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Staging and temporal tolerances

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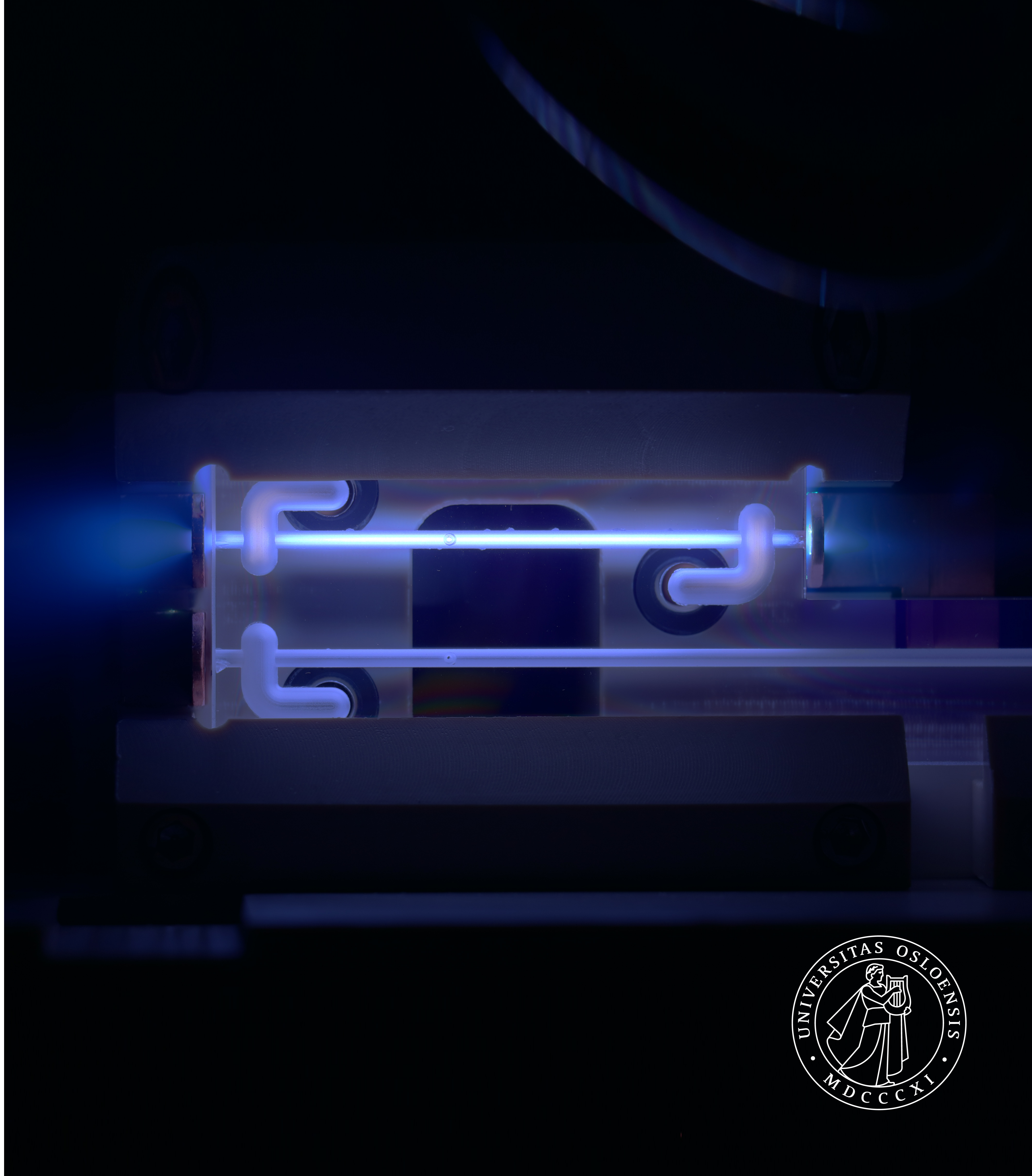
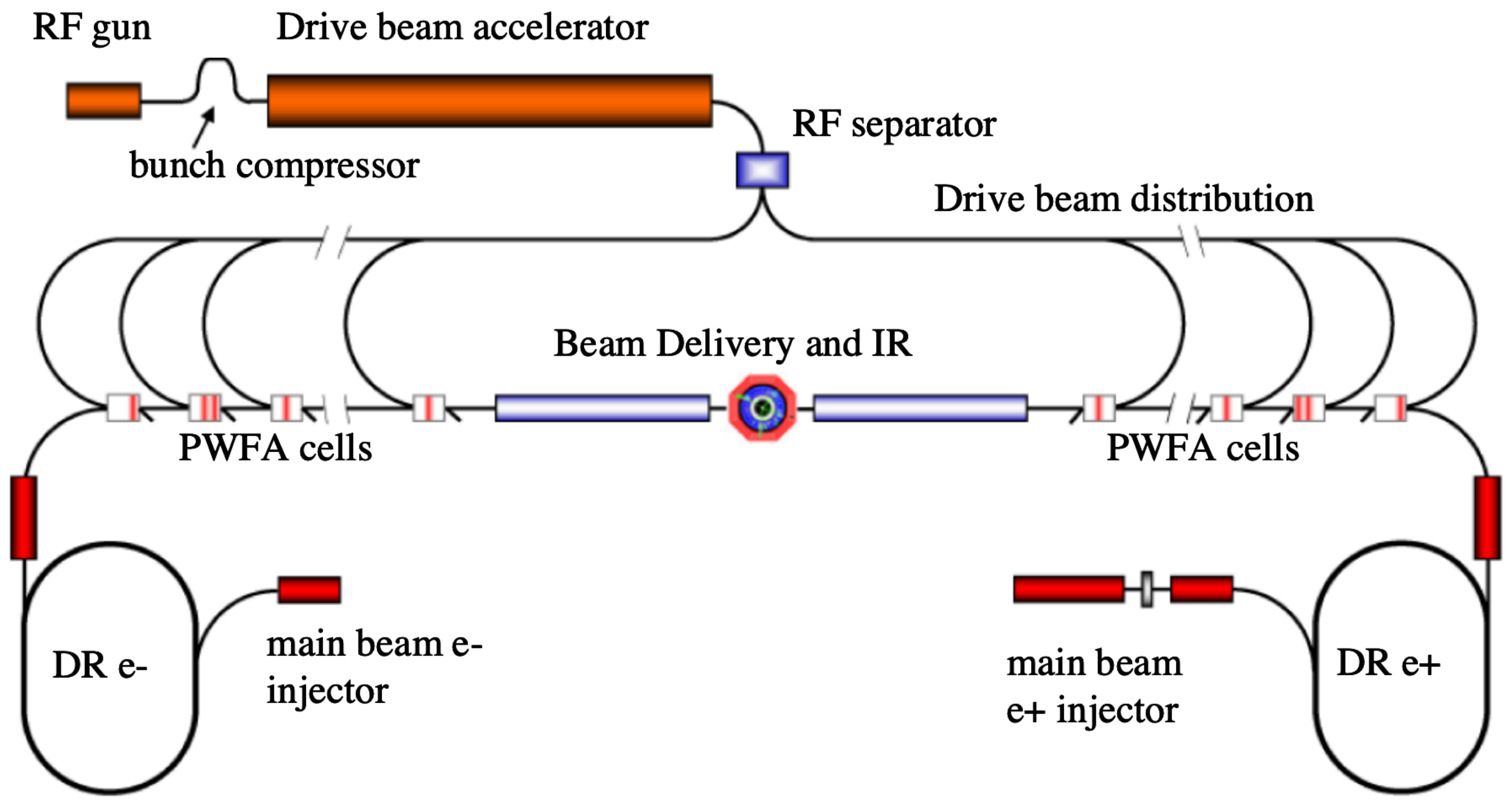


Goal: High energy, compact, high energy efficiency

- **High particle energy required by several high-impact applications:**
  - Hard x-ray FEL: 10+ GeV
  - Higgs factory: 100+ GeV
  - Energy-frontier collider: 1000+ GeV



Strawman design of a plasma-based collider with multiple stages.
Image source: Pei et al., Proc. PAC'2009 (IEEE, Piscataway, NJ, 2009), p. 2682.

- **Single-stage plasma accelerators with high energy gain:**
  - Solution #1: Very-high energy driver (e.g., protons as in AWAKE)
    - *Limits: Low rep. rate / energy efficiency*
  - Solution #2: High transformer ratio (shaped driver)
    - *Limits: Difficult to go beyond 5–10, very sensitive to current profile*

- **Multiple stages (staging) likely required for high energy + high efficiency + compactness.**

Challenges of staging

- **Proof-of-principle experiment at LBNL:**
  - Demonstrated feasibility of staging.
  - Used a compact *active plasma lens*
  - Also **highlighted many challenges** (e.g., only ~3% of charge was coupled)
  - Improved experiments now planned.

- **Staging is non-trivial for <u>four</u> reasons:**

① Reduced average gradient (compactness)

② In- and out-coupling of drivers

③ Emittance growth from chromaticity

④ Tight synchronization tolerances

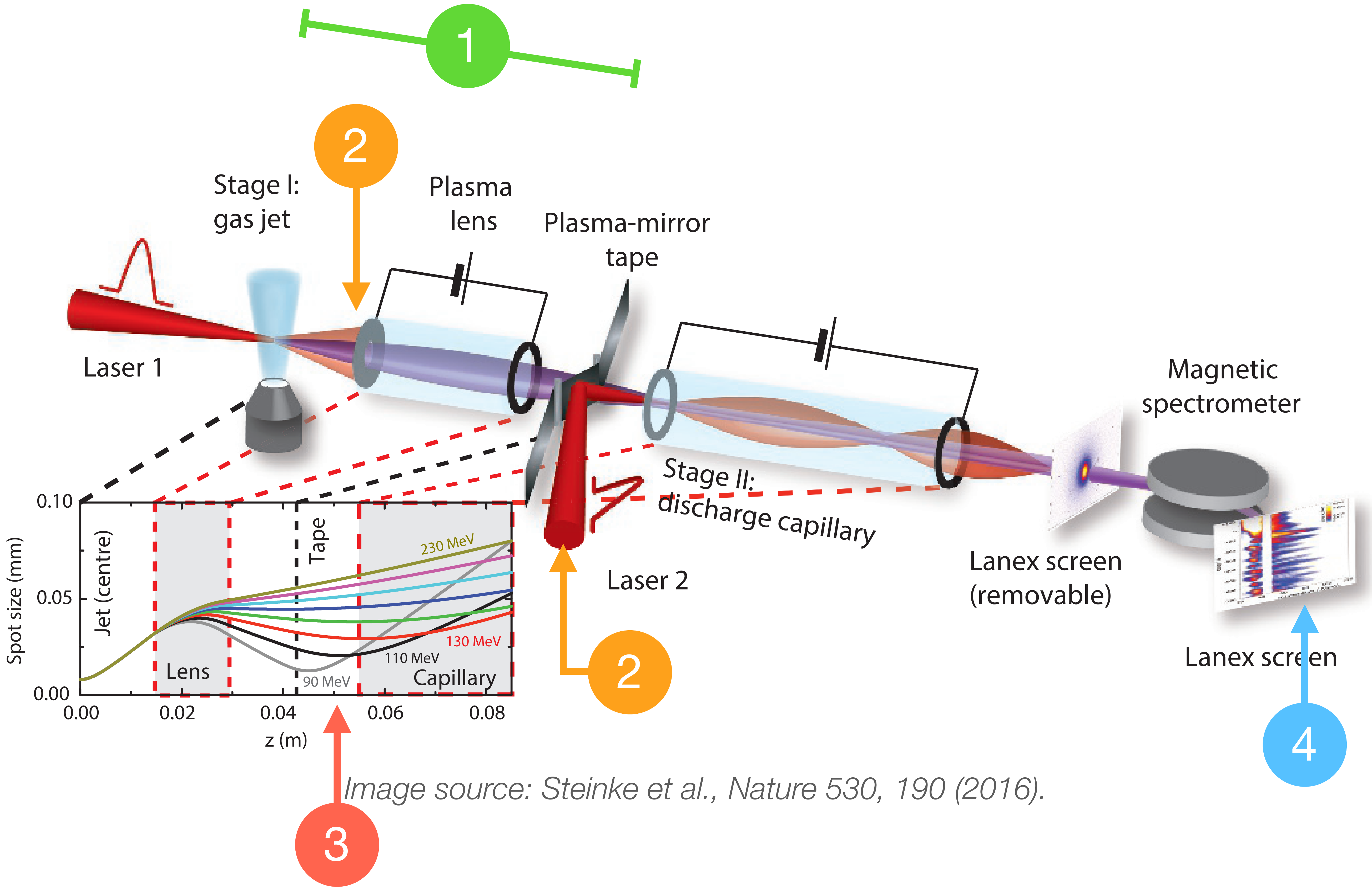
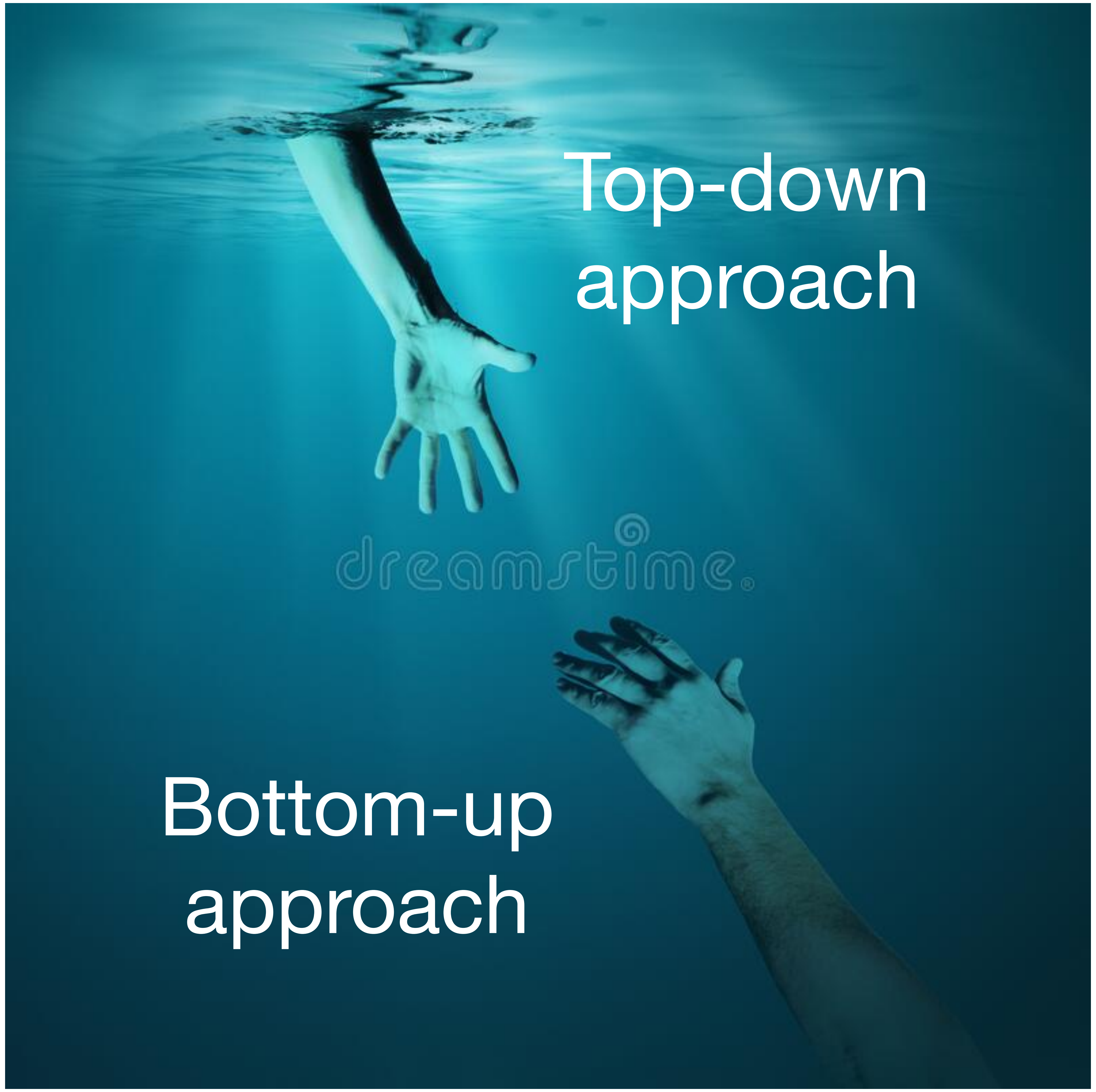


Image source: Steinke et al., Nature 530, 190 (2016).


Top-down approach
Bottom-up approach
dreamstime

Nonlinear plasma lenses for achromatic optics

Novel solution: **Nonlinear plasma lenses**

- Collider final-focus systems already cancel strong chromaticity.
- **Local chromaticity correction** in conventional beam optics:
  - Sextupoles close to quadrupoles (+ dispersion from dipoles)
- **Active plasma lenses provide stronger focusing (kT/m).**
- Applying local chromaticity correction to active plasma lenses:
  - The magnetic field 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 transverse gradient (D_x is the required dispersion).

  - The added field is the **plasma-lens equivalent to a sextupole field**.
- Can in principle also use a passive (wakefield-based) plasma lens

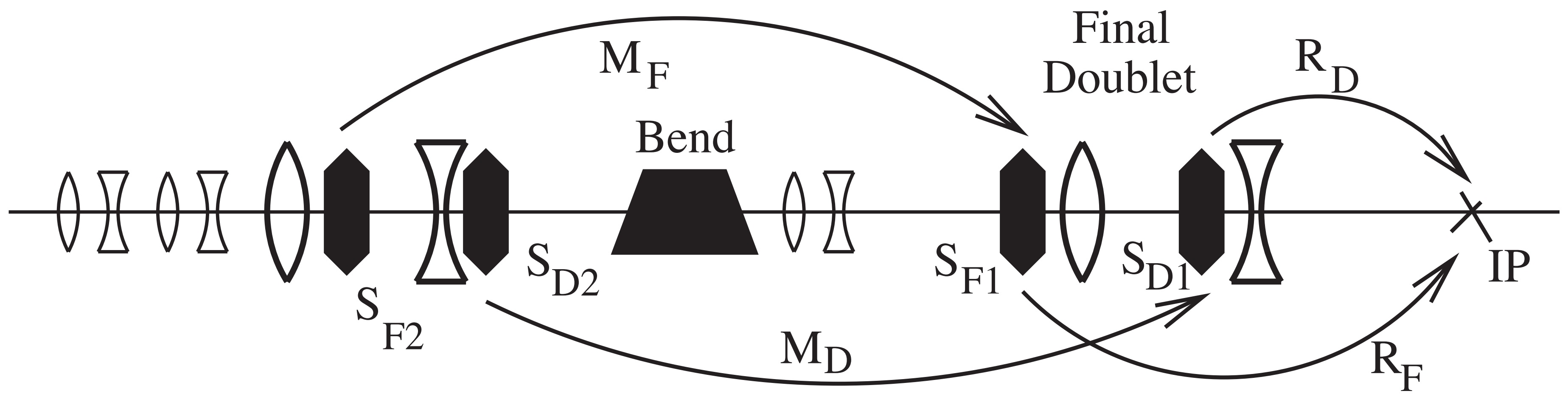
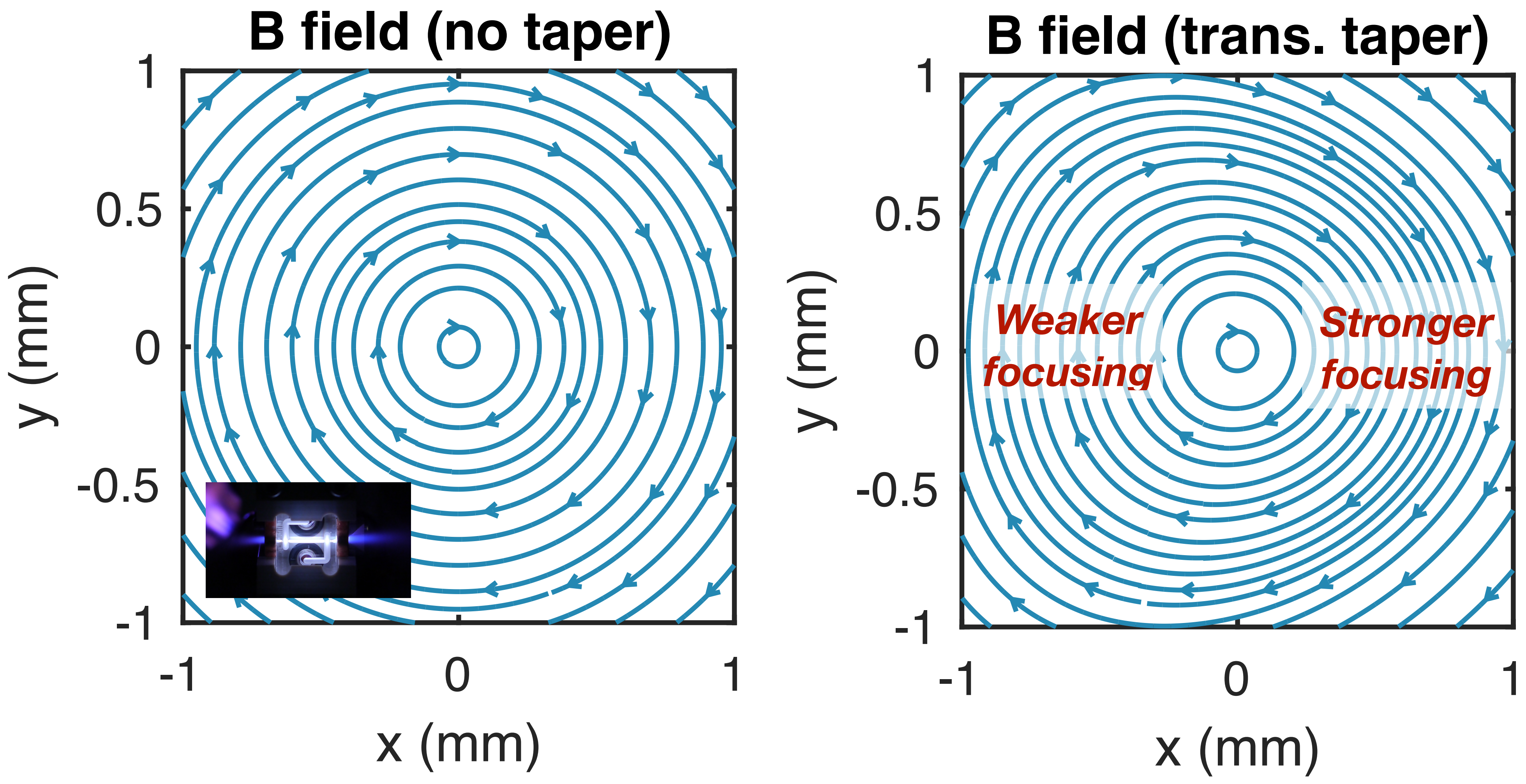
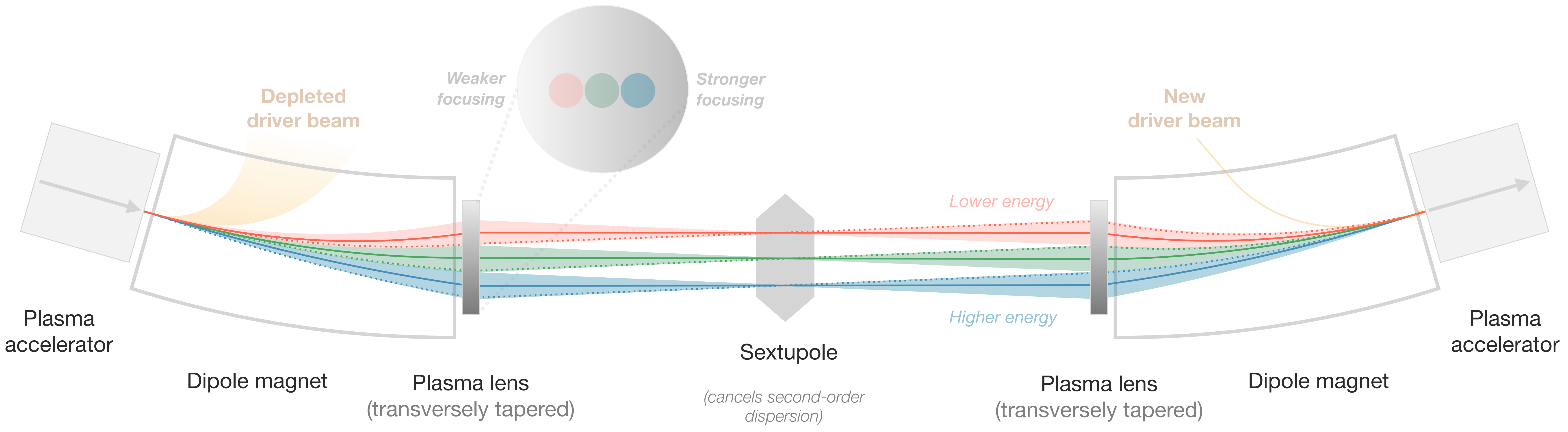


Image source: Raimondi & Seryi, Phys. Rev. Lett. 86, 3779 (2001)



1 Plasma lenses solve staging problem #1:
High average acceleration gradient

An **achromatic lattice** for staging



Weaker focusing

Stronger focusing

Depleted driver beam

New driver beam

Lower energy

Higher energy

Plasma accelerator

Dipole magnet

Plasma lens
(transversely tapered)

Sextupole

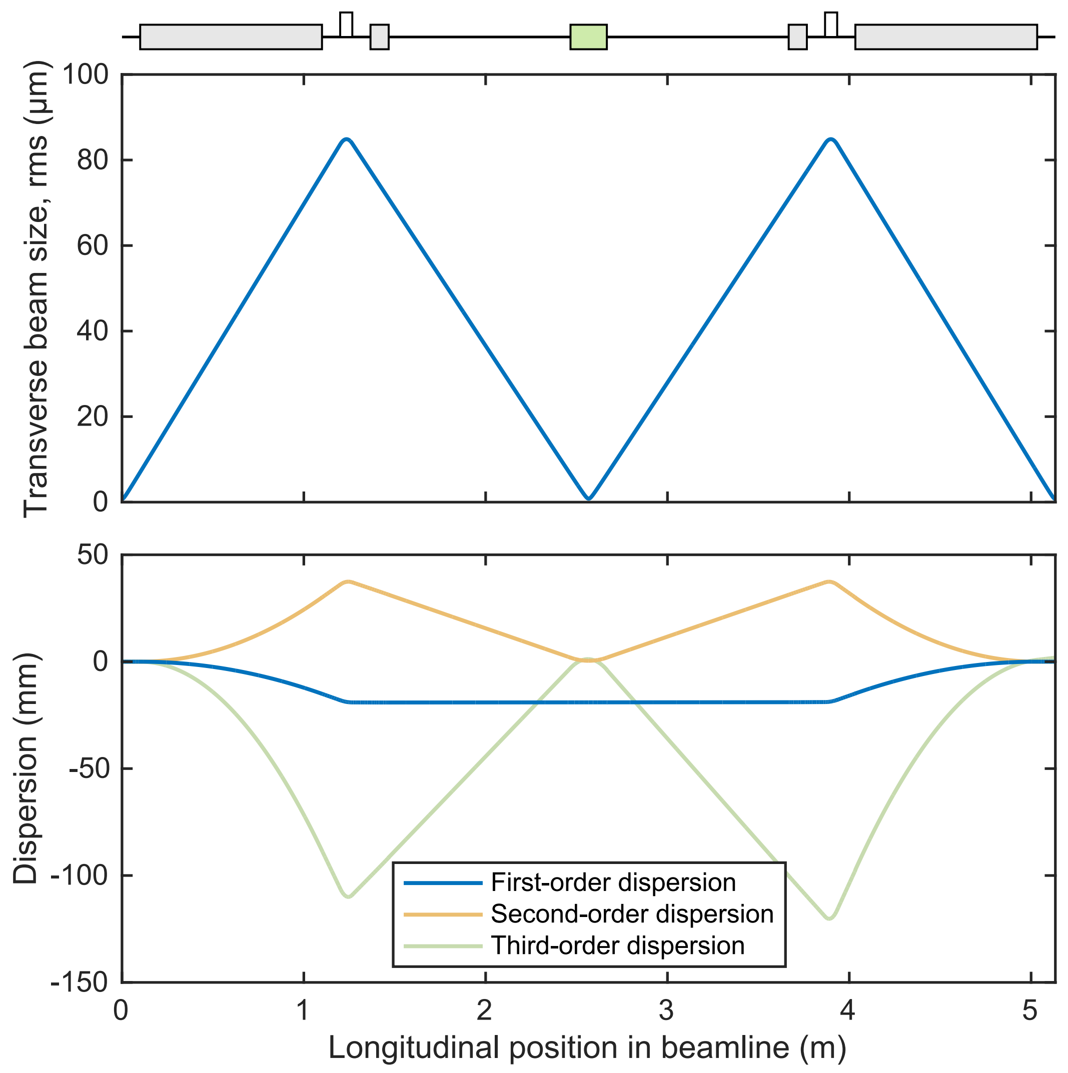
(cancels second-order dispersion)

Plasma lens
(transversely tapered)

Dipole magnet

Plasma accelerator

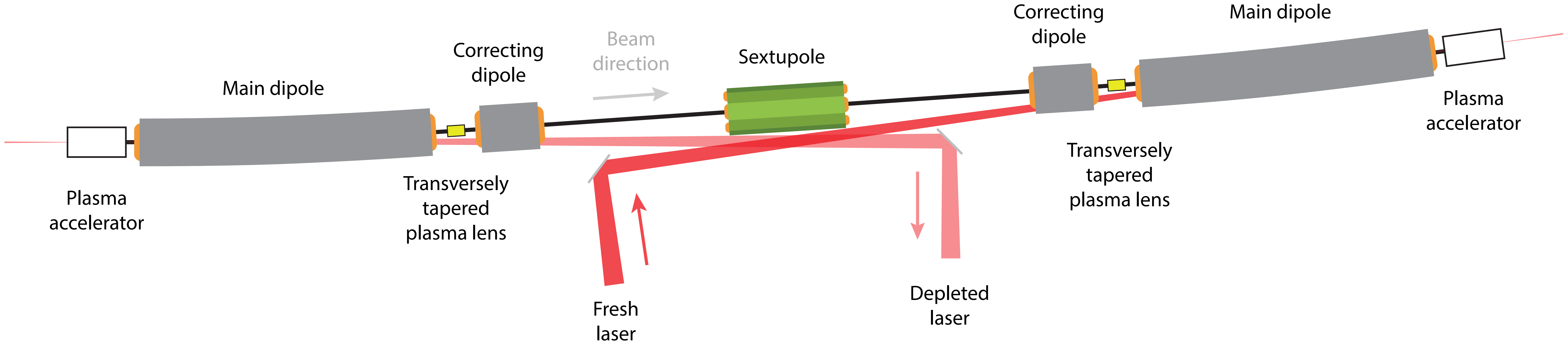
- Simplest lattice for achromatic and emittance-preserving staging:
  - **Two dipoles** (for dispersion)
  - **Two nonlinear plasma lenses** (for chromaticity correction)
  - **One central sextupole** (for second-order dispersion correction)
- Nonlinear focusing causes emittance growth:
  - Use **mirror symmetry** to cancel nonlinear kicks



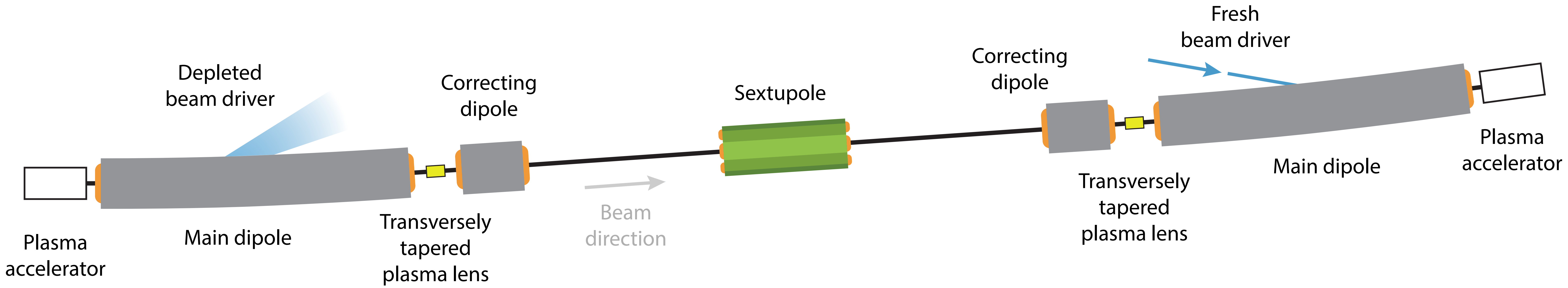
In- and out-coupling of drivers

② Dipoles solve staging problem #2:
Laser/beam drivers can be in- and out-coupled

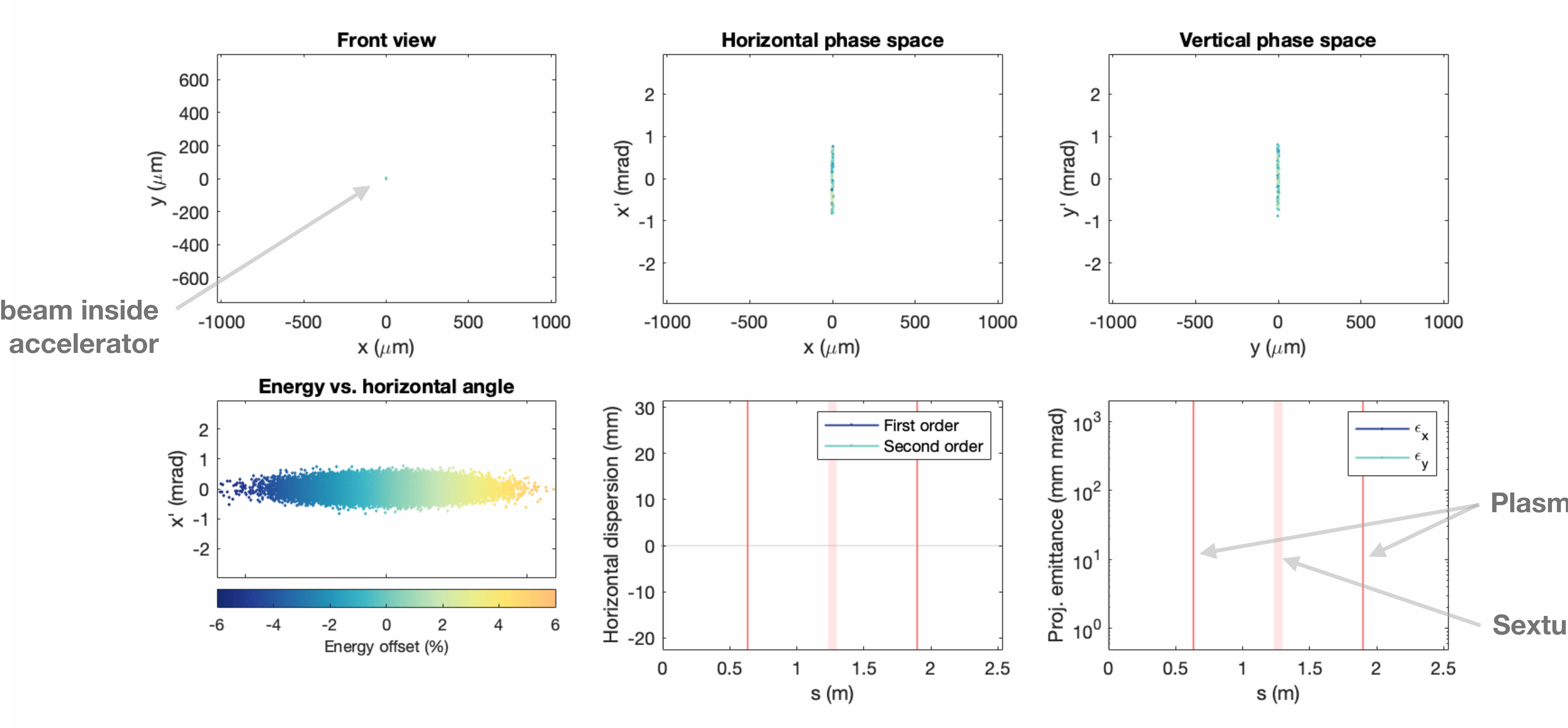
- Dipoles allow in- and out-coupling of **both laser- and beam drivers**.
- A net angle is introduced (decreasing with energy): the linac is **not straight**
- **Laser driven:**



- **Beam driven:**



Achromatic optics, explained

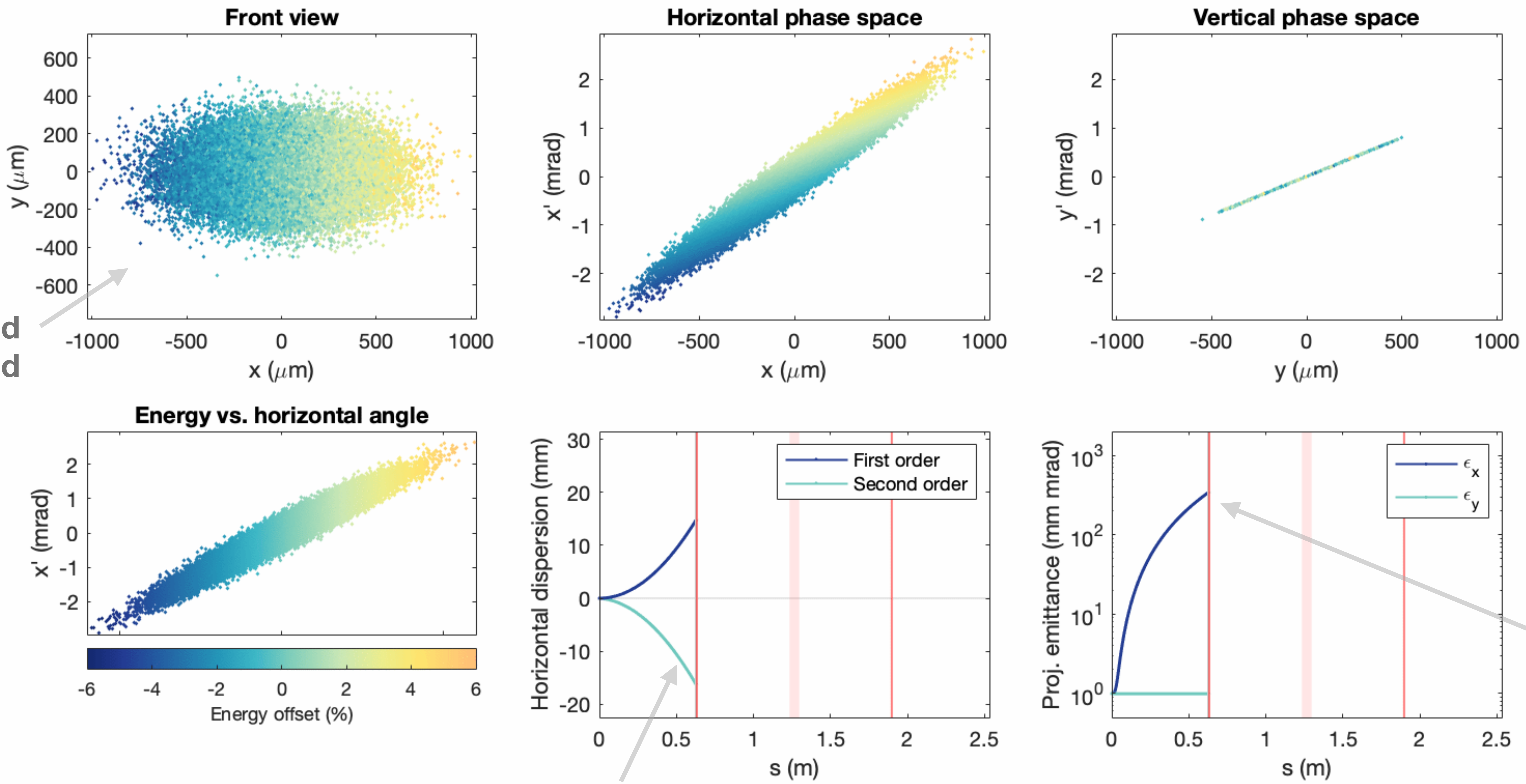


Small beam inside plasma accelerator

Plasma lenses

Sextupole

Achromatic optics, explained

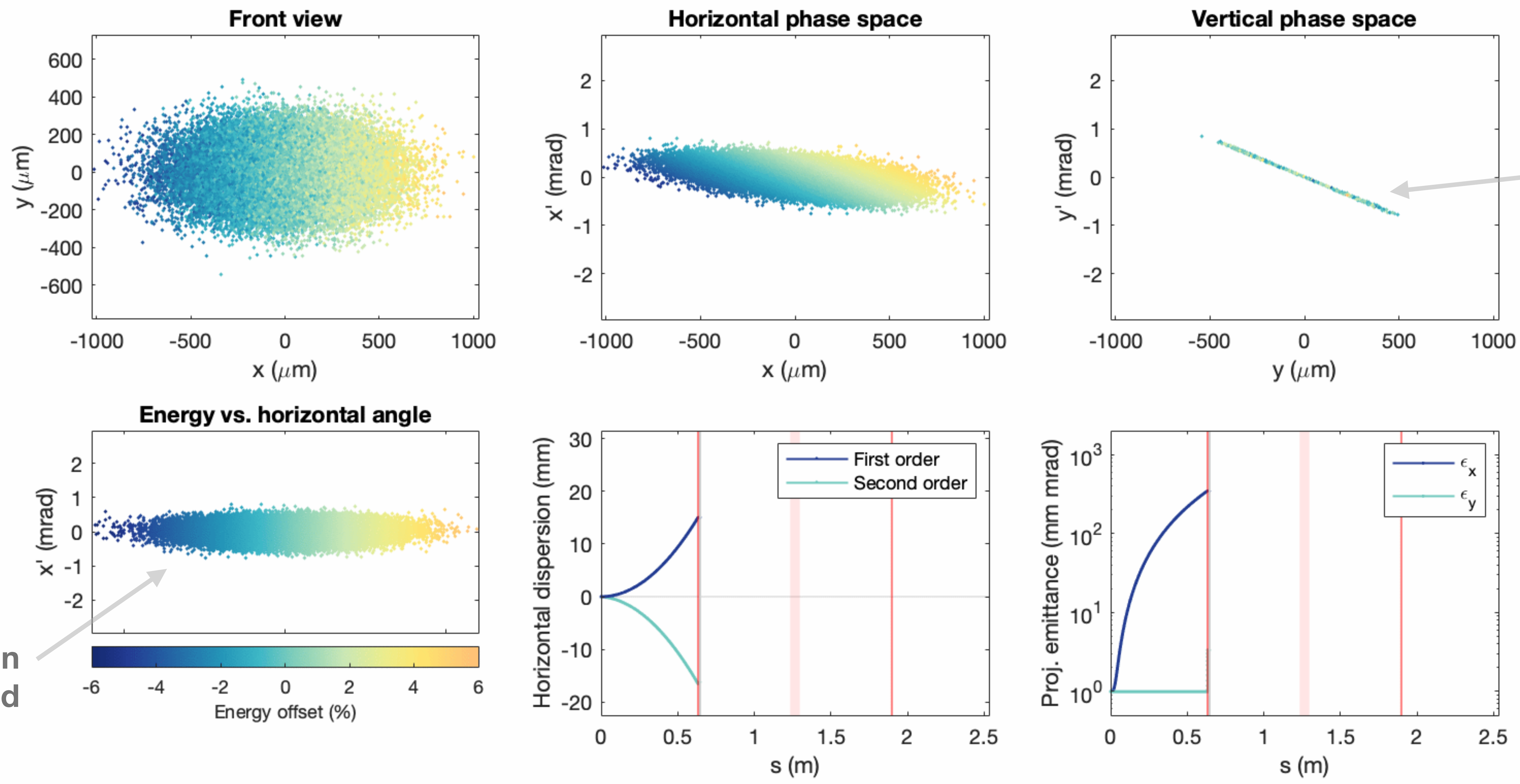


Diverged and dispersed

Dispersed in lens

Emittance growth from dispersion

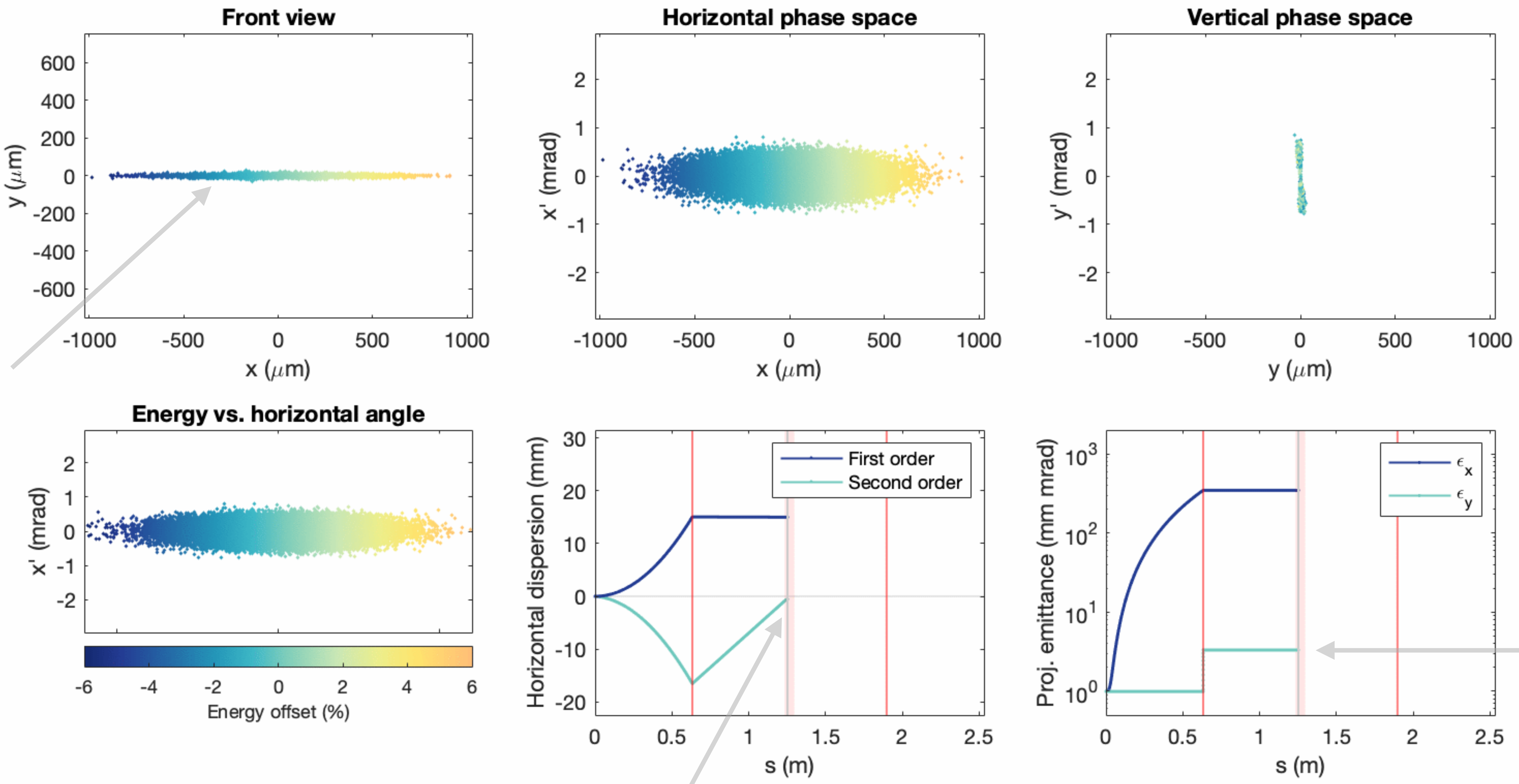
Achromatic optics, explained



Phase spaces are flipped

Dispersion is collimated

Achromatic optics, explained

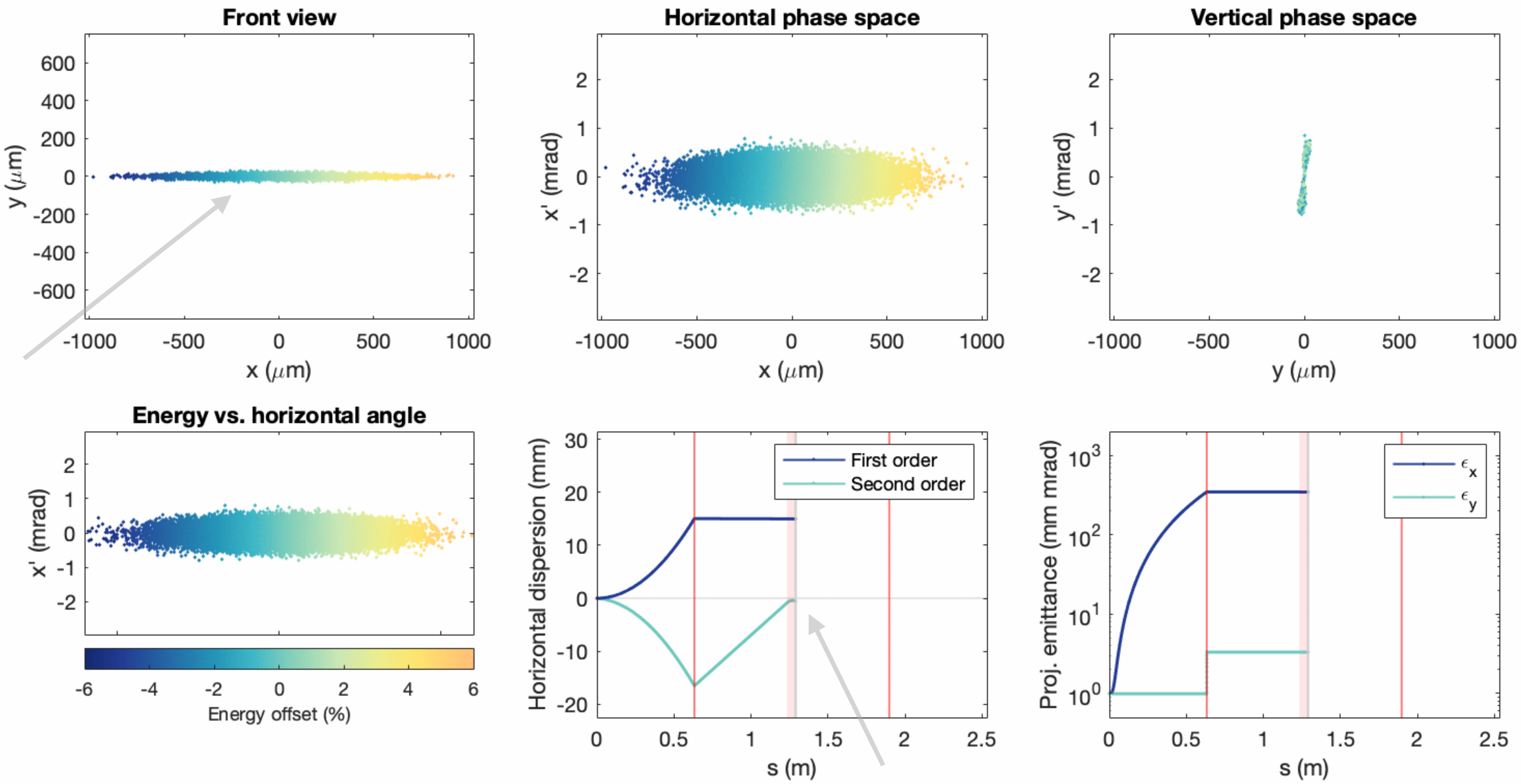


Beam size is small, but dispersed

Second-order dispersion is cancelled

Emittance growth from nonlinear focusing

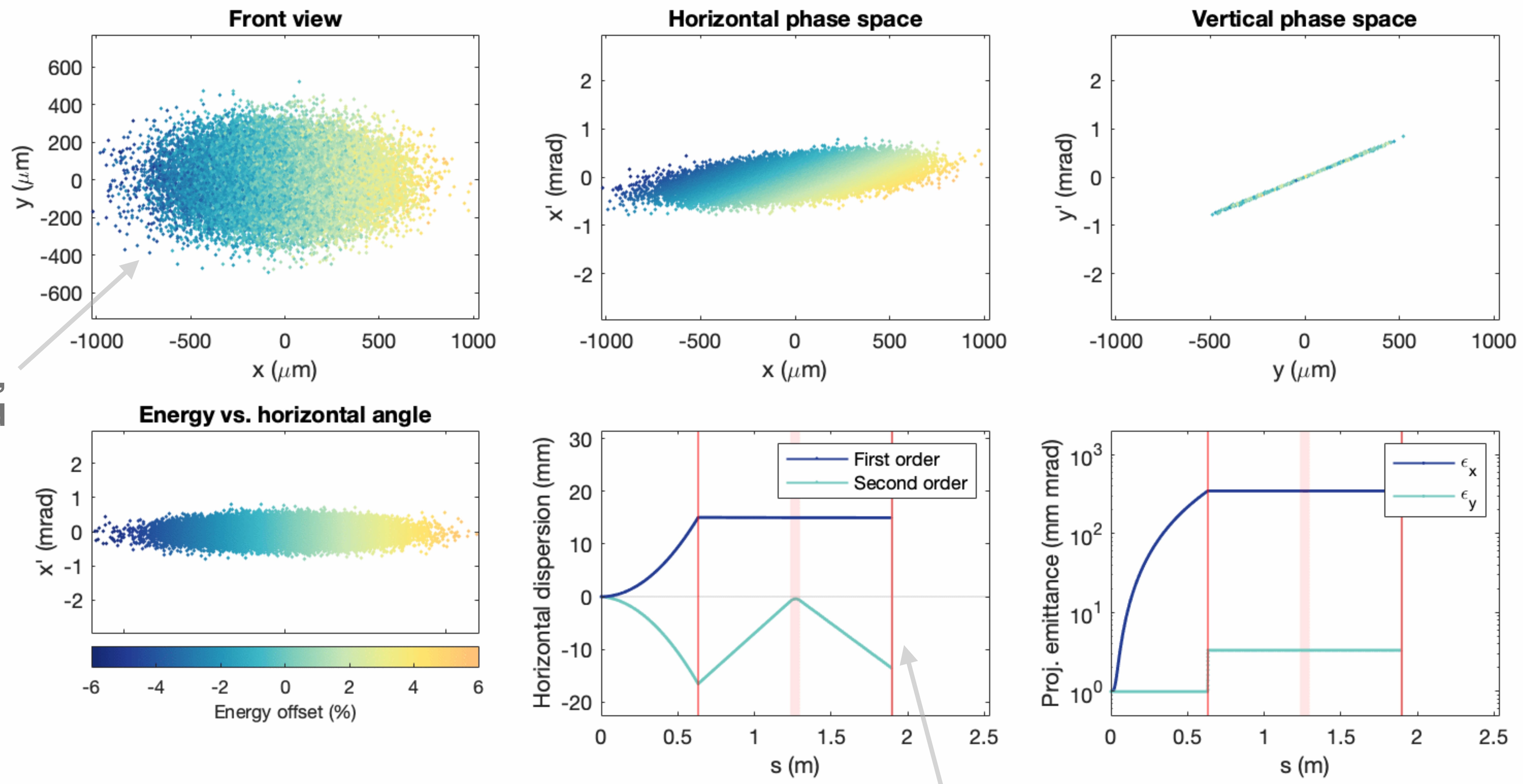
Achromatic optics, explained



Negligible effect of sextupole
(small beam size)

Second-order dispersion flips direction

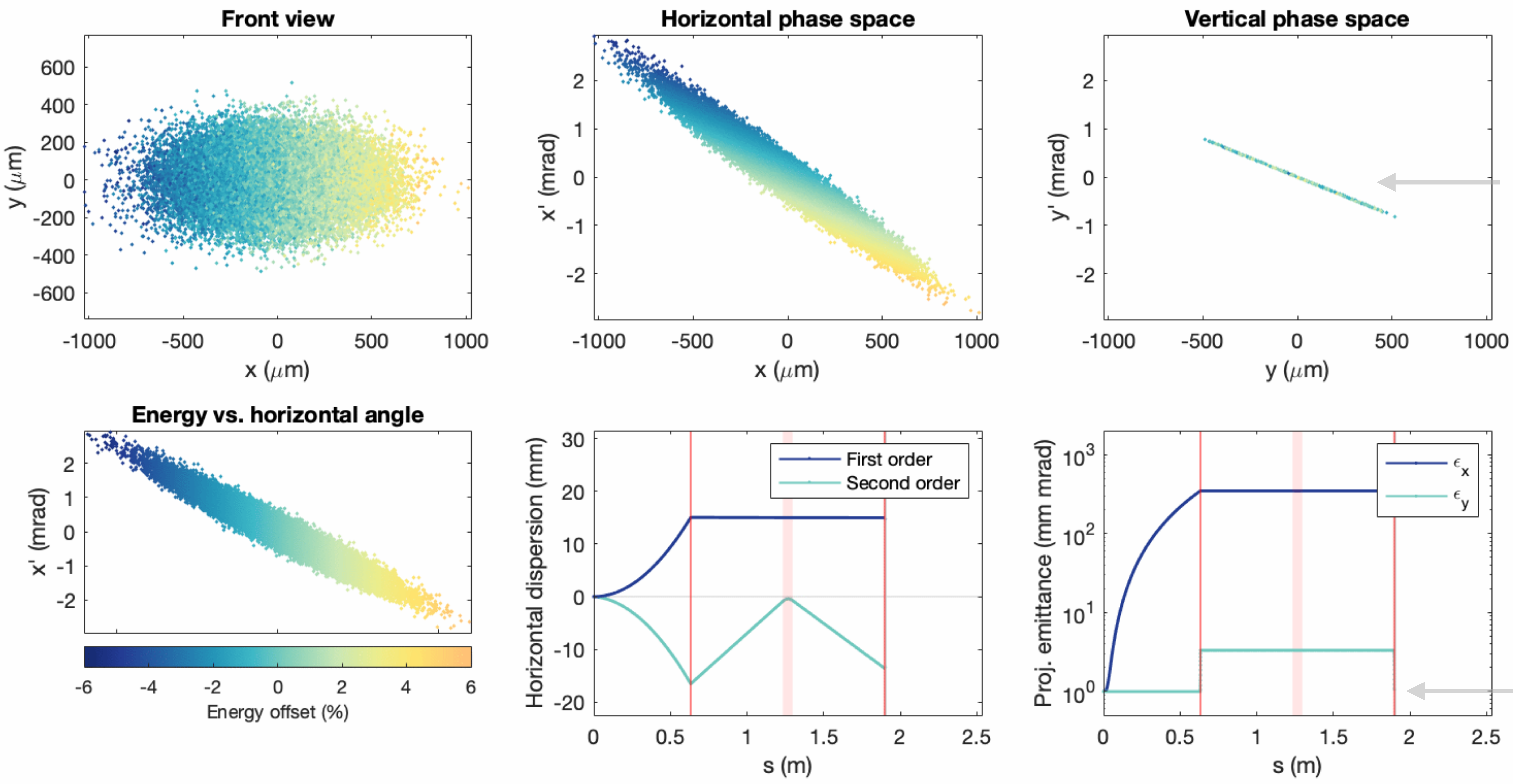
Achromatic optics, explained



Beam size is large, phase is flipped

Same dispersion as in first lens

Achromatic optics, explained

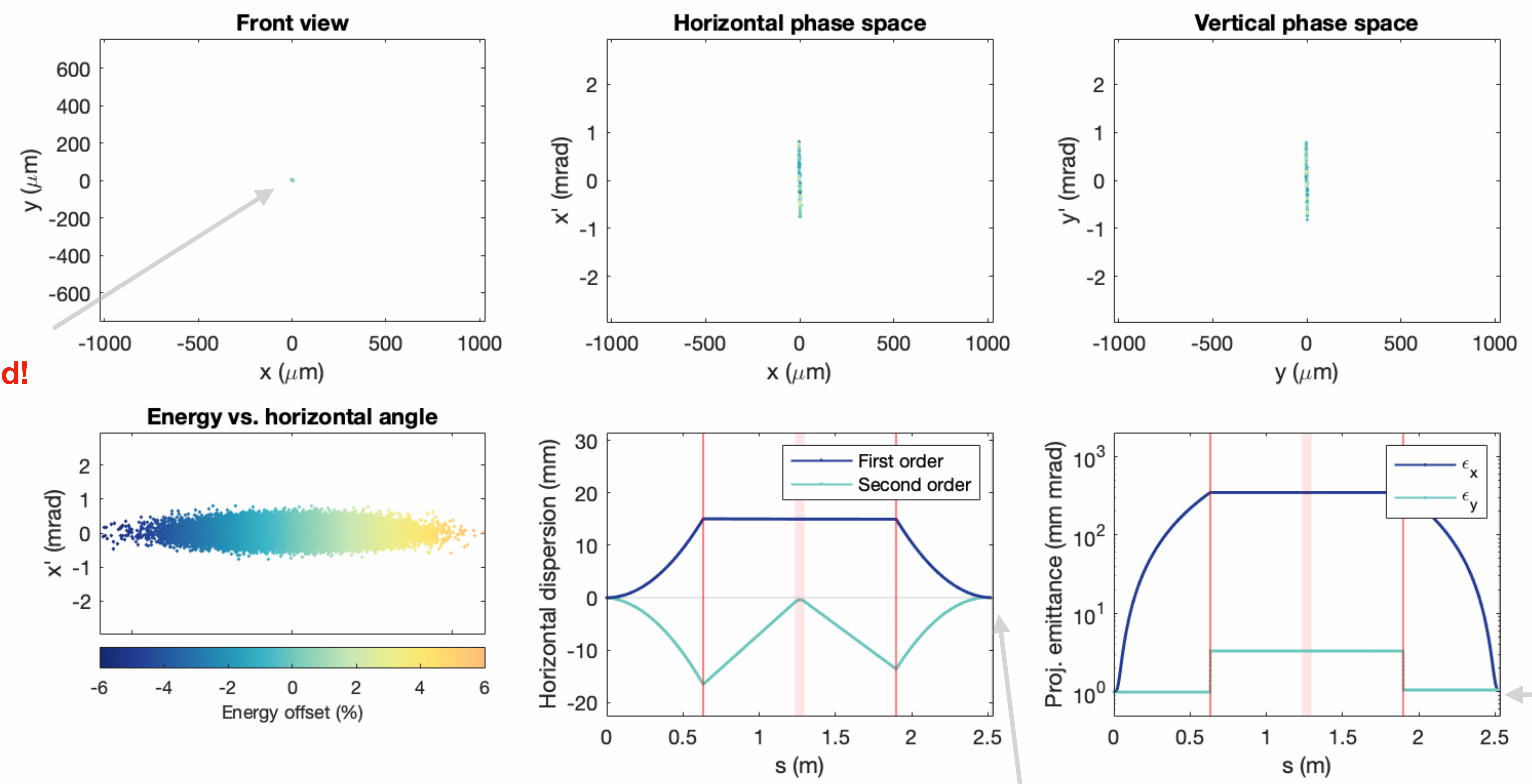


Refocused by second lens

Emittance growth cancelled
(by symmetry)

Achromatic optics, explained

3 Nonlinear plasma lenses solve staging problem #3:
Emittance growth from chromaticity cancelled



Beam refocused!

Dispersion cancelled!

Emittance preserved!

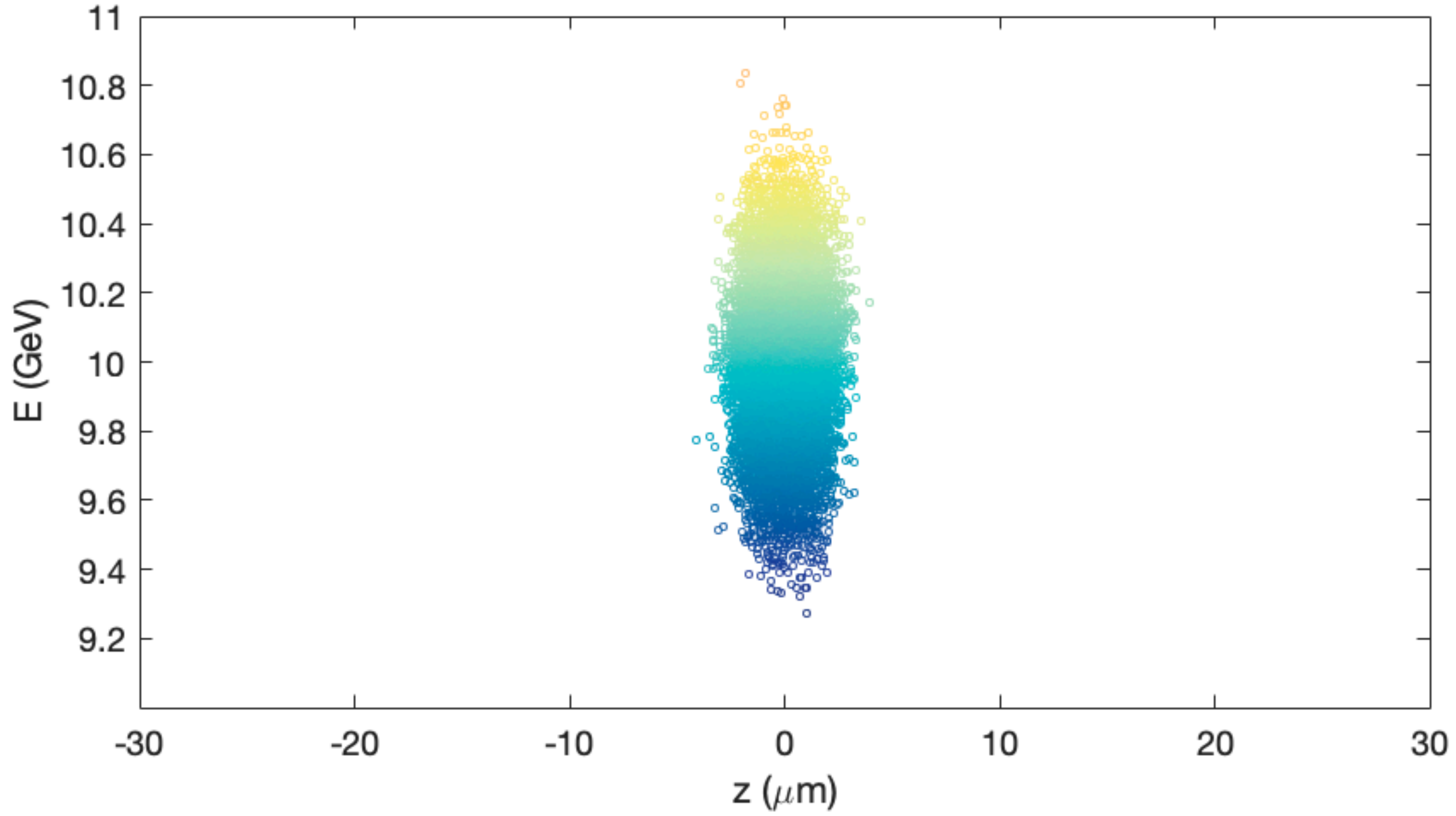
Magnetic chicanes for self-correction in long. phase space

Stages separated by **bunch compressors**

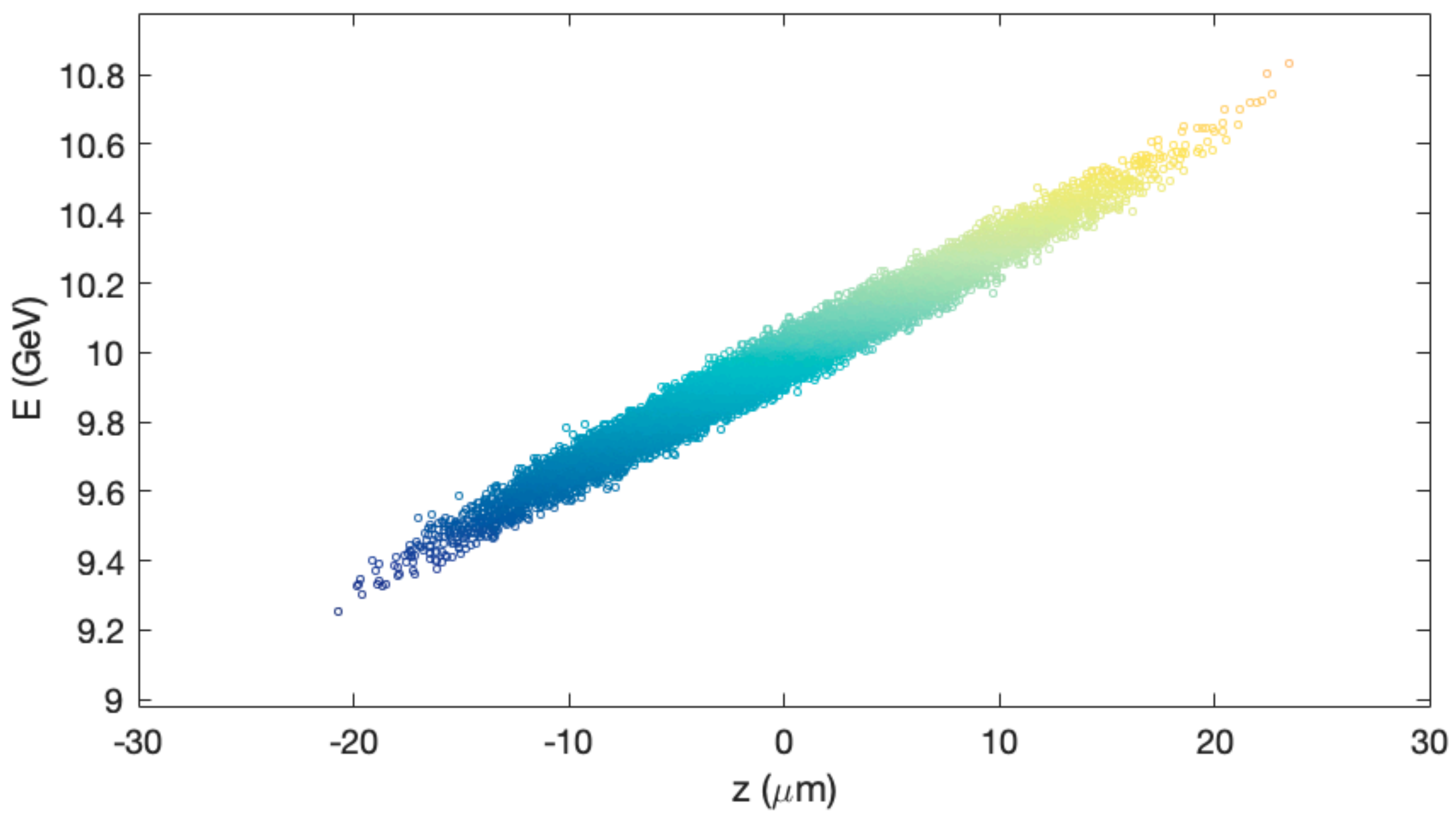
- The achromatic lattice has a non-zero longitudinal lattice dispersion (R_{56}):
  - Results in a **compression/stretching** between stages…

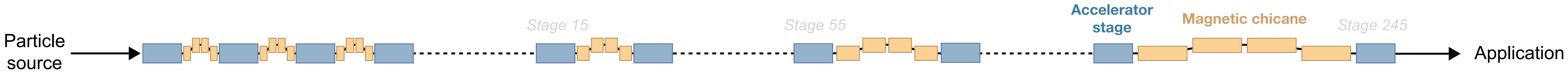
$$R_{56} = \frac{B^2 e^2 c^2 L^3}{3E^2} \neq 0$$

Before chicane



After chicane

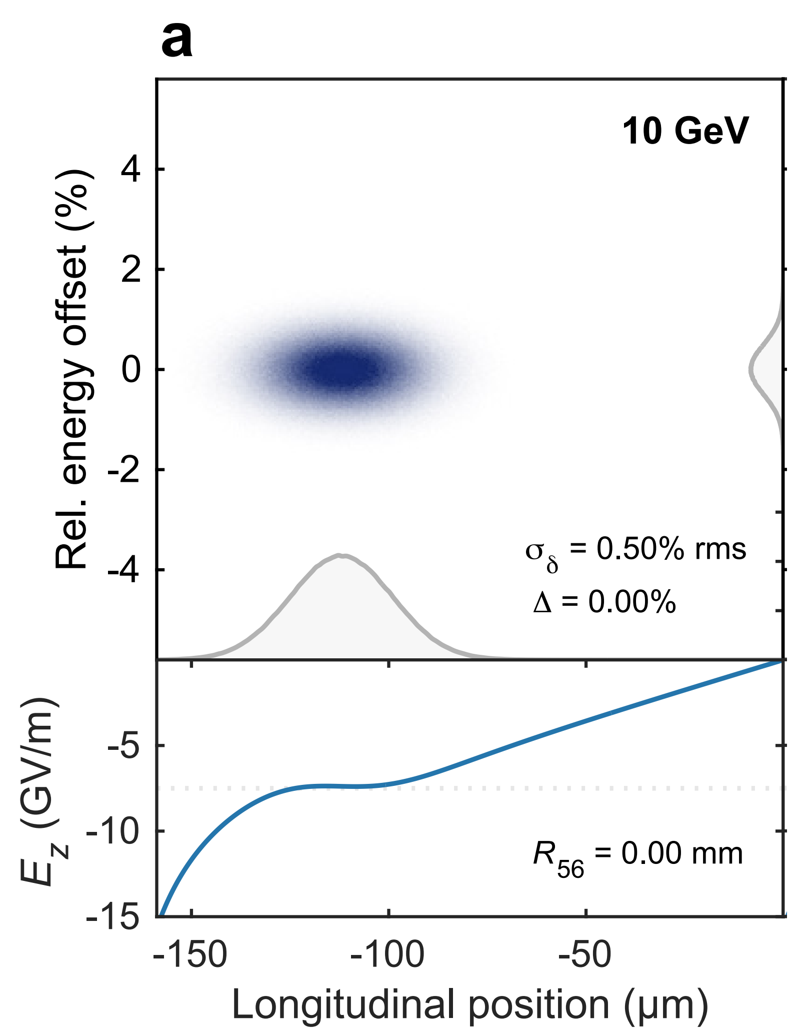


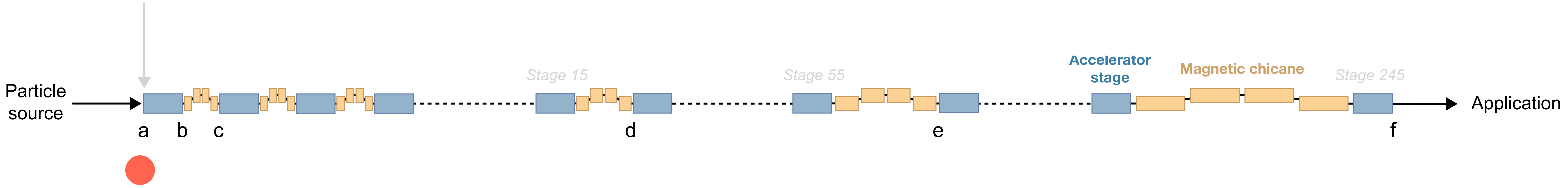


Chicanes and advanced accelerators:

Sears et al. PRSTAB 11, 101301 (2008), Mayet et al. IPAC (2017), Ferran Pousa et al. PRL 123, 054801 (2019), Ferran Pousa et al. PRL 129, 094801 (2022)

A **self-correction mechanism** in longitudinal phase space



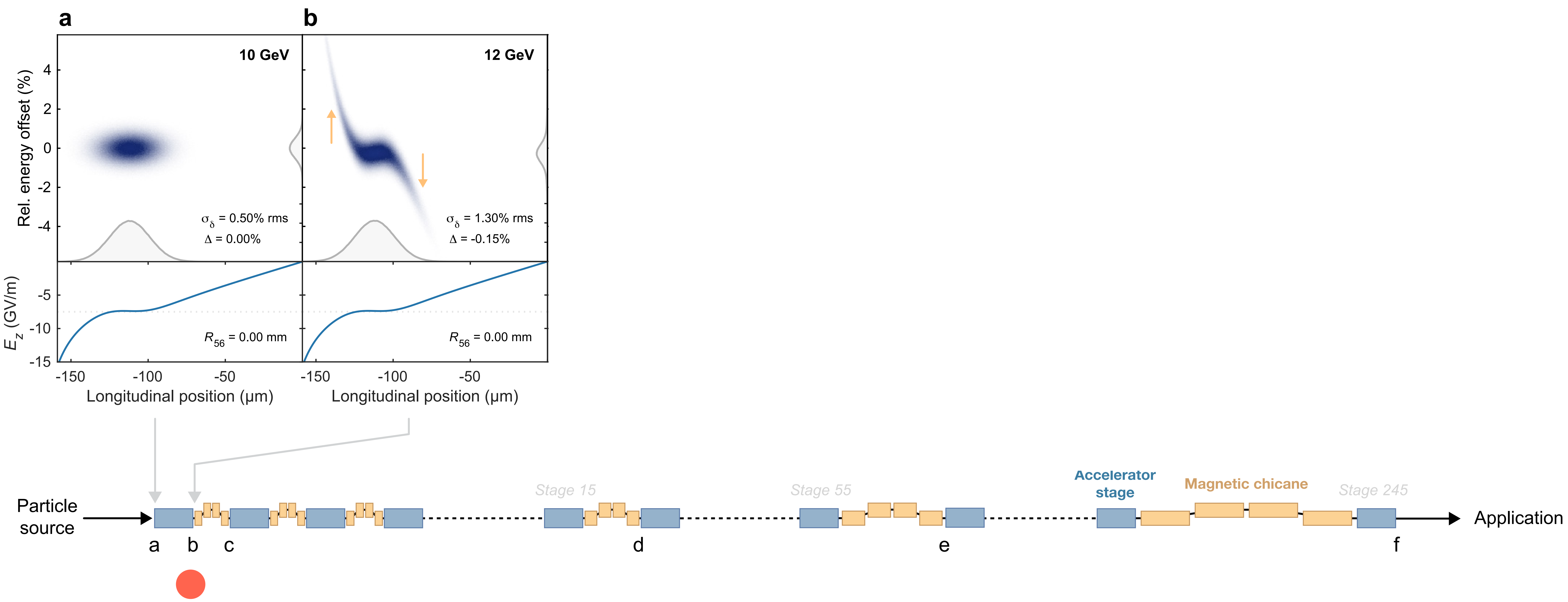


Start:

Initial particle distribution

Preprint: Lindstrøm, arXiv:2104.14460 (2021)

A **self-correction mechanism** in longitudinal phase space

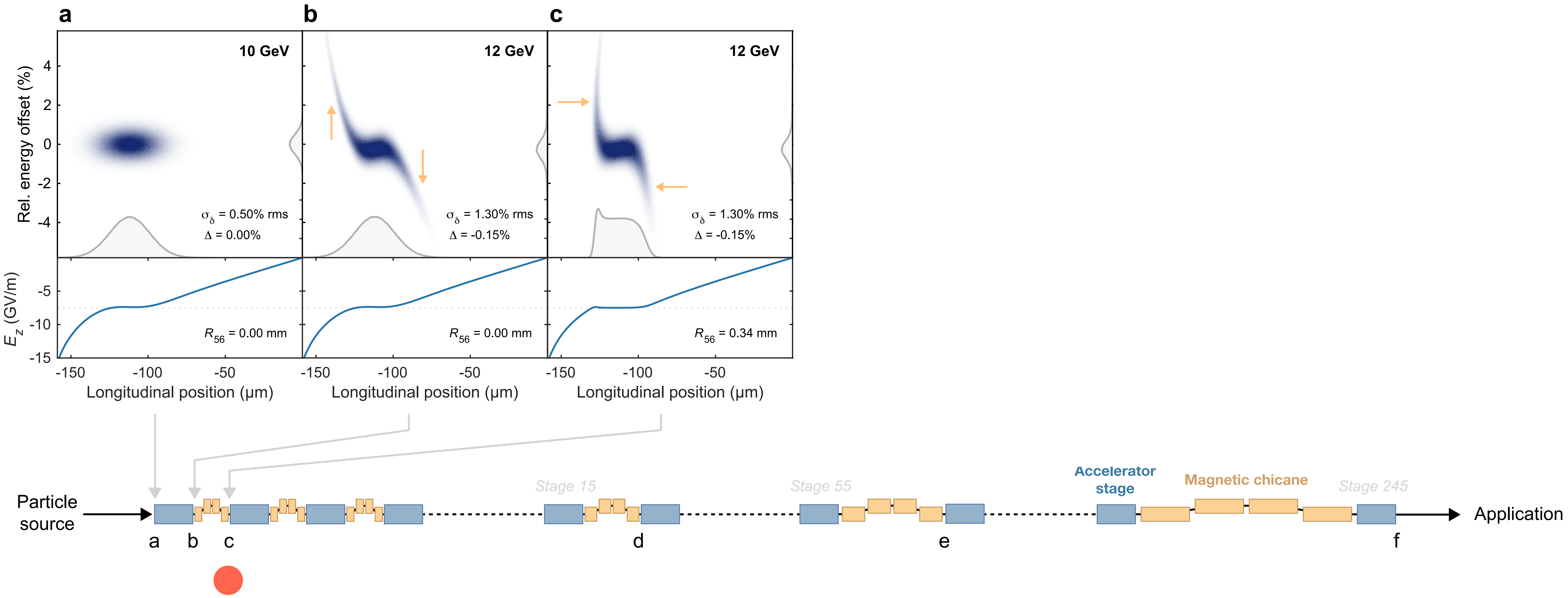


Plasma accelerator stage:

Particles gain energy based on their position

Preprint: Lindstrøm, arXiv:2104.14460 (2021)

A **self-correction mechanism** in longitudinal phase space

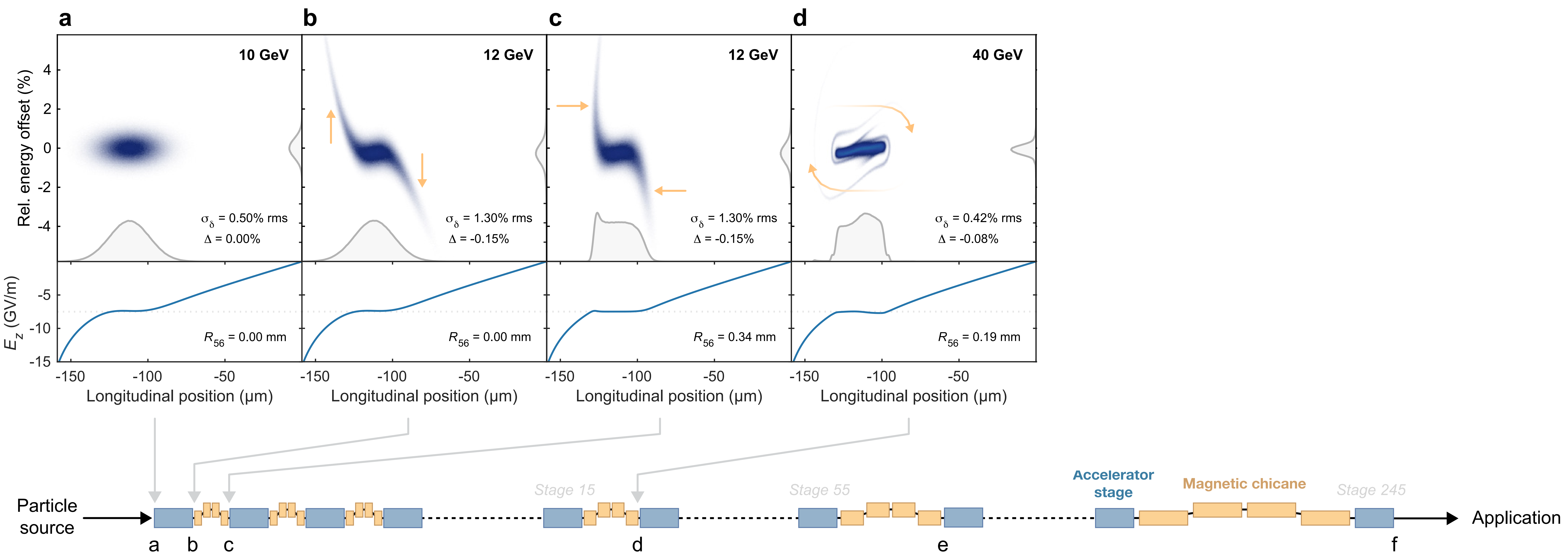


Magnetic chicane:

Move particles longitudinally based on energy offset

Preprint: Lindstrøm, arXiv:2104.14460 (2021)

A **self-correction mechanism** in longitudinal phase space

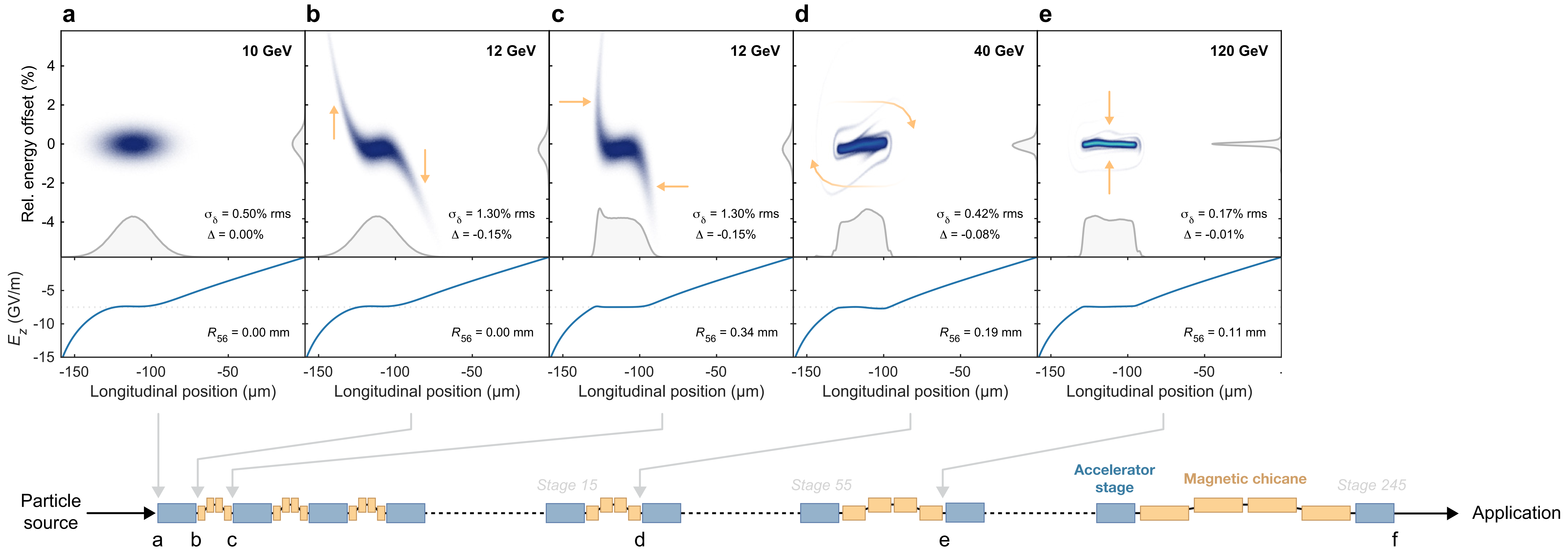


Several stages:

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

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

A **self-correction mechanism** in longitudinal phase space

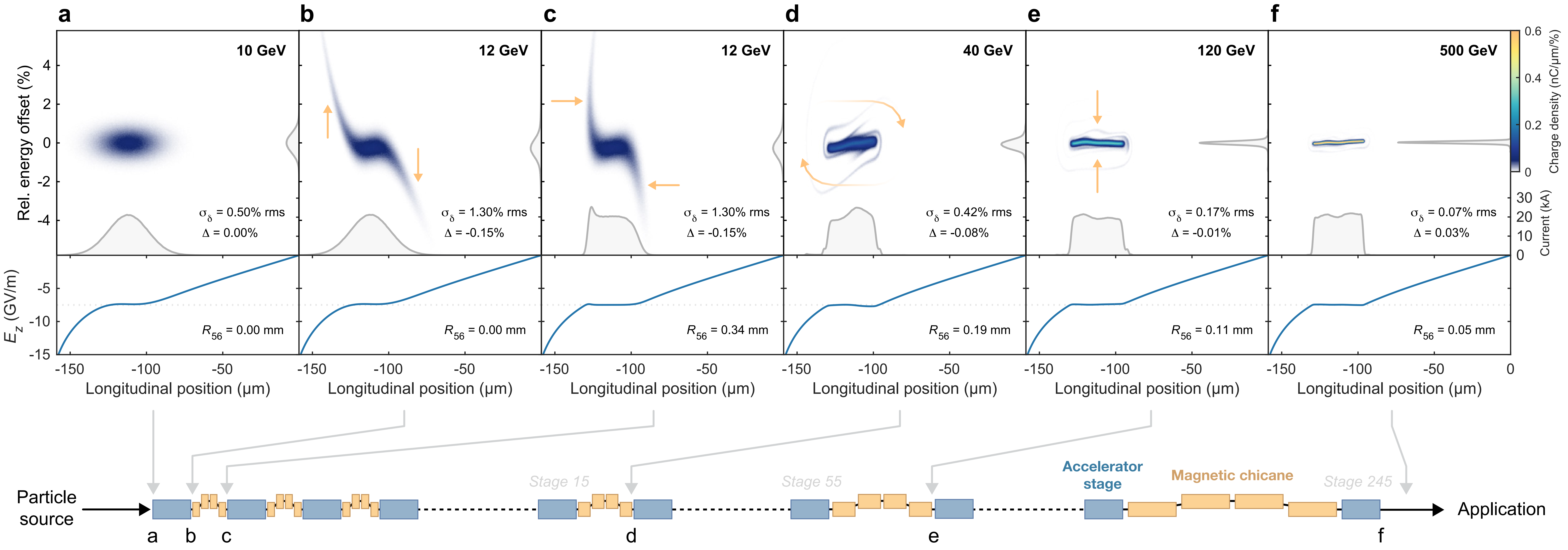


More stages:

Relative energy spread and offsets damped with energy gain

Preprint: Lindstrøm, arXiv:2104.14460 (2021)

A **self-correction mechanism** in longitudinal phase space



End result:

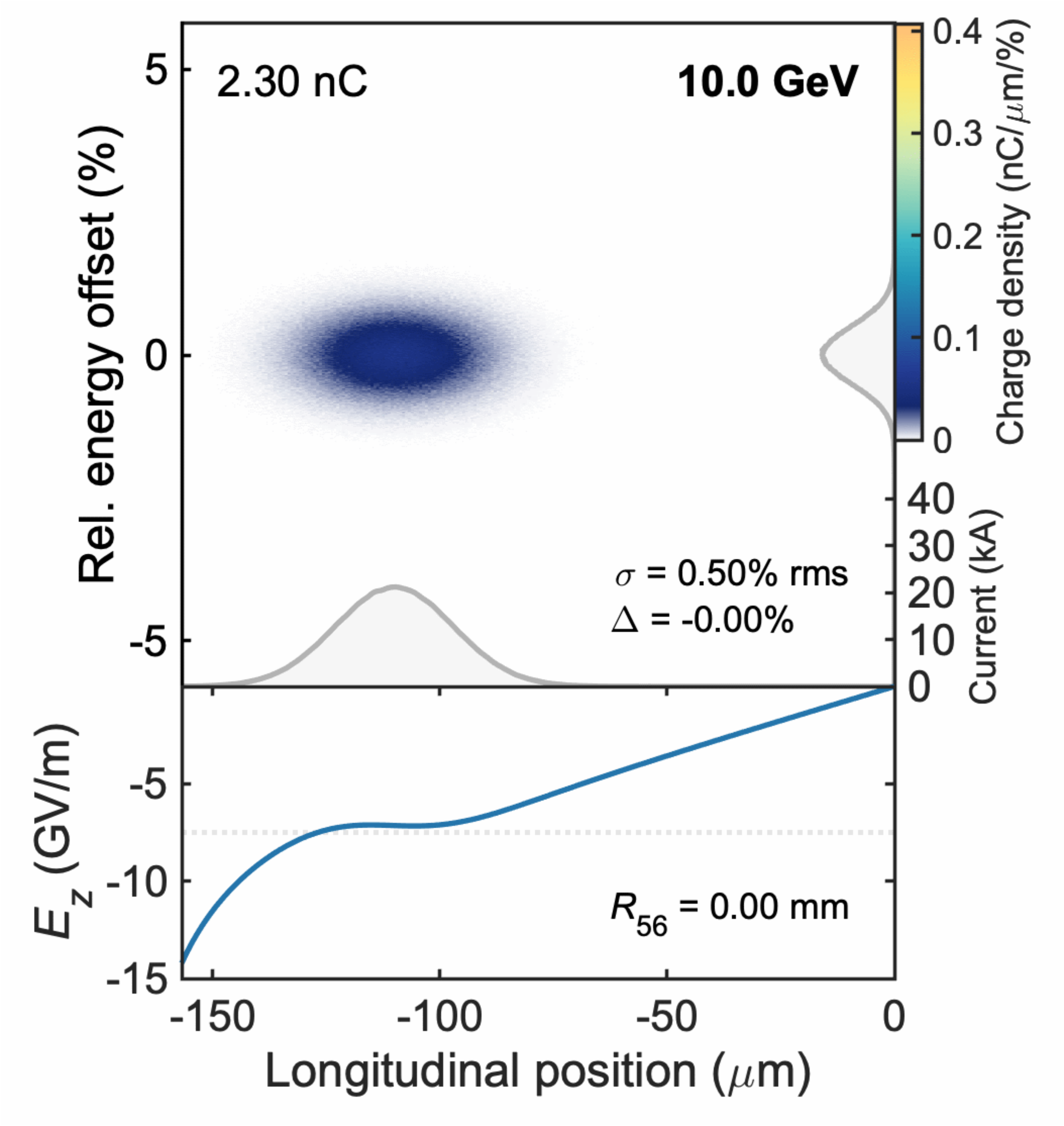
Optimal current profile, flattened wakefield
low energy spread, small energy offset

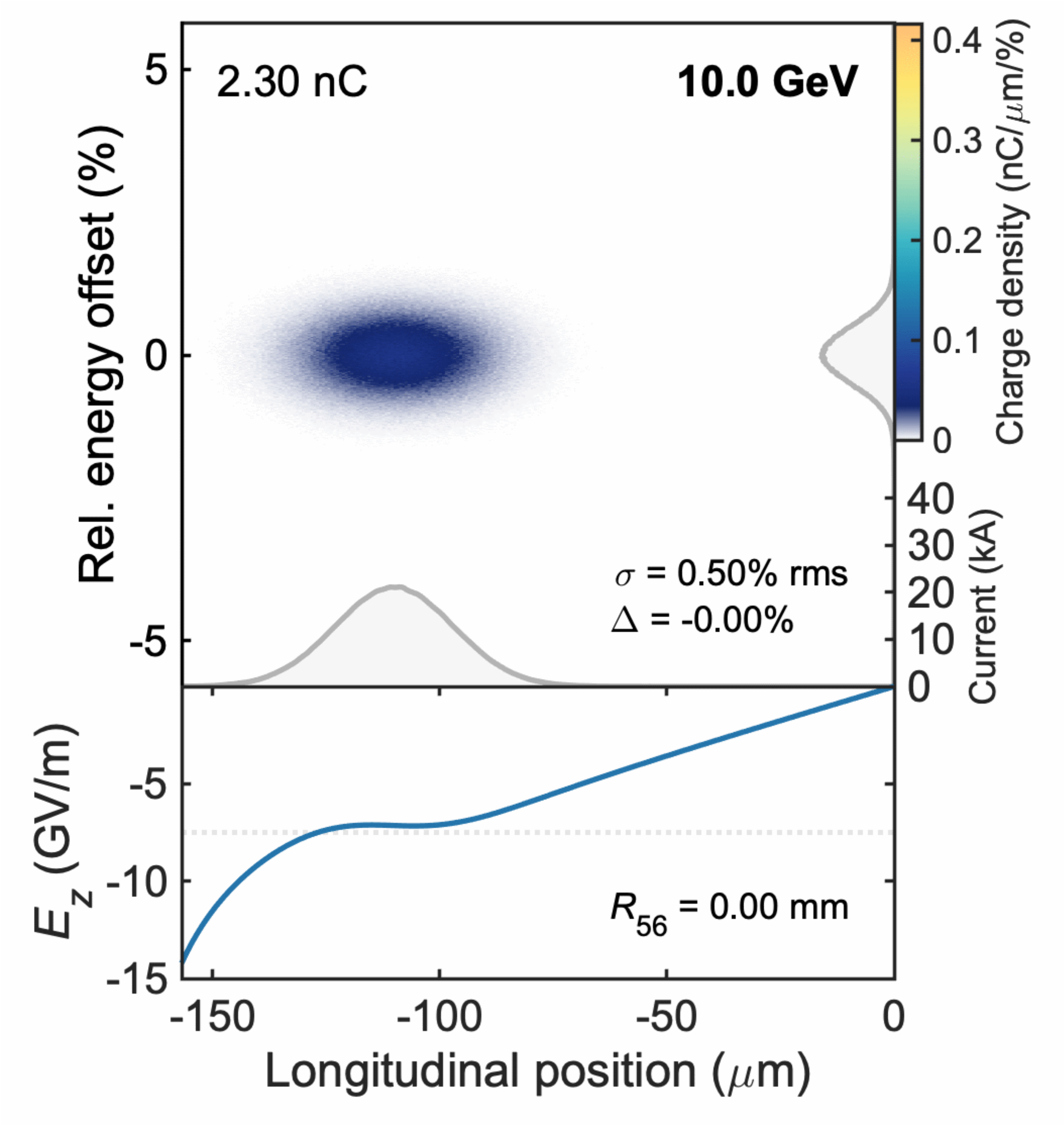
Preprint: Lindstrøm, arXiv:2104.14460 (2021)

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

No correction

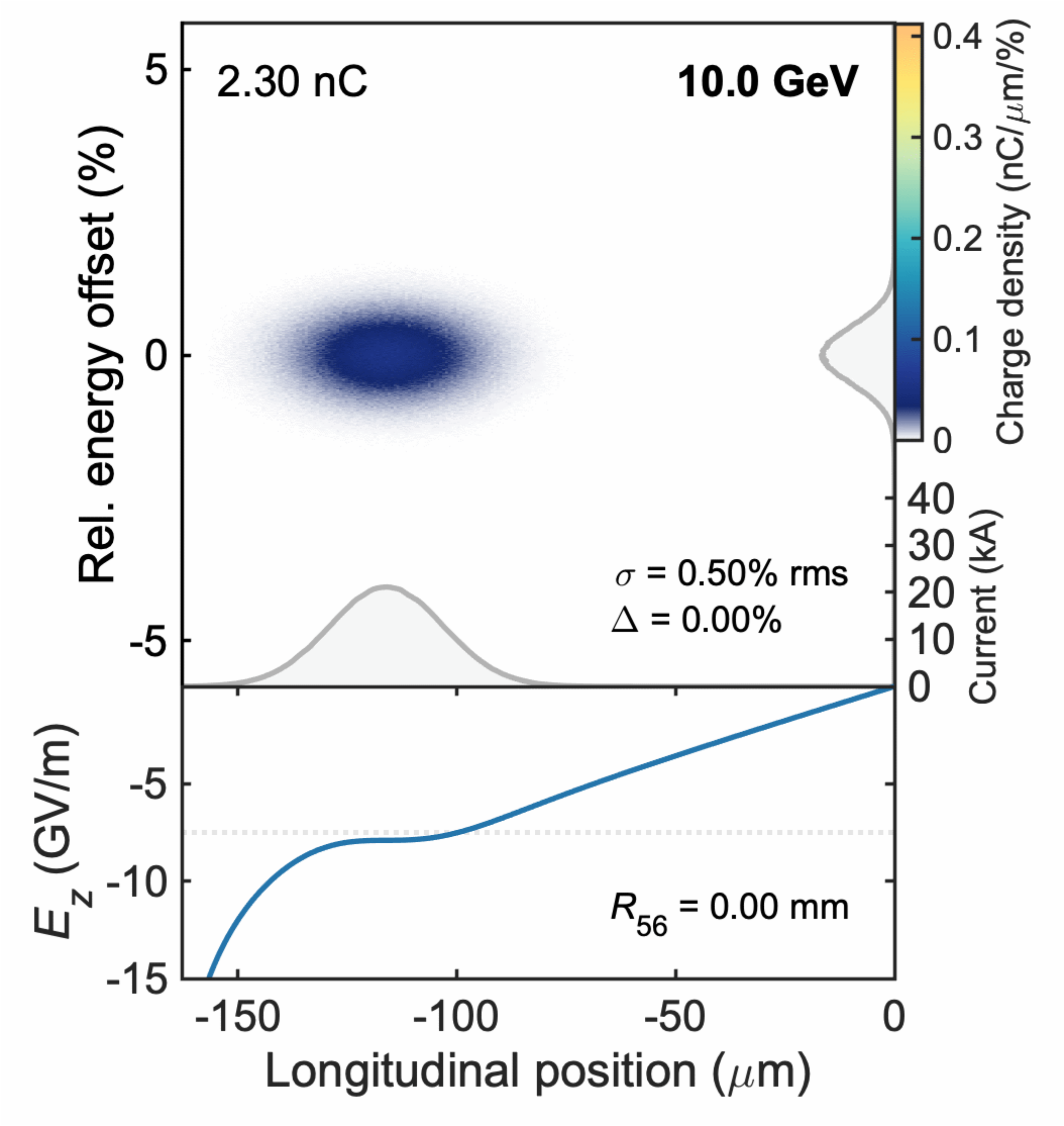
With multistage correction



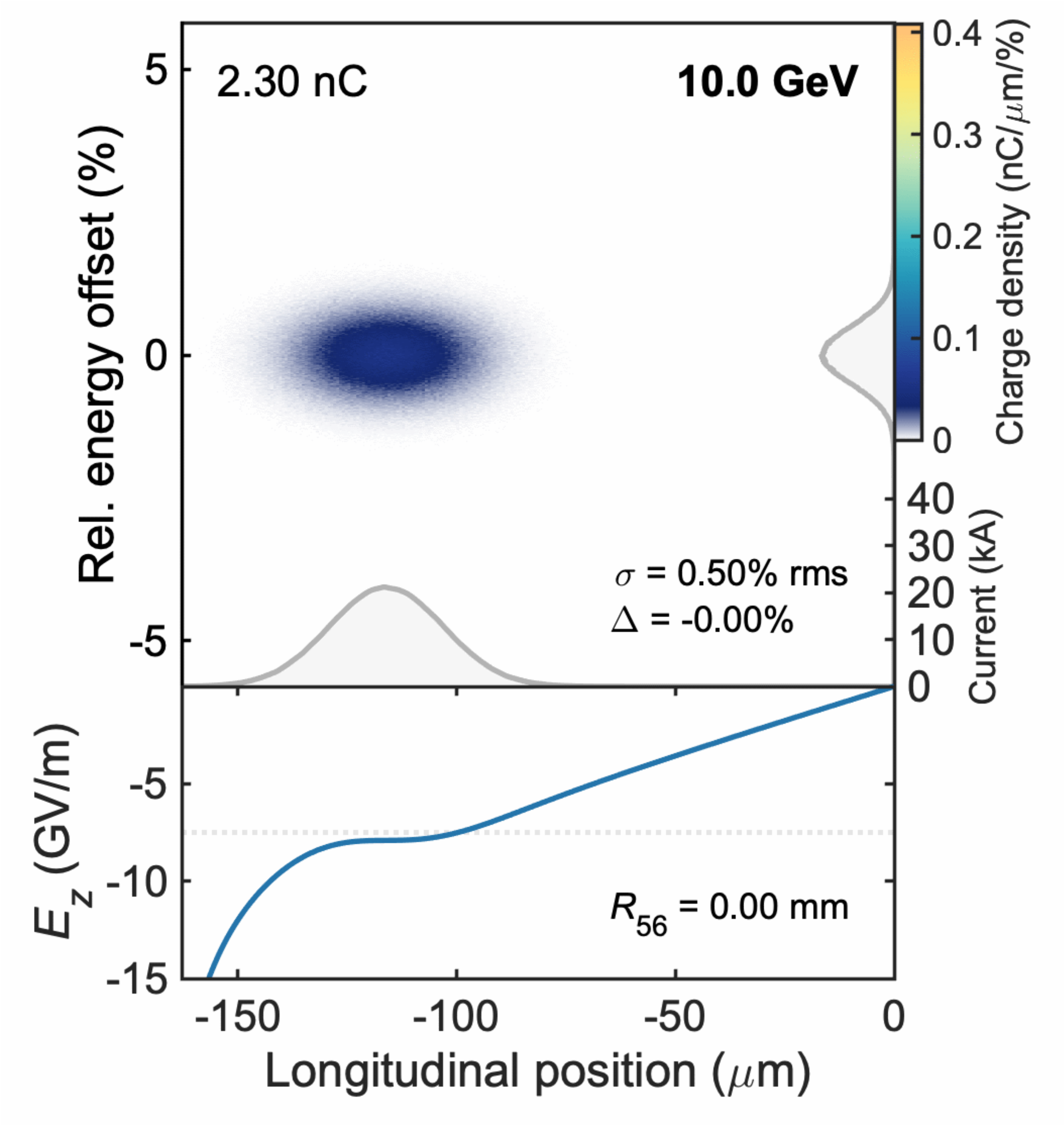


Example #2: Bunch injected too late (10 fs)

No correction



With multistage correction



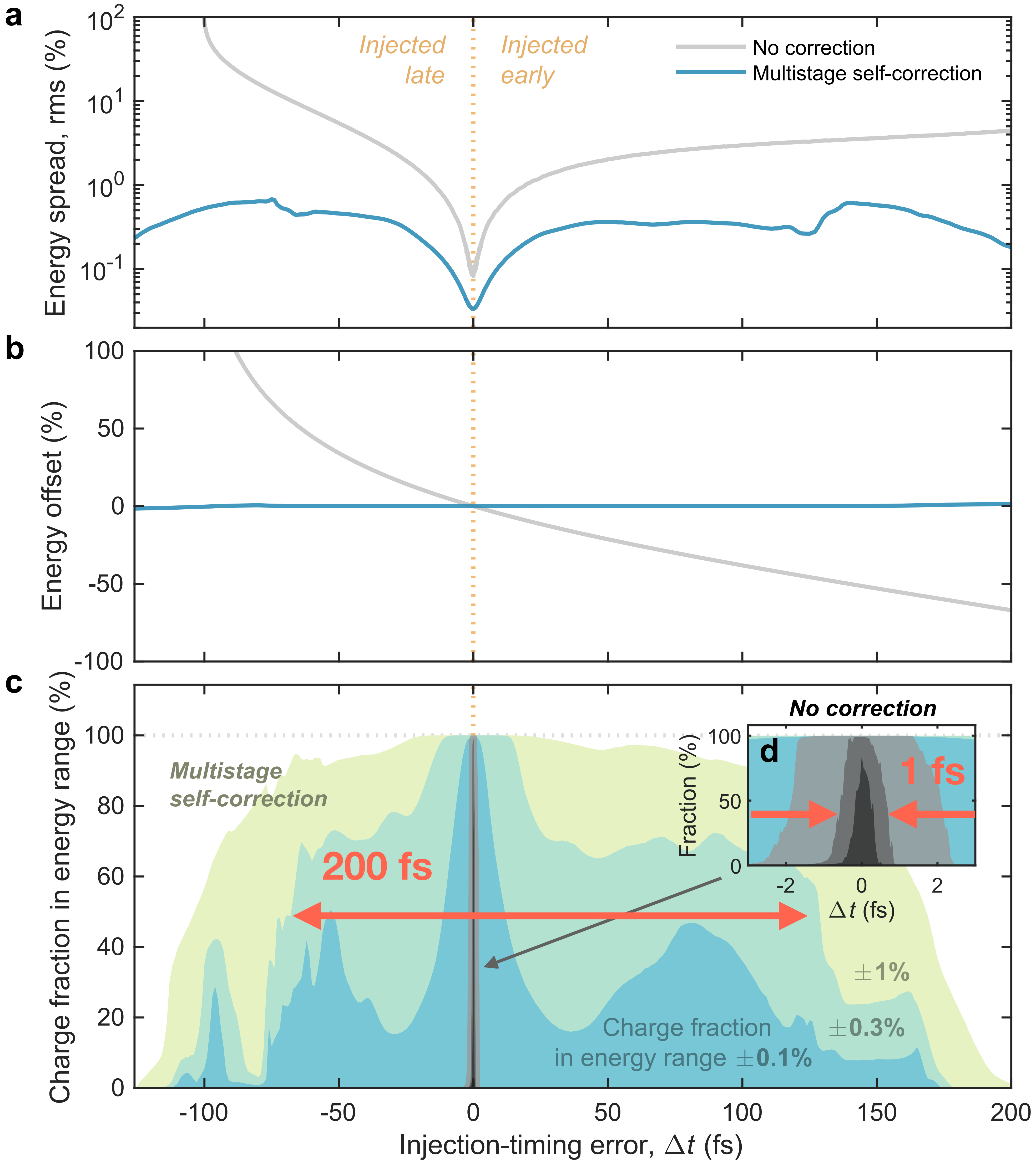
Timing tolerances improve dramatically

- 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

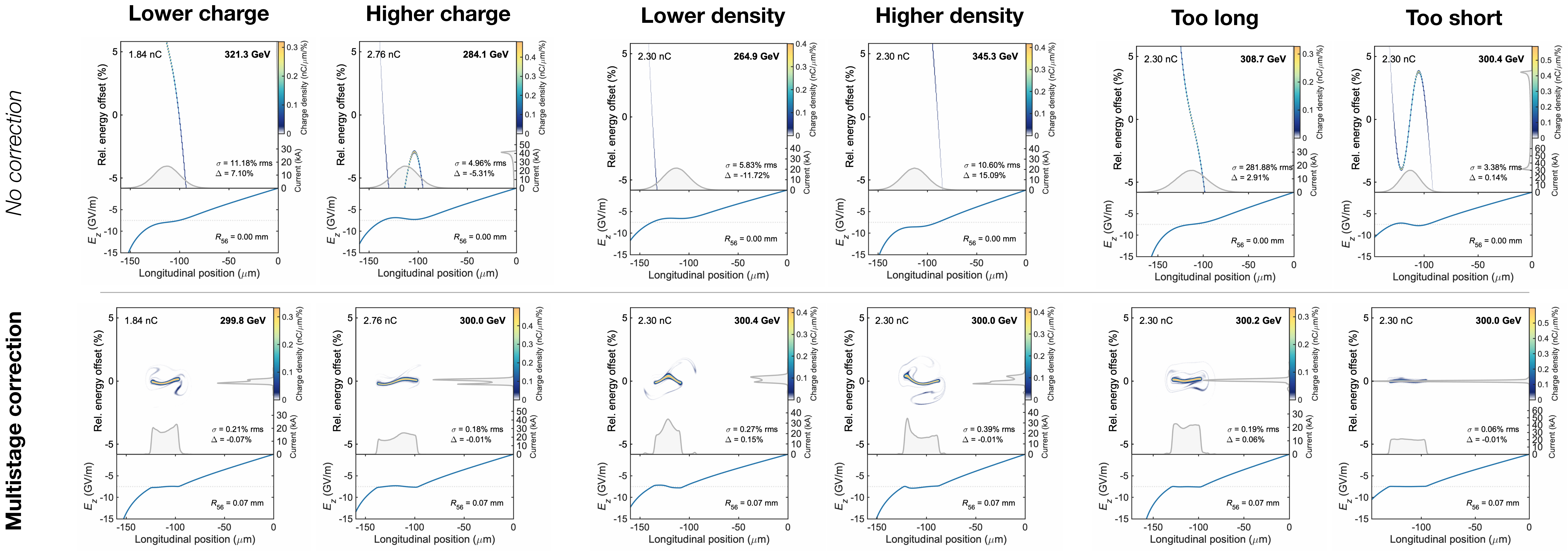
- Well within state-of-the-art synchronization (~10 fs).



Passive stabilization: Significantly improved tolerances

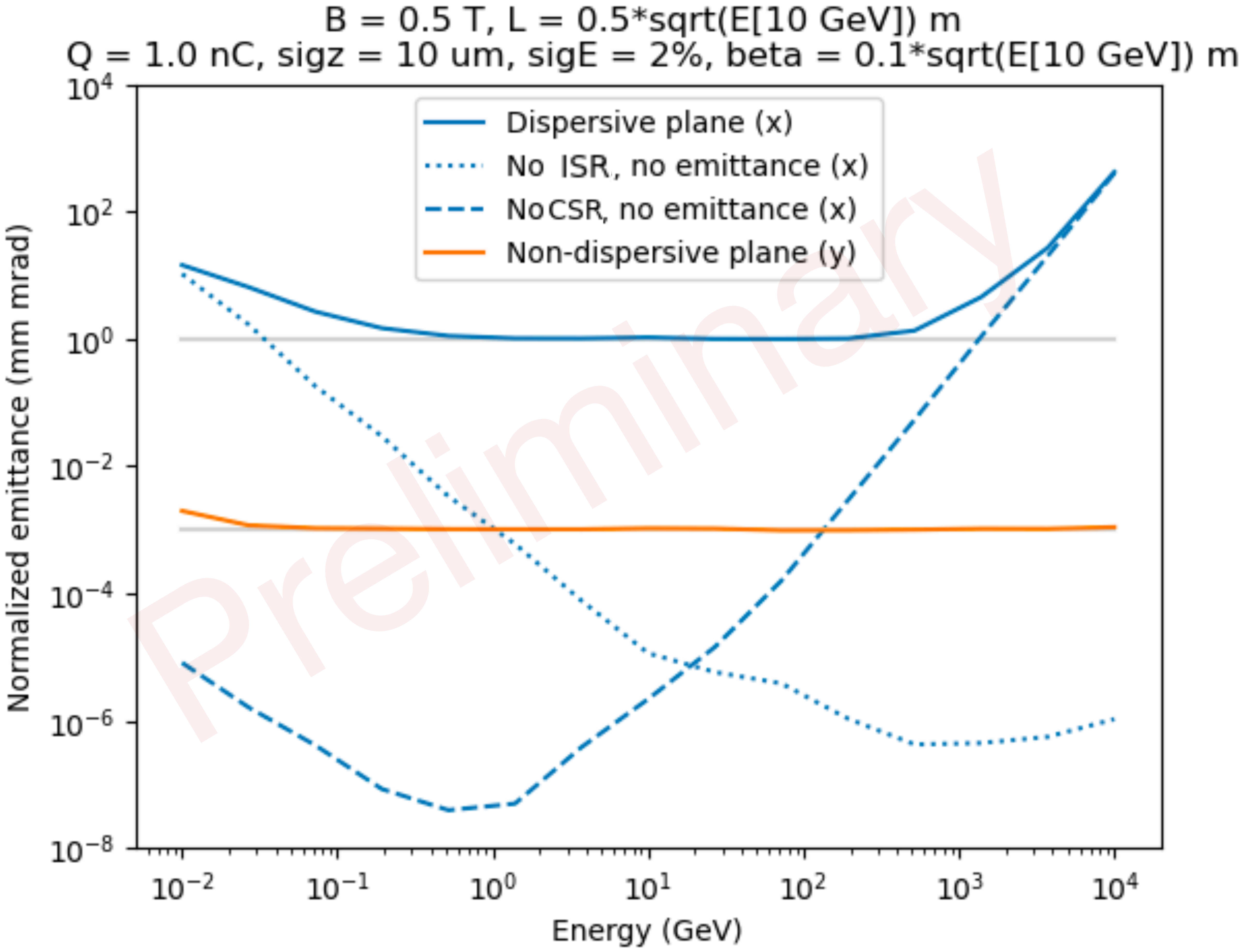
- **Feedback mechanism self-corrects *all* aspects of the current profile:**
  - Tolerant to errors in timing, charge, peak current, bunch length

4 Self-stabilization solve staging problem #4:
Greatly reduced synchronization tolerances



But it has dipoles… **surely CSR or ISR will kill it?** Probably not.

- Using ELEGANT to model coherent and incoherent synchrotron radiation (CSR and ISR).
- Observations:
  - CSR is important at low energy.
  - ISR is important at high energy.
  - No degradation in the non-dispersive plane.
- For a APL-based setup with “reasonable parameters”:
  - **No degradation in range 1 GeV to 1 TeV** for ~20 kA peak current
  - Mostly independent of other parameters (divergence, energy spread, etc.)
- Can further suppress ISR and CSR by using weaker, longer dipoles (same dispersion)—but becomes longer.



Passive stabilization: An analogy

Active stabilization

(Required to some extent
for improved machine performance)

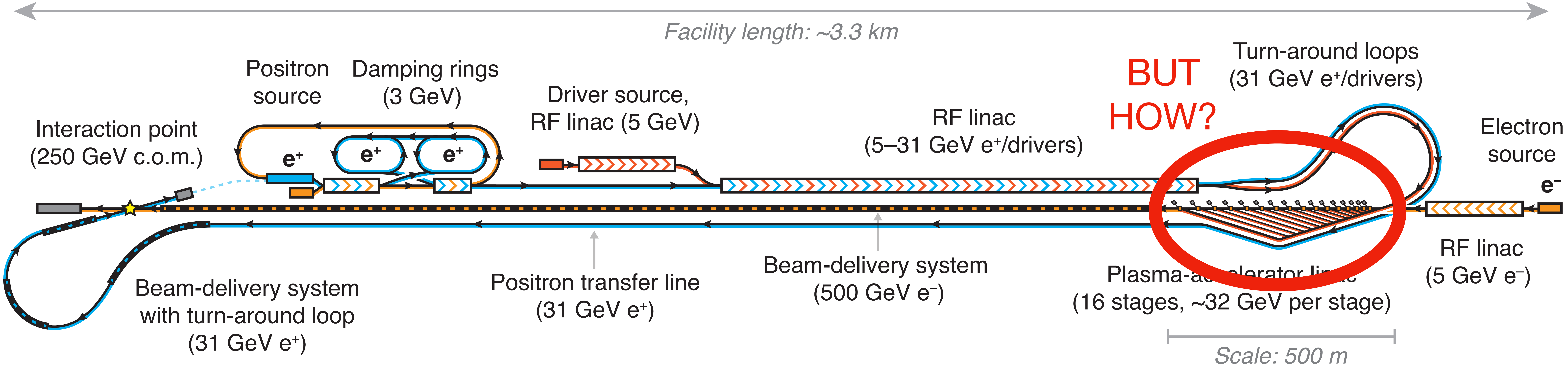
Passive stabilization

(Simpler and cheaper)

A “real-life” example

(work in progress)

Realistic example: hybrid, asymmetric, linear Higgs factory

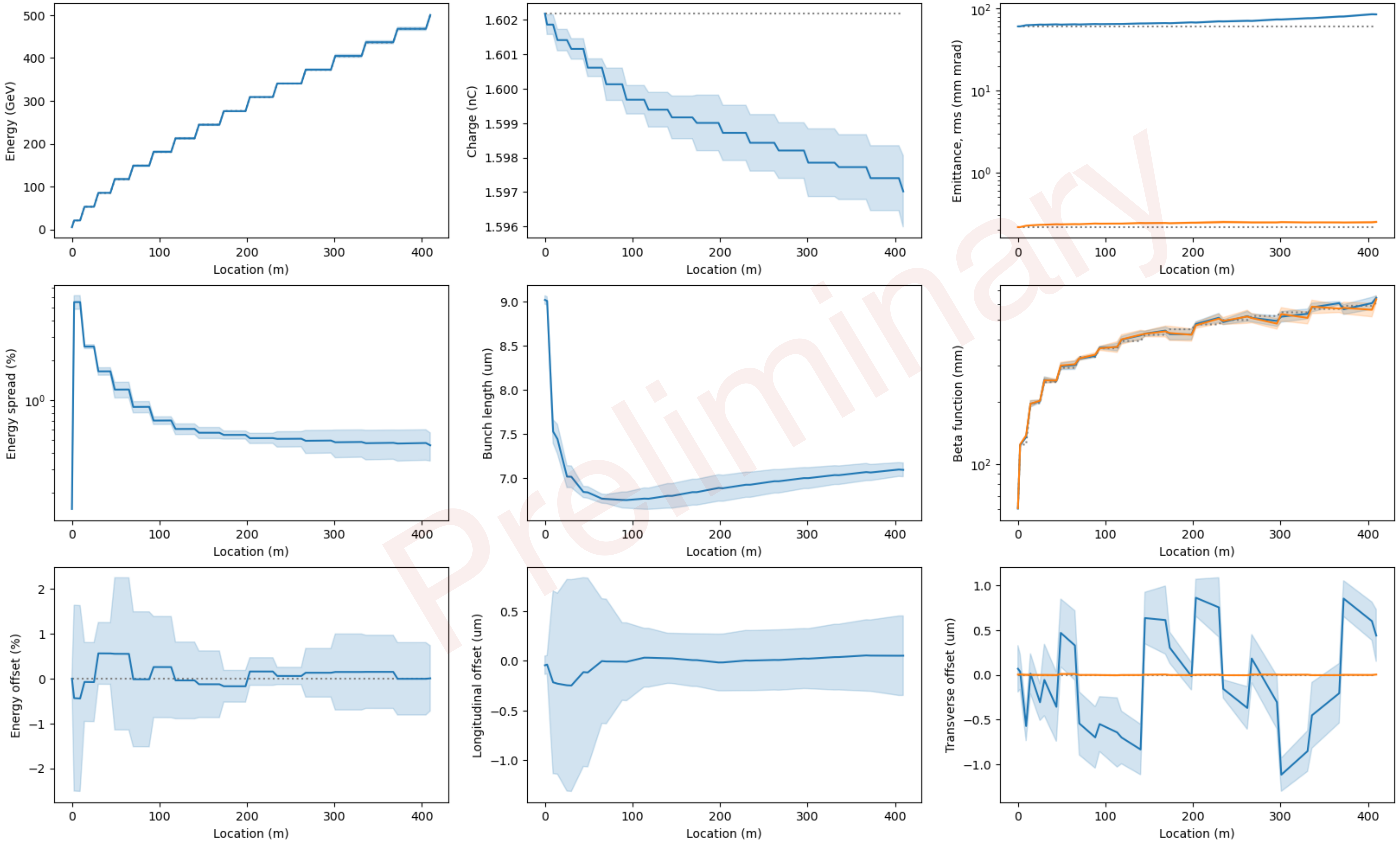


Sketch of the HALFH collider concept. *Source: Foster, D'Arcy and Lindstrøm, preprint at arXiv.2303.10150.*

- Solving the positron problem:
  - Conventional **RF accelerator for positrons** (31 GeV), and **plasma-wakefield acceleration for electrons** (500 GeV).
  - **Asymmetric collisions** at 250 GeV c.o.m. for Higgs–Z (manageable boost at γ = 2.1)
- Will be presented in detail by Brian Foster tomorrow (see preprint on arXiv.2303.10150).

Preliminary multistage plasma linac simulations (reduced 3D model)

- Nonlinear 1D wakefield model
  + Hill's equation for betatron motion
- Achromatic staging using ELEGANT
- Parameters:
  - 16 stages (32 GeV gain per stage)
  - 1.5 x 10^{16} cm^{-2}, 5 m long stages
  - 1.6 nC accel. charge (4.3 nC driver)
  - 74% depletion, 53% transfer efficiency
- **Driver synchronisation jitter: 5 fs rms**
- *Caution: many emittance effects not yet considered (work in progress).*
- More on the simulation approach tomorrow (talk by Erik Adli)



How do we make achromatic staging a reality?

How do we make achromatic staging a reality?

- **Step 1: Demonstrate nonlinear plasma lenses (conceptually, then experimentally)**
  - Can be active or passive plasma lenses.
- **Step 2: Demonstrate beam-quality-preserving staging (experimentally)**
  - In principle, no second stage is required—but good diagnostics is
- **Step 3: Demonstrate self-correction across multiple stages**
  - Can double as a high-energy demonstrator facility for strong-field QED

SPARTA: **S**taging of **P**lasma **A**ccelerators
for **R**ealizing **T**imely **A**pplications

Take-aways

- Staging (likely) required to reach high energy with high efficiency.
- Nonlinear plasma lenses can *potentially* solve all the main problems of staging:
  - *Compactness (with plasma lensing)*
  - *In- and out-coupling of drivers (with dipoles)*
  - *Emittance growth (with local chromaticity correction)*
  - *Tight synchronization tolerances (with self-correction)*
- Next steps:
  - Realize nonlinear plasma lenses
  - Simulate plasma linacs (and colliders) with increasing degree of accuracy (all effects included)
  - Experimental demonstration of
    (1) quality-preserving staging
    (2) self-correction