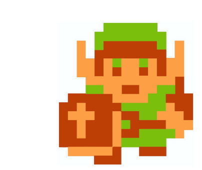
EAAC 2021 | Frascati, Italy / hybrid | 20 September 2021

SELF-CORRECTING BEAMS IN A MULTISTAGE PLASMA ACCELERATOR



Carl A. Lindstrøm

FLASHFORWARD Research Fellow | FTX-AST

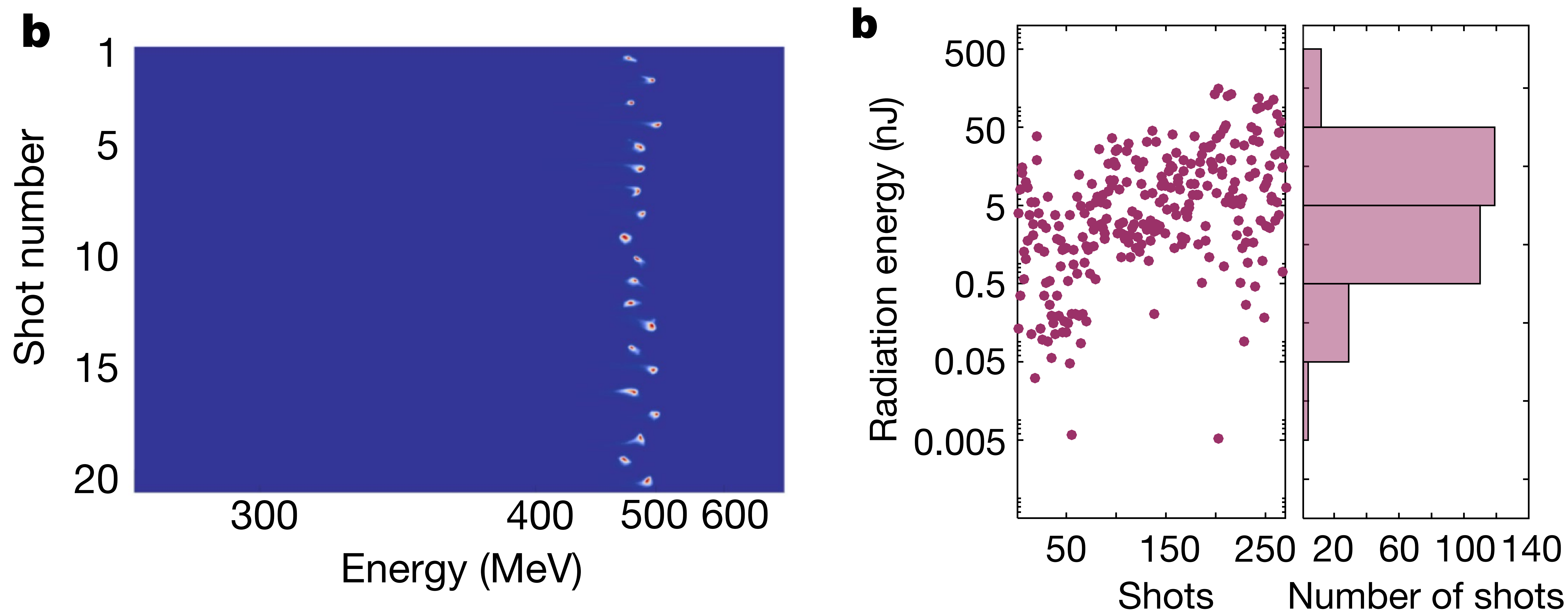
Deutsches Elektronen-Synchrotron DESY, Particle Physics Division, Hamburg, Germany

Accelerator Research and Development, Matter and Technologies

Helmholtz Association of German Research Centres, Berlin, Germany

PART 1:
THE STABILITY PROBLEM

Great experimental progress, but still lacking stability



Source: Wang *et al.* [Nature 595, 516 (2021)]

> Recent demonstration of FEL gain [Wang *et al.,* Nature 595, 516 (2021)] shows the **promise of plasma acceleration**.

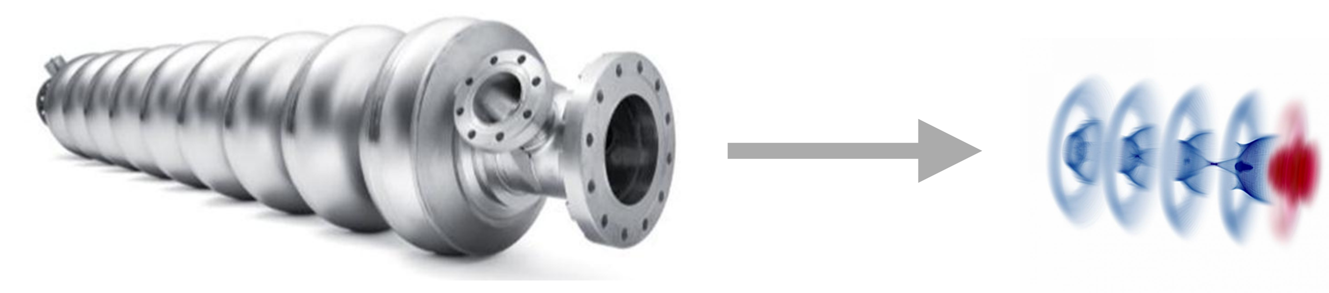
> However, results also **show a need for higher stability**.

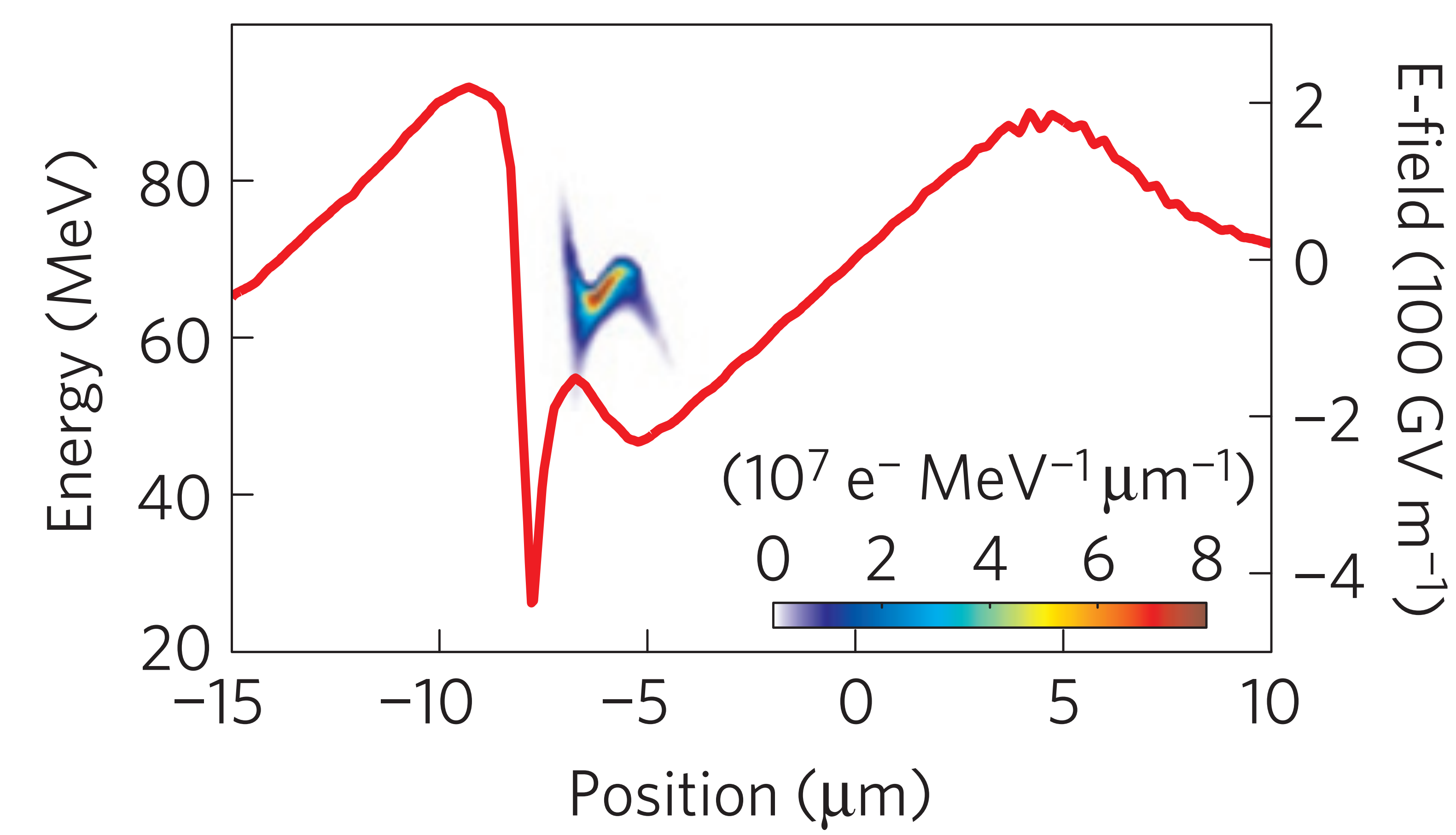
Tight tolerances: a major challenge for plasma accelerators

- Plasma accelerator cavities are small—**trading size for gradient**
- Tight tolerances in both planes:
  - Transverse tolerances (on misalignments and mismatching)
    ⇒ emittance growth and beam loss
  - **Longitudinal tolerances (on synchronization and current profile)**
    ⇒ energy spread and offsets
- Applications require 0.1–1% energy spread and energy stability.
- *Example:*
  Plasma density: n_0 = 10^{18} cm^{-3}
  ⇒ $1/\omega_p$ = 18 fs.
  Field precision required: σ_δ = 0.1%
  Timing precision required: σ_δ/ω_p **= 18 as**
  (for synchronization and current-profile shaping)
- Experimentally very challenging to control and diagnose.

~10 cm
~100 MV/m

~10 µm
~100 GV/m



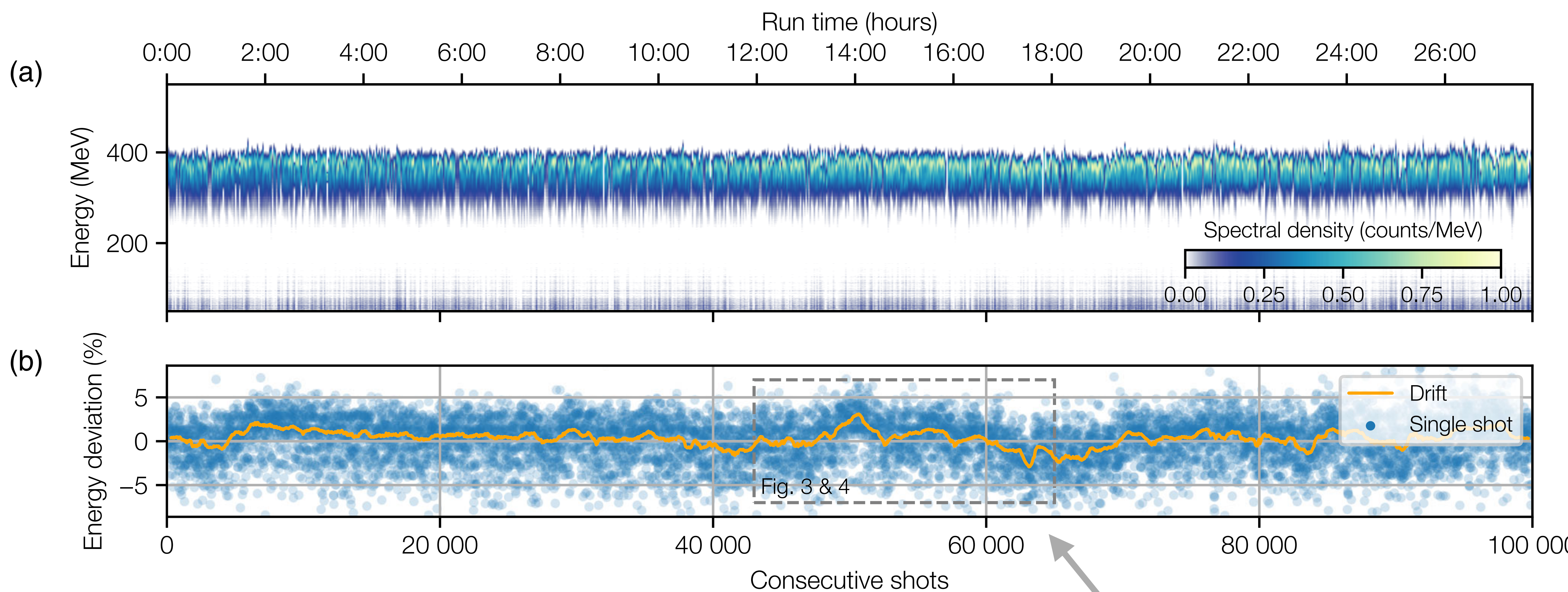


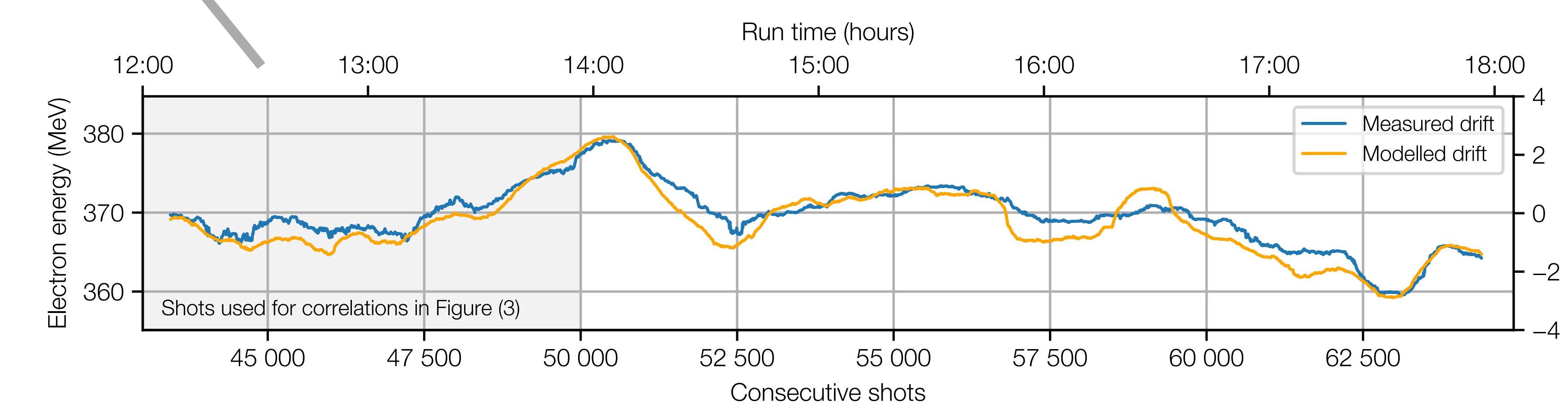
Source: Lundh *et al.* [Nat. Phys. 7, 219 (2011)]

CHOOSE YOUR STABILIZATION ADVENTURE!

CHOOSE YOUR STABILIZATION ADVENTURE! (OPTION 1)

OPTION 1: STABILIZING THE INPUTS (ACTIVE STABILIZATION)





Source: Maier *at al.* [Phys. Rev. X 10, 031039 (2020)]

> *Method: Stabilize all input parameters + active feedbacks.*

> Good for correcting slow drifts (improves with repetition rate).

> Routinely employed by conventional accelerators (e.g., FELs).

> Being introduced also to plasma accelerators (e.g., LUX)—can use machine learning for modelling.

> However, can become complex and expensive—requires fast and accurate diagnostics and actuators everywhere.

> In conclusion: **Essential for plasma accelerators, but may not be the whole solution.**

CHOOSE YOUR STABILIZATION ADVENTURE!

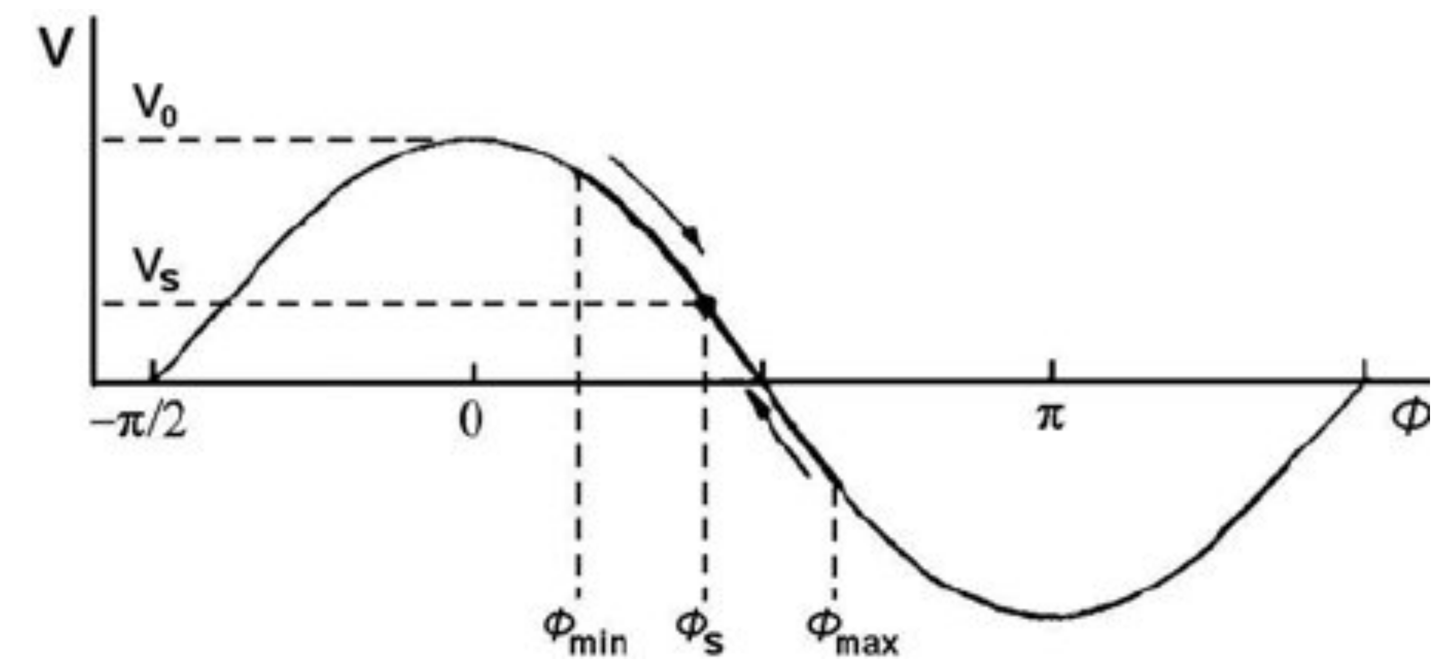
CHOOSE YOUR STABILIZATION ADVENTURE! (OPTION 2)

OPTION 2: STABILIZING THE PROCESS (PASSIVE STABILIZATION)

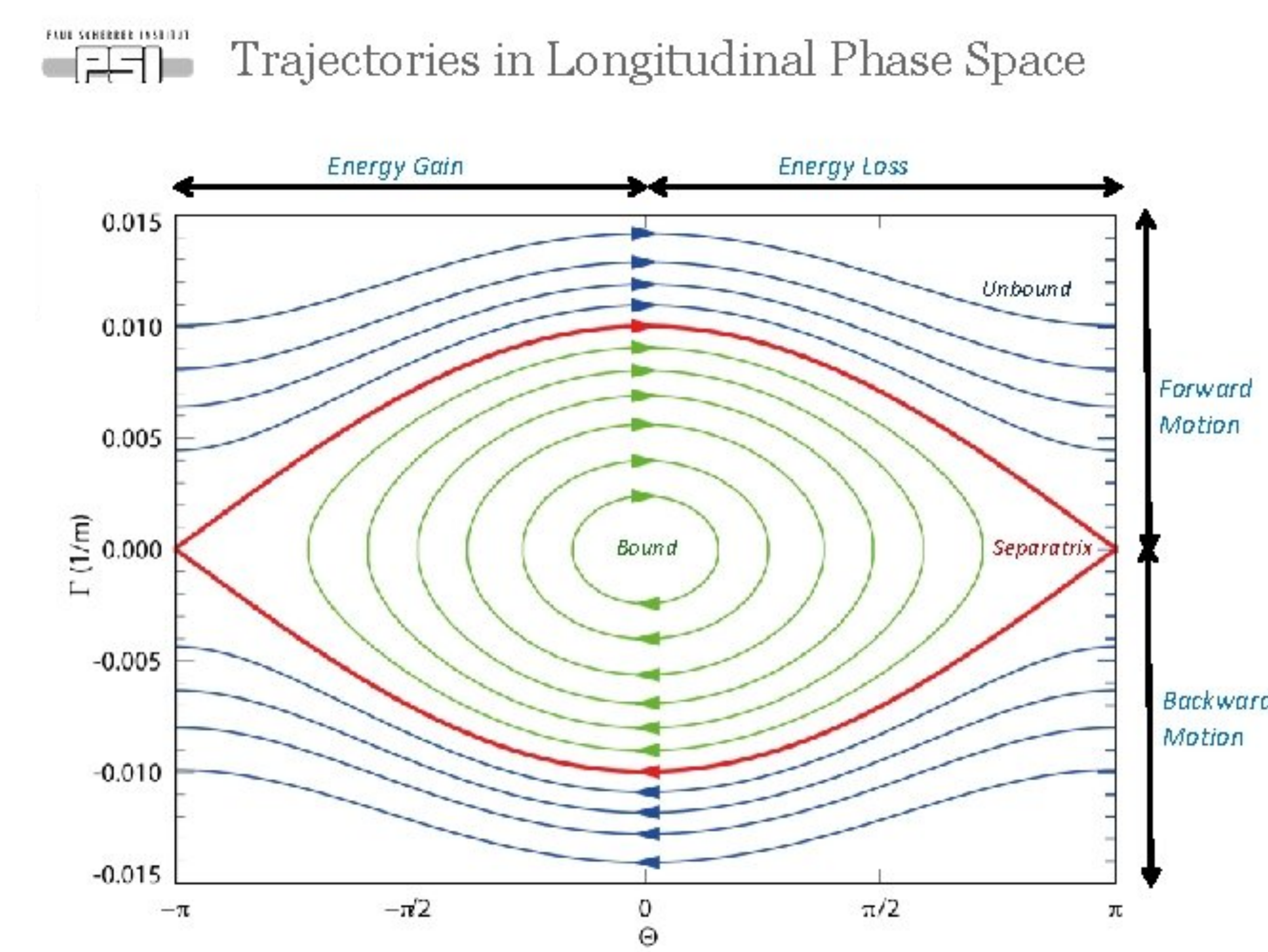
- *Method: make the acceleration process intrinsically stable*

- Lesson from conventional accelerators: **phase stabilization**
  - Introduced by Veksler (1944) and McMillan (1945).
  - A longitudinal lattice dispersion (R_{56}) is required.
  - **Synchrotron oscillations:** Each round, particles at higher energy move forward, where it experiences less acceleration, and vice versa (approx. simple harmonic motion).
  - Synchrotrons are designed around this mechanism.

- Not required in conventional linacs (short accelerator, long bucket)
  - Plasma accelerators may need it (short accelerator, short bucket)



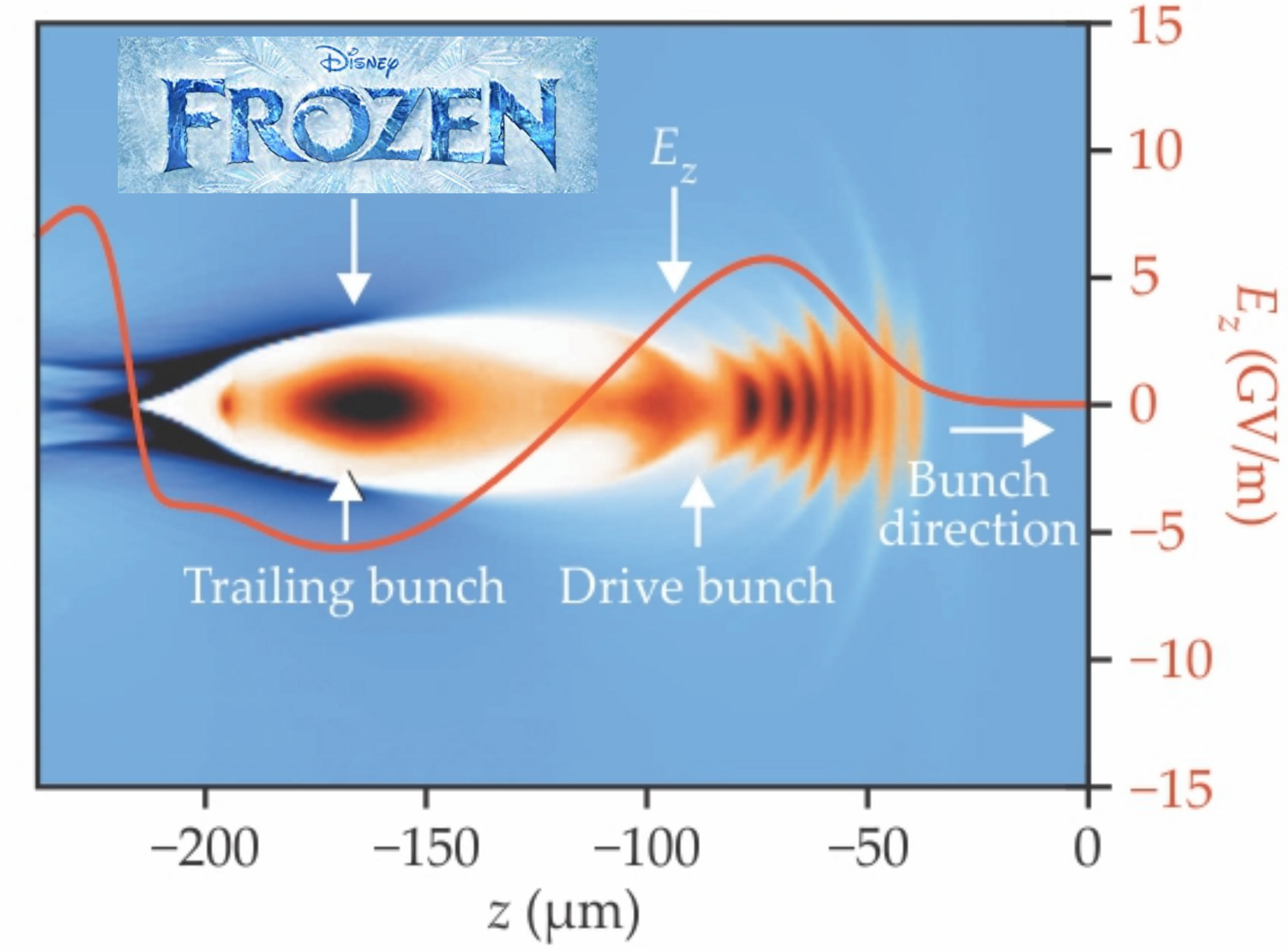
Source: Craddock & Symon [Rev. Accel. Sci. Tech. 1 (2008)]



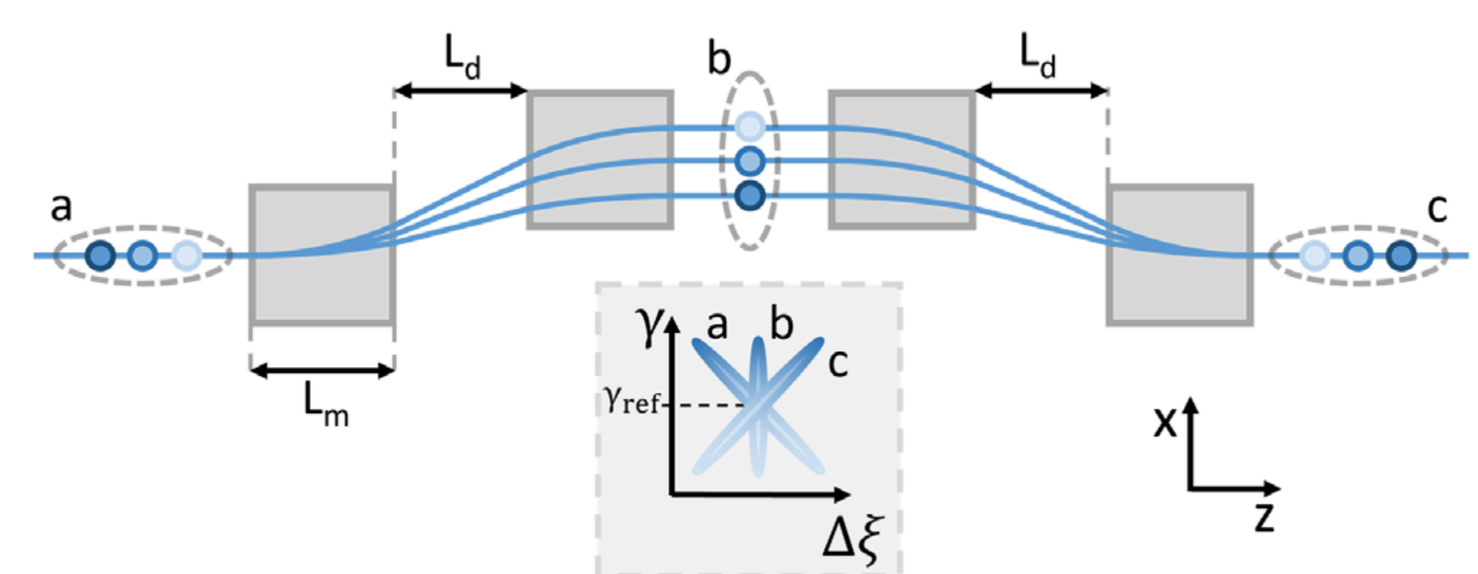
Source: Paul Scherrer Institute (PSI)

R_{56} AND FEEDBACK IN PLASMA ACCELERATORS

- **Practically no R_{56} within a plasma-accelerator stage**
  - On-axis, ultrarelativistic particles effectively *locked in place* longitudinally (not transversely).
  - Stops any feedback loop with the driver/wakefield.
- Feedback **requires multiple stages**:
  - Extract the beam
  - Apply R_{56} (with a magnetic chicane)
  - Re-inject the beam
- Recent work by Ferran Pousa *et al.* makes us of two-stage correction [Phys. Rev. Lett. 123, 054801 (2019)]:
  - Dechirping the energy spread by flipping the phase space.
  - Similar concept can increase energy stability [arXiv:2106.04177].
  - **Two stages: introduces a basic form of passive feedback.**
  - However, this works mainly for linear chirps (no beam loading).



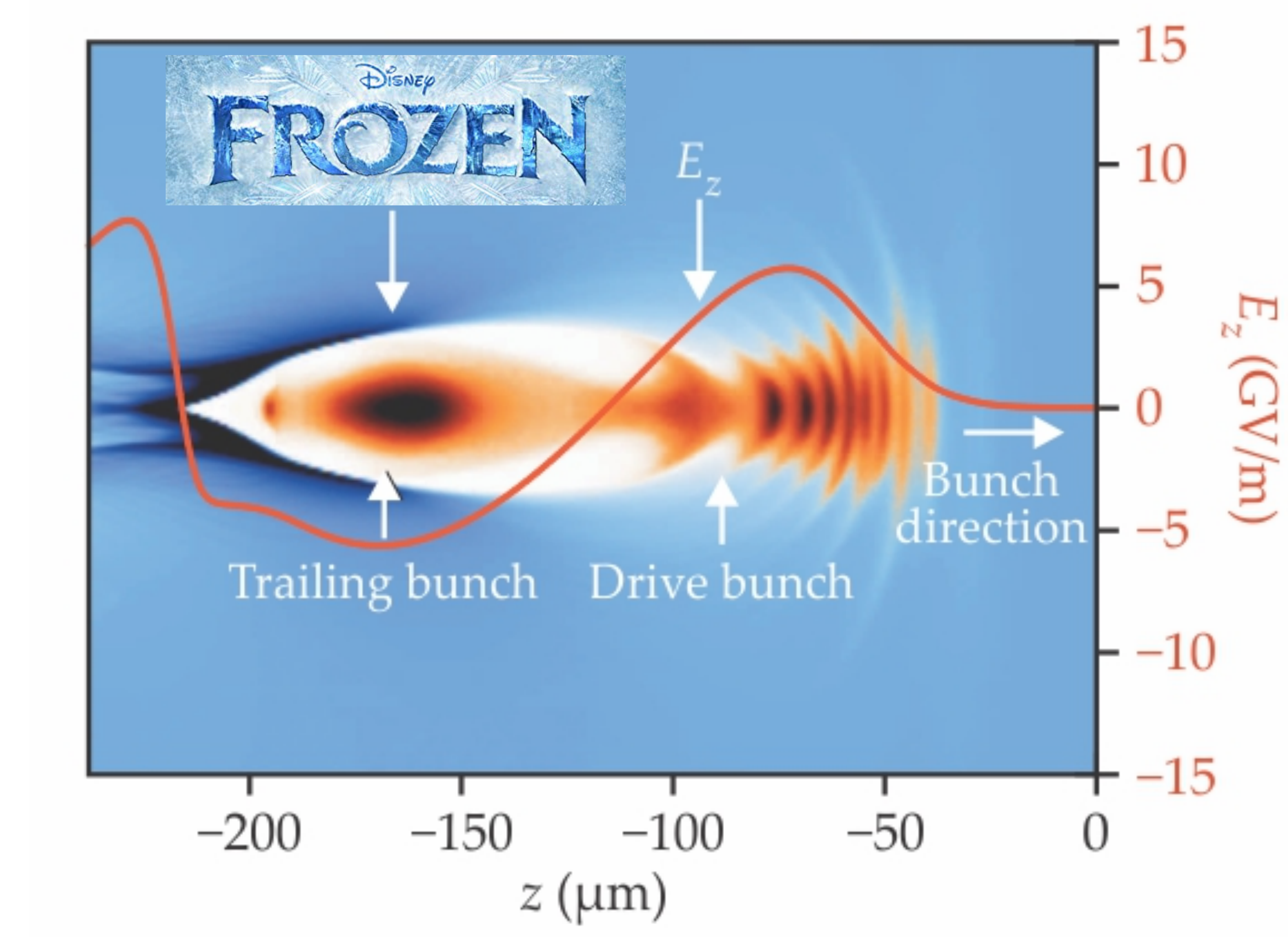
Source: Litos *et al.* [Nature 515, 92, (2014)]



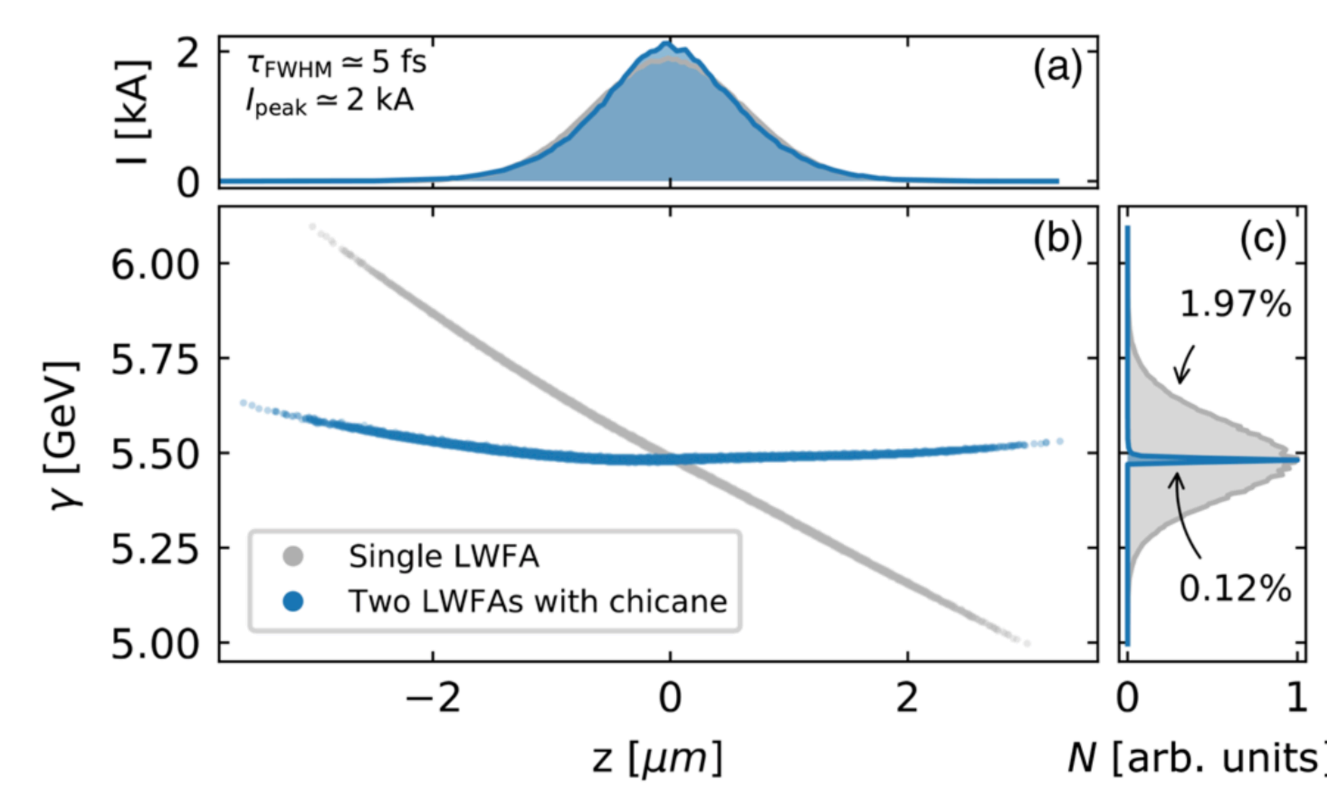
Source: Ferran Pousa *et al.* [Phys. Rev. Lett. 123, 054801 (2019)]

R_{56} AND FEEDBACK IN PLASMA ACCELERATORS

- **Practically no R_{56} within a plasma-accelerator stage**
  - On-axis, ultrarelativistic particles effectively *locked in place* longitudinally (not transversely).
  - Stops any feedback loop with the driver/wakefield.
- Feedback **requires multiple stages**:
  - Extract the beam
  - Apply R_{56} (with a magnetic chicane)
  - Re-inject the beam
- Recent work by Ferran Pousa *et al.* makes us of two-stage correction [Phys. Rev. Lett. 123, 054801 (2019)]:
  - Dechirping the energy spread by flipping the phase space.
  - Similar concept can increase energy stability [arXiv:2106.04177].
  - **Two stages: introduces a basic form of passive feedback.**
  - However, this works mainly for linear chirps (no beam loading).

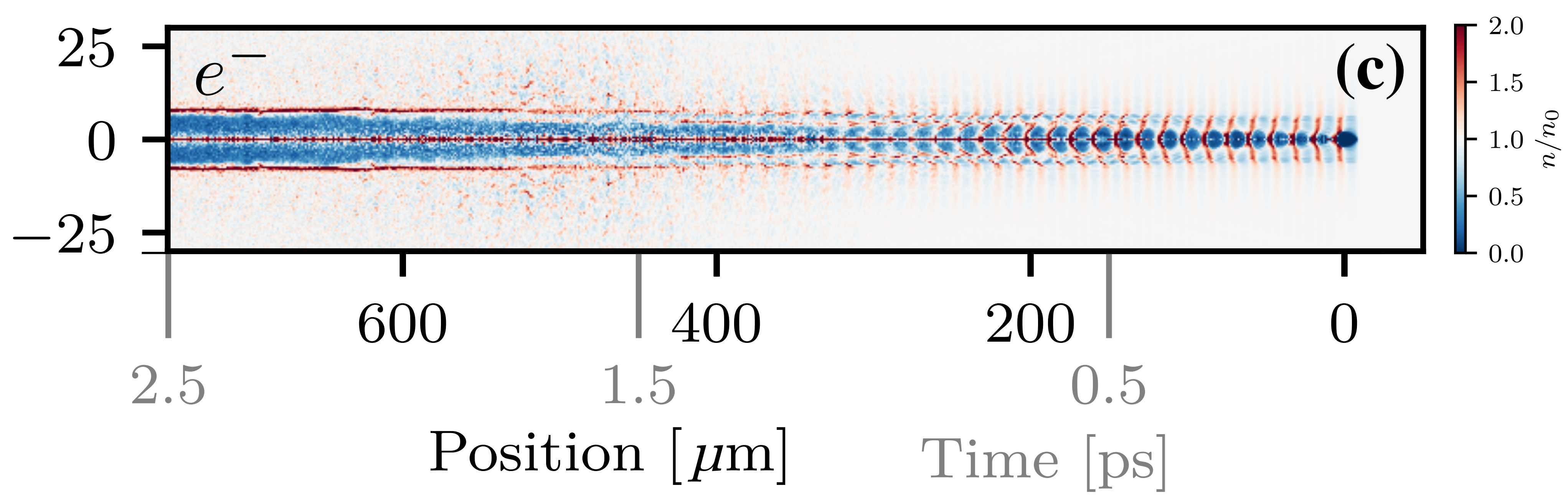


Source: Litos *et al.* [Nature 515, 92, (2014)]

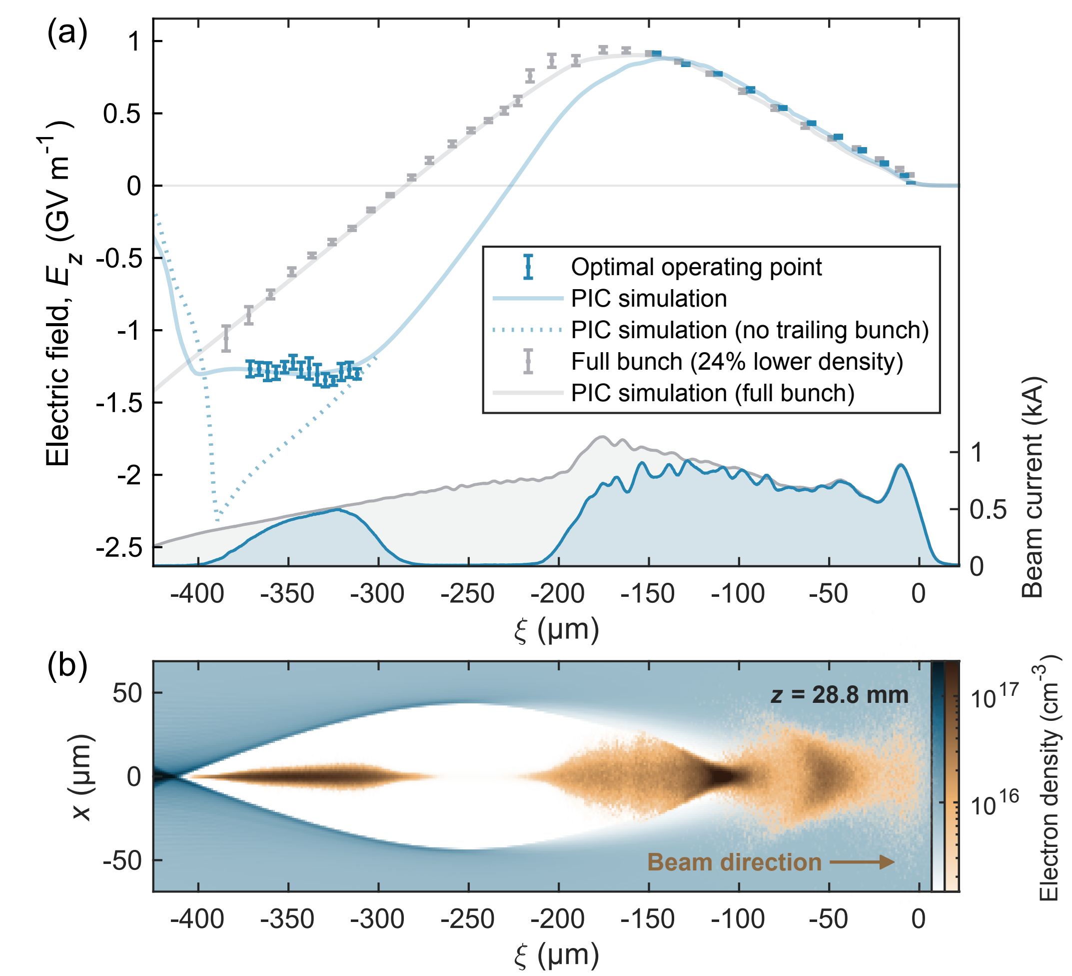


Source: Ferran Pousa *et al.* [Phys. Rev. Lett. 123, 054801 (2019)]

BEAM LOADING AND NONLINEAR FIELDS



Source: Gilljohann *et al.* [Phys. Rev. X 9, 011046 (2019)]



Source: Lindstrøm *et al.* [Phys. Rev. Lett. 126, 014801 (2021)]

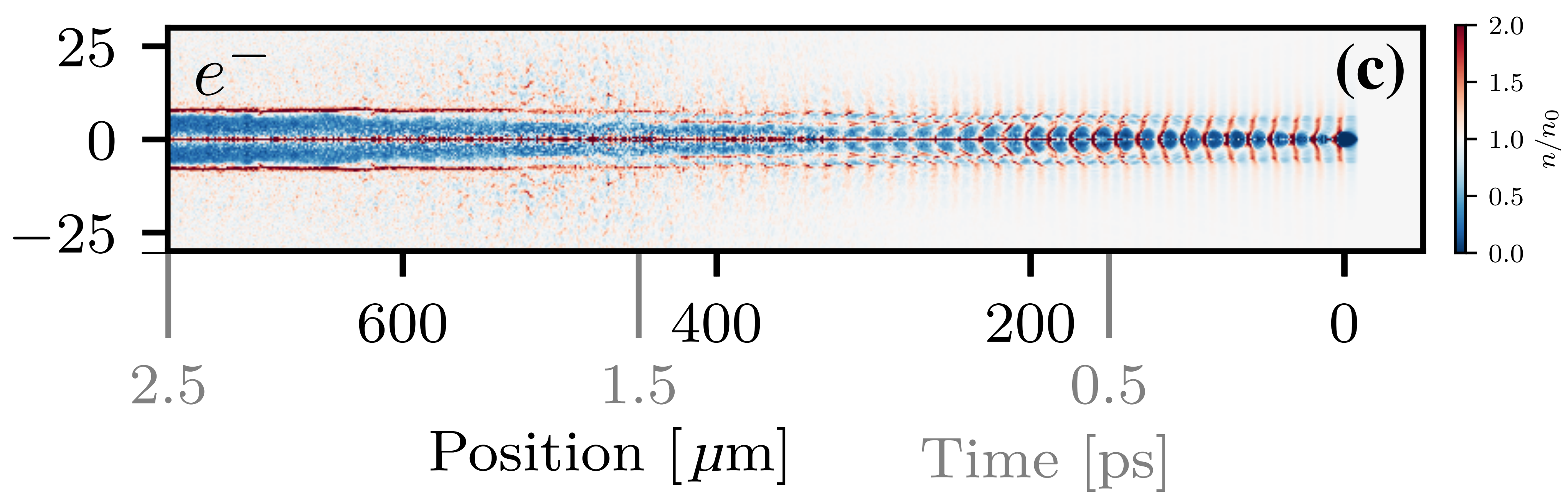
> High-power applications (linear colliders, FELs) require energy efficiency.

> Plasma wakes decay rapidly: must extract energy within the ~first bucket
⇒ **beam loading**

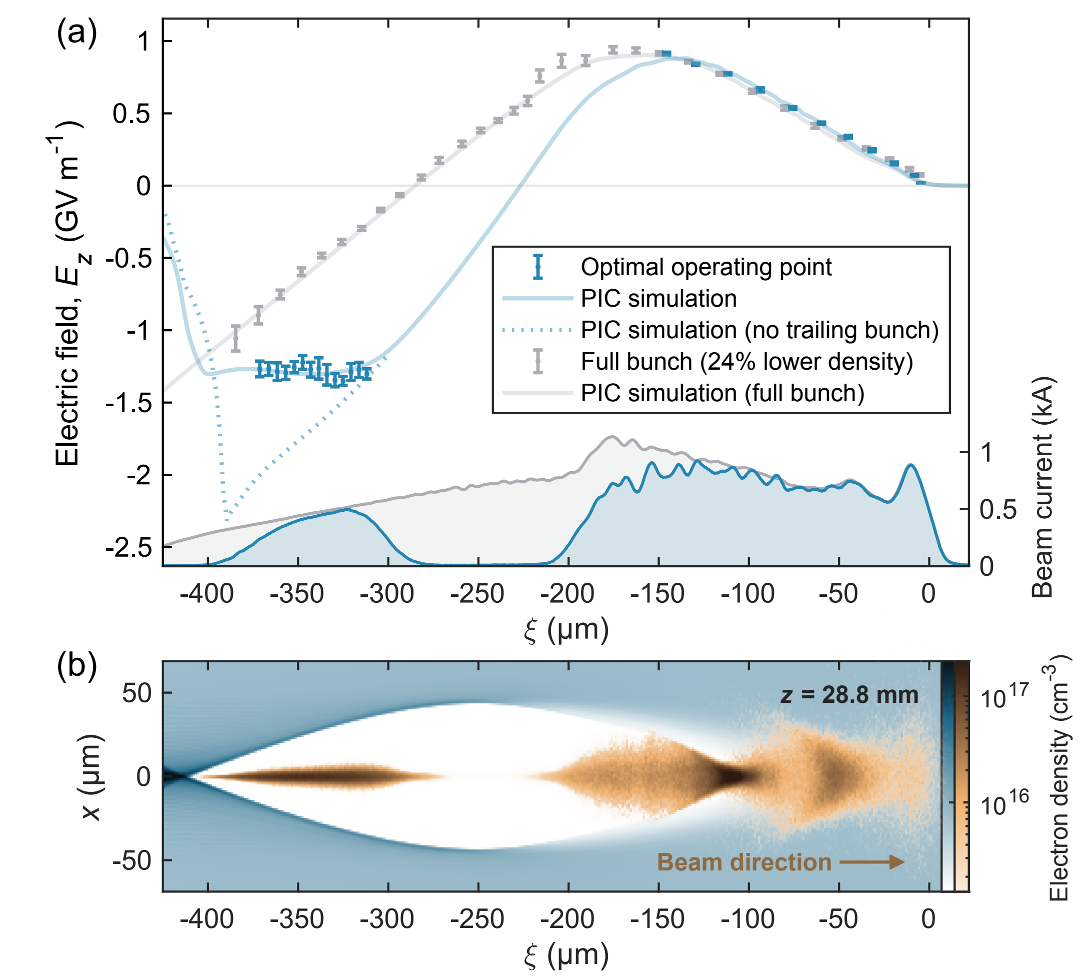
> Introduces a nonlinear wakefields that depend on the current profile of the bunch.

> > Can achieve low energy spread through current-profile shaping.

Beam loading and nonlinear fields



Source: Gilljohann *et al.* [Phys. Rev. X 9, 011046 (2019)]



Source: Lindstrøm *et al.* [Phys. Rev. Lett. 126, 014801 (2021)]

> High-power applications (linear colliders, FELs) require energy efficiency.

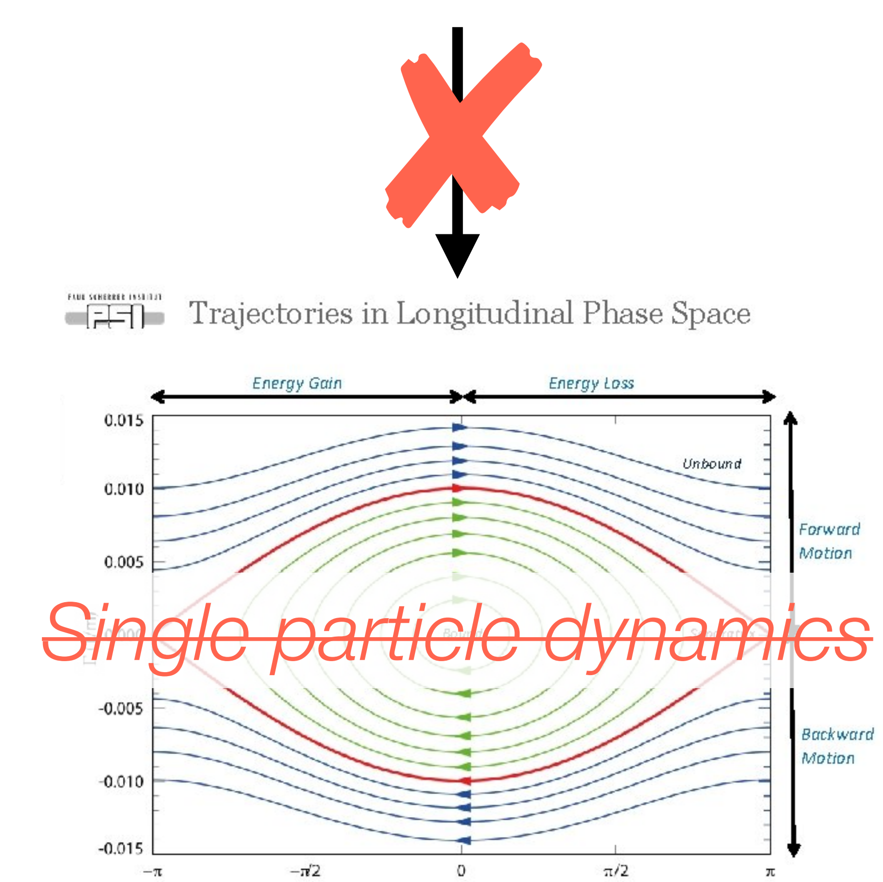
> Plasma wakes decay rapidly: must extract energy within the ~first bucket
⇒ **beam loading**

> Introduces a nonlinear wakefields that depend on the current profile of the bunch.

> > Can achieve low energy spread through current-profile shaping.

> ***Problem:*** **Beam loading breaks the usual mechanism of phase stability.**

> **Need a generalized (*collective-effect*) version for both phase stability and energy-spread stability**



Source: Paul Scherrer Institute (PSI)

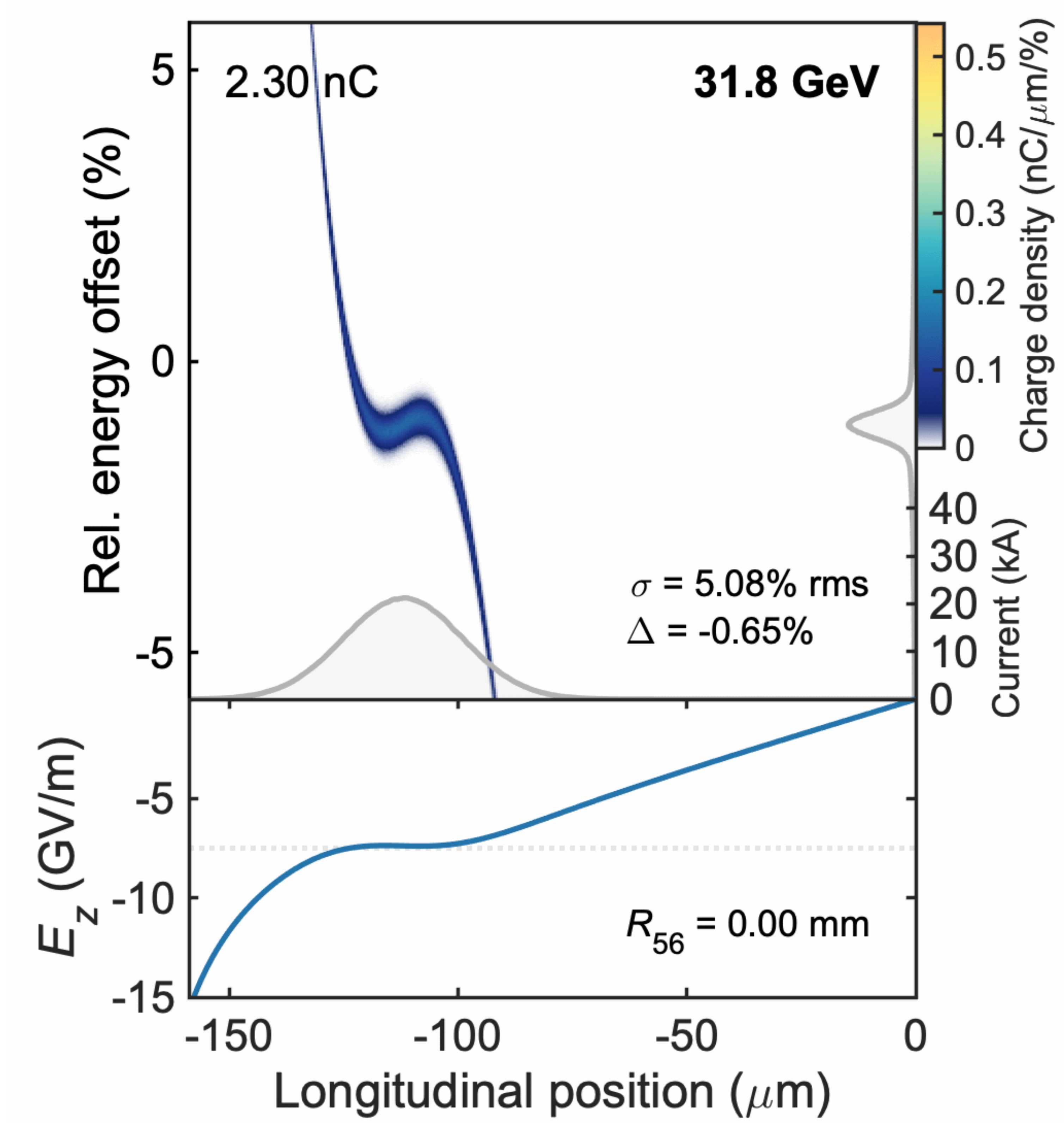
PART 2:
PASSIVE STABILIZATION WITH A MANY STAGES

Preprint: Lindstrøm, arXiv:2104.14460 (2021)

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

BASELINE:
No R_{56} — no correction mechanism

Starts at 10 GeV



245 stages

2 GeV per stage

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

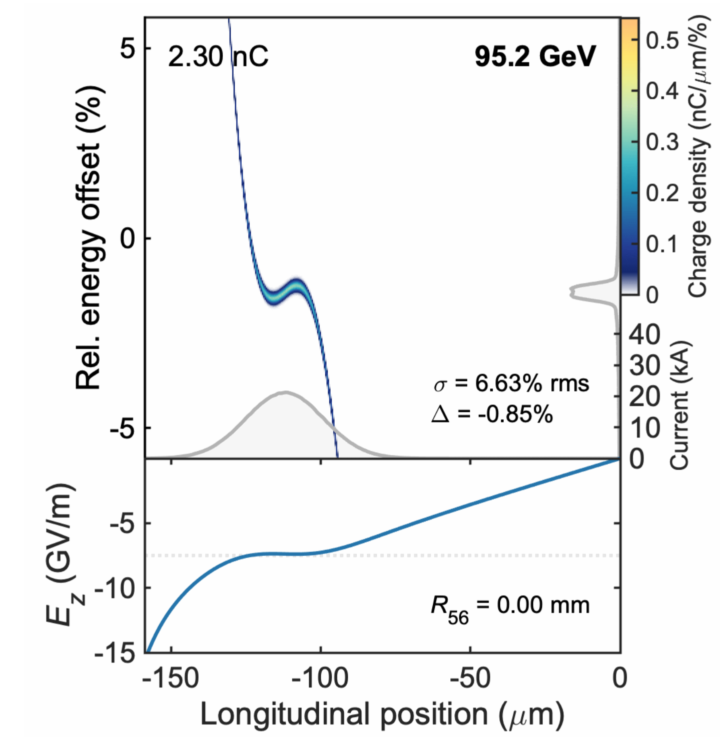
1D SIMULATIONS BASED ON 3D WAKEFIELDS

- Need **exaflops of computing power** to simulate 100+ stages in 3D.
- In a blowout, we can **treat longitudinal and transverse phase spaces as separate.**
- However, we can approximate 3D using the 1D Lu equation:

$$r_b \frac{d^2 r_b}{d\xi^2} + 2\left(\frac{dr_b}{d\xi}\right)^2 + 1 = \frac{2}{\pi n_0 r_b^2} \frac{dN_d}{d\xi},$$

$$E_{\|} = -2\pi n_0 e r_b \frac{dr_b}{d\xi}.$$

- Improved multi-sheath model (used here) [Dalichaouch *et al.*, Phys. Plasmas 28, 063103 (2021)]
- *An idealized scenario—lets us explore the mechanism.*



Define initial longitudinal phase space

Calculate the electric field using the Lu equation
(based on the current profile)

Accelerate particles in wakefield
(based on z-location)

Compress bunch in chicane
(based on energy)

THE SETUP

Large number of stages

+

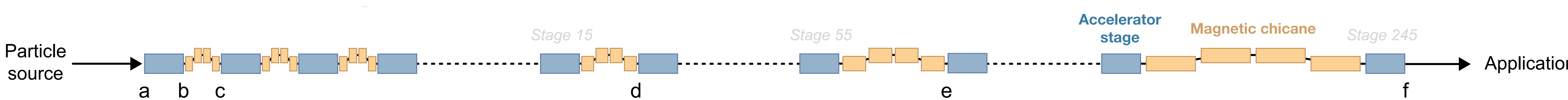
Magnetic chicanes between stages

+

Beam loading

"Linear synchrotron"

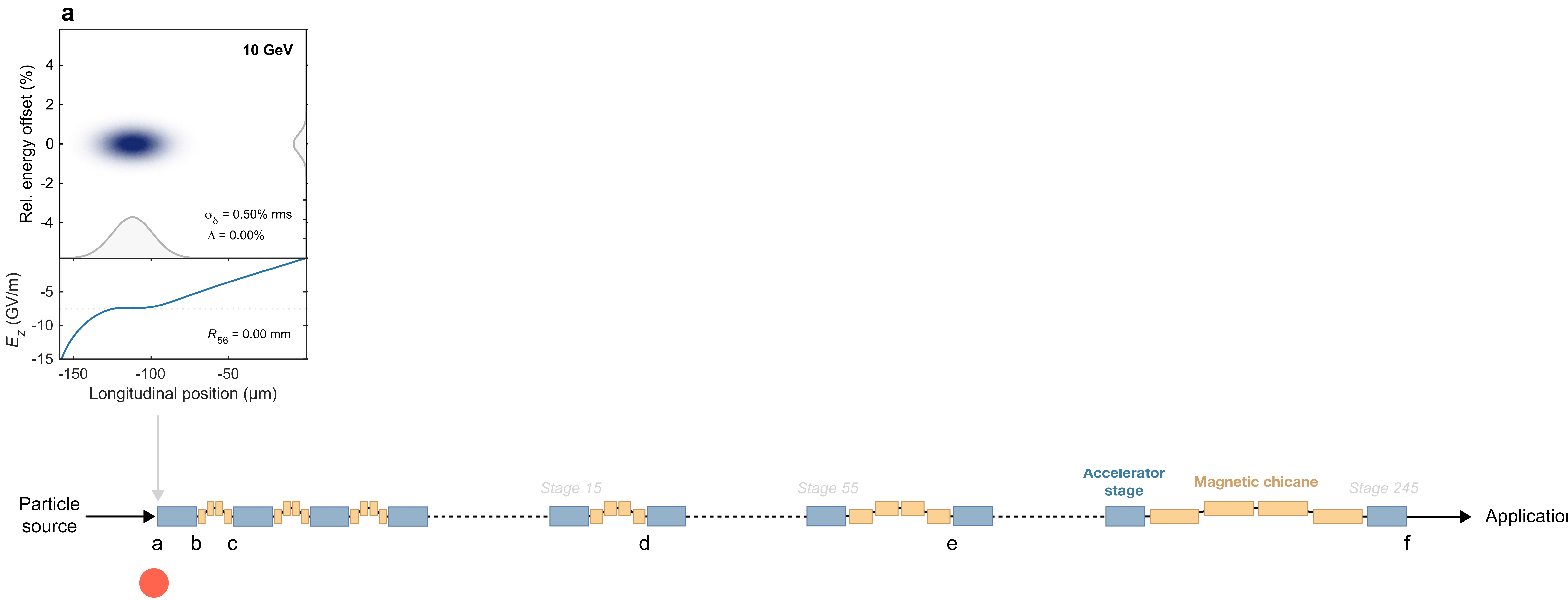
New part



Assuming: Preserved transverse phase space

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

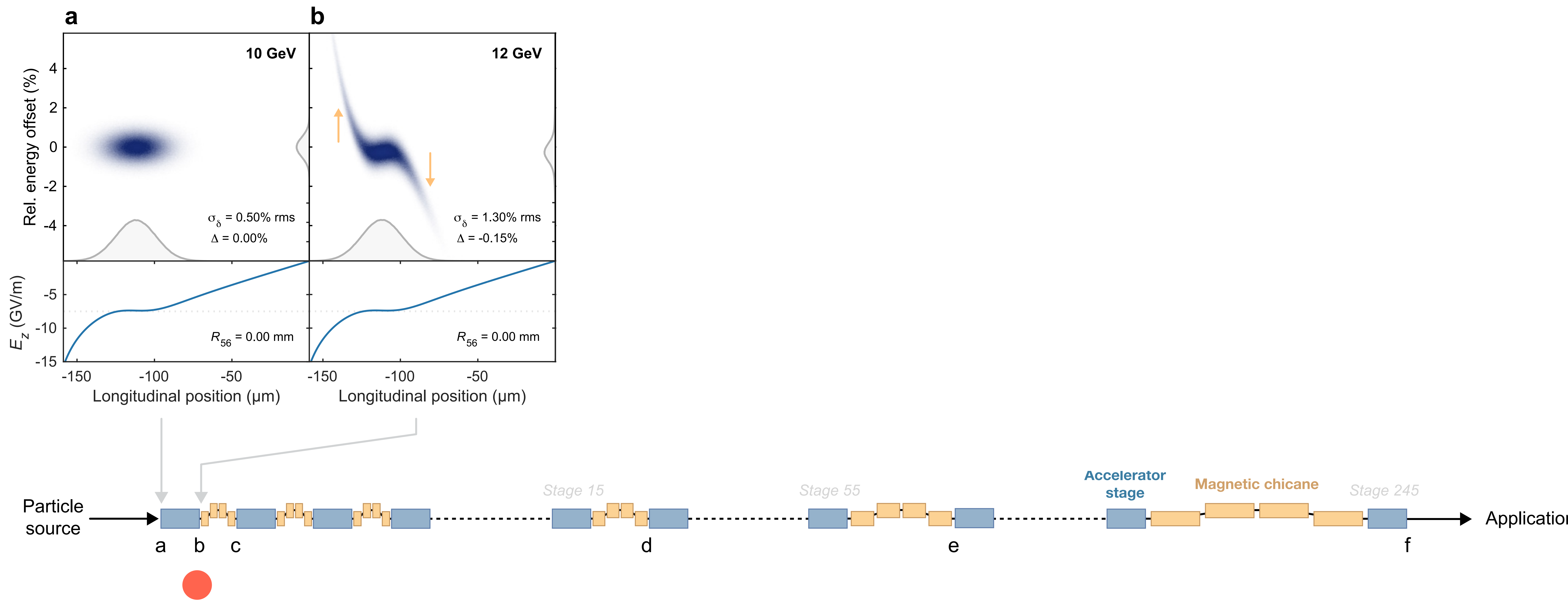
A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE



Start:

Initial particle distribution

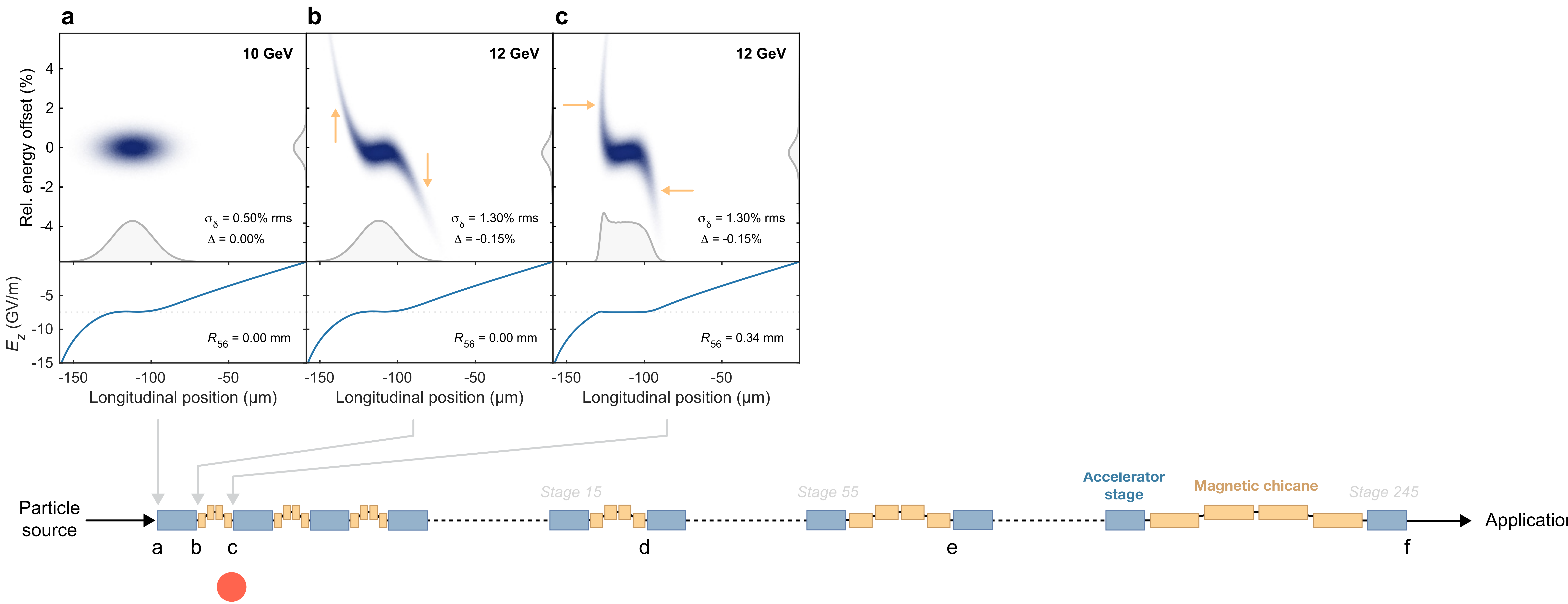
A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE



Plasma accelerator stage:

Particles gain energy based on their position

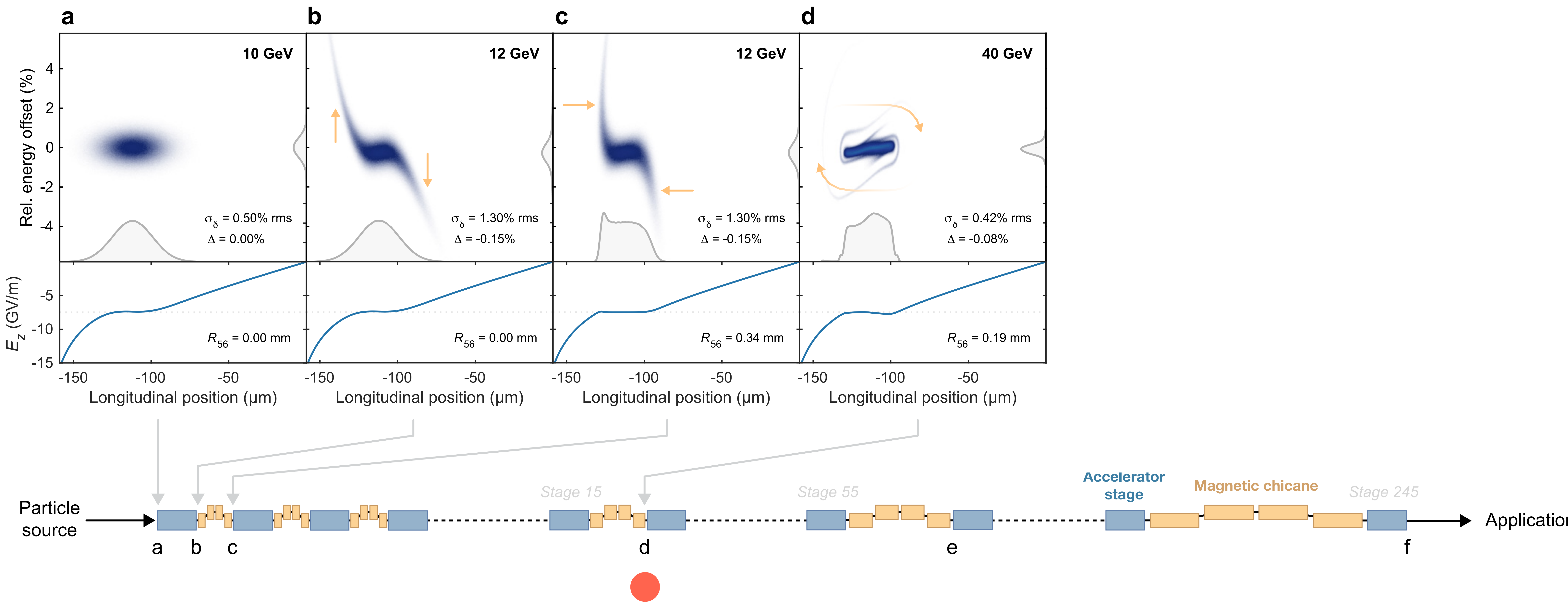
A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE



Magnetic chicane:

Move particles longitudinally based on energy offset

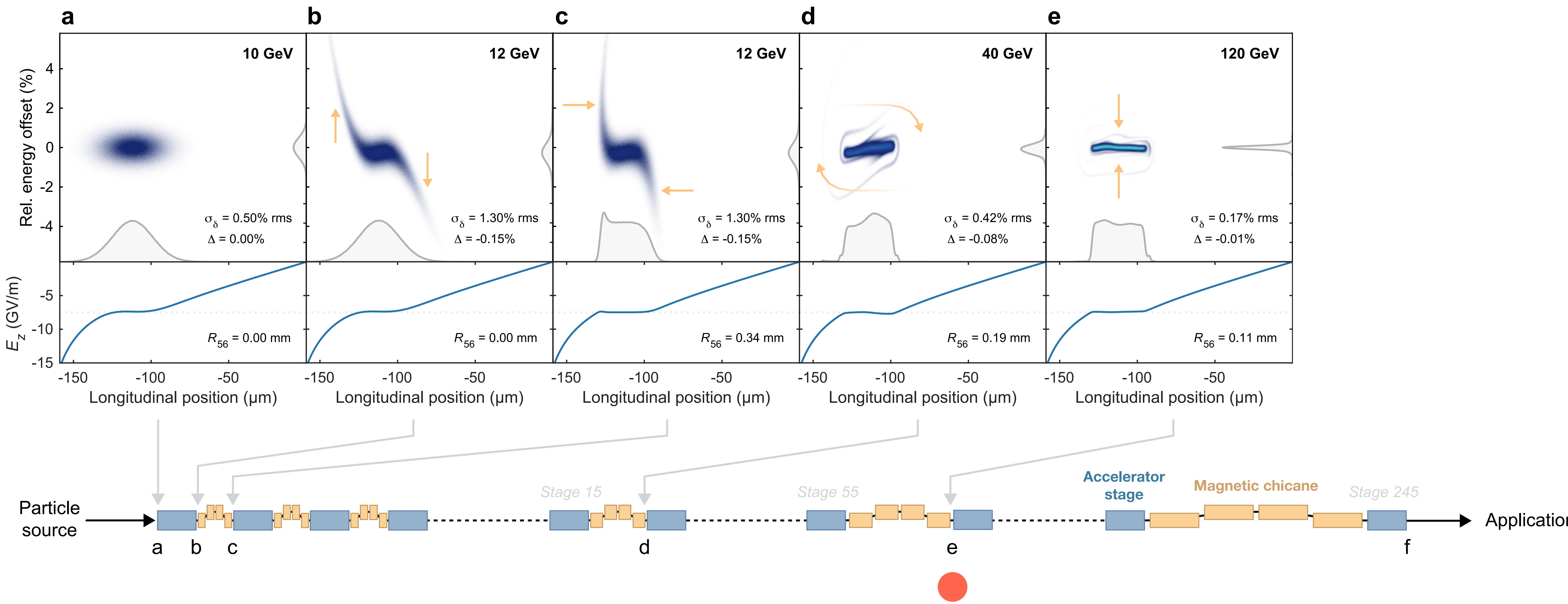
A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE



Several stages:

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

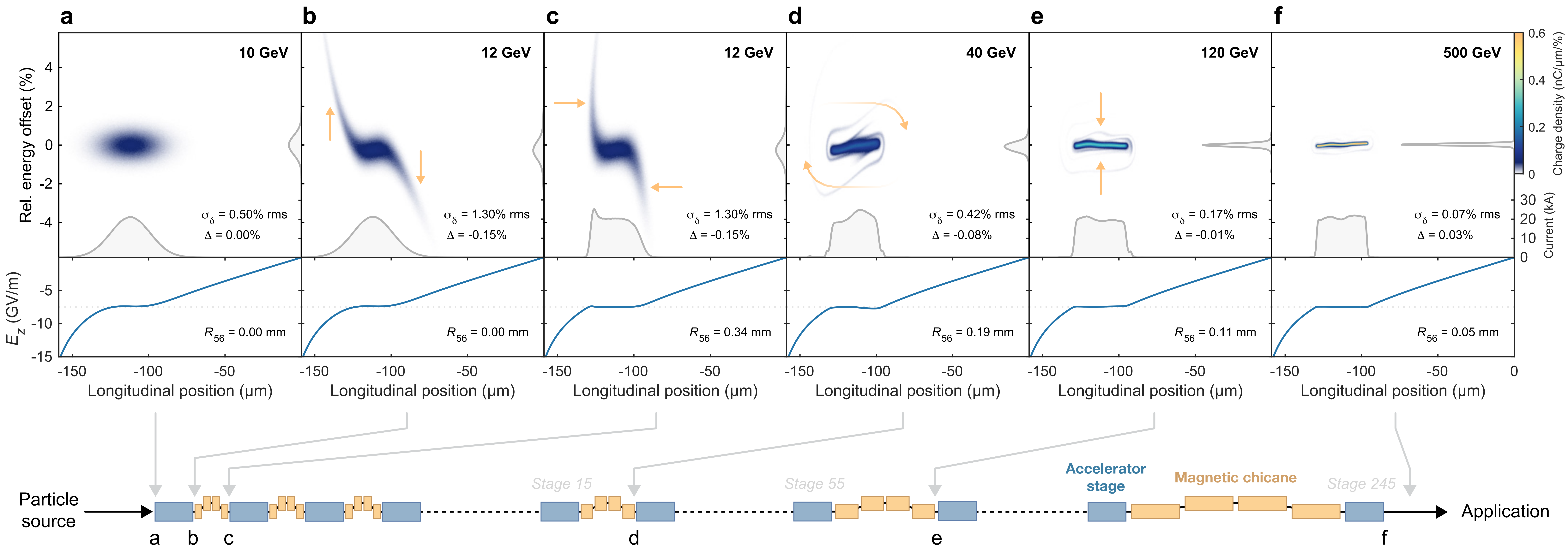
A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE



More stages:

Relative energy spread and offsets damped with energy gain

A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE

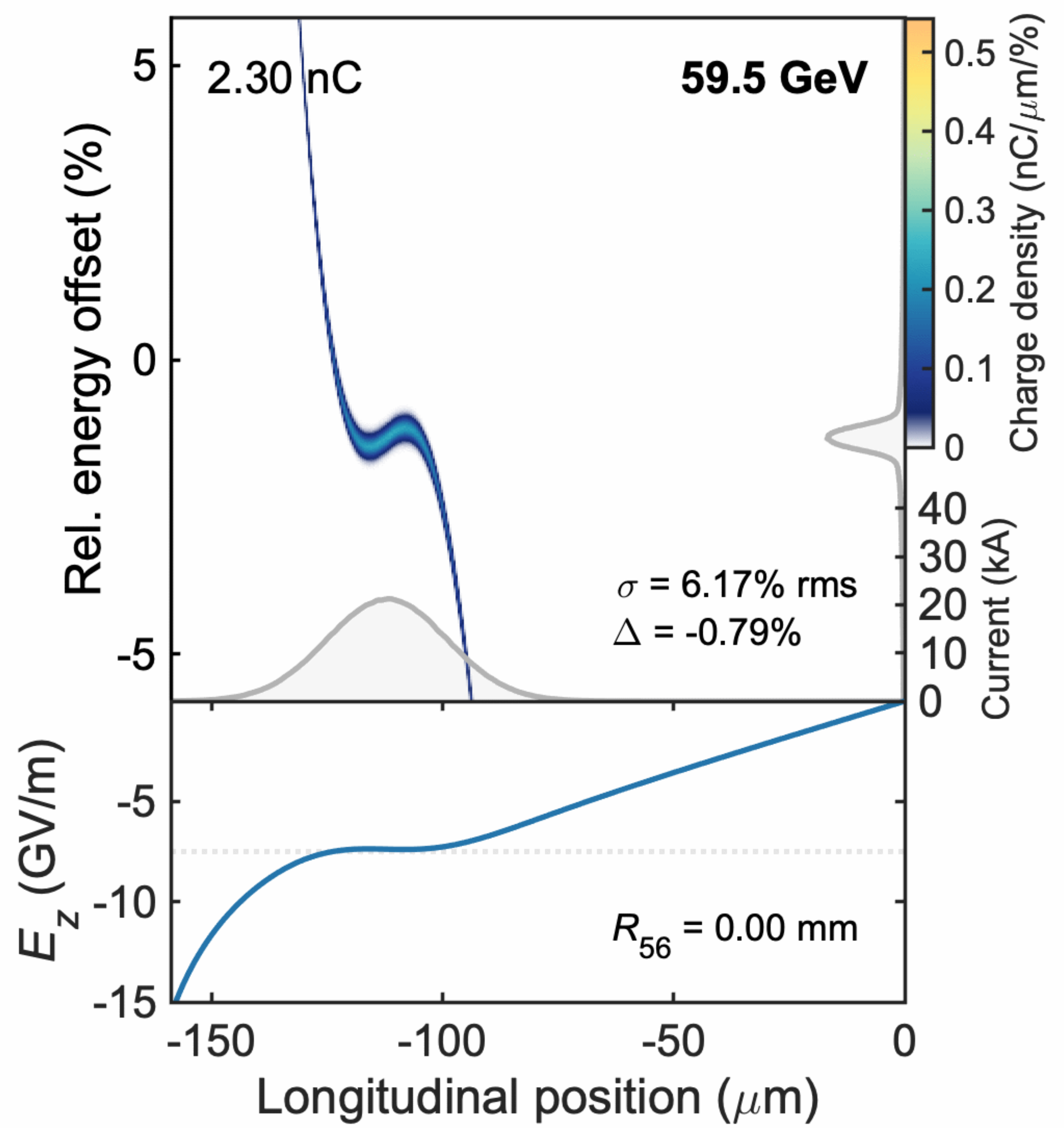


End result:

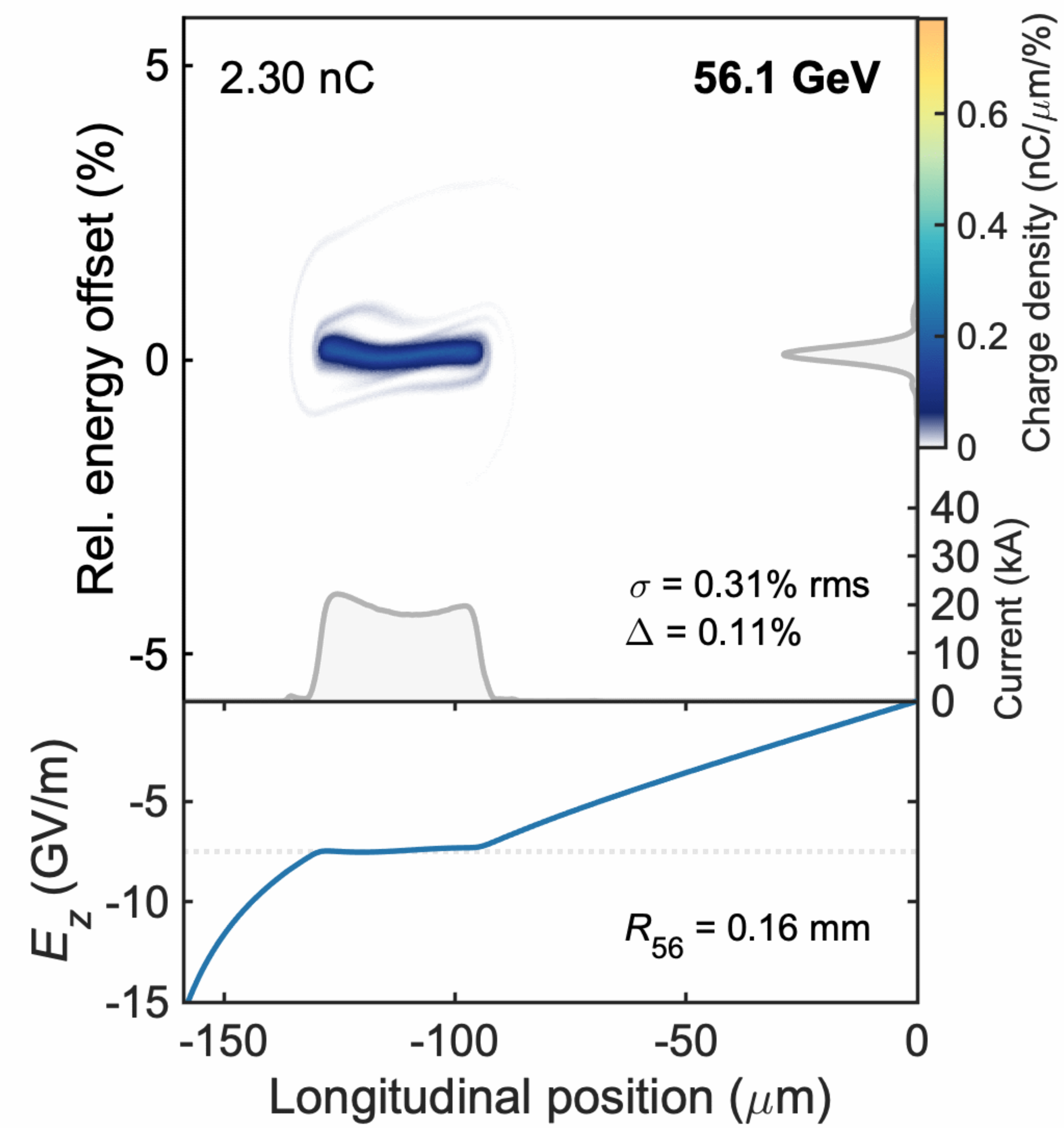
Optimal current profile, flattened wakefield low energy spread, small energy offset

A SELF-CORRECTION MECHANISM IN LONGITUDINAL PHASE SPACE

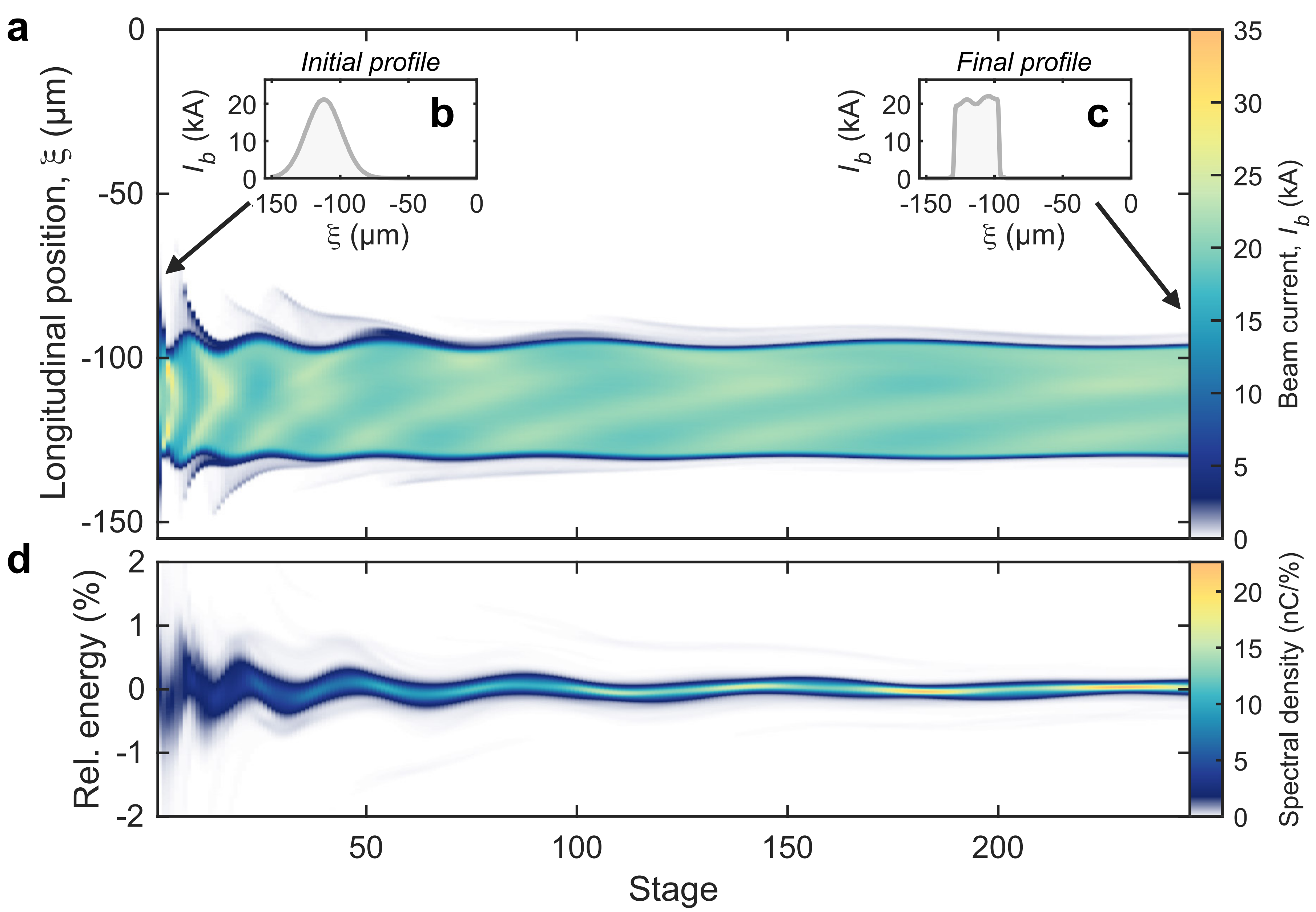
No R_{56}—no correction
(same as before)



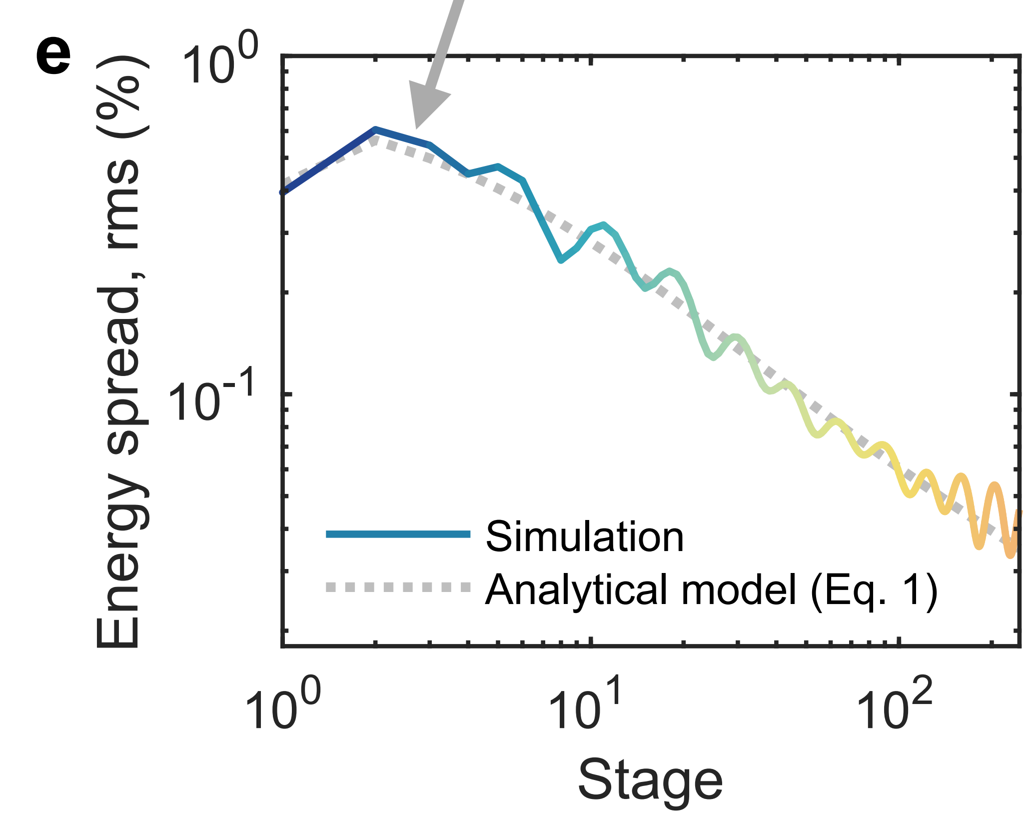
With multistage correction

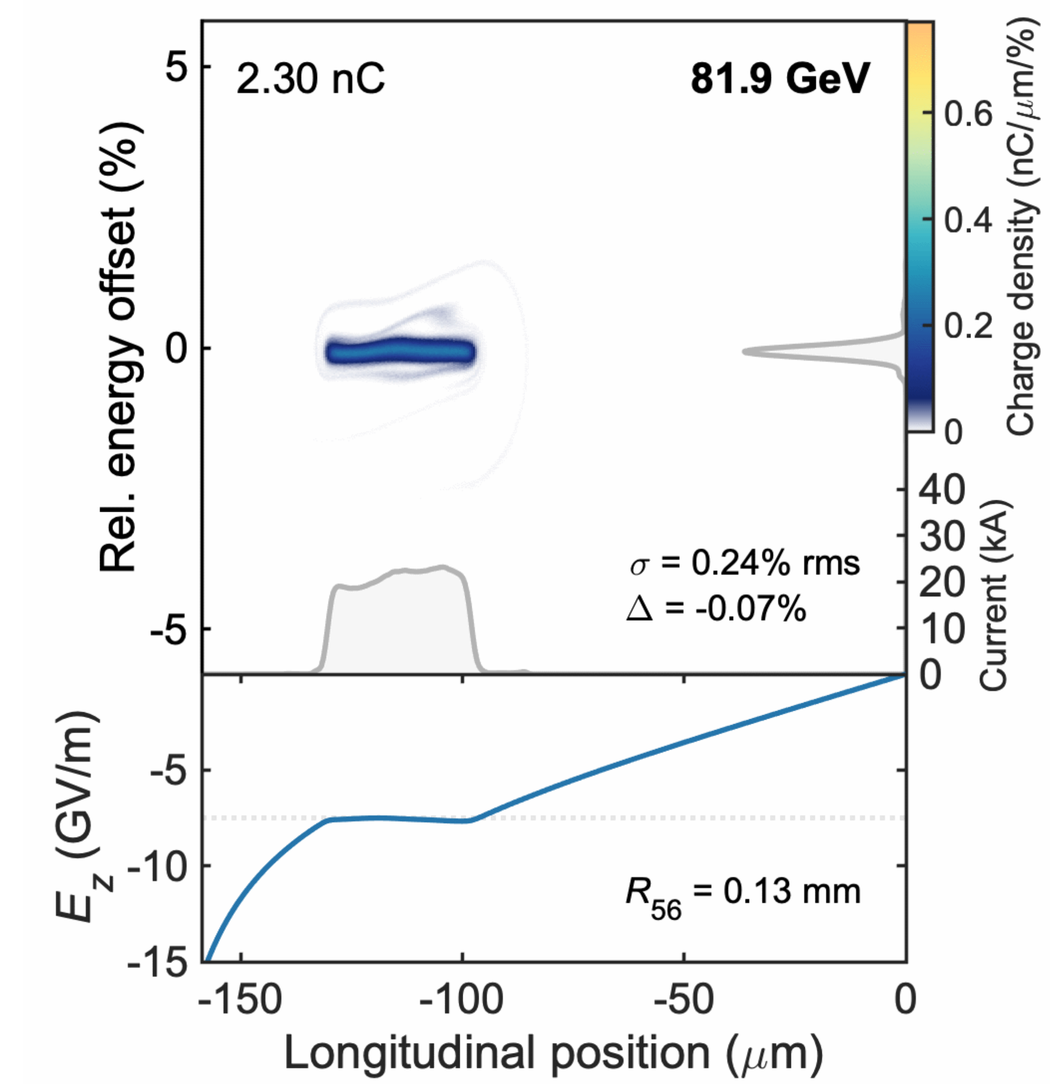


SELF-MATCHING IN THE LONGITUDINAL PHASE SPACE



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

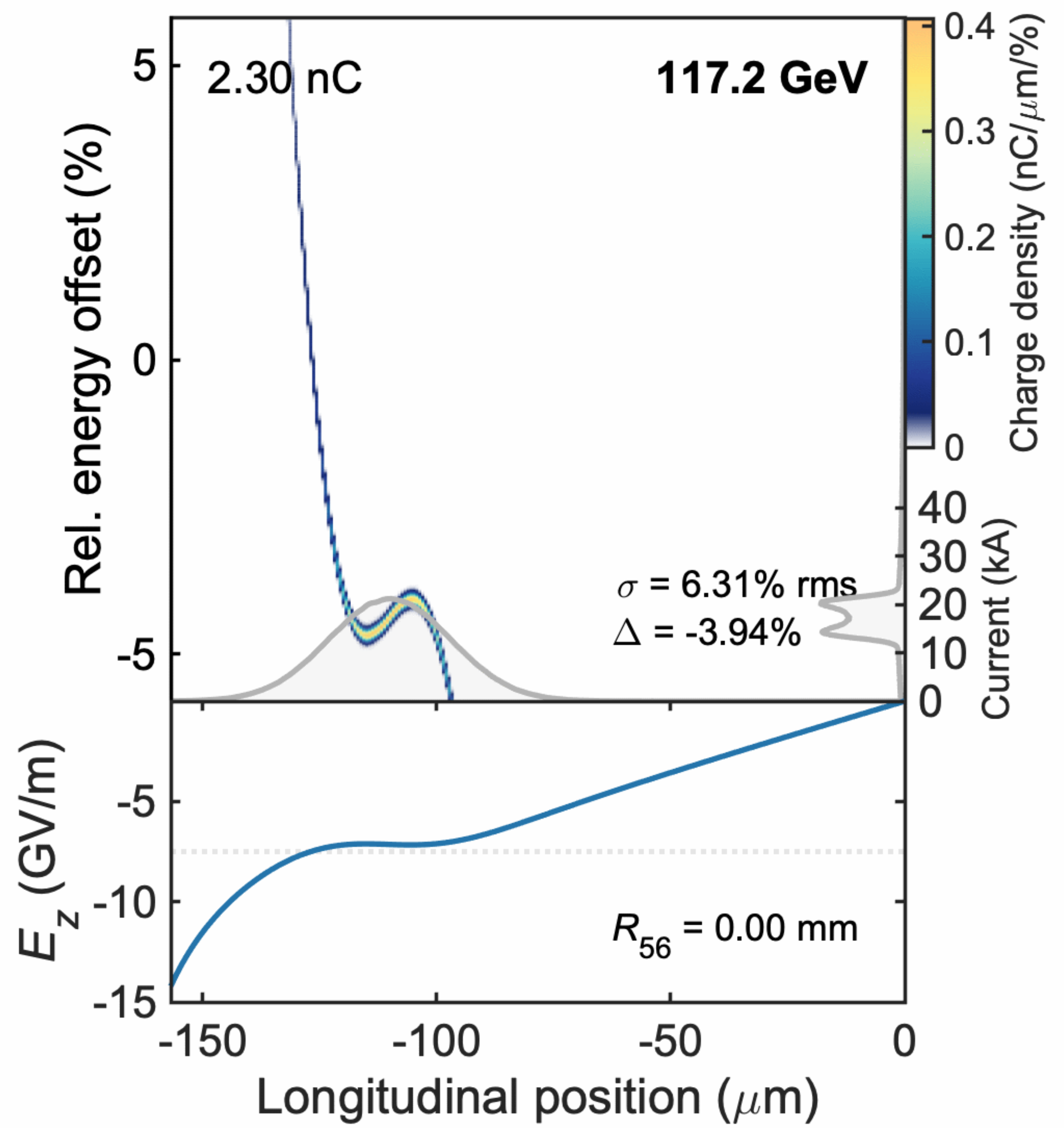
  > **Relative energy spread** (and rel. longitudinal emittance) **is eventually damped** with acceleration

RESULT:

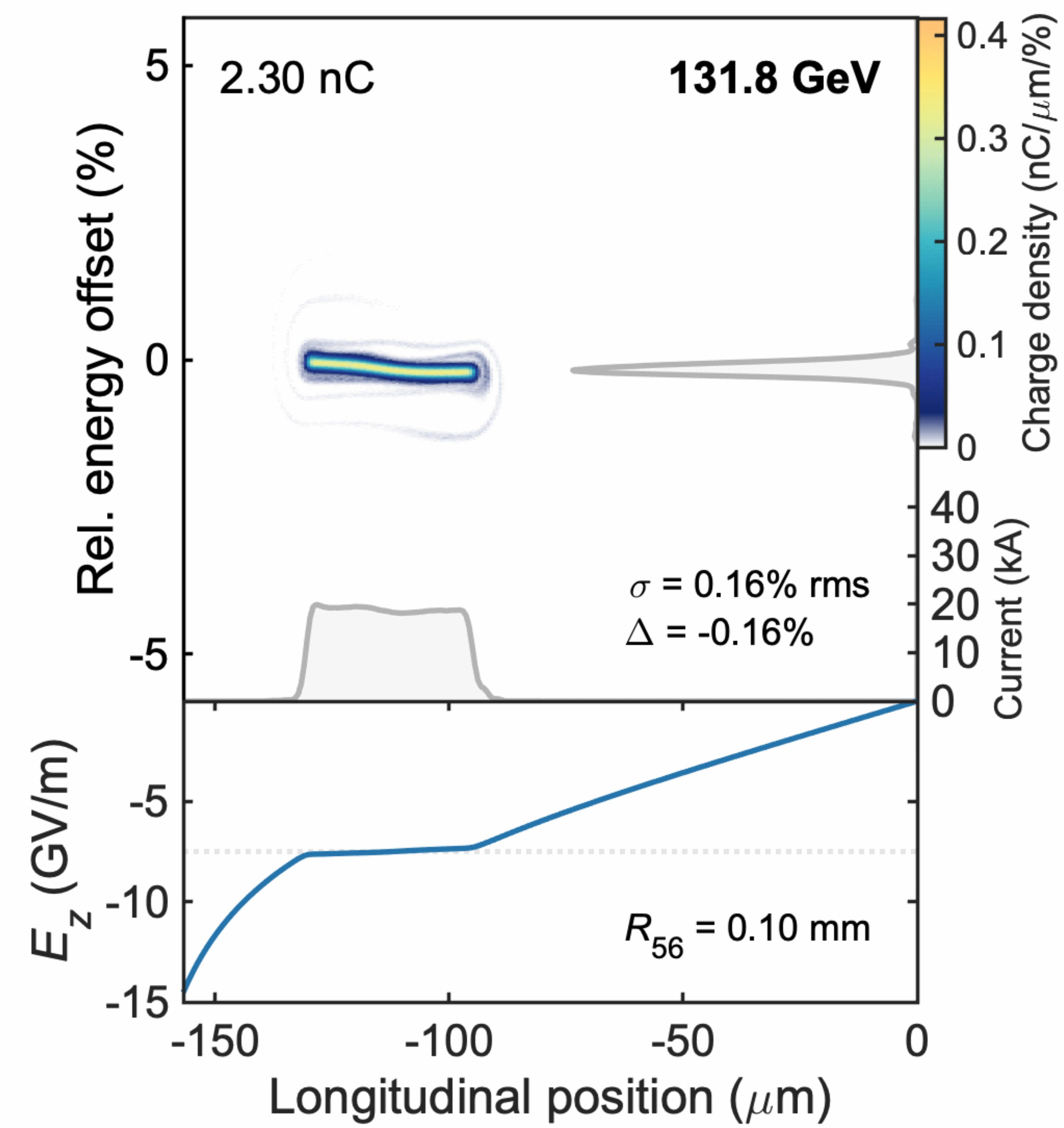
IMPROVED TOLERANCES

EXAMPLE #1: BUNCH INJECTED TOO EARLY (10 FS)

No correction

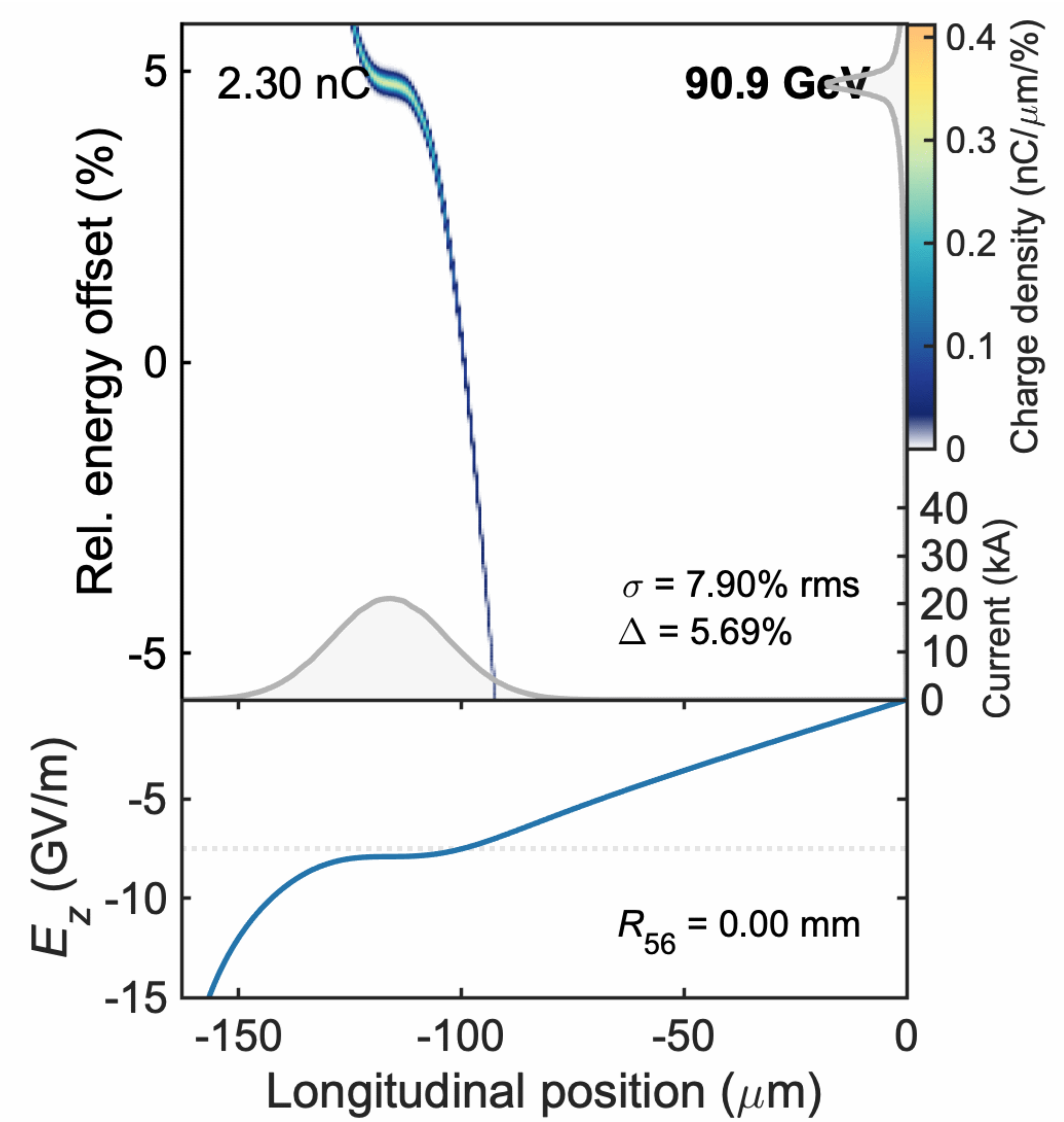


With multistage correction

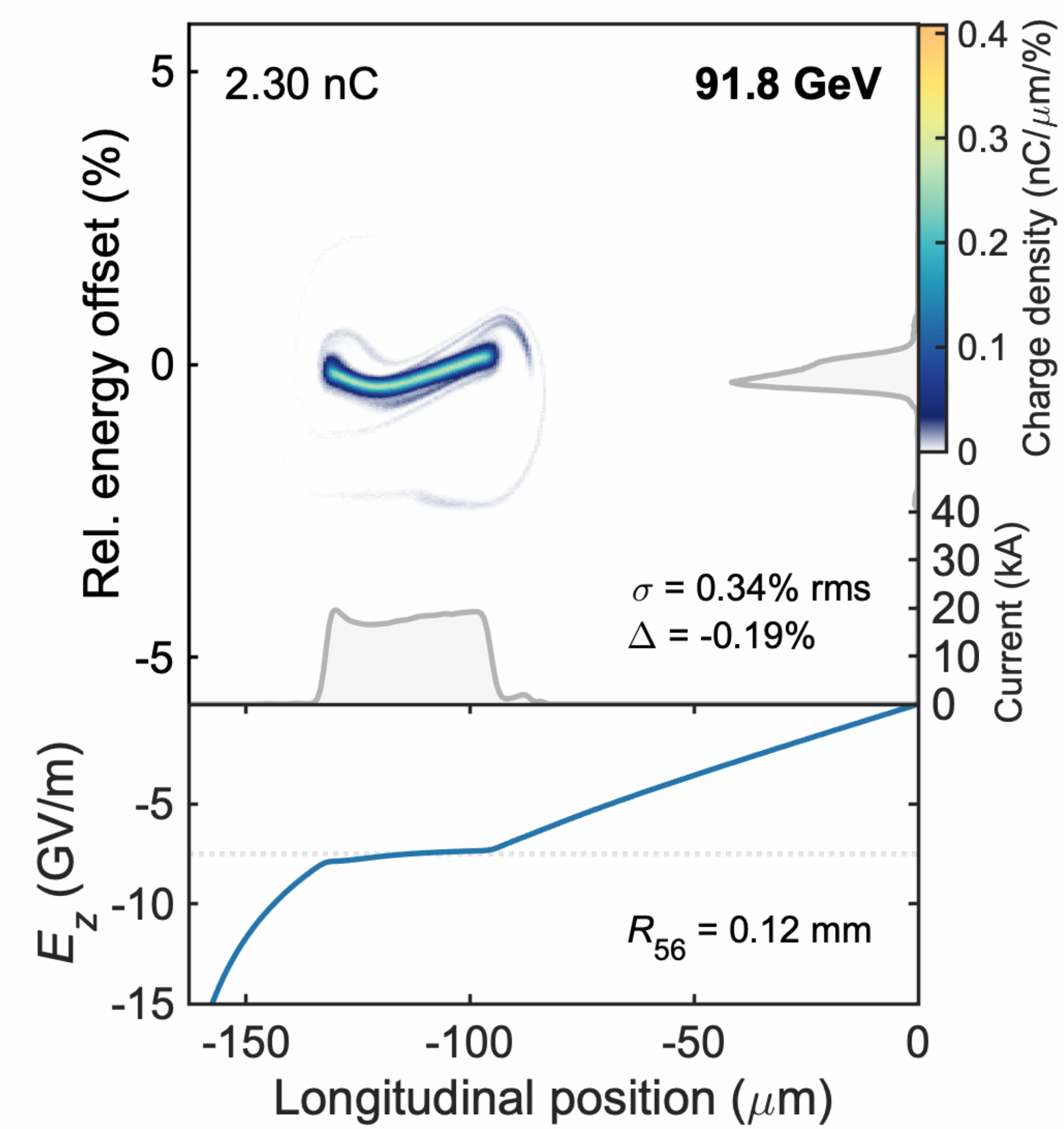


EXAMPLE #2: **BUNCH INJECTED TOO LATE (10 FS)**

No correction



With multistage correction



Timing tolerances improve dramatically

> Scan of injection timing/phase

> *Timing tolerance in this example:*

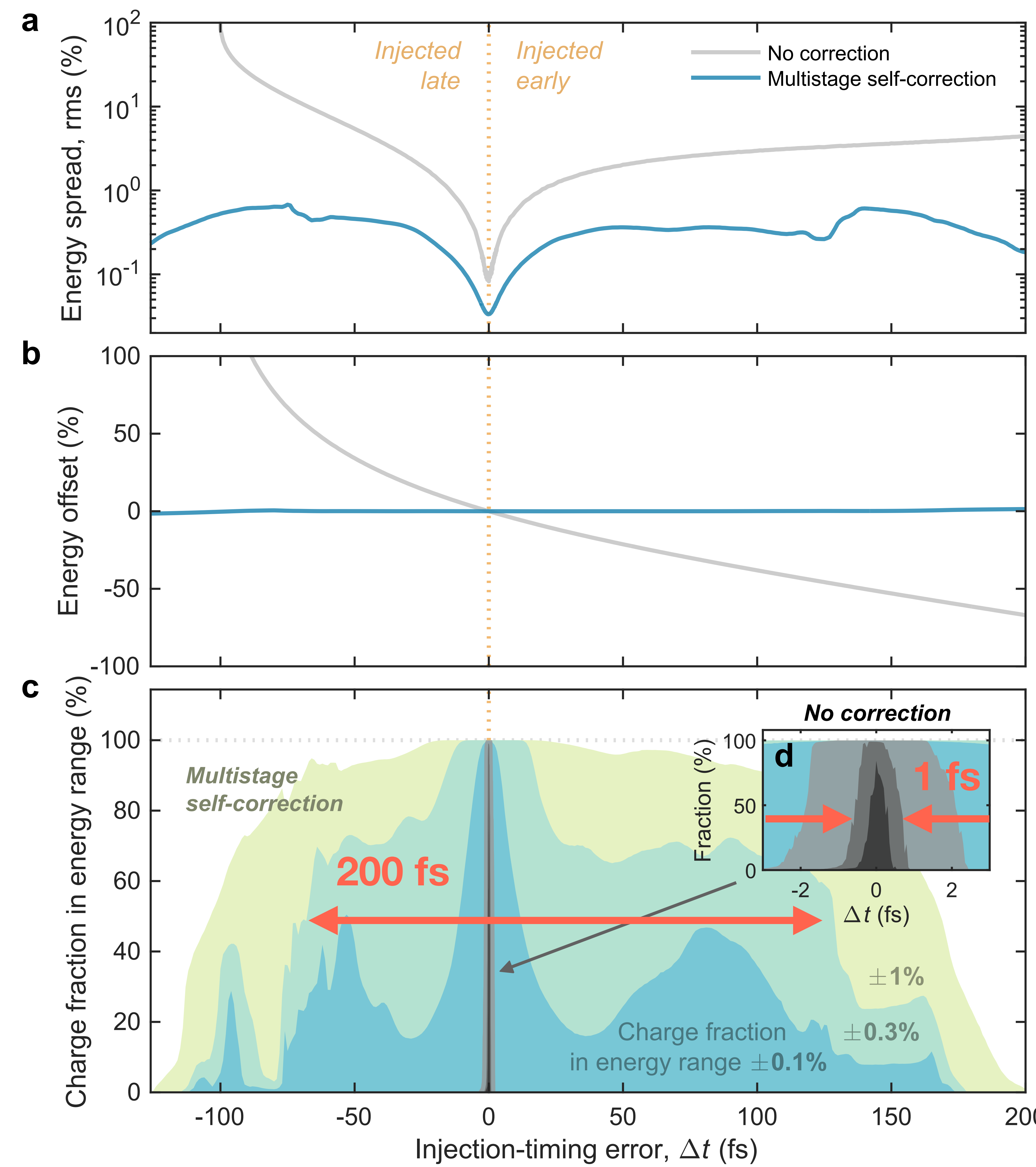
  > Assuming 0.3% FWHM energy acceptance.

  > ~1 fs FWHM without correction

  > **~200 fs FWHM with self-correction.**

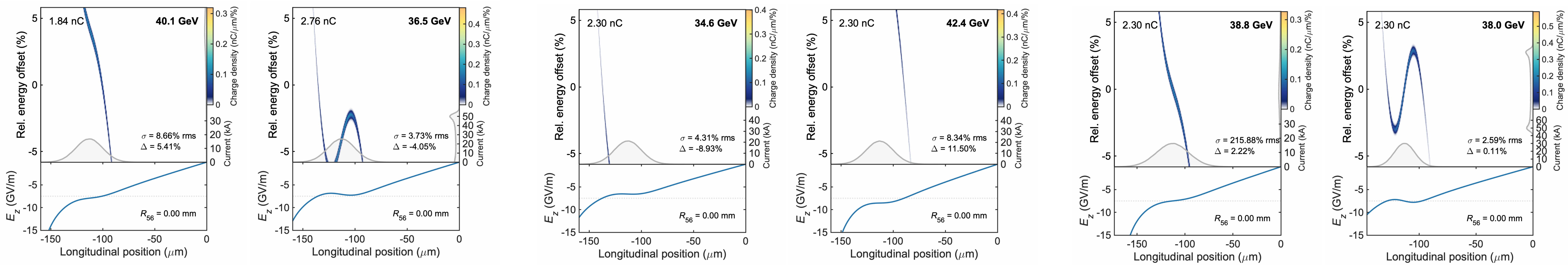
> Orders of magnitude improvement

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



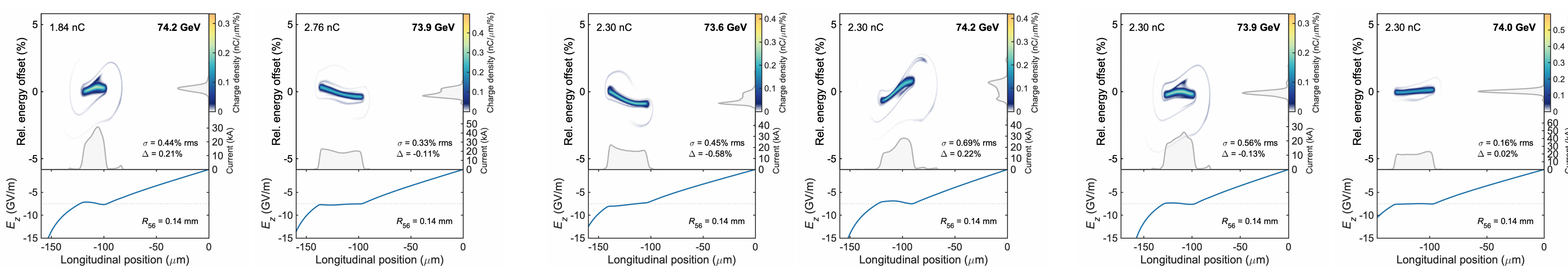
IMPROVED TOLERANCES, ACROSS THE BOARD

Lower charge | **Higher charge** | **Lower density** | **Higher density** | **Too long** | **Too short**



No correction

Multistage correction



Conclusions

Preprint: [Lindstrøm, arXiv:2104.14460 (2021)]

- **Tight tolerances**—a major challenge for plasma accelerators
- **Passive stabilization**: stabilizing the acceleration process itself
  - Plasma accelerators lack R_{56} for feedback—likely requires staging.
  - Beam loading required for efficiency—conventional phase stability not possible.
- **Multistage plasma accelerator separated by magnetic chicanes:**
  - Feedback between the current profile and the wakefield shape.
  - Redistributes charge to self-correct any mismatch in longitudinal phase space.
  - Energy spreads and offsets are damped with acceleration.
  - Dramatic improvement in tolerances, across all parameters.
- **Many open questions**:
  - Ion motion? (i.e., transversely nonuniform focusing and acceleration)
  - Is complete 6D damping possible? (including transverse radiation damping)
  - Good staging? (achromatic, emittance-preserving and compact)
  - How to implement this experimentally?