Latest Results from the FLASHForward Experiment

Jonathan Wood

A. Kanekar, J. Beinortaitė, J. Björklund Svensson, L. Boulton, J. Cowley, R. D'Arcy, A. Ferran Pousa, B. Foster, M. J. Garland, P. González-Caminal, M. Huck, H. Jones, C. A. Lindstrøm, G. Loisch, T. Long, A. Maier, S. M. Mewes, J. Osterhoff, F. Peña, S. Schröder, M. Thévenet, S. Wesch, M. Wing

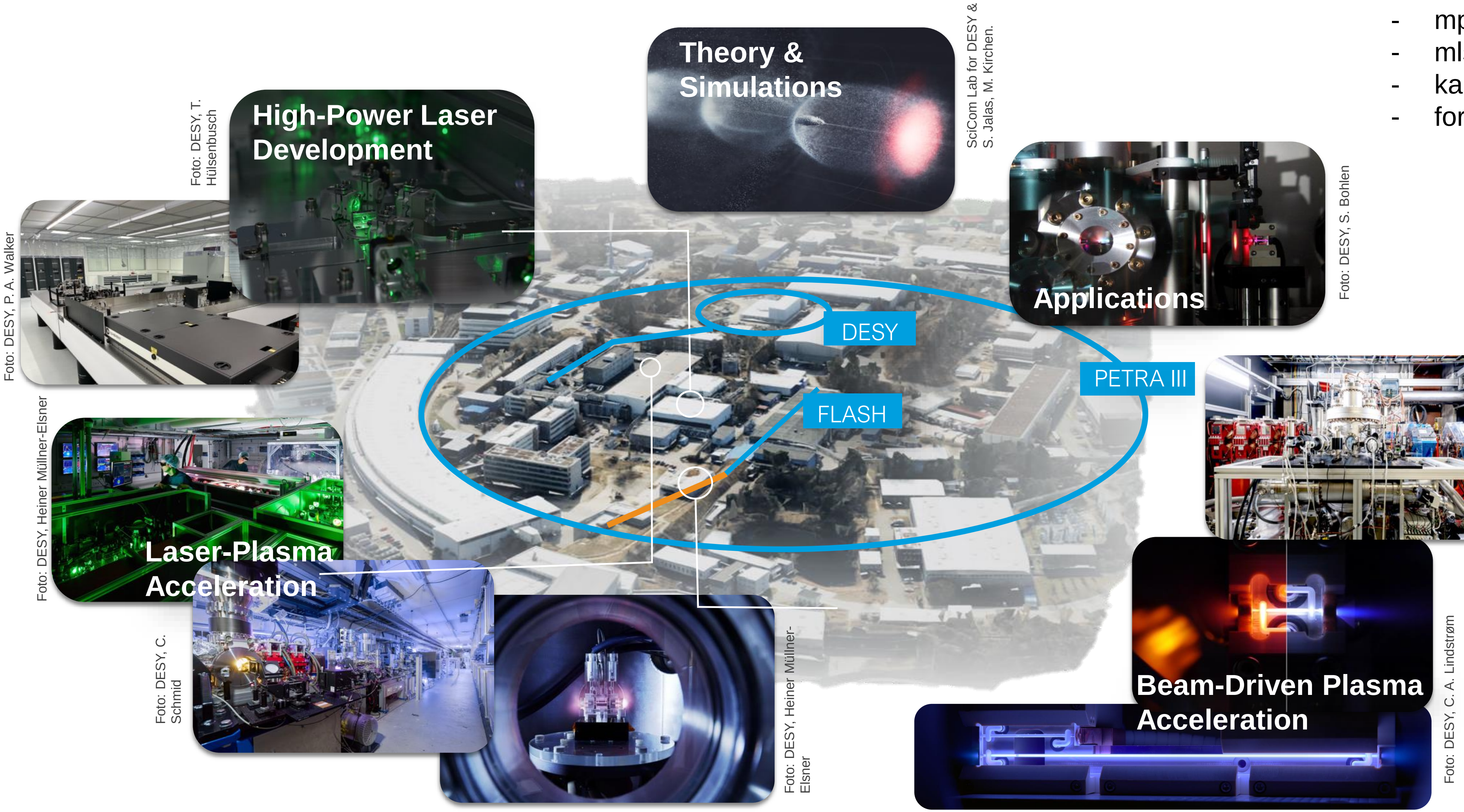
2024 AAC Conference, Naperville, Illinois

HELMHOLTZ

DESY.

Plasma Acceleration at DESY

For More Info:
- mpa.desy.de
- mls.desy.de
- kaldera.desy.de
- forward.desy.de

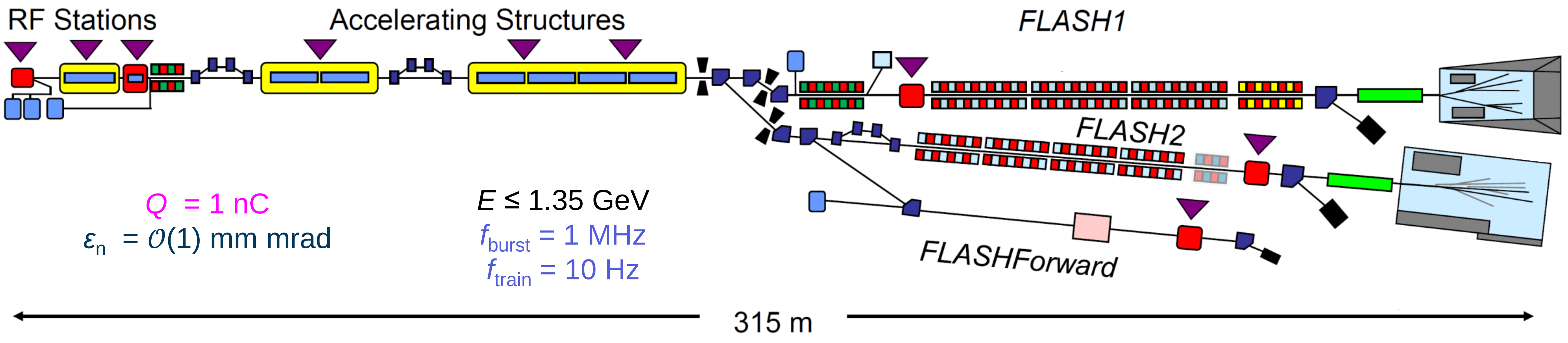


Plasma Acceleration at DESY

Who we are

- Laser Scientists
- Plasma Accelerator Physicists
- Laser & Beamline Engineers
- Software, Mechanical and CAD Engineers
- Scientific Project Management
- Safety Coordination & Admin Support
- A team of 50+ people and growing
- Strong support from DESY Directorate

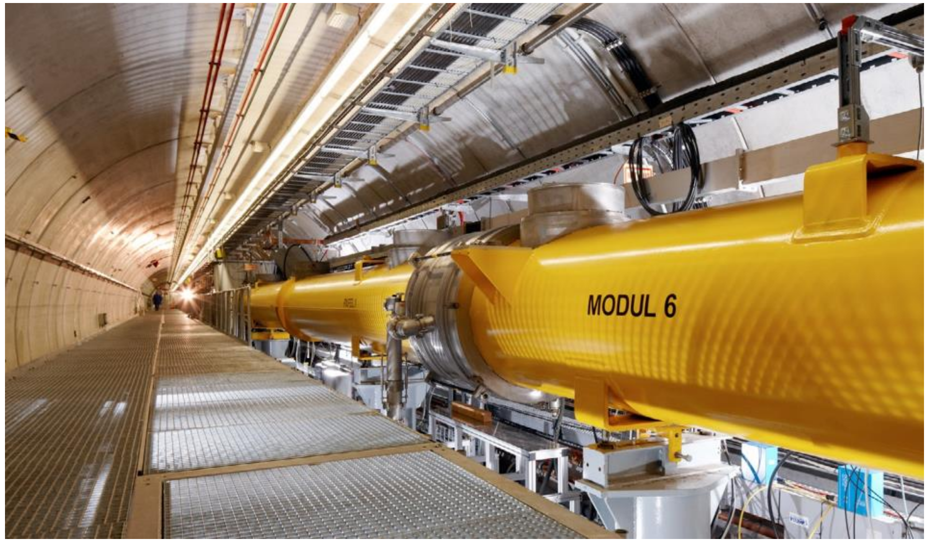
FLASH



$Q = 1$ nC
$\varepsilon_n = \mathcal{O}(1)$ mm mrad

$E \leq 1.35$ GeV
$f_{burst} = 1$ MHz
$f_{train} = 10$ Hz

- SRF linac delivering trains of high-quality bunches for XUV & soft x-ray FEL beamlines & the FLASHForward plasma-accelerator beamline.
- Approx 800-900 h of FF≫ beamtime per year. We have full machine control for around 400 of these.



https://flash.desy.de/
B. Faatz at al., NJP, 2016, 10.1088/1367-2630/18/6/062002

FLASHForward Facility

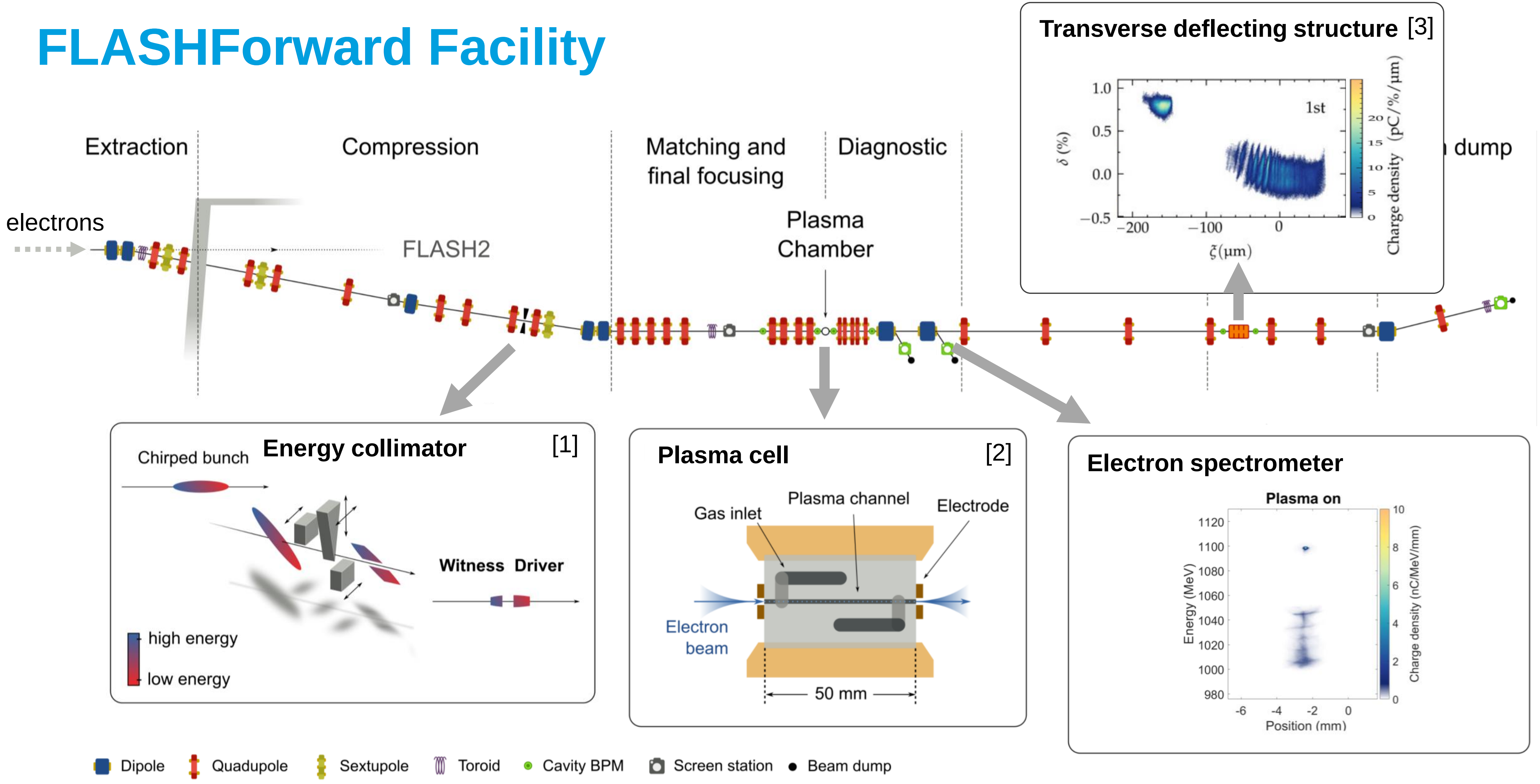
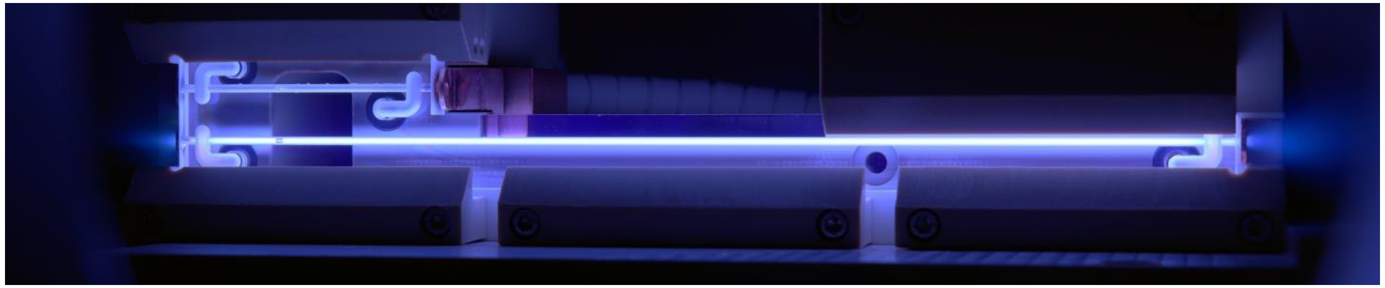


Diagram courtesy: P. González Caminal

[1] S. Schröder et al., J. Phys. Conf. Ser. 1596, 012002 (2020)
[2] J. M. Garland et al., Rev. Sci. Instrum. 92, 013505 (2021)
[3] P. González Caminal et al., Phys. Rev. Accel. Beams 27, 032801 (2024)

FLASHForward Goals



To develop a plasma stage with:

Bunch quality preserving acceleration

- Energy spread preservation
- Emittance preservation
- Brightness preservation

High energy gain and efficiency

- Towards energy doubling
- High overall efficiency (witness energy gain / driver energy loss)

High repetition rate capabilities

- Plasma evolution studies
- Experimenting with various bunch train structures
- Then: high average power

Simultaneously!

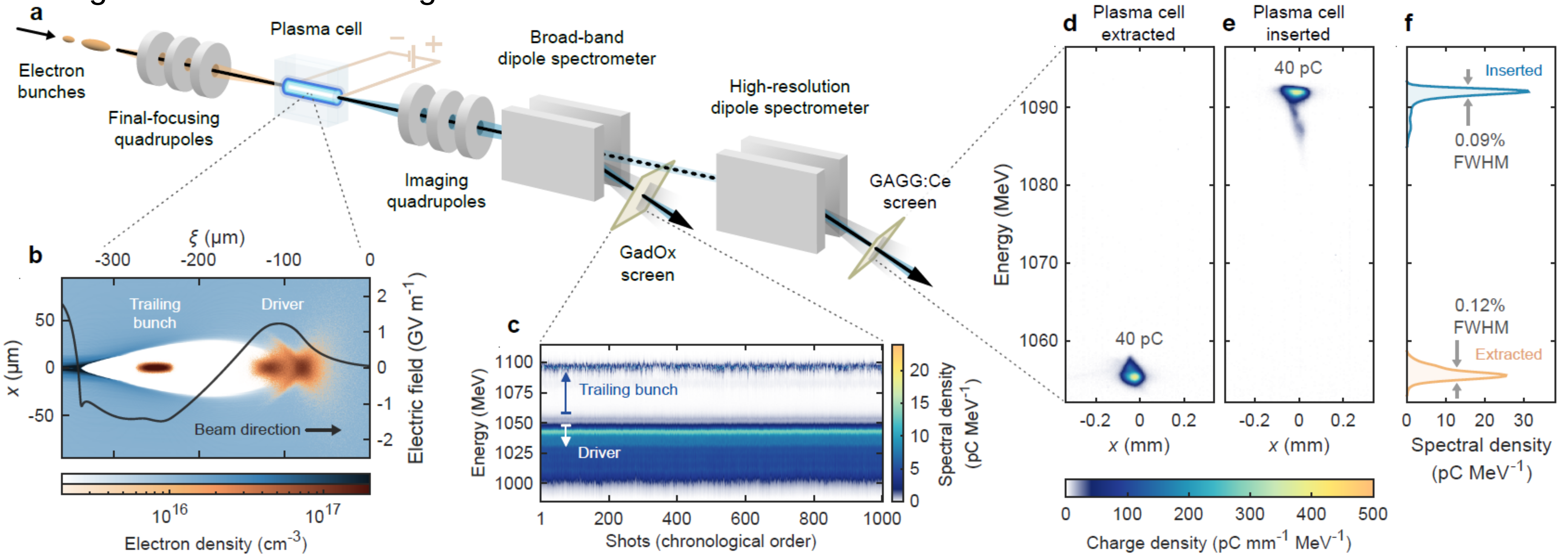
Emittance Preservation: Motivation and Setup

Beam Quality Preservation

- It is essential to preserve accelerating beam quality for major applications (FEL, collider).
- Low emittance required for high luminosity & short-wavelength free-electron lasing.

Setup

- 400 pC, 1 kA driver, 40 pC witness, n_e=1.2x10^{16} cm^{-3}.
- Established an optimally beamloaded working point



C. A. Lindstrøm, Nat. Comms., **15**, 6097 (2024), https://www.nature.com/articles/s41467-024-50320-1

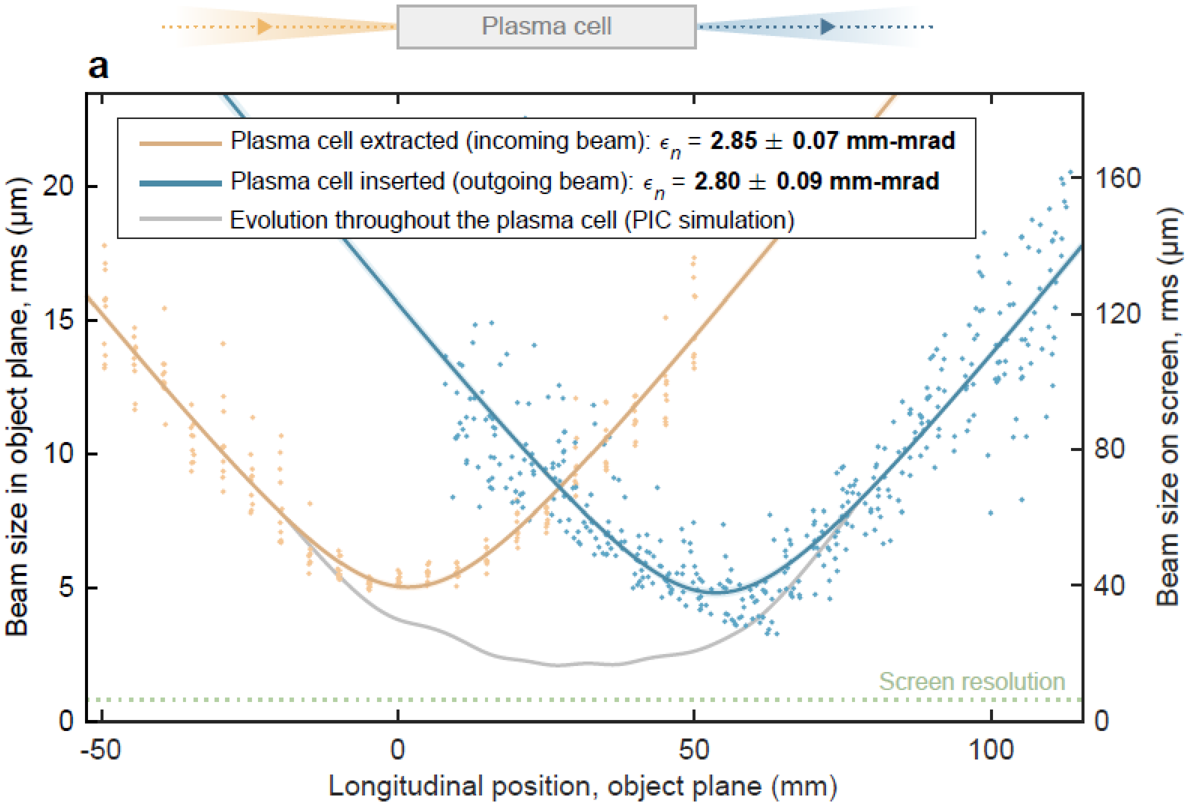
Emittance Preservation

Emittance Measurements

- Emittance calculated from object plane scans of the witness bunch on a high-resolution screen.
- Comparison between non-interacted (plasma cell extracted) and accelerated bunch.

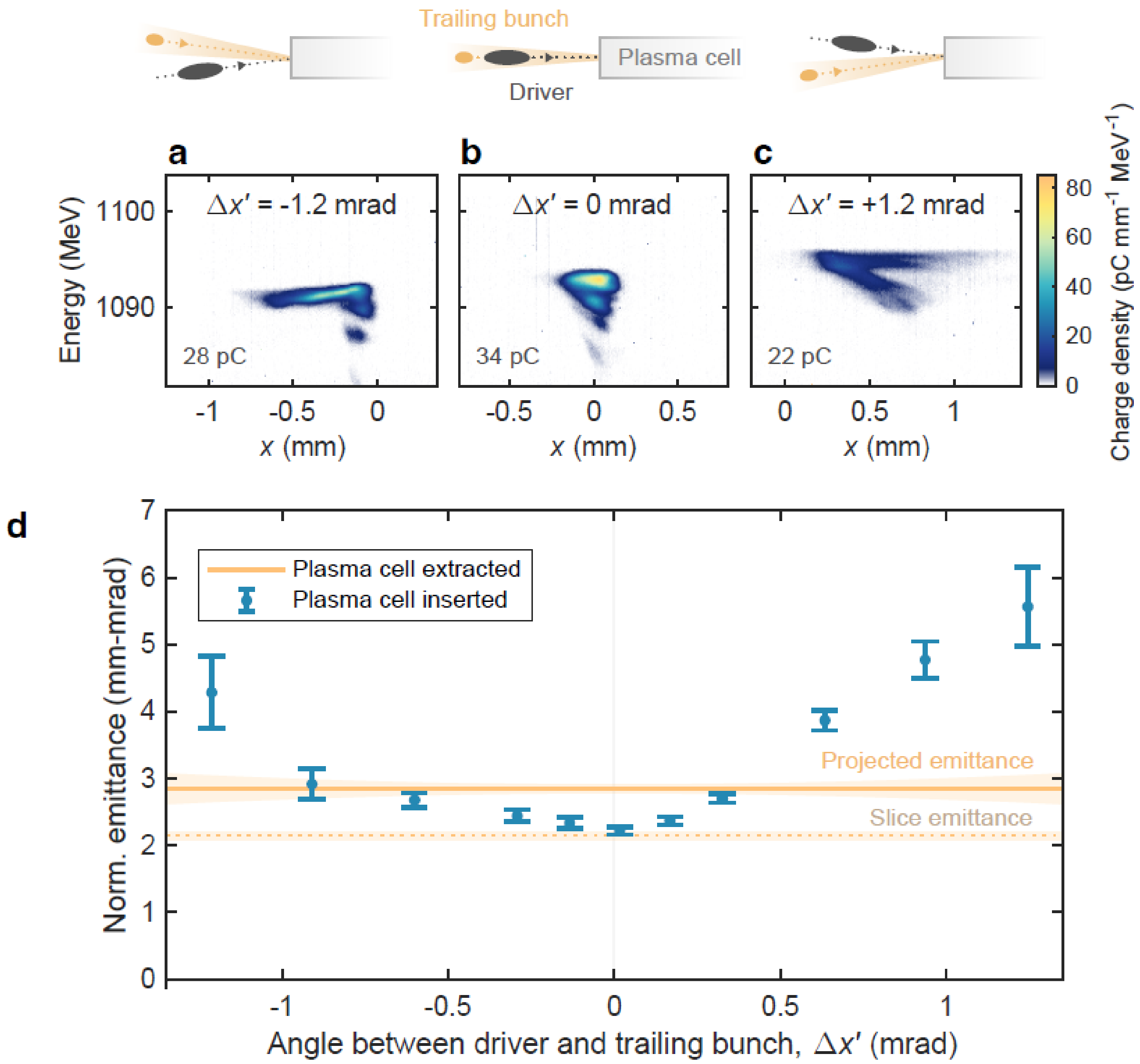
Results

- Object plane scans for non-interacted and accelerated bunches show same emittance, except the latter is moved 50 mm downstream.
- $\varepsilon_{n,x}$ preseved at 2.8 mm-mrad within 3% uncertainty.



C. A. Lindstrøm, Nat. Comms., **15**, 6097 (2024), https://www.nature.com/articles/s41467-024-50320-1

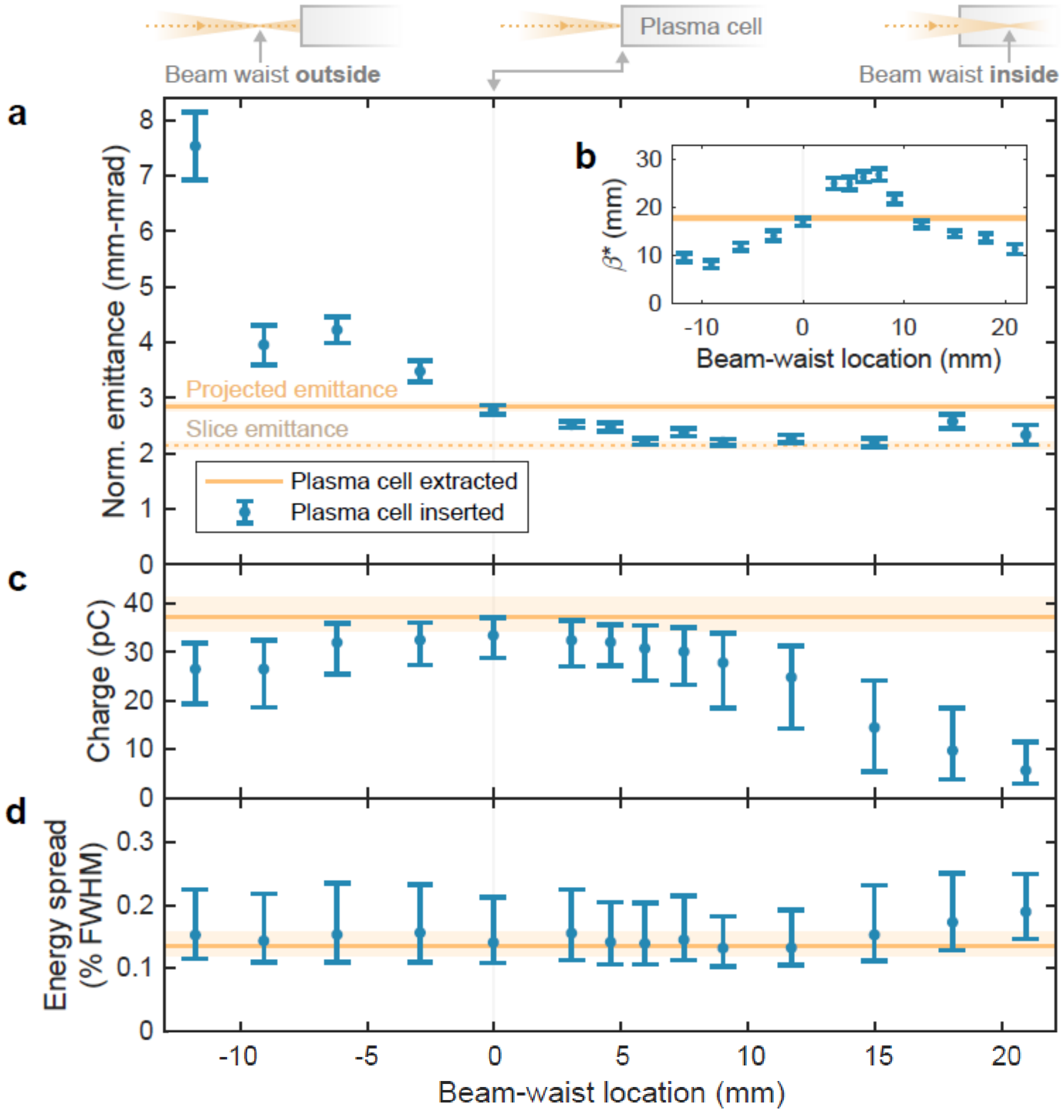
Tolerances



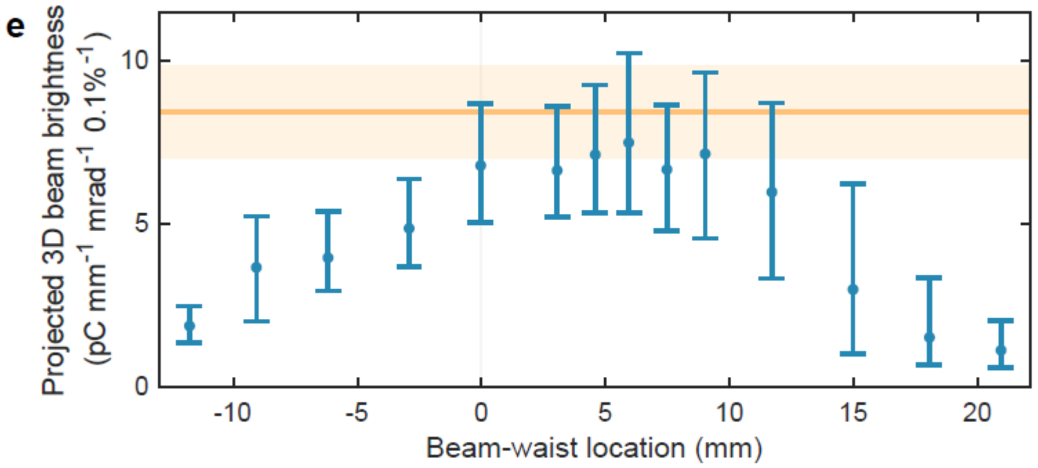
- Angular misalignment tolerance (ε_n growth from varying oscillation radii along the bunch) < 0.5 mrad offset required for 50 mm plasma.
- Simulations show < 0.1 mrad offset needed for 500 mm plasma, although the emittance could still be preserved.
- Best to build up from shorter plasmas (50 mm = 870^o phase advance here).

C. A. Lindstrøm, Nat. Comms., **15**, 6097 (2024), https://www.nature.com/articles/s41467-024-50320-1

Tolerances



- Varied the witness beam waist longitudinal position to observe the effects of mismatching.
- Trade-off between focussing before the plasma (mismatching) and too far in to the plasma (charge loss).
- Regime with many instances (~40%) of 3D brightness preservation focussing slightly in to the plasma.



C. A. Lindstrøm, Nat. Comms., **15**, 6097 (2024),
https://www.nature.com/articles/s41467-024-50320-1

Bayesian Optimisation

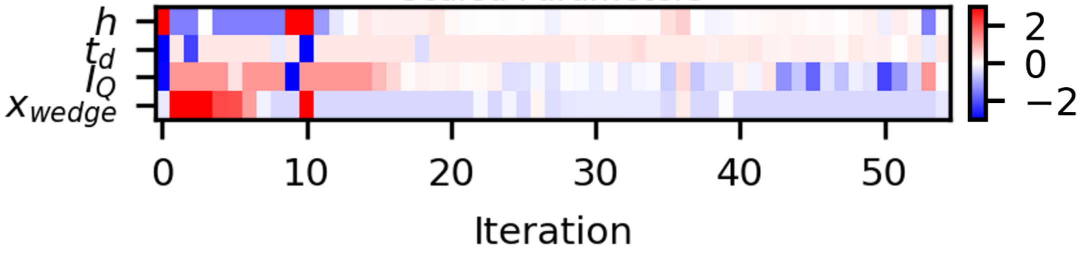
Aim

- Automate optimisation routines with fast optimum finding & gain insights in to new working points.

$$G = (\Delta E)^2 \left(\frac{\mathrm{d}Q}{\mathrm{d}E}\right)_{max}$$

Witness energy gain

Peak spectral density



Methods

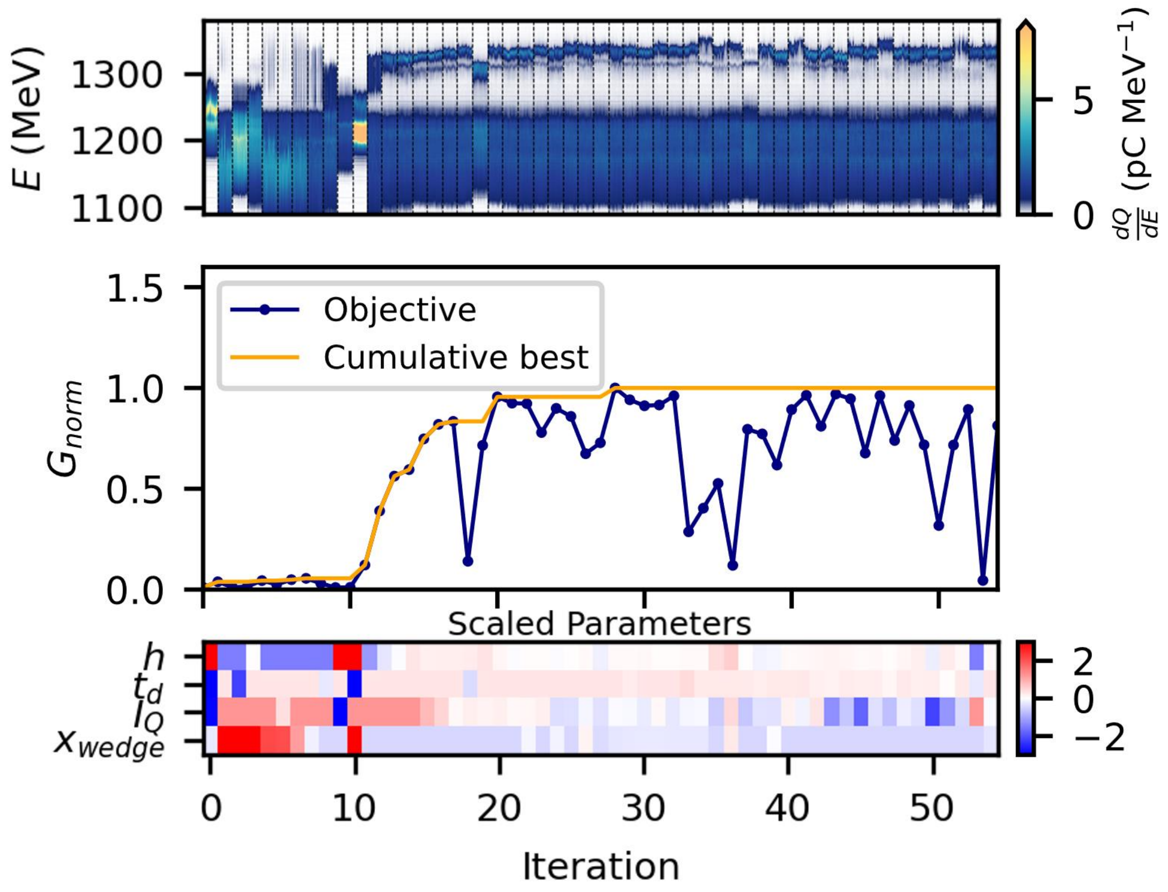
- Developments made to the Optimas library to improve functionality for experiments [4].
- Maximisation of goal function *G*.
- ~ Closed loop- software automatically analyses 20-point averaged data & updates the machine settings.
- Exposed 4 parameters to the optimizer:
  - Chirp *h* (compression)
  - Discharge delay t_d (plasma density)
  - Current I_Q of a quad in a dispersive section (1st order horizontal dispersion)
  - Position of wedge x_{wedge} (driver/ witness charge distribution)

[4] A. Ferran Pousa et al., PRAB, 2023, 10.1103/PhysRevAccelBeams.26.084601

Bayesian Optimisation

Beam & plasma parameters

- Bunch parameters:
  - 1208 MeV (witness)
  - Driver: 230 pC, 1 kA peak currrent
  - Driver/ witness 3.5 / 1 mm-mrad $\varepsilon_{n,x}$, β ~ 10 mm



Results

- Starting from ~ noise, converged on a solution in 28 iterations to:
  - (34 ± 2) pC accelerated charge
  - (103 ± 1) MeV energy gain in 50 mm (2.1 GV/m)
  - Scan time: 37 minutes total, 19 to reach optimum

J. C. Wood et al., Proc. 15th IPAC, 2024, doi: 10.18429/JACoW-IPAC2024-MOPR40

Low-Energy-Spread Acceleration in a 195 mm Plasma Cell

Setup

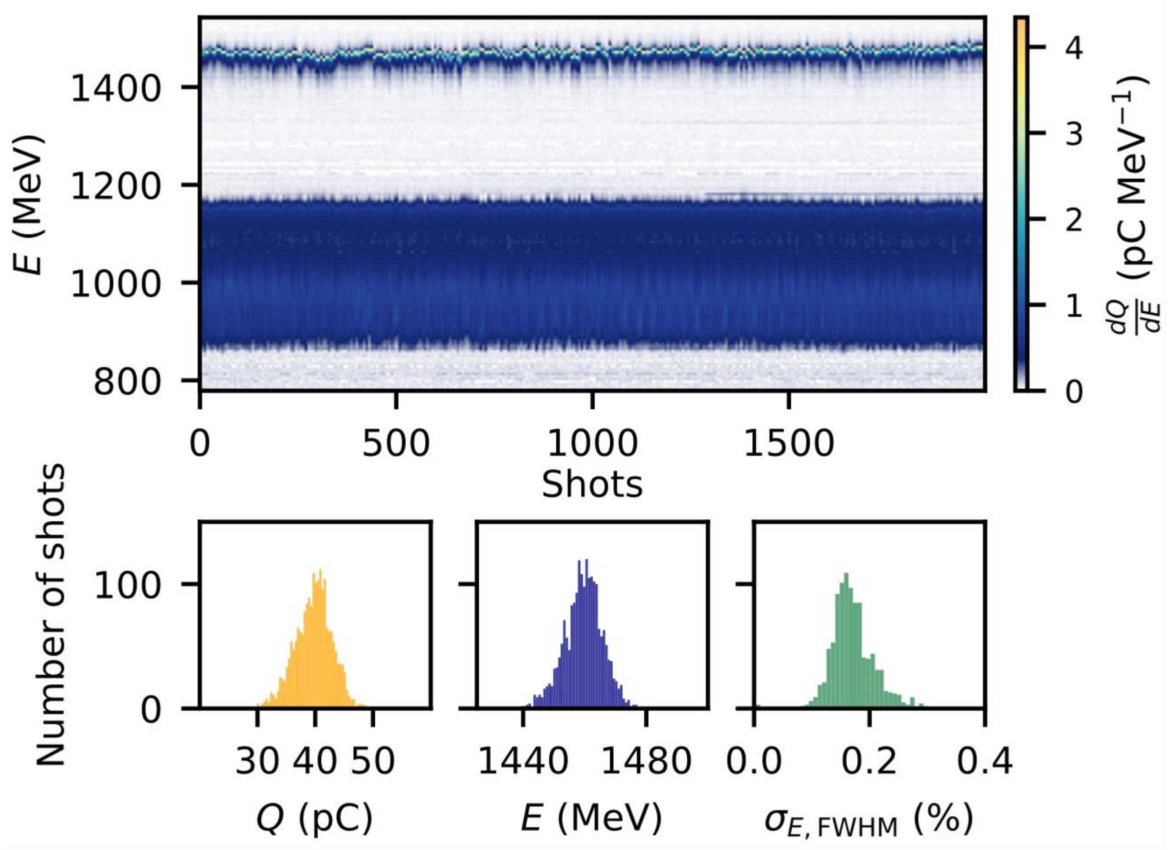
- Bunch compression limits our acceleration gradients- longer acceleration distances required.
- Switched 50 mm cell for a 195 mm cell:
  - Relaxed n_e from 10 to 7.8x10^{15} cm^{-3}
  - Made some small manual tweaks to the scraper position & width.

Results

- From 2000 consecutive events achieved:

Q (pC)	E (MeV)	$\sigma_{E,FWHM}$ (%)	Efficiency (%)
40 ± 3	1460 ± 6	0.17 ± 0.04	3.6 ± 0.3

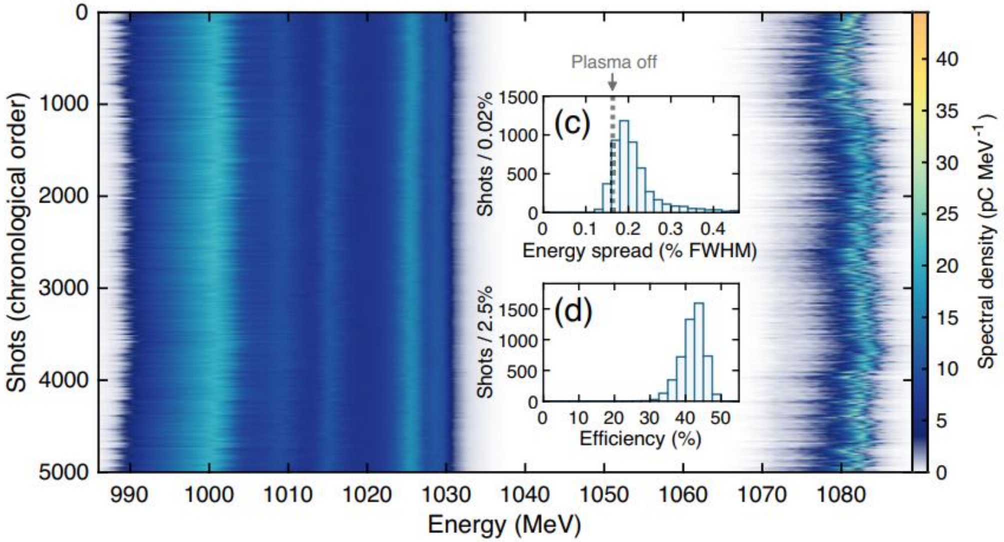
- 1.3 GV/m acceleration rate (250 MeV gain), 2.6% energy gain stability.

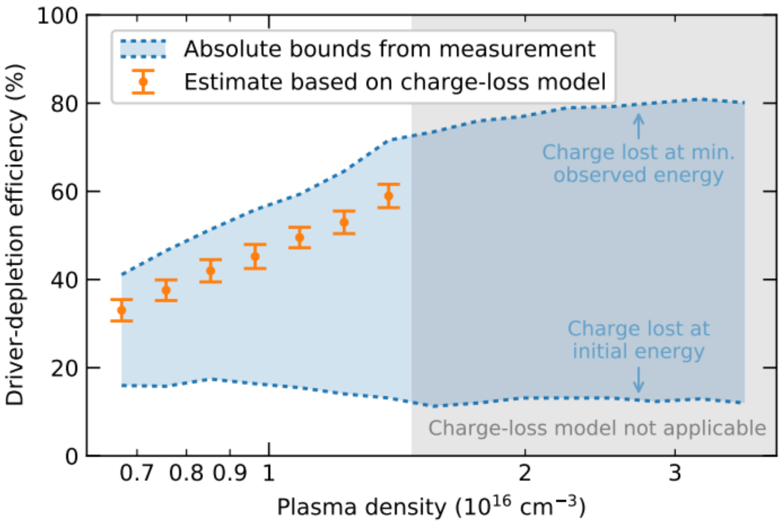


J. C. Wood et al., Proc. 15th IPAC, 2024, doi: 10.18429/JACoW-IPAC2024-MOPR40

Energy Efficiency Overview

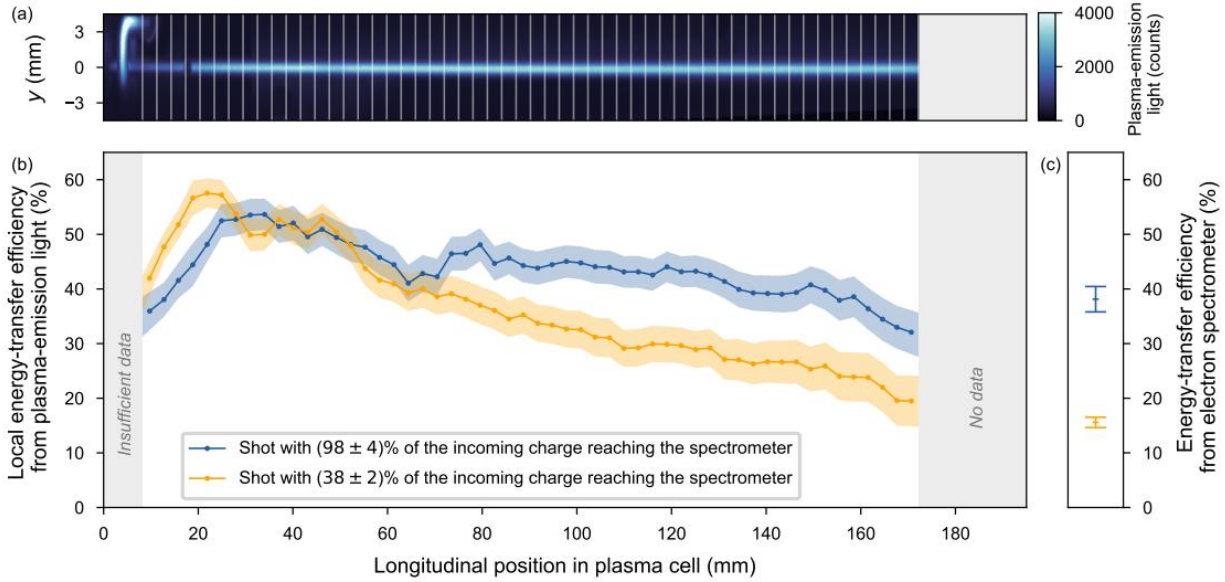
C. A. Lindstrøm et al., 2021, PRL, https://doi.org/10.1103/PhysRevLett.126.014801





F. Peña et al., 2023, https://arxiv.org/pdf/2305.09581

L. Boulton et al., 2022, https://arxiv.org/abs/2209.06690



- Previous experimental results at FF≫ indicate ~40% instantaneous efficiency (witness energy gain/ driver energy loss).
- Also (59 ± 3) % driver energy loss before reacceleration.
- Wish to combine these to achieve high overall efficiency (witness energy gain/ initial driver energy), and improve on previous 3.6%.

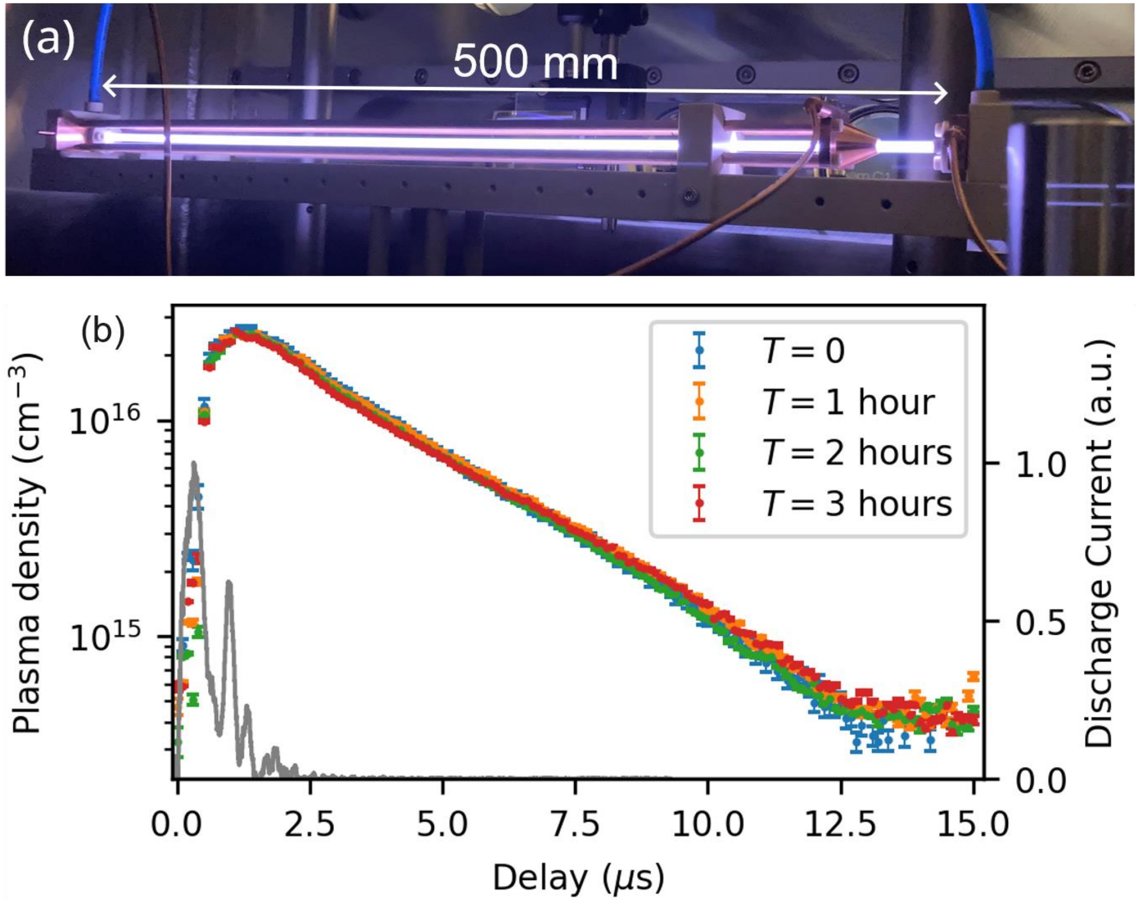
500 mm Plasma Cell Development

Cell Design

- Wish for 0.5 GeV gain at 1 GV/m: 500 mm plasma at 0.8-1.2x10^{16} cm^{-3}.
- Ar gas, 3.2 kV glow discharge required for stable discharges.

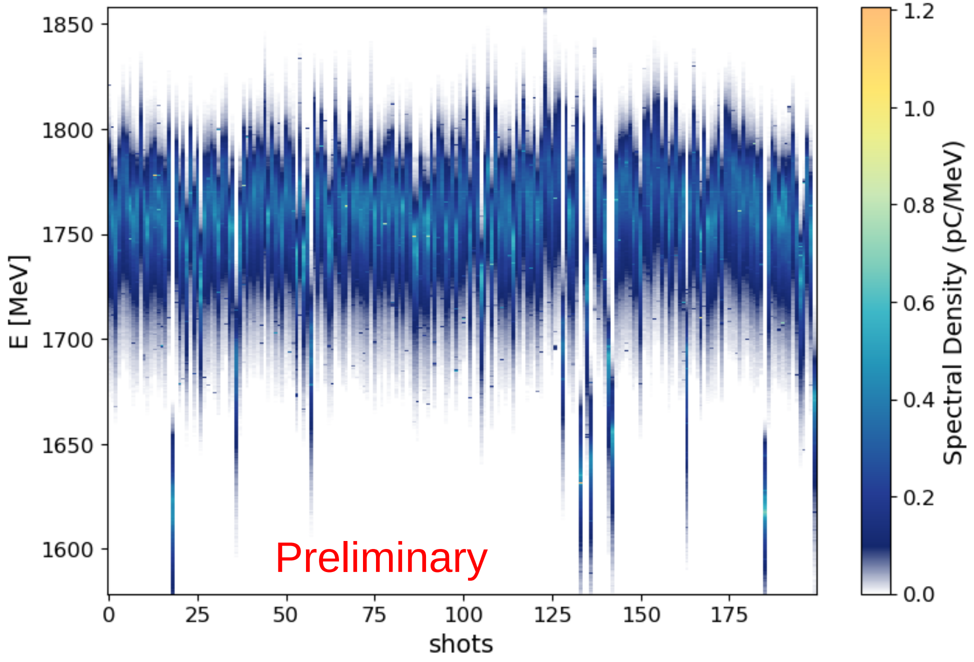
Test Measurements & Stability

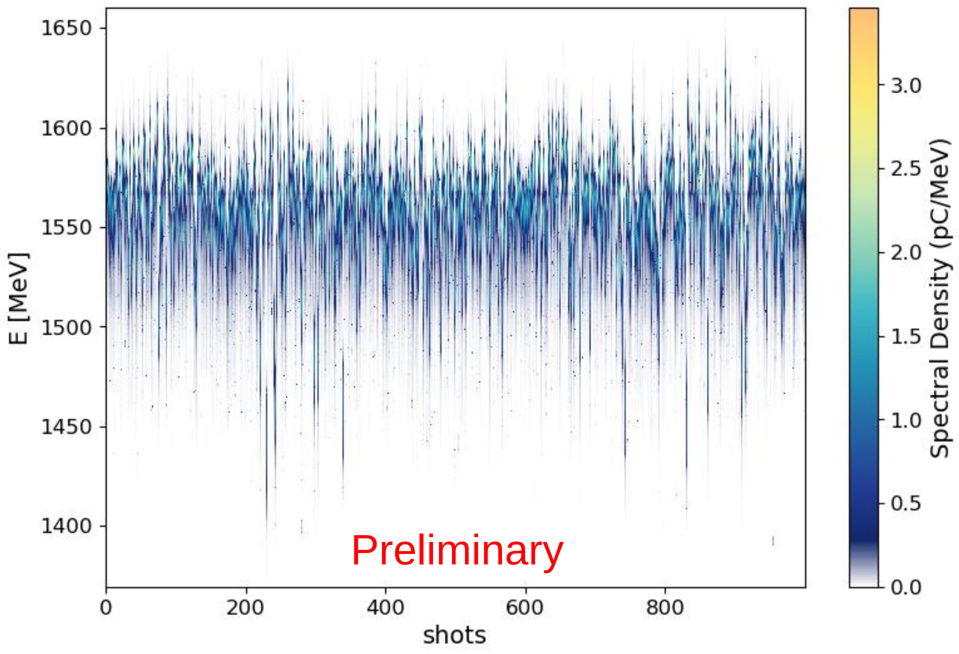
- 5 Hz high-voltage discharge plasma creation over several hours, punctuated by n_e measurements.
- 66,000 plasma creation events without damage.
- Target n_e reached at 4.6 μs, where the 12 ns discharge timing jitter results in a 0.4% density jitter.



500 mm Plasma Cell Acceleration Results

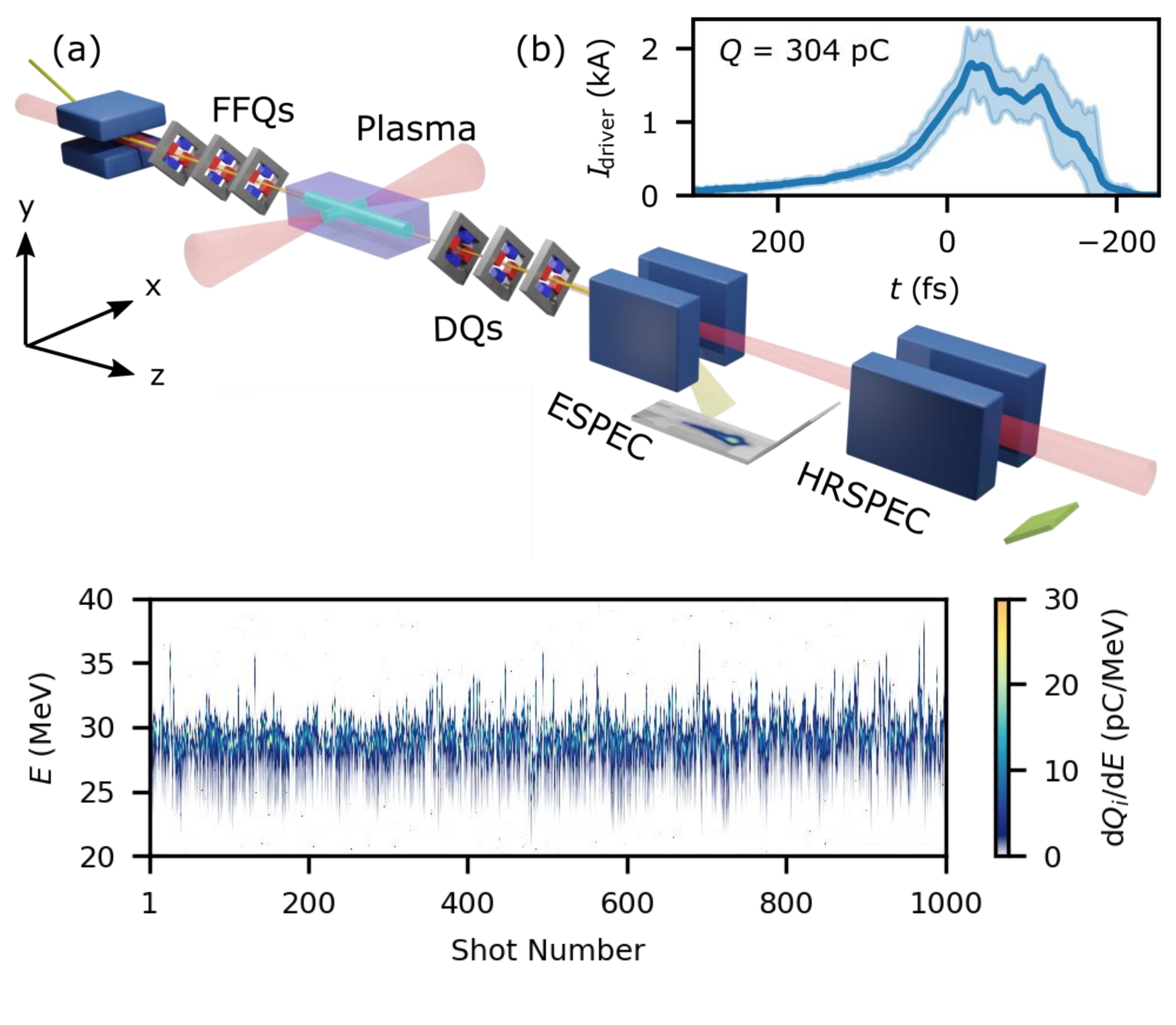
- First data taking!
- After optimisation in 50 mm plasma, rapidly found 1.2 → 1.7 GeV acceleration.
- 18.5 pC, 1.6% FWHM energy spread.
- Trade-off between charge and energy gain (likely due to coupling difficulties).
- 1.2 → 1.55 GeV energy gain, 31 pC, 0.9% FWHM energy spread.
- More work required on charge coupling & input bunch control.



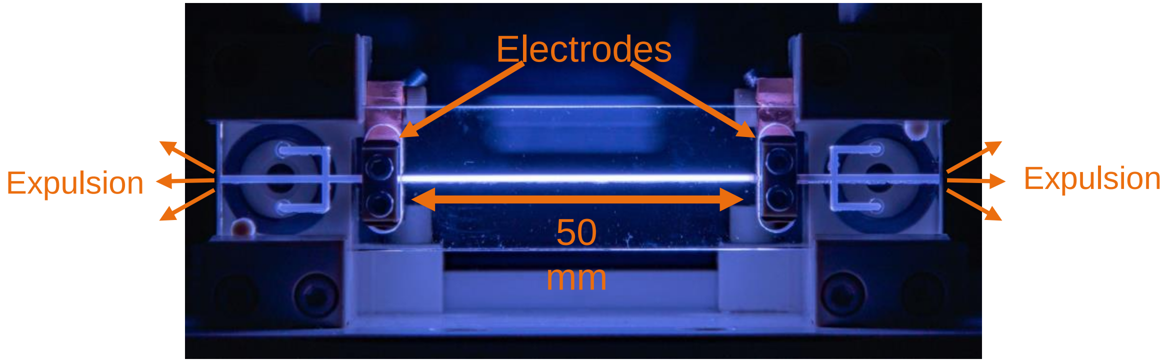


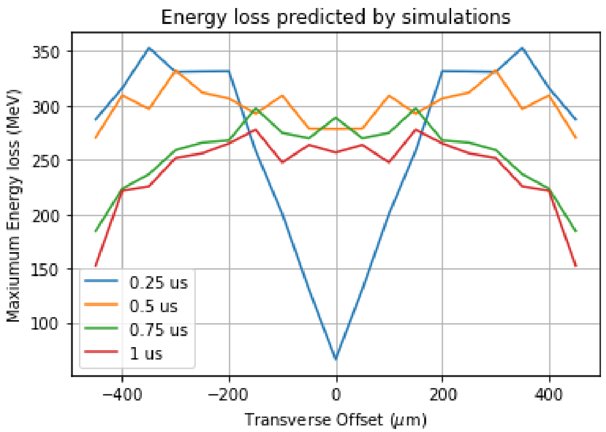
Other Results at AAC 2024

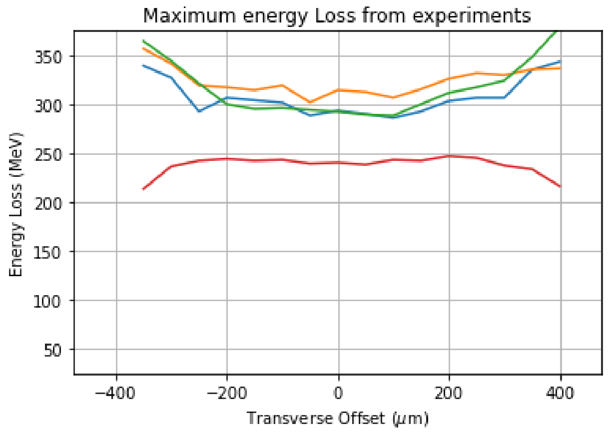
High quality, stable internal injection (J. Wood, WG3)



Plasma evolution modelling (A. Kanekar, WG3)







Conclusions

Emittance preservation at 2.8 mm-mrad

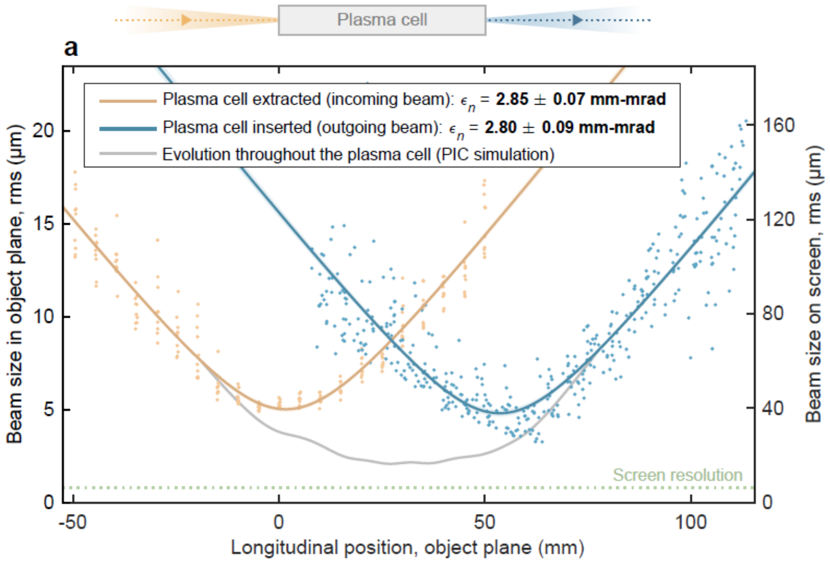
- Fine control of current profile (optimal beamloading), focal position and head-tail tilt required.
- Energy spread and emittance preservation, frequently preserving 3D brightness.

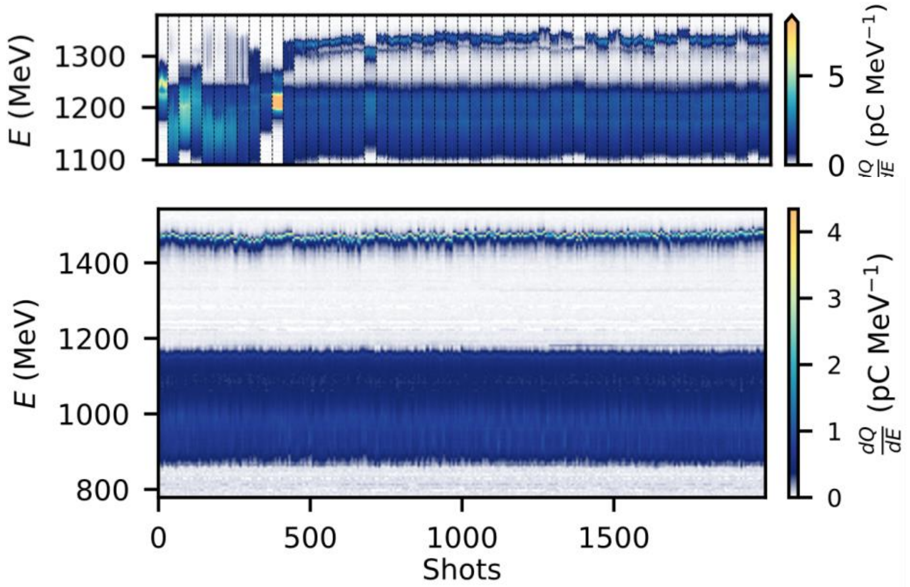
Bayesian optimisation & stable working points

- High-gradient witness bunch acceleration from ~ noise with from 4 variables.
- Led to acceleration by 250 MeV with < 0.2% energy spread.

Towards high overall energy efficiency

- Reliable 500 mm plasma sources under development and testing for high-energy-gain experiments.





Outlook

Simultaneously achieving goals

- 500 mm cell for studies with 0.5 GeV energy gain
  - First challenges: charge coupling and energy spread preservation
  - Towards high-overall-efficiency acceleration
- Multi-parameter optimisations (for energy spread or emittance preservation) to be performed with Bayesian optimization & ML routines.
  - Data-driven decisions
  - Rapid exploration
  - Multi-parameter optimisation & tradeoffs (e.g. energy gain and stability)
  - Virtual diagnostics

European XFEL Study

- We are working towards an XFEL-funded CDR on the feasibility of a plasma booster for the European XFEL
  - Boost electron and photon energies
  - Maintain photon energies for high duty-cycle XFEL
- Working on design challenges
  - Two-bunch generation & acceleration
  - Plasma stage specs & design
  - Beamline design
  - Managing extreme power levels
- A postdoc advert on this project will be out very soon!