Dephasingless laser wakefield acceleration of electrons using a flying focus

Charlie Arrowsmith

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LABORATORY FOR LASER ENERGETICS
University of Rochester

Collaborators

K. G. Miller, M. V. Ambat, B. Boni, I. A. LaBelle, A. Martin, J. J. Pigeon, H. G. Rinderknecht, I. A. Settle, J. P. Palastro, J. L. Shaw, D. H. Froula

Plasma and Ultrafast Laser Science and Engineering

A. Rigatti, J. Spaulding

Optical Manufacturing

S.-W. Bahk, I. A. Begishev, S. Bucht, N. Dauphin, C. Jeon, C. Mileham, S. Qin, R. Roides, M. Spilatro, B. Webb

Laser Technology Development Group, MTW and MTW-OPAL

J. Kendrick, M. Romonofsky, J. Szczepanski

Engineering

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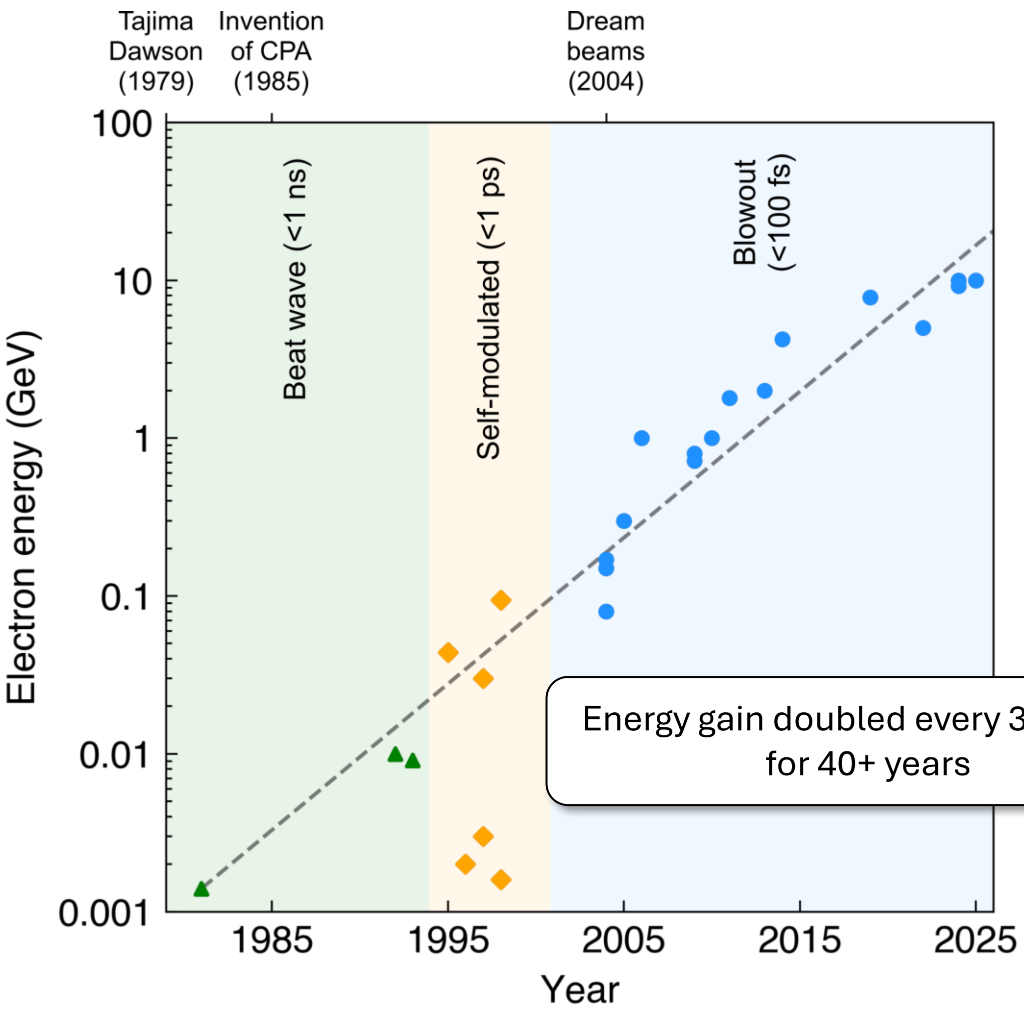
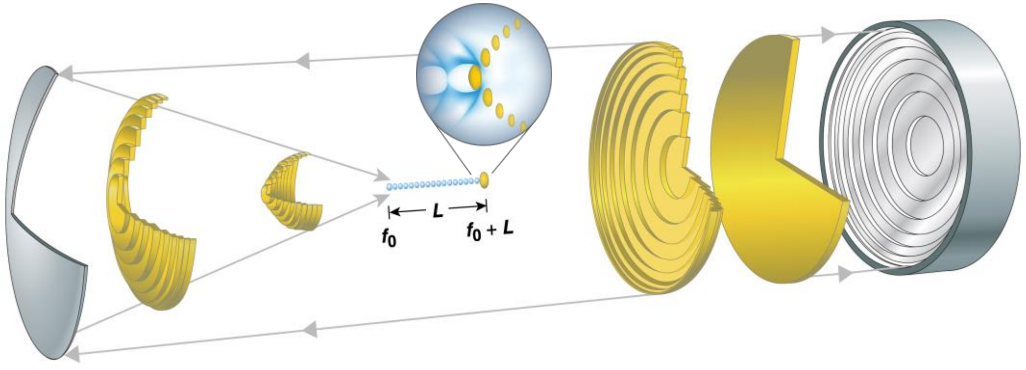
Moore’s law of laser-plasma accelerators



Energy gain doubled every 3-4 years for 40+ years

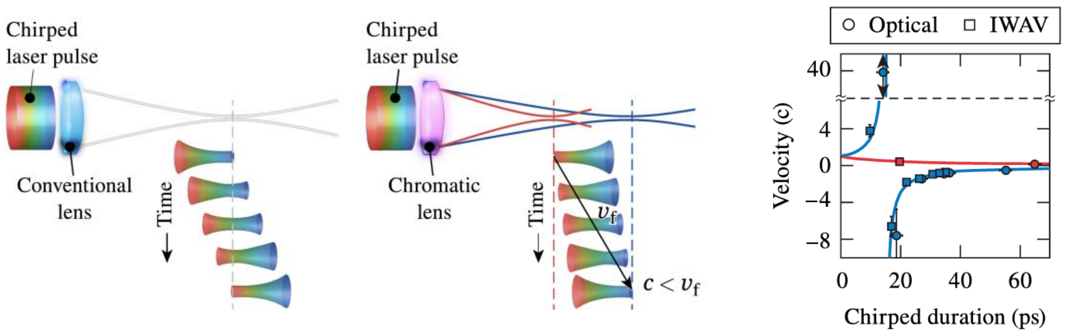
Dephasingless laser wakefield acceleration provides a credible path towards TeV-class electron beams in a single-stage, compact accelerator

- Achieved by using a flying focus to drive a wakefield in plasma at the vacuum speed of light.
- Projected to lead to a step-change increase in the electron energy producible in a sub-meter accelerator.
- Initial proof-of-concept experiments have showed that dephasing can be eliminated (published in Nature Physics).
- Future experiments are being planned to optimize the scheme in preparation to scale to the multi-GeV regime.



Spatiotemporal pulse shaping is enabling a new generation of radiation sources, diagnostics, and laser–plasma interactions

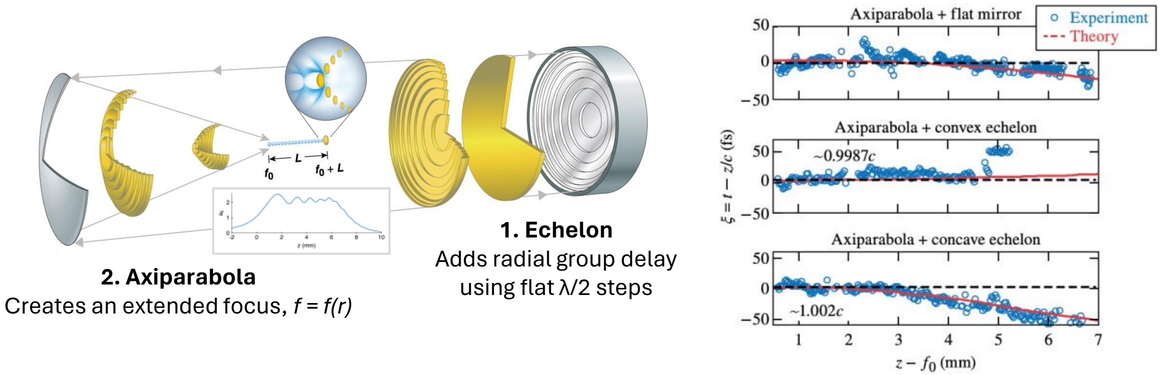
Chromatic flying focus



M. Piccardo et al., *Optica* **12**, 732-752 (2025).

- Inverse Compton Scattering (ultra bright and highly tunable)
  E. Gerstmayr et al., arXiv:2607.15805v1 (2026).
- Radiation reaction and vacuum birefringence
  M. Formanek et al., *Phys. Rev. A* **105**, L020203 (2022).
  M. Formanek et al., *Phys. Rev. D* **109**, 056009 (2024).
- Photon acceleration, vacuum electron acceleration and others...
  J. Howard et al., *Phys. Rev. Lett.* **123**, 124801 (2019).
  D. Ramsey et al., *Phys. Rev. E* **102**, 043207 (2020).

Achromatic/ultrashort/ultrafast flying focus



J. J. Pigeon et al., *Optics Express* **32**, 1 (2024).

- Two-color terahertz (THz) generation
  T. T. Simpson et al., *Phys. Rev. Research* **6**, 013041 (2024).
  J. P. Pigeon et al., *Nat. Comms.* (accepted, 2026).
- Laser wakefield acceleration
  J. P. Palastro et al., *Phys. Rev. Lett.* **124**, 13 (2020).
  A. Liberman et al., *Phys. Rev. Research* **8** (2), L022001 (2026).
  C. D. Arrowsmith et al., *Nat. Phys.* (2026).

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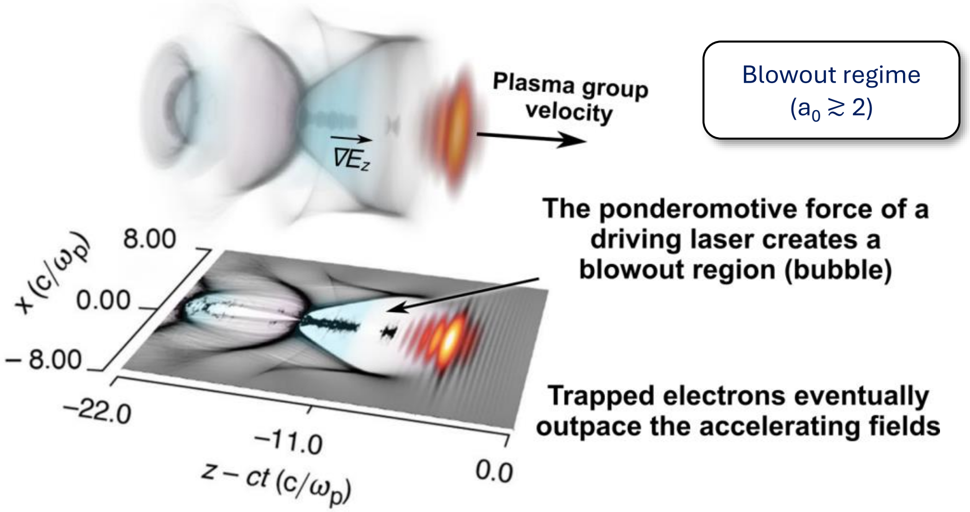
A. Sainte-Marie et al., *Optica* **4**, 10 (2017).
S. Smartsev et al., *Optics Letters* **44**, 14 (2019).
D. H. Froula et al., *Nat. Photonics* **12**, 5 (2018).
D. Turnbull et al., *Phys. Rev. Lett.* **120**, 225001 (2018).

A flying focus can be used to eliminate dephasing in a laser-plasma accelerator

Traditional laser wakefield acceleration (LWFA)

Gaussian pulse drives a wakefield at roughly the plasma group velocity



Blowout regime
($a_0 \gtrsim 2$)

Accelerator length = dephasing length	$L_\mathrm{d} = \frac{cR_\mathrm{b}}{c-v_\mathrm{w}} \propto n_\mathrm{e}^{-3/2}$
Maximum energy gain	$E_\mathrm{max} = e\xi_z L_\mathrm{d} \propto n_\mathrm{e}^{-1}$
Strength of the accelerating field	$\xi_z \propto n_\mathrm{e}^{1/2}$

Plasma densities ~10^{17} cm^{-3} are used to reach multi-GeV energies.

$$L_\mathrm{acc}\,[\mathrm{m}] \approx 13.5 \left(\frac{E_\mathrm{max}}{100\ \mathrm{GeV}}\right)^{3/2} \left(\frac{\lambda_\mathrm{L}}{800\ \mathrm{nm}}\right) \left(\frac{a_0}{2.0}\right)^{-1/2}$$

W. Lu et al., *Phys. Rev. ST Accel. Beams* **10**, 061301 (2007).

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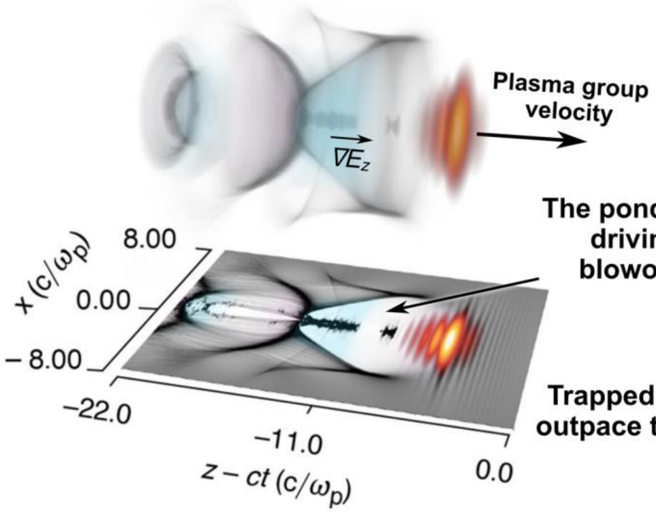

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Dephasingless laser wakefield acceleration (DLWFA)

Flying focus drives a wakefield at the vacuum speed of light

W. Lu et al., *Phys. Rev. ST Accel. Beams* **10**, 061301 (2007). J. P. Palastro et al., *PRL* **124**, 13 (2020). K. G. Miller et al., *Sci. Rep.* **13**, 21306 (2023).

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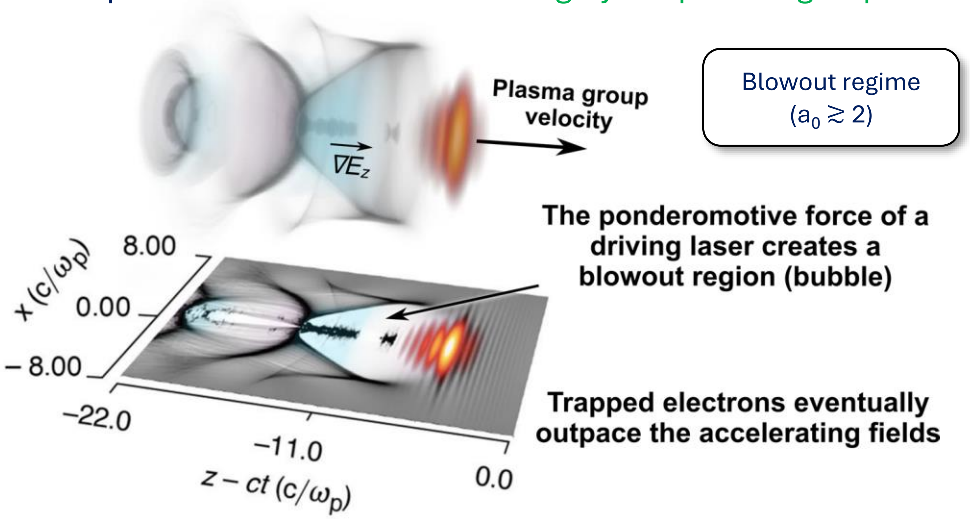

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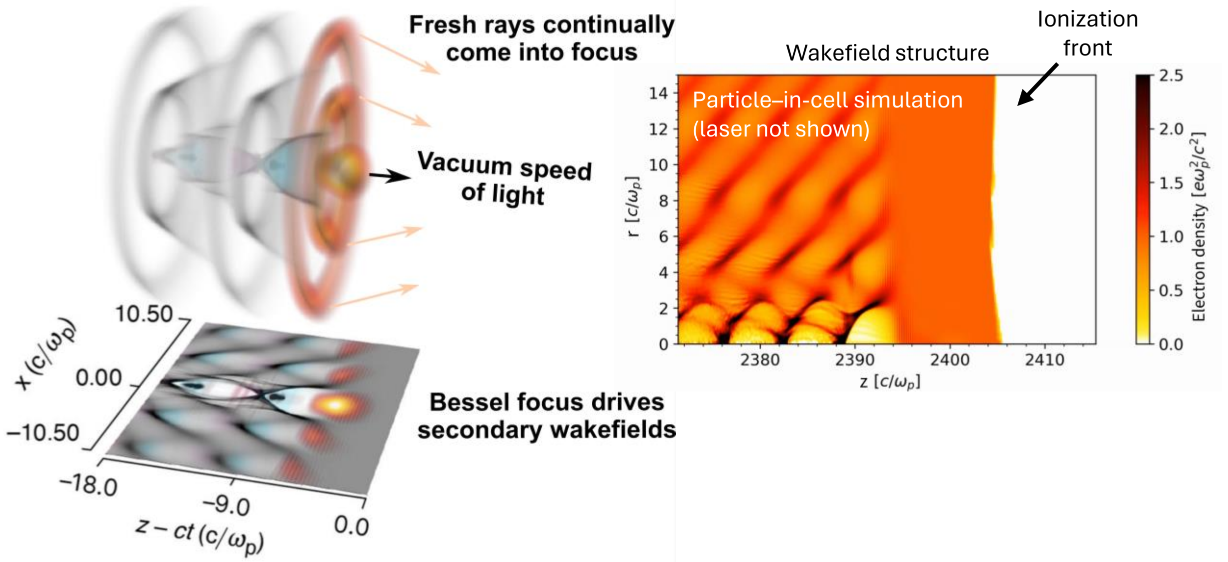

Accelerator length	$L_{acc} \propto E_L$
Maximum energy gain	$E_{max} = e\xi_z L_{acc} \propto n_e^{1/2} E_L$

Plasma densities >10^{18} cm^{-3} can be used (>GV/cm accelerating fields).

$$L_{acc}\,[\mathrm{m}] \approx 0.7 \left(\frac{E_{max}}{100\ \mathrm{GeV}}\right) \left(\frac{n_e}{5\times 10^{18}\ \mathrm{cm}^{-3}}\right)^{-1/2} \left(\frac{a_0}{2.0}\right)^{-1/2}$$

W. Lu et al., *Phys. Rev. ST Accel. Beams* **10**, 061301 (2007). J. P. Palastro et al., *PRL* **124**, 13 (2020). K. G. Miller et al., *Sci. Rep.* **13**, 21306 (2023).

Shrinking multi-GeV laser-plasma accelerators

Facility (Pulse durations ≲ 25 fs)	Accelerator length (cm)	Predicted energy (GeV)	Shot cycle
MTW-OPAL (0.24 PW)	0.7	0.9	1 / 20 mins
ELI-Beamlines HAPLS (0.5 PW)	1.5	3	3.3 Hz
EPAC (1.5 PW) Expected 2027	4.4	6	0.1-10 Hz
Apollon (2 PW)	6	9	1 / min
ZEUS (3 PW) Expected 2026	9	15	1 / min
CoReLS (4 PW)	12	17	0.1 Hz
ELI-NP HPLS (10 PW)	30	42	1 / min
Vulcan 20-20 (8 PW, long focal length) Expected 2030s	23	34	TBC
NSF-OPAL (25 PW) Expected 2040	73	105	1 / 5 mins

Next step: ELI-Beamlines HAPLS through ELI-NP HPLS

Next gen.: Vulcan 20-20 and NSF-OPAL

d ~ 4” (MTW-OPAL)

d ~ 12” (ELI-Beamlines HAPLS through CoReLS)

d ~ 24” (ELI-NP HPLS through NSF-OPAL)

5 GeV in 3.5 cm (>10 cm for LWFA)
10 GeV in 7 cm (~30 cm for LWFA)
40 GeV in 30 cm using 10 PW

Pulse guiding not required (single beam)
More compact focusing optics (~f/10)

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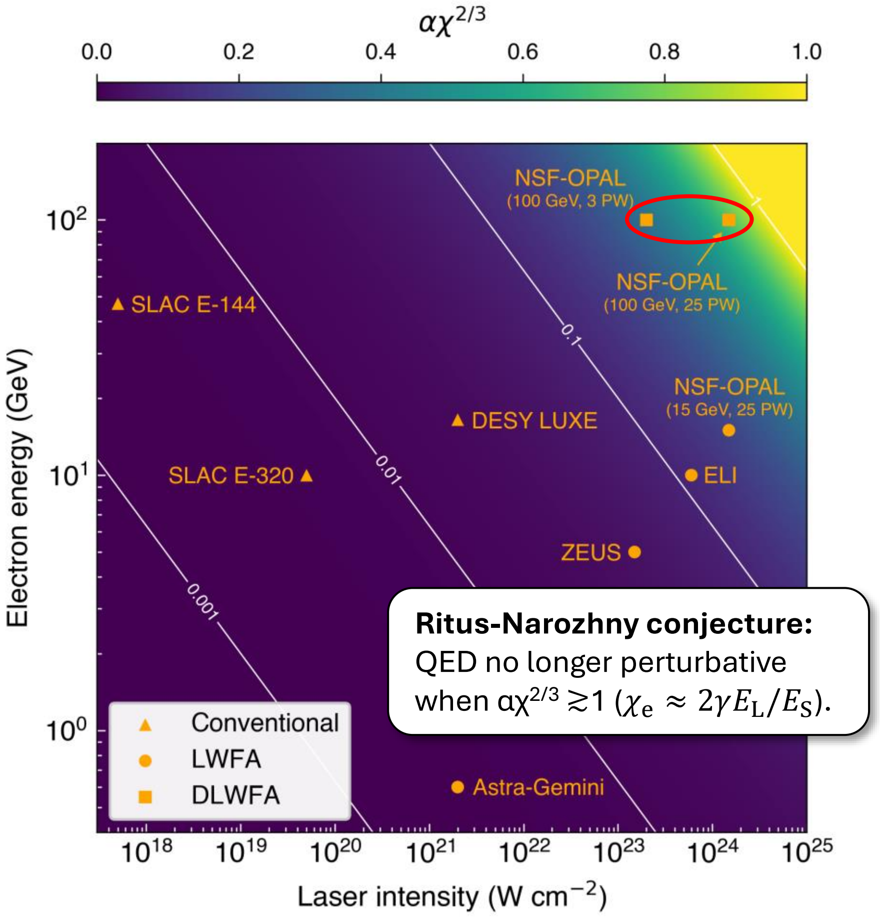

Ritus-Narozhny conjecture:
QED no longer perturbative
when $\alpha\chi^{2/3} \gtrsim 1$ ($\chi_e \approx 2\gamma E_L/E_S$).

A possible workhorse for 10’s of GeV electron beams for SF-QED

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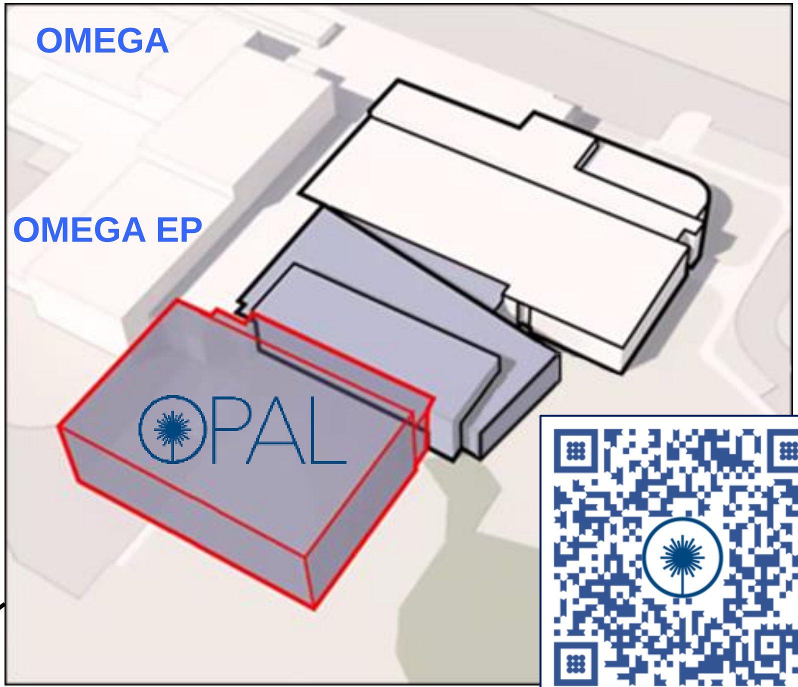
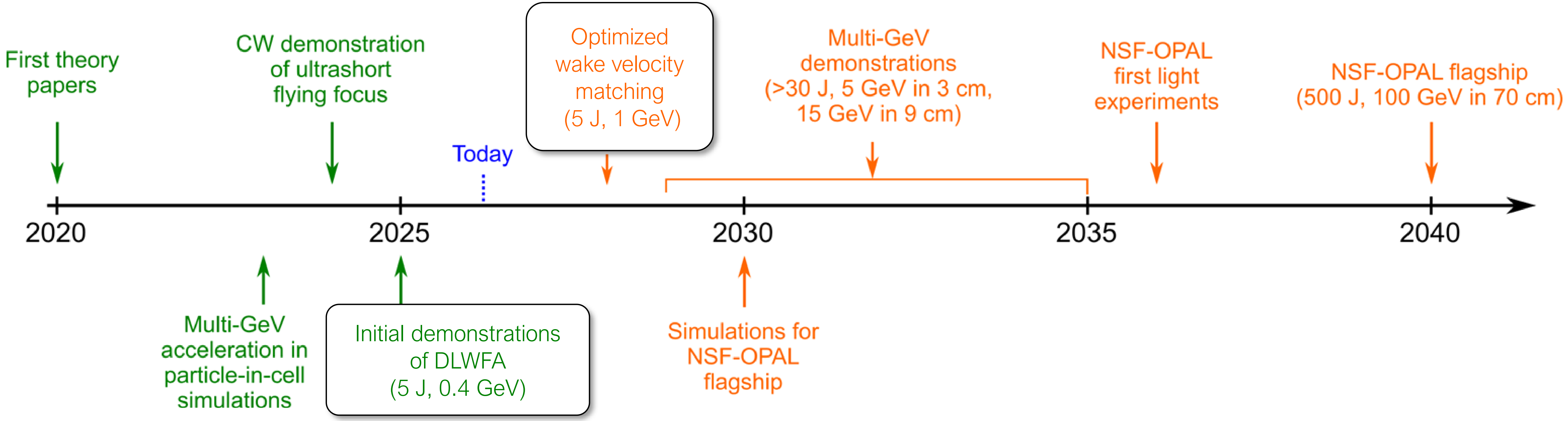


Proposed NSF-OPAL Facility

- *“Alpha” beams: **2× 25 PW / 5 mins***
- *“Beta” beam: **2 PW***
- *Up to 4× multi-kJ long-pulse beams*
- *Two target areas: highest intensity, **flexible focus***

100 GeV in 0.7 m at NSF-OPAL

Roadmap to 100 GeV electron acceleration



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J. J. Pigeon et al., *Optics Express* **32**, 1 (2024).

Design considerations for blowout-regime dephasingless laser wakefield acceleration

Objective: Propagate a laser pulse with $a_0 \sim 2$ at $v = c$ in a high-density plasma ($n_e > 10^{18}$ cm^{-3}) for the longest distance possible.

Limited by pulse duration to ensure $c\tau < \lambda_p/2$

$\tau = 20$ fs $\longrightarrow n_e \lesssim 8\times10^{18}$ cm^{-3}

Limited by laser energy

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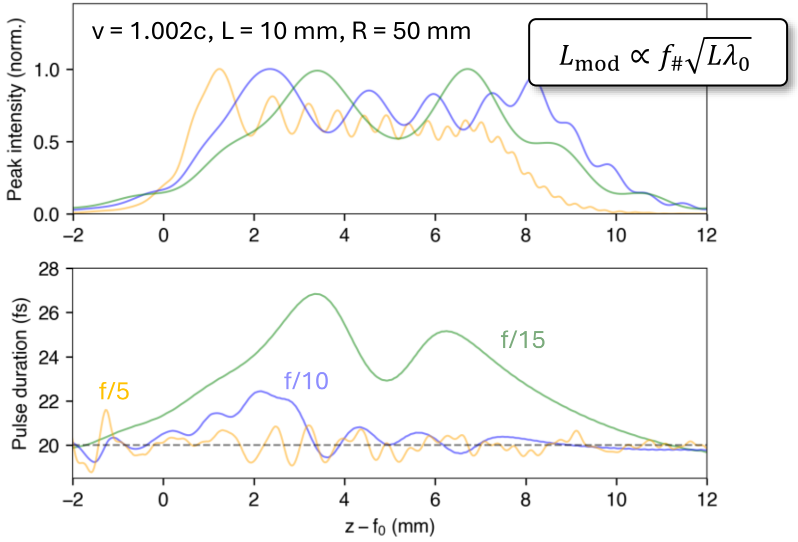
Limited by P

Frequency-domain Fresnel diffraction integral



1. Focal length decided by minimizing intensity modulations and keeping pulse duration short

$f_\# = f_0/2R < 15$

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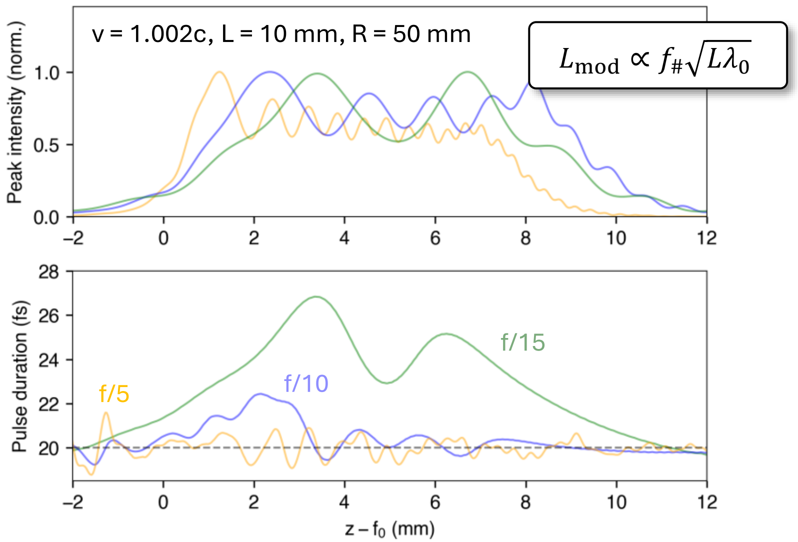
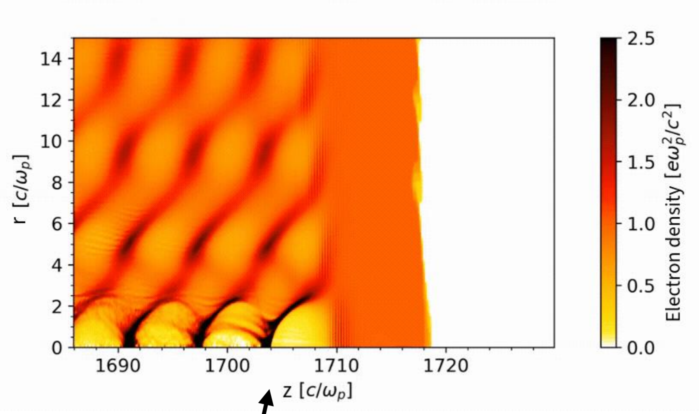


OSIRIS Particle-in-cell simulations



Fluctuations in size and shape of bubble

More stable for 20 fs pulses when $n_e \sim 5\times10^{18}$ cm^{-3}

1. Focal length decided by minimizing intensity modulations and keeping pulse duration short

$f_{\#} = f_0/2R < 15$

2. Minimize non-linear propagation effects and relativistic self-focusing

$P \lesssim P_c/2 \longrightarrow n_e \lesssim 5\times10^{18}$ cm^{-3}

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Limited by P

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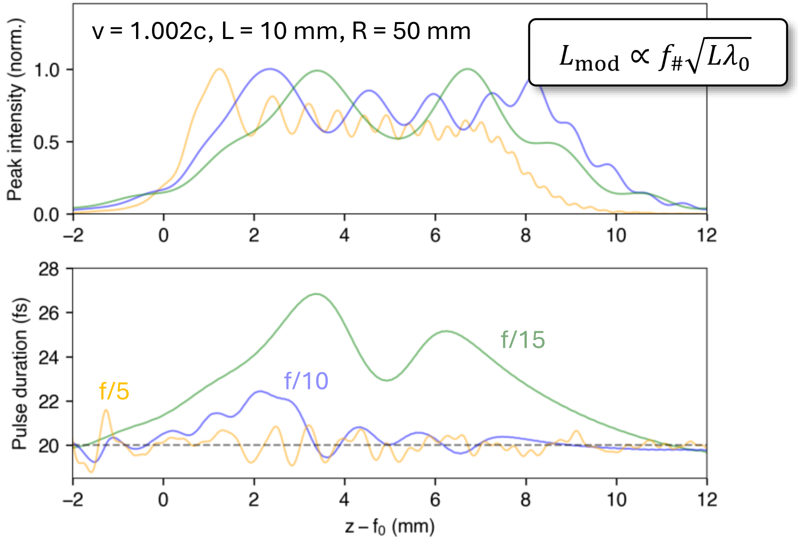

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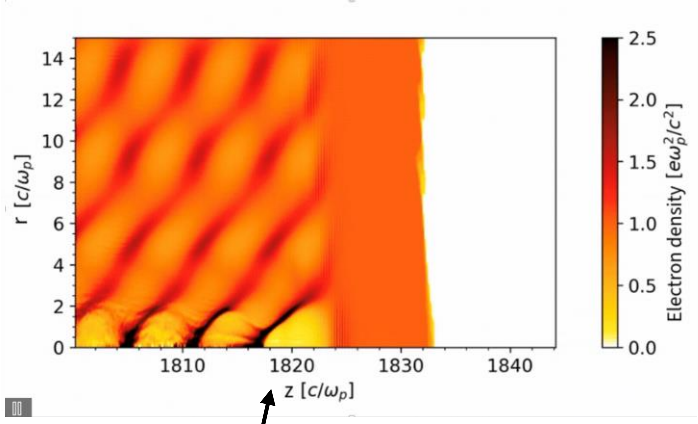

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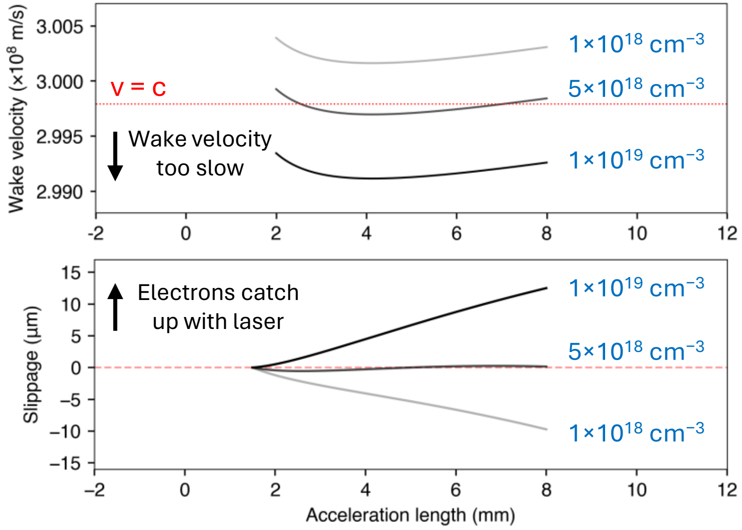
Calculations of the wakefield velocity (f/8 axiparabola)



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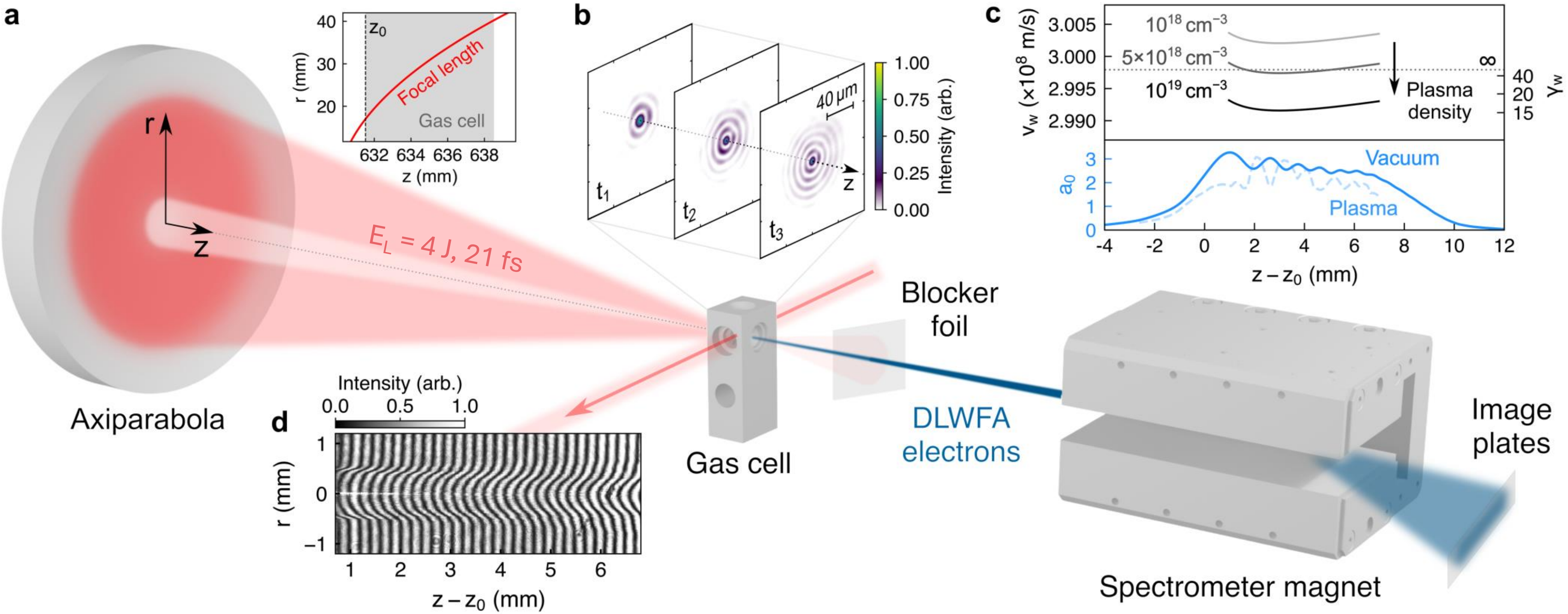
2. Minimize non-linear propagation effects and relativistic self-focusing

$P_0 \lesssim P_c/2 \longrightarrow n_e \lesssim 5\times10^{18}$ cm^{-3}

3. Match the desired wakefield velocity as closely as possible

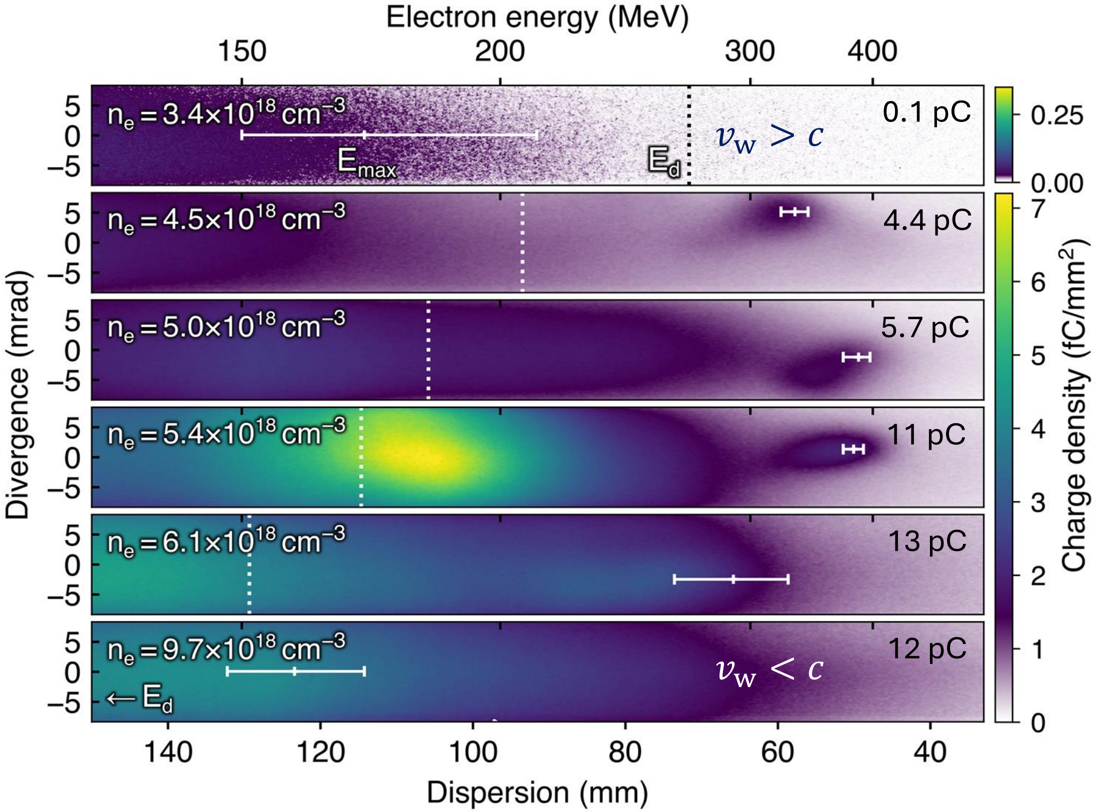
$f_{\#} = 8$

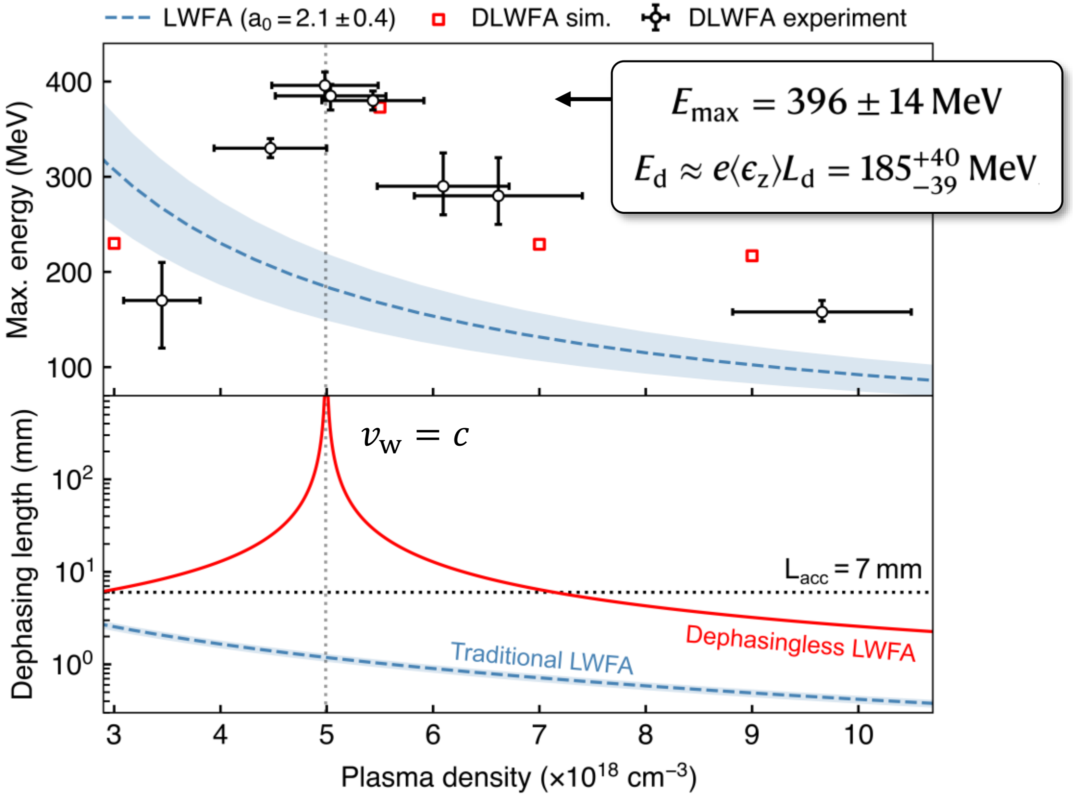
Initial proof-of-concept experiments at LLE were performed last year



C. D. Arrowsmith et al., *Nat. Physics*, 1-6 (2026).

Electrons at twice the dephasing-limited energy were observed





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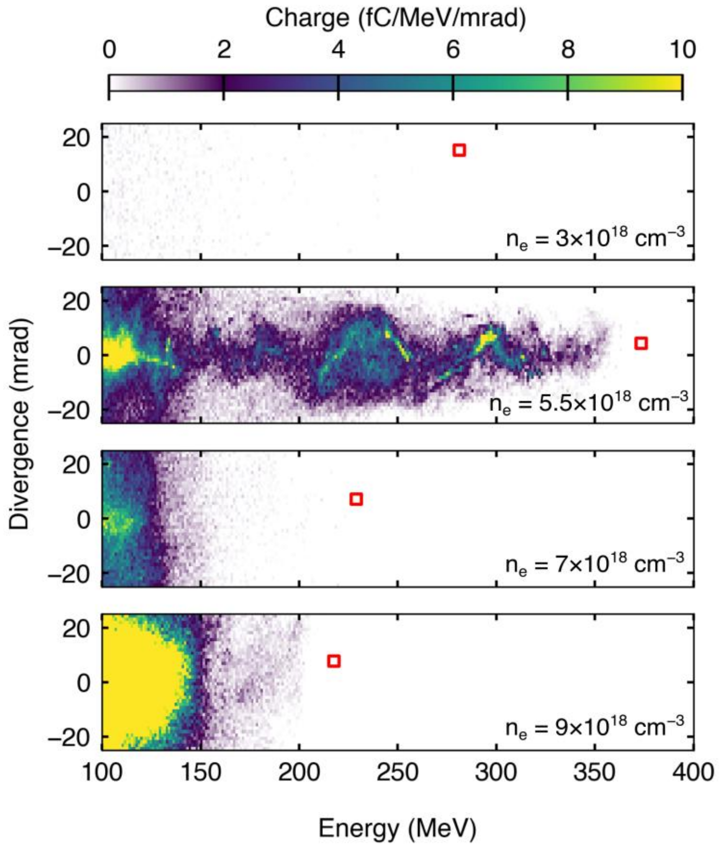
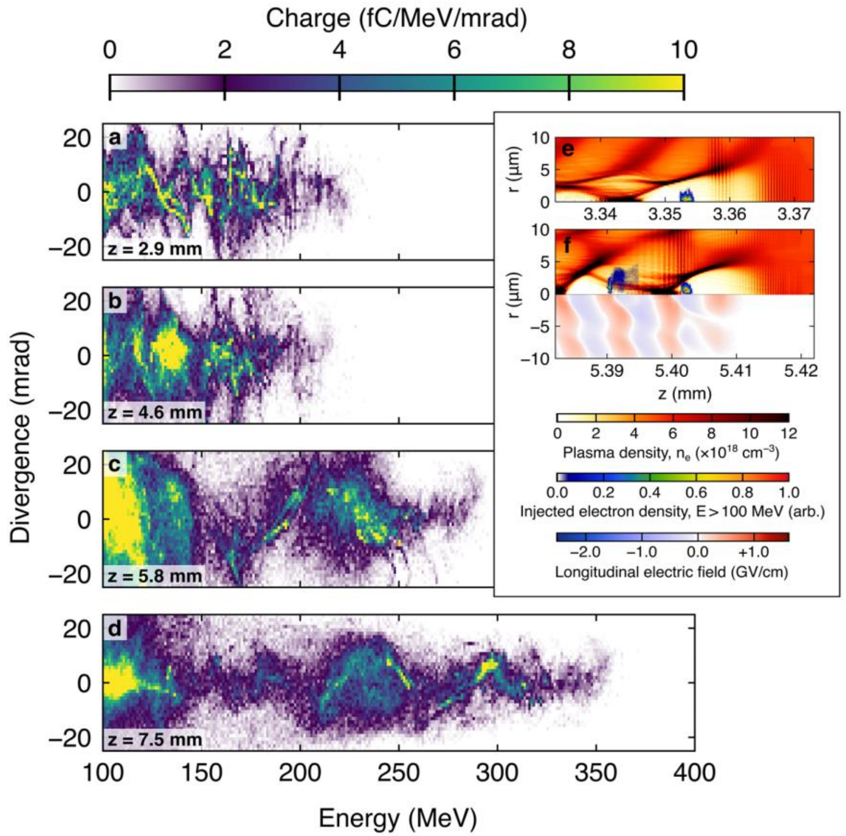
C. D. Arrowsmith et al., *Nat. Physics*, 1-6 (2026).

Particle-in-cell simulations observed the same trend between plasma density and maximum electron energy





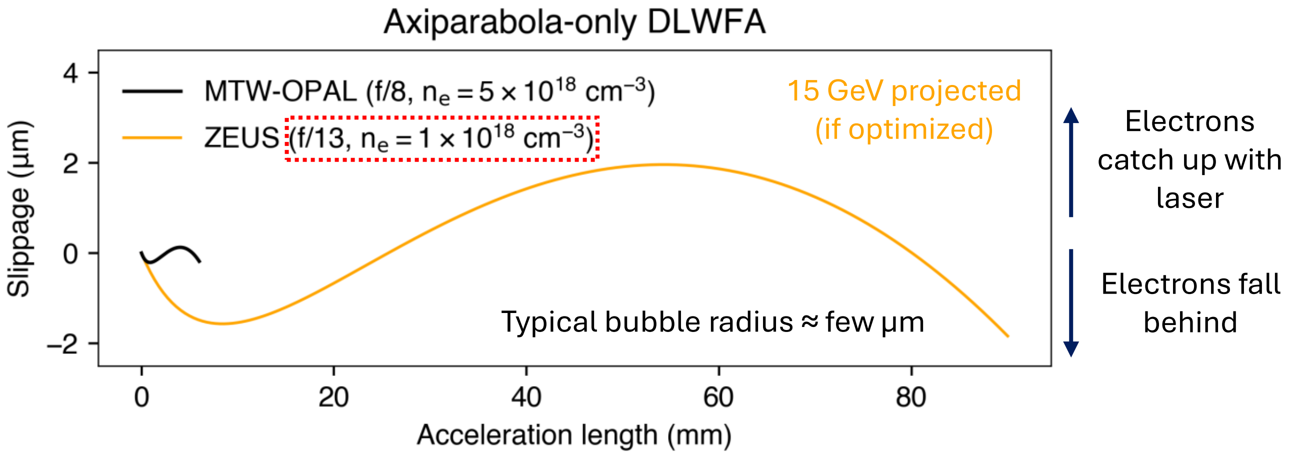
The imperfect velocity matching of the axiparabola caused periods of stalled acceleration.

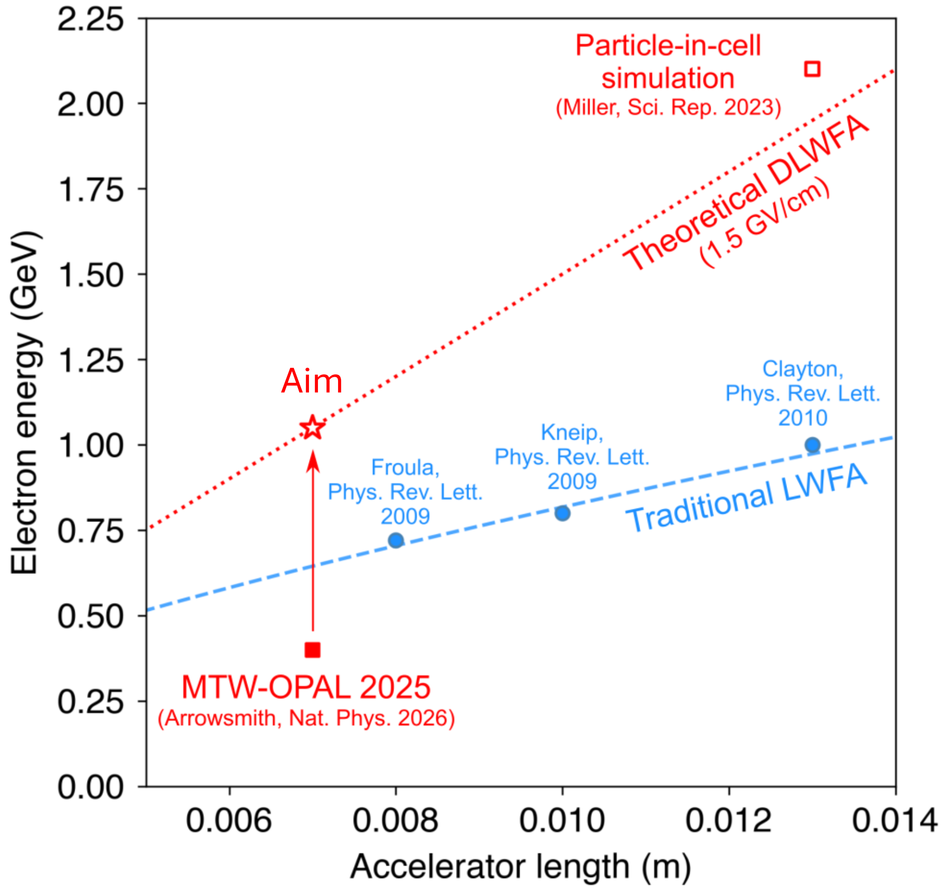
C. D. Arrowsmith et al., *Nat. Physics*, 1-6 (2026).

Control of the radial group delay is required to achieve perfect wakefield velocity matching

Using an axiparabola without an echelon can only get you so far…

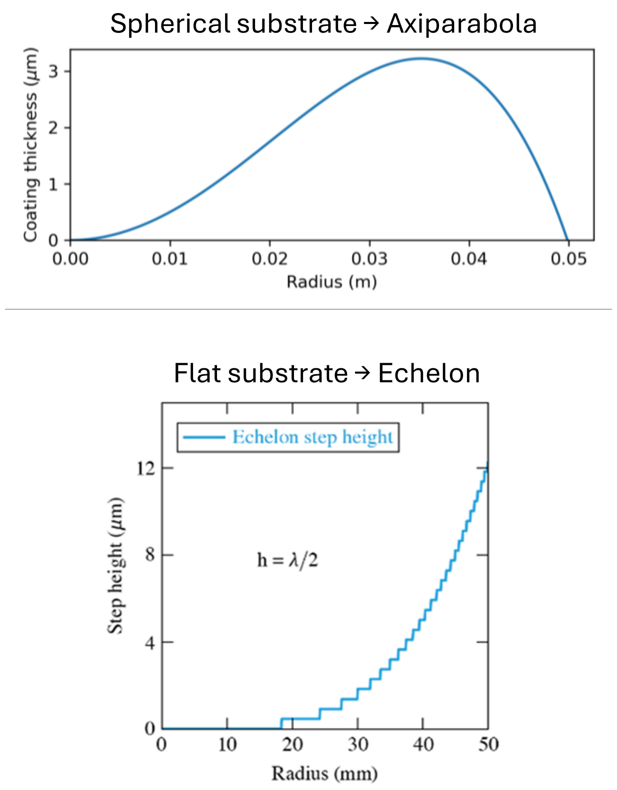
The longer the accelerator, the more necessary an echelon becomes.



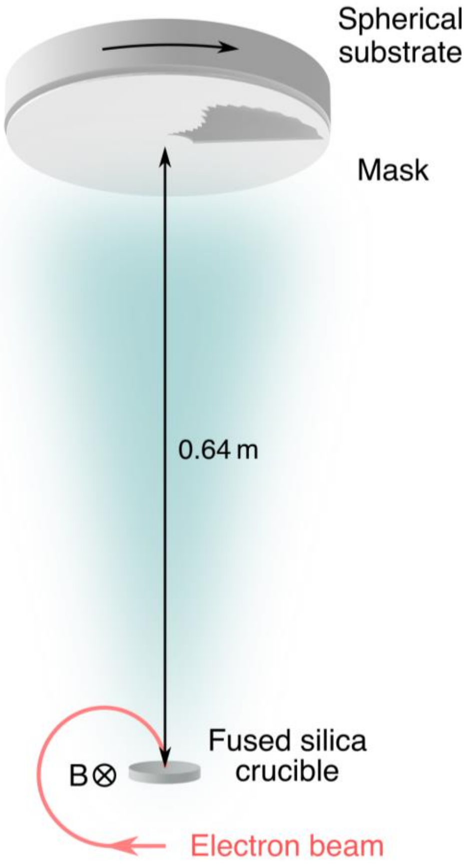


Fabricating flying focus optics in-house at LLE

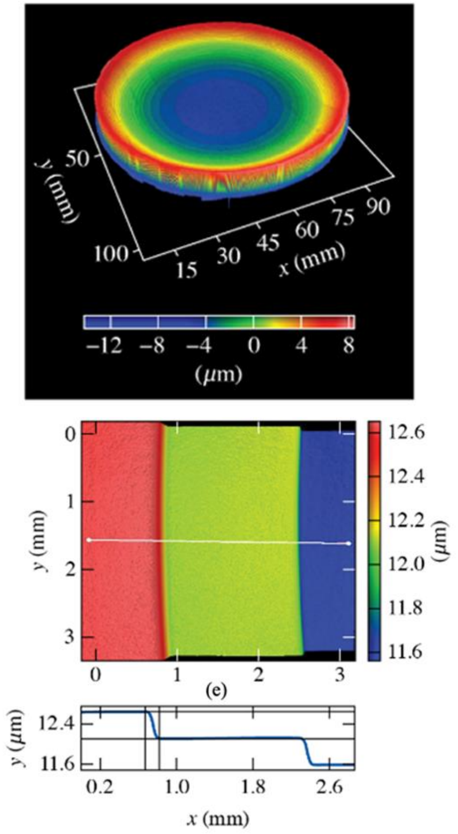
1. Design



2. Fabrication



3. Metrology

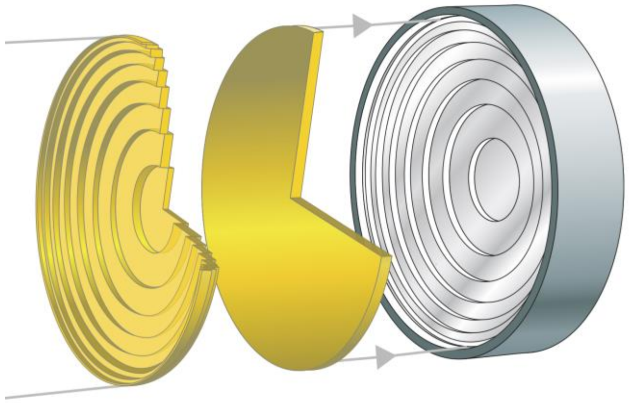


J. J. Pigeon et al., *Optics Express* **32**, 1 (2024).

Axiechelons can be made using the same fabrication technique

Echelon

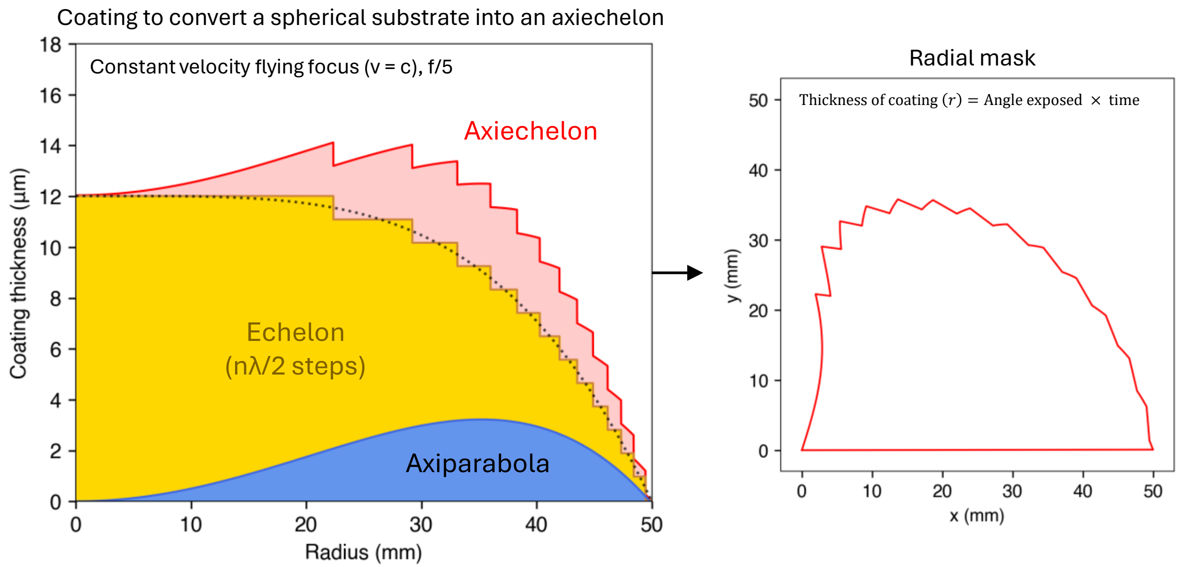
Adds radial group delay without tilting phase fronts



- Oblique incidence makes the projection of steps elliptical
  - Annuli of the beam may be split over multiple steps
  - May have an effect of stretching the pulse
- Precise alignment required
  - Makes it difficult to swap out and try lots of configurations

Axiechelon

Combines an axiparabola and an echelon into a single optic



- Extended focal region and spatiotemporal couplings achieved with a single optic
  - Easy to align and swap in and out during experiments

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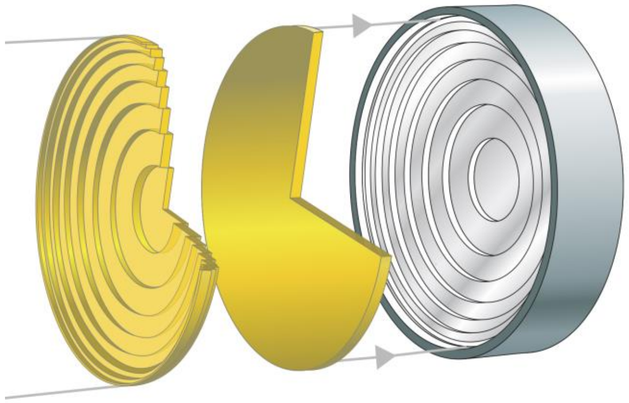
Echelon

Adds radial group delay without tilting phase fronts



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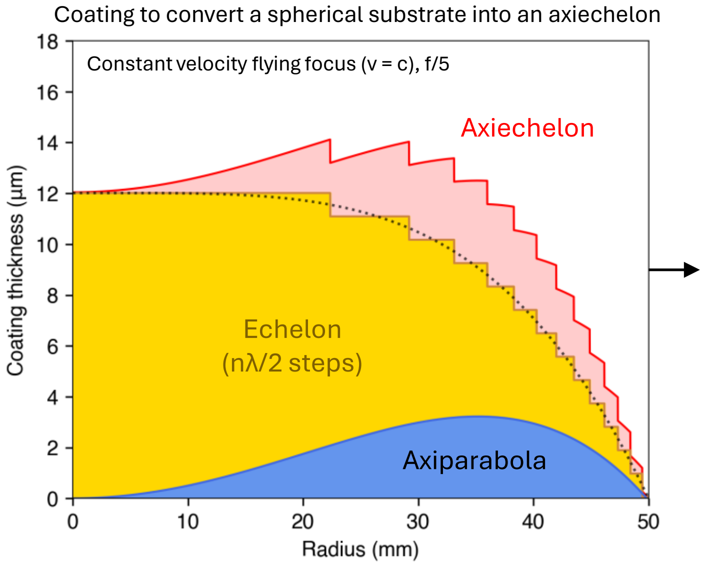
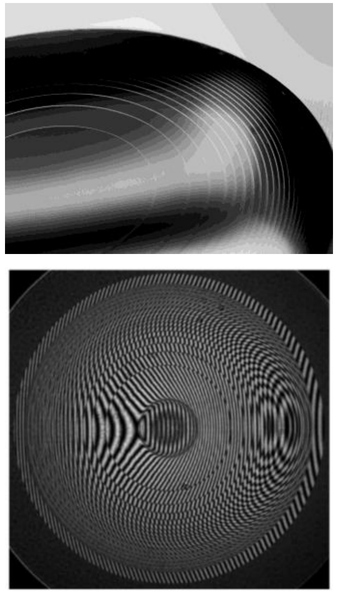
  - May have an effect of stretching the pulse
- Precise alignment required
  - Makes it difficult to swap out and try lots of configurations

Axiechelon

Combines an axiparabola and an echelon into a single optic

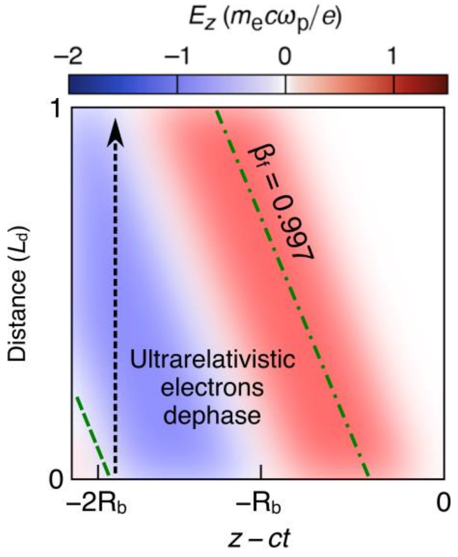




- Extended focal region and spatiotemporal couplings achieved with a single optic
  - Easy to align and swap in and out during experiments
- The first axiechelons have been made and are being characterized

The axiechelon approach gives the fine control required to produce a perfectly luminal wake

Traditional
(electrons dephase)

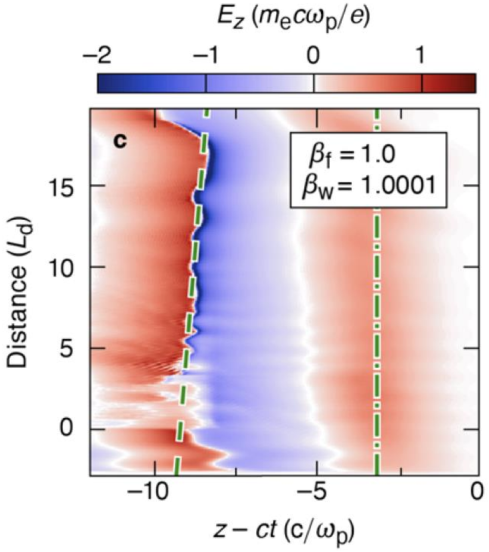


$$\beta_{\rm f} = \beta_{\rm g}$$

Focus velocity

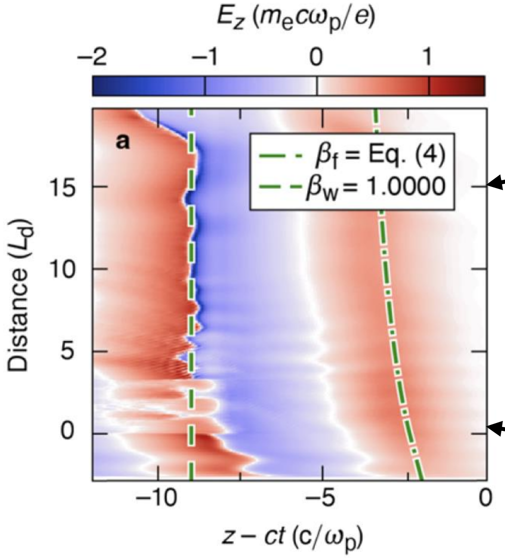
Plasma group velocity

Dephasingless
(constant focus velocity)



$$\beta_{\rm f} = 1$$

Dephasingless
(accounting for bubble shrinkage)

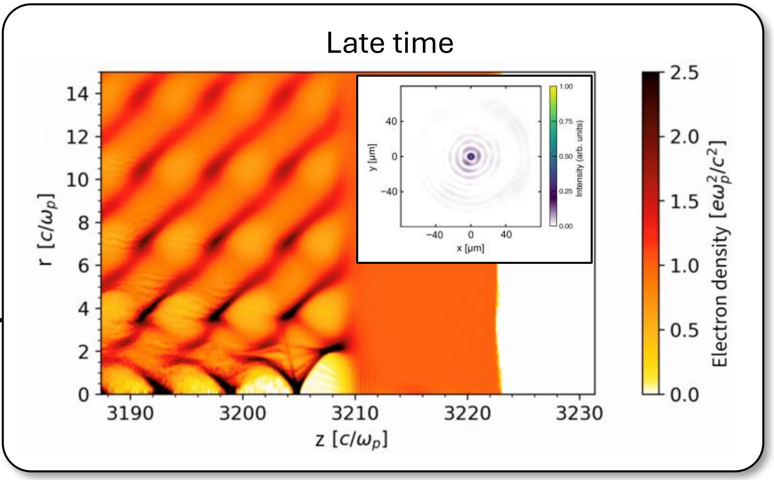


$$\beta_{\rm f} = 1 + \frac{1}{c}\frac{dR_{\rm b}}{dt}$$

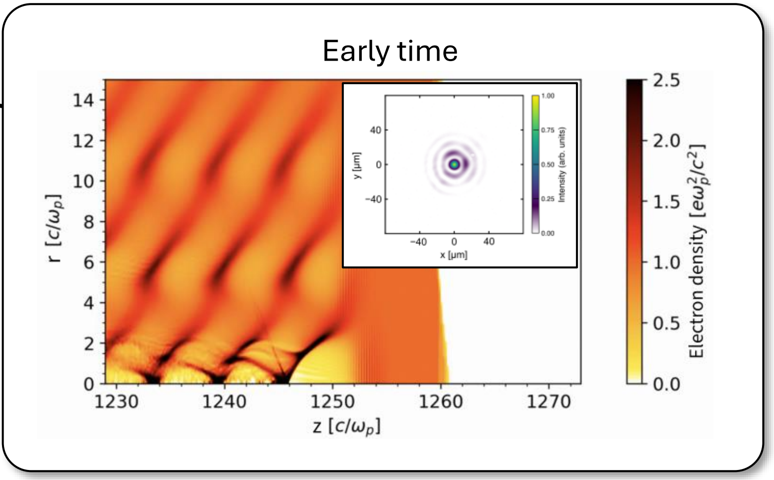
Desired wakefield velocity

Bubble shrinkage term

Late time



Early time



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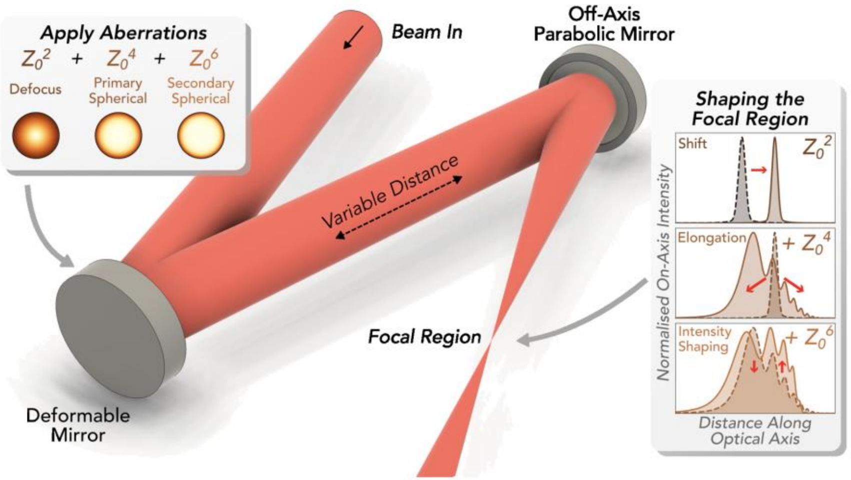
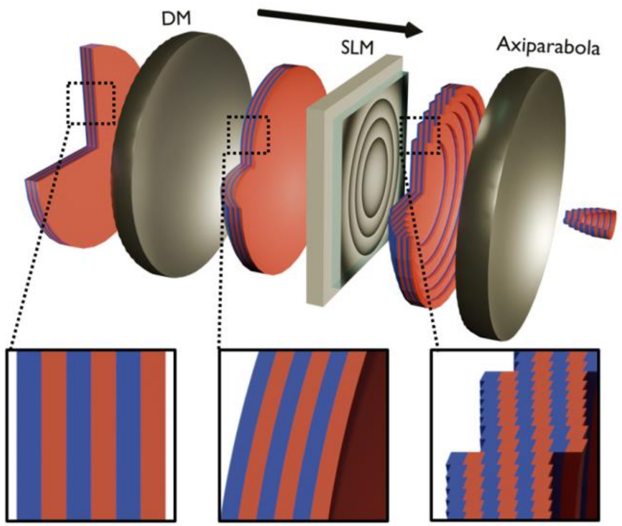
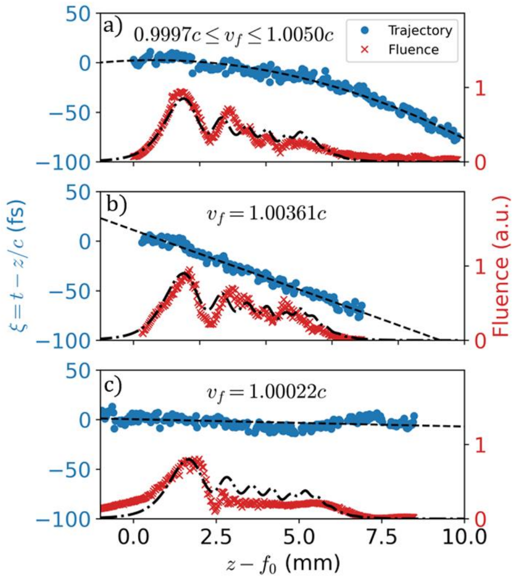
K. G. Miller et al., *Scientific Reports* **13**, 21306 (2023).

Using adaptive optics for rapidly tunable flying-focus trajectories is a promising direction



P. Blum et al., *Optics letters* **51**, 9–12 (2025).





Markland, H. et al. *Optics Letters* **51**, 676–679 (2026).

- Measuring flying focus velocities in real time remains a challenge
- Optics can creep over time
- Has not yet been implemented at high power

Dephasingless laser wakefield acceleration provides a credible path towards TeV-class electron beams in a single-stage, compact accelerator

- Initial proof-of-concept experiments have showed that dephasing can be eliminated using a flying focus (published in Nature Physics).
- May be possible to drastically shrink multi-GeV accelerators. No pulse guiding. Shorter focal length optics.
- Future experiments are being planned to optimize the scheme in preparation to scale to the multi-GeV regime.

Some outstanding experimental challenges:

- Demonstration of high-charge, narrow-energy-spread beams, ideally free of dark current
- Plasma source (~70 cm length required for 100 GeV flagship)
- Transport and diagnostics (for 10-100 GeV electron beams)
- Fabrication of large flying focus optics (12” diameter required for demonstrations at e.g. EPAC, ZEUS, CoReLS)