TOWARDS PLASMA-ACCELERATION FOR COLLIDERS:
STAGING OF PLASMA ACCELERATORS

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ACCELERATORS FOR HIGH ENERGY PHYSICS

> High-energy physics demand higher energy and lower cost:

  > *Solution:* Plasma accelerators — significantly higher acceleration gradients.

> Simultaneously, particle colliders have strict demands for luminosity:

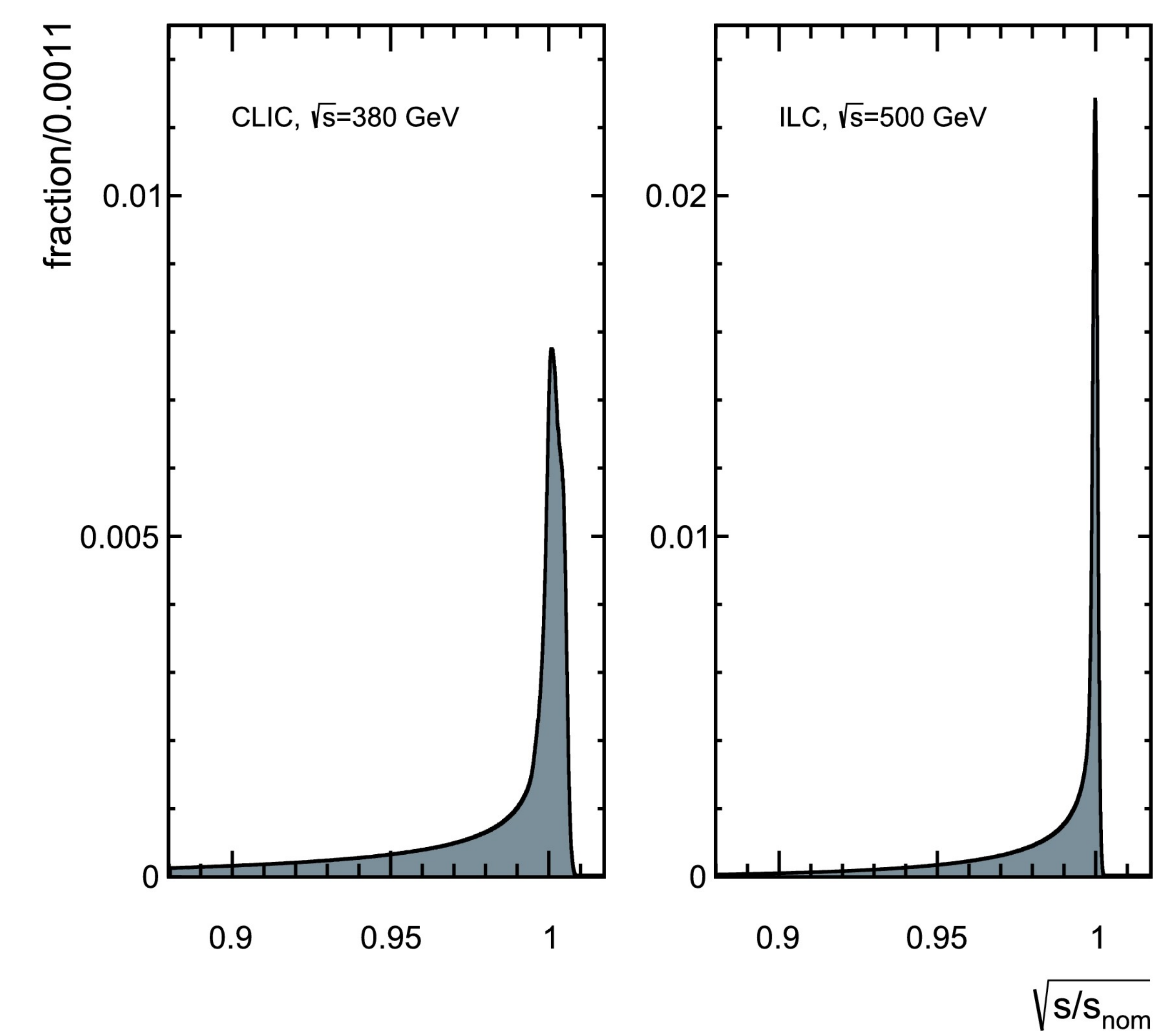
High repetition rate

High energy efficiency

$$\mathscr{L} = \frac{H_D}{8\pi m_e c^2} \frac{P_{\text{wall}}}{\sqrt{\beta_x \beta_y}} \frac{\eta N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

Low energy spread
(luminosity spectrum, final focusing)

Low emittance
High stability



Luminosity distribution across collision energies.
Source: M. Boronat *et al.*, Phys. Lett. B 804, 135353 (2020).

$$\eta = \eta_{wall \to DB} \times \eta_{DB \to WB}$$

Beam-drivers are orders of magnitude more efficient
than laser-drivers (for now)

> Energy efficiency motivates use of beam-driven plasma acceleration.

THE COLLIDER CHOICE: BEAM-DRIVEN PLASMA ACCELERATION

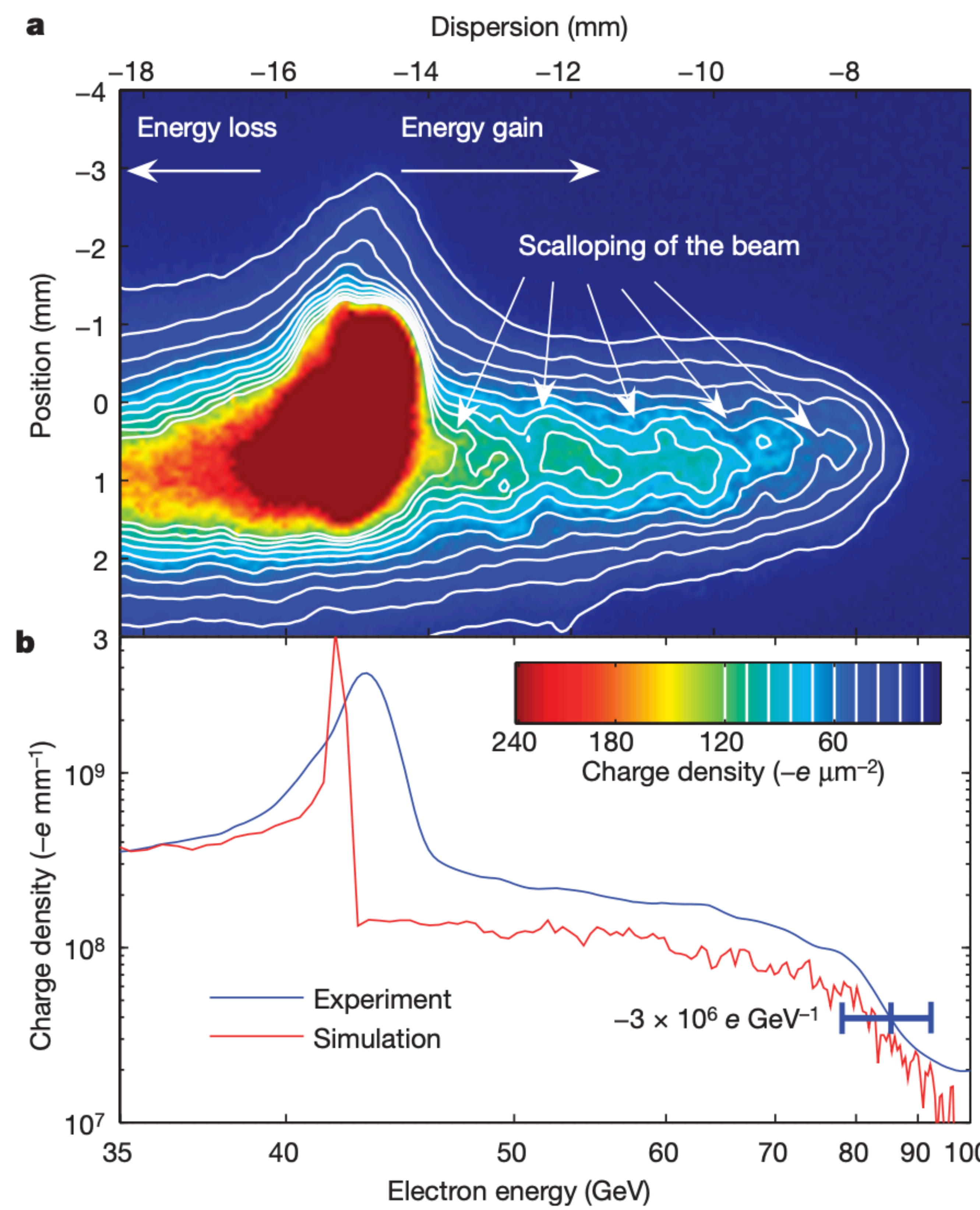
High-gradient ↓

Energy efficient →

Driver \ Medium	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

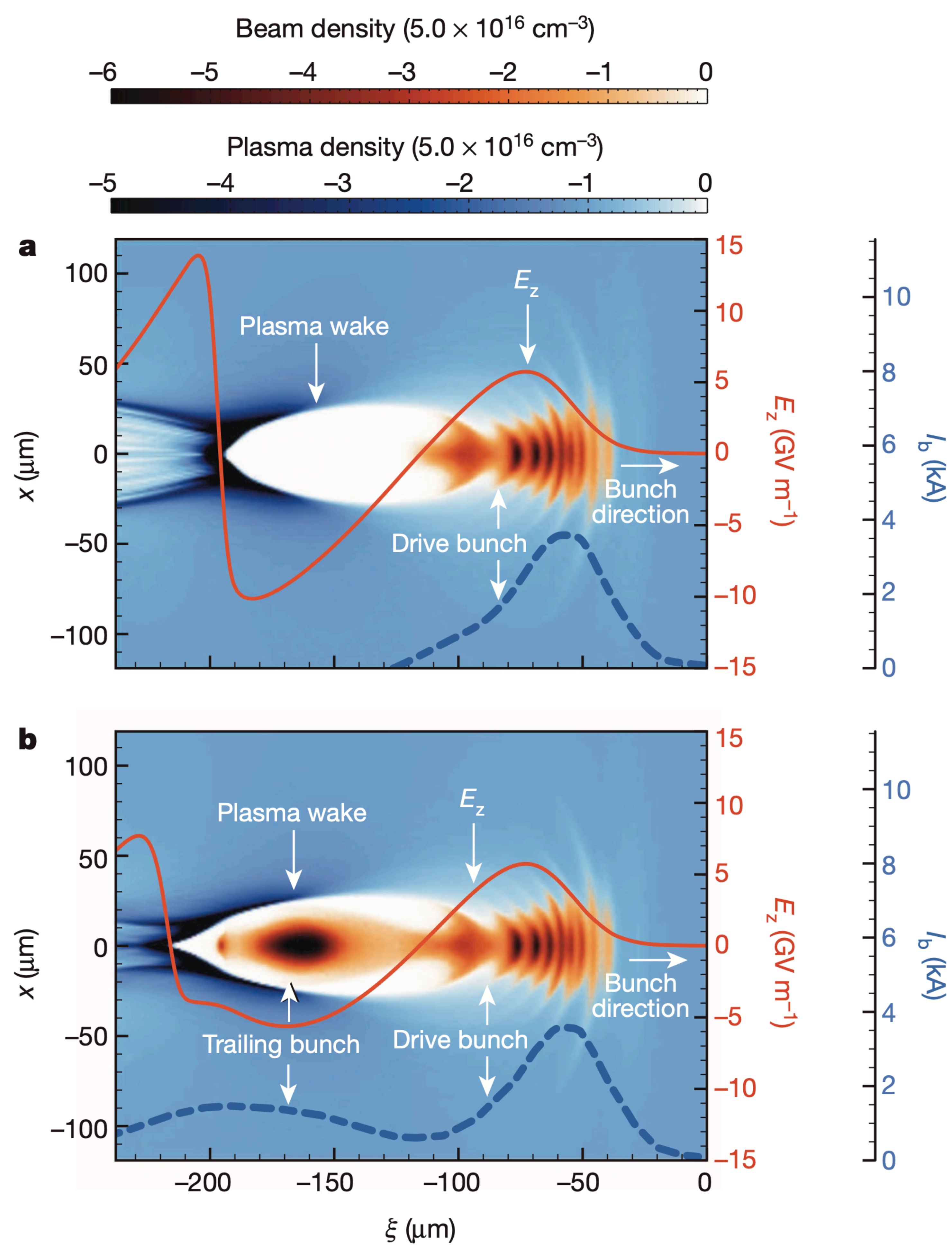
Source: Cros & Muggli et al., ANAR Roadmap 2017

STATUS QUO IN PLASMA-WAKEFIELD ACCELERATION: **HIGH GRADIENTS**



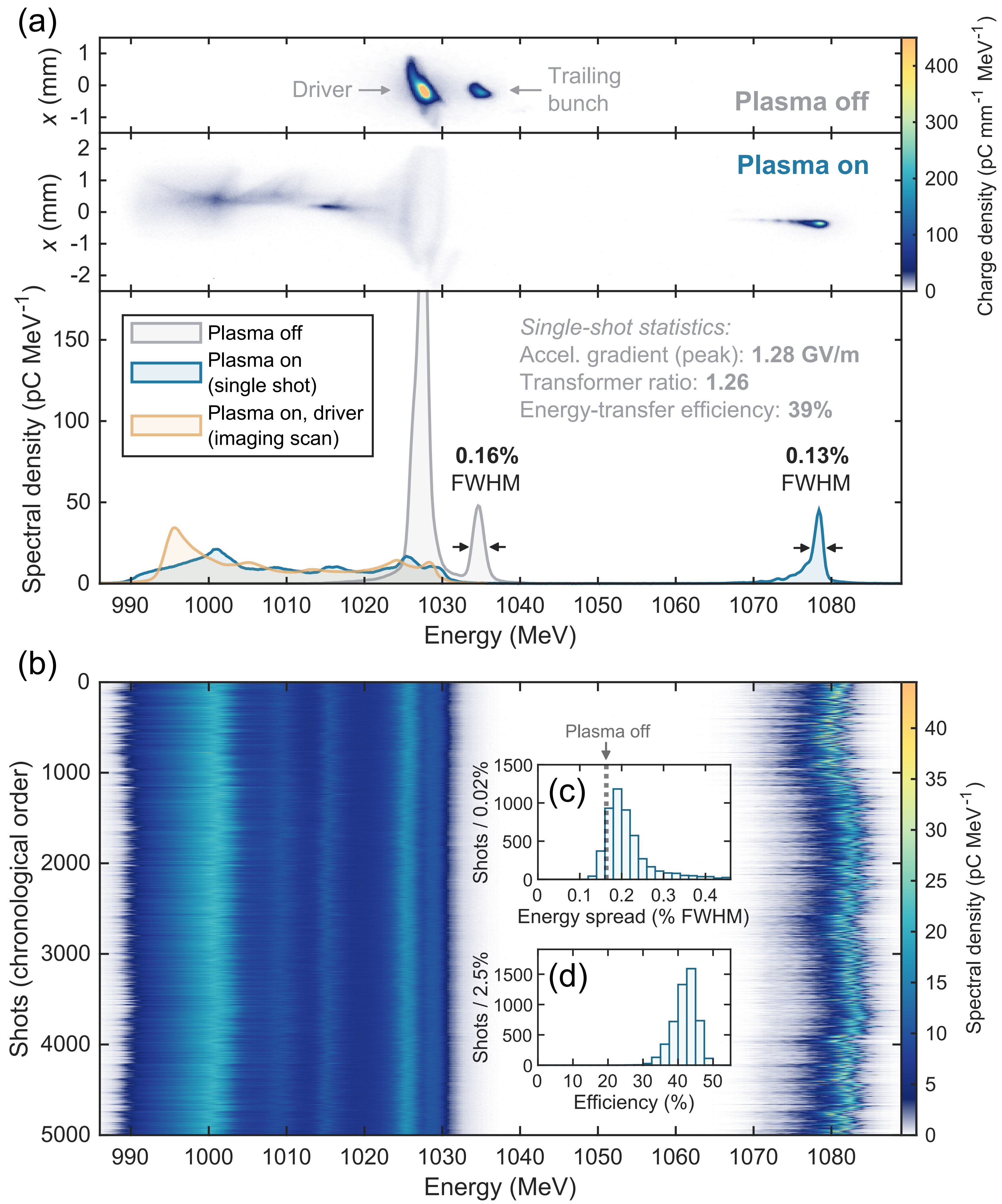
Energy doubling from 42 GeV to 85 GeV in a PWFA at SLAC (FFTB).
Source: Blumenfeld et al. Nature 445, 741 (2007).

STATUS QUO IN PLASMA-WAKEFIELD ACCELERATION: **HIGH EFFICIENCY**

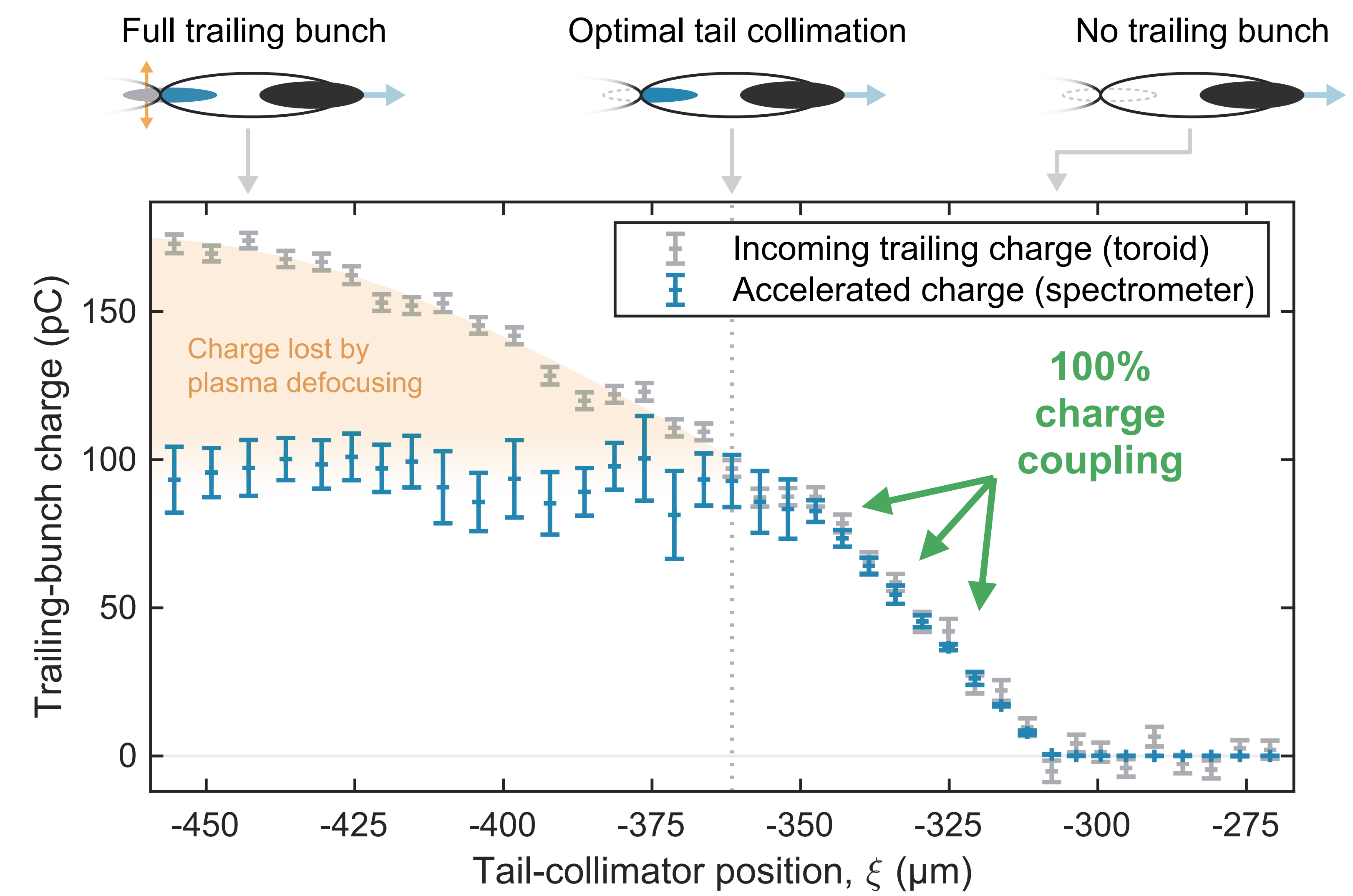


Experimental demonstration of up to 30% energy efficiency at FACET, SLAC.
Image credit: M. Litos et al., Nature 515, 92 (2014)

STATUS QUO IN PLASMA-WAKEFIELD ACCELERATION: **BEAM QUALITY**



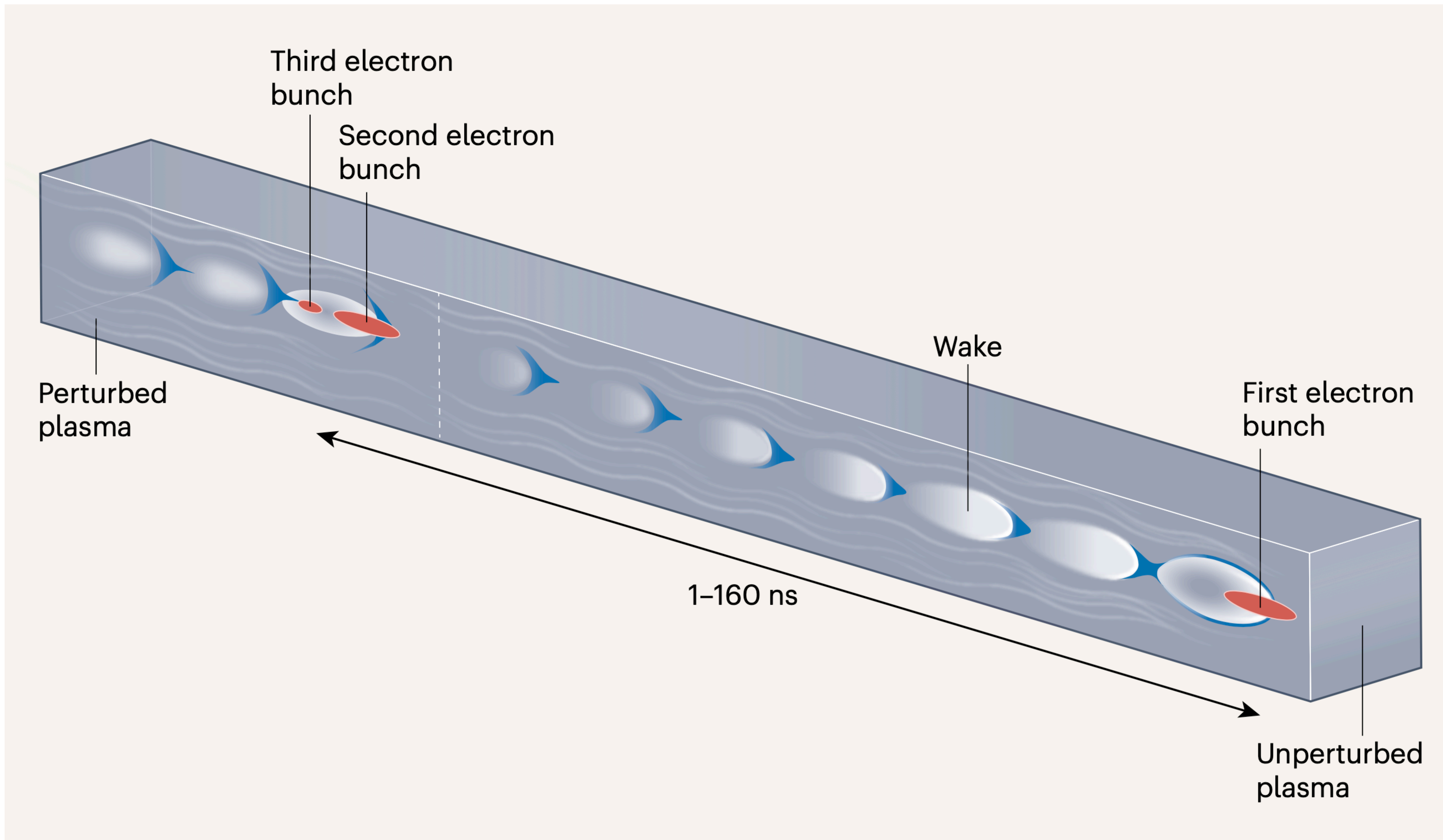
Preservation of 0.1%-level energy spreads, at FLASHForward.
Image credit: C. A. Lindstrøm *et al.*, Phys. Rev. Lett. 126, 014801 (2021)



Preservation of 100-pC-level charge, at FLASHForward.
Image credit: C. A. Lindstrøm *et al.*, Phys. Rev. Lett. 126, 014801 (2021)

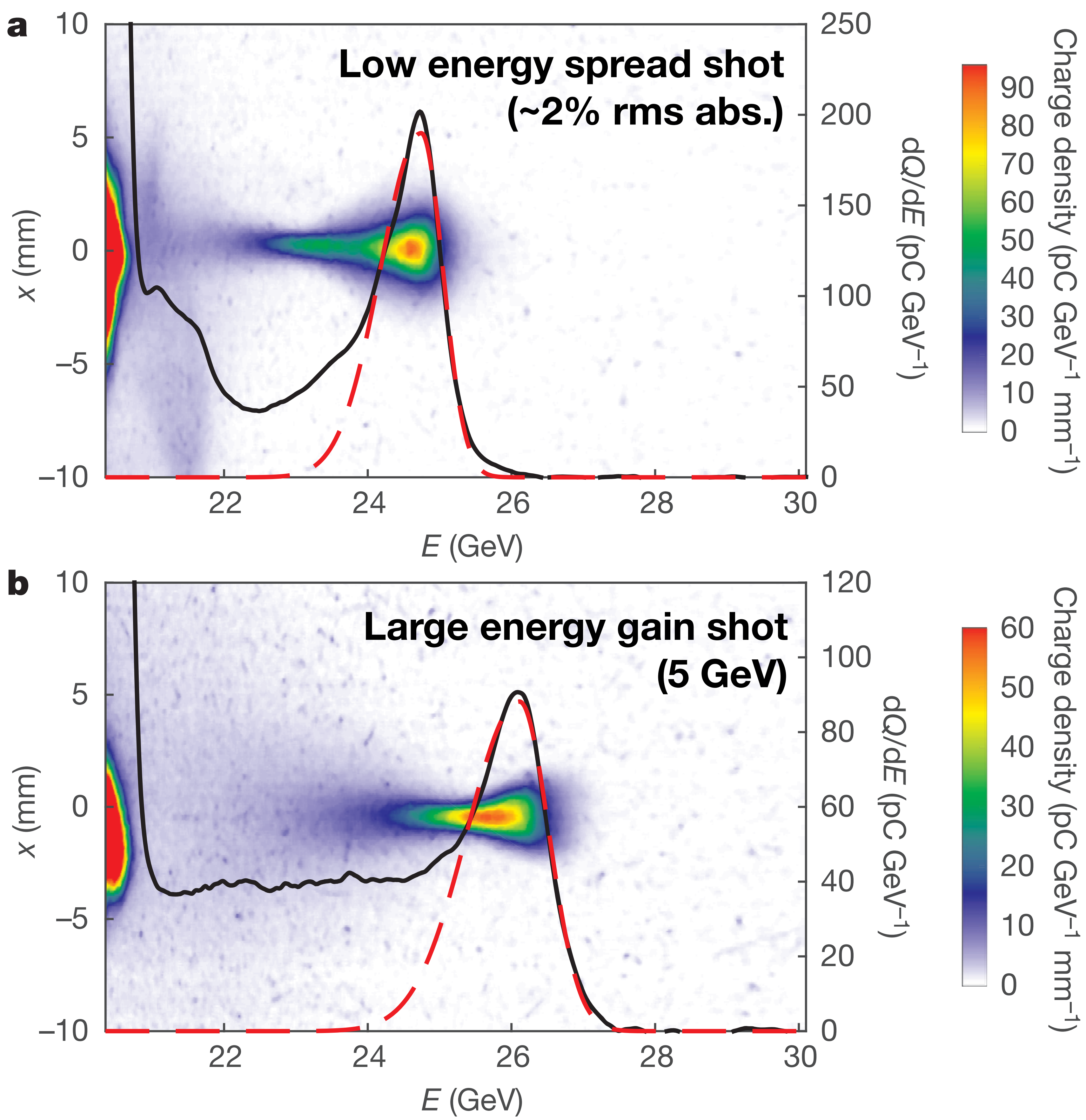
…and emittance?
(we're on it!)

Published in Nature **TODAY!**



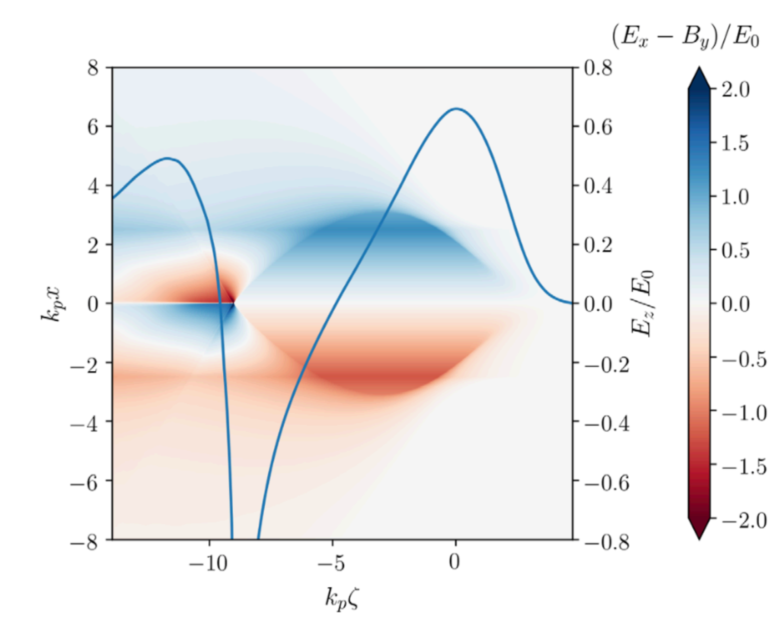
Potential for multi-MHz repetition rates demonstrated experimentally at FLASHForward.
Source: R. D'Arcy et. Nature 603, 58 (2022)

Status quo in plasma-wakefield acceleration: **Positrons**



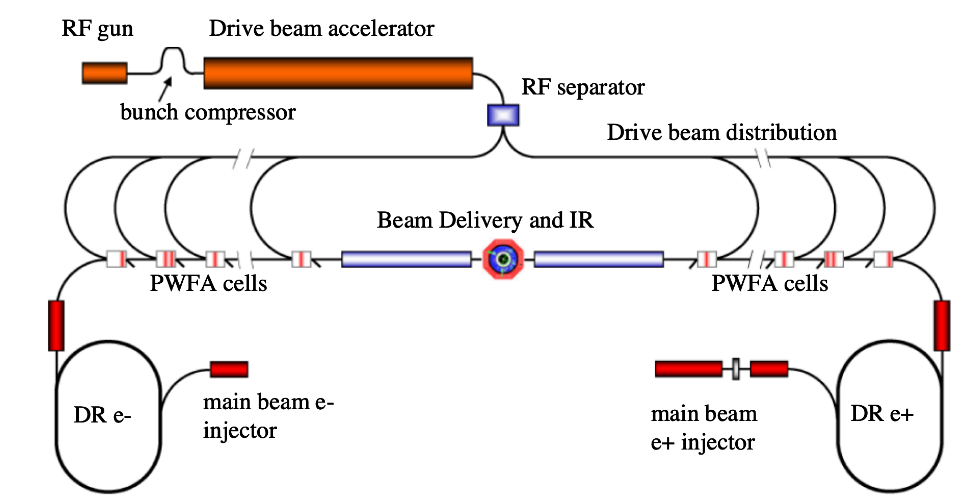
GV/m gradient acceleration of positrons at FACET, SLAC.
Image credit: S. Corde *et al.*, Nature 524, 442 (2015)

Evolution



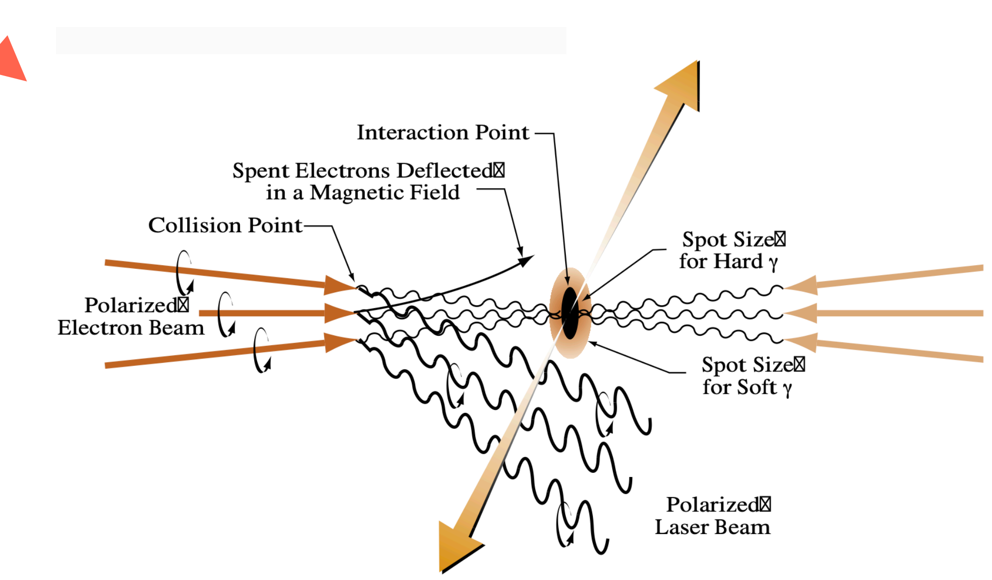
Positron bubble in a plasma filament.
Source: Diederichs *et al.*, Phys. Rev. Accel. Beams 22, 081301 (2019).

If successful (e+e- collider)



Strawman design of a plasma collider.
Source: Pei et al., Proc. PAC'2009 (2009), p. 2682.

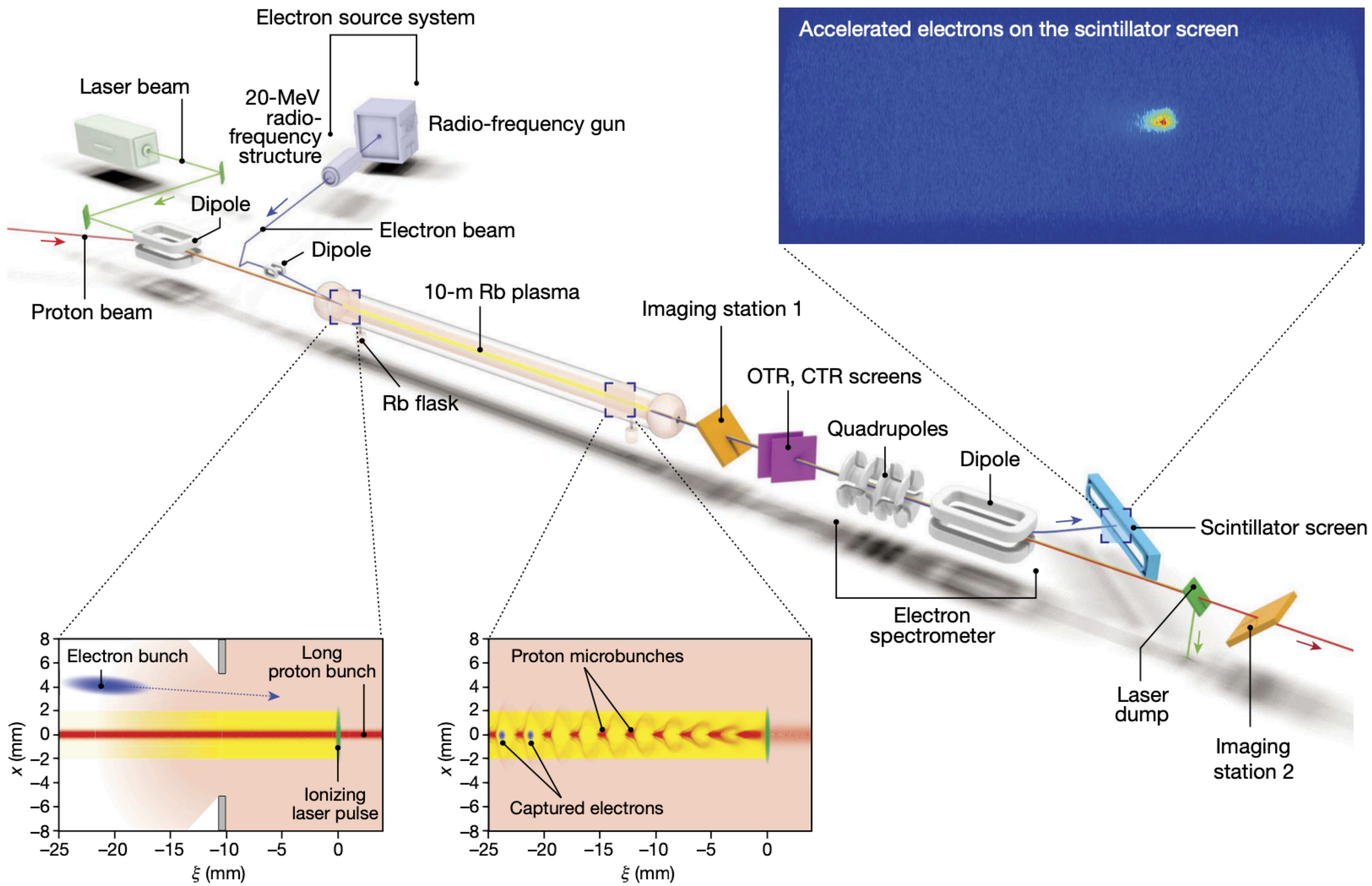
If unsuccessful (γ–γ collider)



Gamma–gamma interaction.
Source: Kim & Sessler (1996)

REACHING VERY HIGH ENERGY — BUT HOW?

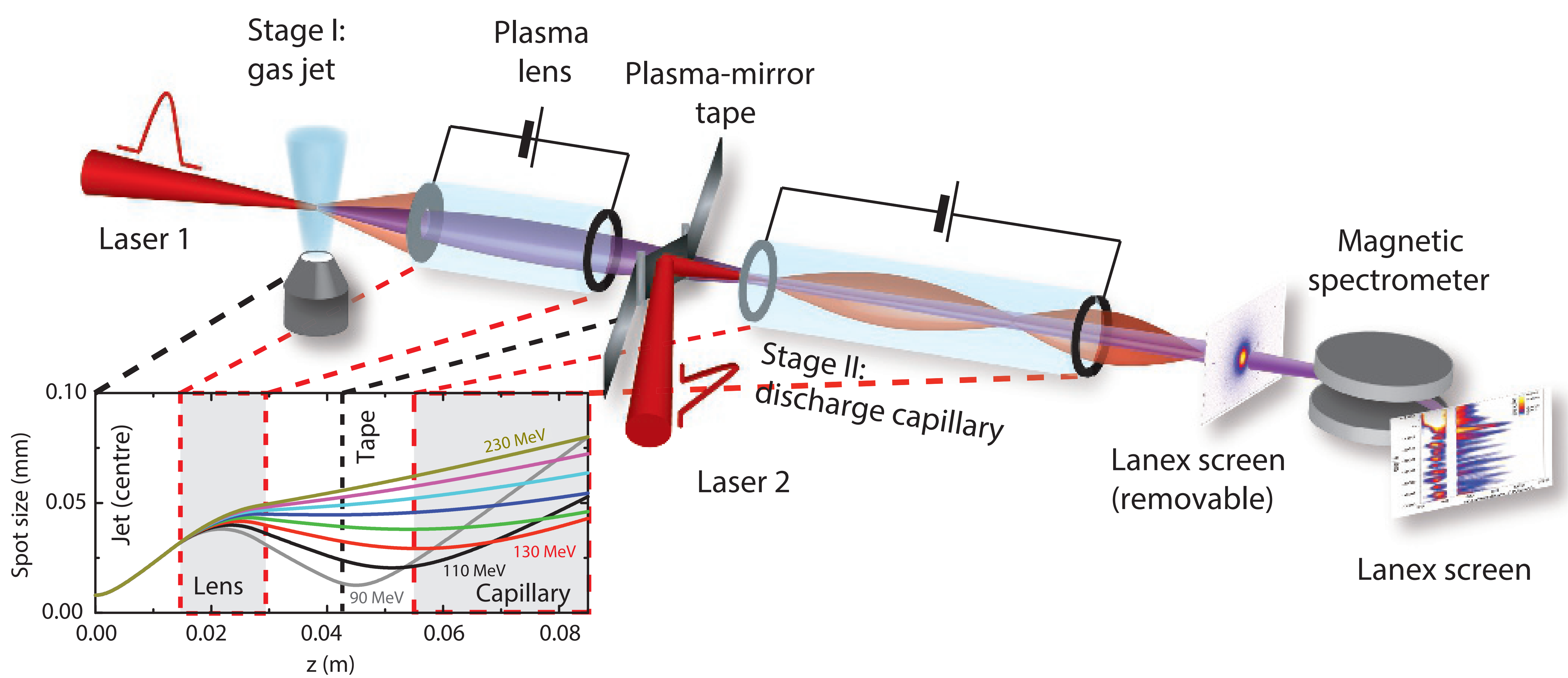
REACHING VERY HIGH ENERGY: **IN ONE STAGE?**



Plasma accelerator driven by 400 GeV protons from SPS, at CERN's AWAKE experiment.
Source: Adli et al. Nature 561, 363 (2018).

Major problems:
Repetition rate
Energy efficiency

REACHING VERY HIGH ENERGY: **IN MULTIPLE STAGES?**



Proof-of-principle demonstration of staging at LBNL (laser driven).
Image source: Steinke et al., Nature 530, 190 (2016).

Problem:
Only ~3.5% of the charge survived

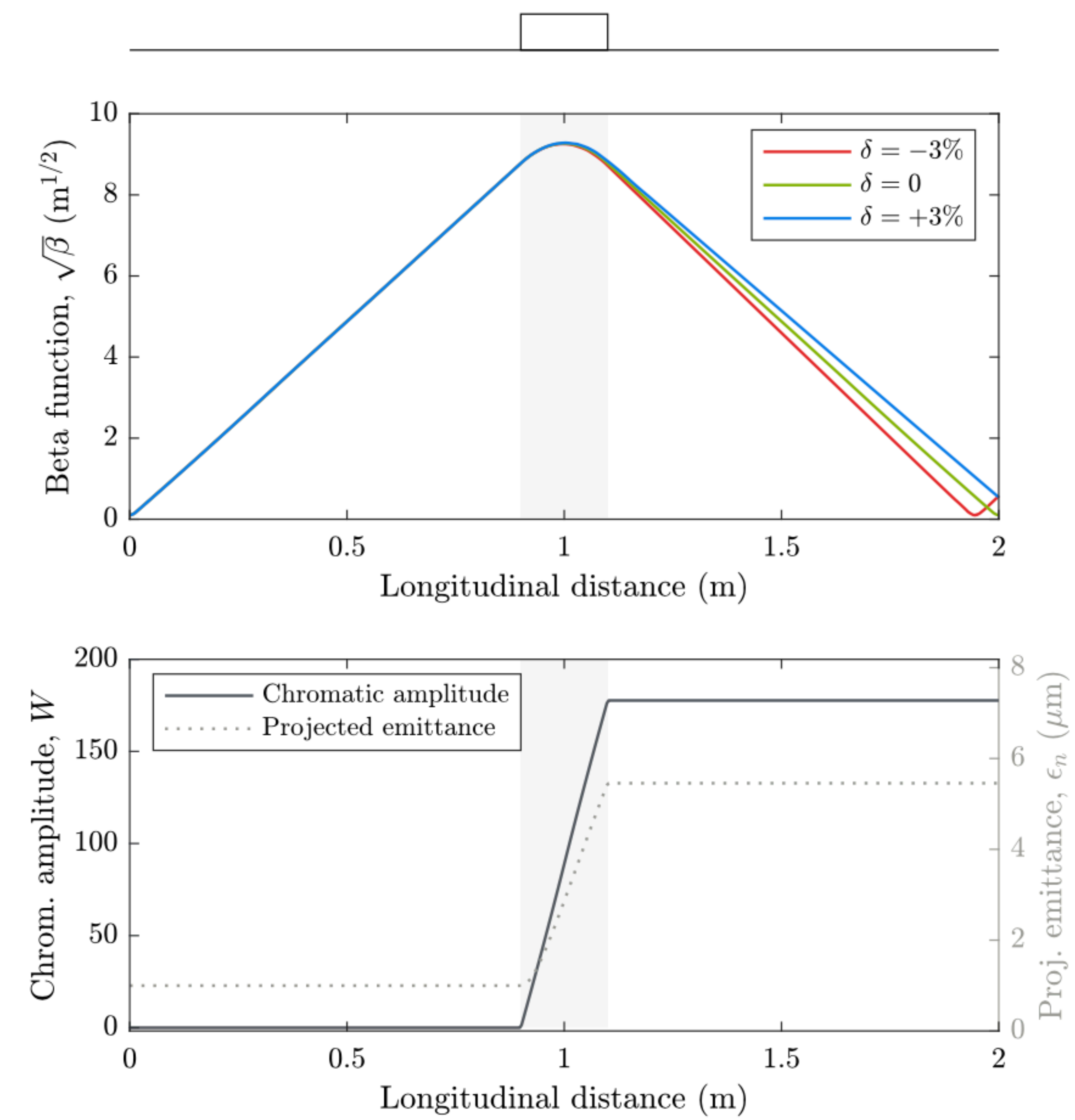
MAIN CHALLENGES WITH STAGING

Review: **C. A. Lindstrøm, Phys. Rev. Accel. Beams 24, 014801 (2021)**

> Staging is nontrivial for four reasons:
>
> > ***In- and out-coupling of drivers***
> >
> > ***Emittance growth from chromatic mismatching***
> >
> > ***Synchronization***
> >
> > ***Compactness***

> **Chromaticity is particularly challenging** in plasma accelerators because they typically operate with:
>
> > High-divergence
> >
> > Large/finite energy-spread beams.

> Several staging designs exist, but **none so far preserve the charge and emittance** such that a large number of stages is feasible.



Projected emittance growth due to unequal focusing of different energies (i.e., chromaticity).

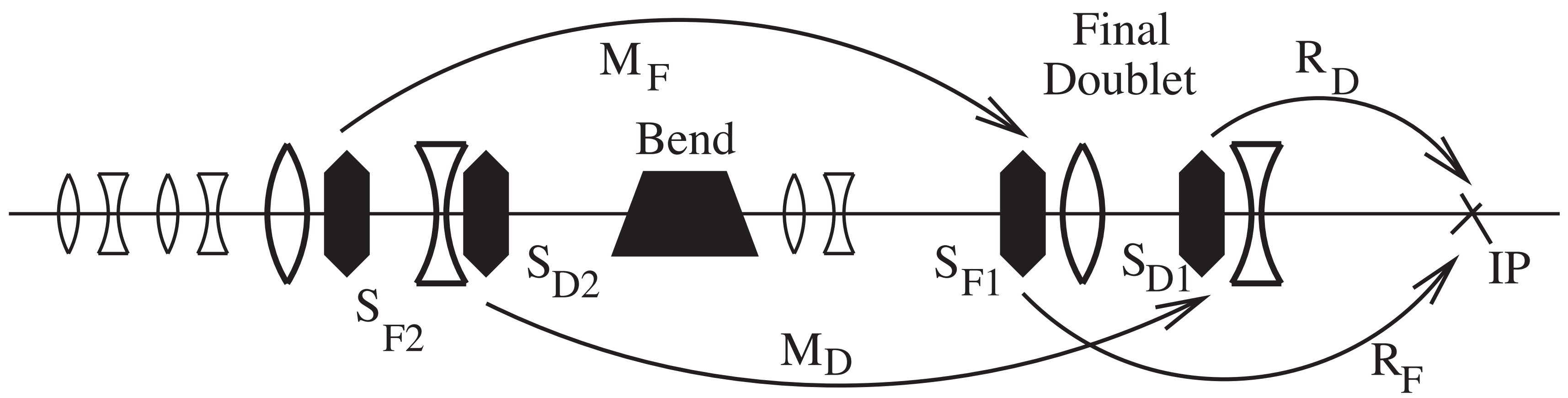
Image source: Lindstrøm, Phys. Rev. Accel. Beams 24, 014801 (2021)

Two novel solutions

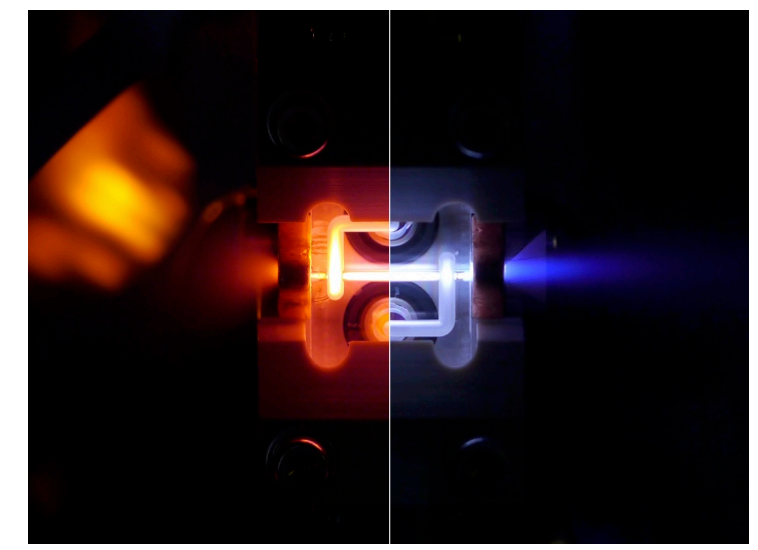
(1) **Achromatic staging with nonlinear plasma lenses**

(2) Self-correction mechanism in longitudinal phase space

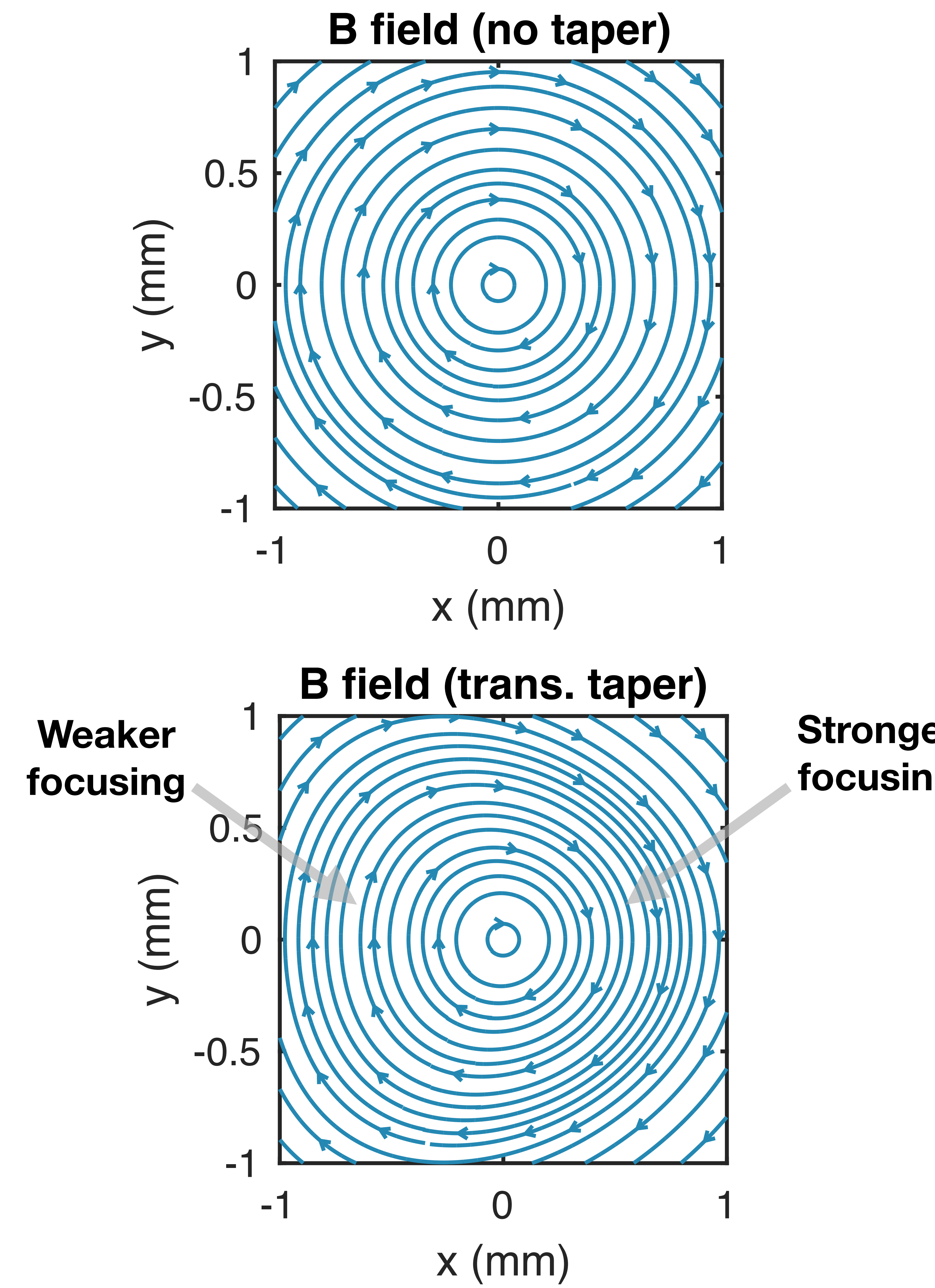
TRANSVERSELY TAPERED PLASMA LENSES



Schematic view—two sets of sextupoles (separated by 180 degree phase advance) are placed close to strong quadrupoles.
Image source: Raimondi & Seryi, Phys. Rev. Lett. 86, 3779 (2001)



Active plasma lens



Transverse magnetic field profile in a regular active plasma lens (top) versus a transversely tapered plasma lens (bottom).

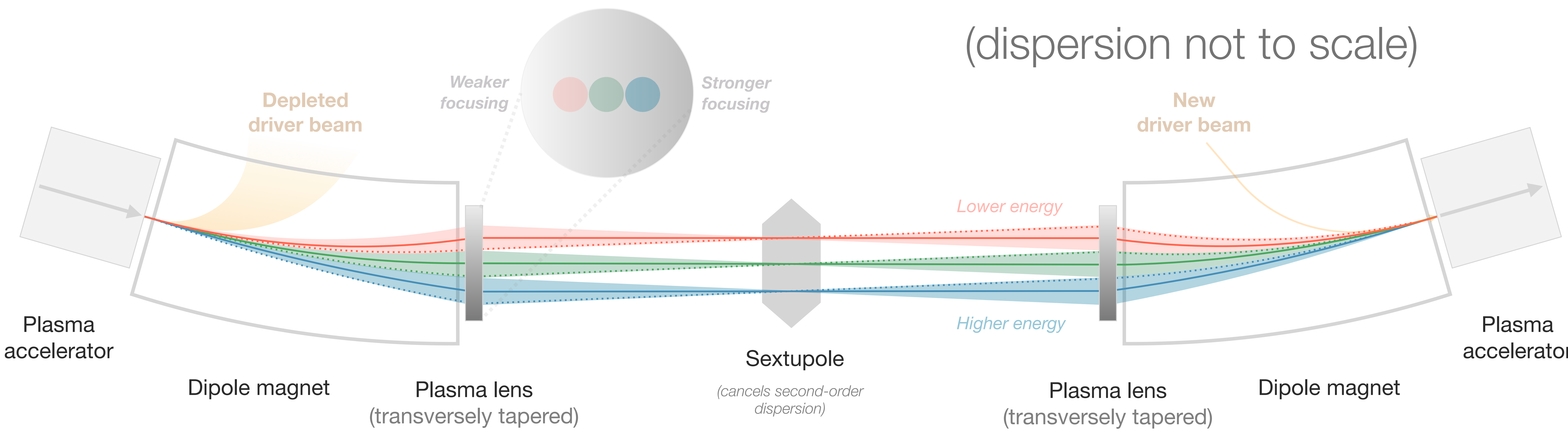
- **Local chromaticity correction**: sextupoles close to the quadrupoles (requires dispersion from dipoles)
- The magnetic field (assuming an APL) is given by

$$B_x = -g\left(x + \frac{1}{D_x}\frac{(x^2+y^2)}{2}\right) \qquad B_y = g\left(y + \frac{1}{D_x}xy\right)$$

where g is the magnetic field gradient, and $1/D_x$ is the (relative) transverse gradient.

  - This field is **similar, but not identical to a sextupole** field (there is a sign difference in one plane).

NONLINEAR BEAM OPTICS FOR EMITTANCE-PRESERVED STAGING



Schematic overview of the lattice (dispersion not to scale), showing conceptually how each energy slice is transversely achromatically.

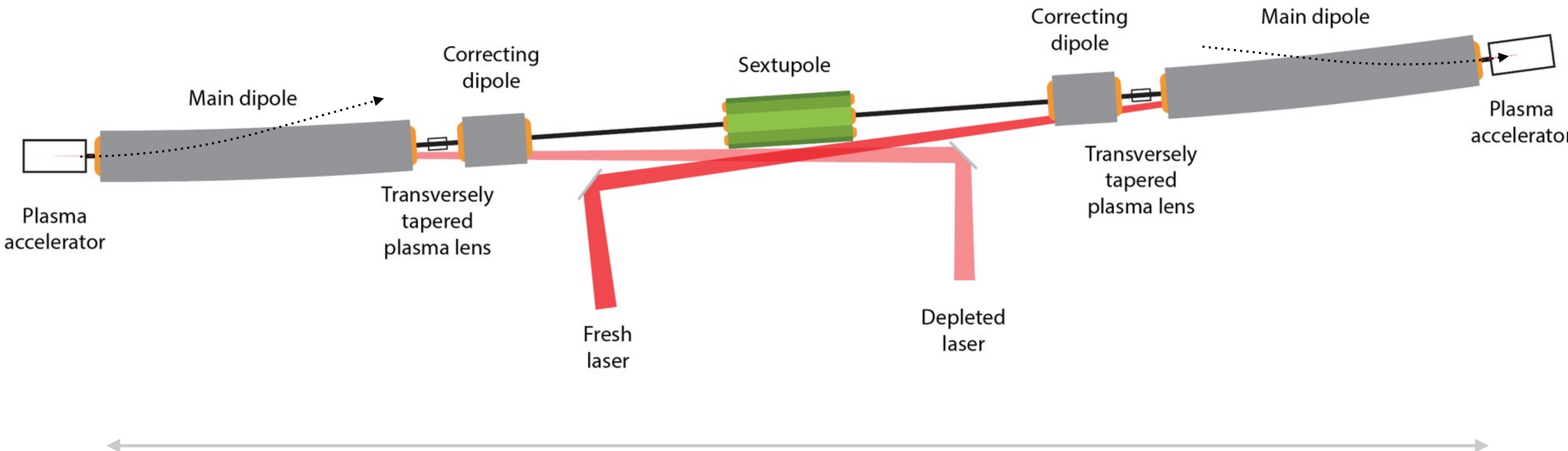
> The simplest possible lattice that provides achromatic and emittance-preserving transport between stages is:

  > *Two dipoles and two transversely tapered plasma lenses are used for chromaticity correction.*

  > *A central sextupole fixes the second-order dispersion.*

> Can be used for separating **both beam- and laser drivers**.

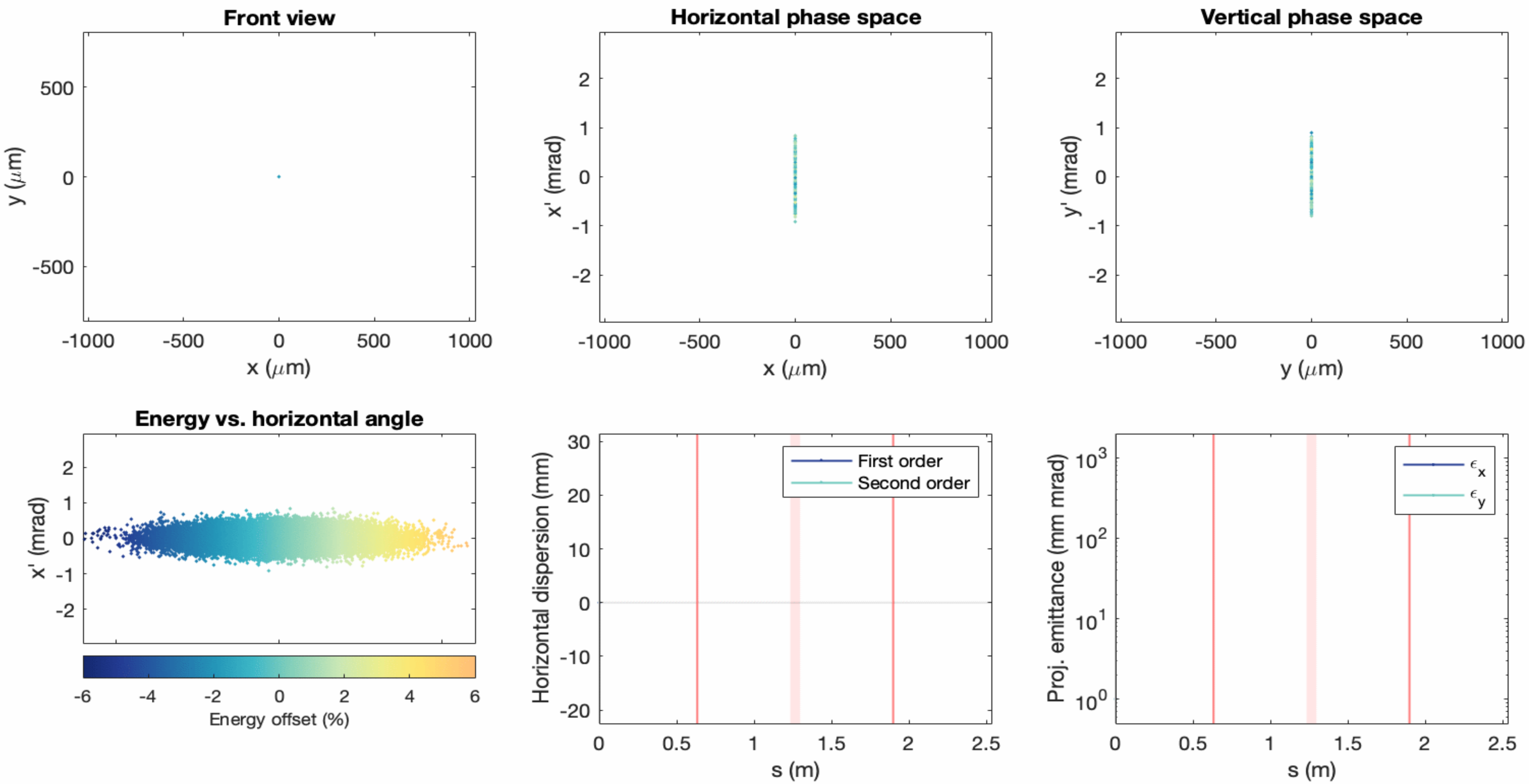
POSSIBLE LAYOUT FOR STAGING WITH LASER DRIVERS



Scale: ~2.5 m @ 4 GeV

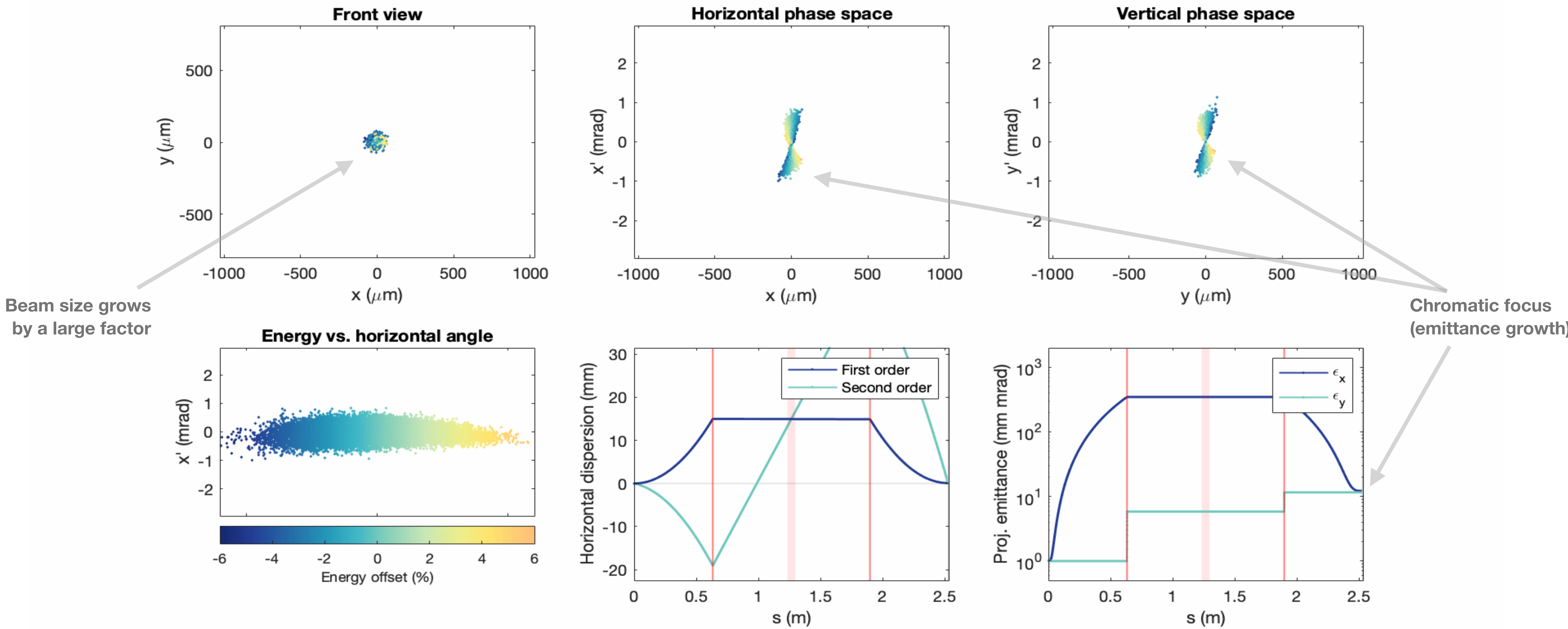
(scales with √Energy)

SIMULATION: USING REGULAR (NON-TAPERED) PLASMA LENSES



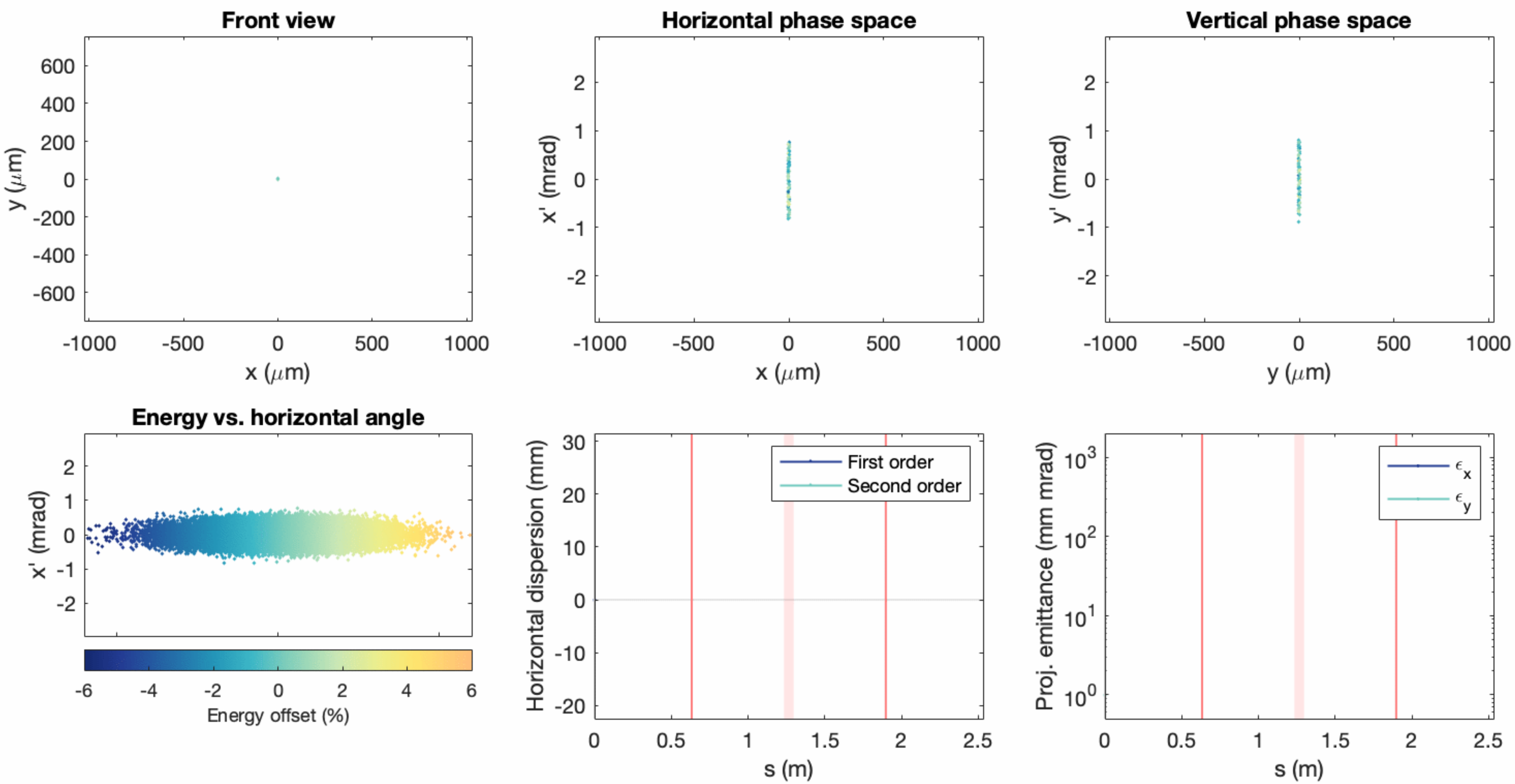
> **Setup: 4 GeV beam, 1.5% rms energy spread, 3.3 mm beta function, 1 mm mrad emittance, 1 T dipole field.**

SIMULATION: USING REGULAR (NON-TAPERED) PLASMA LENSES



> A strong chromaticity is observed, resulting in a large (projected) emittance growth (here: a factor ~10 per stage).

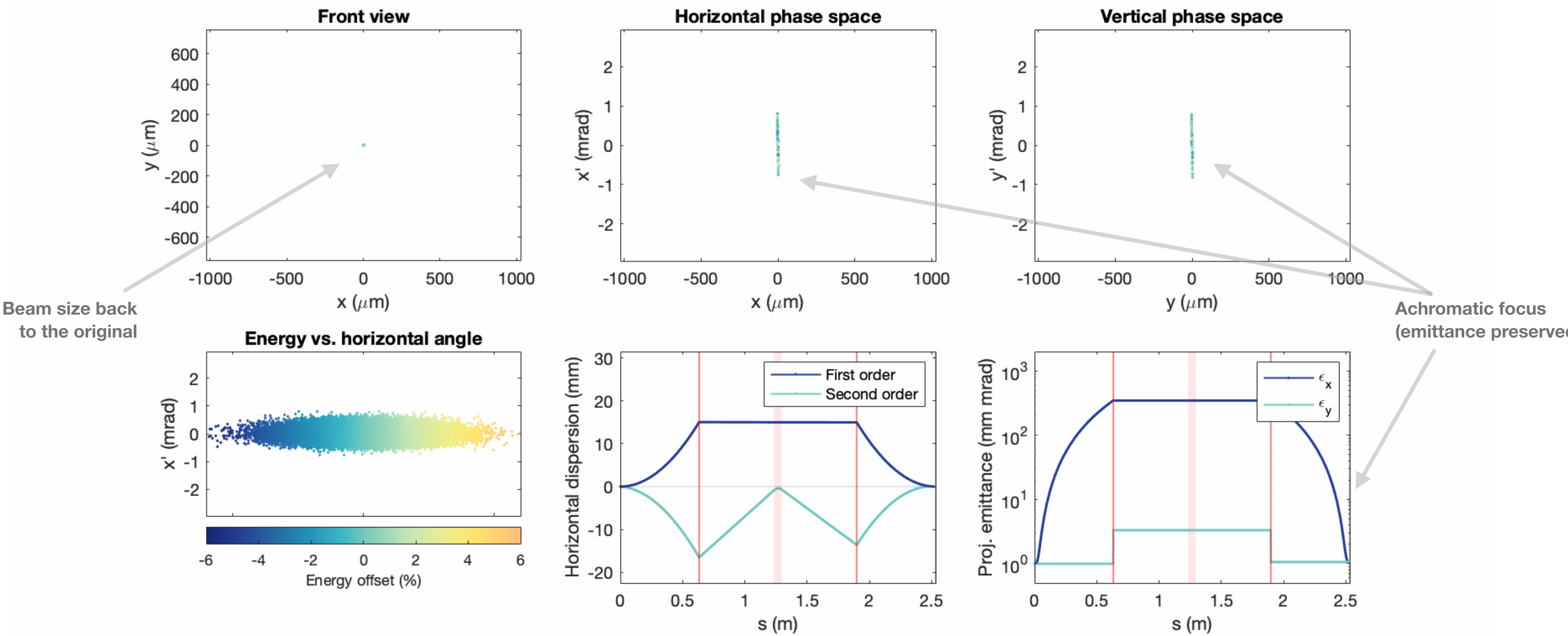
SIMULATION — USING NONLINEAR (TAPERED) PLASMA LENSES



> **Setup: 4 GeV beam, 1.5% rms energy spread, 3.3 mm beta function, 1 mm mrad emittance, 1 T dipole field.**

> Emittance is preserved despite large energy spreads.

SIMULATION — USING NONLINEAR (TAPERED) PLASMA LENSES



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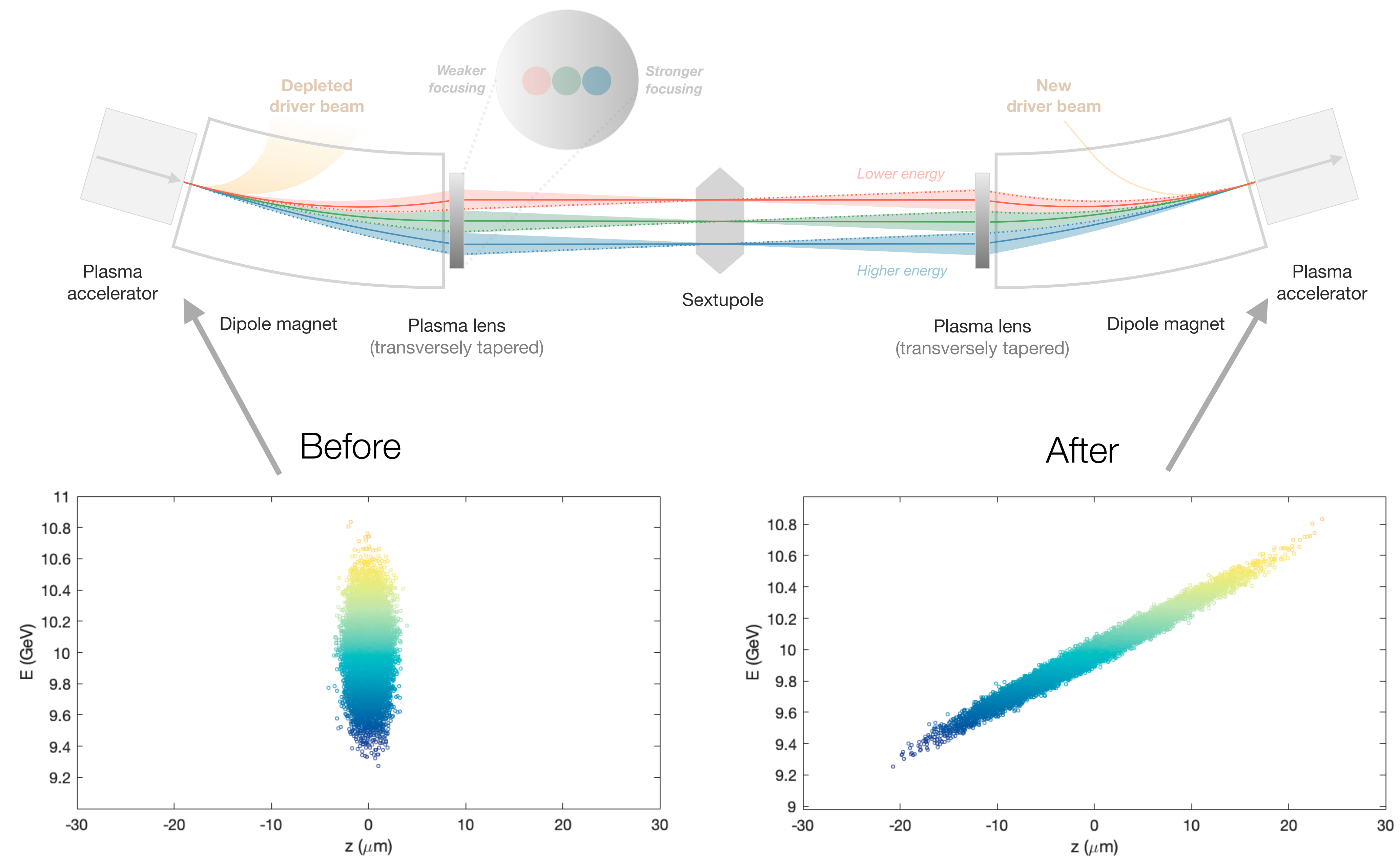
> Emittance is preserved despite large energy spreads.

LONGITUDINAL LATTICE DISPERSION: THE BUNCH LENGTH IS NOT CONSTANT…



ELEGANT simulation of a 10 GeV beam in a 4-meter long lattice (*L* = 1 m long dipoles) with dipole strength *B* = 1 T. We observe that the longitudinal phase space is sheared, indicating a positive R_{56} (consistent with the formula).

- In the proposed lattice, **the longitudinal lattice dispersion (R_{56}) is not cancelled:**
- This results in a small bunch compression/stretching between stages…

$$R_{56} = \frac{B^2 e^2 c^2 L^3}{3E^2} \neq 0$$

Two novel solutions

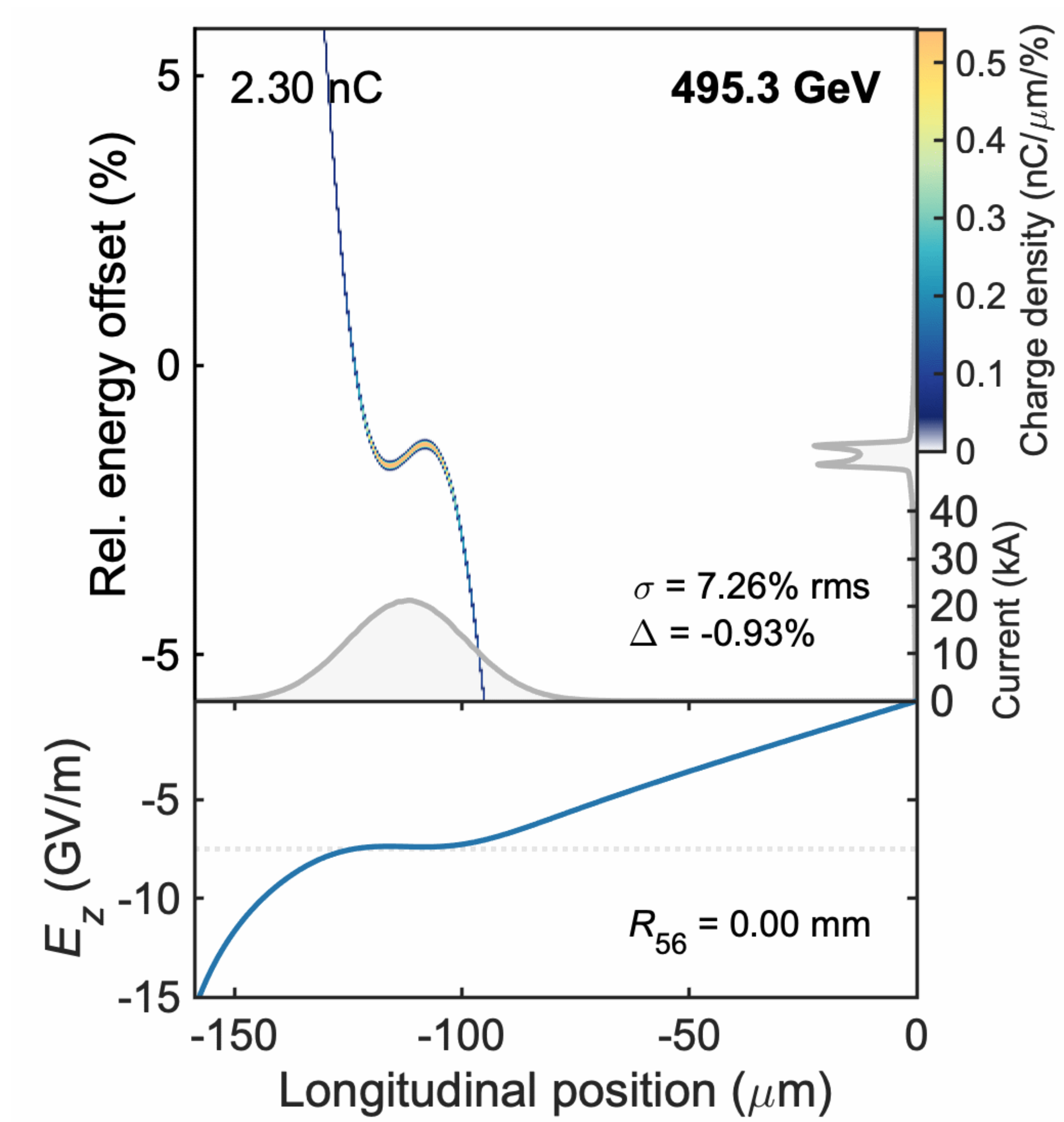
(1) Achromatic staging with nonlinear plasma lenses

(2) Self-correction mechanism in longitudinal phase space

LINEAR-COLLIDER EXAMPLE: ACCELERATION TO 500 GEV WITH AN IMPERFECT BEAM

Single plasma-accelerator stage (no R_{56})

Starts at 10 GeV



Plasma density:
10^{16} cm^{-3}

245 stages
2 GeV per stage

(= a single 490 GeV stage)

THE PROPOSED SETUP

Large number of stages

+

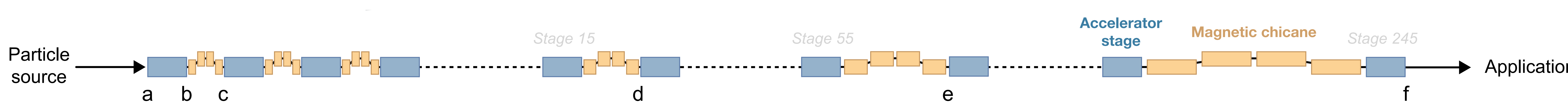
Magnetic chicanes between stages

+

Strong beam loading

"Linear synchrotron"

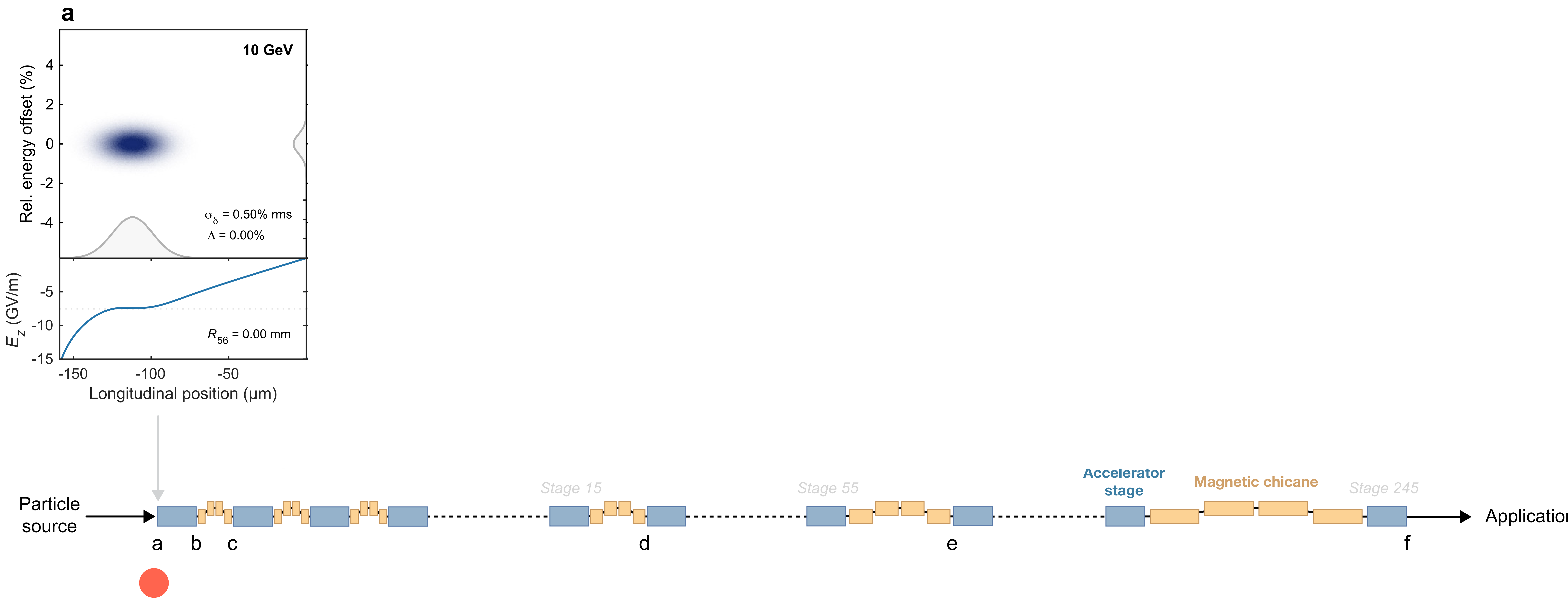
New part



Assuming: Preserved transverse phase space

R_{56} scales as $1/\sqrt{\text{Energy}}$ (any scaling works)

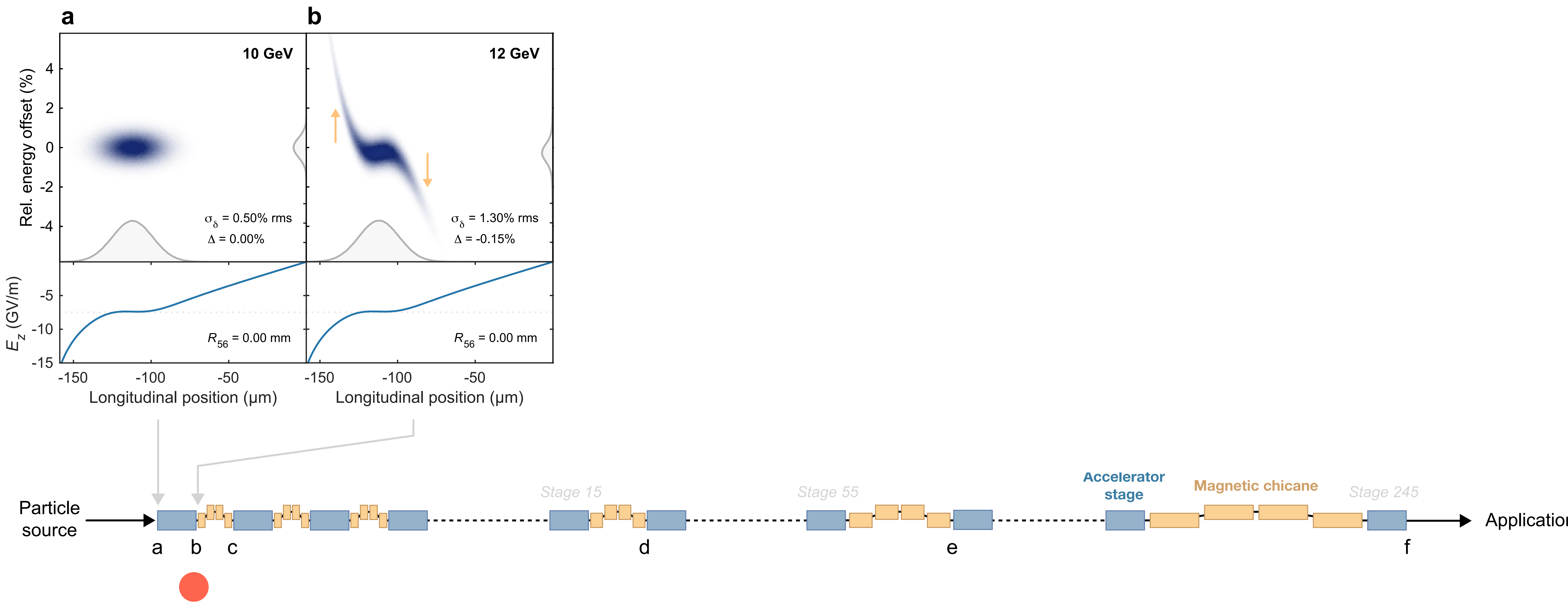
A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE



Start:

Initial particle distribution

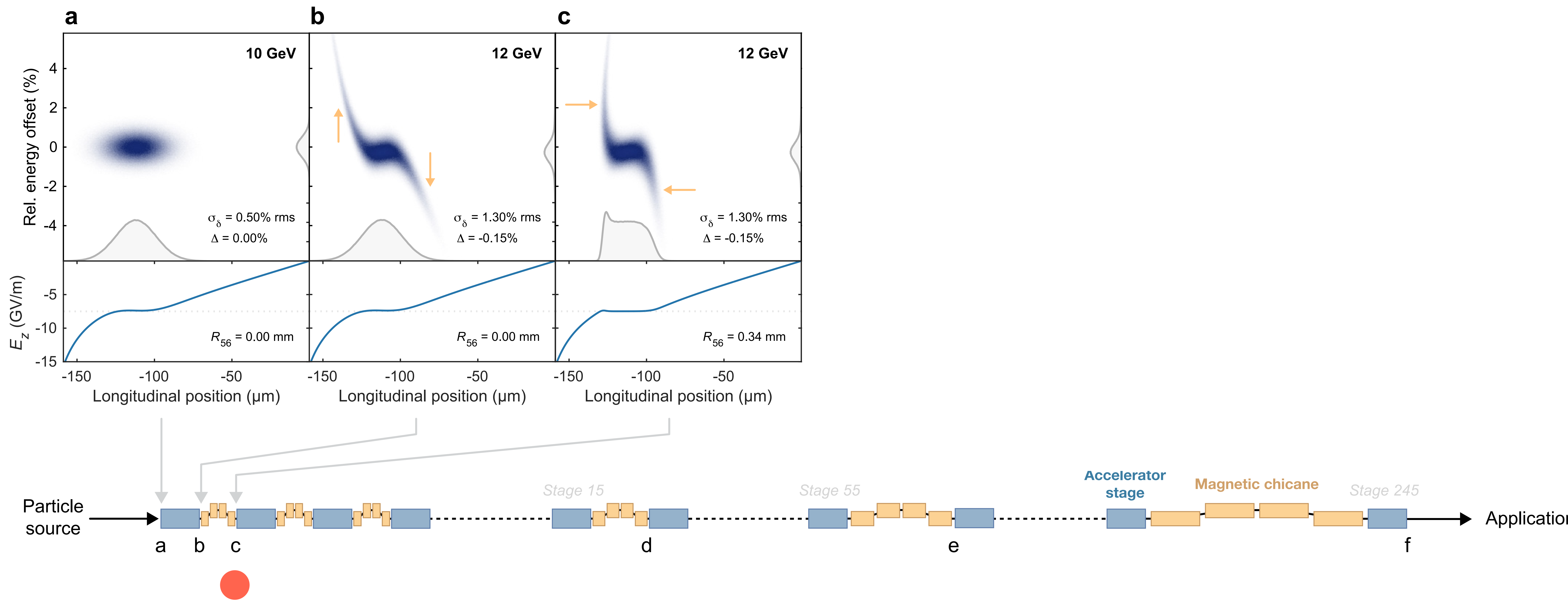
A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE



Plasma accelerator stage:

Particles gain energy based on their position

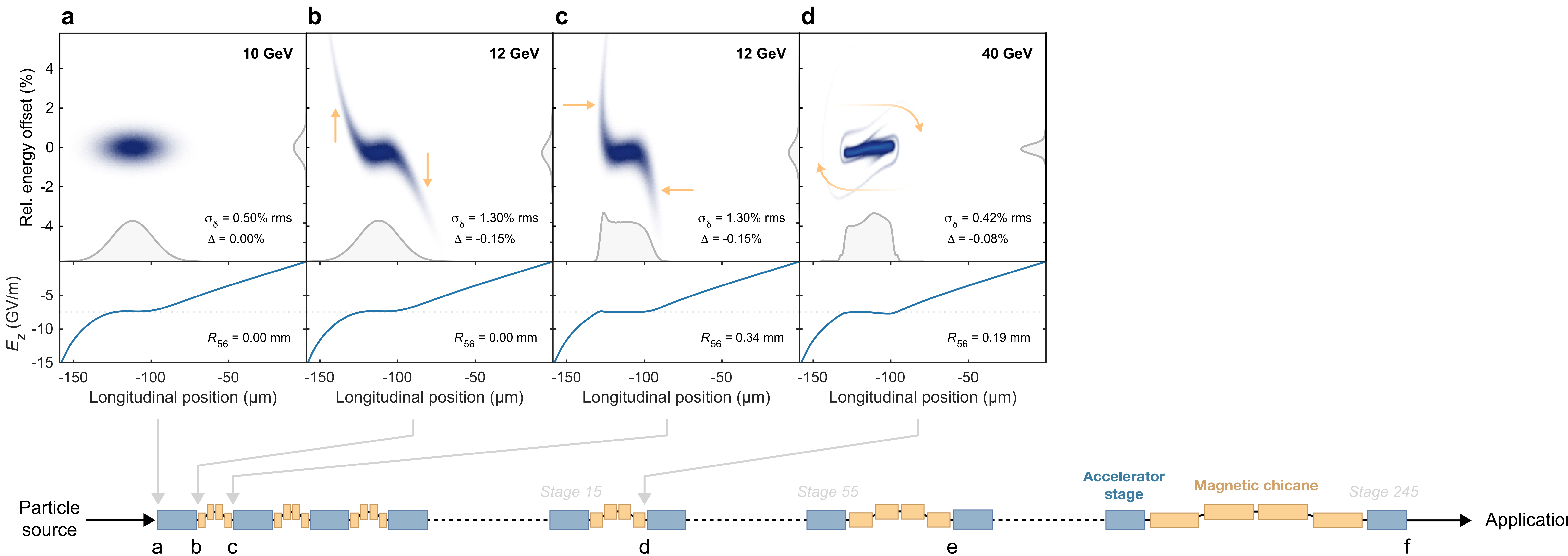
A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE



Magnetic chicane:

Move particles longitudinally based on energy offset

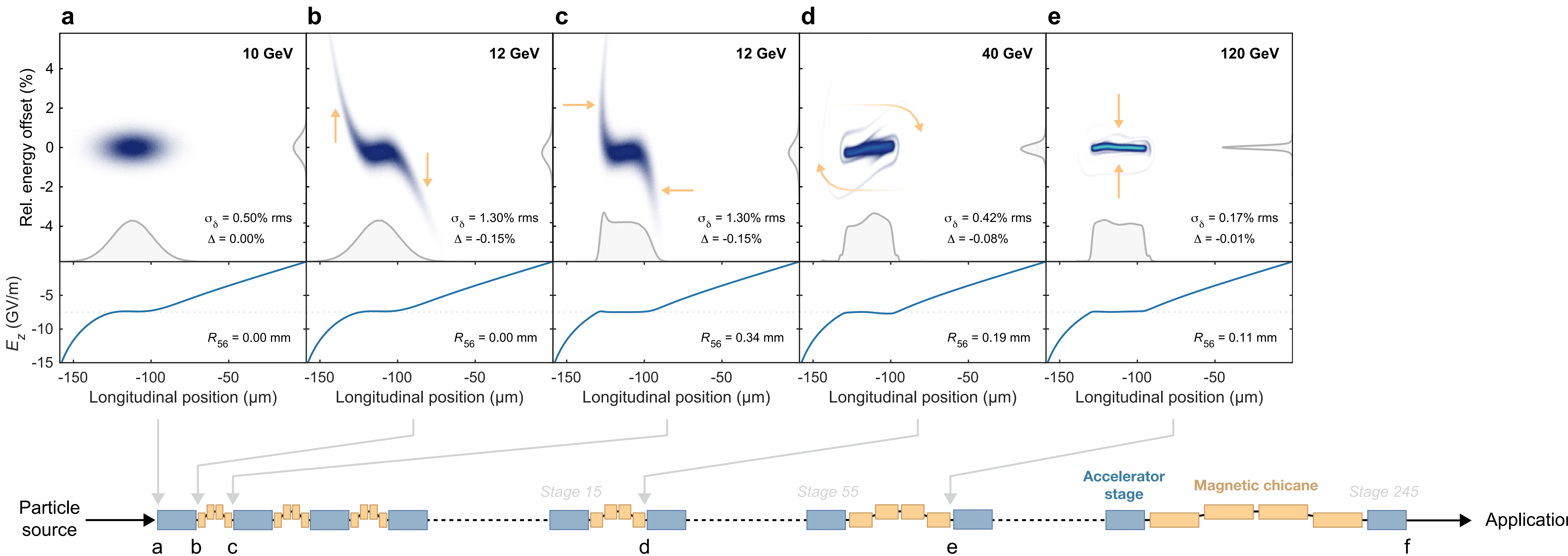
A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE



Several stages:

Particles move in oval tracks,
converging to an equilibrium current profile

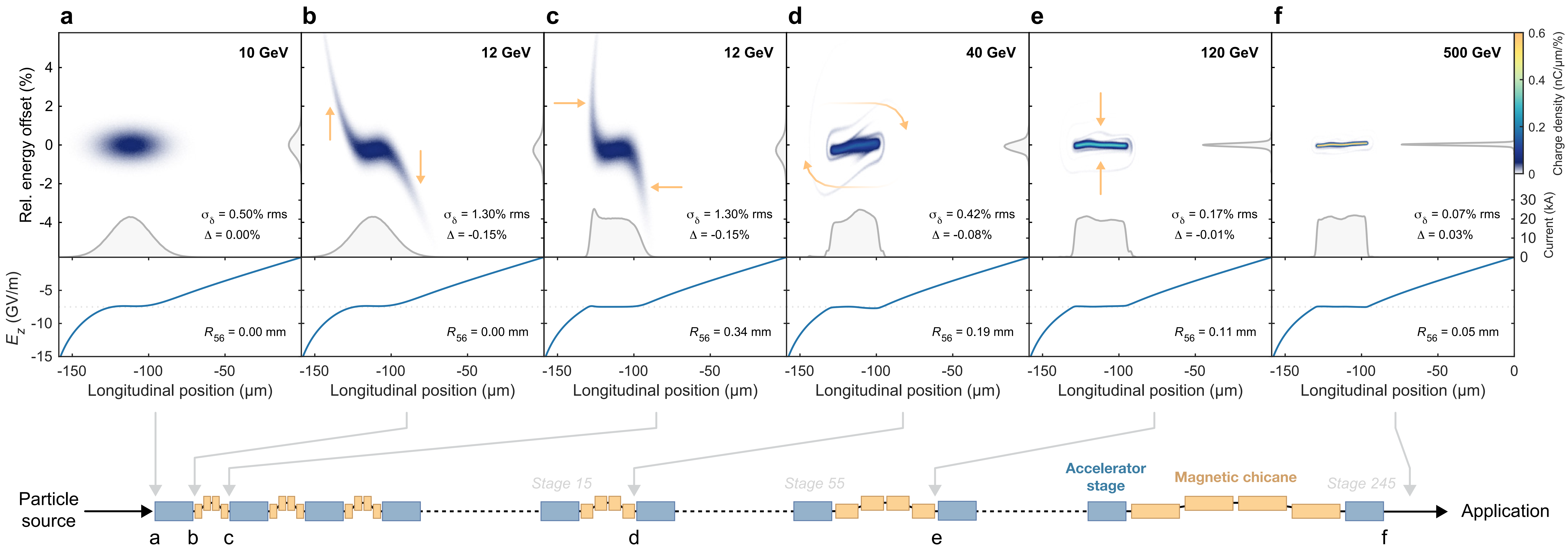
A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE



More stages:

Relative energy spread and offsets damped with energy gain

A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE



End result:

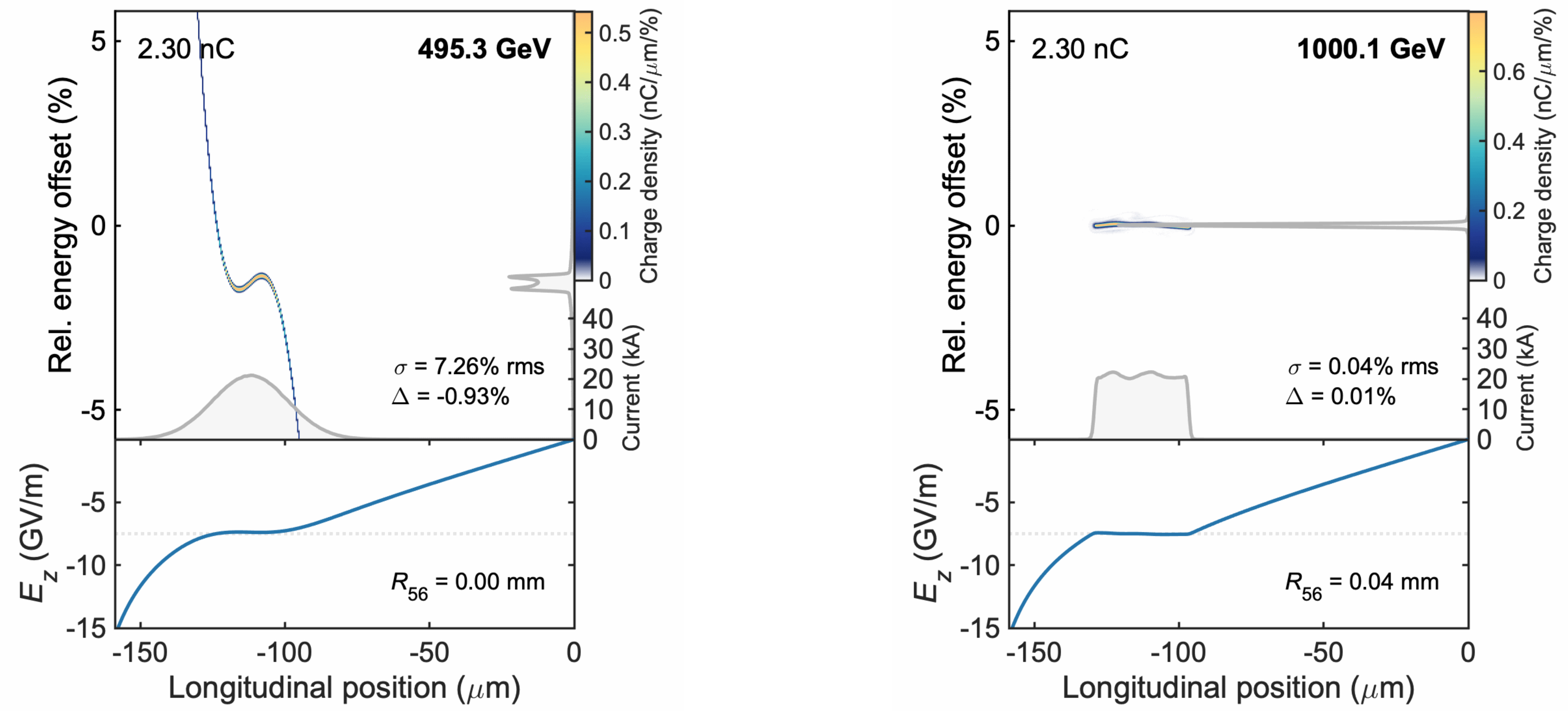
Optimal current profile, flattened wakefield
low energy spread, small energy offset

A self-correction mechanism in longitudinal phase space

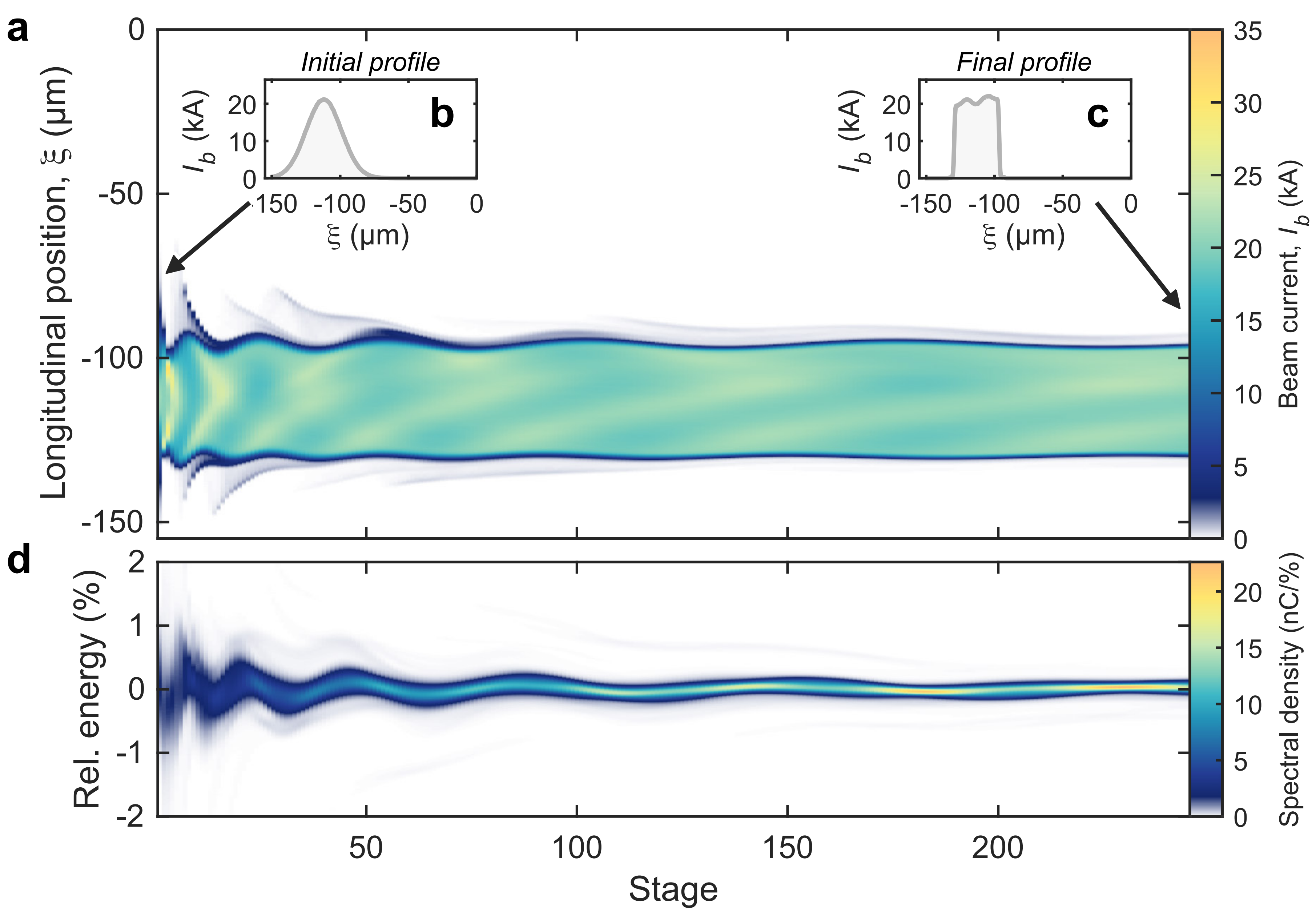
Preprint: ***C. A. Lindstrøm, arXiv:2104.14460 (2021)***

No R_{56}—no correction
(same as before)

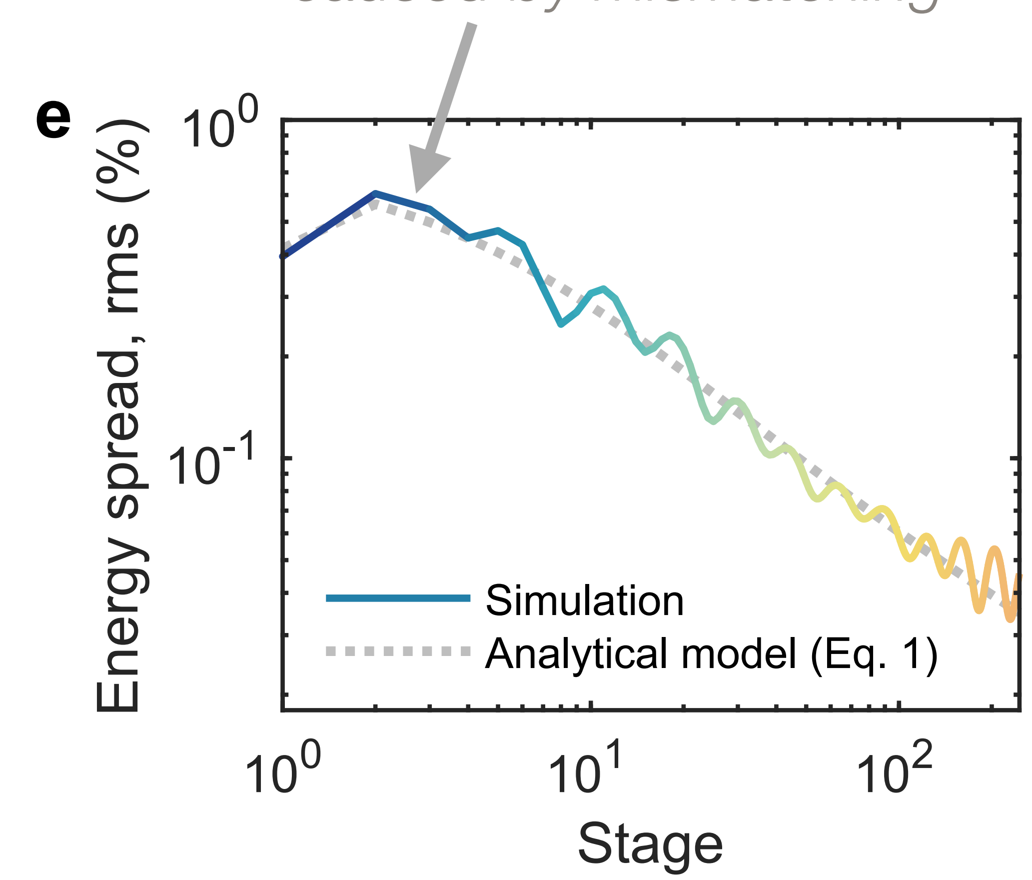
With multistage correction

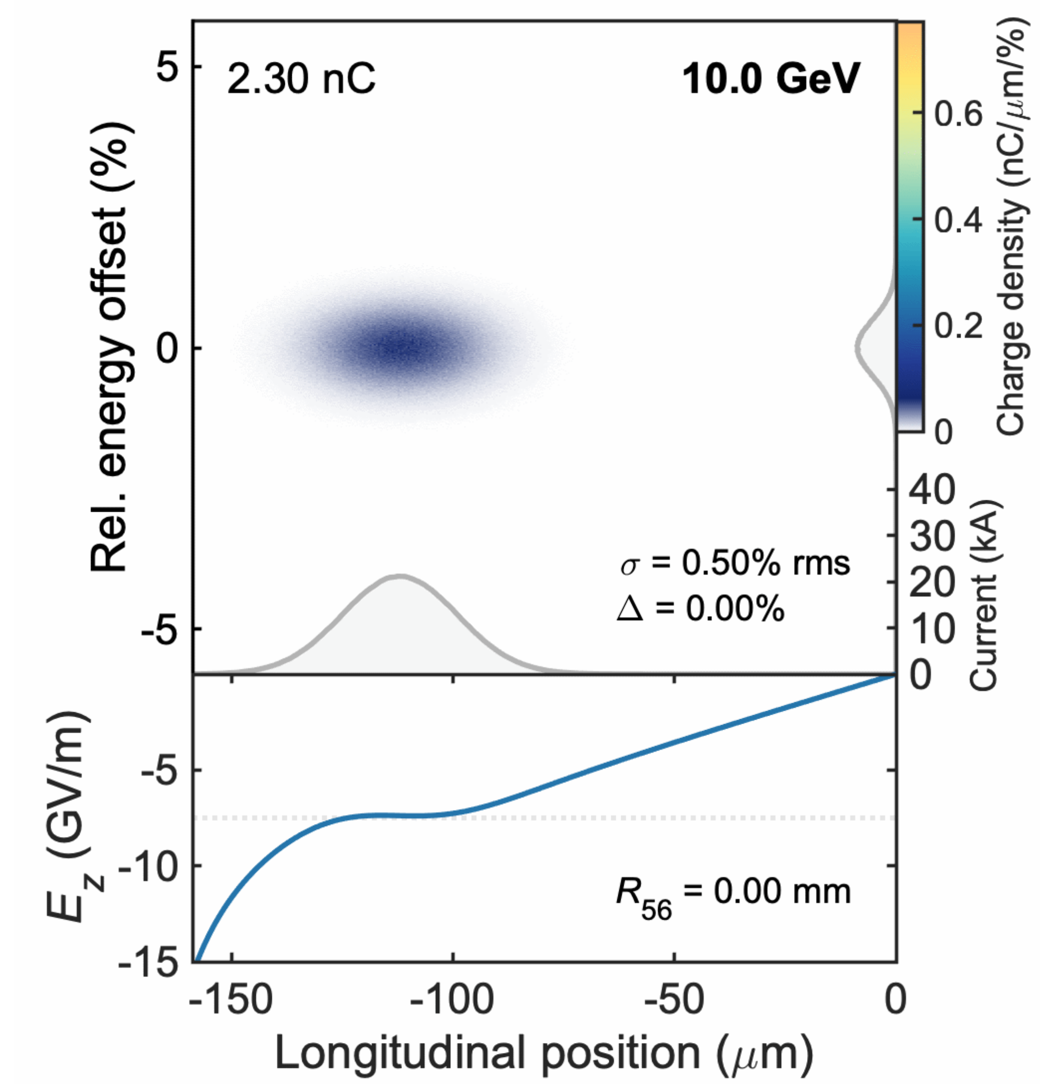


Self-matching in the longitudinal phase space



Initial increase in energy spread caused by mismatching





> Similar to mismatching and emittance growth in transverse phase space.

> Before: **A “mismatched” bunch in longitudinal phase space** (wrong current profile and phase for the wakefield)

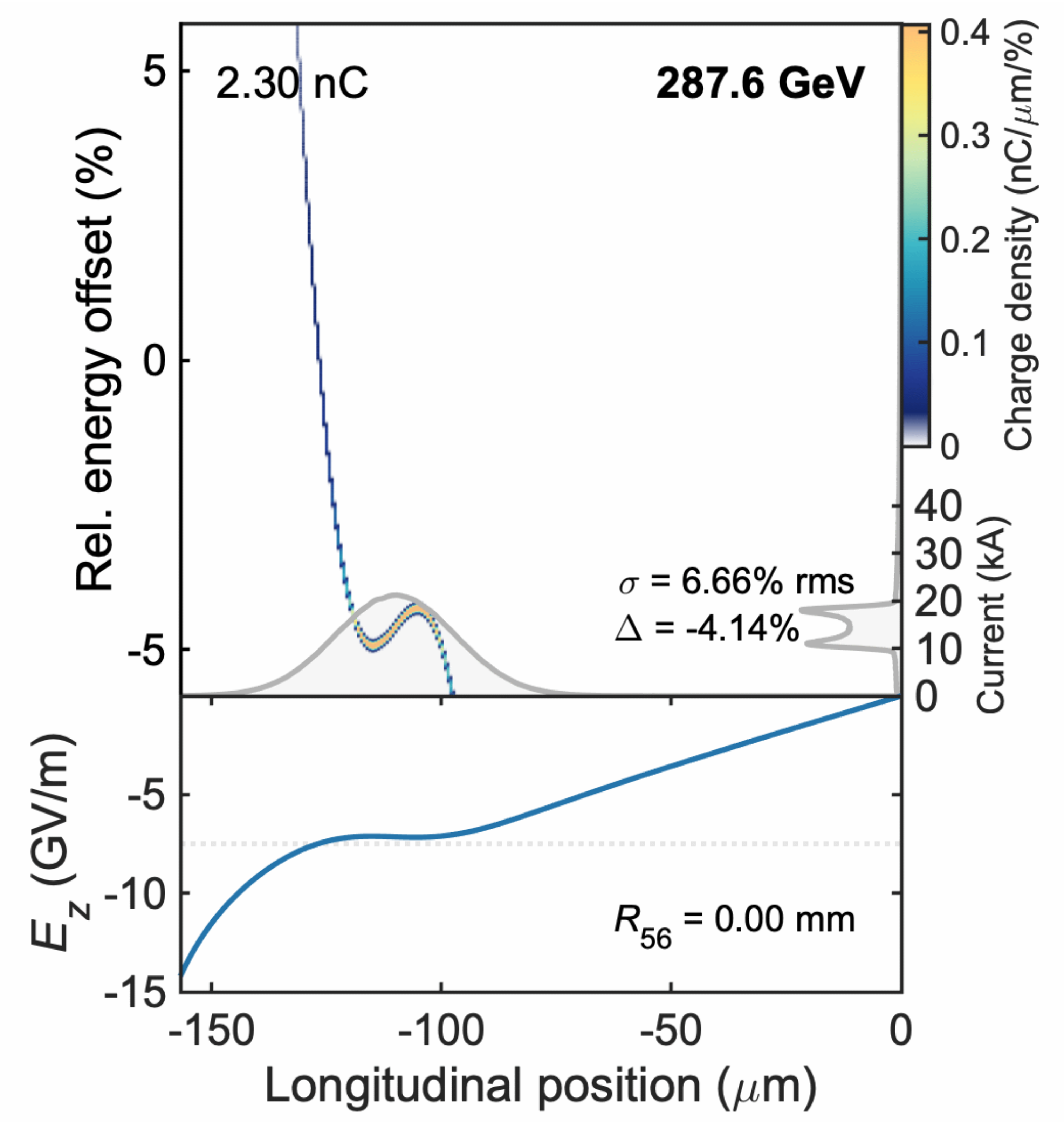
> After: **A (self-)matched bunch in longitudinal phase space**

> > **Absolute energy spread** (and abs. longitudinal emittance) **only increases** during the matching process

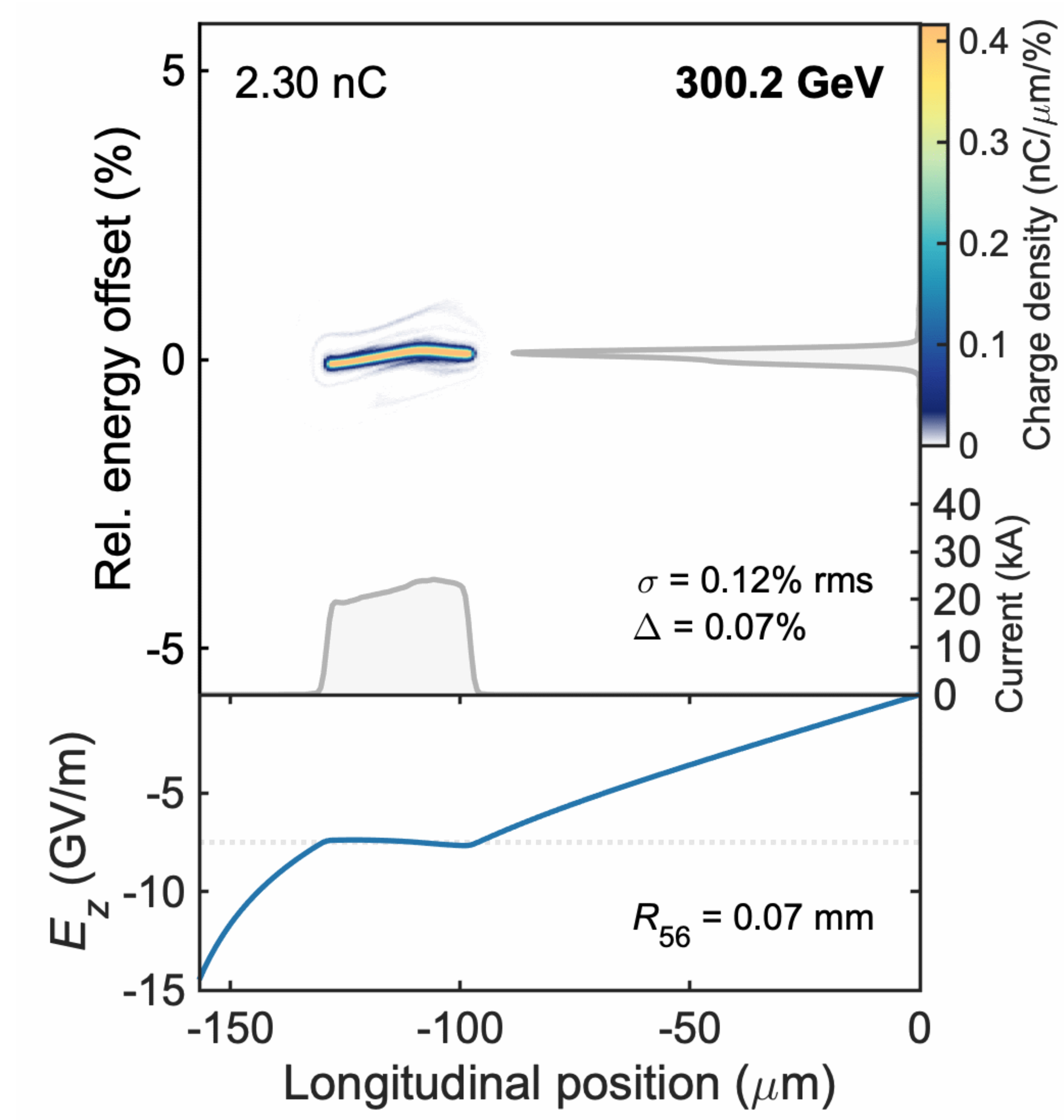
> > **Relative energy spread** (and rel. longitudinal emittance) **is eventually damped** with acceleration

Example #1: Bunch injected too early (10 fs)

No correction

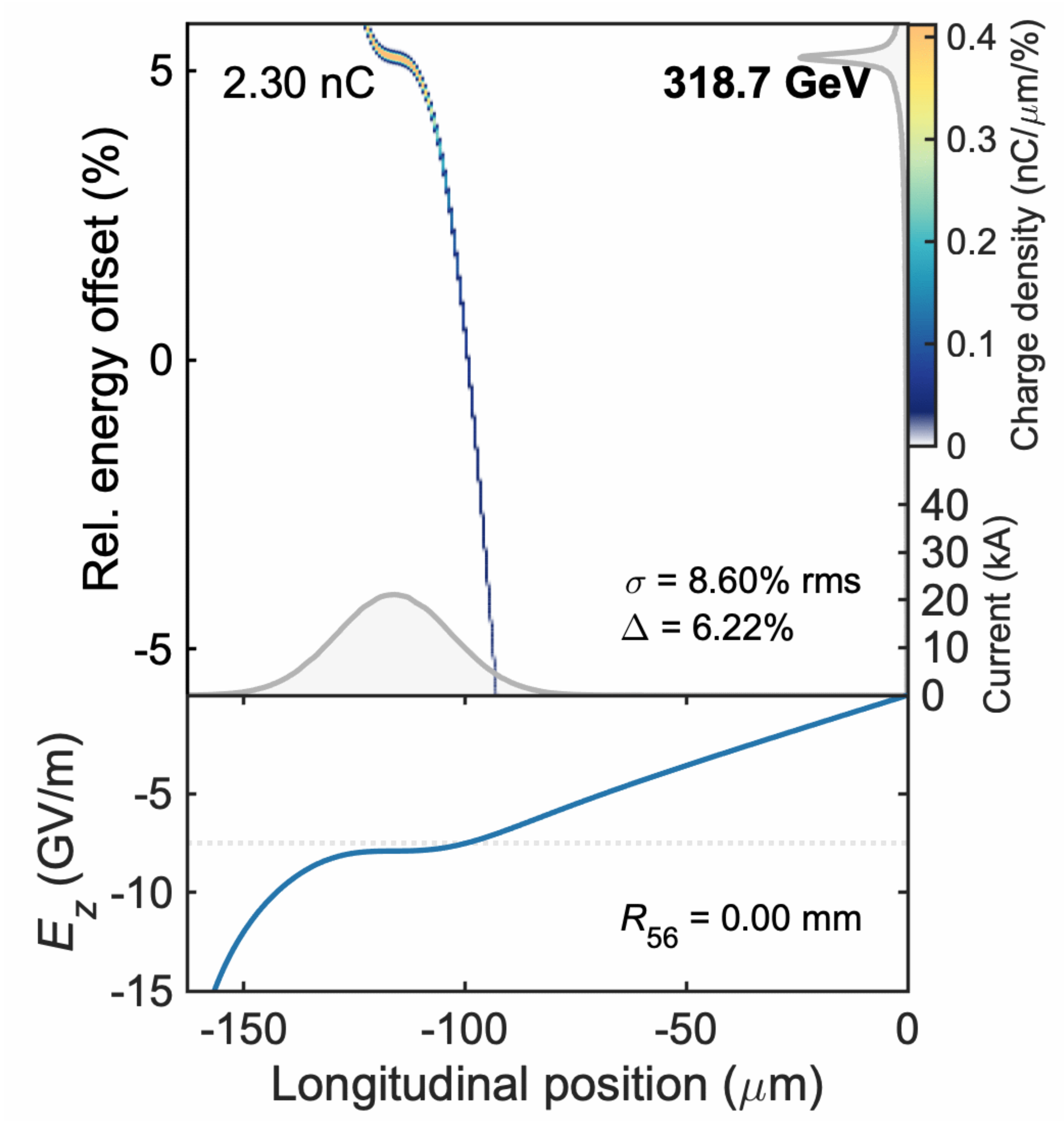


With multistage correction

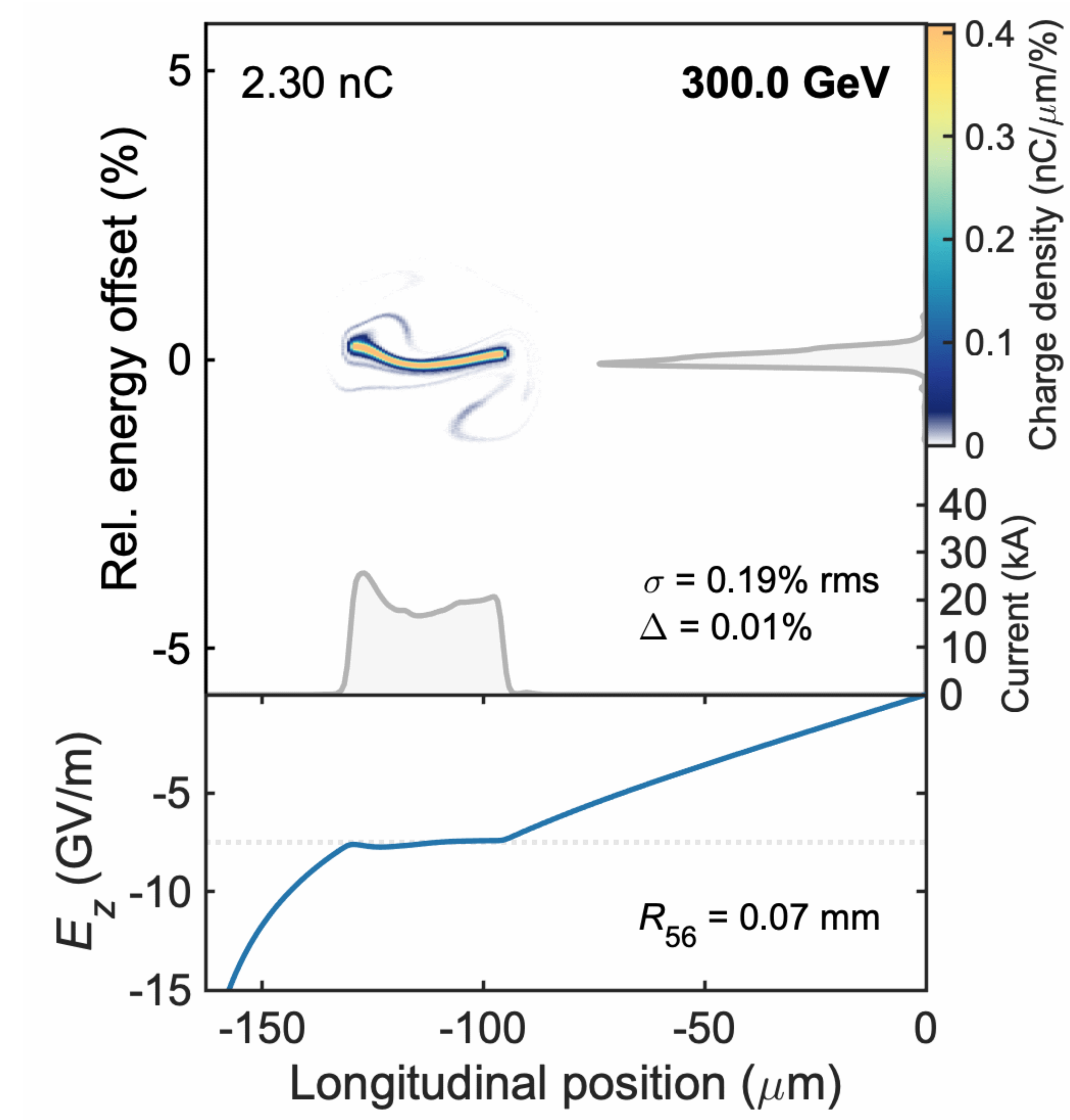


EXAMPLE #2: **BUNCH INJECTED TOO LATE (10 FS)**

No correction



With multistage correction



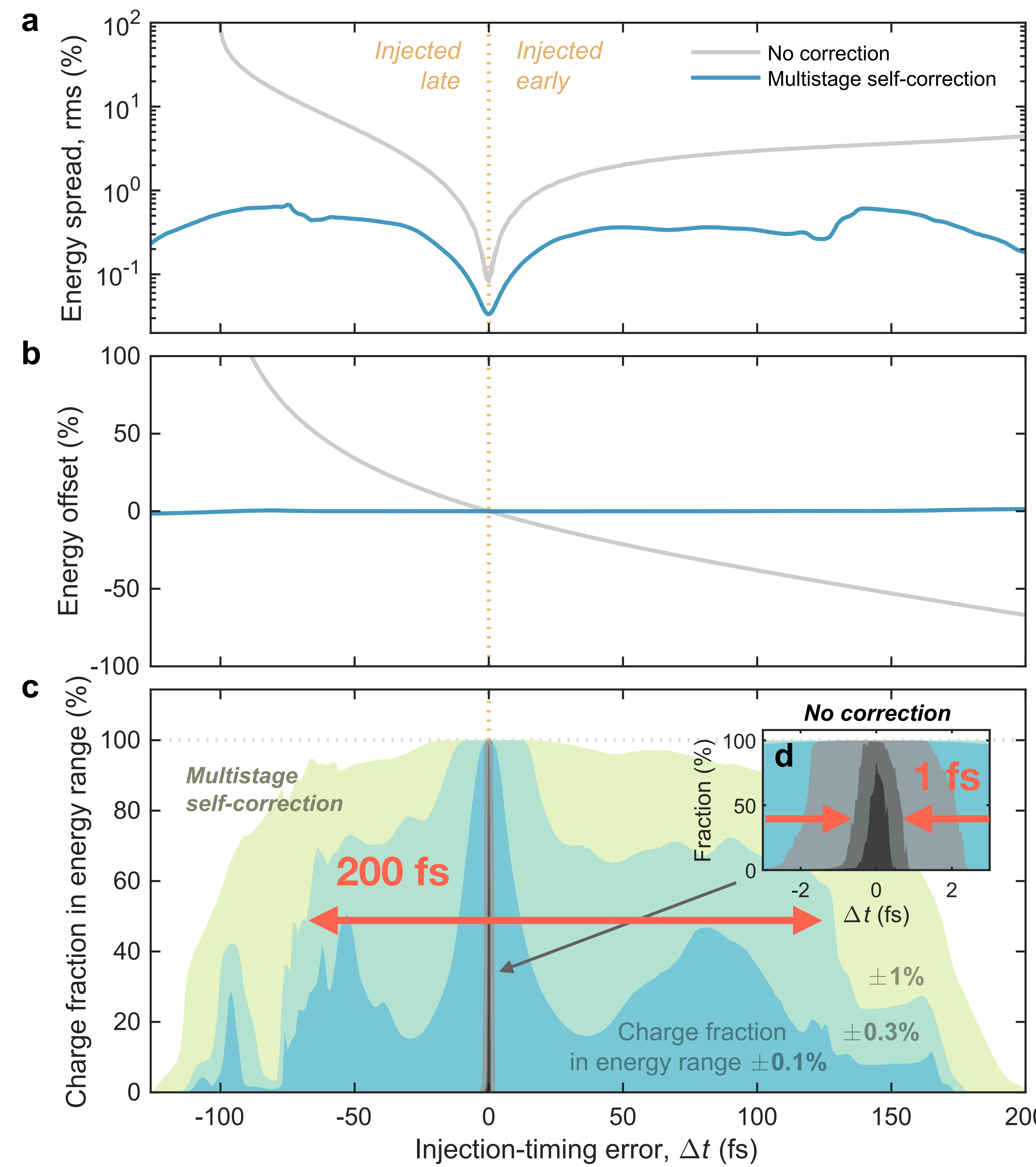
TIMING TOLERANCES IMPROVE DRAMATICALLY

- Scan of injection timing/phase

- *Timing tolerance in this example:*
  - Assuming 0.3% FWHM energy acceptance.
  - ~1 fs FWHM without correction
  - **~200 fs FWHM with self-correction.**

- Orders of magnitude improvement

- Well within state-of-the-art synchronization (~10 fs).

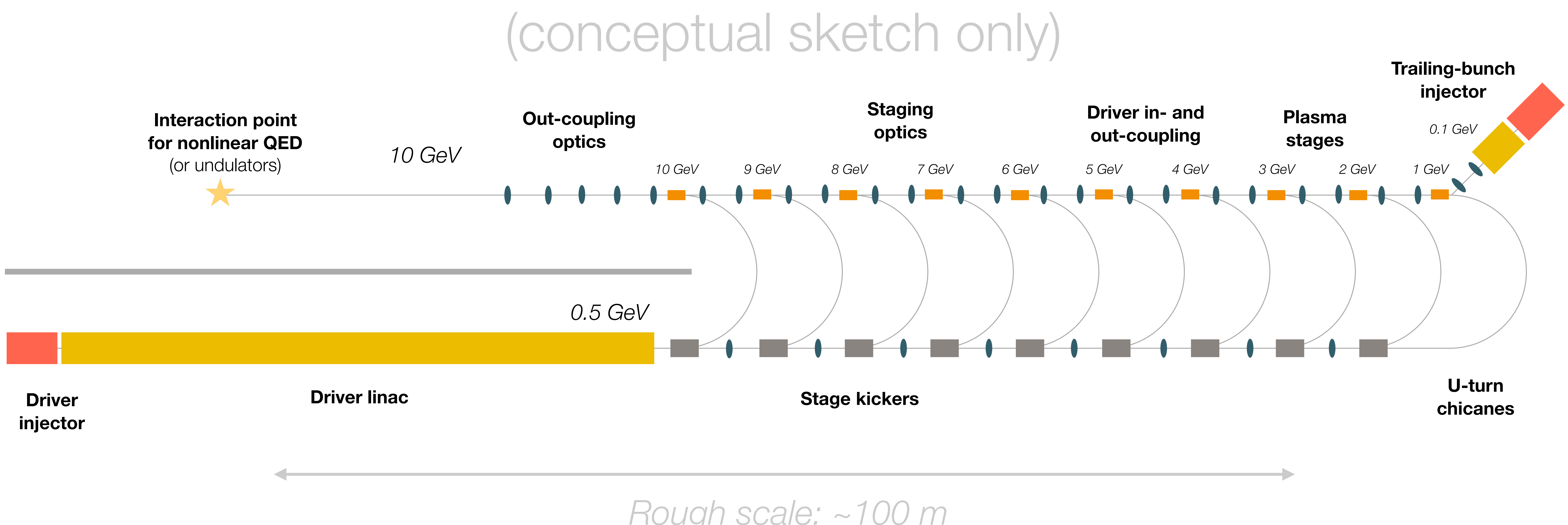


Mars Shot Initiative: A multi-stage plasma accelerator at DESY?

> Can we demonstrate these concepts experimentally at DESY?

> Large and long-term project, much R&D to be done prior.

> **Applications: nonlinear QED, potentially x-ray FEL**



SUMMARY

> Plasma accelerators hold great promise for compact colliders.
    > Much recent progress across the board.

> Staging of plasma accelerators is key to reaching very high energy, but is challenging.

> Two novel concepts may change this:
    > Nonlinear plasma lenses for achromatic stage coupling.
    > Intra-stage chicanes create a self-correction mechanism with high stability.

> Experimental demonstration is still a ways away
    > However, concepts are being considered at DESY (Mars Shot Initiative).
    > *Watch this space…*