High average gradient in a laser-gated multistage plasma wakefield accelerator

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SLAC NATIONAL ACCELERATOR LABORATORY

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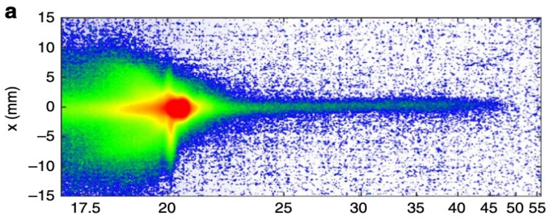
Stanford University | U.S. DEPARTMENT OF ENERGY

Single-stage PWFAs are continuously improving

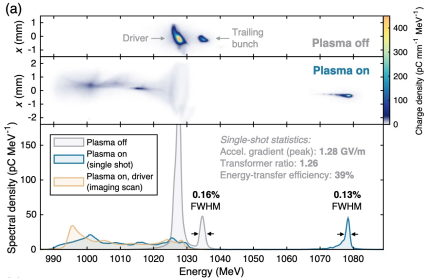
130 GV/m



FACET-I: Measurement of high accelerating gradient in Ar

Source: S. Corde, et al. *Nature Comm.* (2015)

1.28 GV/m



FLASHForward: optimized for high efficiency and energy-spread conservation

Source: CA Lindstrøm, et al. *Phys. Rev. Lett.* (2021)

- GV/m operation
- Quality preservation (emittance, energy spread)
- High energy transfer efficiency

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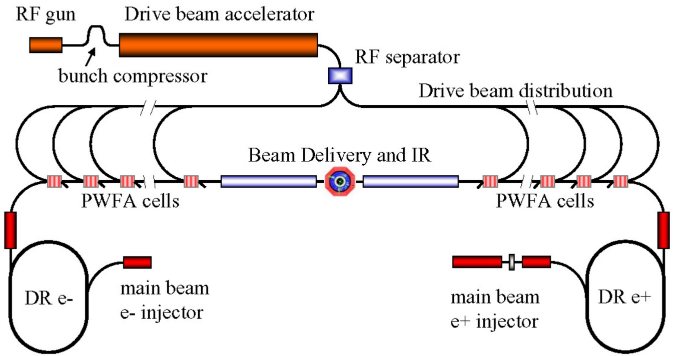
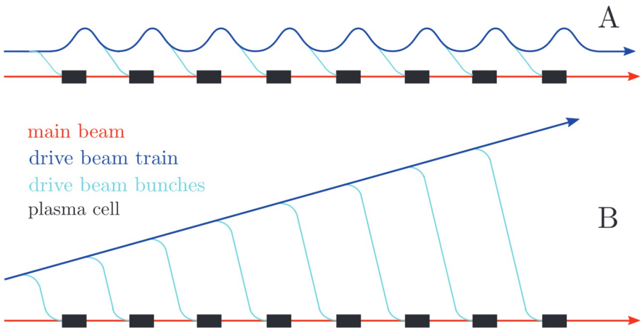
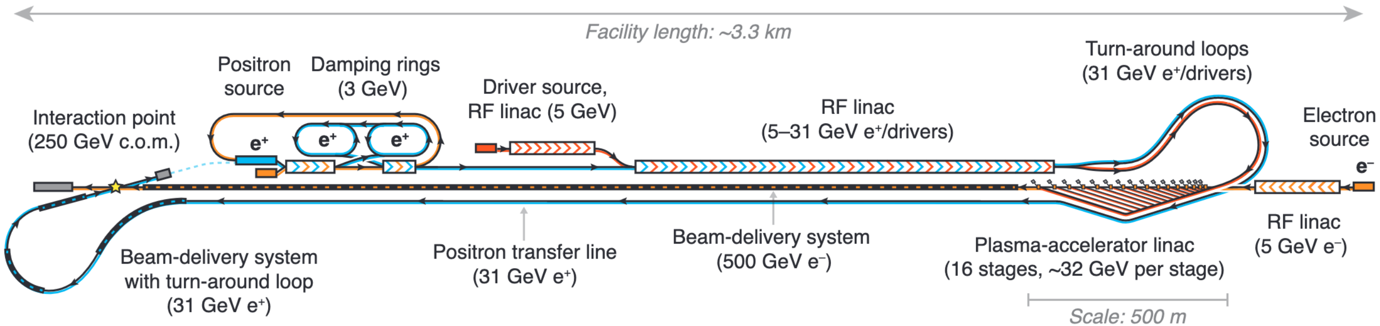
The logical next step: More PWFAs



Source: A. Seryi, et al. *PAC09, Vancouver, BC* (2009)



J. Pfingstner, et al. No. *CERN-ACC-2016-211* (2016)



Source: B. Foster et al. (2023) → Plenary C. Lindstrøm Fr. 11 AM

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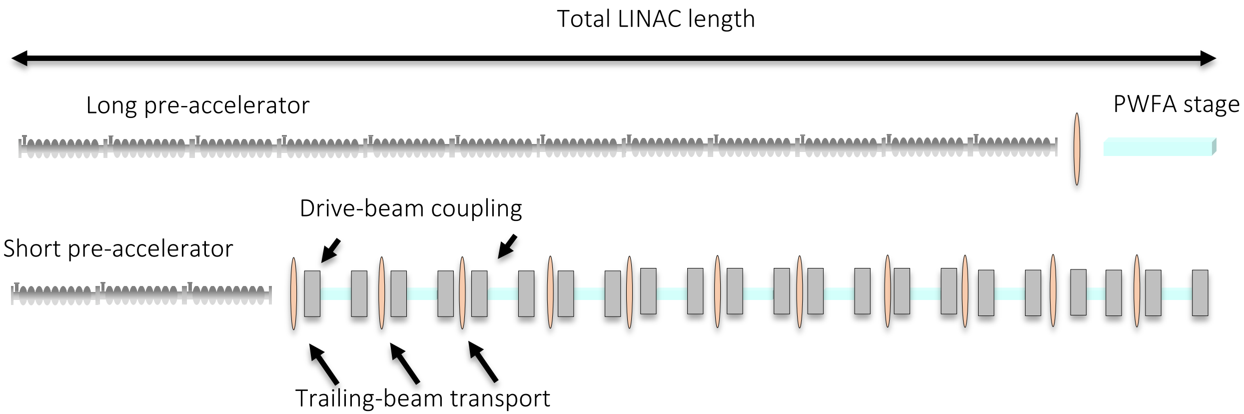
How do we reach beyond TeV ?

Single-stage PWFAs don't shrink accelerators (by a lot)



Energy doubled

n_{stage} x energy doubling

Reduced energy from pre-acc.

$$L_{\text{accelerator}} = \frac{L_{\text{stage}}(W_{\text{final}} - W_{\text{Driver}})}{TW_{\text{Driver}}} + \frac{W_{\text{Driver}}}{E_{\text{avg.,pre}}}$$

$$E_{\text{avg.}} = \frac{W_{\text{final}}}{L_{\text{accelerator}}}$$

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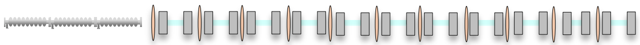
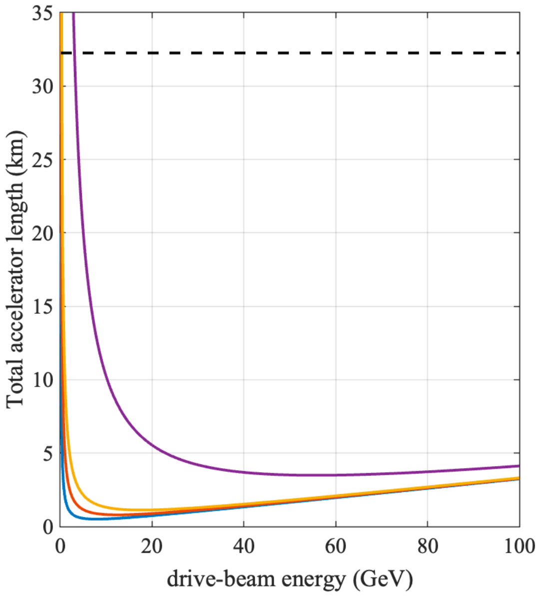
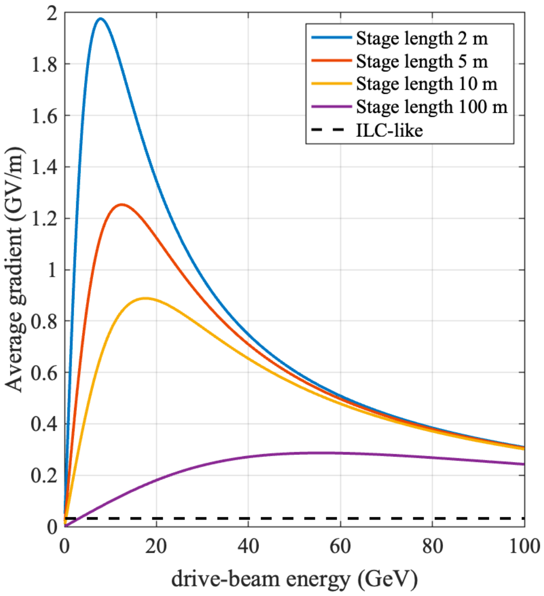
Single-stage PWFAs don't shrink accelerators (by a lot)

Many-stage limit



One-stage limit





$$L_{\text{accelerator}} = \frac{L_{\text{stage}}(W_{\text{final}} - W_{\text{Driver}})}{TW_{\text{Driver}}} + \frac{W_{\text{Driver}}}{E_{\text{avg.,pre}}}$$

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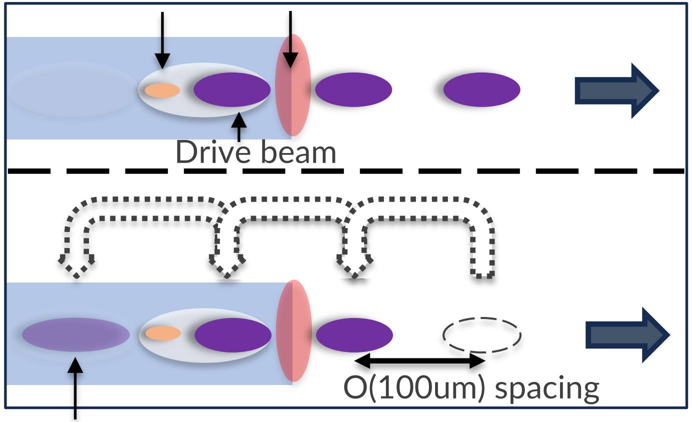
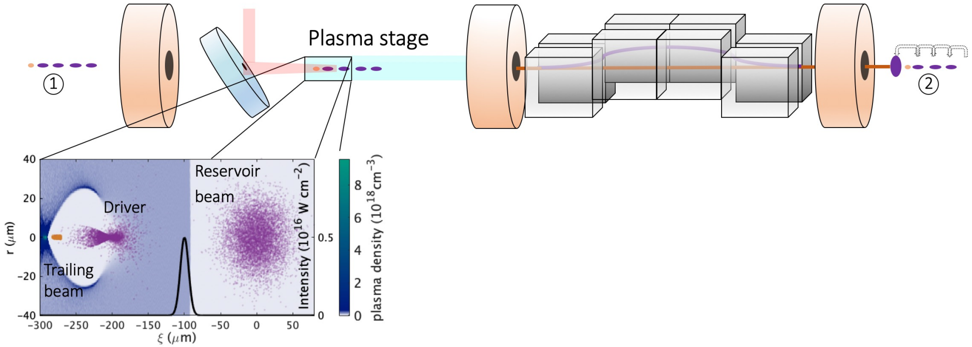
Laser-gated staging

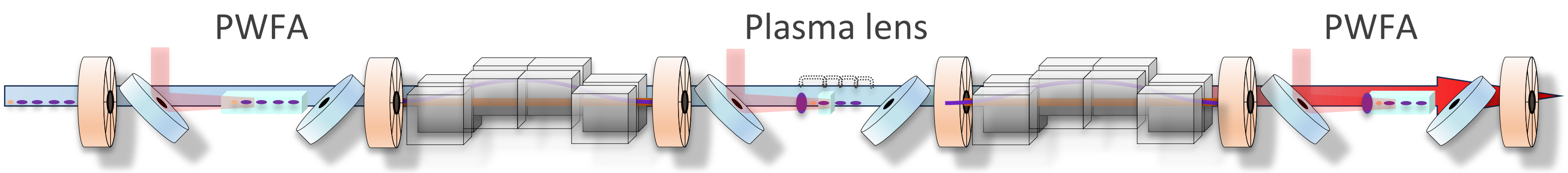




- Ultrashort ionization front separates plasma-dominated and magnet-dominated lattice
- In and outcoupling of driver-beams in temporal domain
- Small spacing between driver beams minimizes intra-stage path length

A. Knetsch, et al. *arXiv preprint arXiv:2210.02263* (2022), accepted for PRL

Laser-gated staging



- Ultrashort ionization front separates plasma-dominated and magnet-dominated lattice
- In and outcoupling of driver-beams in temporal domain
- Small spacing between driver beams minimizes intra-stage path length
- Trailing-beam transport with beam-driven plasma lens

A. Knetsch, et al. *arXiv preprint arXiv:2210.02263* (2022), accepted for PRL

Introduction into different orbits: The beam reservoir

Drive beam parameters:

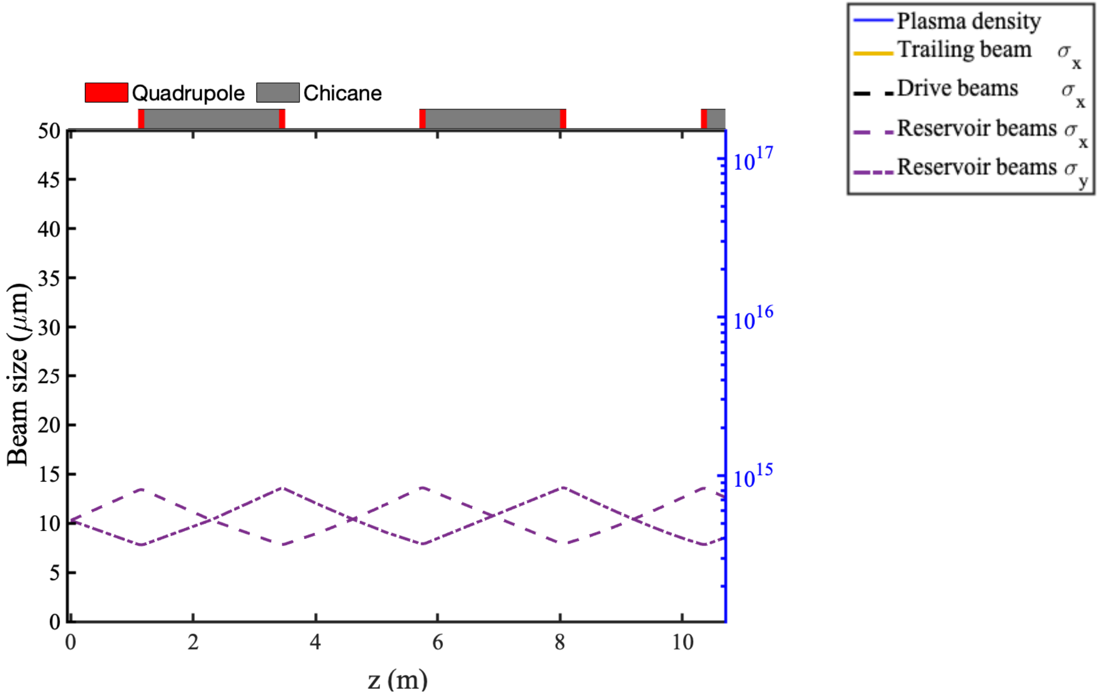
- Beam energy 10 GeV
- Charge: 700 pC
- Bunch length: 22.7 um

FODO Quadrupoles:

- Magnetic field strength: 146 T/m
- Length: 100 mm

Chicane:

- Magnetic field: 1.27 T, 1.73 T
- Dipole length: 0.55 m



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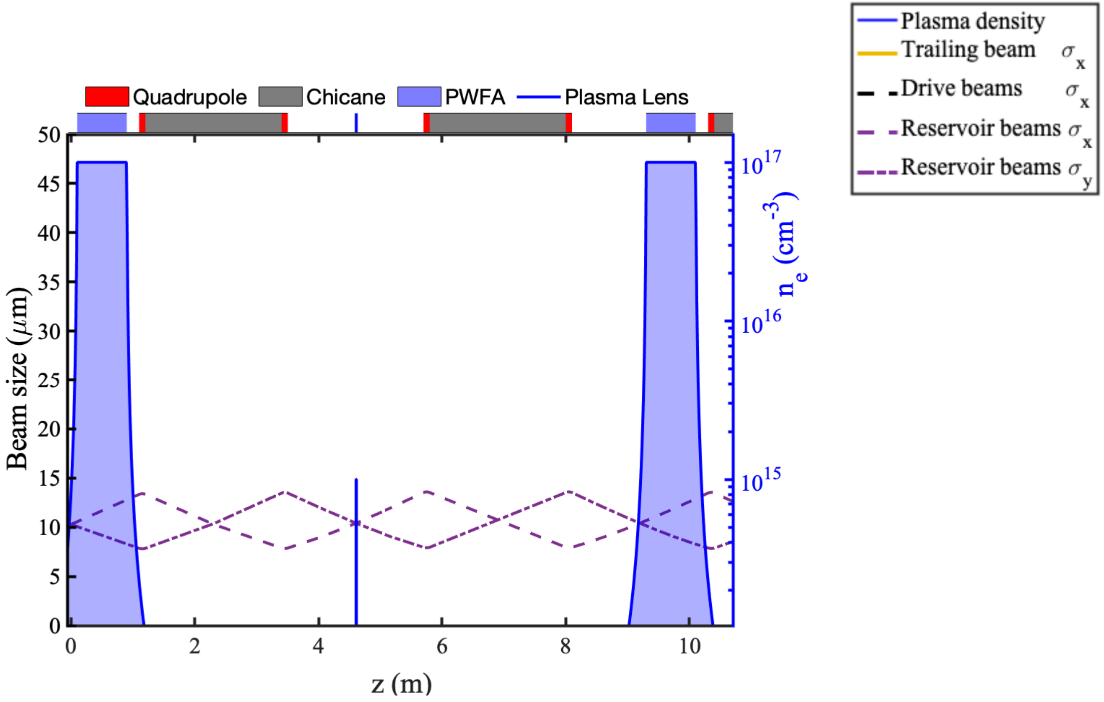
Introduction into different orbits: The plasma stages

- Set plasma entrance at waist location
- Long density ramps around PWFA stages



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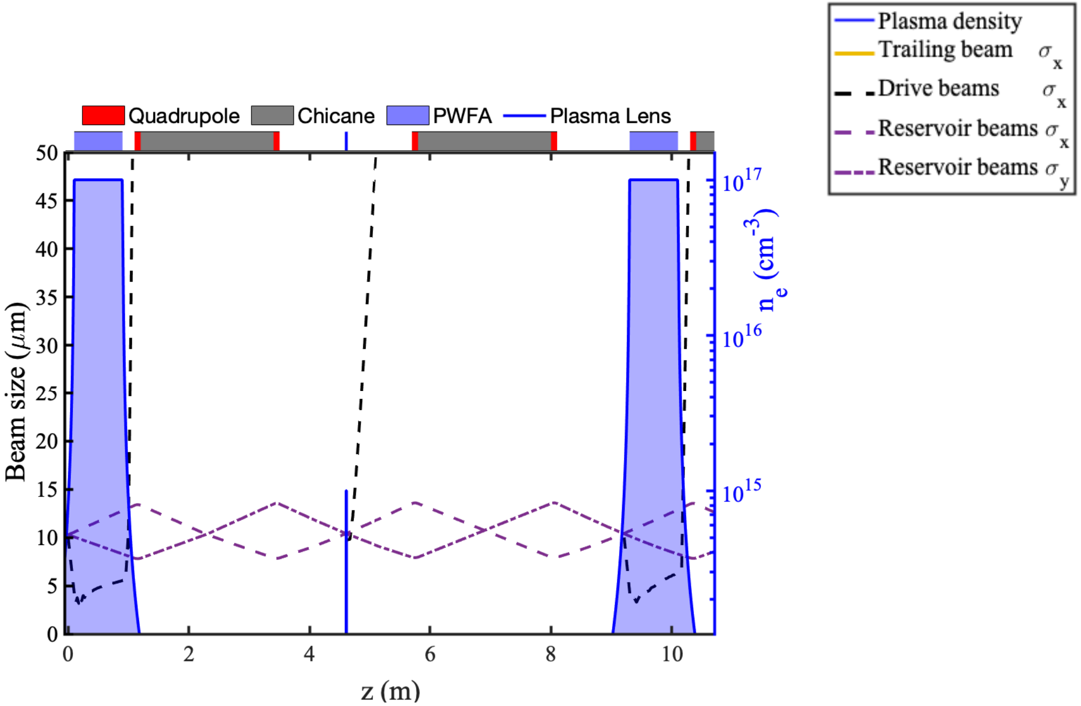
Introduction into different orbits: Drive-beams

- Depleted drive -beams defocused at the PWFA exit

- Lens focusing scaling law:

$$f = \frac{2\gamma}{k_p^2 L_{lens}}$$

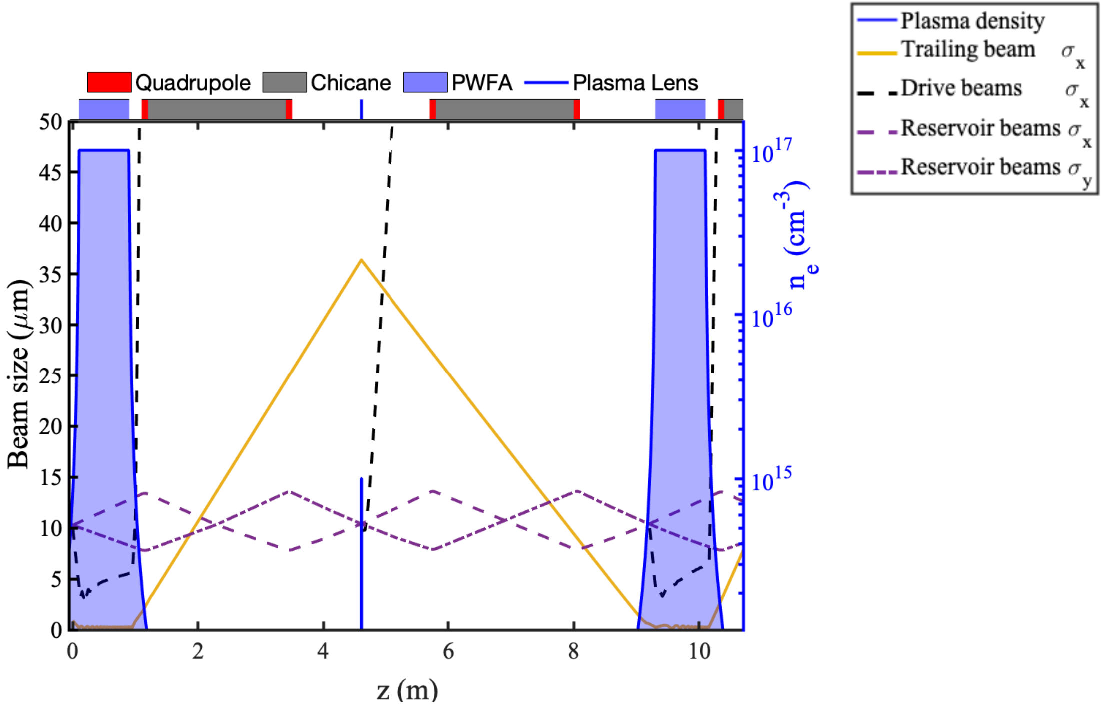


Introduction into different orbits: The trailing beam

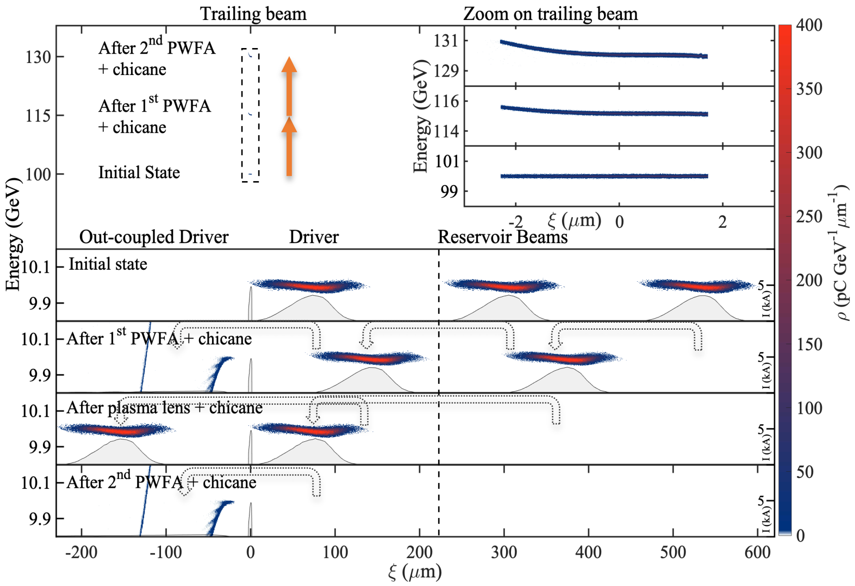
Trailing beam:

- Initial energy: 100 GeV
- Bunch length: 4 um
- Charge: 50 pC
- Trailing beam guided through PWFA
- Ramps reduce divergence
- Lens refocuses trailing beam

$$f = \frac{2\gamma}{k_p^2 L_{\text{lens}}}$$

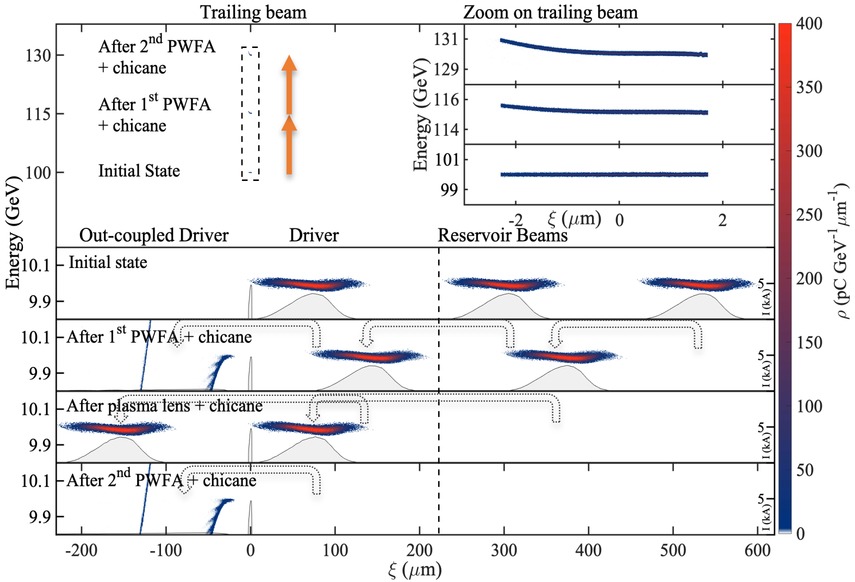


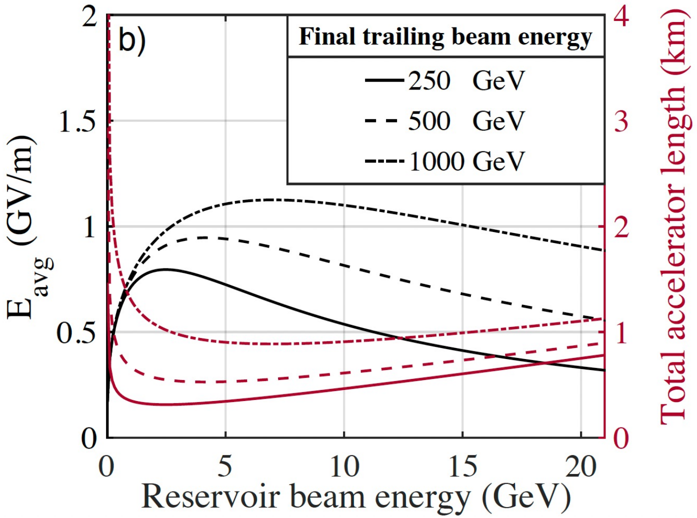
Development of longitudinal phase spaces



- Trailing beam gains 15.05 GeV of energy per PWFA stage
- Driver coupled out to the back of the bunch train after PWFA or plasma lens

Average gradient

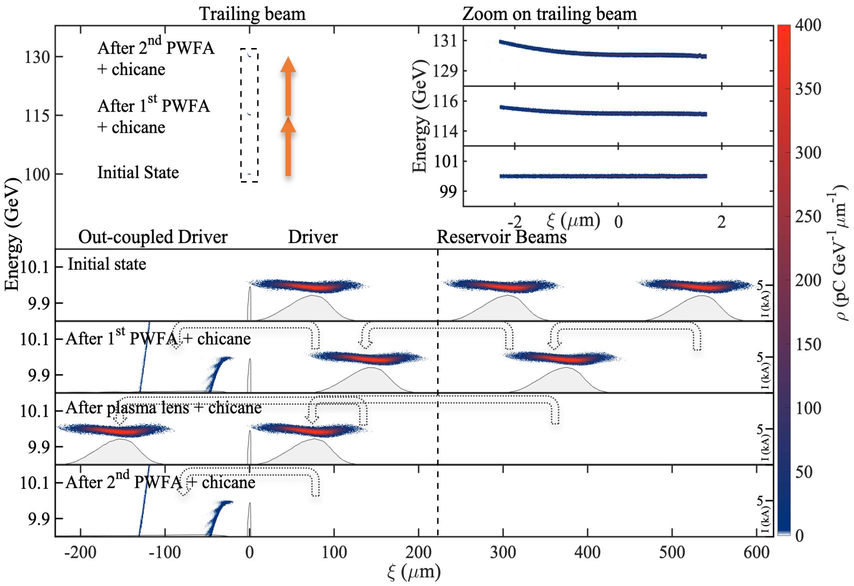




- Trailing beam gains 15.05 GeV of energy per PWFA stage
- Driver coupled out to the back of the bunch train after PWFA or plasma lens

- Average gradient 2 PWFAs: **1.64 GV/m**
- Average gradient for ILC-like pre-accelerator: **1.1 GV/m**
- Average gradient for 100 MV/m pre-accelerator: **1.4 GV/m**

Efficiency



- Trailing beam gains 15.05 GeV of energy per PWFA stage
- Driver coupled out to the back of the bunch train after PWFA or plasma lens

- Energy-transfer efficiency 1 PWFA:

  19.5 %

- Energy-transfer efficiency pre-accelerator to trailing beam

  10.7 %

- Considering plasma-lens driver

  5.4

Simulations not optimized for efficiency

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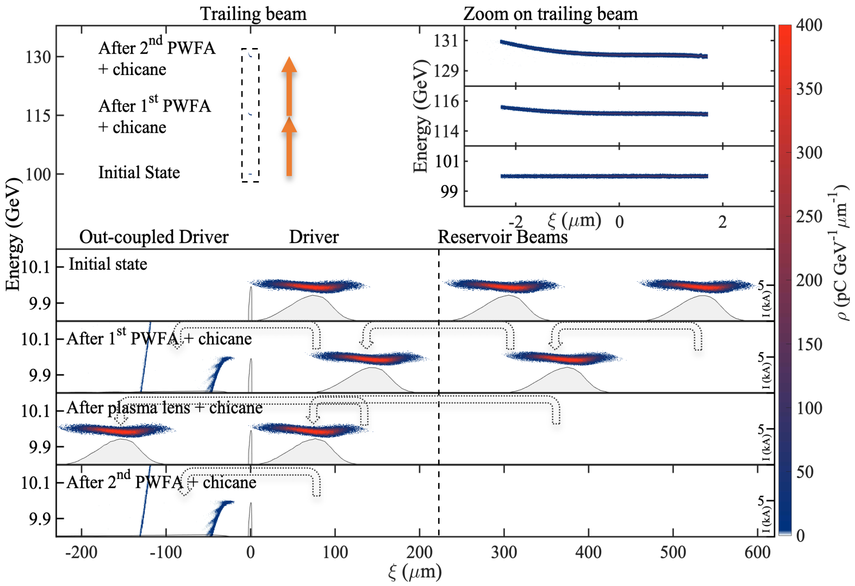
Efficiency – An optimistic projection



- Trailing beam gains 15.05 GeV of energy per PWFA stage
- Driver coupled out to the back of the bunch train after PWFA or plasma lens

- Energy-transfer efficiency 1 PWFA:
  - Increase trailing-beam charge to 100 pC

19.5 % → ~ 40 %

- Energy-transfer efficiency pre-accelerator to trailing beam

10.7 % → ~ 21 %

- Considering plasma-lens driver
  - Decrease charge of plasma-lens driver factor 10

5.4 % → 19.6 %

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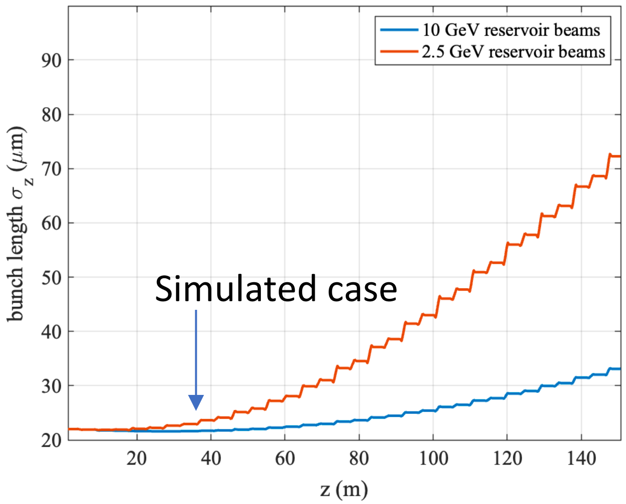
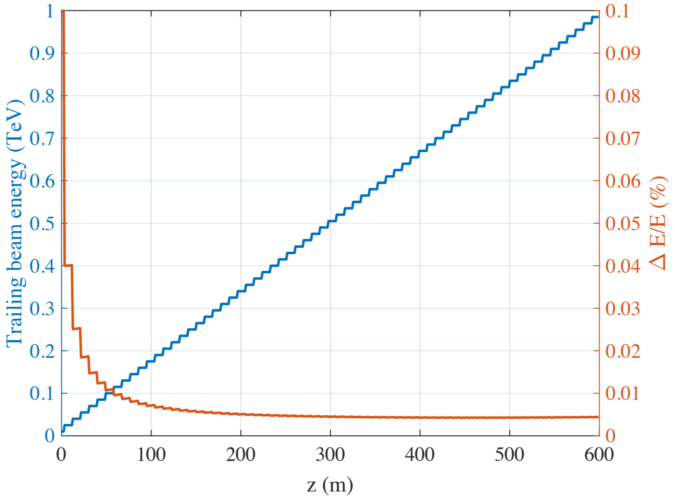
Coherent synchrotron radiation

Driver beams

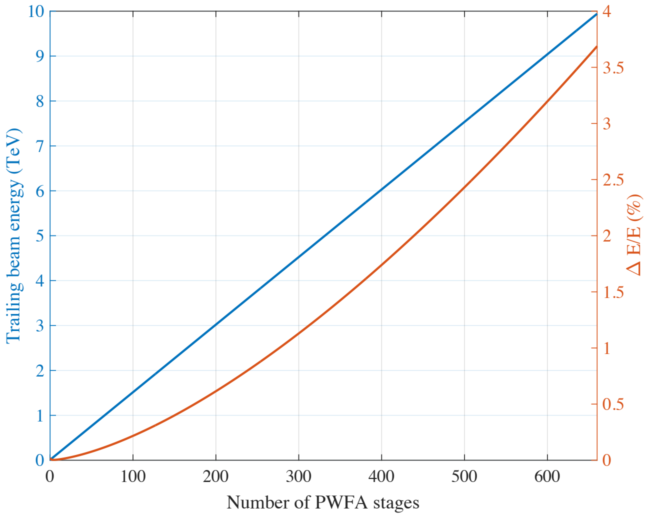


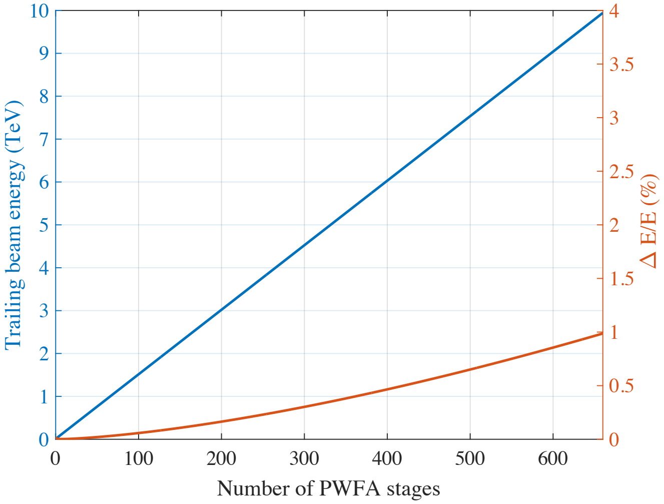
Trailing beam



- Drive-beam bunch lengthening much more resilient at 10 GeV then at 2.5 GeV
- Energy spread increase of trailing beam tapers off

Incoherent synchrotron radiation





- ICS acceptable for energies up to 1 TeV
- At higher energies, chicane design needs adjustment at cost of stage length
- This comes at cost of average gradient

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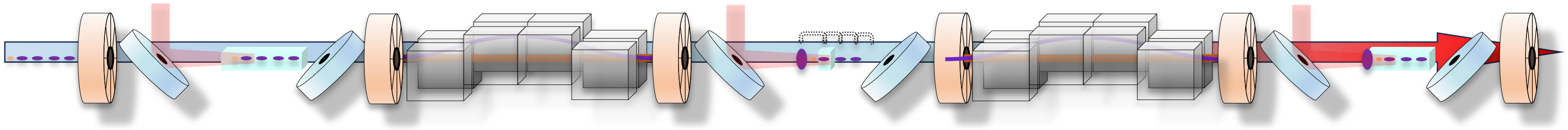
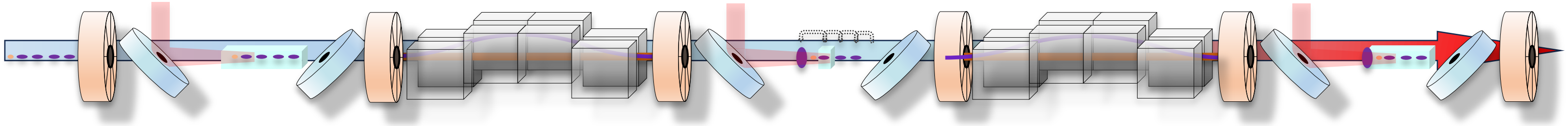
M. Sands Phys. Rev. 97, 470 (1955)

Conclusion



- Proposed staging method combines two aspects unique to PWFA
  - Laser-gated PWFA
  - Temporal drive-beam coupling
- Small interstage distances
- Average gradient over 2 stages: **1.64 GeV/m**
- Scalable to 1 TeV with an average gradient of **1.1 GeV/m**
- Many open questions, but so far we found no deal-breaker



Thank you for your attention !