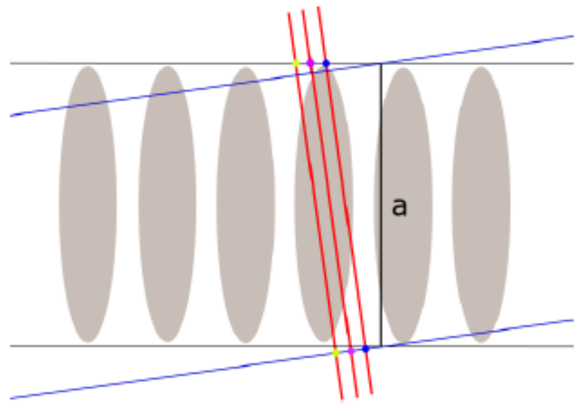


$$\frac{\Delta\omega}{\omega_0} \approx -\frac{\omega_p^2}{2\omega_0^2}\frac{1}{n_0}\int \frac{\partial n}{\partial \zeta} ds \quad \longrightarrow \quad \frac{\Delta\omega}{\omega_0} \approx -\frac{\omega_p^2}{2\omega_0^2}\frac{v_w}{v_l \sin\theta}\frac{1}{n_0}\int_y^\infty 2\frac{\partial n}{\partial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

Abel Transform



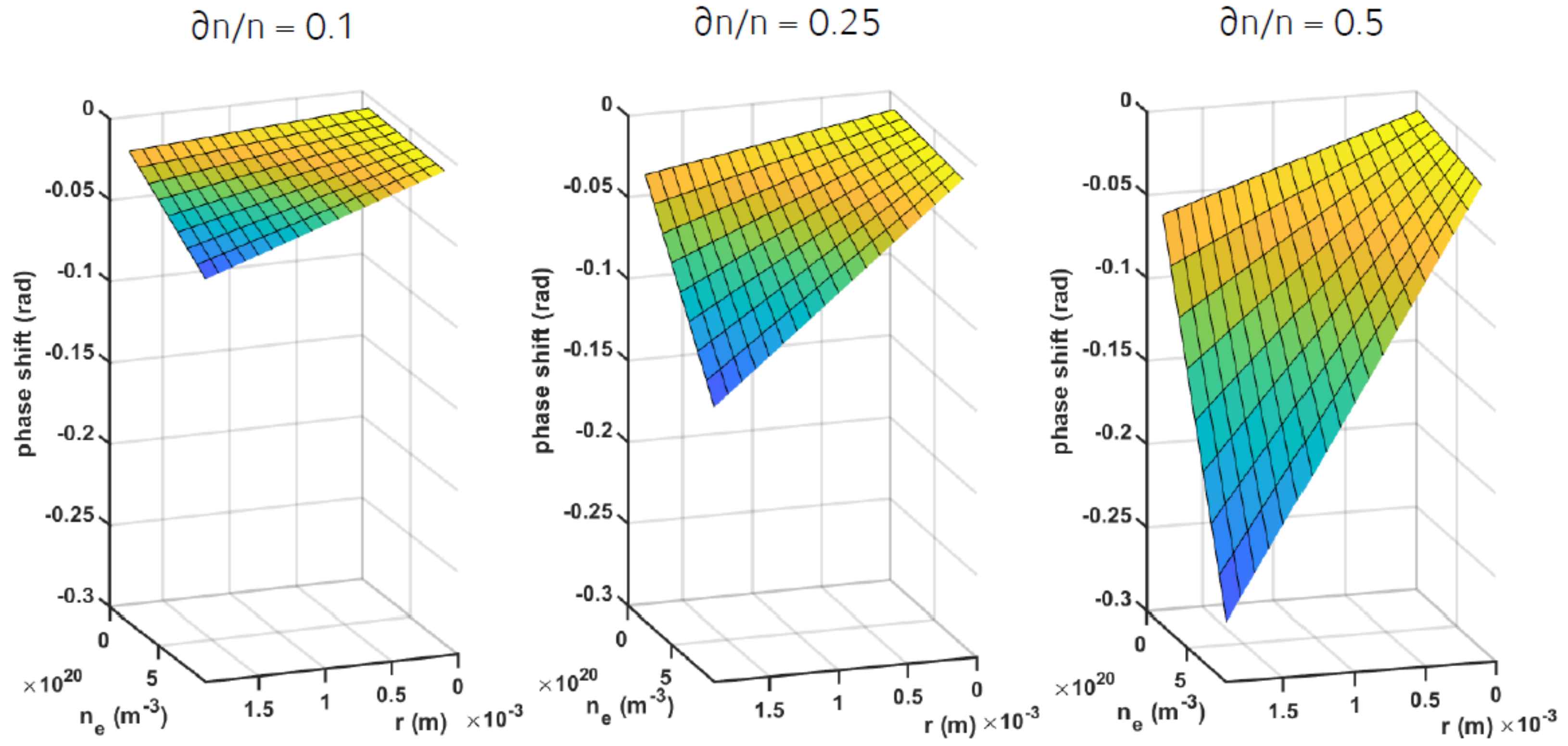
- Cylindrical symmetry assumed
- Beam passing through along x



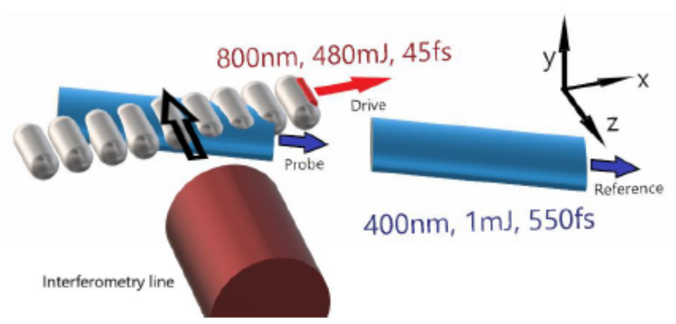
$$\tilde{f}(r,k) = -\frac{1}{\pi}\int_r^\infty \frac{\partial \tilde{F}}{\partial y}(y,k)\frac{\cosh\left(ka\sqrt{y^2 - r^2}\right)}{\sqrt{y^2 - r^2}}dy$$

$$a \equiv [(\cos\theta - u_p/v_g)/\sin\theta]$$

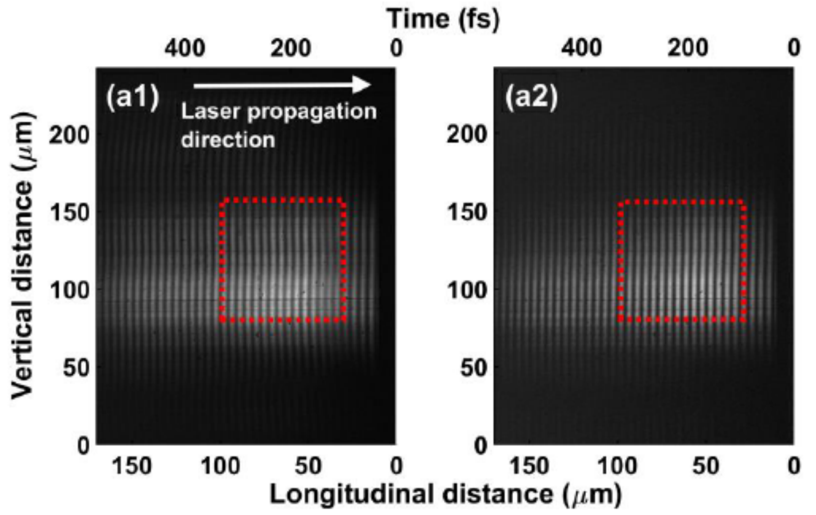
Expected phase shift for different amplitudes for AWAKE and 0.46° incidence angle



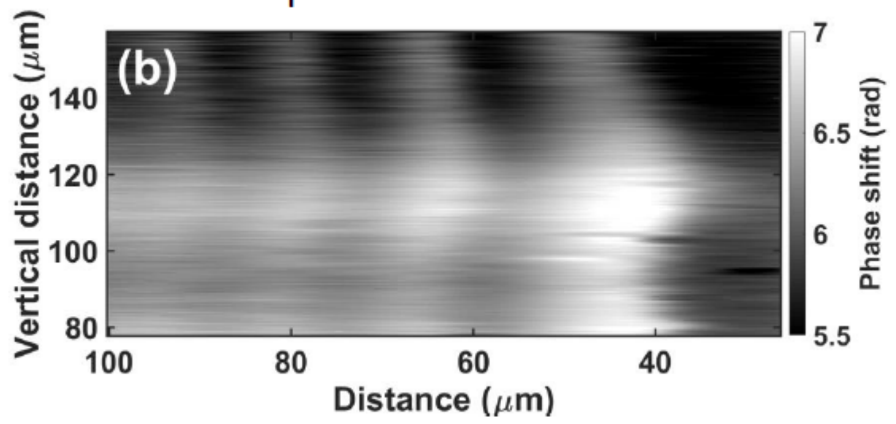
Astra experiment



Interferogram from spectrometer



Shape of wakefield

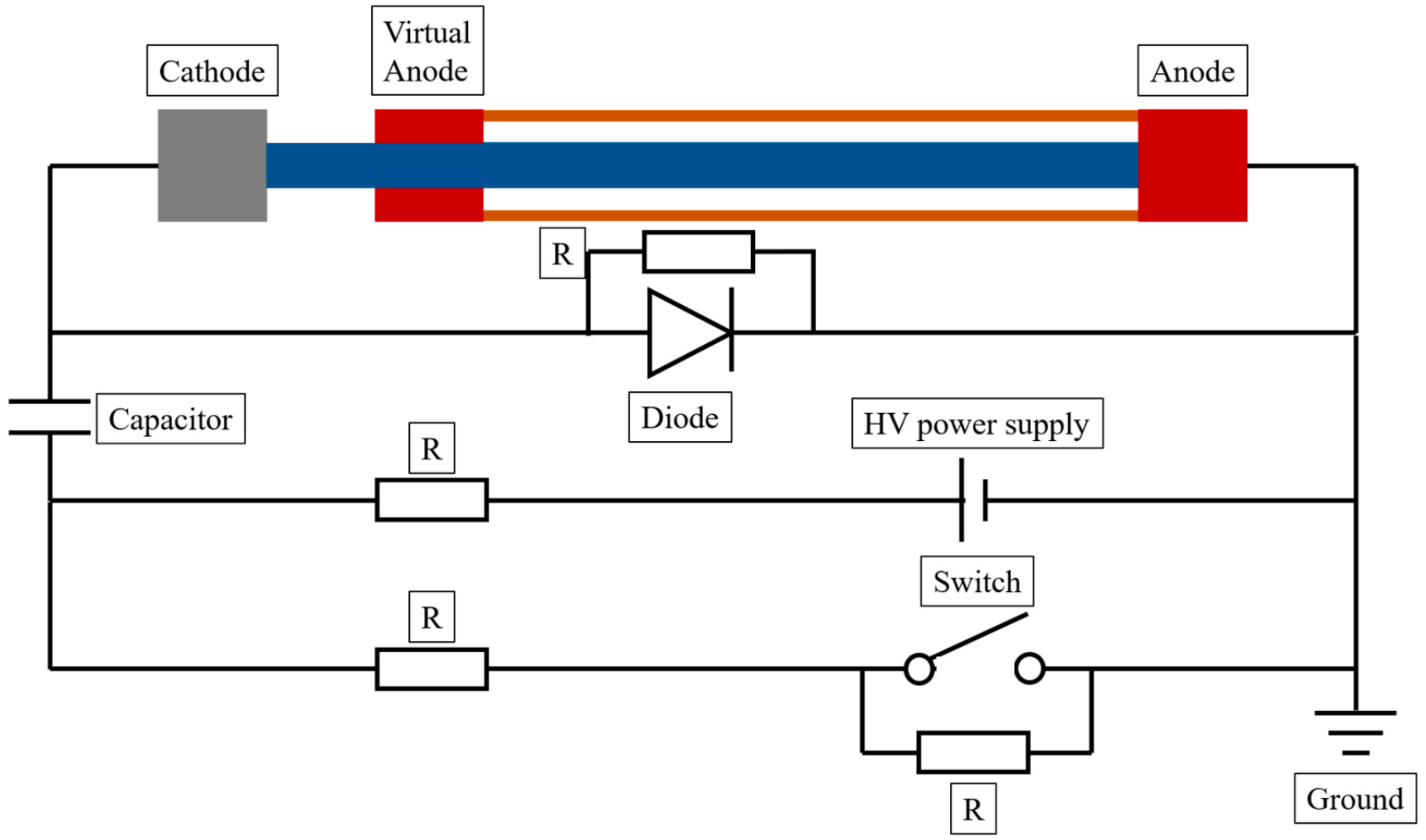


- Frequency mapped to time
- Phase shift obtained after subtracting null-shot data
- Phase unwrapping necessary
- Interest was in shape rather than amplitude estimation

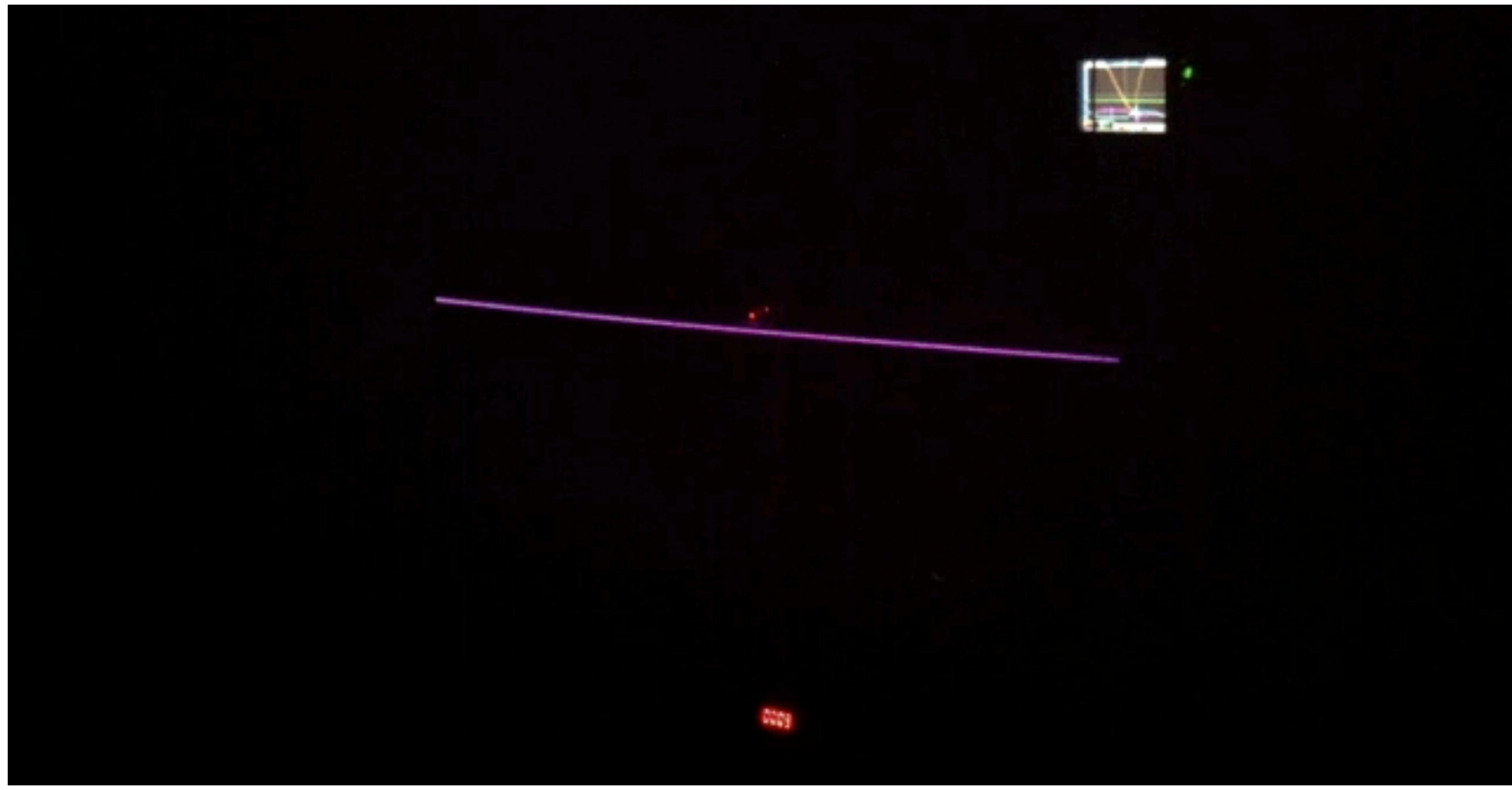
peter.norreys@physics.ox.ac.uk

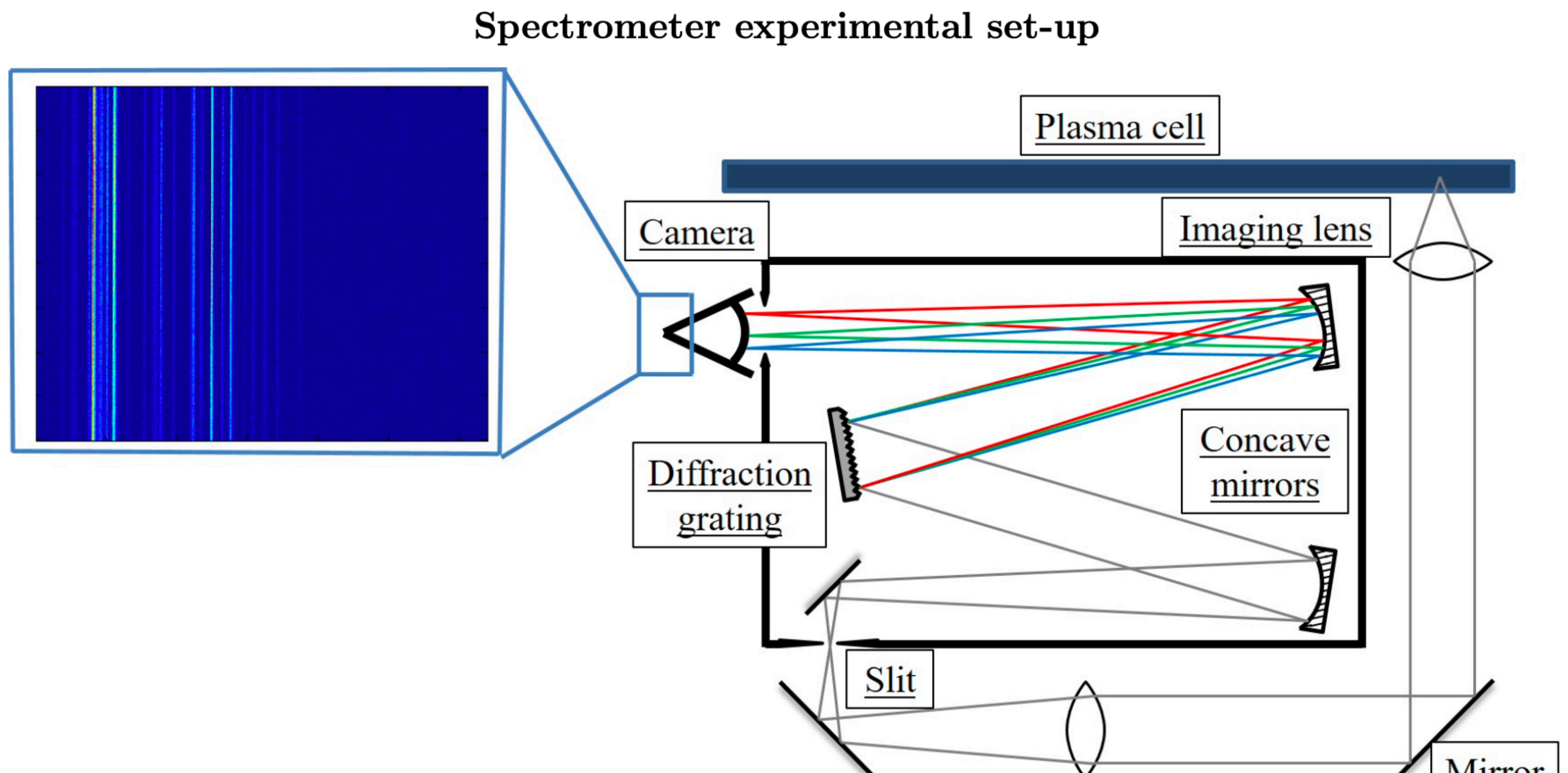
Plasma discharge development at ICL

10 m Ar discharge plasma to be developed with IST /CERN



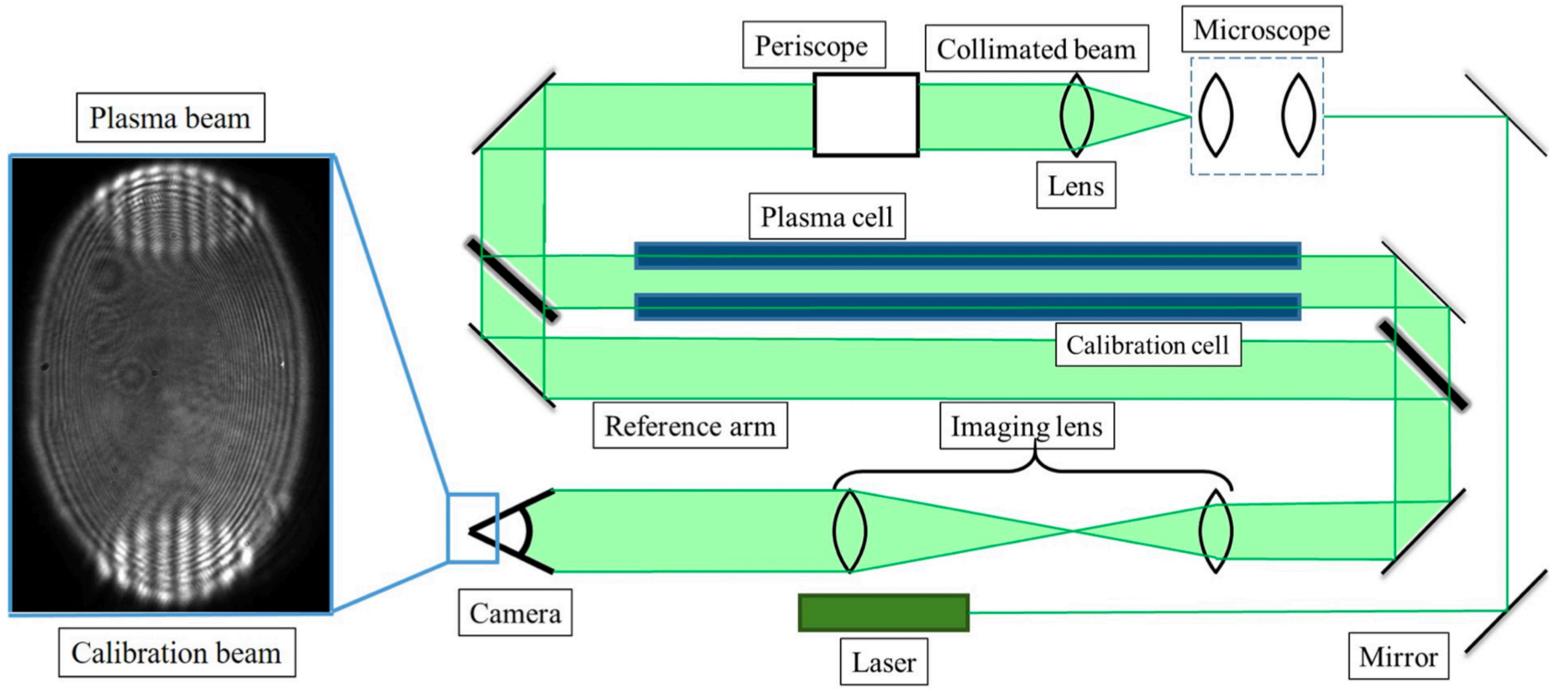
Discharge based on Lopes design with solid-state switches





Developing plasma diagnostics including:

- Spectroscopy
- Interferometry



John Adams Institute for Accelerator Science

Imperial College London

University of Oxford

Royal Holloway University of London

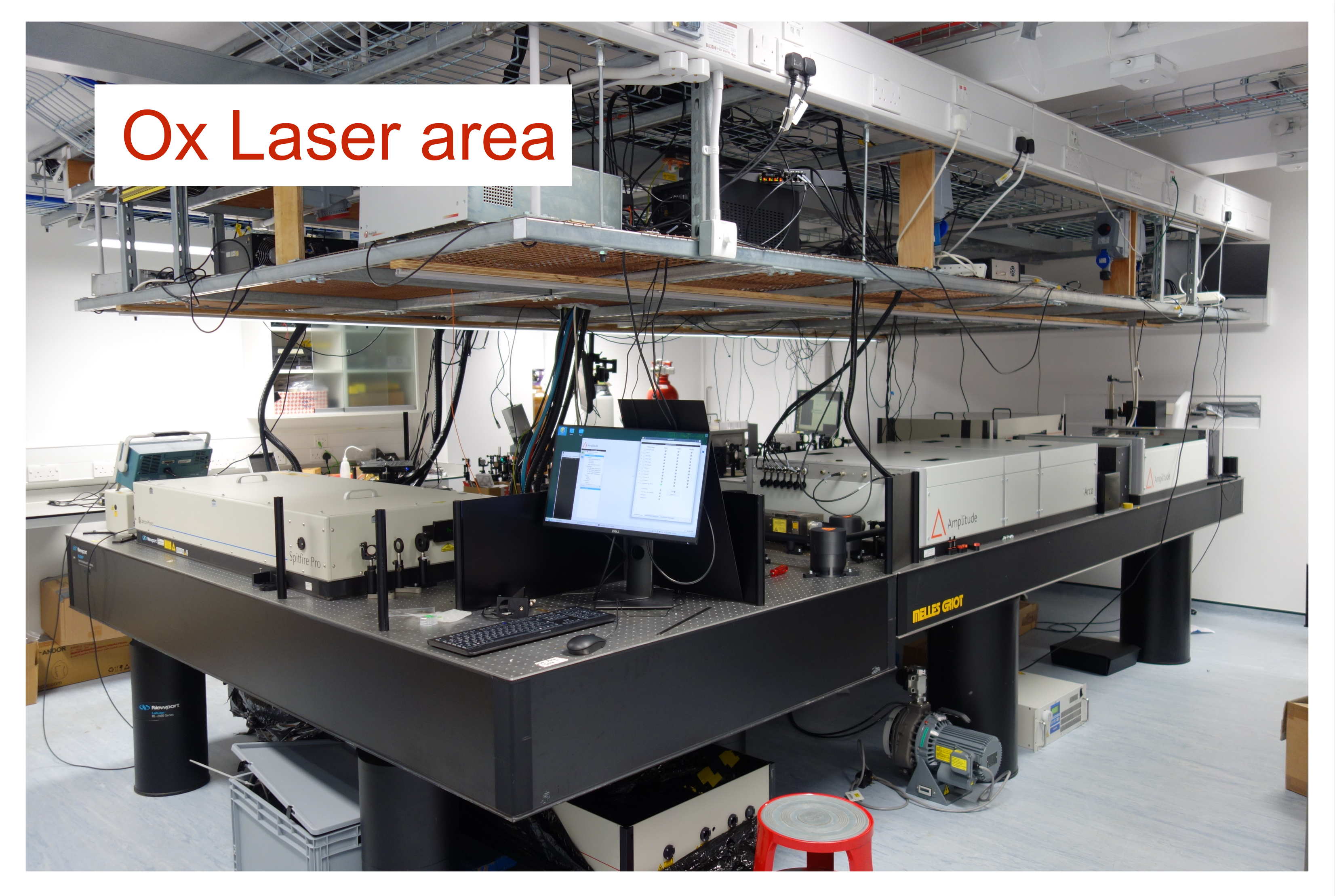
High-power laser lab development

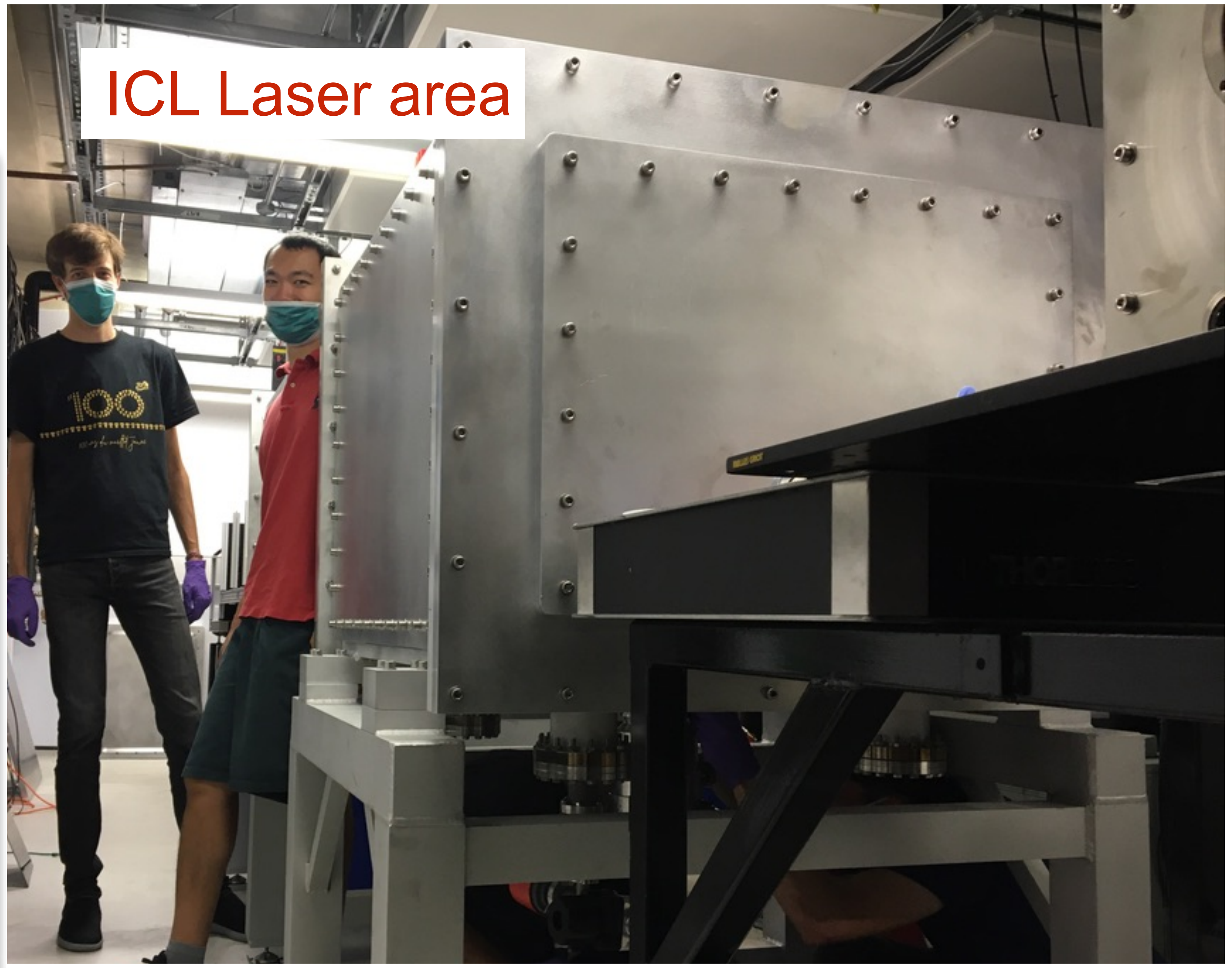
Oxford

- £1.45M (OU) + £640k (STFC) to upgrade Oxford Ti:sa laser to 600 mJ, 40 fs, 10 Hz:
  - Construction completed
  - Laser system purchased and installed
  - Preliminary experiments underway!
  - Further capital items to be from JAI grant

Imperial

- Pump laser from MPQ Munich, £205k (STFC/ICL) to upgrade existing ICL Ti:sa laser to 600 mJ, 10 Hz, / 100 mJ, 100Hz
  - Upgrade in progress
  - Further capital items from new JAI grant





Funding news

- All-Optical Plasma Channels and Electron Injection with Spatio-temporal Control
- Hooker, Walczak, Booth (Engineering), Milchberg (Maryland)
- £2m over 4 years
  - Develop high-rep-rate, GeV-scale stages
  - Use spatio-temporal control to:
    - Generate advanced plasma channels, including curved and tapered channels
    - Control electron injection
  - Demonstrate controlled electron acceleration in HOFI plasma channels for the first time

- The new intensity frontier: exploring quantum electrodynamic plasmas
- Ridgers, Murphy, Lancaster (York), Sarri (| QUB), McKenna (Strath), Mangles, Najmudin (ICL)
- >2m over 4 years
  - Investigate strong field QED effects on plasmas
  - Realisation of QED-plasmas
  - Benchmarking of QED models of electron beam-laser collisions

EuPRAXIA

- Hooker, Mangles, *Najmudin*, *Walczak*,
- CDR (>600 pages) published:
  - European Physical Journal Special Topics, 229, 3675 (2020)
- Funding request to ESFRI (596 M€)
- Consortium signed covering 40 members and 10 observers from 15 countries
- Options being investigated for laser driven site - including Rutherford Lab.
- Beam driven site already chosen - Frascati
- LWFA design of EUPRAXIA experiment at Lund Laser Centre funded by Aries

Effects of Covid

John Adams Institute for Accelerator Science

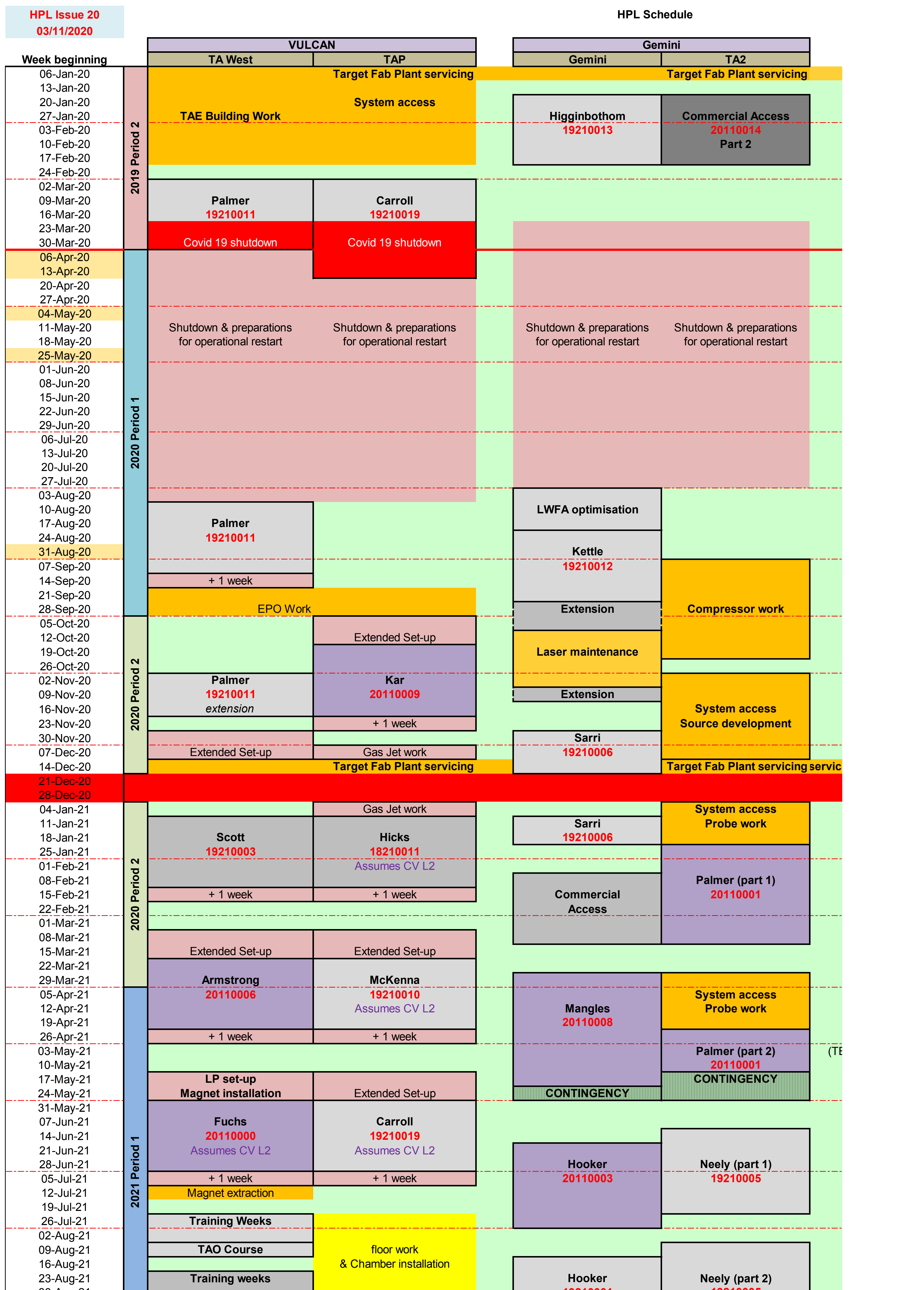
Imperial College London

University of Oxford

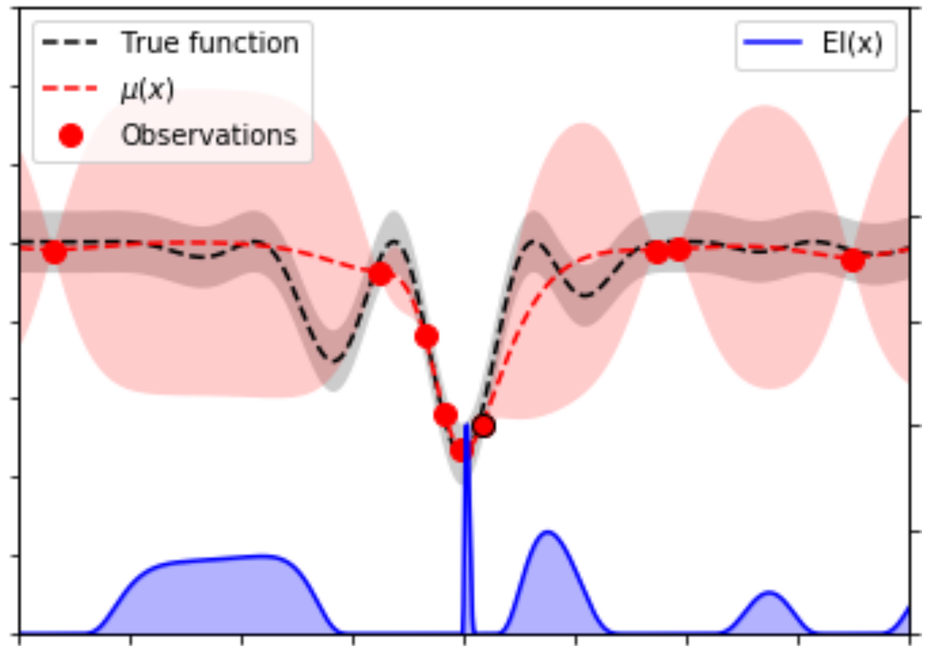
Royal Holloway University of London

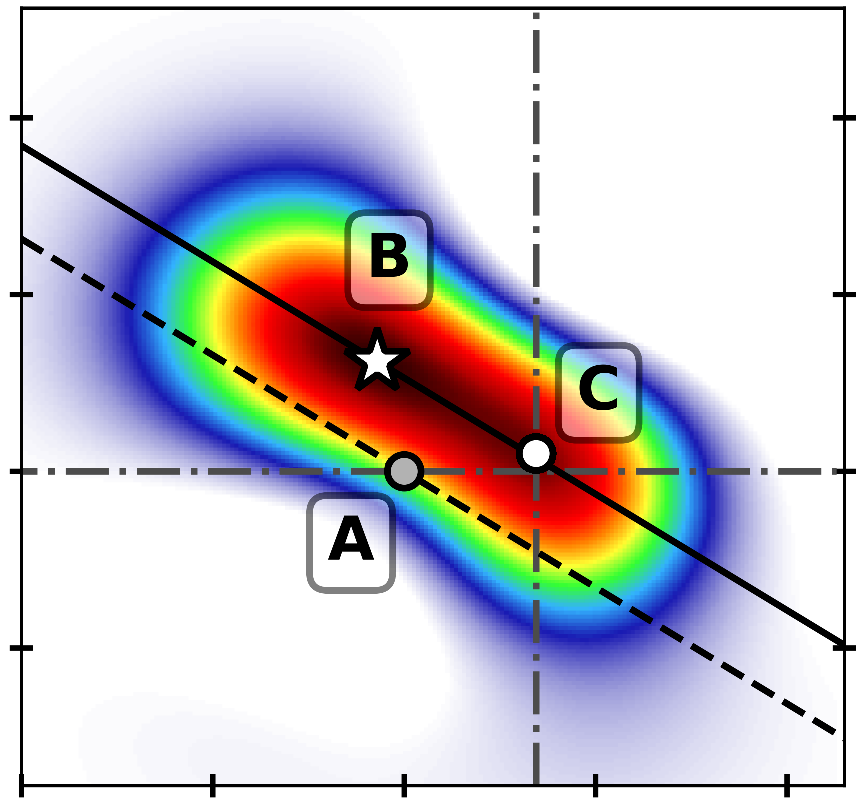
Effects of Covid

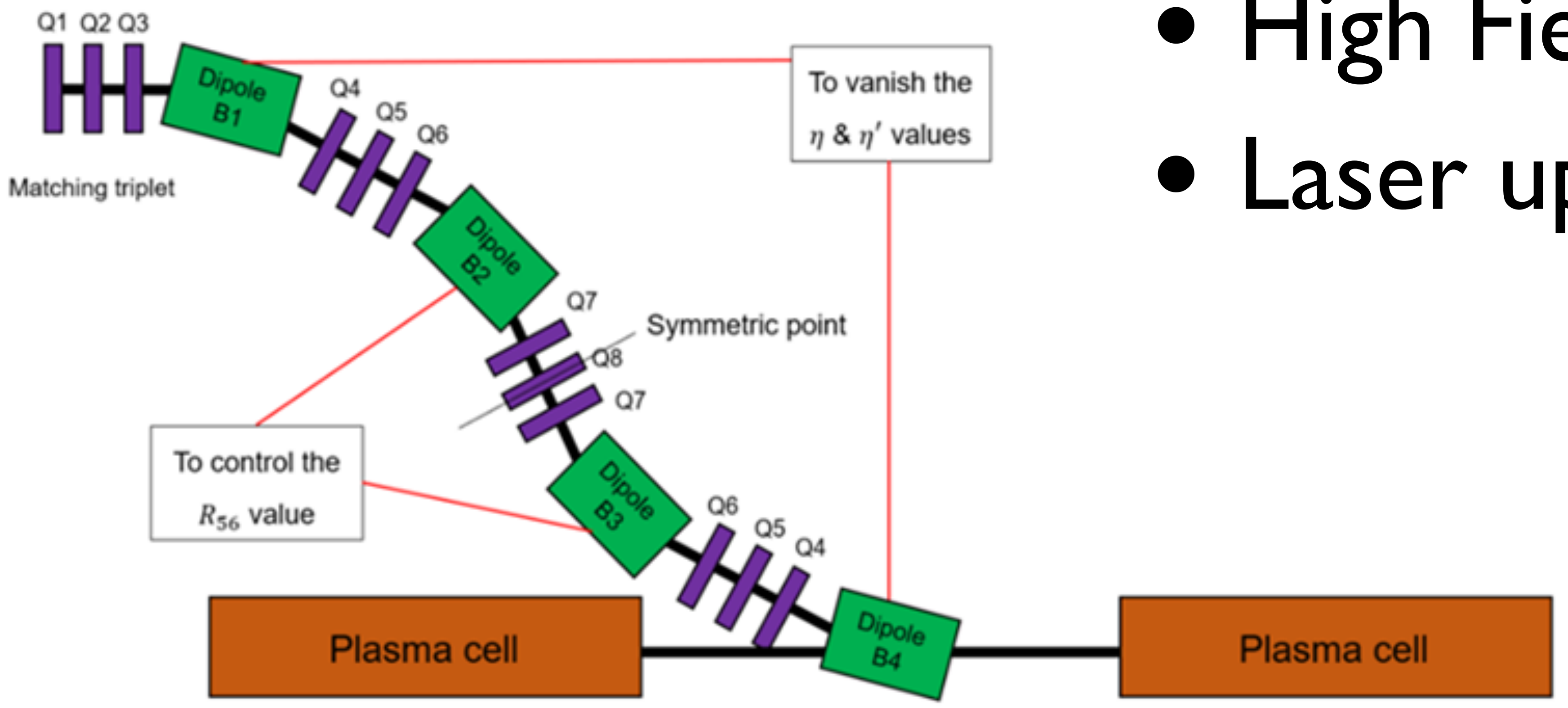
- Long delays to RAL schedules (closed from Mar-Jul 20):
  - (QUB/ICL) Collisionless evolution of Weibel-like magnetic fields - Delayed from May 20 to Jan 21
  - (ICL) Definitive measurement of quantum radiation reaction - Delayed from Jul 20 to Mar 21
  - (OX) Electron acceleration in HOFI channels- Delayed from Dec 20 to Sep 21
  - (OX) Multi-pulse LWFA experiment - Delayed from January 21 to Nov 21
  - (ICL) Hole-boring acceleration - Delayed from Jan 21 to Jul 21
  - Experiments partially remote; only 2 people on site (some experiments extended to 7 weeks)
- Unable to participate in experiments in Maryland, Colorado State, Brookhaven, Lund, CALA (Munich)
- Upgrades of new laser labs slowed



Conclusions







- Research Highlights:
  - Bayesian optimisation of LWFA implemented
  - CHOFI plasma waveguides show better guiding
  - First single shot EXAFS of laser irradiated samples
- Other highlights:
  - New grants for:
    - AWAKE
    - HOFI waveguides/spatiotemporal control
    - High Field Effects
    - Laser upgrades to OX, ICL lasers