Advanced Acceleration : Laser-Driven

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JAI effort on laser-driven accelerators

- Faculty
  - Imperial: K. Long, S. Mangles, J. Pasternak, Z. Najmudin
  - Oxford: S. Hooker & P. Norreys
- JAI staff
  - Imperial: M. Backhouse, A. Hughes
- Externally-funded post-docs
  - Imperial: Claudia Cobo, Nicholas Dover, Brendan Kettle
  - Oxford: L. Feder, B. Greenwood, R. Lahaye, M. Moreira
- Students
  - Imperial: L Bradley, G. Casati, L. Forrester, J. Hills, R. Luo, F. Yang, G. Weis, A. Yousif
  - Oxford: D. Chan, J. Thistlewood, A. Harrison, T. Madden

Challenges & research directions

- Laser driven accelerators seek to exploit the huge electric fields generated by laser interactions with solid, liquid, or gaseous targets to accelerate charged particles to high energies in very short distances

Challenge	Strategies
Improving bunch quality (energy spread, emittance, …)	Controlling electron injection
Increasing the bunch energy	Decreasing plasma density & guiding Staging
Increasing the pulse repetition rate & wall-plug efficiency	Novel laser technologies Novel driver concepts
Demonstrating applications	Radiation generation Muon beams Fundamental science

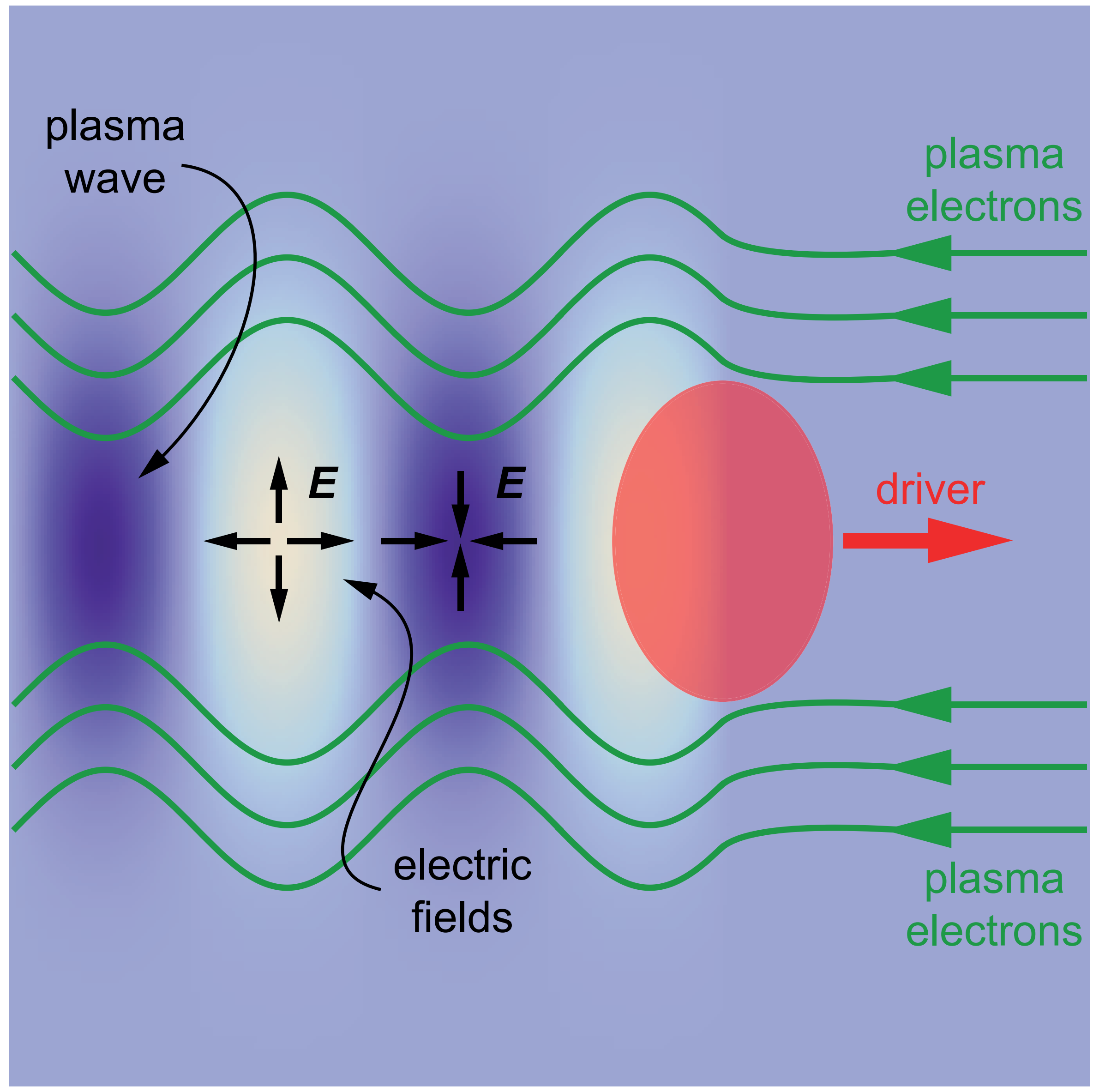
Laser wakefield acceleration: basic concepts

- Ponderomotive force of an intense laser pulse expels plasma electrons
- Charge separation within trailing density wave creates huge electric fields, of order the wave-breaking field E_{wb}
- Plasma oscillates at plasma frequency ω_p
- Efficient wake excitation requires laser pulse duration $\tau \lesssim T_p = 2\pi/\omega_p$

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

$$E_{\mathrm{wb}} = \frac{m_e \omega_p c}{e}$$

$$a_0 = \frac{e A_0}{m_e c}$$

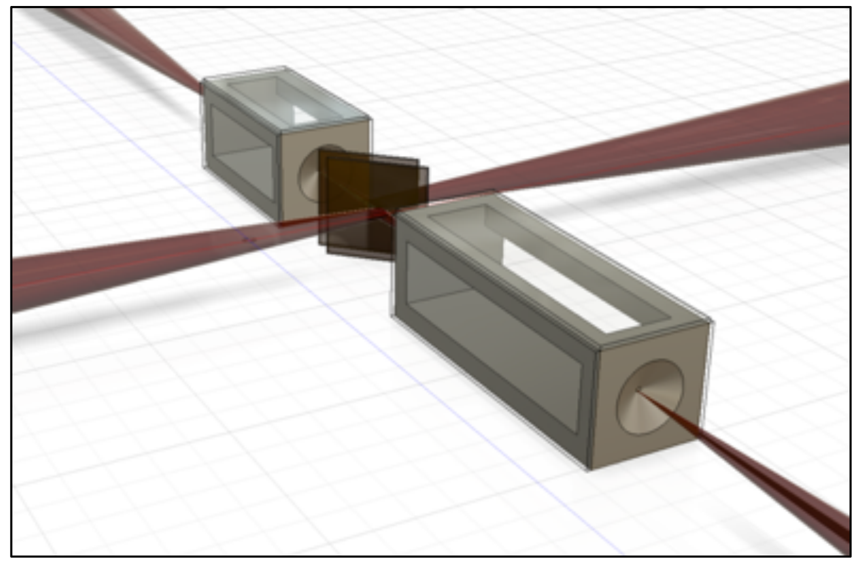


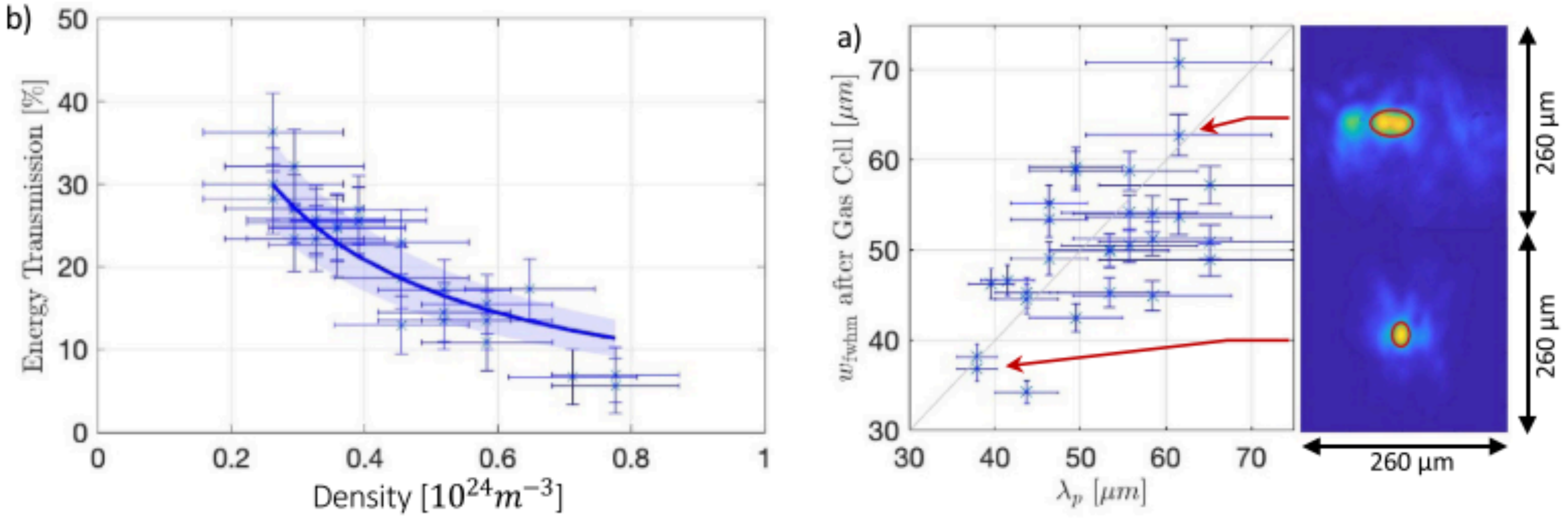
		Comment
Laser intensity	10^{18} W cm^{-2}	1 J, 50 fs, 25 μm
Plasma density	10^{18} cm^{-3}	i.e. 100 mbar
Accel. field	100 GV m^{-1}	10^3 to 10^4 > RF machine
Plasma period	100 fs	Need short laser pulses, get short electron bunches
Plasma wavelength	30 μm	

Increasing bunch energy : Staging

Staged acceleration with plasma mirrors

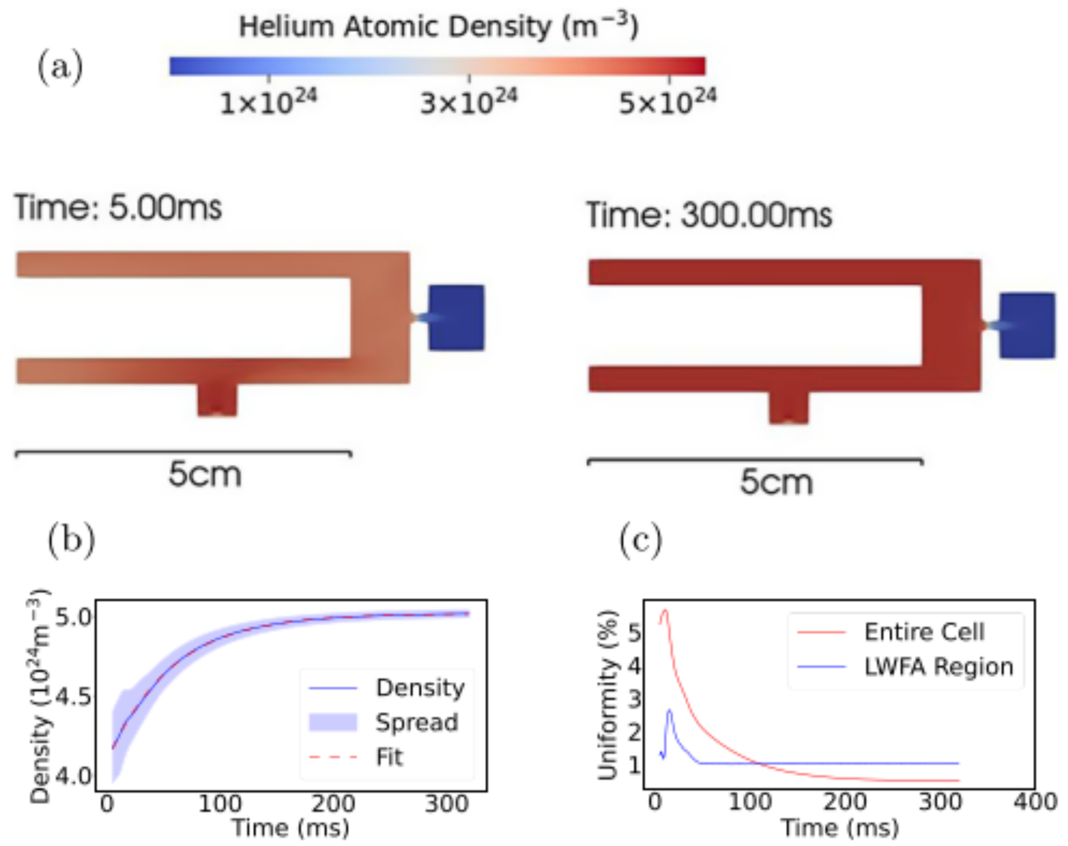
J.-N. Gruse *et al.* *New J. Phys.*, 27 124302 (2025)
https://doi.org/10.1088/1367-2630/ae2cbf

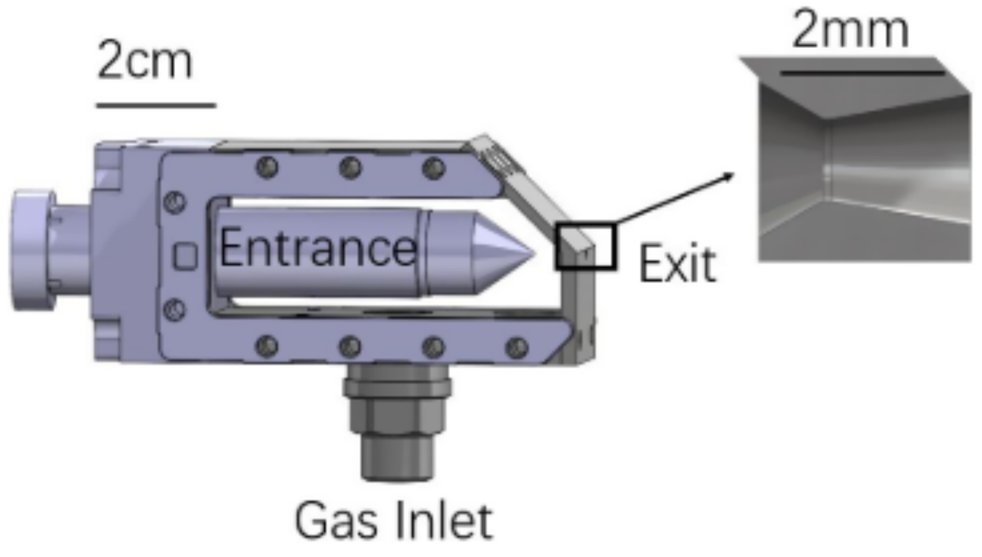




- > 70% total reflectivity observed in previous measurements
- Coupling of laser energy into guided spot demonstrated by reduction in guided spot size with increasing density (since $w_m \propto 1/n_e$)

R. Luo *et al.* *High. Power, Las. Sci. Eng.* **13** e95 (2025)
https://doi.org/10.1017/hpl.2025.10085

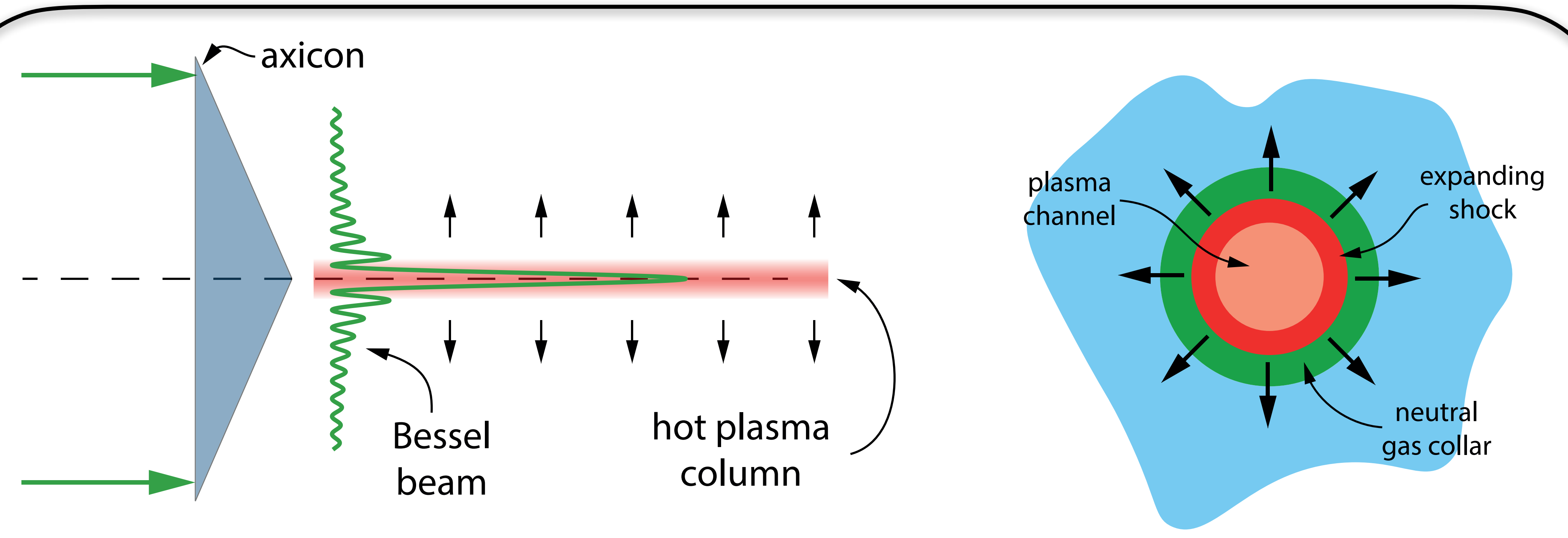


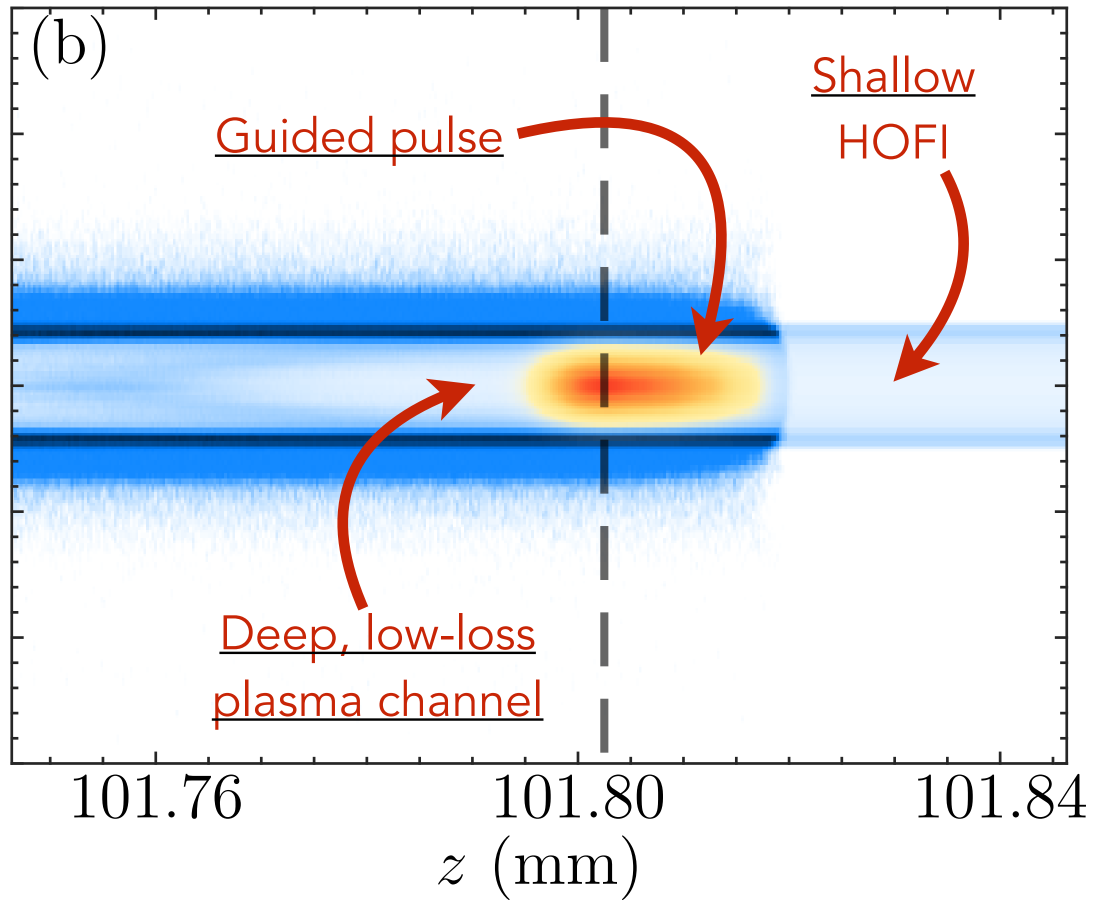


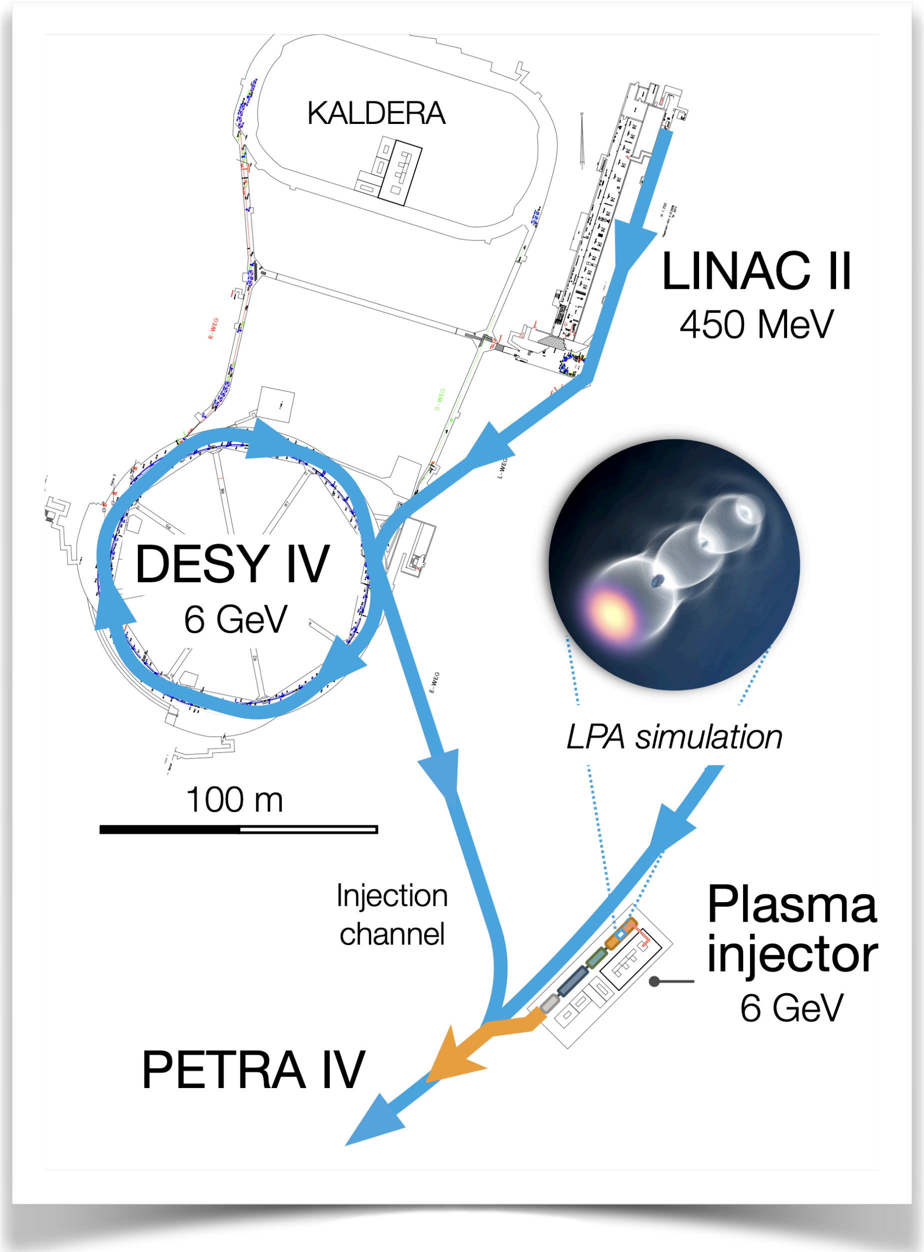
- Shaped exit nozzle for variable ramp length gas targets necessary for staging
- Full 3D simulations with convex limiting hydro code Ryujin ensuring stability without ad hoc tuning parameters
- % level uniformity achieved in our targets for < 100 ms fill times

Staging with curved HOFI plasma channels

- Channels formed by hydrodynamic expansion of collisionally-heated plasma column developed in 1990s
  - Free-standing & “indestructible”
  - Requires high density ($n_e \gtrsim 10^{18}\,\mathrm{cm}^{-3}$) for efficient heating
- JAI-Oxford group proposed low density channels required for GeV accelerators ($n_e \approx 10^{17}\,\mathrm{cm}^{-3}$) could be generated by OFI
  - Rel. low T_e generated by OFI gives rel. weak channel
  - But, ionization of neutral gas collar by guided pulse → deep, very low loss ($L_{attn} \gg 1$ m) channels
- Many important results in recent years
  - Low-loss guiding of relativistically-intense pulses over 100s mm
  - Operation at kHz rep. rates for > 6 hours
  - Controlled electron injection and acceleration to > GeV
- Adopted by several groups around world



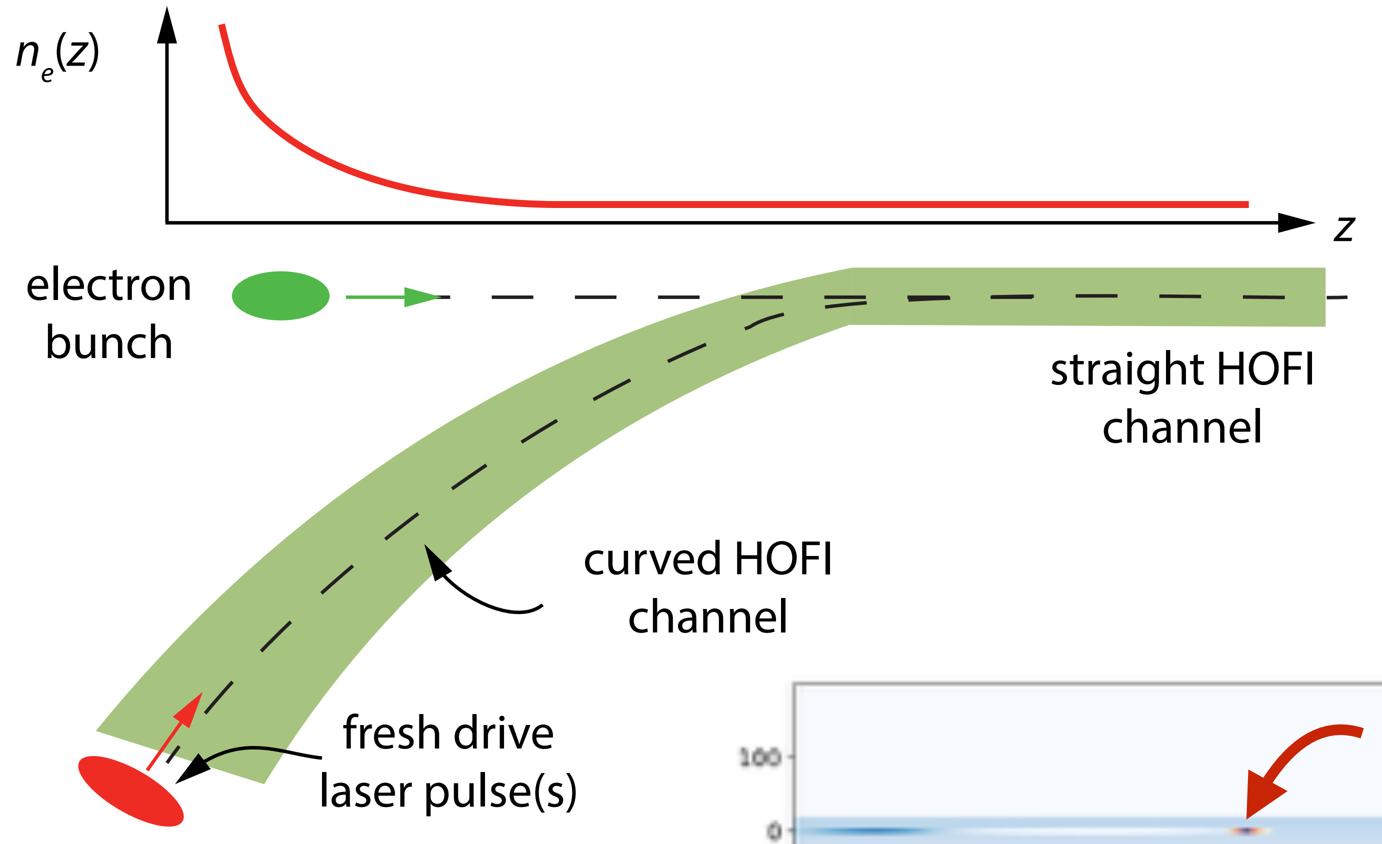


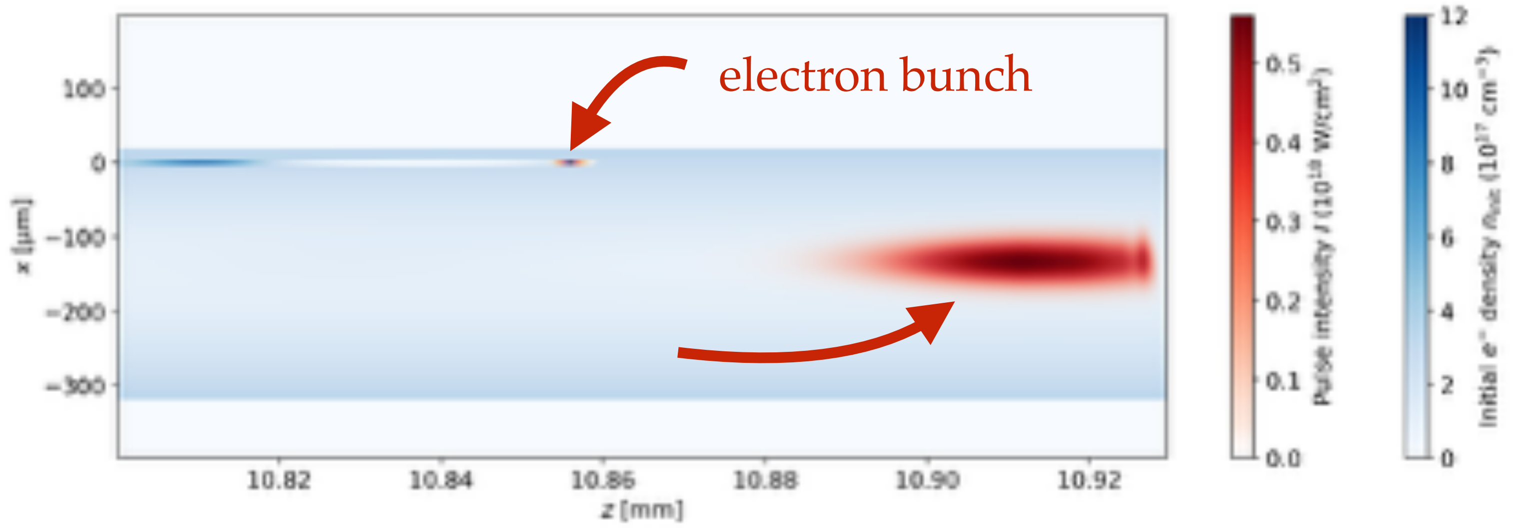


I. Agapov *et al. The Plasma Injector for PETRA IV : Enabling Plasma Accelerators for Next-generation Light Sources. Conceptual Design Report*
DOI: 10.3204/PUBDB-2024-06078

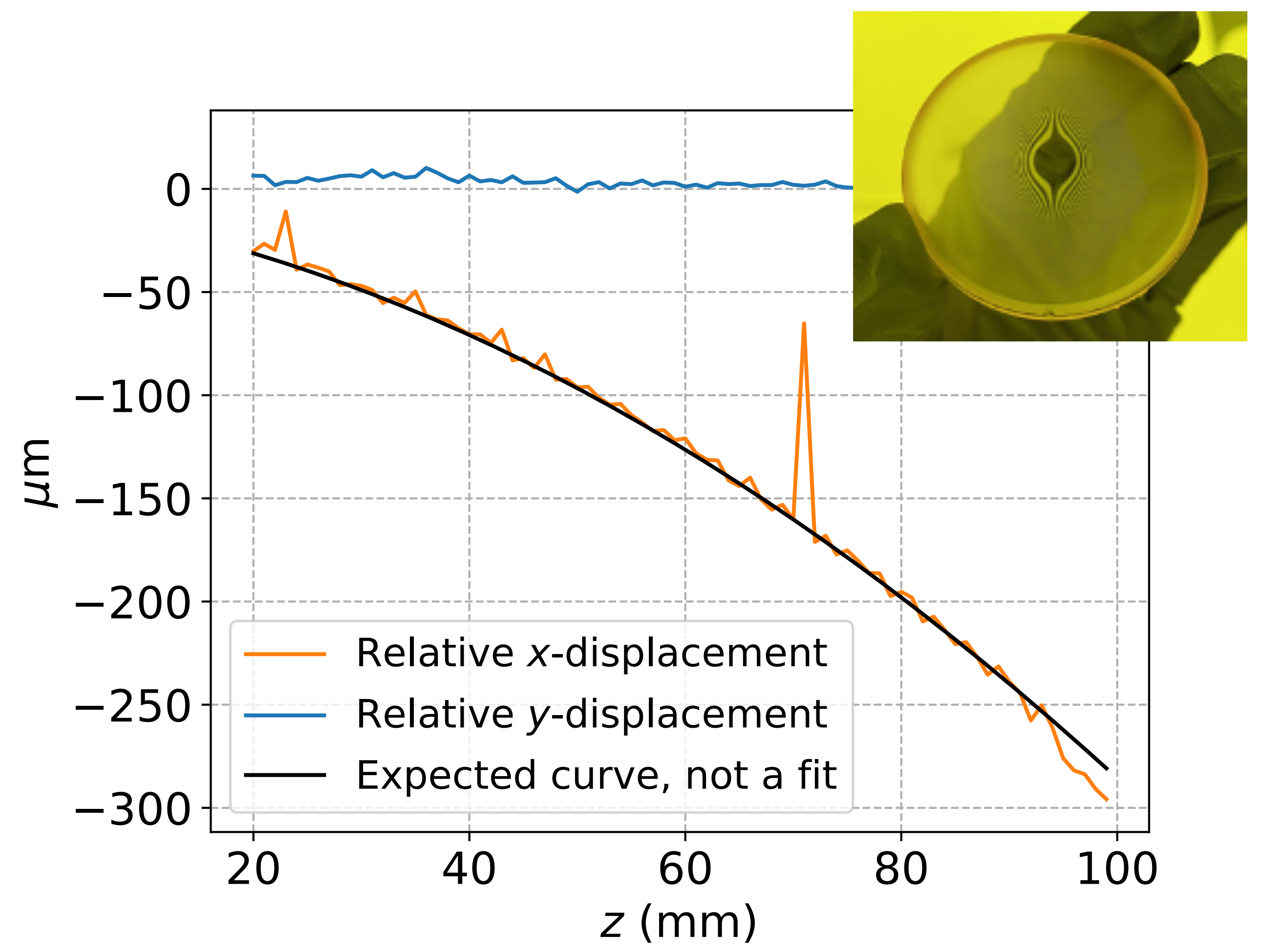
Staging with curved HOFI plasma channels

- Curved HOFI channels could be used to inject fresh laser pulses into multiple LWFA stages
- Demonstrated curved precursor to HOFI channels using axicon + phase plate
- Currently running PIC simulations to model bunch injection & capture. Study includes:
  - Ionization of channel neutral gas collar
  - Tapered channel + density ramp
  - Single and multi-pulse laser drivers
  - Bayesian optimization of laser, channel, and plasma parameters
- Studies ongoing … currently achieved:
  - Emittance growth reduced from factor 1000 to ~5
  - > 10 GV / m gradient in main stage

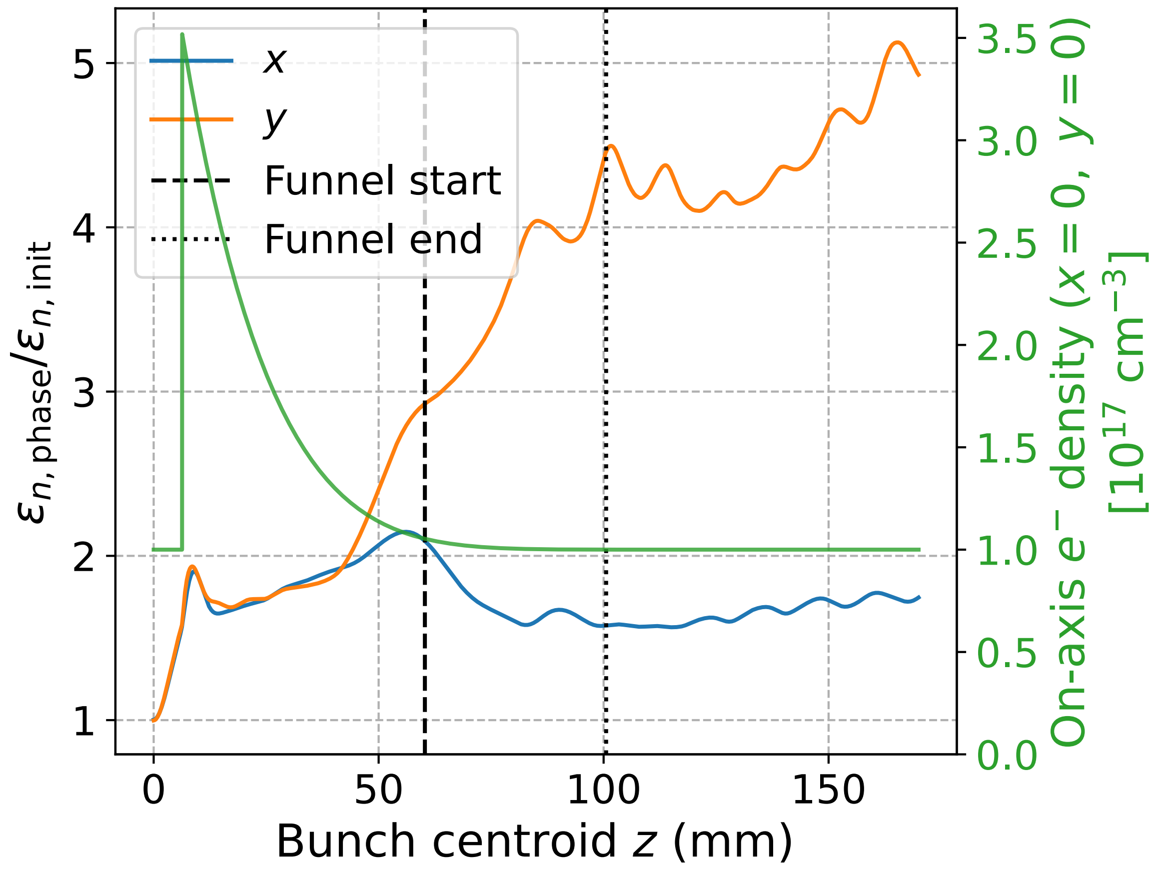




Measured displacement of channel axis

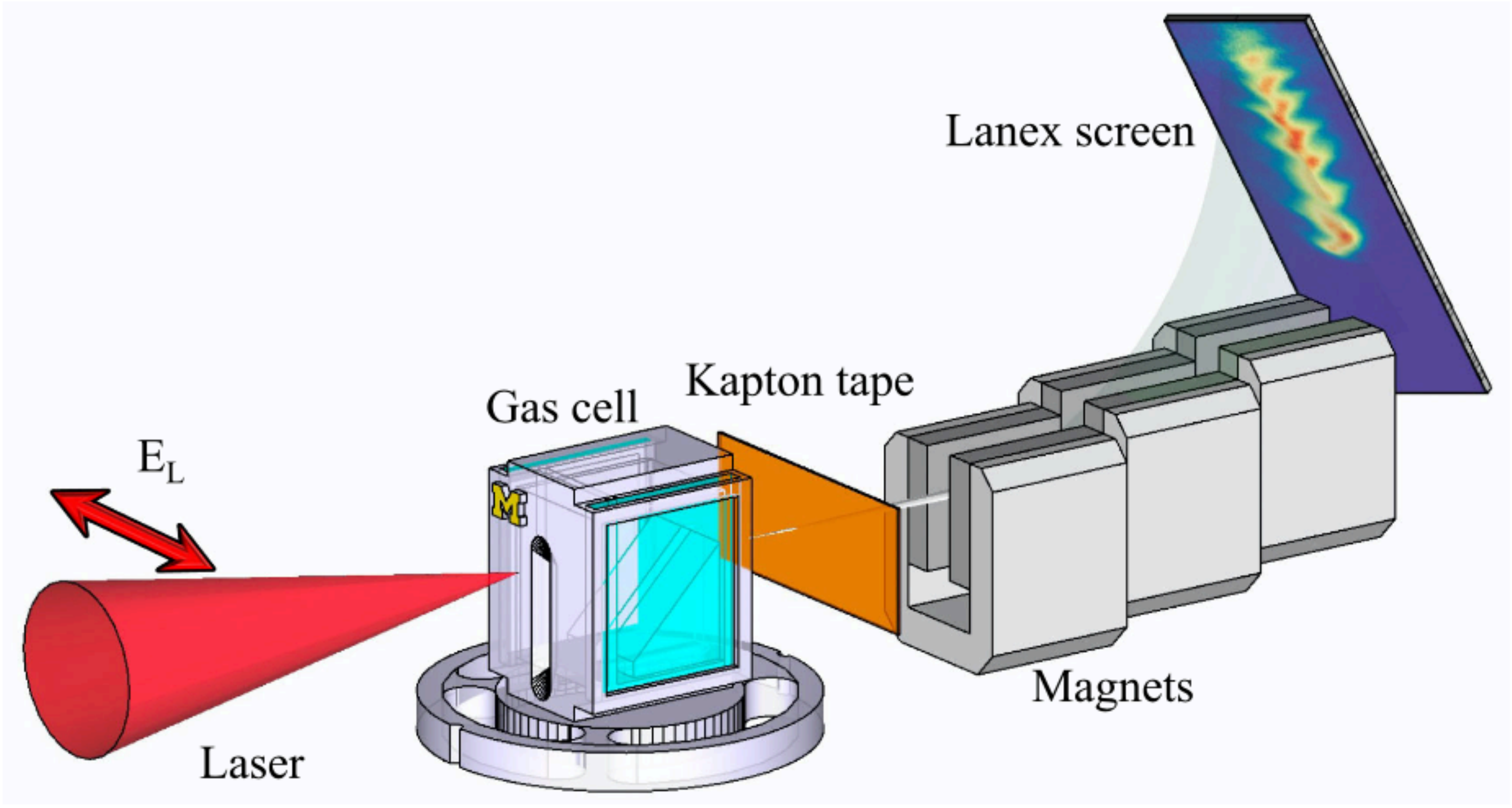


PIC: Growth of bunch emittance

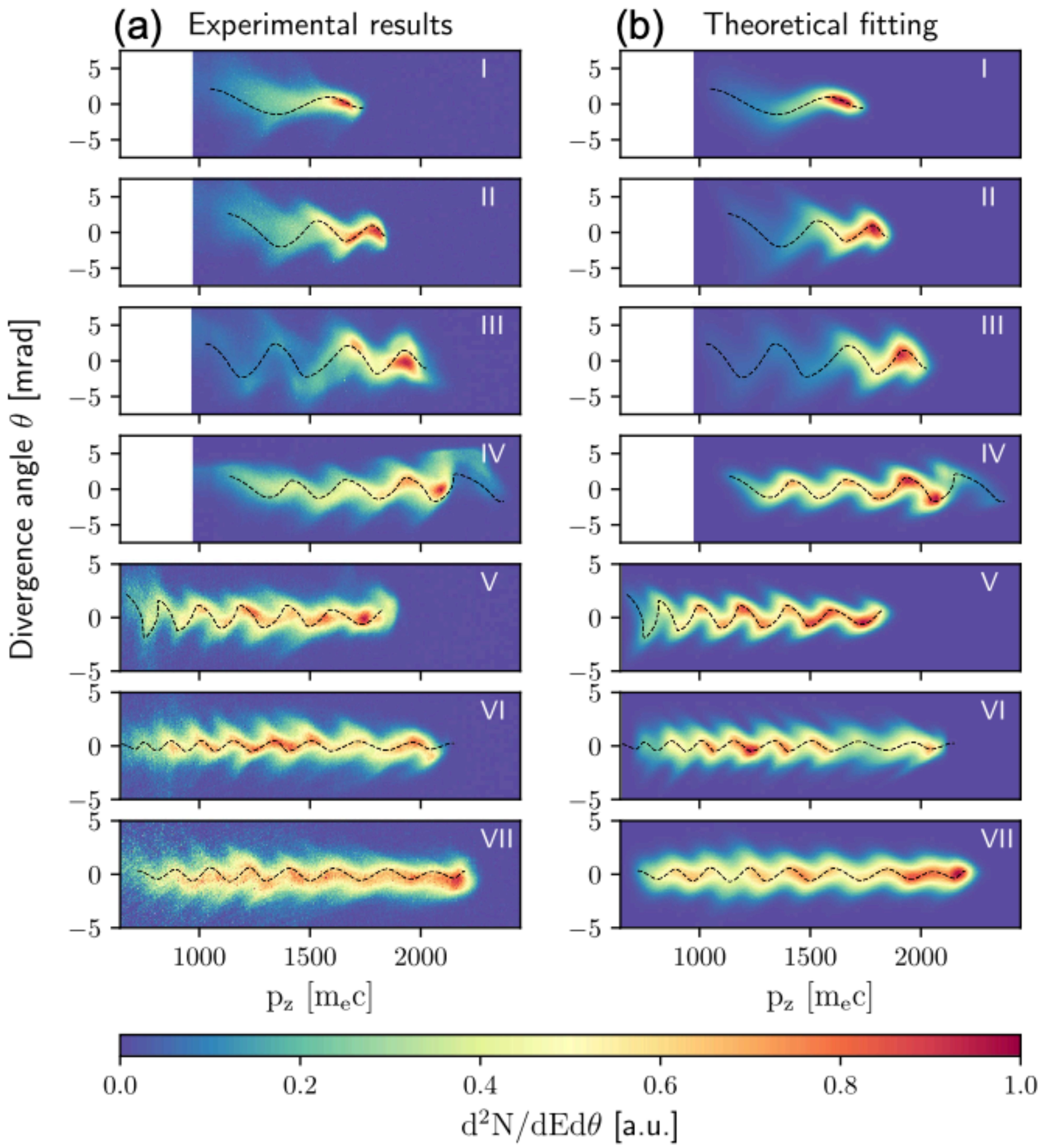


Improving bunch quality :
Novel bunch diagnostics & Bayesian optimization

Single-Shot Longitudinal Phase Space Reconstruction of LWFA



Ma Y. et al, Phys. Rev. X **15** 031062. (2025)
https://doi.org/10.1103/sxqf-l6mp

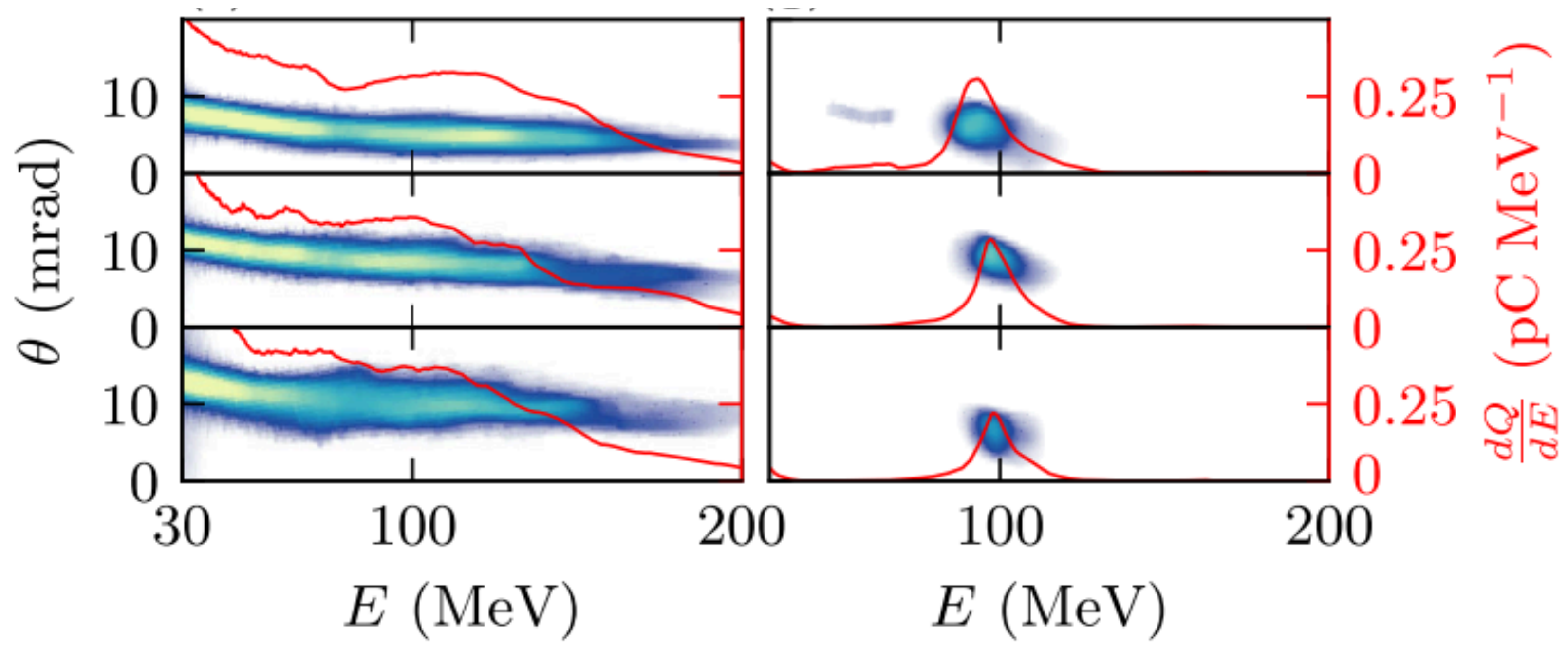


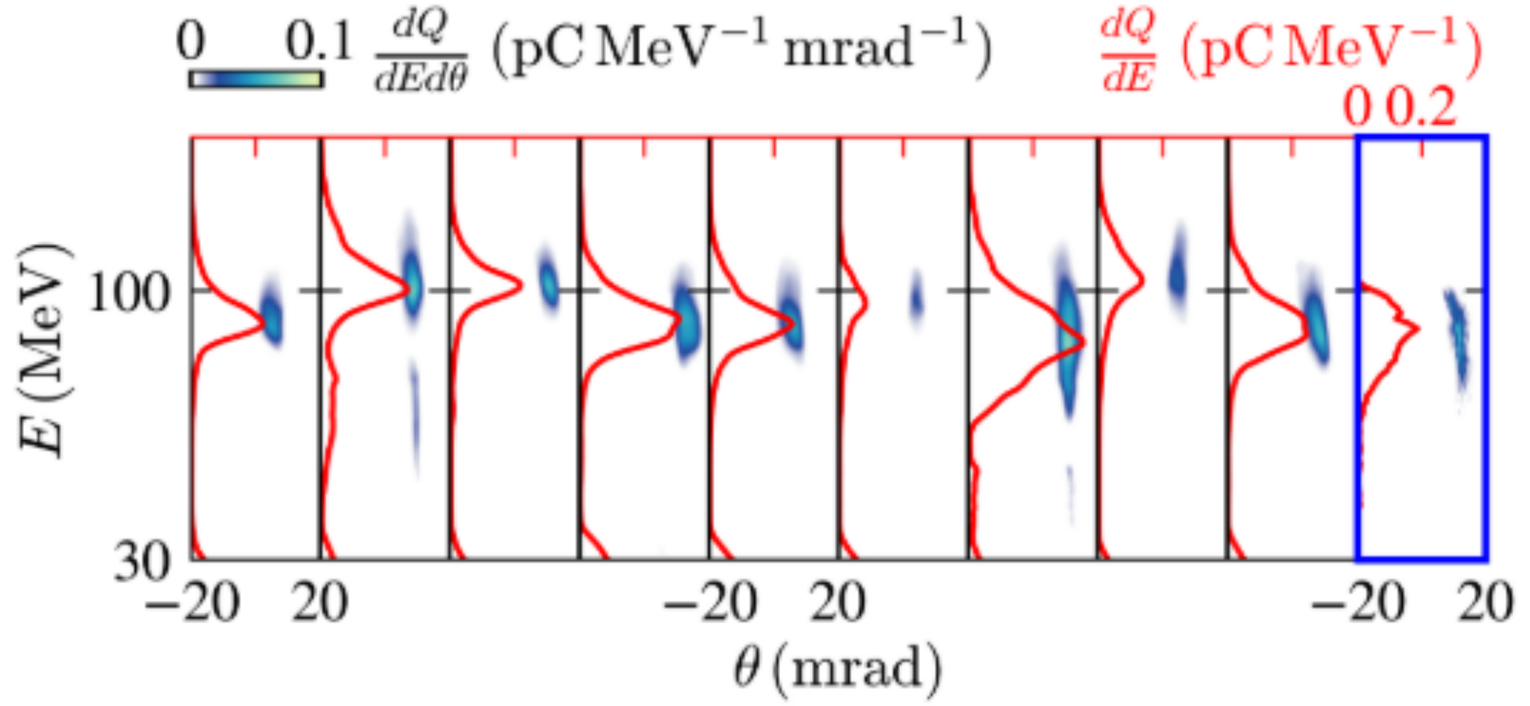
- Transverse fields of laser can be used to measure longitudinal phase space of LWFA beams
- Driving acceleration beyond dephasing length allows electrons to interact with rear of drive pulse
- Constrained model (assisted by genetic algorithm) enables measurement of longitudinal phase-space distribution with resolution ≈ 1.3 fs.
- Slice energy spread measured to be ΔE = 9.9 MeV (0.9-3%) despite total spread of 100%

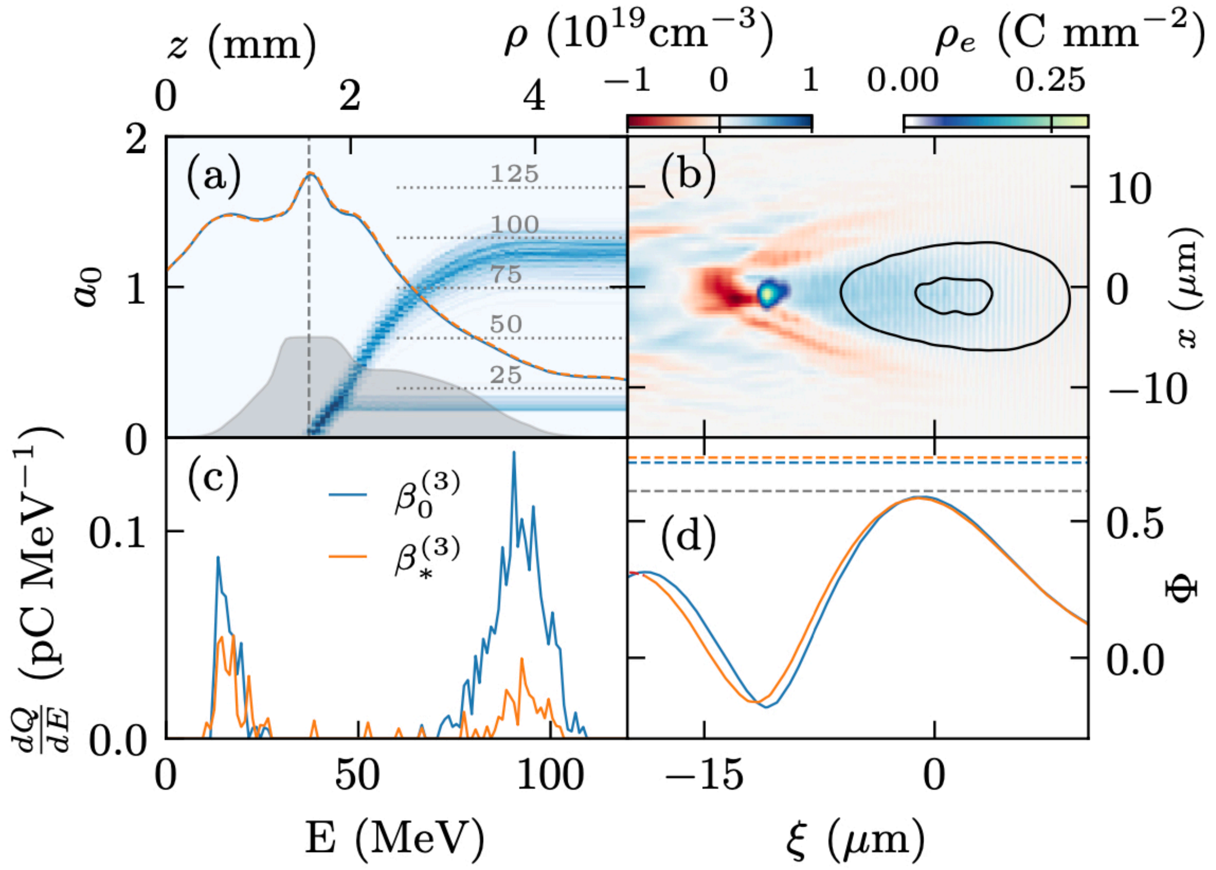
Spectral phase control for optimised ionisation injection in LWFA

M. P. Backhouse *et al*, *Phy. Rev. Accel. Beams*, **28** 121301 (2025).
https://doi.org/10.1103/9gjq-htzn

- Experiments at LLC, Lund (0.8 J, 42 fs, 12 μm)
- Bayesian Optimisation (spectral phase and focus position) converted $\Delta E/E \sim 100\,\%$ beams to $\Delta E/E \sim 5\,\%$ beams with no dark current in <100 generations
- Ideal injector for Eupraxia?
- Results show high level of reproducibility (for LWFA!)
- Convolutional neural network (CNN) used to obtain full wavefront information of laser pulse
  - Allows modelling with unprecedented accuracy
  - Shows importance of subtle effects, such as the addition of 3rd order spectral phase to enhance ionisation injection.







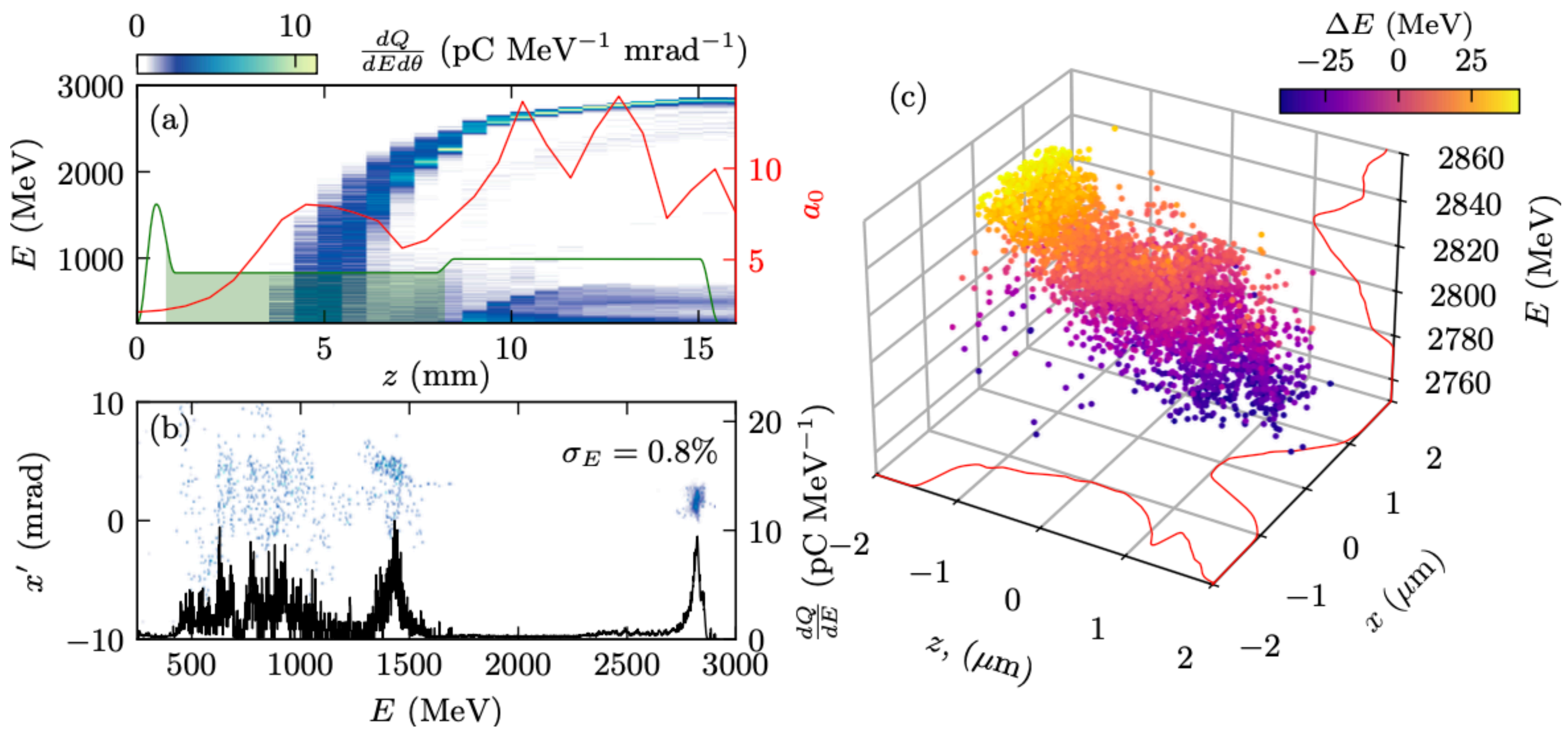
Multi-Task Multi-objective Bayesian Optimisation for EPAC

- Extreme Photonics Application Centre (EPAC) is a new ~ £100M facility at Harwell Campus to develop and exploit applications of laser-driven accelerators
- First experiments in 2026
- JAI groups working with Central Laser Facility (CLF) to:
  - Optimize laser & plasma parameters
  - Determine and refine accelerator performance
  - Plan initial experiments

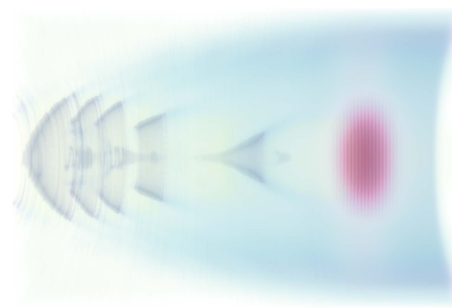
Multi-Task Multi-objective Bayesian Optimisation for EPAC

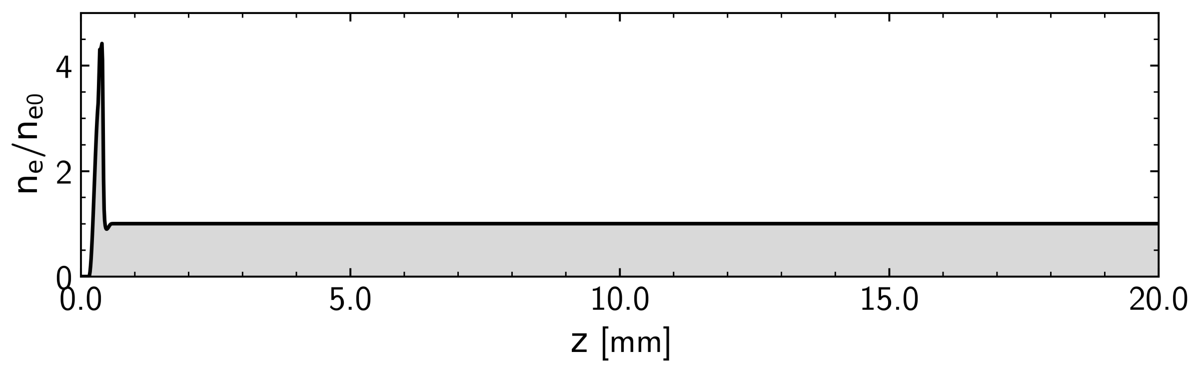
- Optimisation of next-gen LWFAs is computationally expensive
- Reduce computational needs by using lower fidelity simulations to define the Pareto front in multi-objective searches
- Used by IC and Oxford groups to plan expts at EPAC (Energy scaled-down to 15 J):
  - Multi-task, MOBO for ionisation injection yielded E = 3 GeV, ΔE/E < 1% and brightness > 10^{16} Am^{-2} sr^{-1} for gas cell target
  - E = 4.3 GeV, ΔE/E < 1% for truncated channel injection in 200 mm long HOFI channel
- JAI PDRA Michael Backhouse asked to coordinate LWFA expts. at EPAC

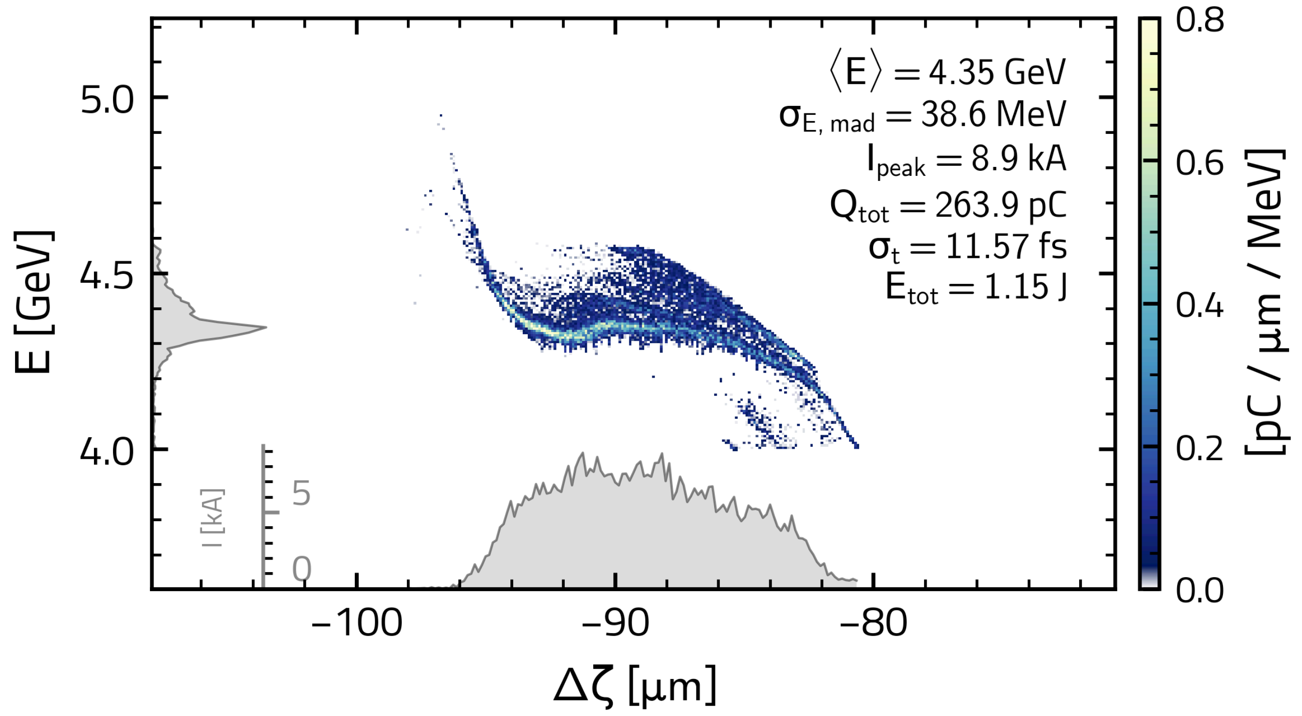
M. P. Backhouse *et al, submitted to Machine Learning: Science and Technology*



Simulations by J. Chappell

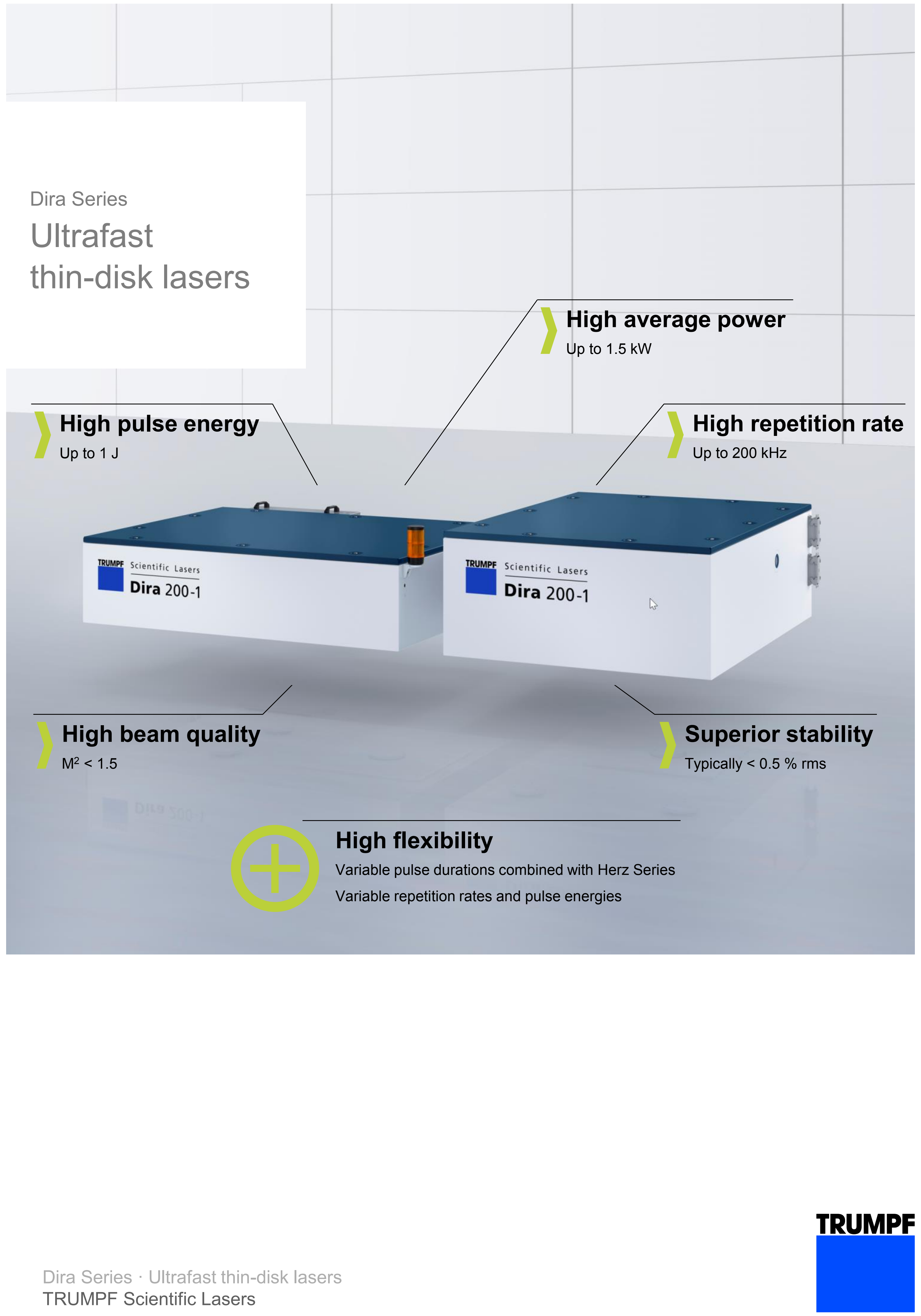


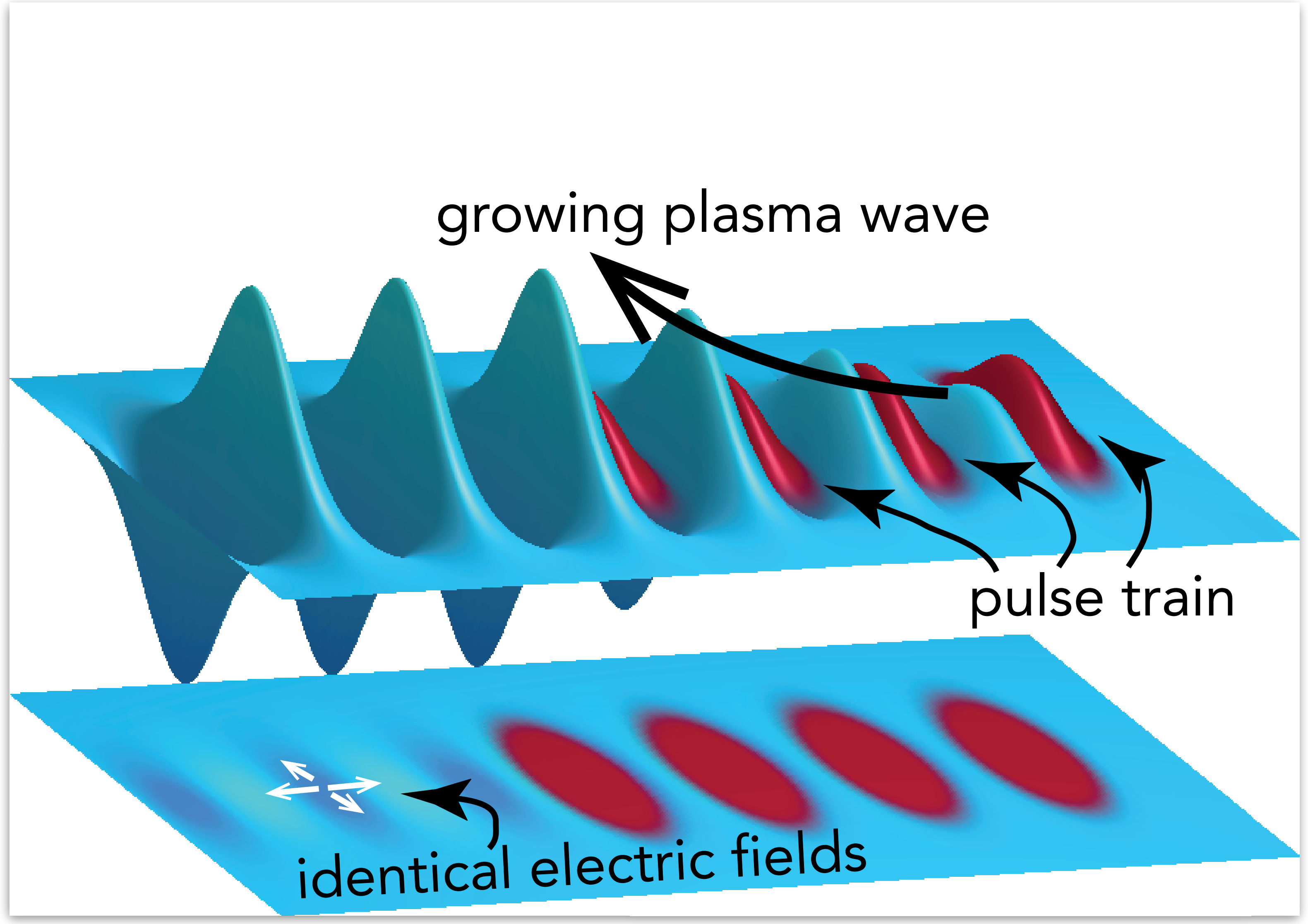




Increasing repetition rate and efficiency : Novel driver concepts

GeV-scale, kHz accelerators with existing lasers?

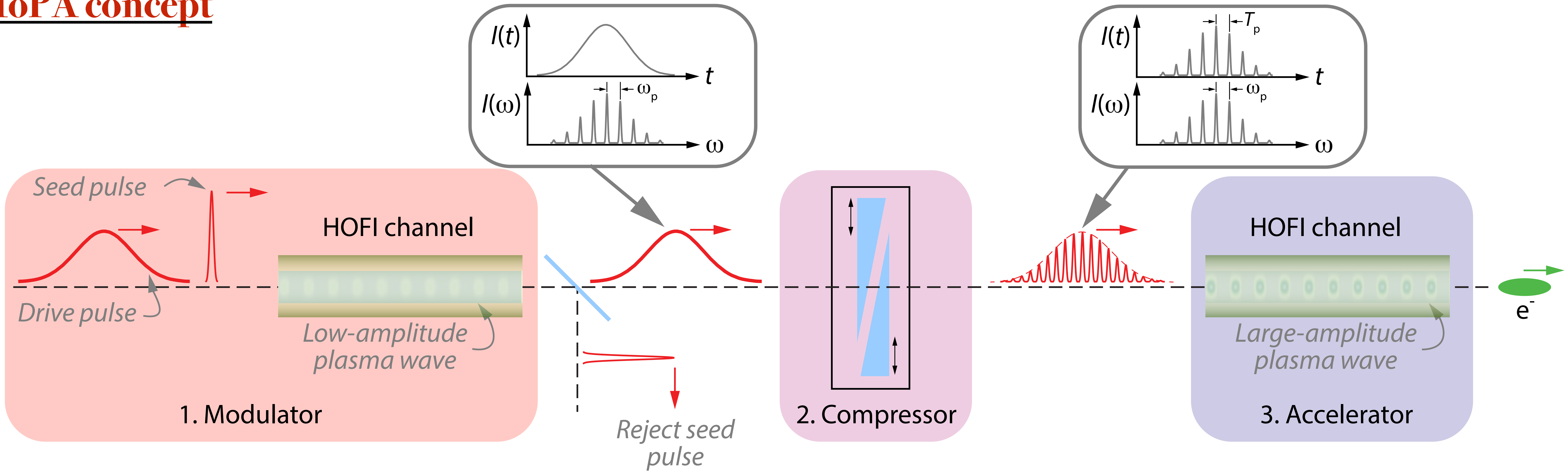




- High-energy Ti:sapphire lasers typically operate at a repetition rate < 10 Hz
- Commercially-available Yb:YAG thin-disk lasers can already provide ~ 1 J, 1 kHz pulses:
- Pulses too long (~ 1 ps) to drive wake directly … but could resonantly excite wakefield if we could modulate pulse at plasma period

P-MoPA: Plasma-Modulated Plasma Accelerator

The P-MoPA concept



Step 1: Modulator:

- Co-propagate long (1 ps), high-energy "drive" pulse with low-amplitude wake driven by short (< 100 fs), low-energy "seed" pulse
- Drive develops sidebands at $\omega = \omega_0 \pm m\omega_p$

Step 2: Compressor:

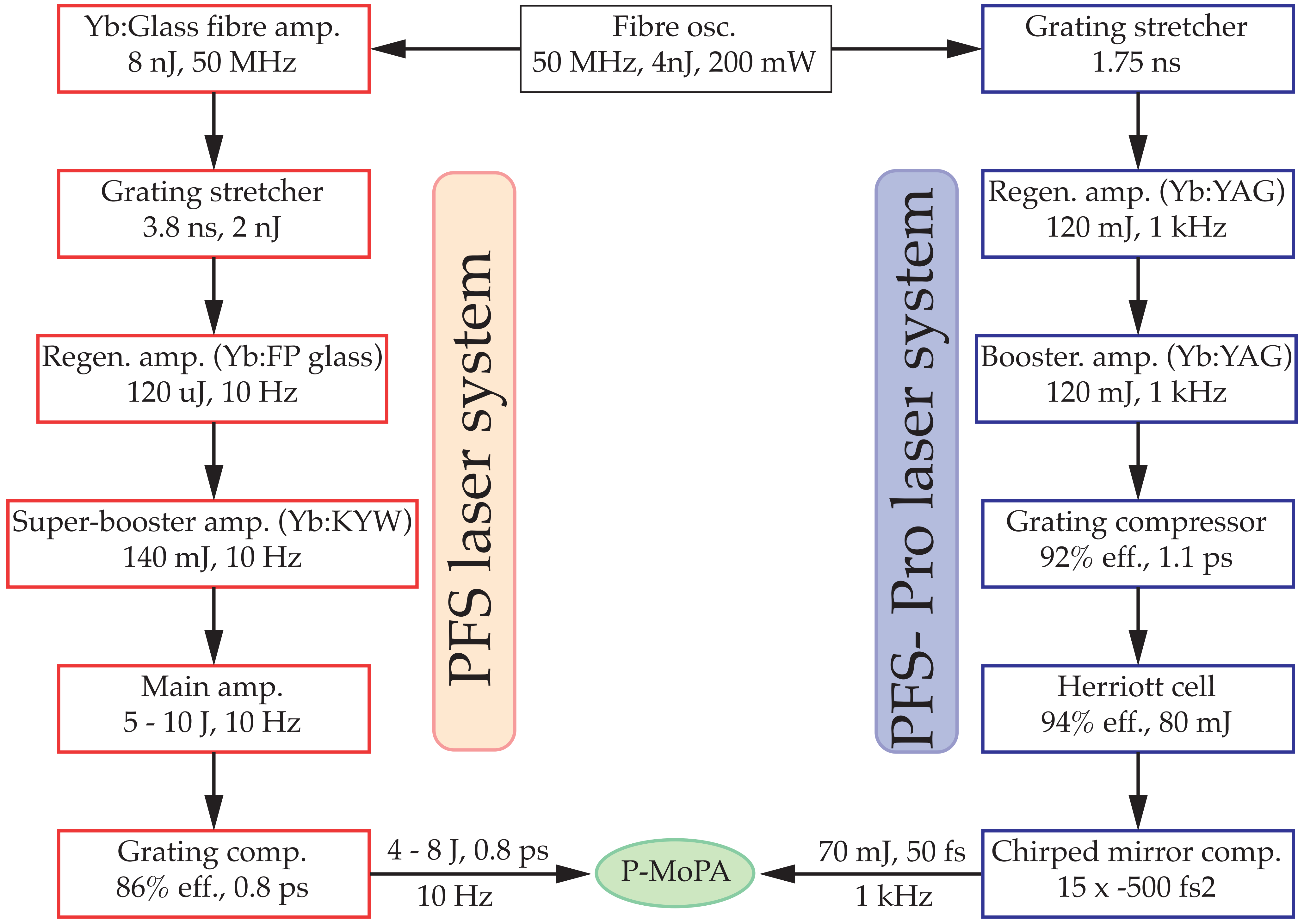
- Remove spectral phase of spectrally-modulated drive
- Forms a train of short pulses spaced by $\Delta t = 2\pi/\omega_p$

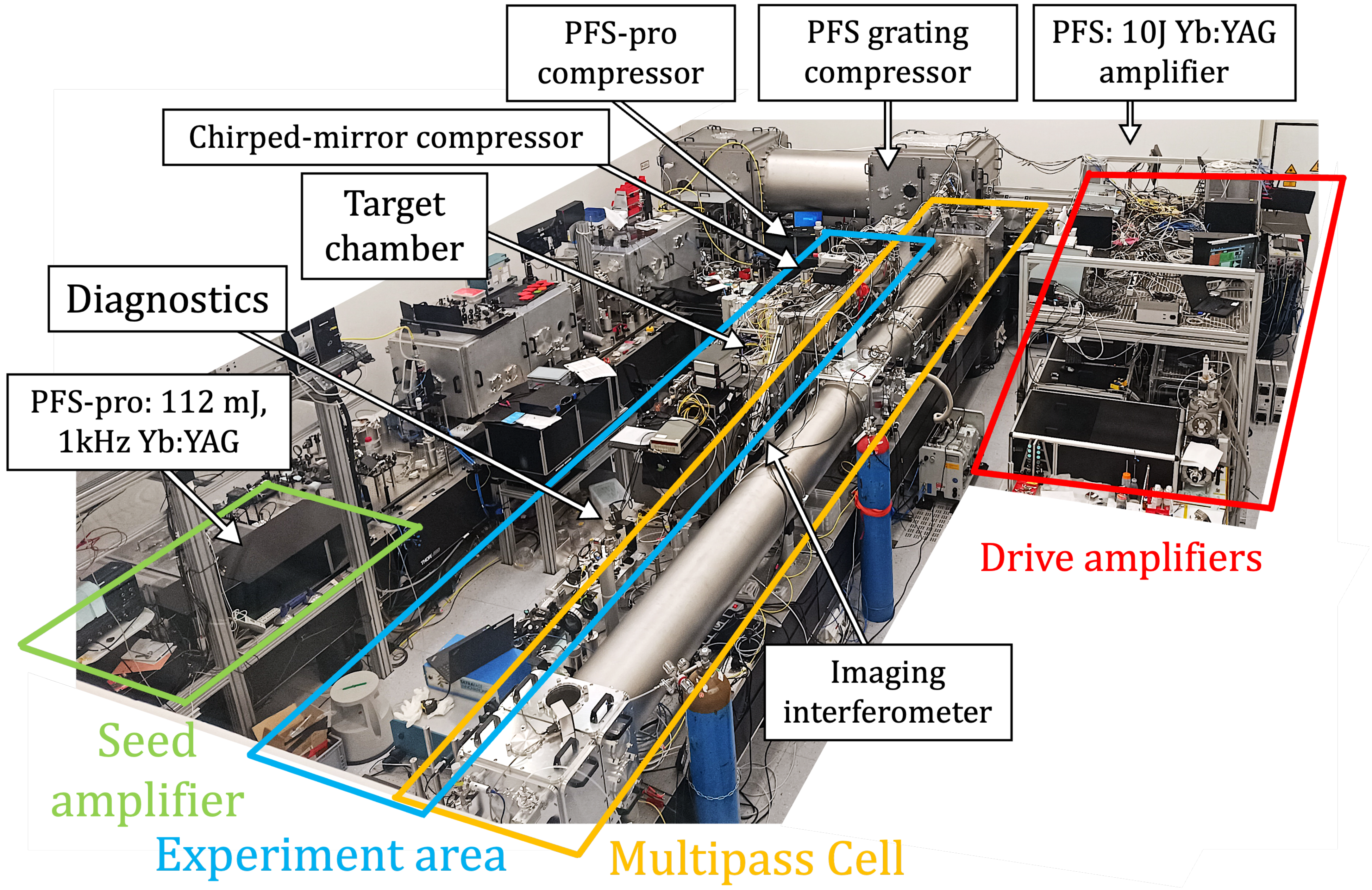
Step 3: Accelerator:

- Train resonantly excites a large-amplitude wakefield

We are working with Stefan Karsch at CALA to demonstrate P-MoPA

- 4-year, £1.8M grant from EPSRC to demonstrate P-MoPA scheme
- Completed extensive work to re-commission thin-disk laser, construct new beamlines & target chambers at CALA

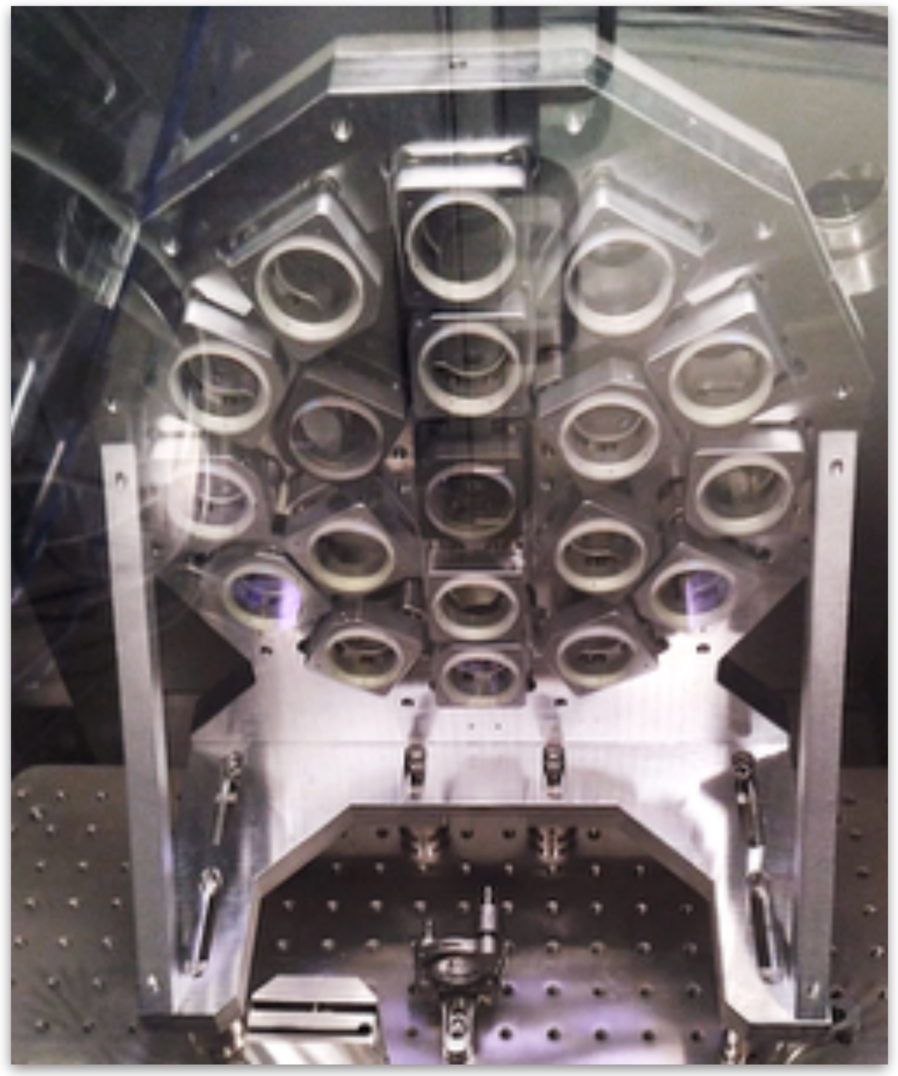




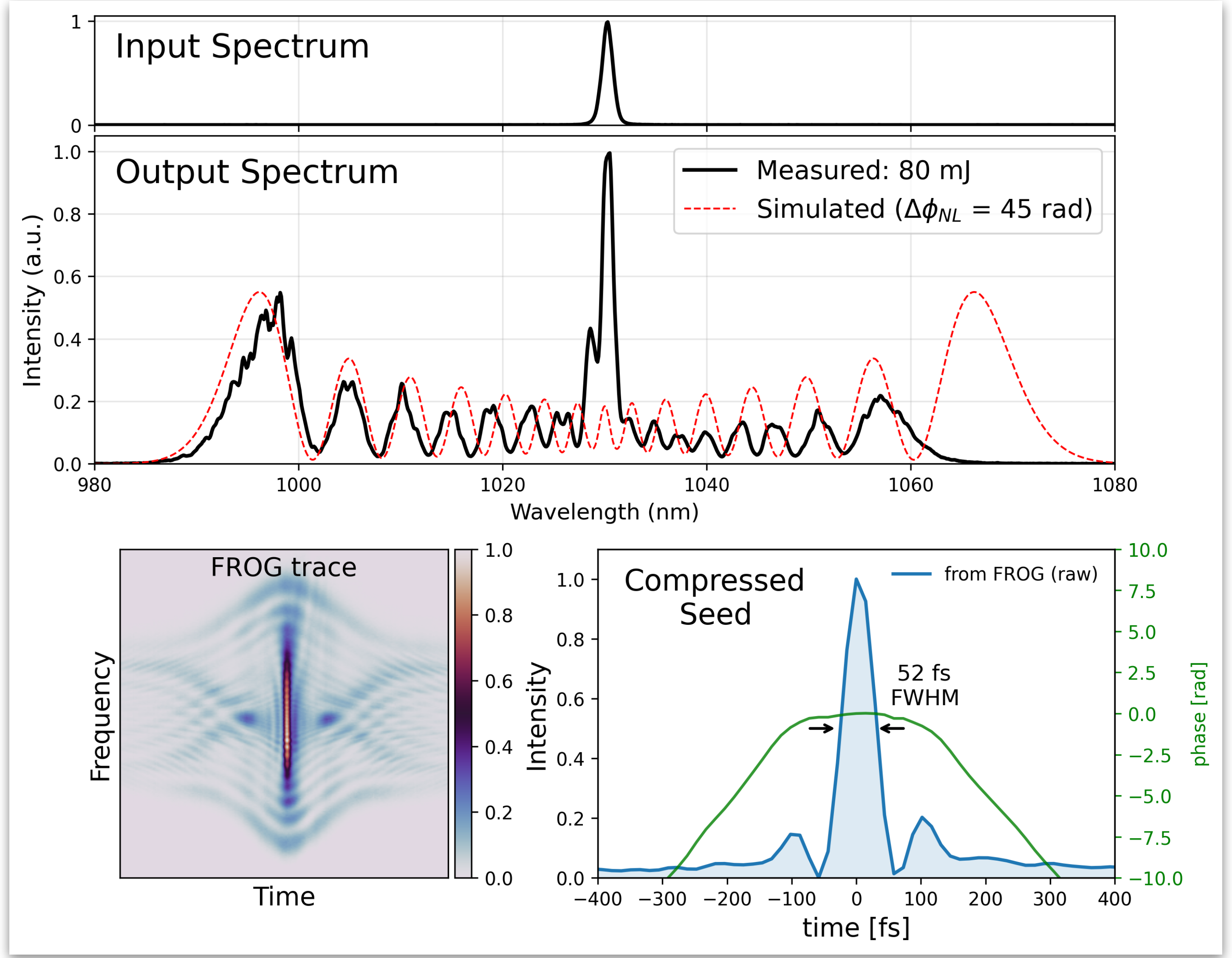
We are making good progress at CALA …

- HOFI channels generated with ps-duration pulses
- Guiding of joule-scale, ps-duration pulses
- Spectral broadening ~ 70 mJ pulses in Herriot cell, compressible to ~ 50 fs
- Simulations show seed pulse guided & drive pulse modulated

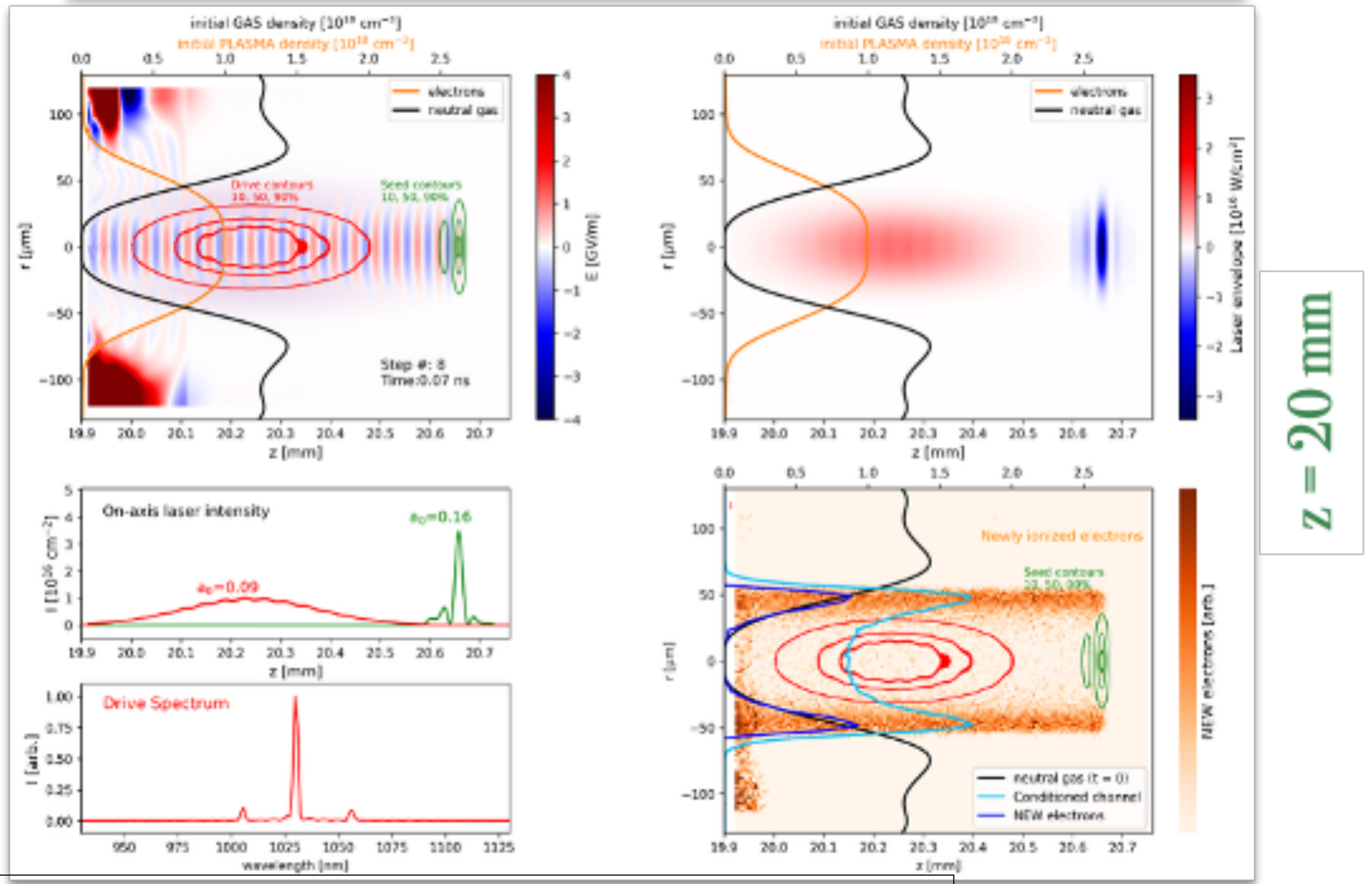
One of two mirror arrays in multi-pass gas-filled cell



Spectral broadening in multi-pass cell



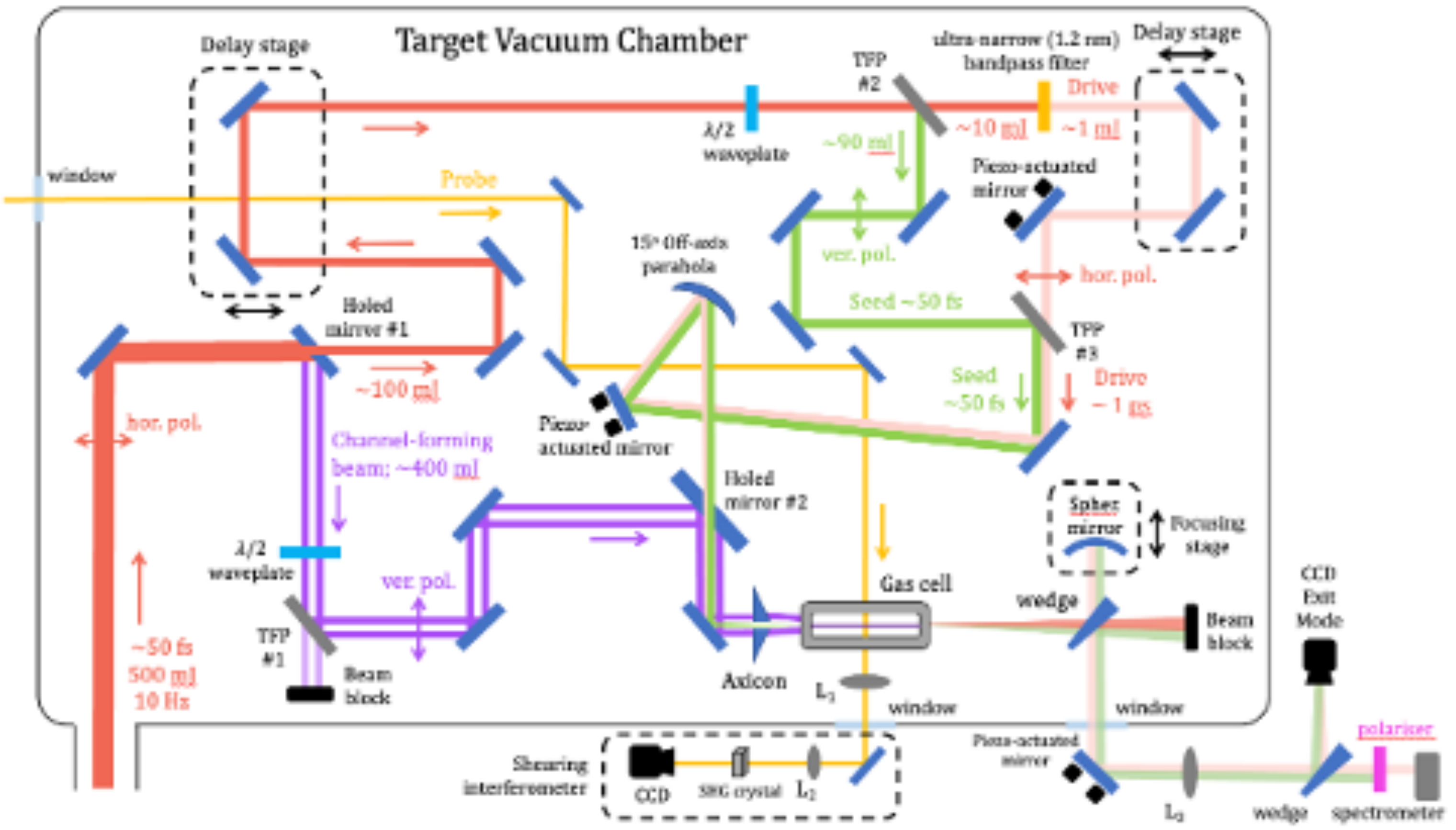
Generation & characterization of HOFI channels with ps-duration pulses

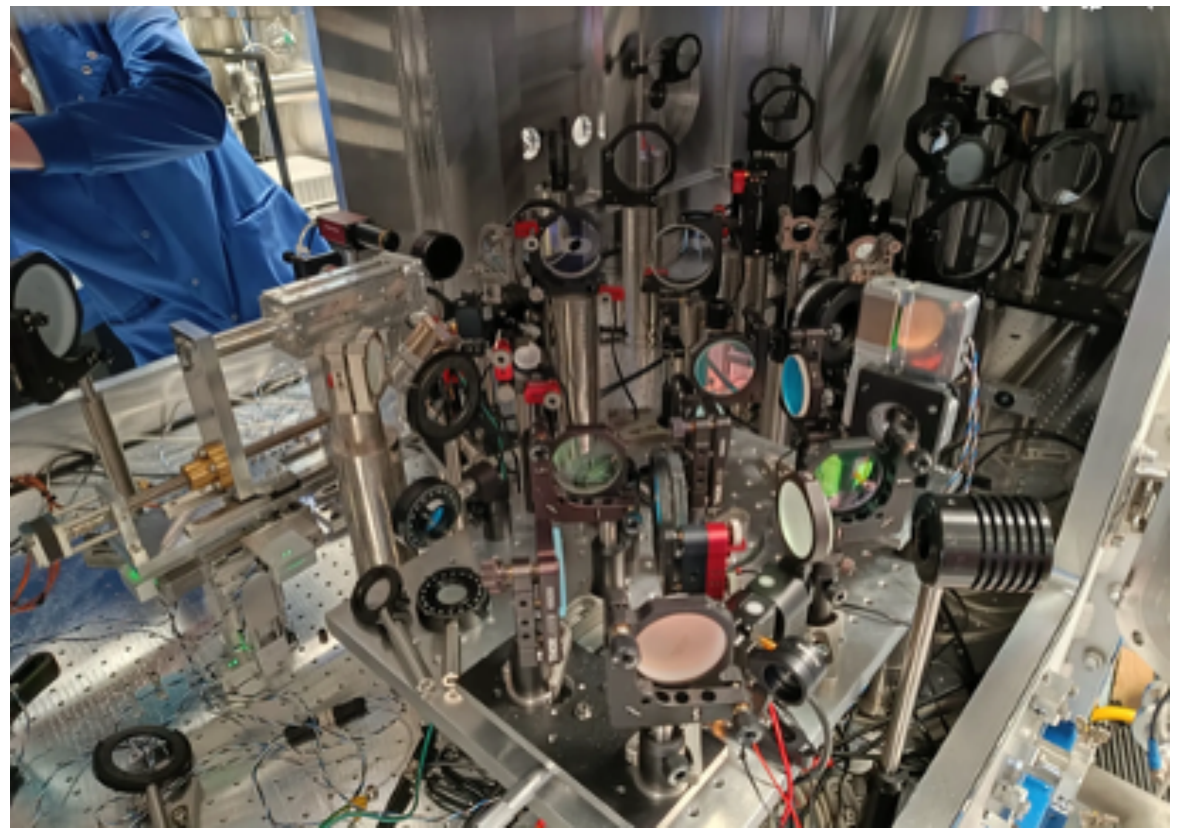


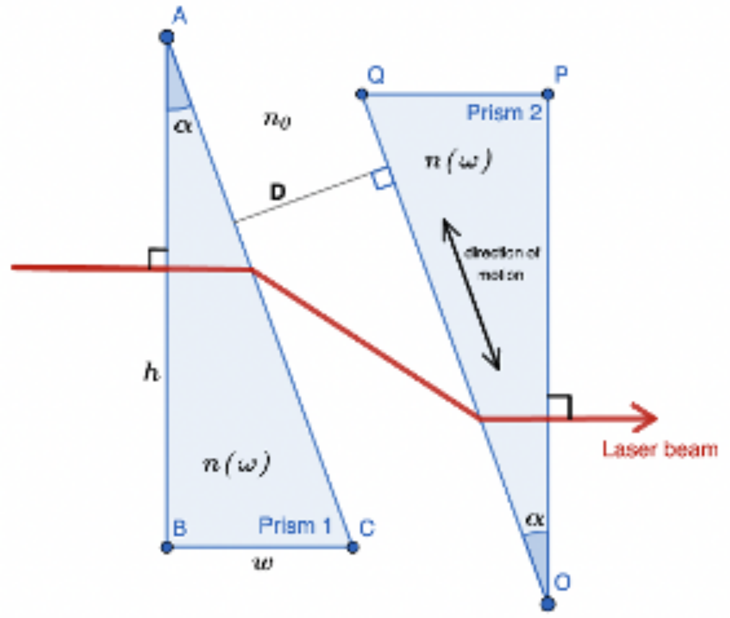
PIC simulations of seed & drive propagation

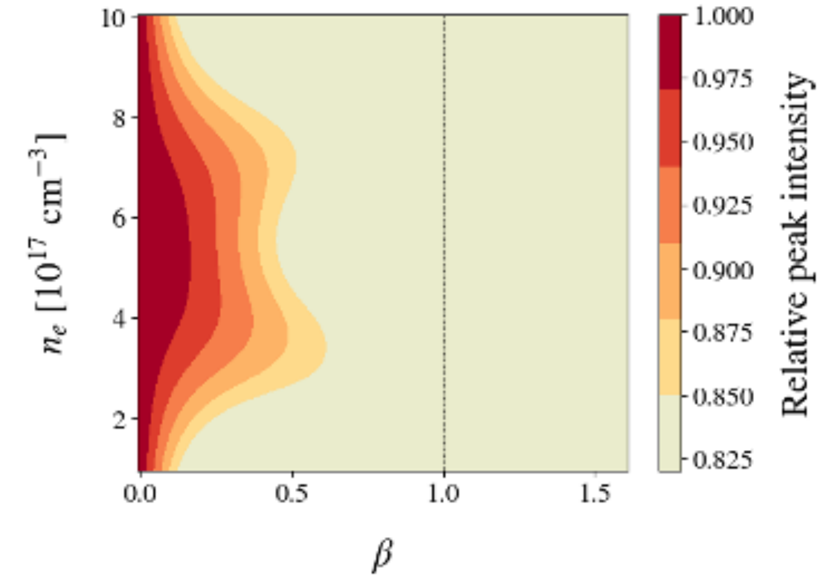
… and at OPAL

- Experiments in the Oxford Plasma Accelerator Lab (OPAL) aim to demonstrate spectral modulation at low pulse energies
  - Spectrally-filter Ti:sapphire pulse to generate ~ 1 ps “drive” pulse
- Aim to understand influence of seed energy, relative timing between seed & drive pulses etc.
- Provisional design of two concepts for compressor stage:
  - Material dispersion
  - Chirped mirrors
- Working with CALA group to produce custom chirped mirrors
- Planning to test both compressor designs in experiments at OPAL and CALA

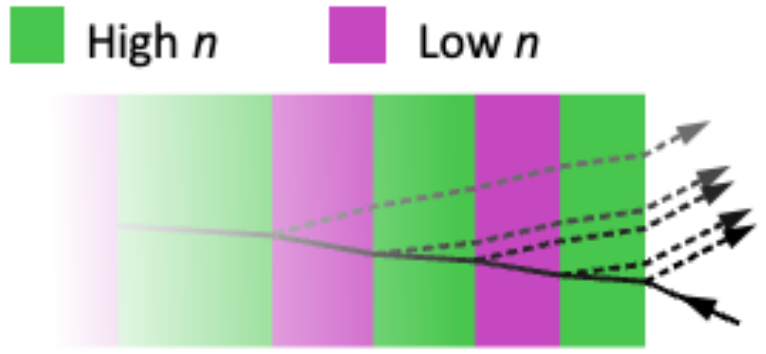


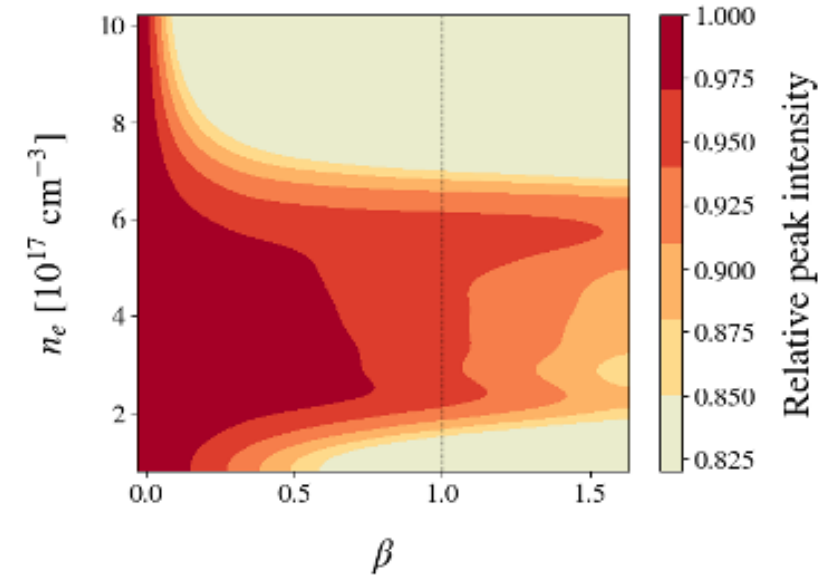






Prism-based compressor design





Chirped-mirror compressor design

John Adams Institute for Accelerator Science

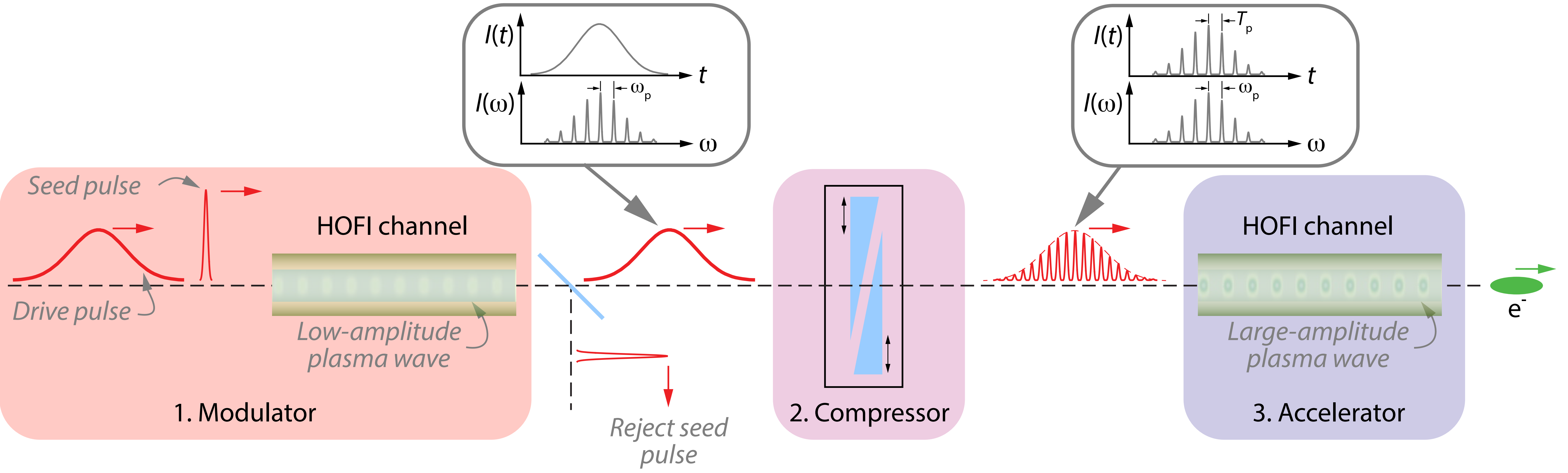
Summary of P-MoPA progress

Technologies

Drive laser
- ✓ Industrial-class
- ✓ Multi-joule
- ✓ Multi kilohertz
- ✓ Optical efficiency ~ 40%

Seed laser
- ✓ Industrial-class
- ✓ ~ 100 mJ
- ✓ Multi kilohertz

HOFI plasma channel
- ✓ Low loss
- ✓ > 100 mm guiding
- ✓ kHz rep. rate



Key
- [x] Concept demonstrated
- [ ] To be demonstrated

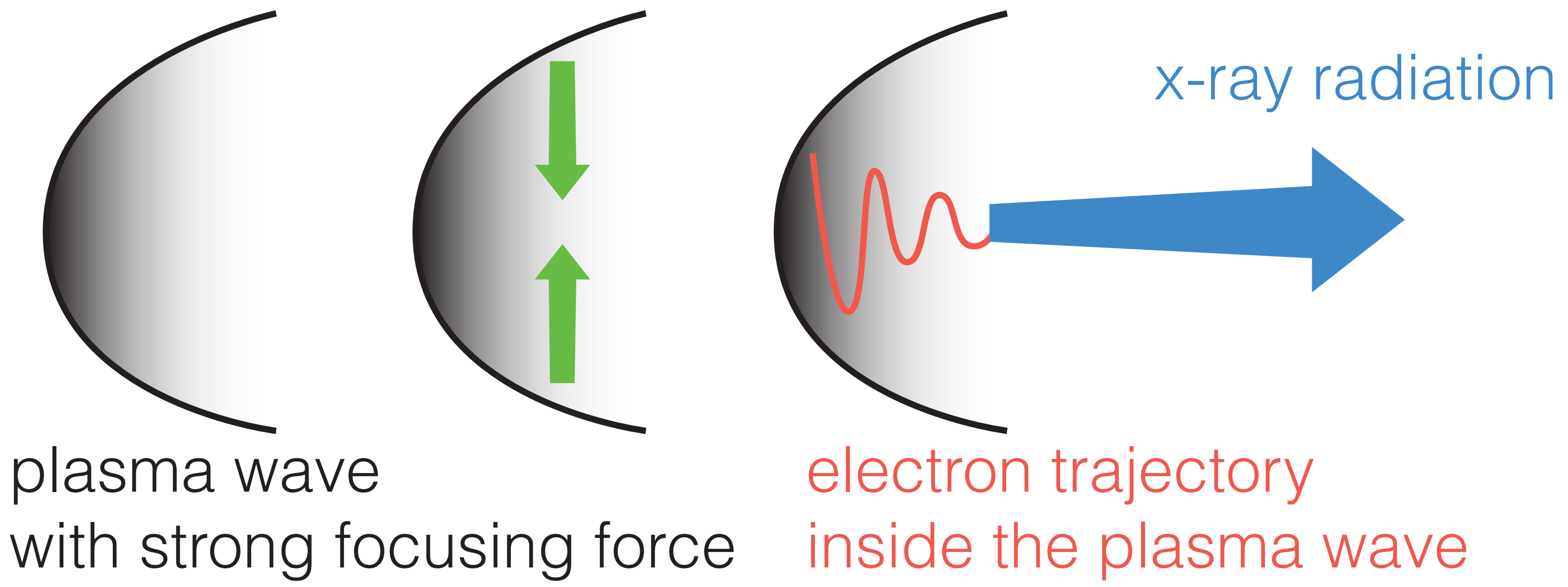
Step 1: Plasma modulator
- [x] HOFI channel generated by ps TDL pulses
- [x] Drive pulse guided in HOFI channel
- [x] Seed pulses generated
- [x] Seed pulses guided (in simulation!)
- [ ] Seed pulses guided (expt.)
- [ ] Spectral modulation of drive demonstrated

Step 2: Train generation
- [ ] Compressor system designed
- [ ] Spectrally-modulated drive pulse converted to pulse train by dispersive system

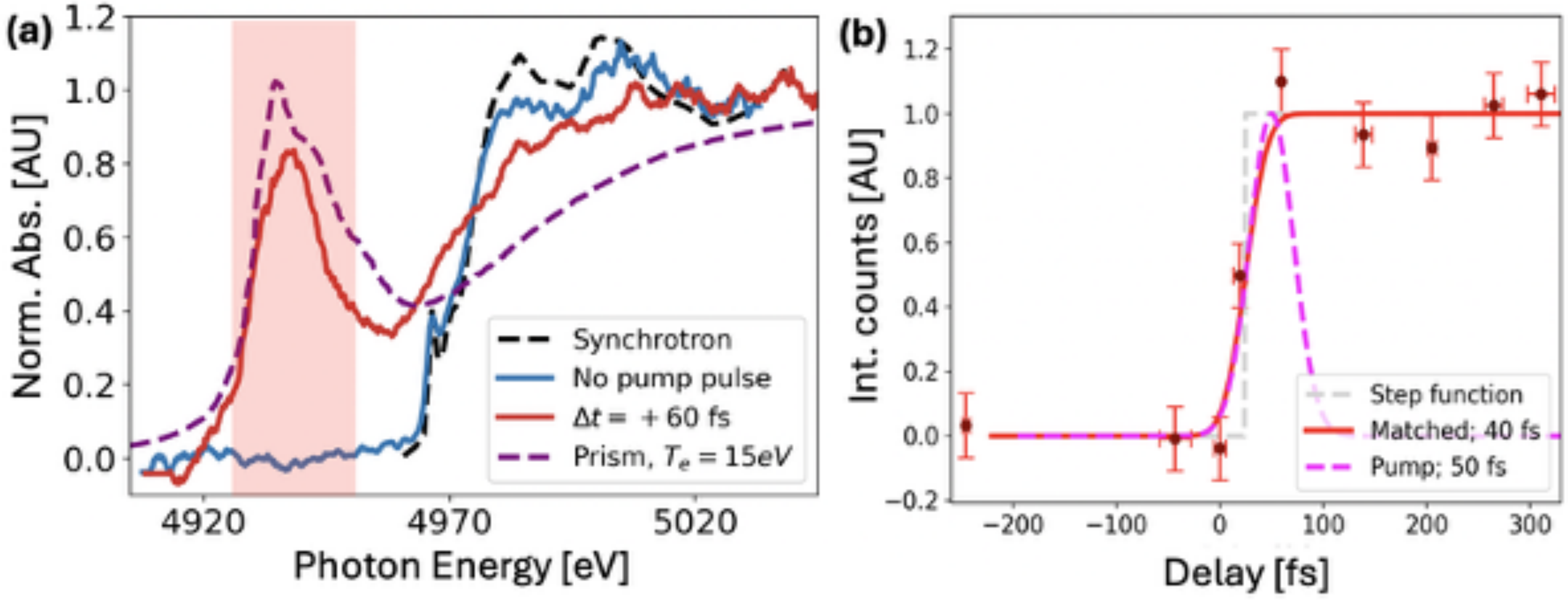
Step 3: Accelerator
- [x] Resonant wake excitation by pulse train guided in HOFI channel
- [ ] Acceleration of injected electrons to multi-GeV energies @ kHz rep. rate

Demonstrating applications

X-ray absorption spectroscopy for HED physics



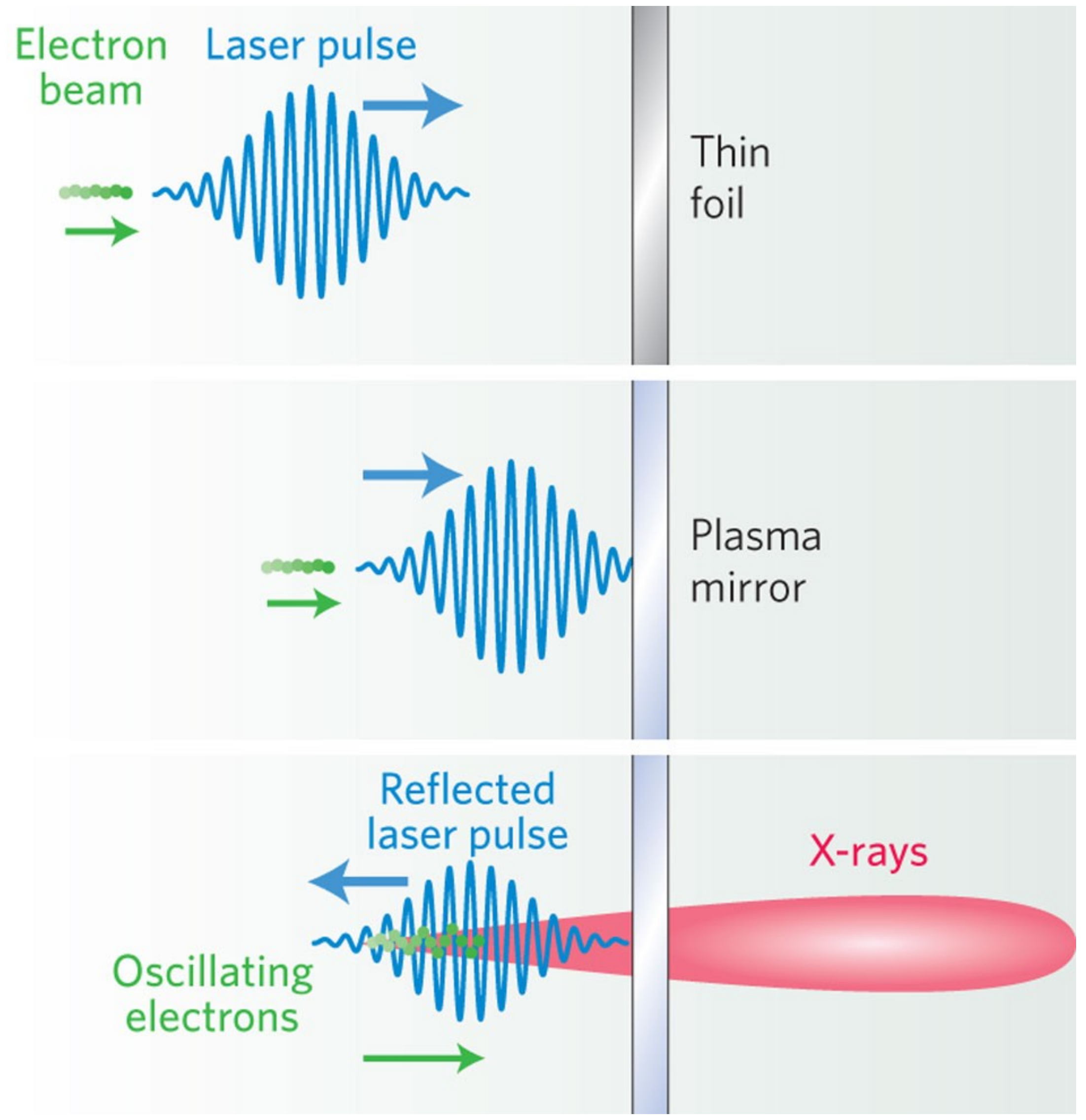
Generation of betatron radiation in a LWFA

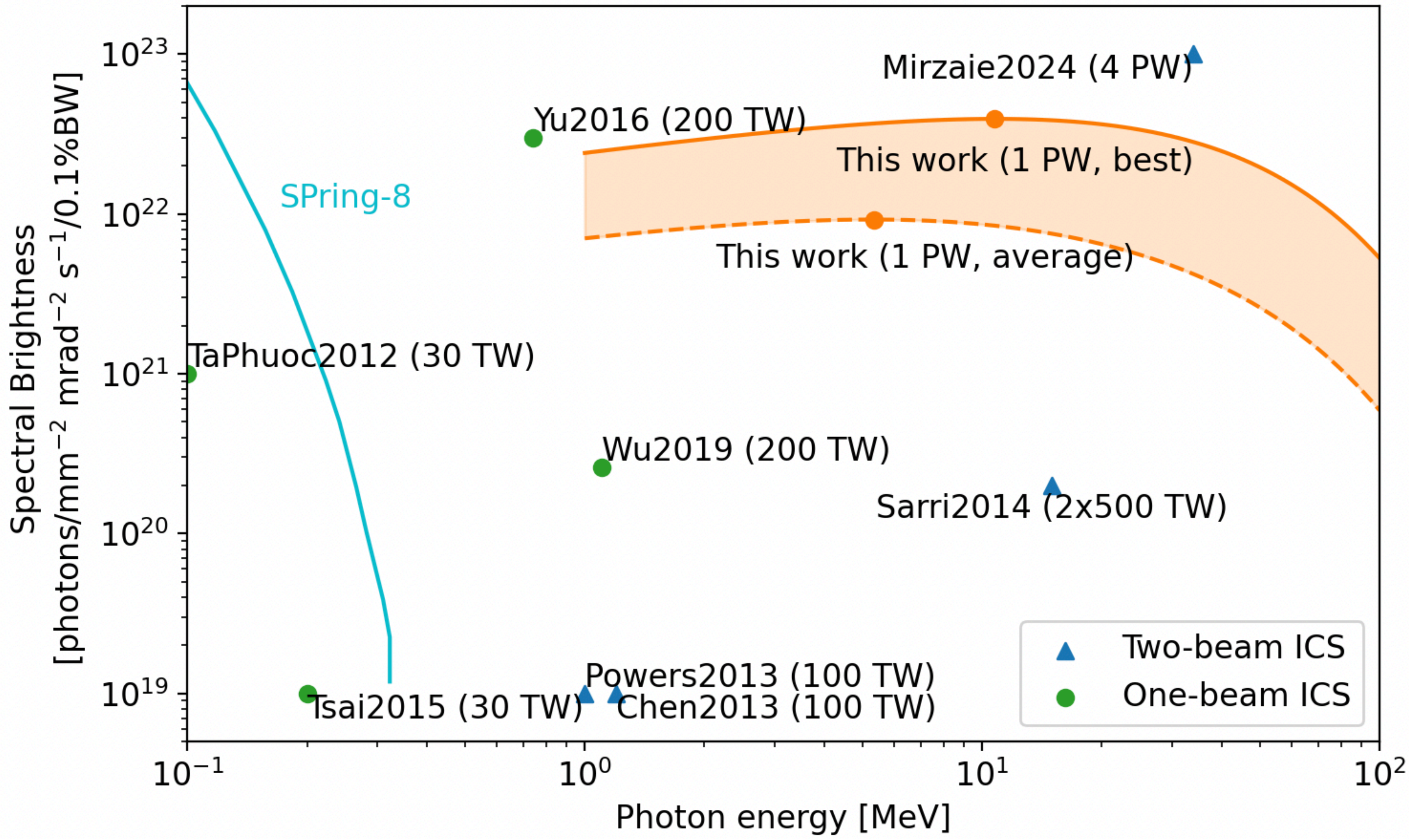


- Synchrotron-like X-rays produced by betatron motion in a LWFA are broadband and ultrafast.
  - Ideal for X-ray absorption of ultra-fast processes
- By probing a laser heated metal, we have shown a response time ~ 40 fs
  - Shortest duration measurement to-date
- X-ray absorption reveals rapid ionization of warm dense matter

Demonstration of inverse Compton scattering in 10 MeV range

- Inverse Compton scattering (ICS) from laser-accelerated bunches → bright photon sources in keV to 100s MeV range
  - Radiography of cargo
  - Medical imaging
  - Nuclear resonance fluorescence
- Major issue is jitter in laser pointing → unstable ICS source
- One solution is self reflection of LWFA drive pulse by plasma mirror
  - Allows ICS with single beam
  - Automatic alignment
- Experiments by IC group at ELI-NP has extended this method to 10 MeV range

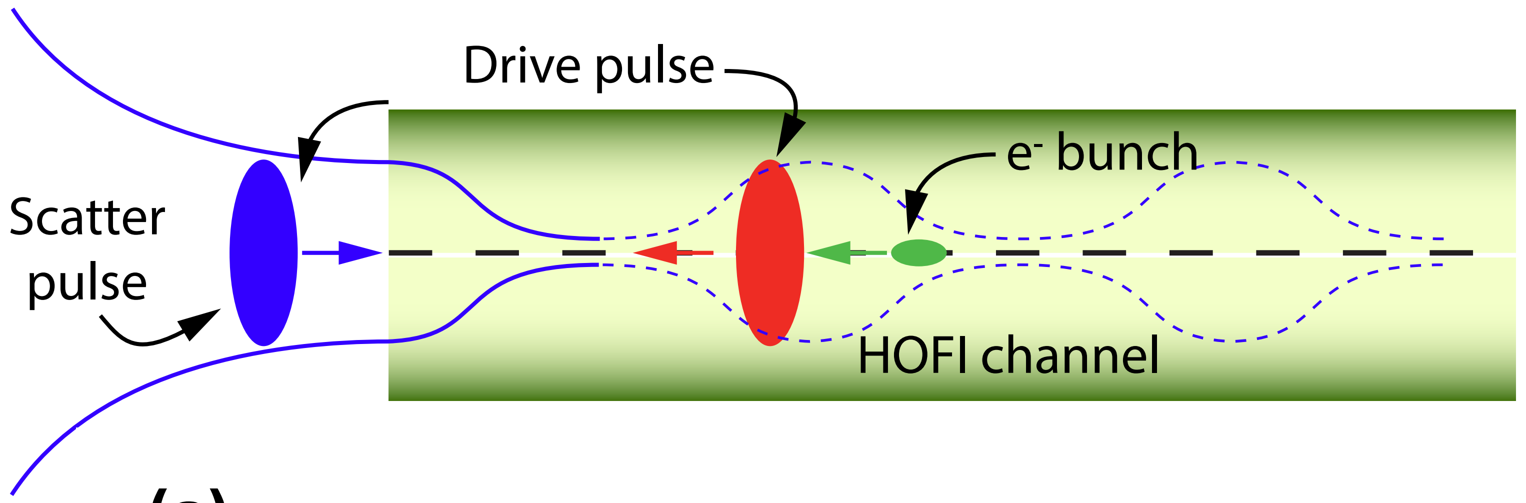




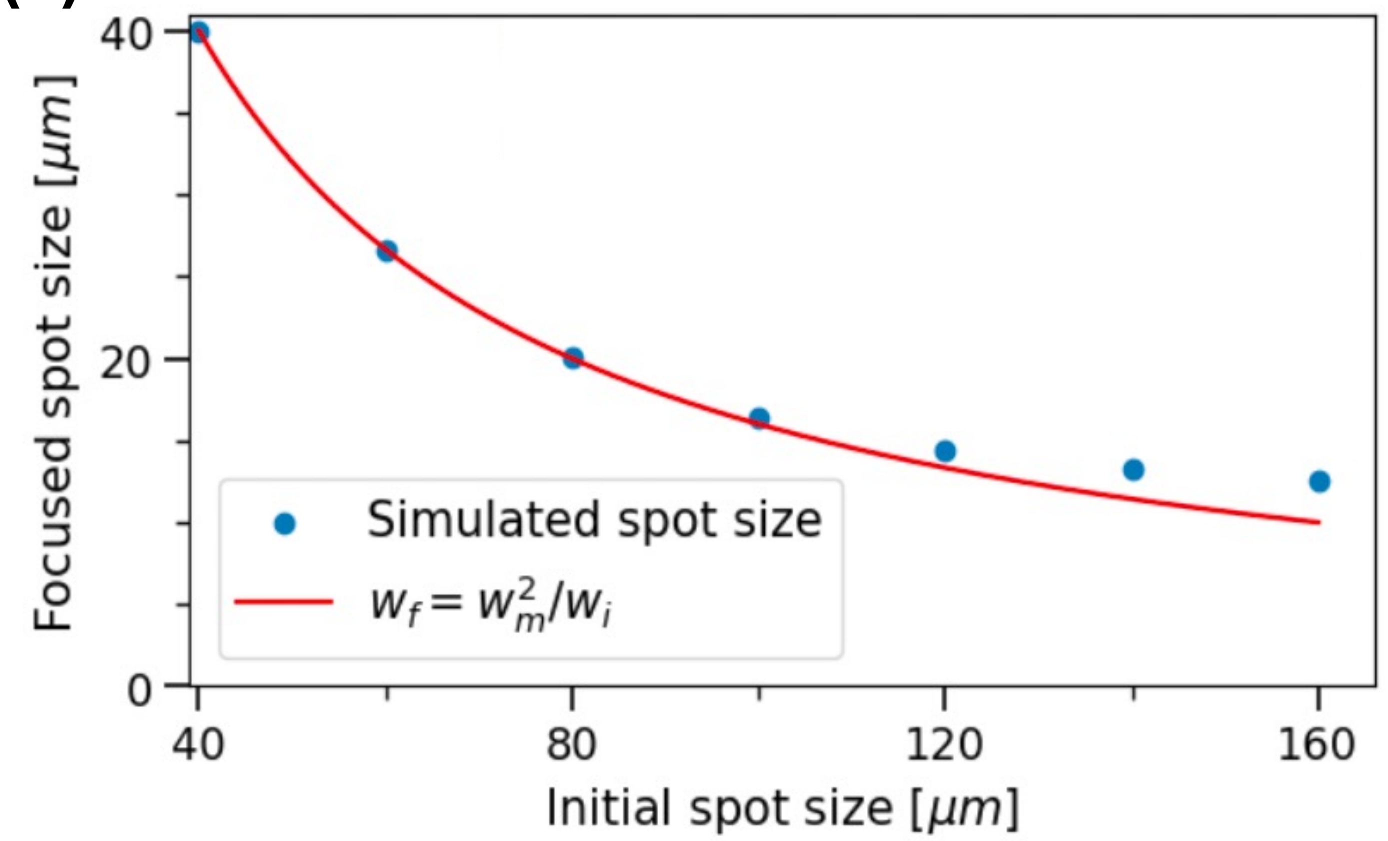
Gerstmayr et al, in review
https://doi.org/10.48550/arXiv.2506.23718

Inverse Compton scattering in HOFI channels

- An alternative approach would be to drive ICS driven in a plasma channel:
  - HOFI channel acts as short focal length lens ($f_{\text{ch}} \lesssim 1$ mm).
  - Input laser pulse of spot size w_0 focused to w_M^2/w_0
  - Jitter in transverse position of focus $\Delta r_{\text{rms}} = f_{\text{ch}}\Delta\theta_{\text{rms}} \ll 1\ \mu m$
  - Electrons accelerated along same axis
- Same concept could be used for nonlinear QED studies
- Recently awarded 6 weeks of beam time on the Astra-Gemini laser to test this concept



(a)



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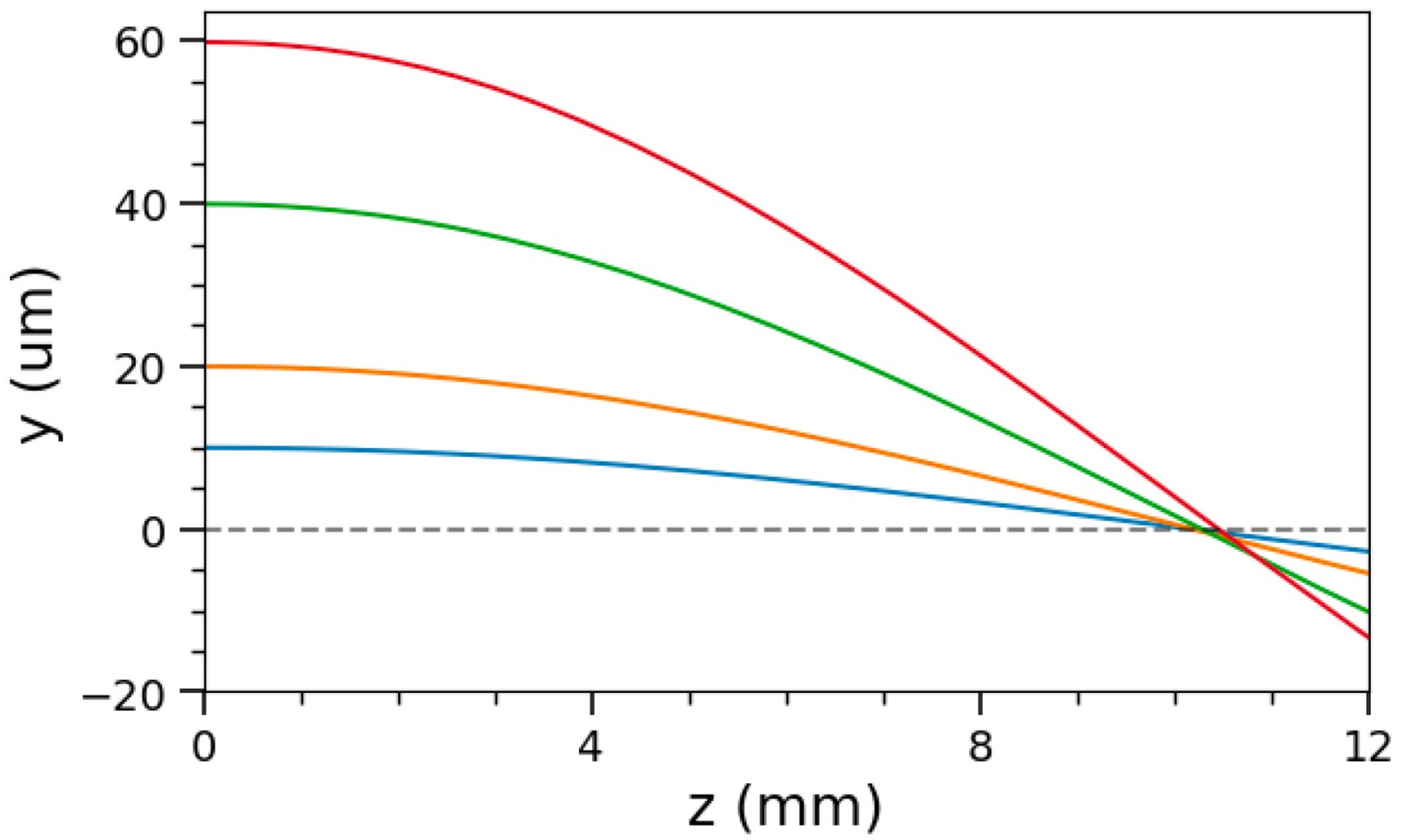
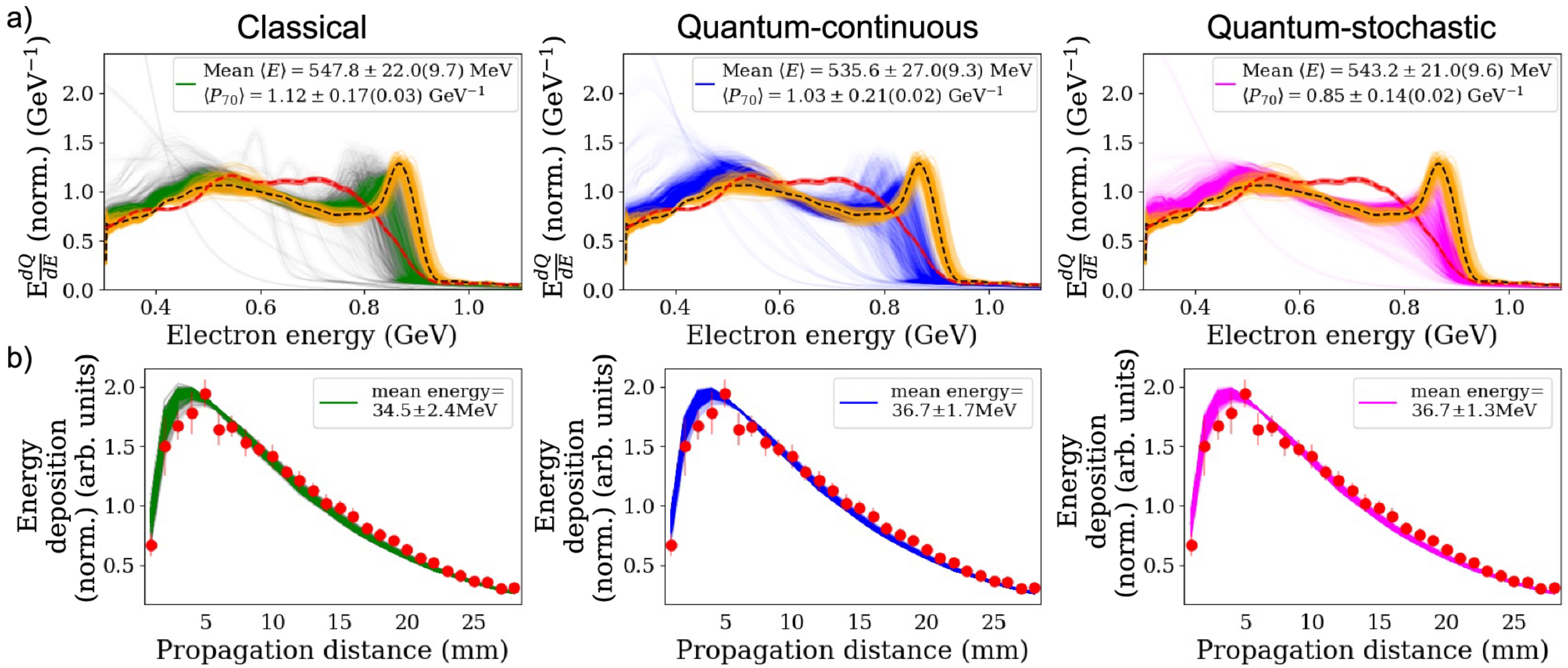
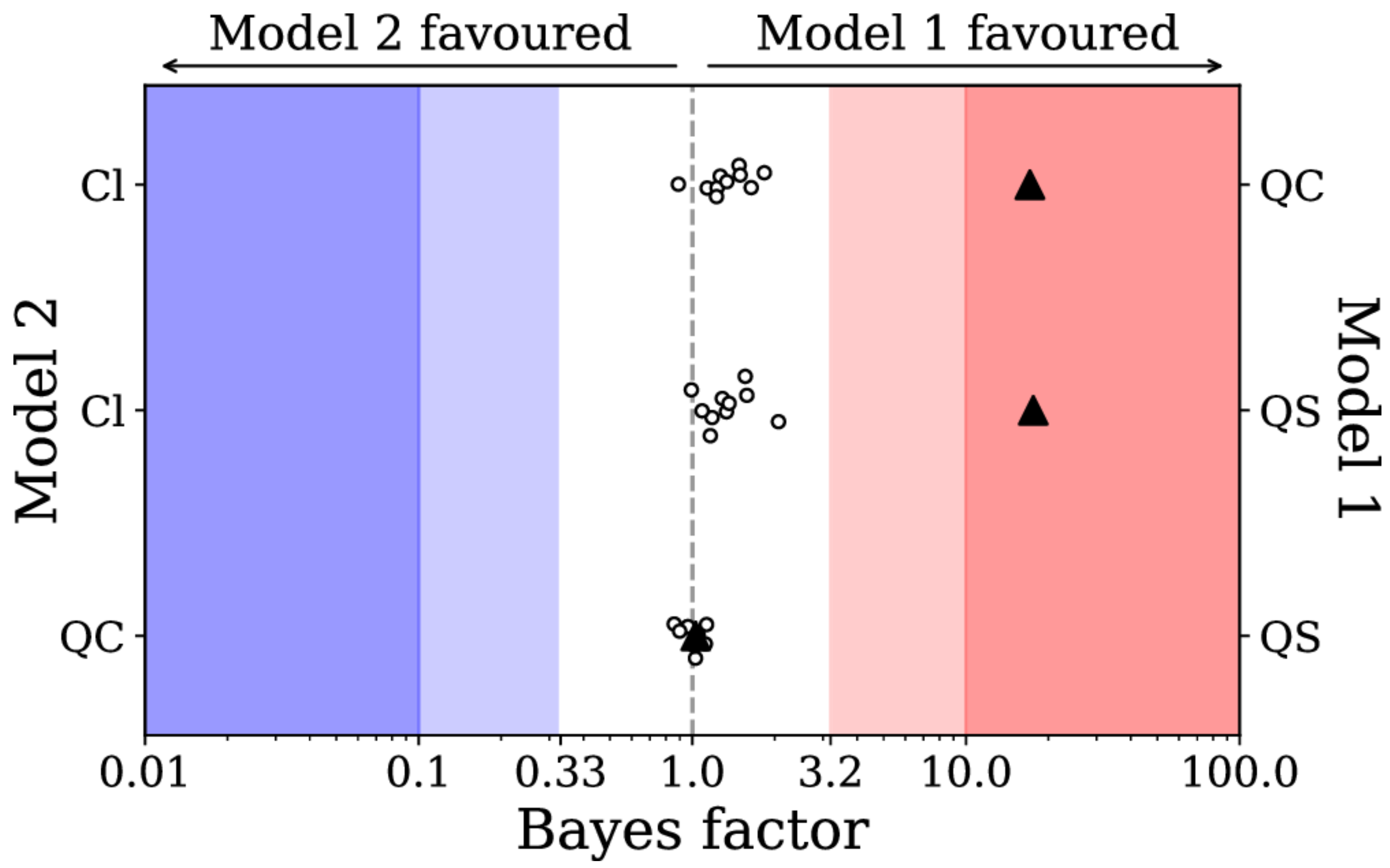


Tests of fundamental physics

E. Los. *et al.* *Nat. Comms* **17** 1157 (2026)
https://doi.org/10.1038/s41467-025-67918-8

- Collisions between LWFA electron beams and high intensity laser allows access to close to "Schwinger Field" of QED.
- Experiments by IC group at Gemini show:
  - Observation of the effects of radiation reaction (at 5σ significance level)
  - Bayesian inference-based model comparison shows strong evidence for strong field QED models of radiation reaction



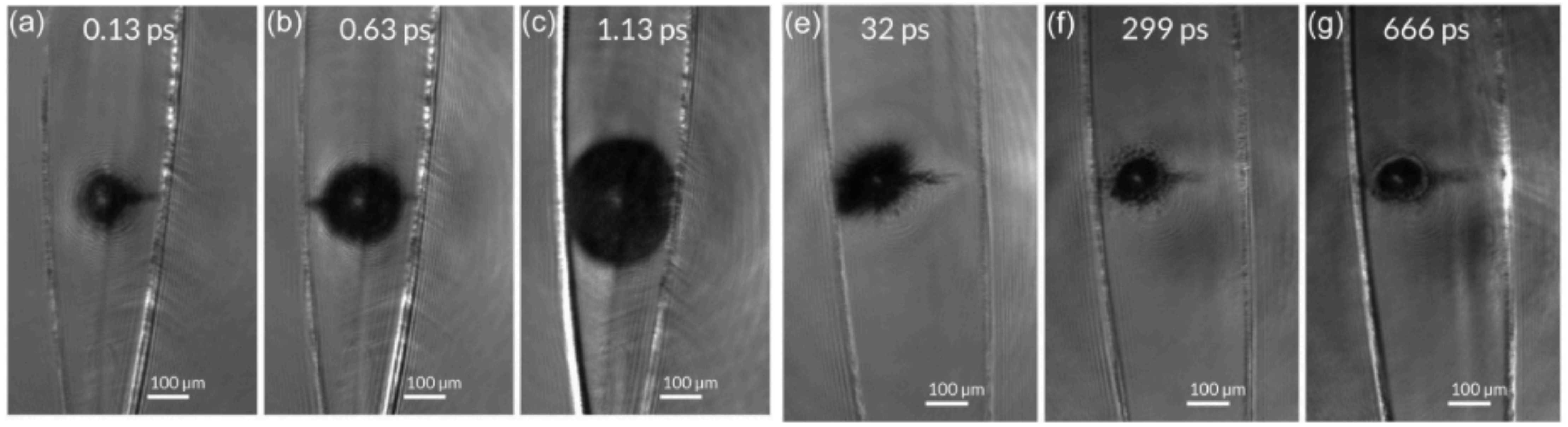


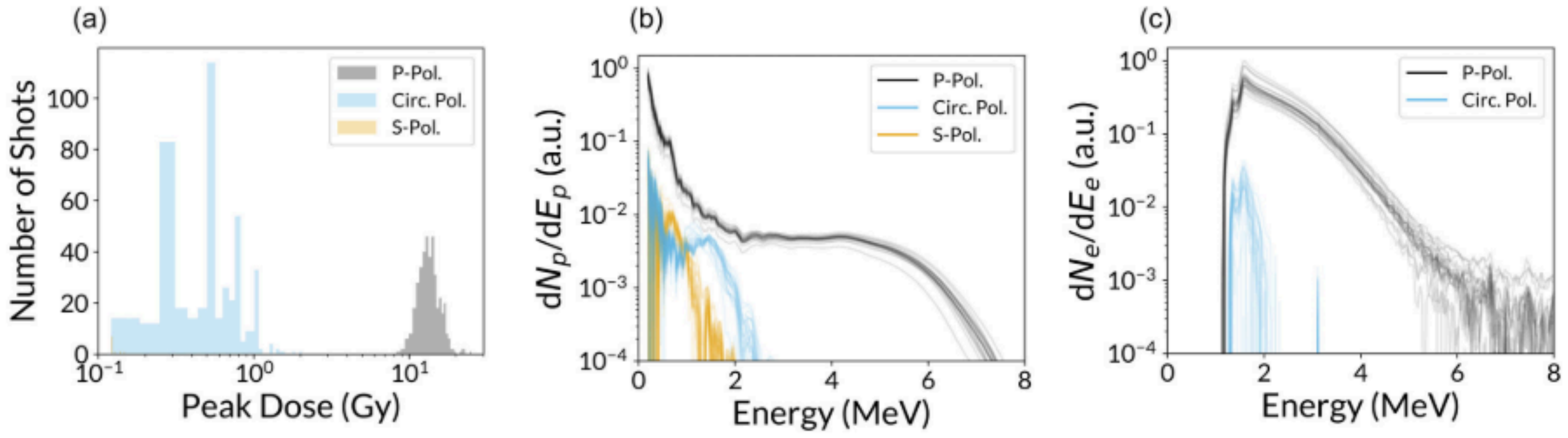
Ion acceleration

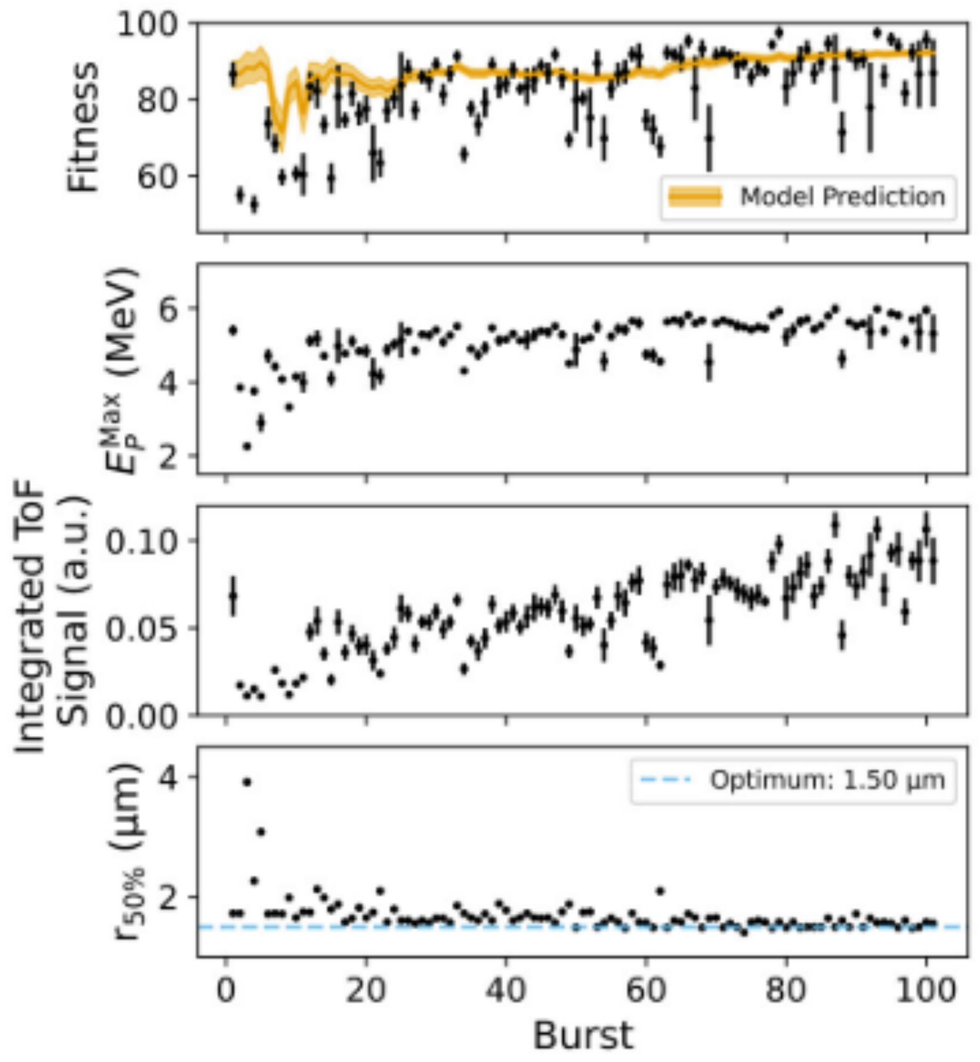
John Adams Institute for Accelerator Science

Automated optimization of laser-driven proton beams from converging liquid sheet jet targets

- Water sheet target developed at SLAC
  - Reproducible source of ions
  - Enables high rep rate operation; allows ML optimisation of ion energies and yield
- Obtain higher dose and proton and electron energies with p-polarization, as expected
- Real-time, closed-loop, Bayesian optimisation of ion beam energies by tuning laser wavefront
  - Increased signal by x 10 and max. proton energy by 11%
- Limited access to Gemini or BNL this year, but access to J-Karen and Gemini using gas and liquid sheet targets next year







Summary

- The JAI groups have strong research programmes in the advanced acceleration of electrons and ions
- Working on improving the performance of advanced accelerators
  - Improving bunch properties
  - Increasing beam energies
  - Increasing repetition rate and efficiency
- Demonstrating applications of advanced accelerators
  - Radiation generation
  - Tests of fundamental science