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Solutions and challenges for a multi-stage plasma accelerator

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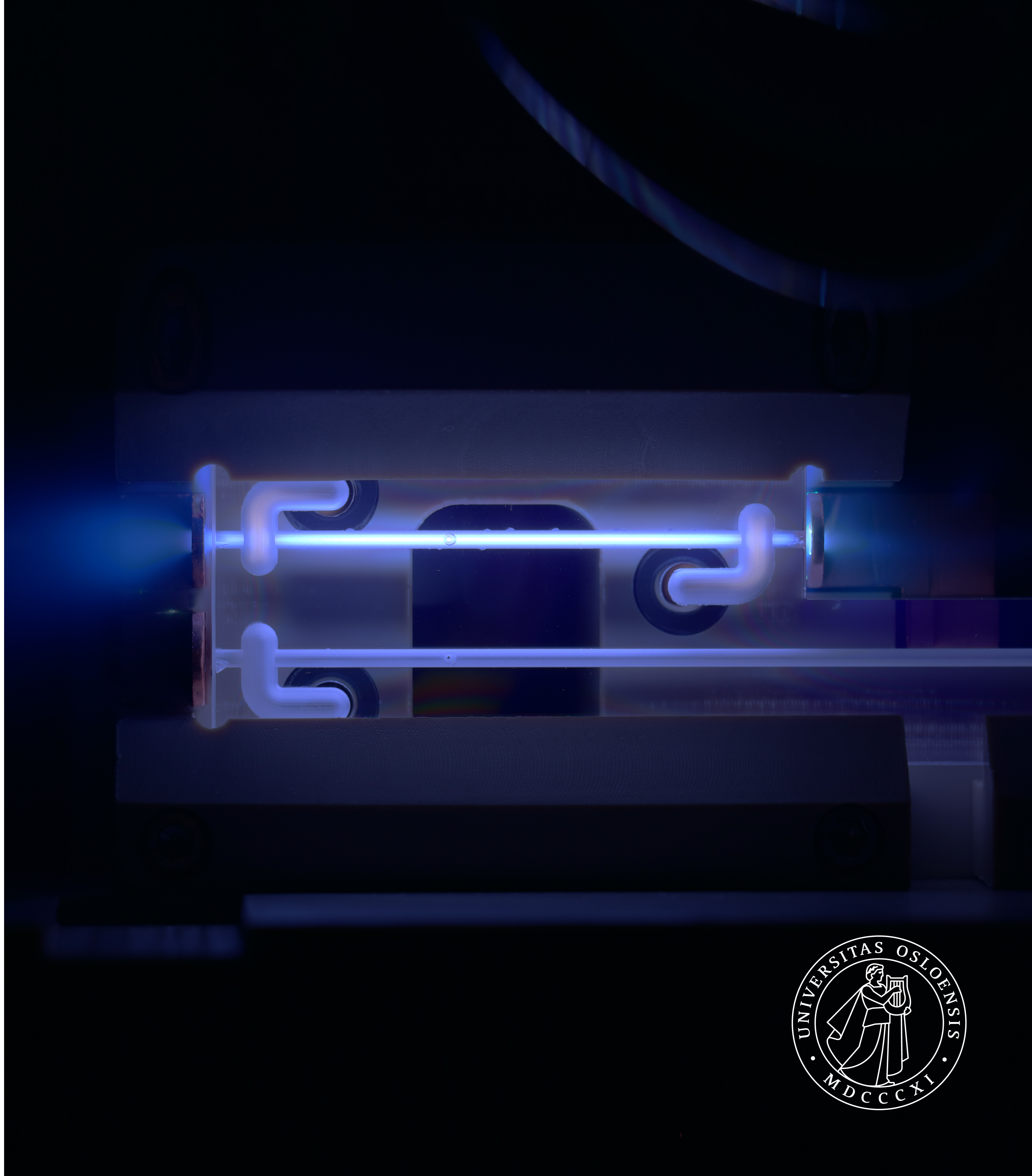
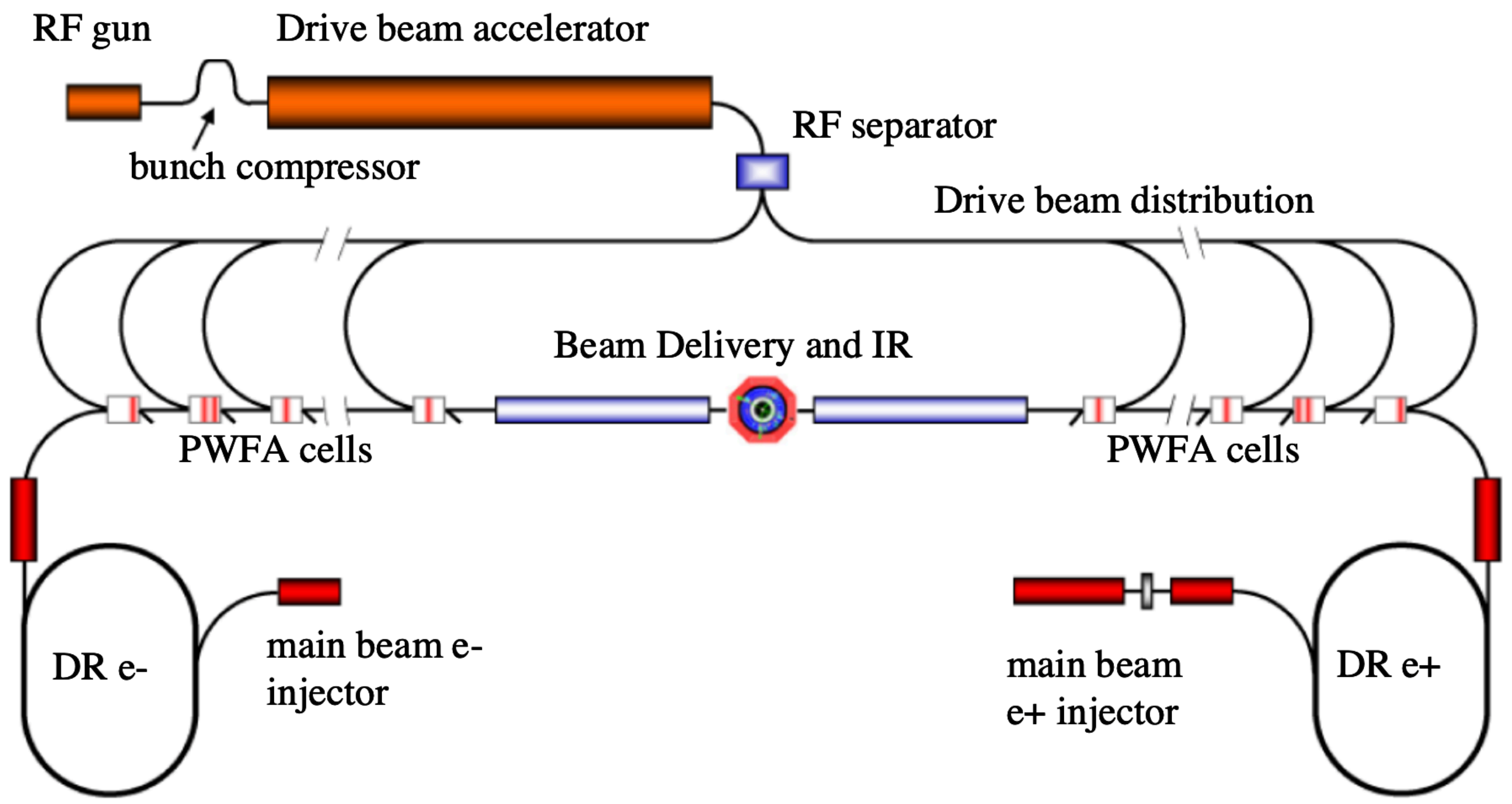


Motivation: Reaching **high energy, compactly** and **efficiently**

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

> **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, overall not compact*
>> Solution #2: High transformer ratio (shaped driver)
>>> *Limits: Difficult to go beyond 5–10, very sensitive to current profile*



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

> **Use of multiple stages (staging) is 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)

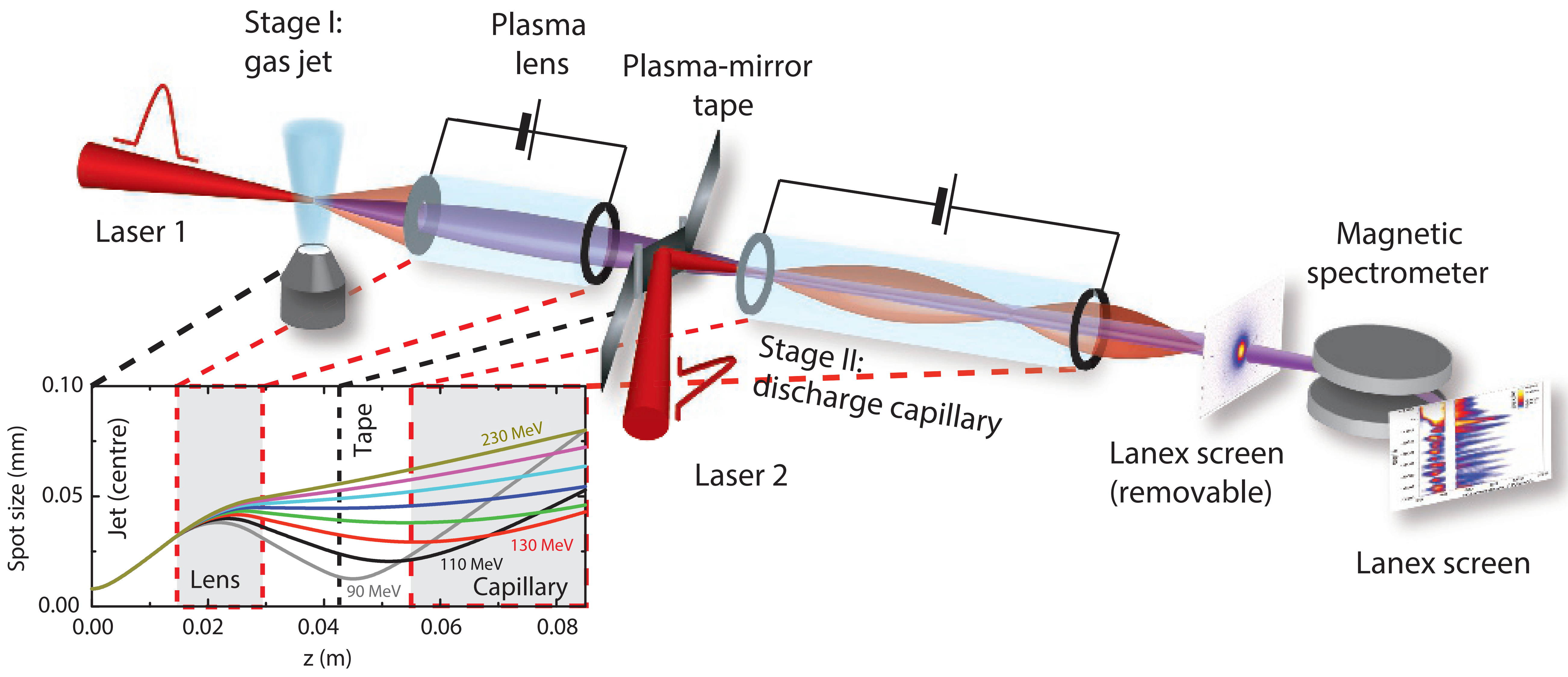


Image source: Steinke et al., Nature 530, 190 (2016).

> **Staging is non-trivial for four reasons:**
>
> > Reduced average gradient (compactness)
> >
> > In- and out-coupling of drivers
> >
> > Emittance growth from chromaticity
> >
> > Tight synchronization tolerances

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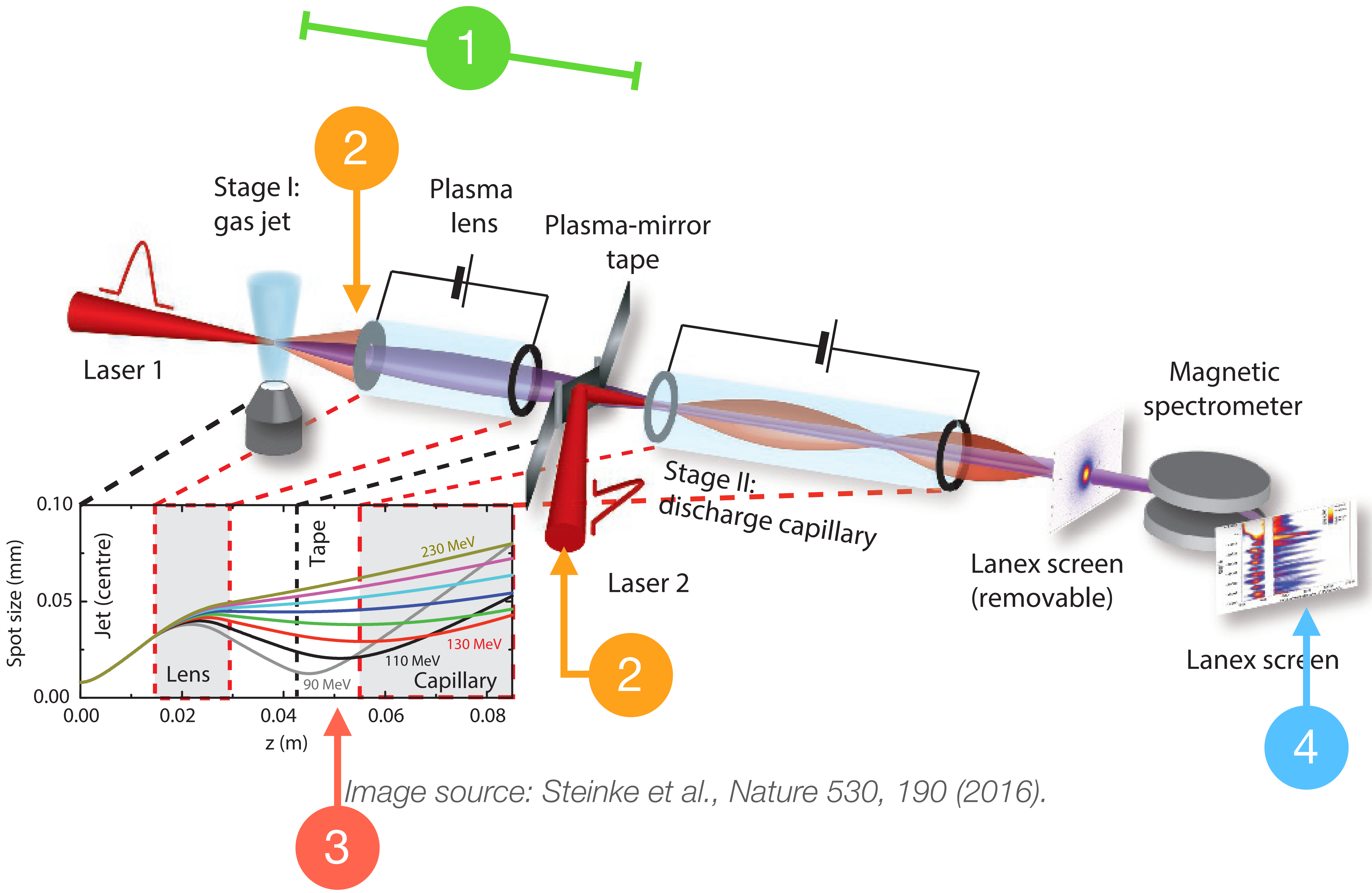

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  2. In- and out-coupling of drivers
  3. Emittance growth from chromaticity
  4. Tight synchronization tolerances

Novel solutions for staging

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

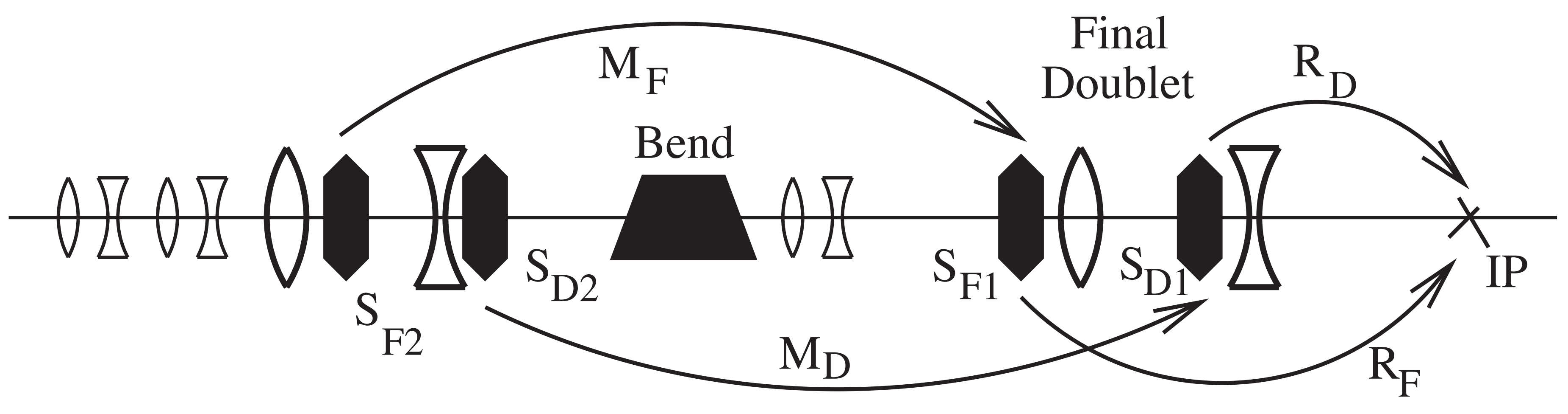
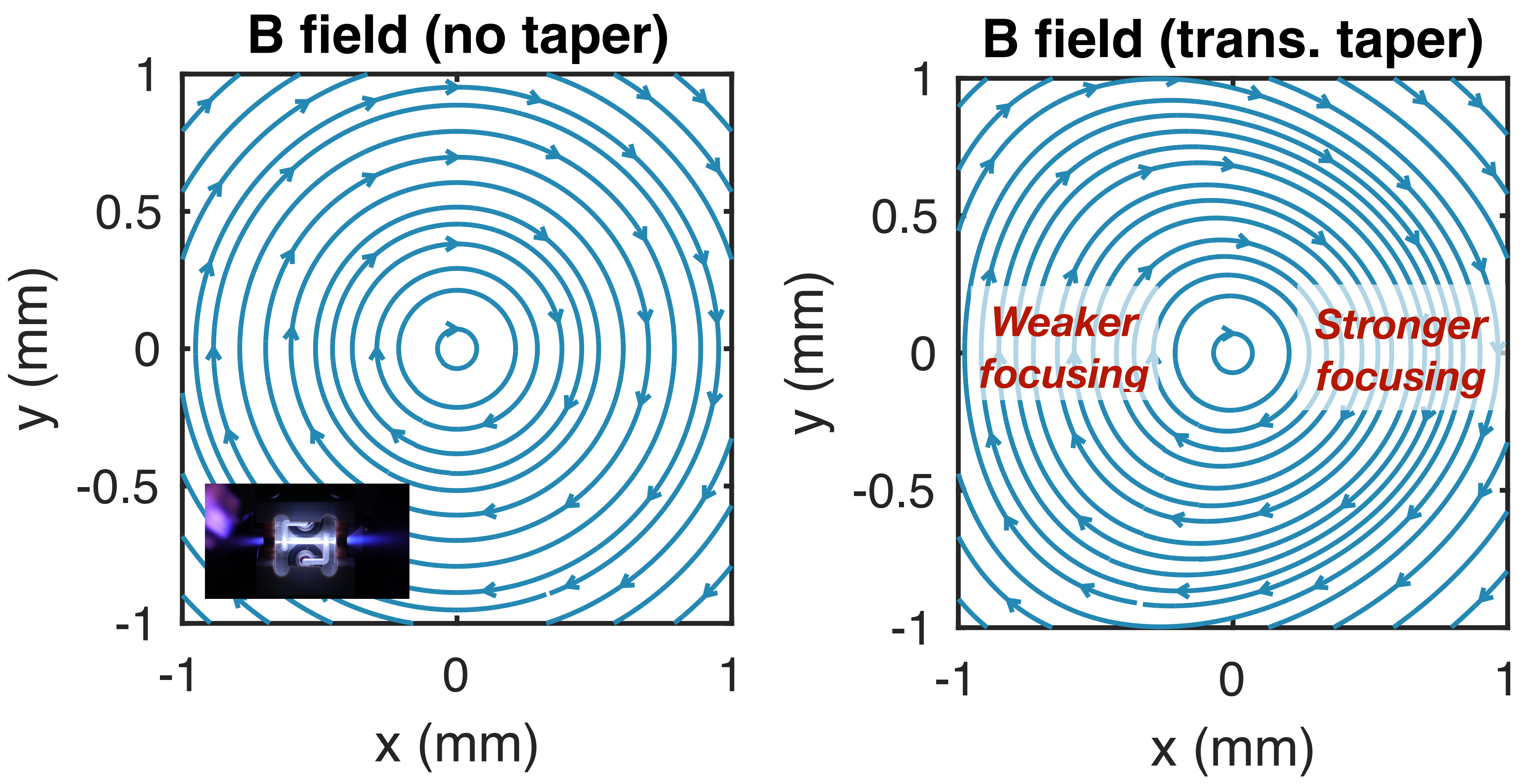


Image source: Raimondi & Seryi, Phys. Rev. Lett. 86, 3779 (2001)



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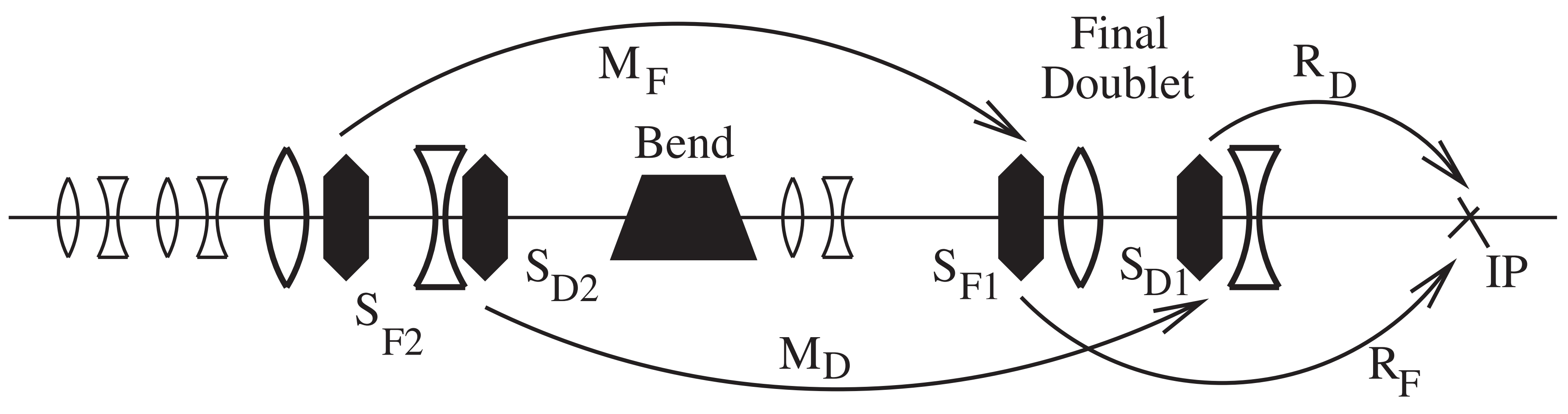

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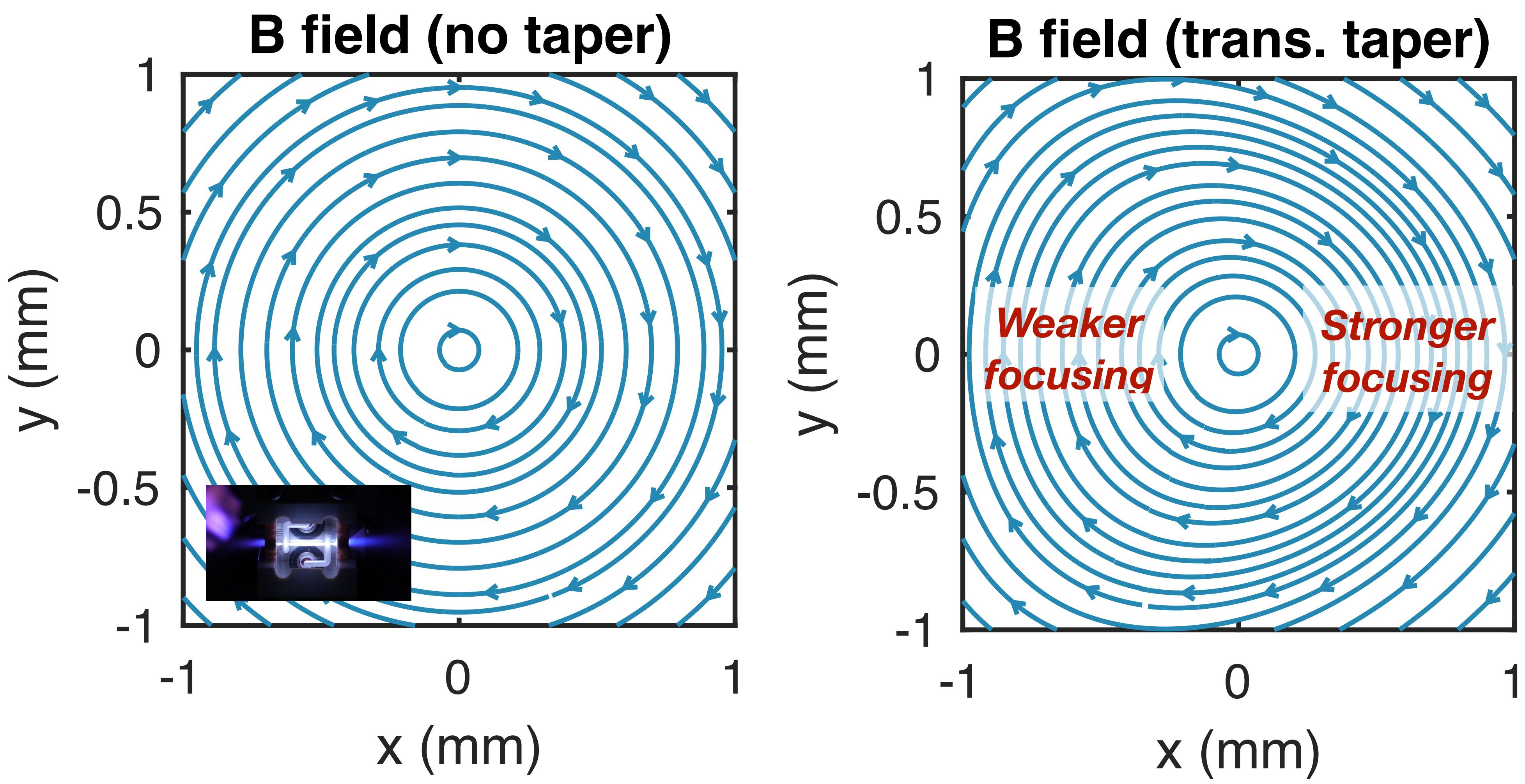
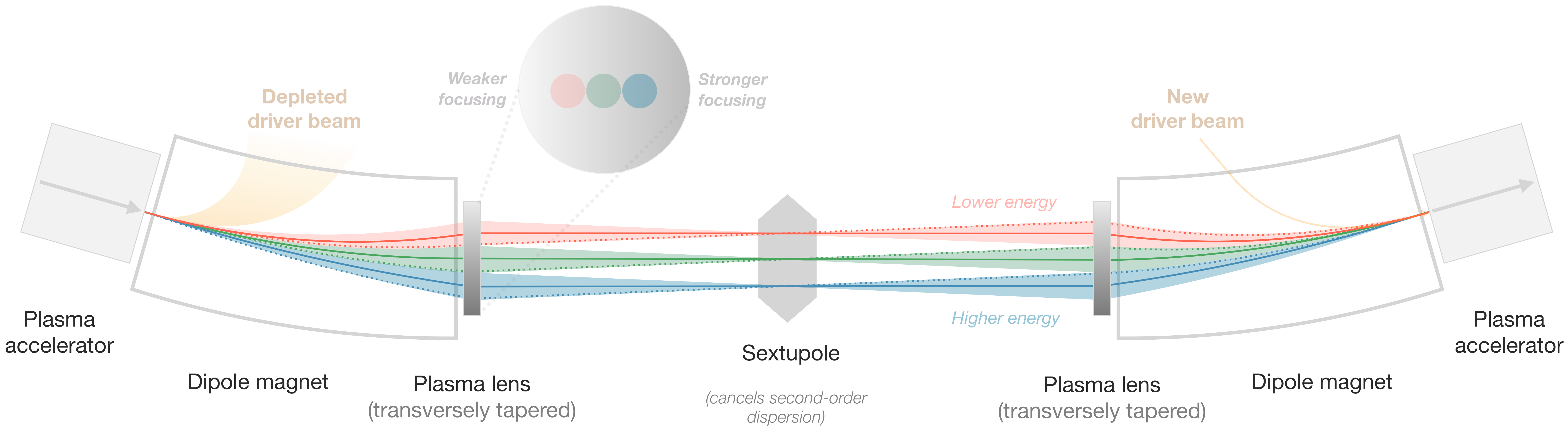
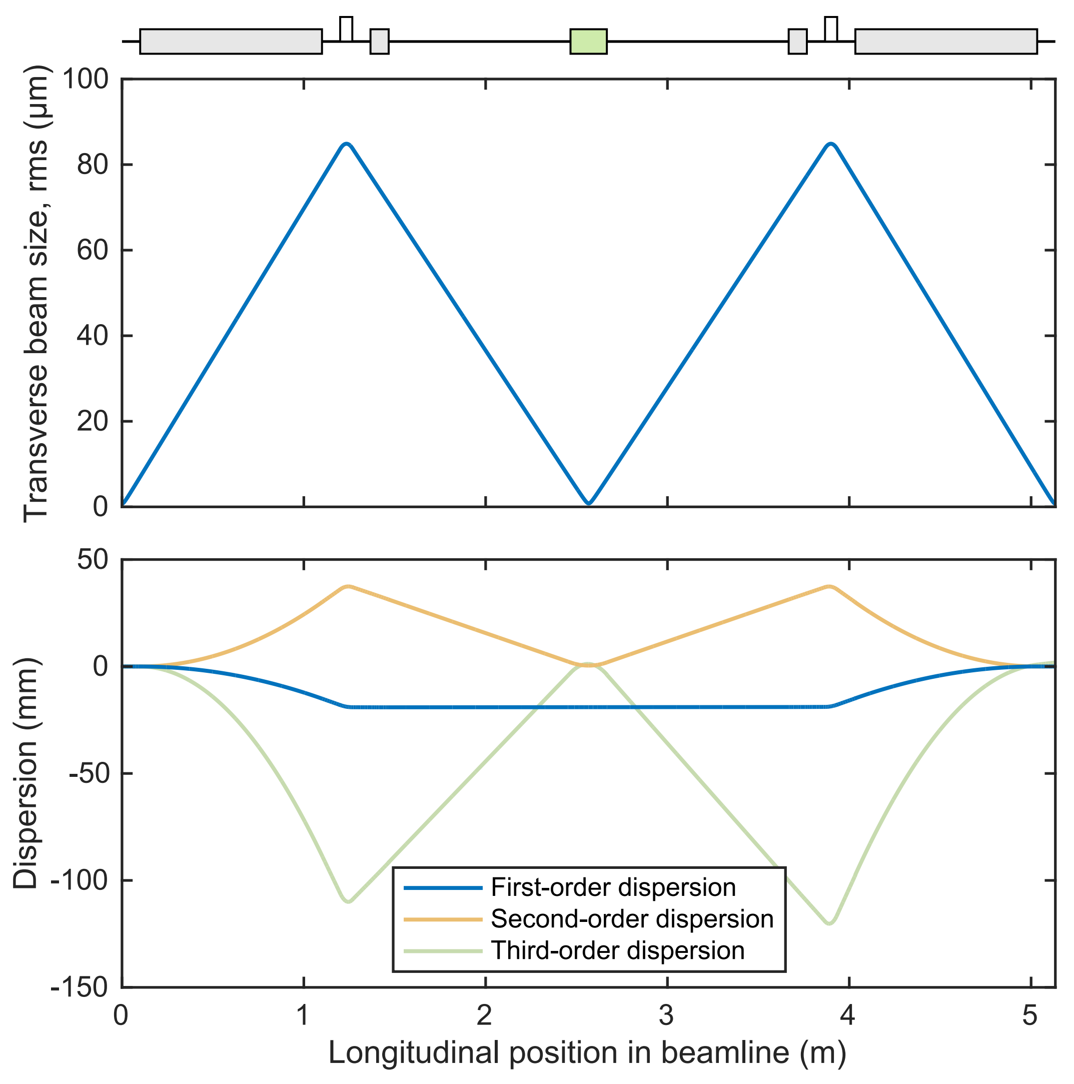


1 Plasma lenses solve staging problem #1:
High average acceleration gradient

An **achromatic lattice** for staging

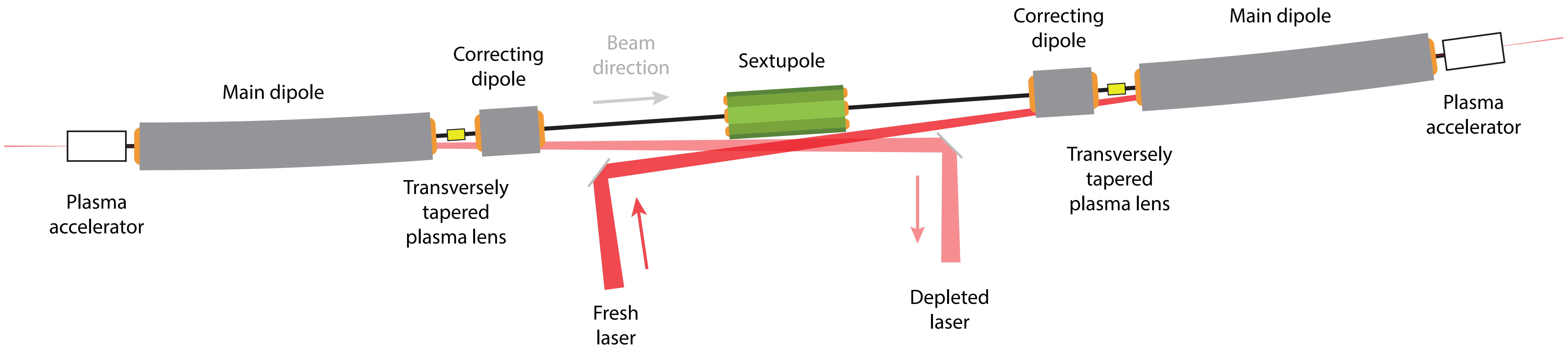


- Simplest lattice for achromatic and emittance-preserving staging:
  - **Two dipoles** (for dispersion)
  - **Two nonlinear plasma lenses** (for chromaticity correction)
  - **One central sextupole** (for second-order dispersion correction)
- Nonlinear focusing causes emittance growth:
  - Use **mirror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

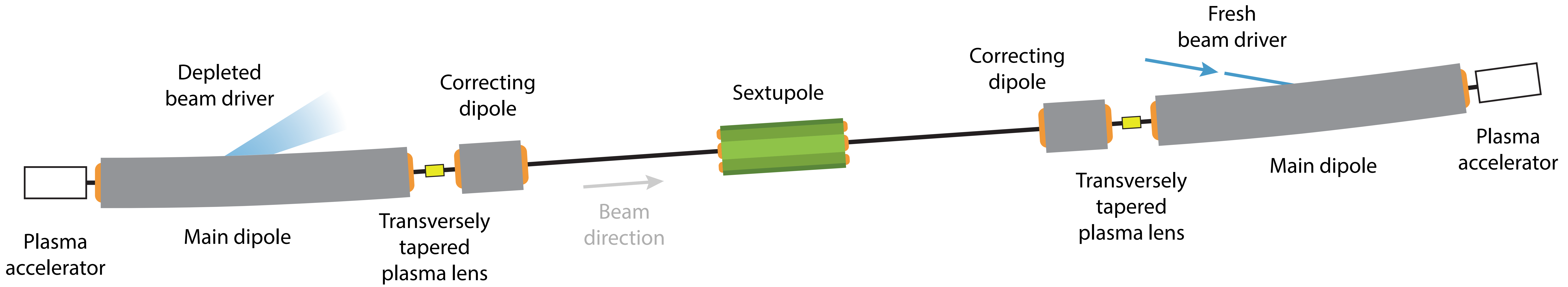


In- and out-coupling of drivers

- Dipoles allow in- and out-coupling of **both laser- and beam drivers**.
- A net angle is introduced (decreasing with energy): “linac” ⇒ “**bananac**”
- **Laser driven:**



- **Beam driven:**

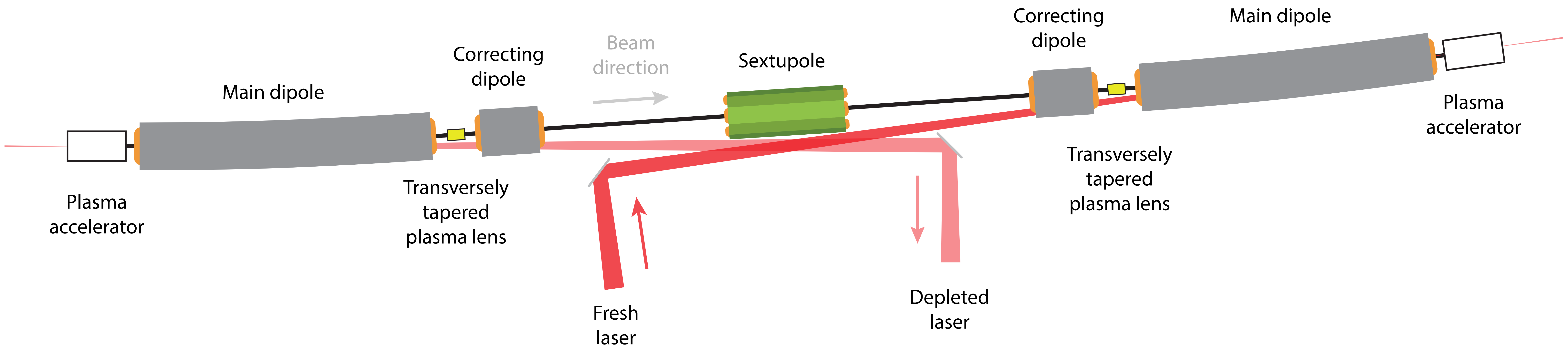


In- and out-coupling of drivers

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): “linac” ⇒ “**bananac**”

Laser driven:



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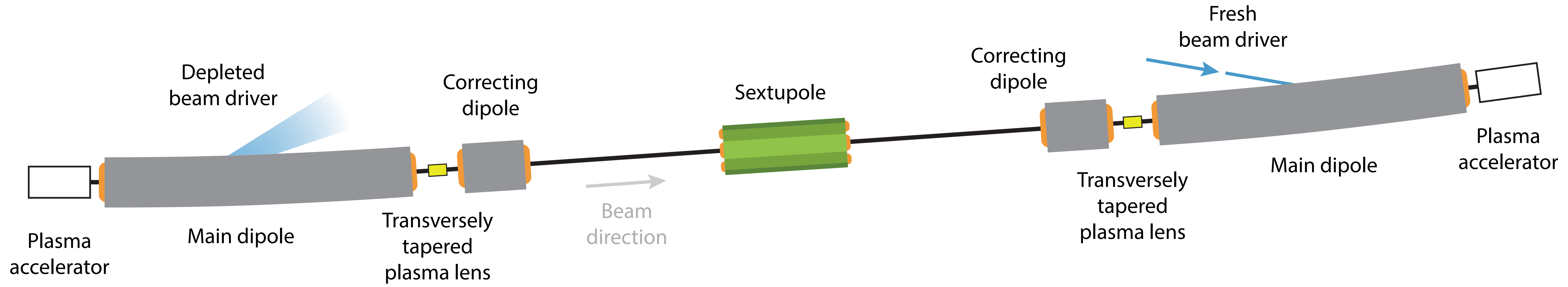
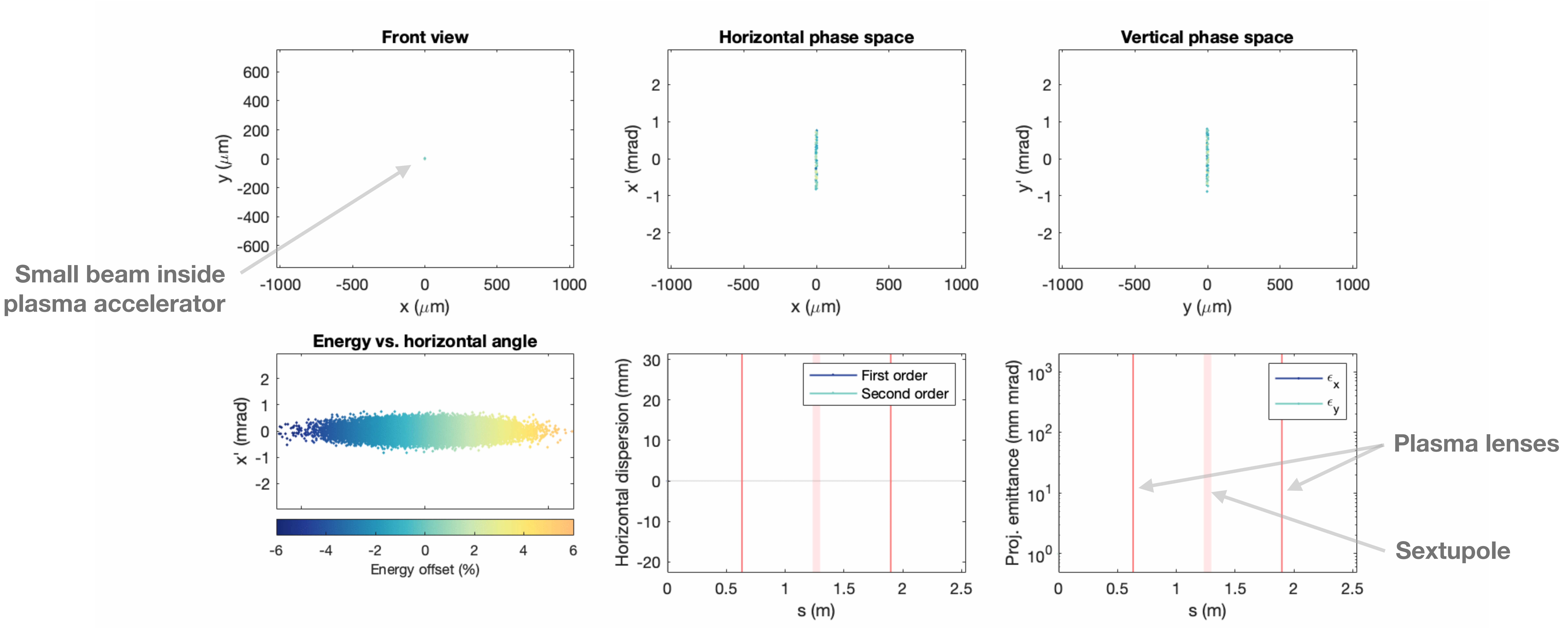


Achromatic optics, explained



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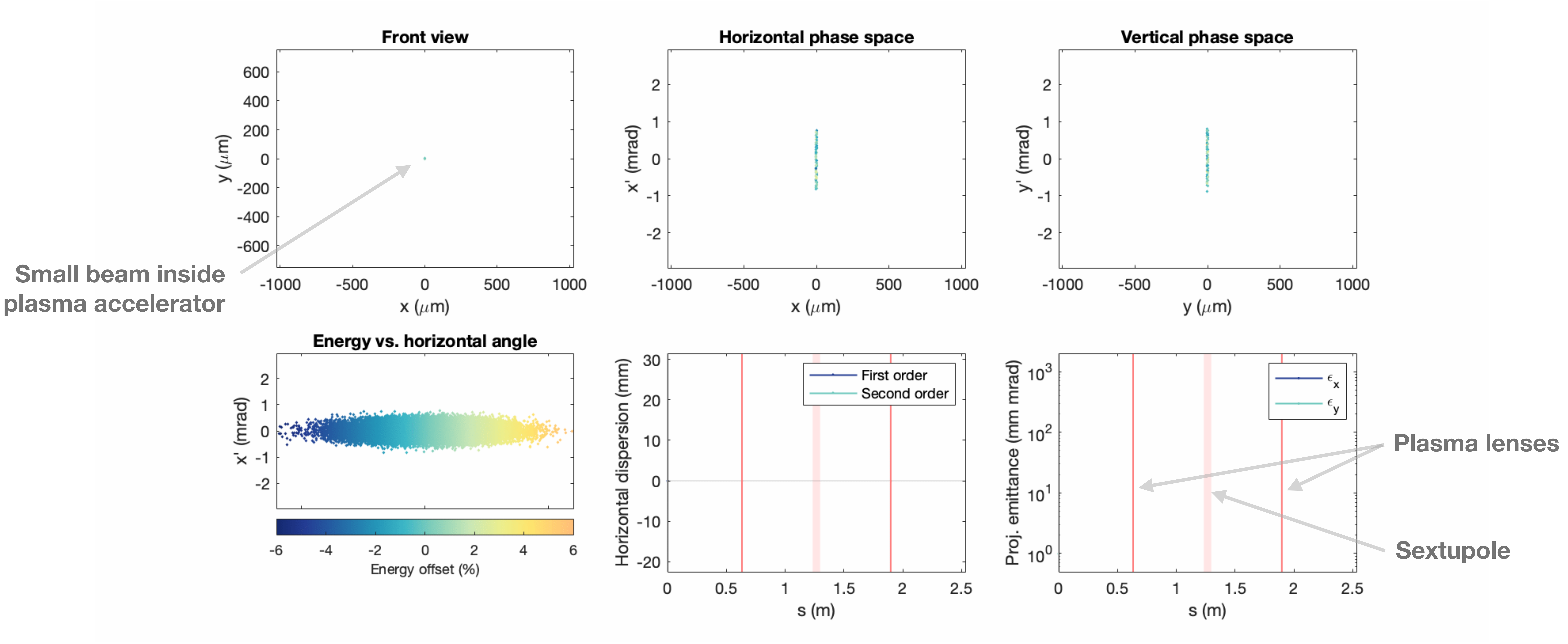

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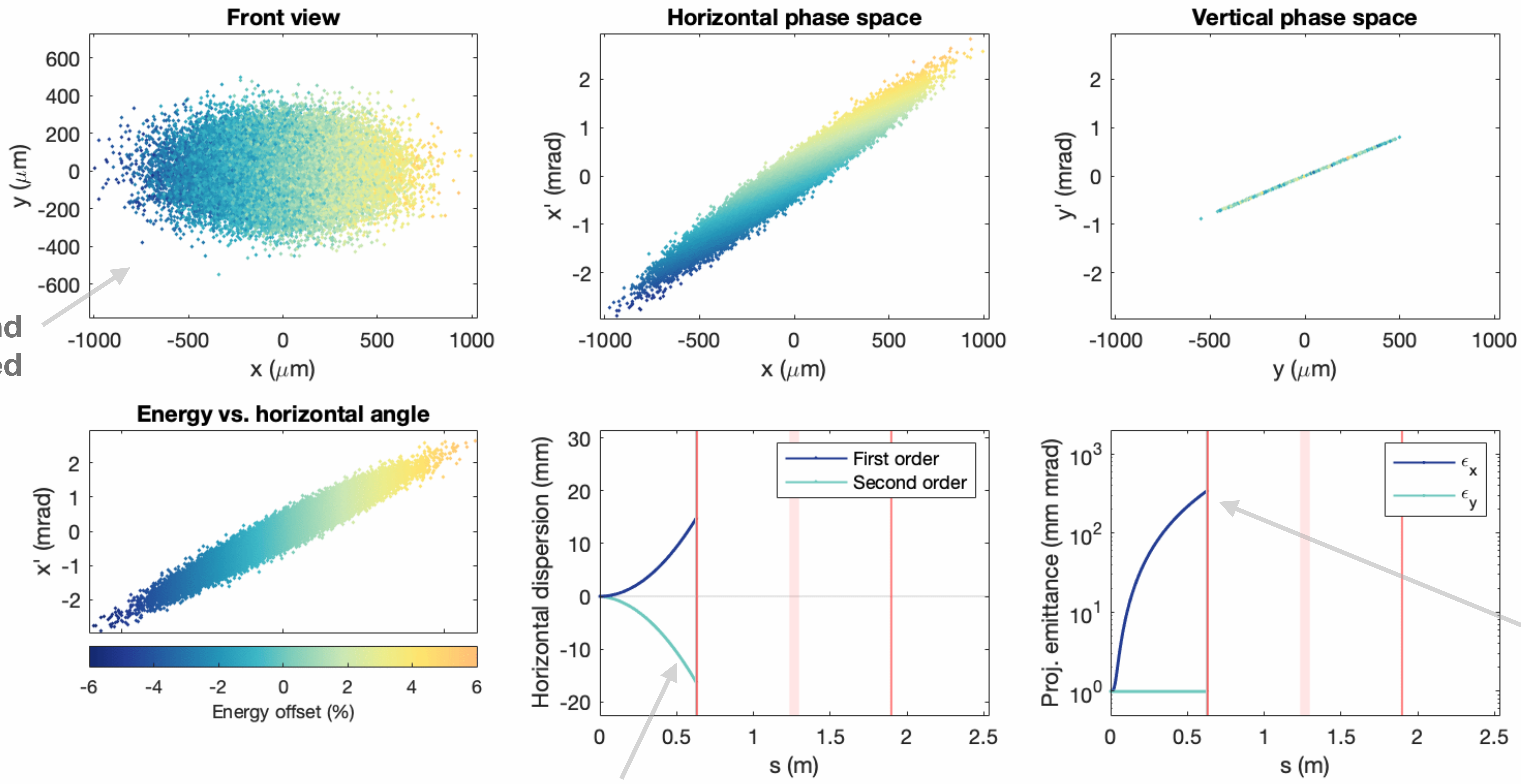

Diverged and dispersed

Dispersed in lens

Emittance growth from dispersion

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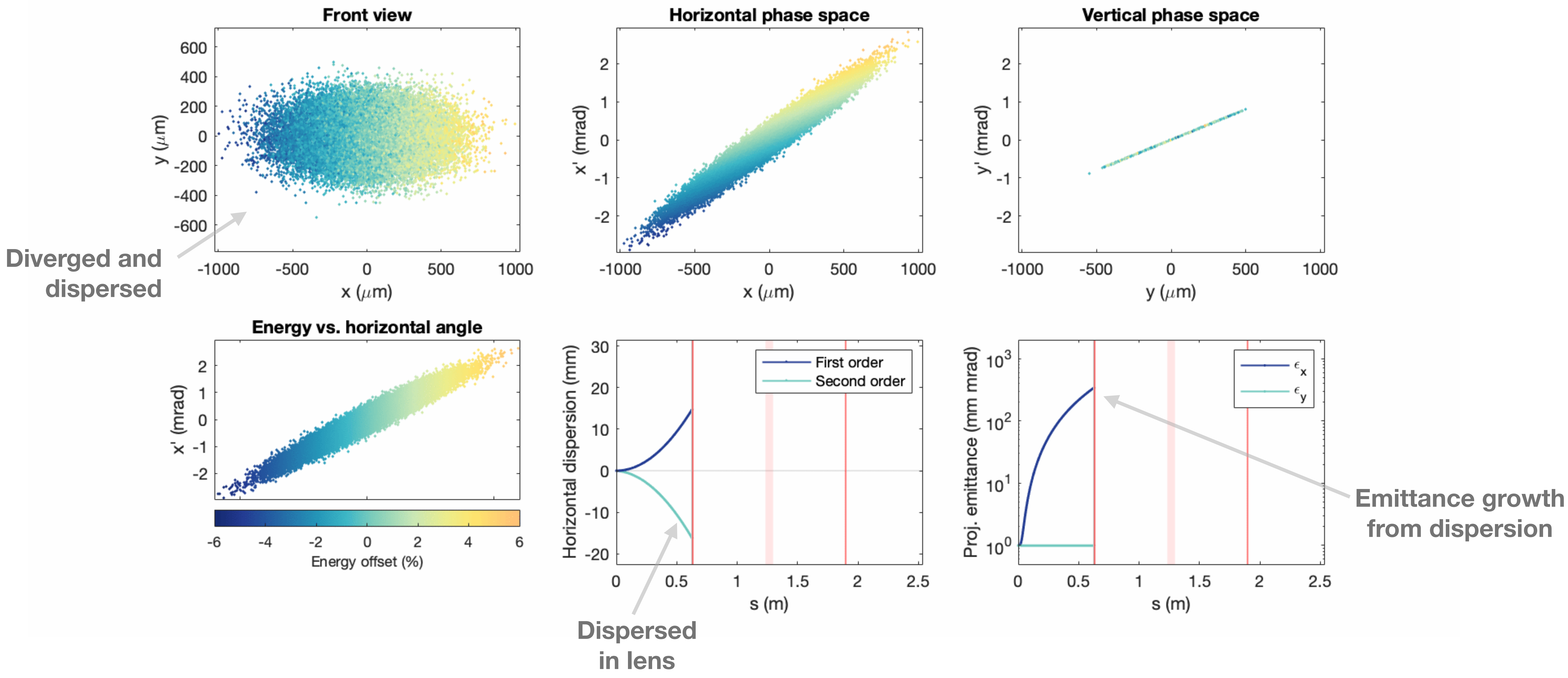

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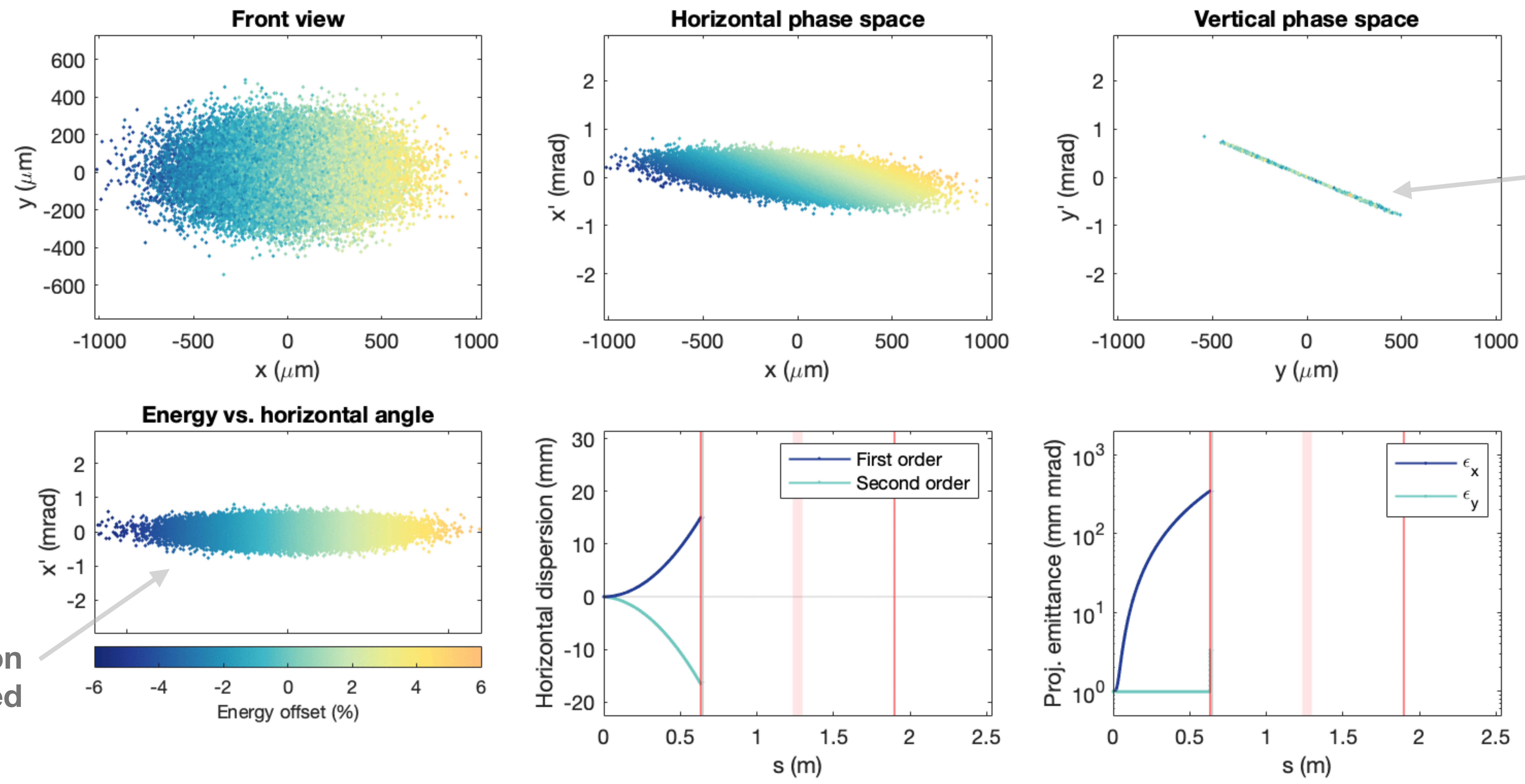

Phase spaces are flipped

Dispersion is collimated

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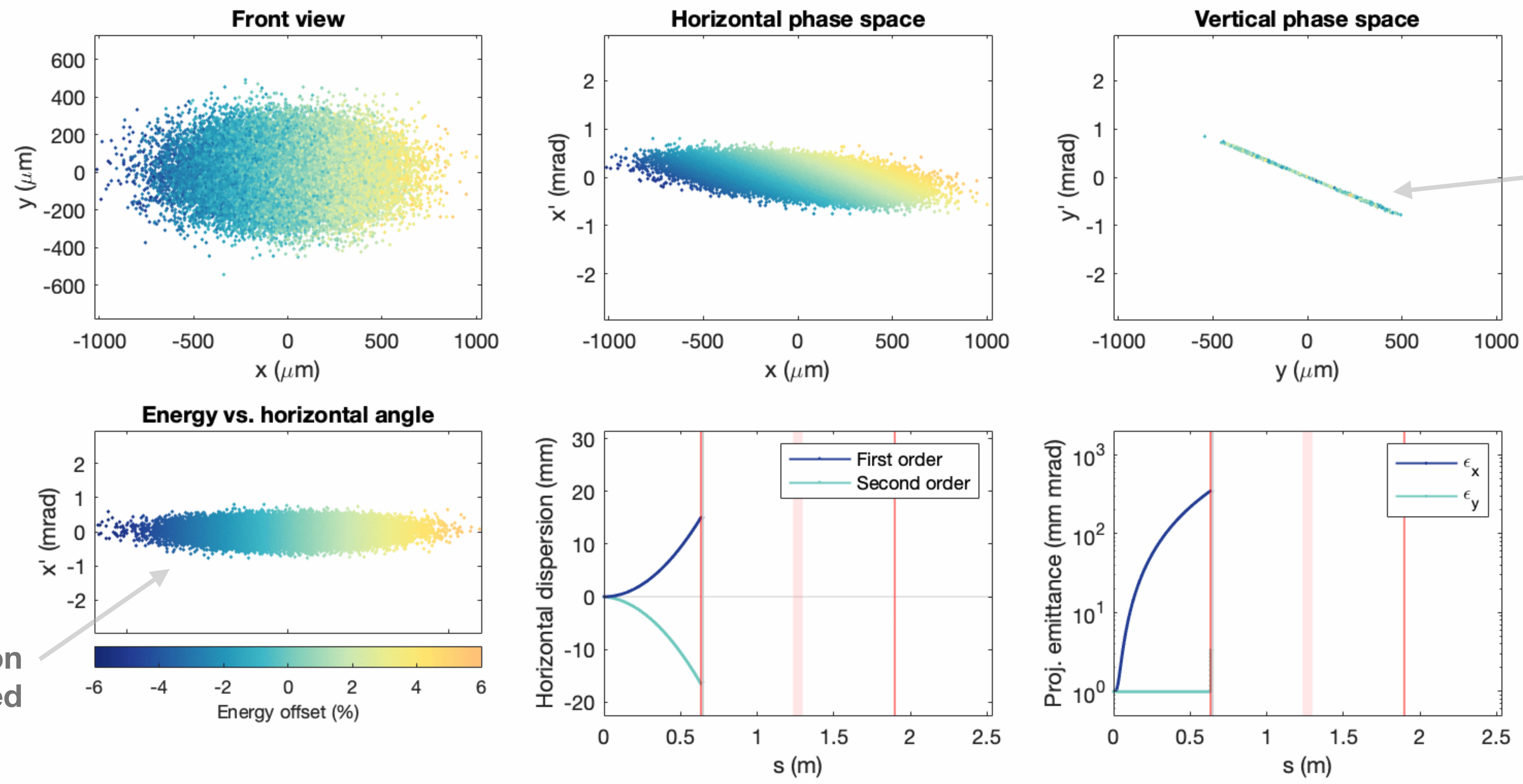

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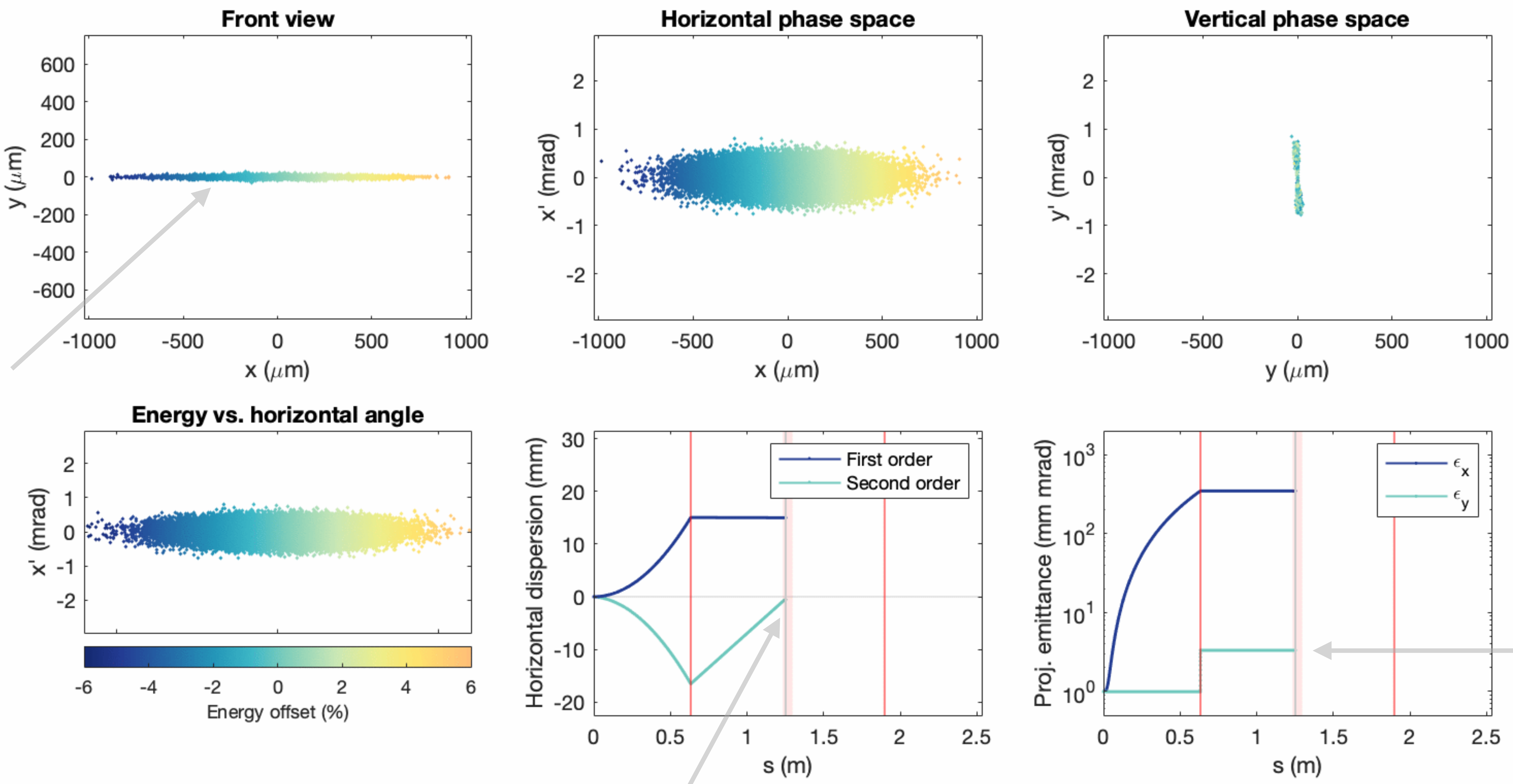

Beam size is small, but dispersed

Second-order dispersion is cancelled

Emittance growth from nonlinear focusing

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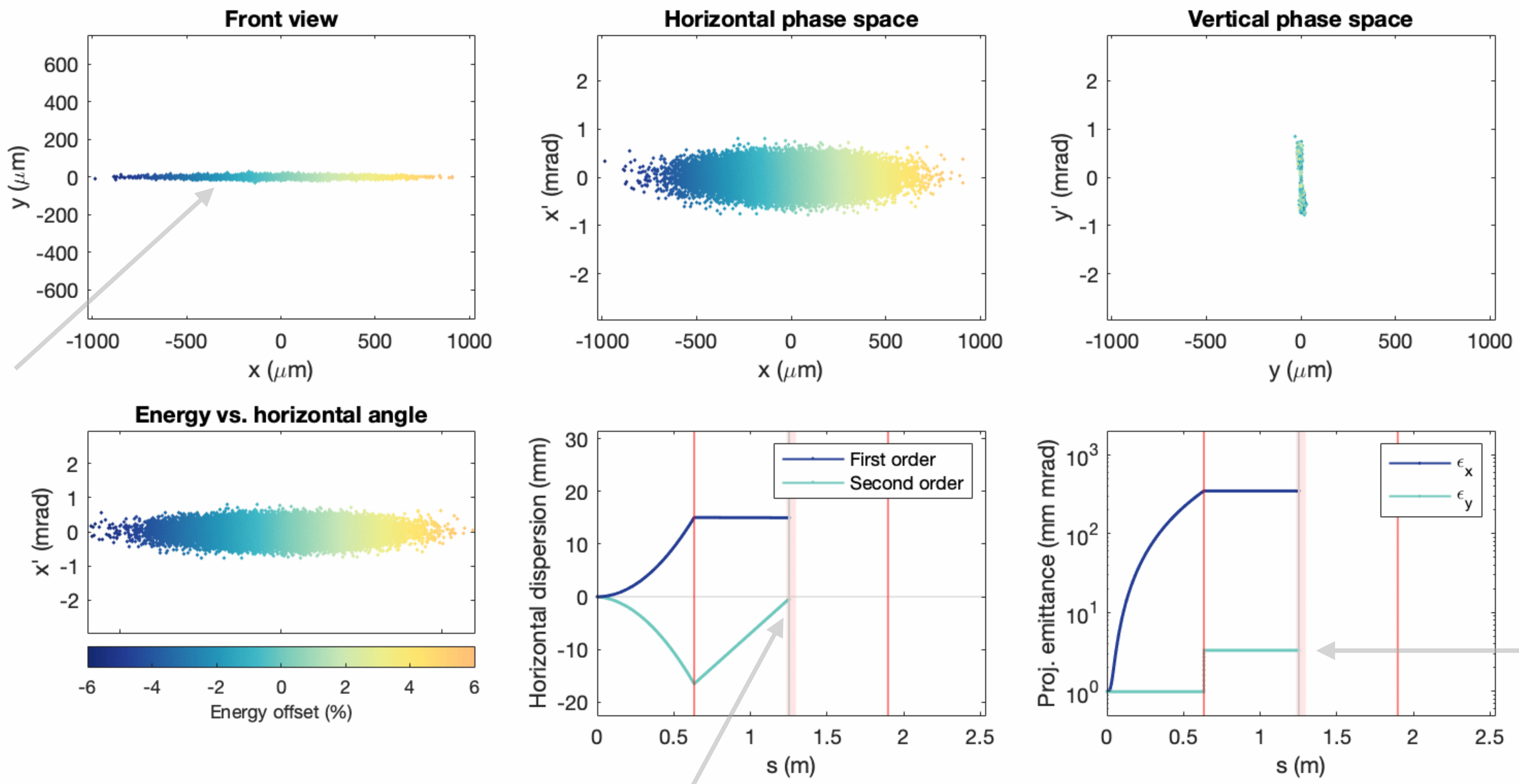

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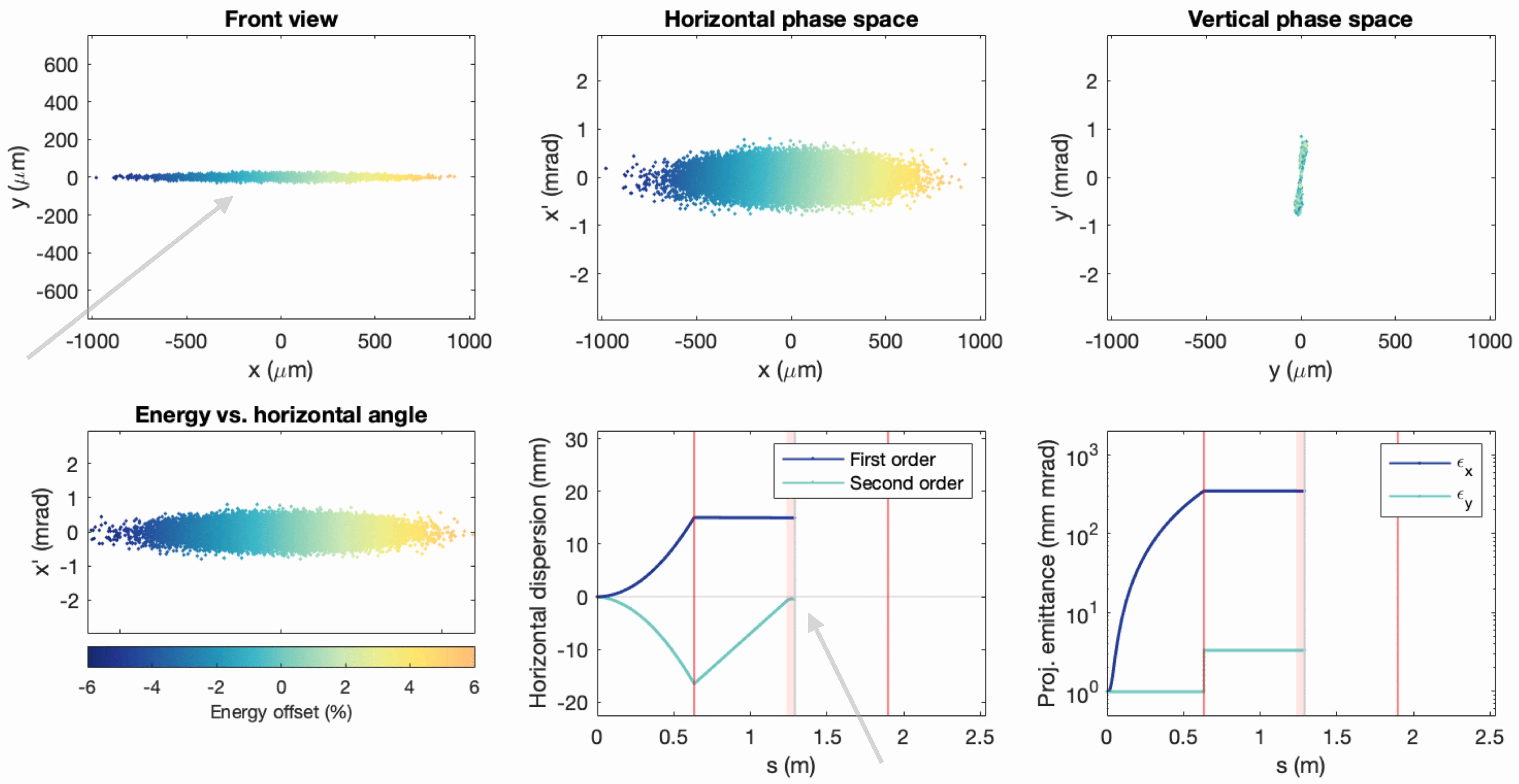

Negligible effect of sextupole (small beam size)

Second-order dispersion flips direction

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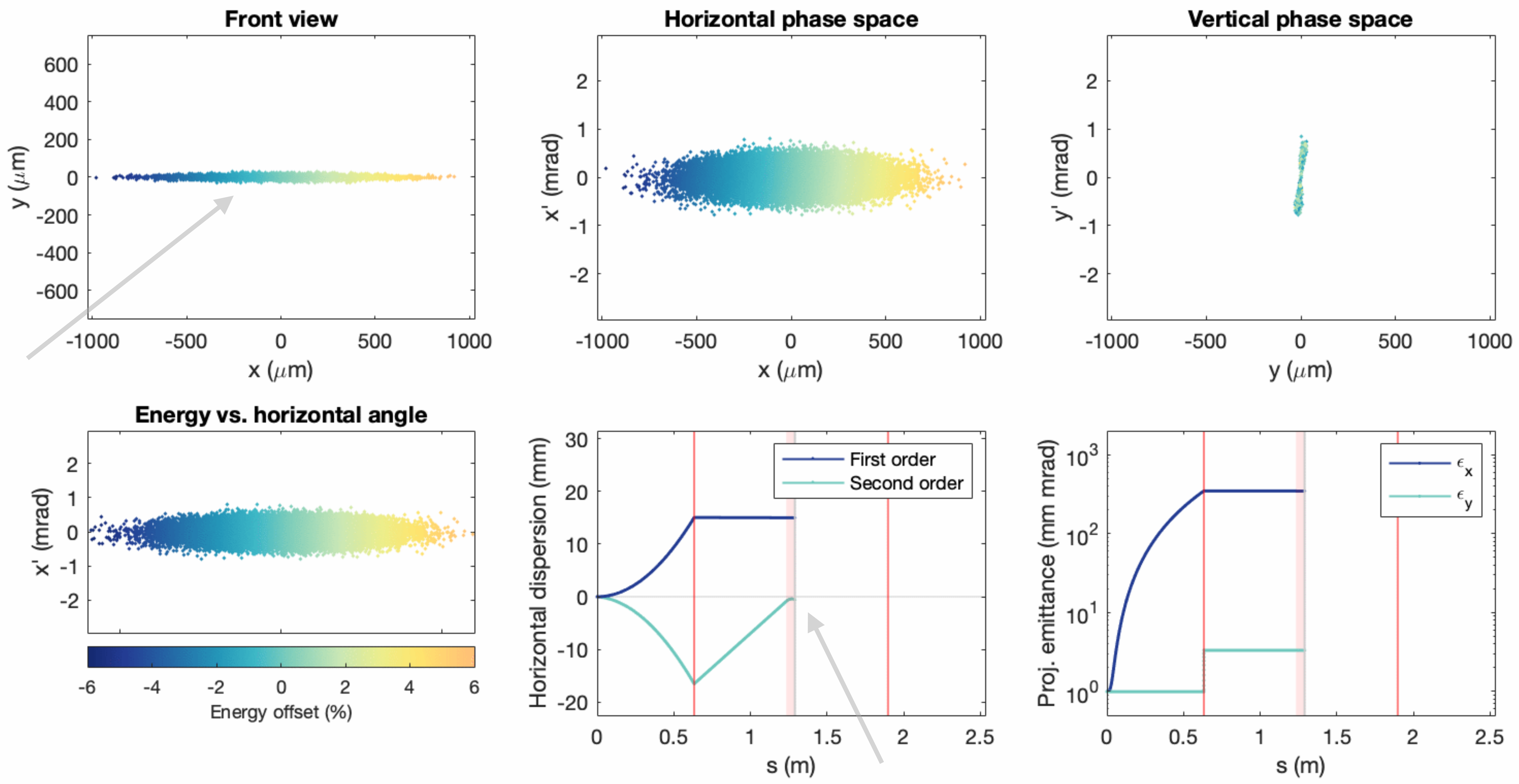

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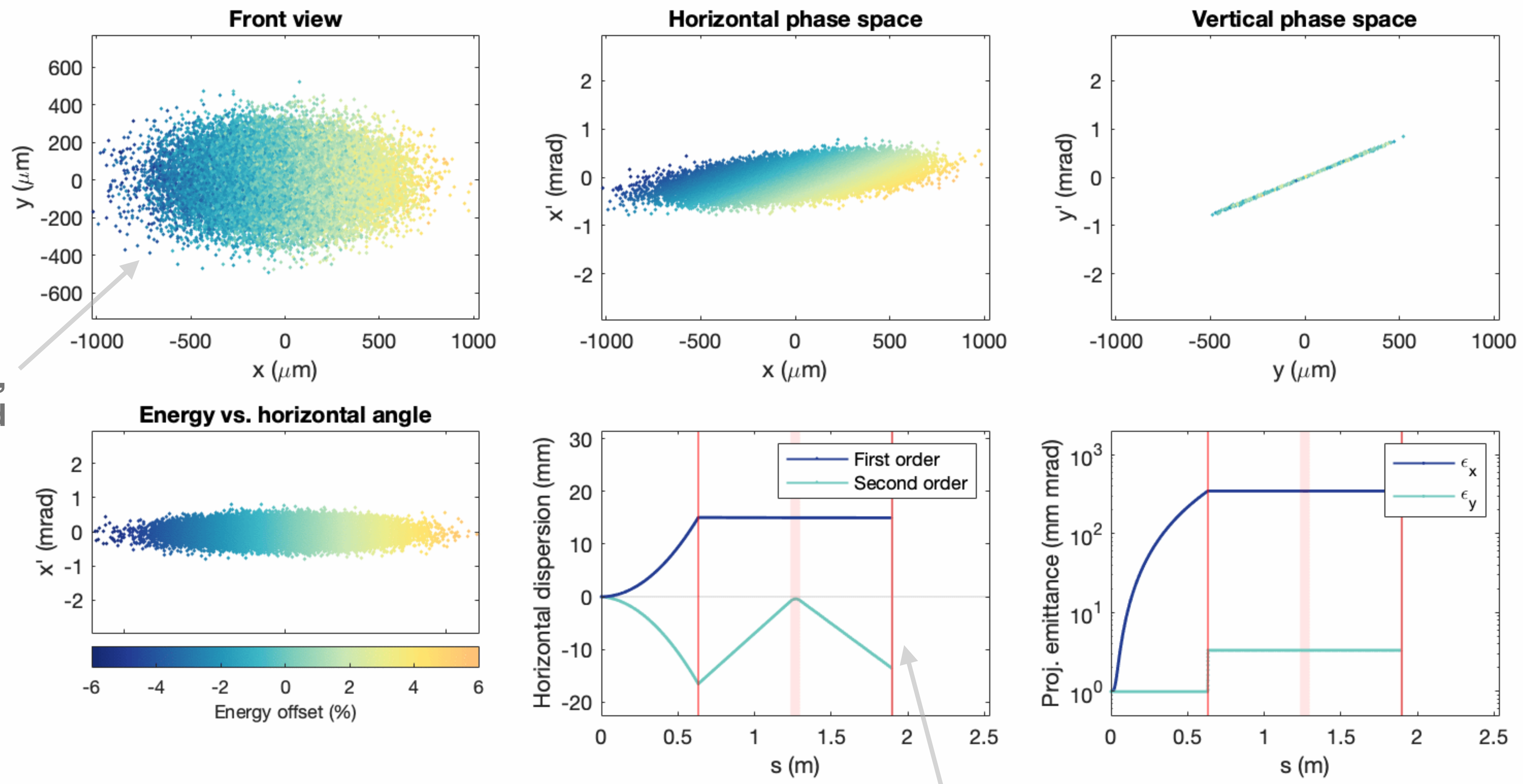

Beam size is large, phase is flipped

Same dispersion as in first lens

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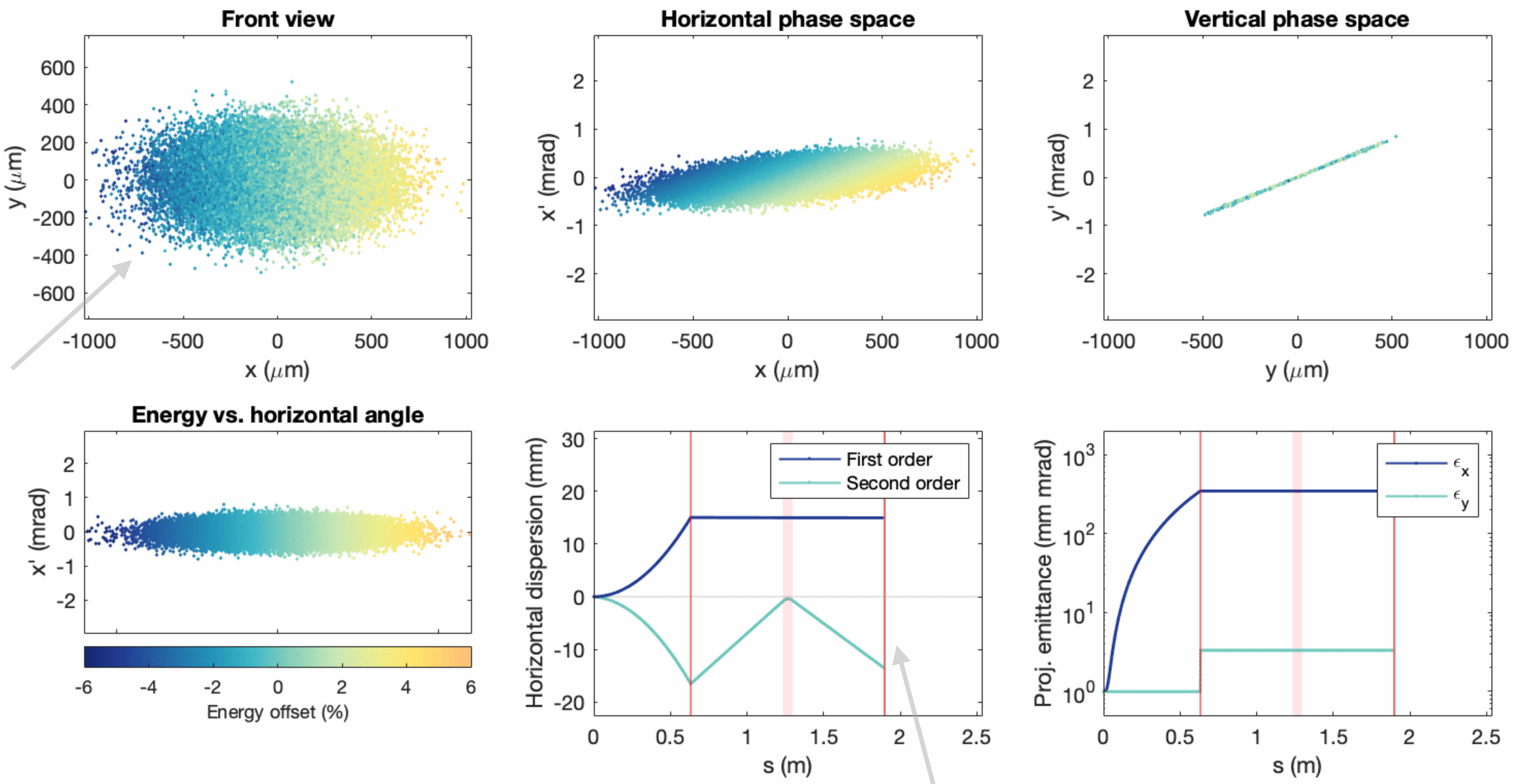

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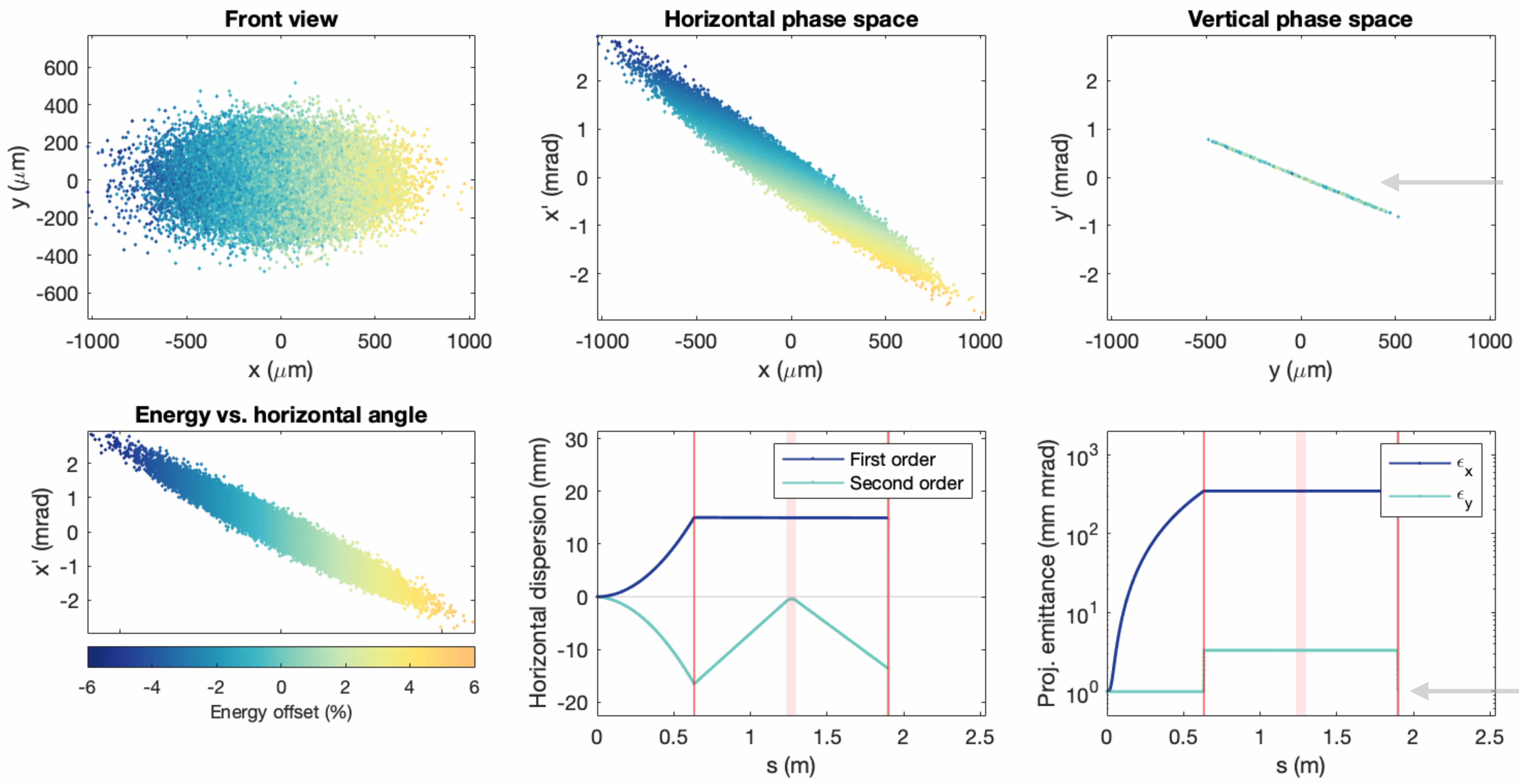

Refocused by second lens

Emittance growth cancelled
(by symmetry)

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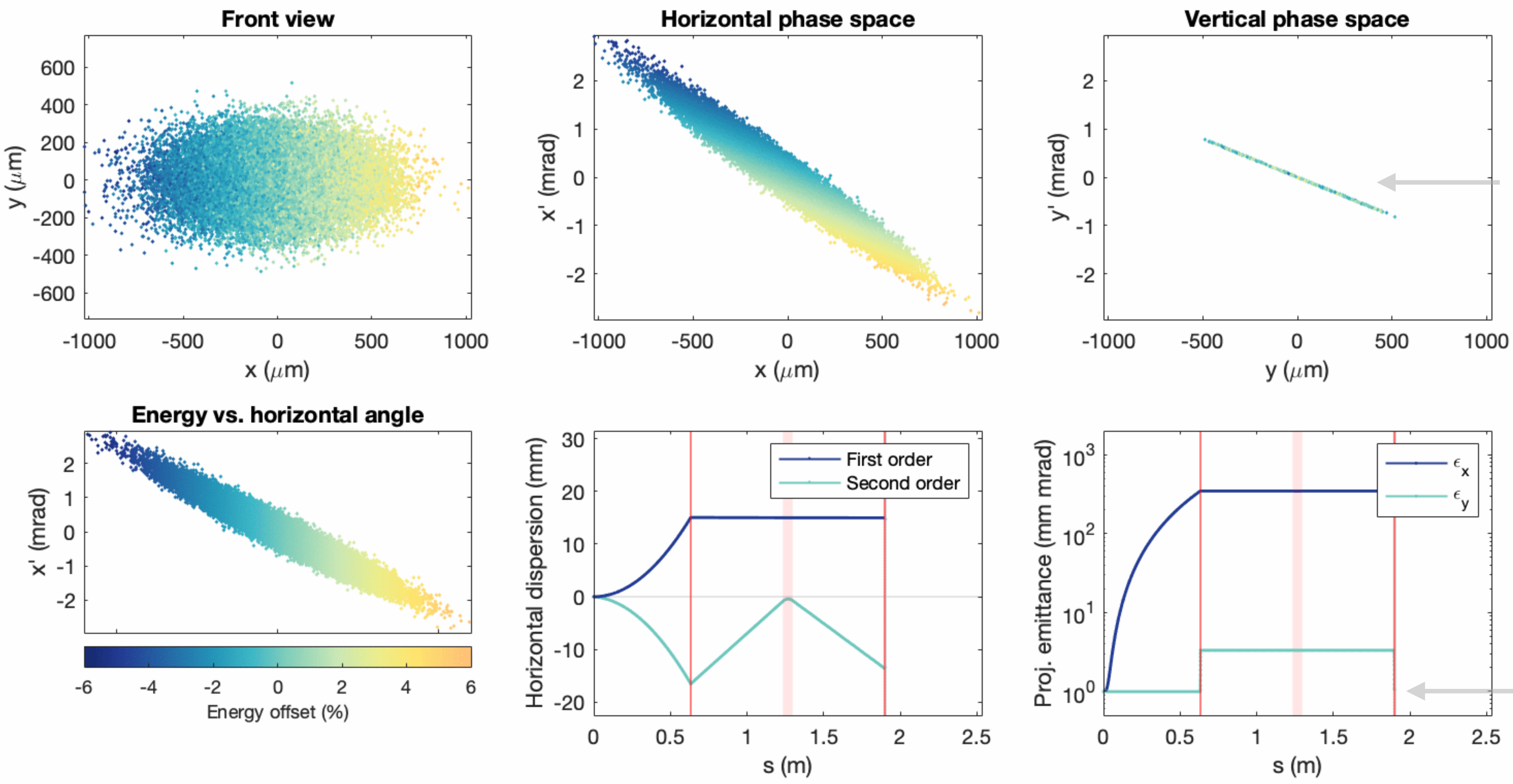

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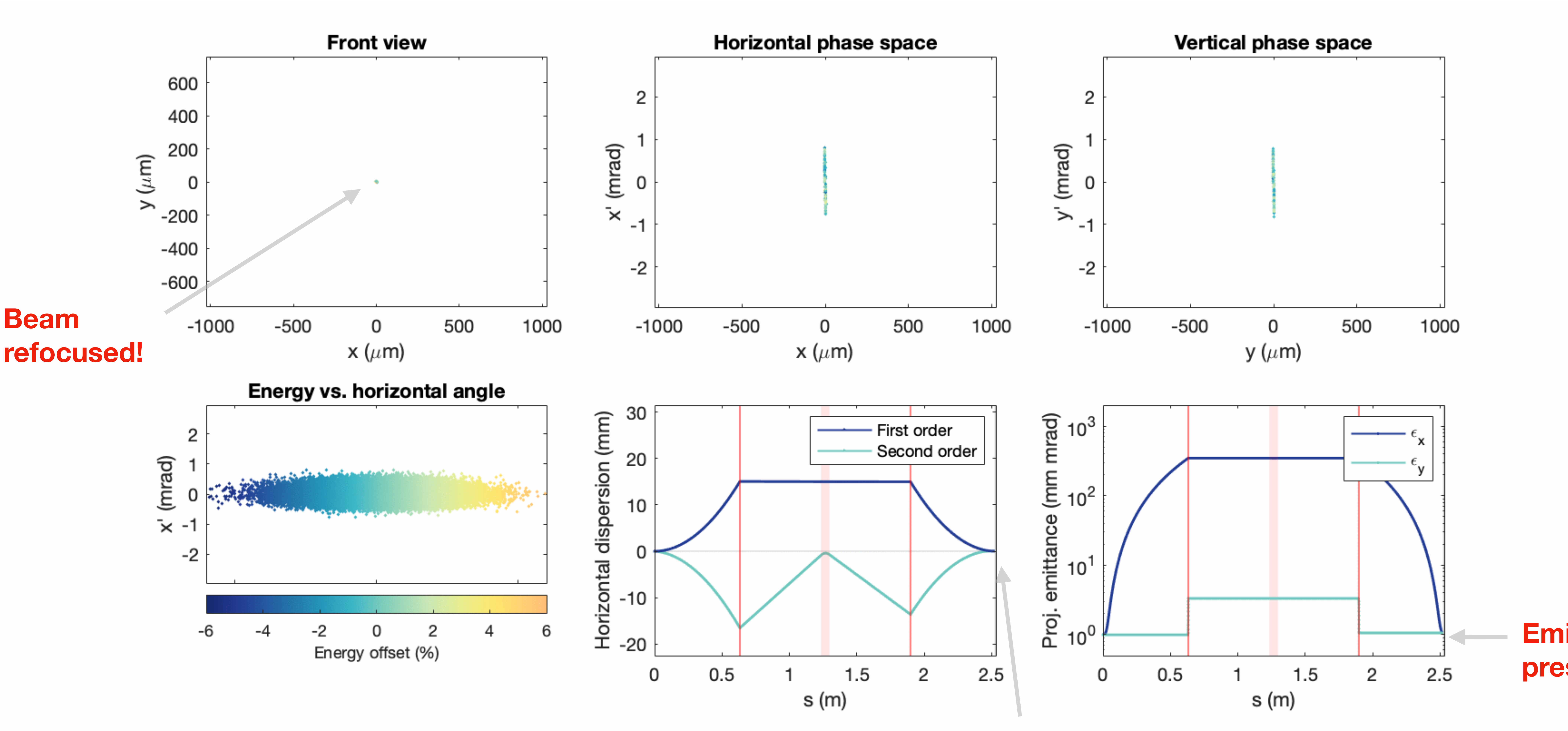

Beam refocused!

Dispersion cancelled!

Emittance preserved!

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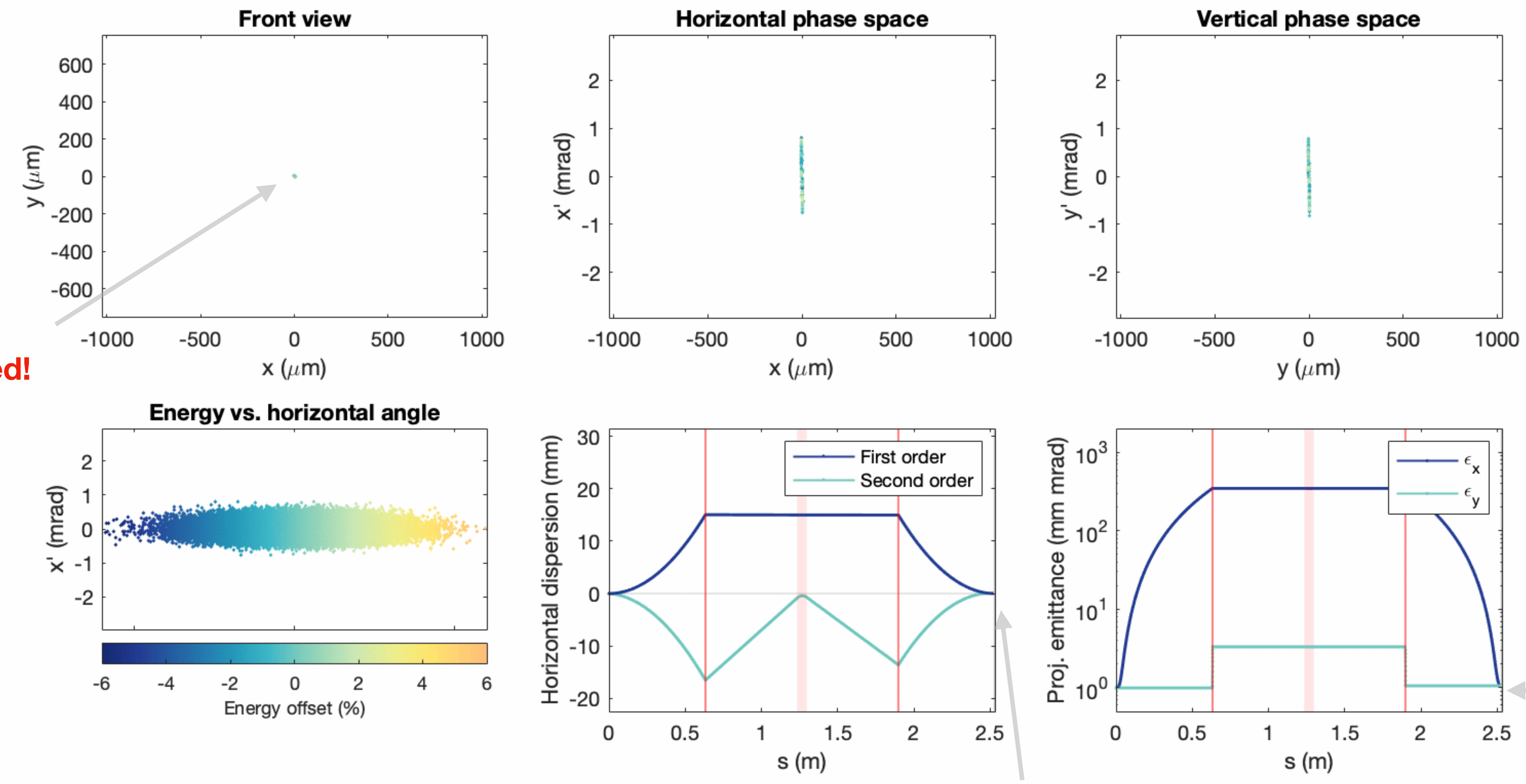

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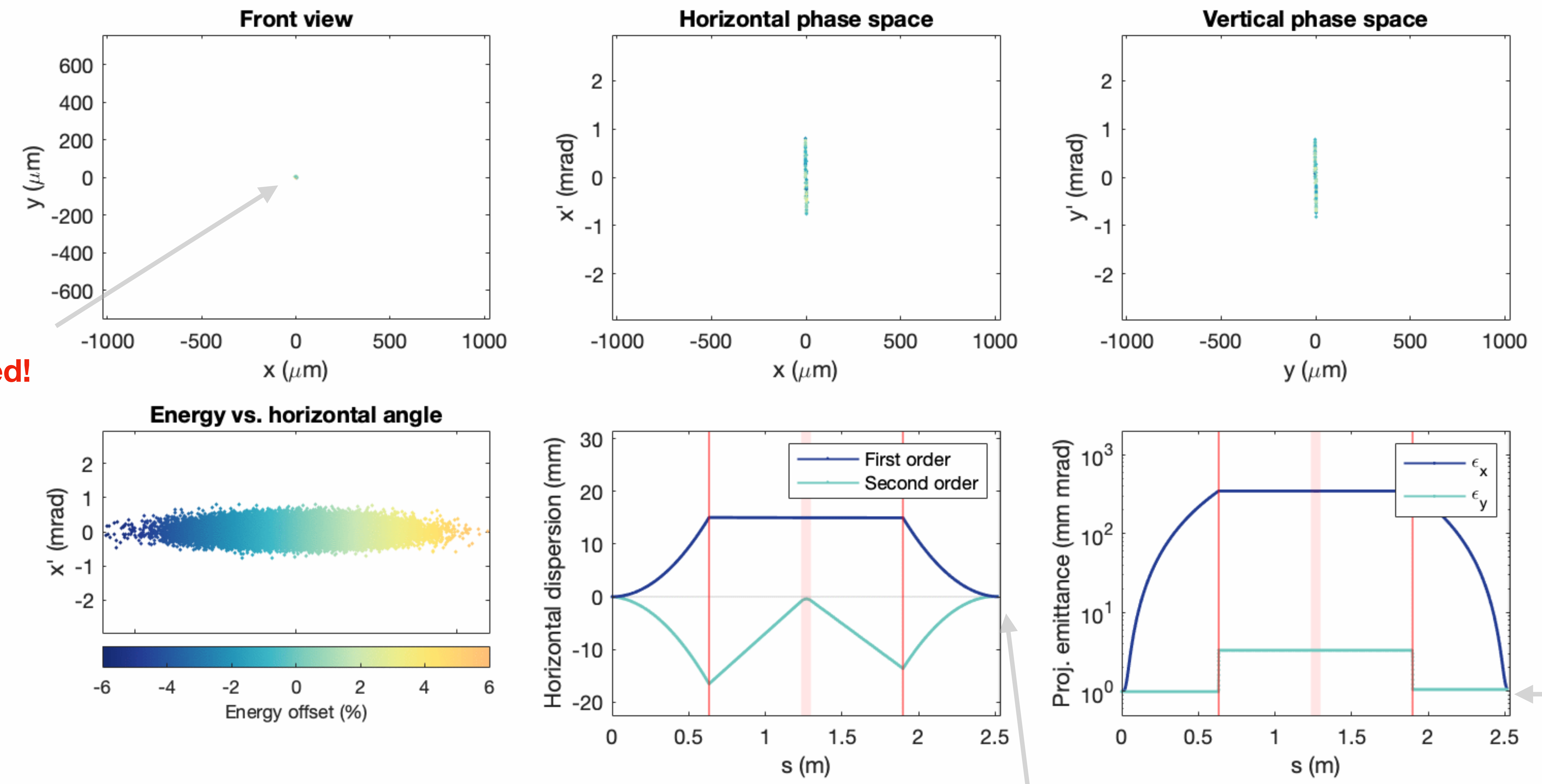
3 Nonlinear plasma lenses solve staging problem #3:
Emittance growth from chromaticity cancelled



Beam refocused!

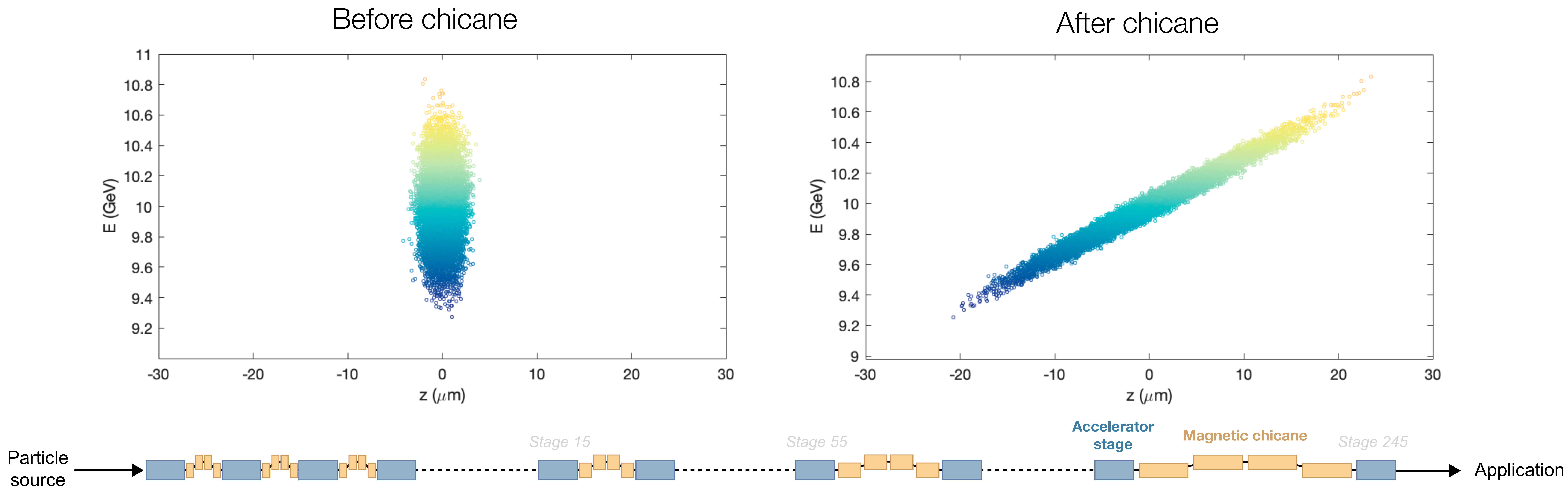
Emittance preserved!

Dispersion cancelled!

Stages separated by **bunch compressors**

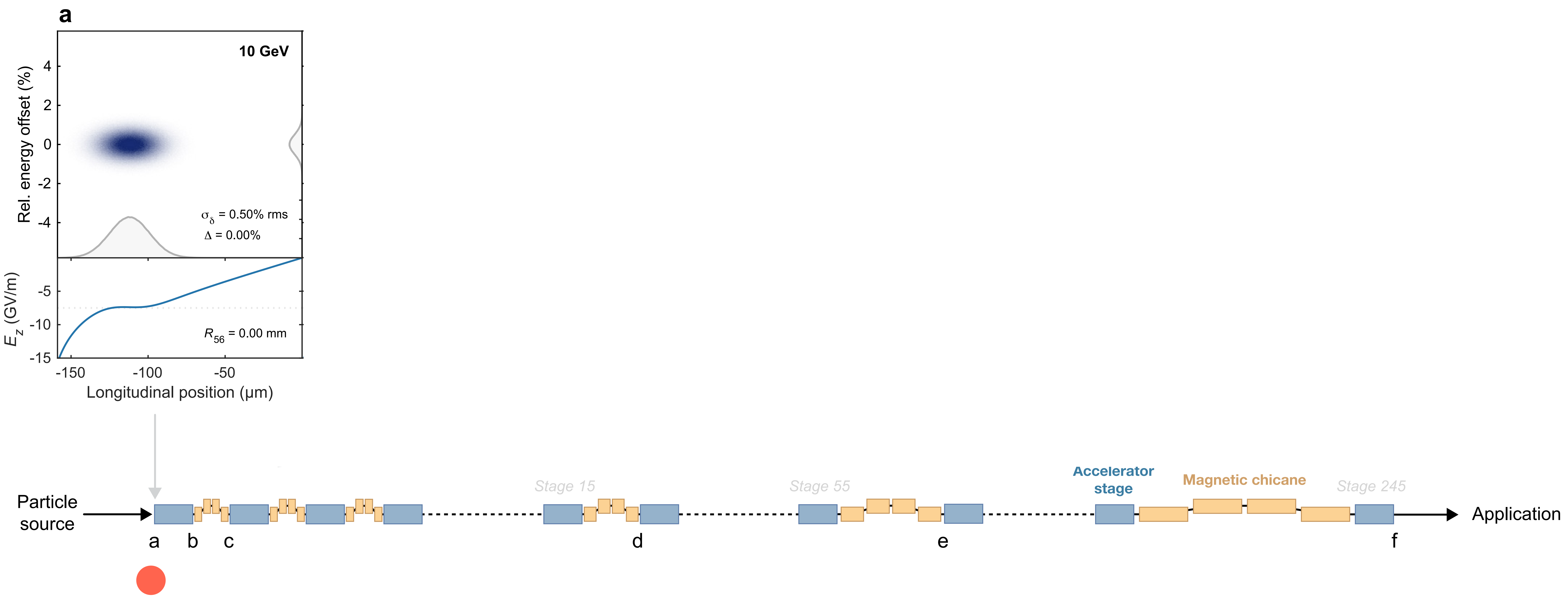
> The achromatic lattice has a non-zero longitudinal lattice dispersion (R_{56}):
>> Results in a **compression/stretching** between stages…

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



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)

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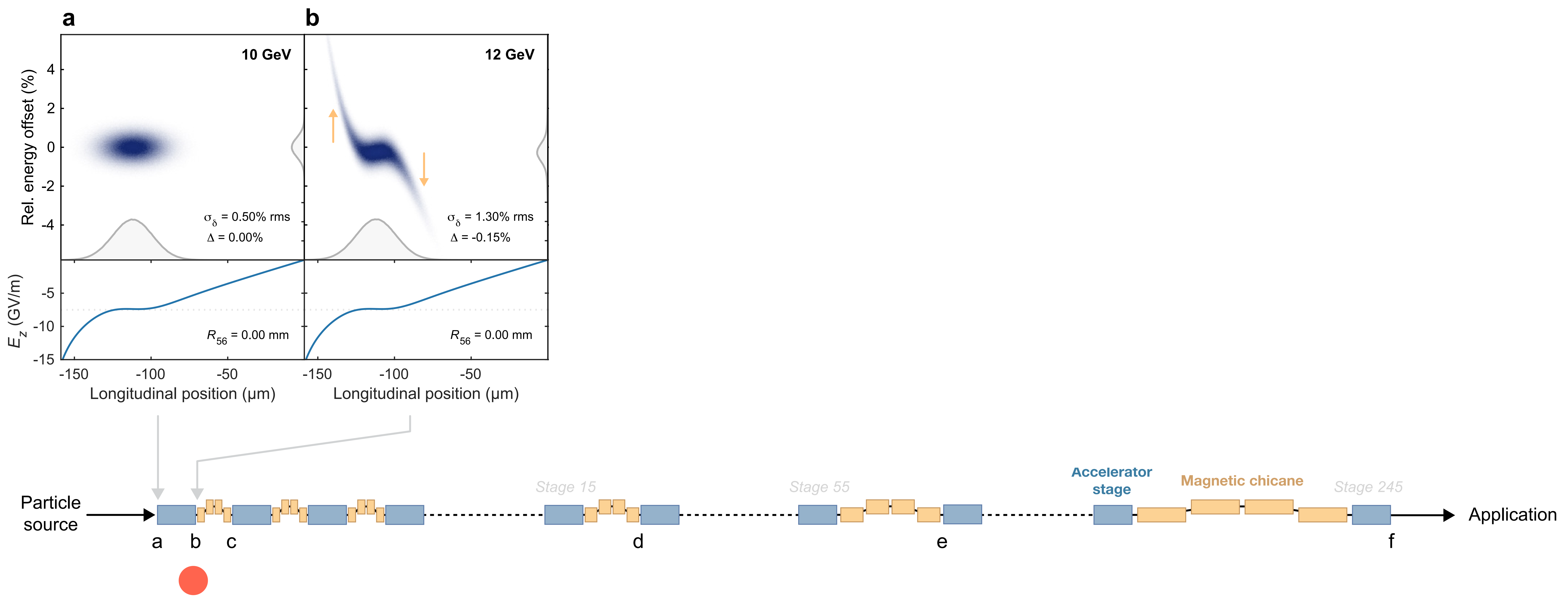

Plasma accelerator stage:

Particles gain energy based on their position

Preprint: Lindstrøm, arXiv:2104.14460 (2021)

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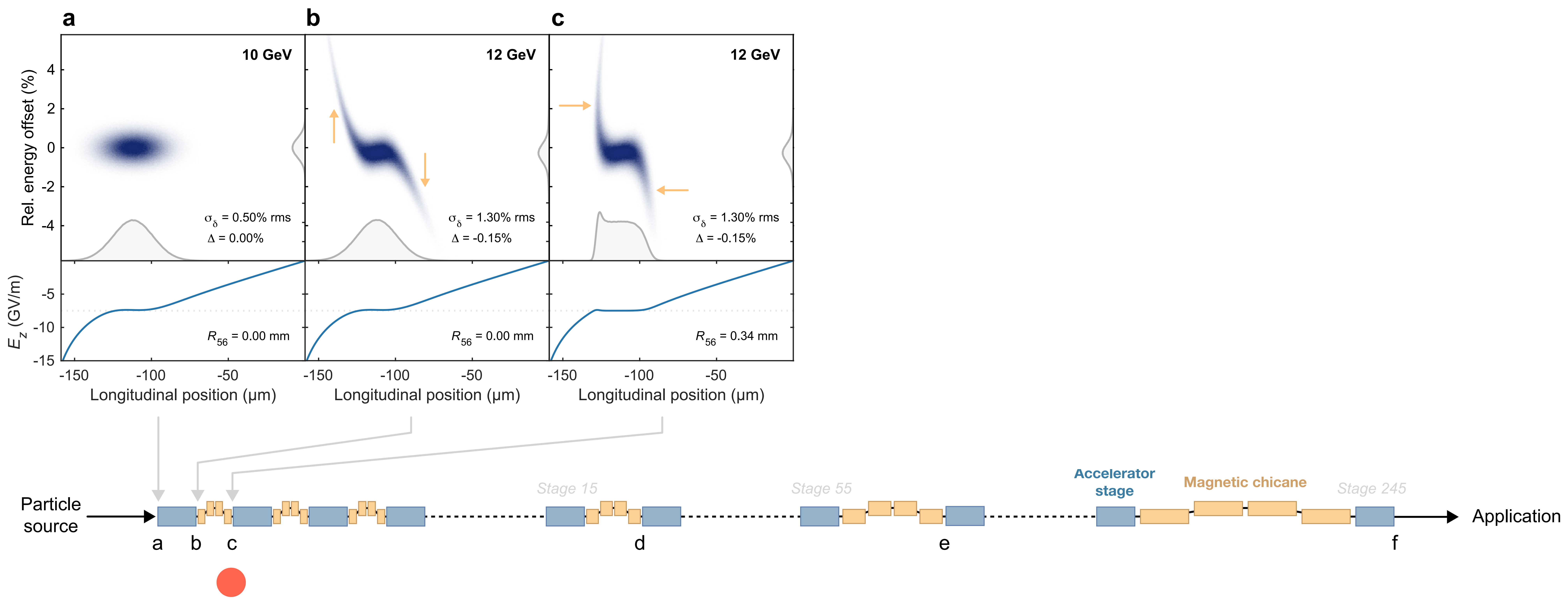

Magnetic chicane:

Move particles longitudinally based on energy offset

Preprint: Lindstrøm, arXiv:2104.14460 (2021)

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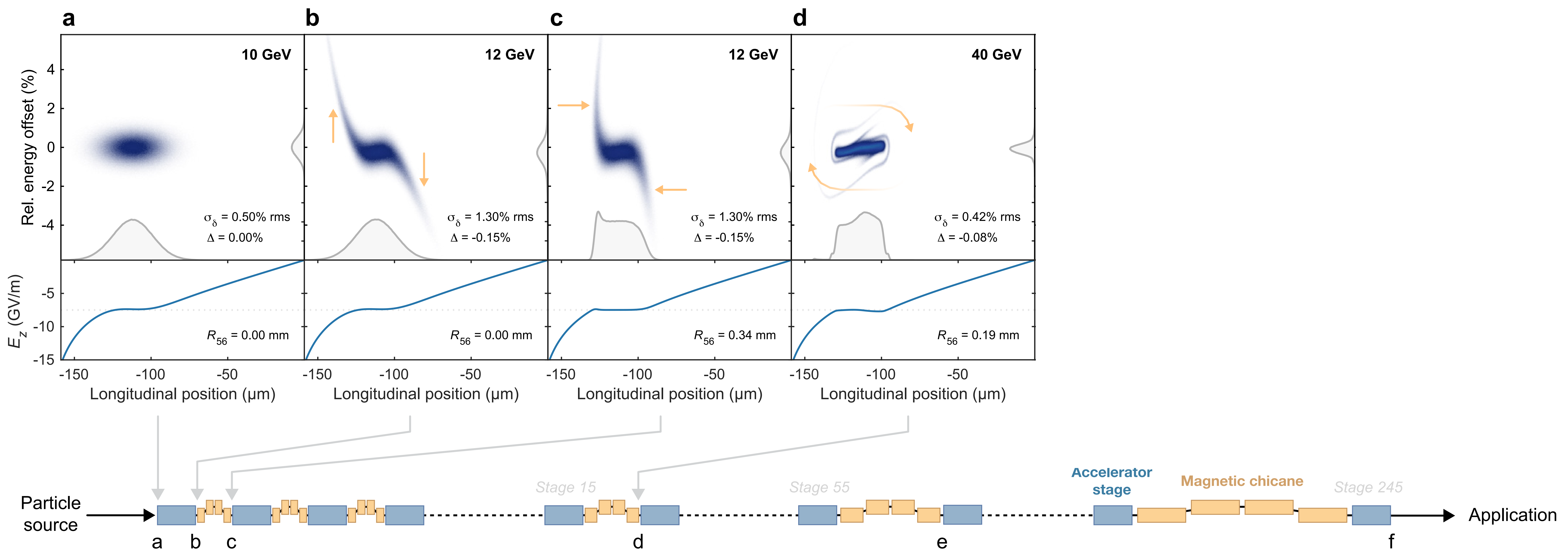
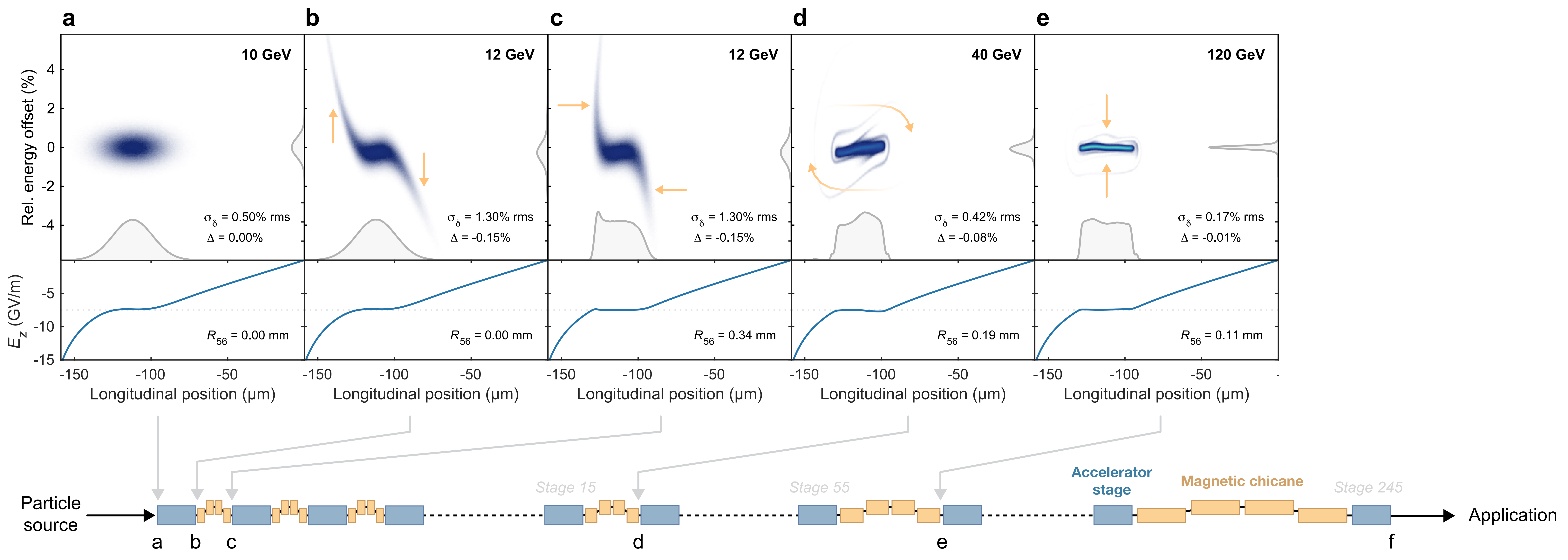


Several stages:

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

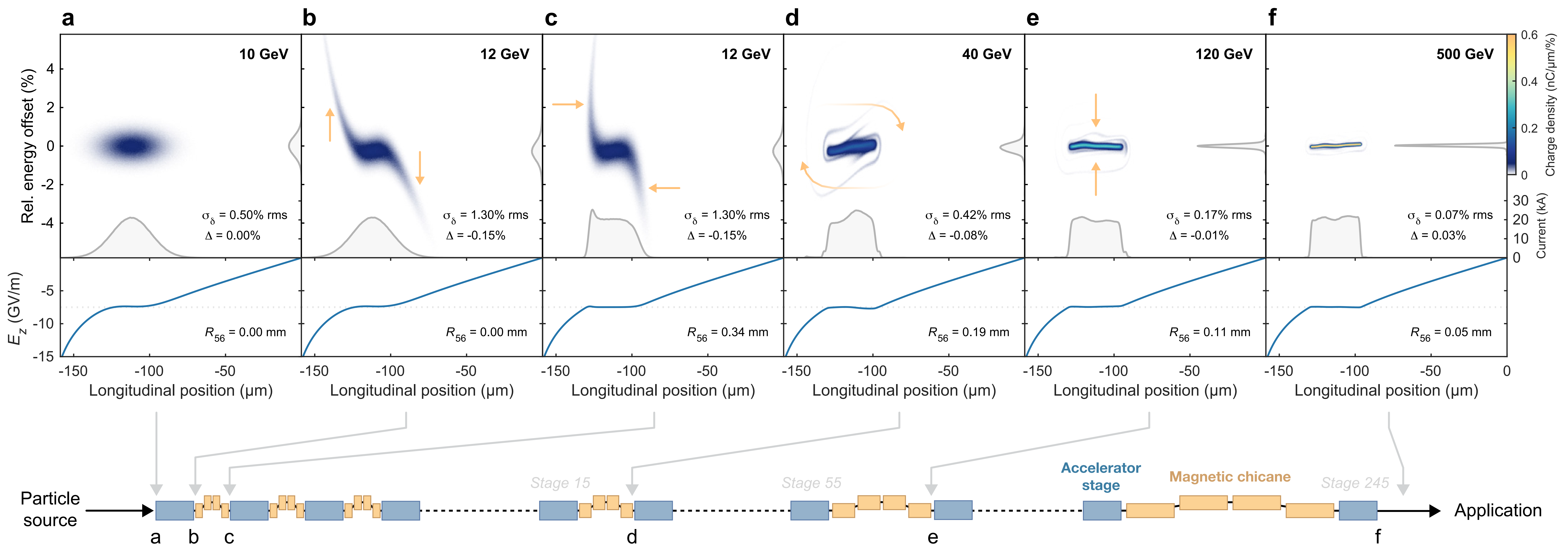


More stages:

Relative energy spread and offsets damped with energy gain

Preprint: Lindstrøm, arXiv:2104.14460 (2021)

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



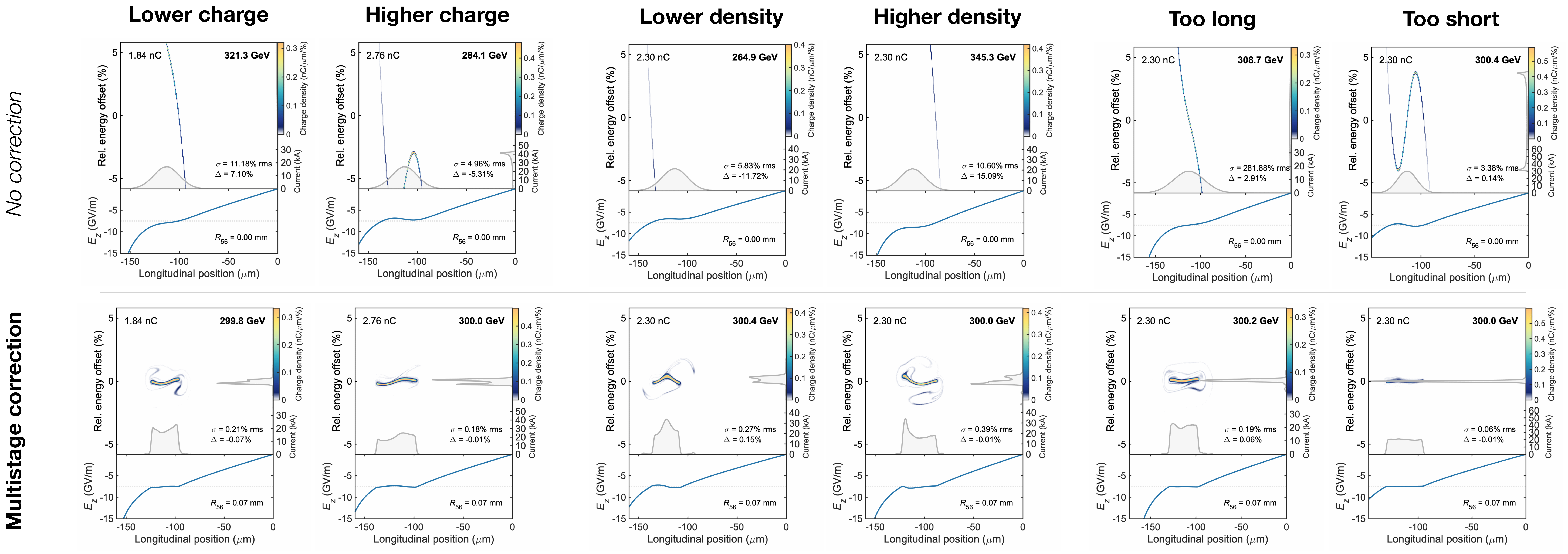
End result:

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

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

Passive stabilization: Significantly improved tolerances

- **Feedback mechanism self-corrects every aspect of the current profile:**
  - Tolerant to errors in timing, charge, peak current, bunch length
  - In this example: 1 – 200 fs FWHM synchronisation tolerance



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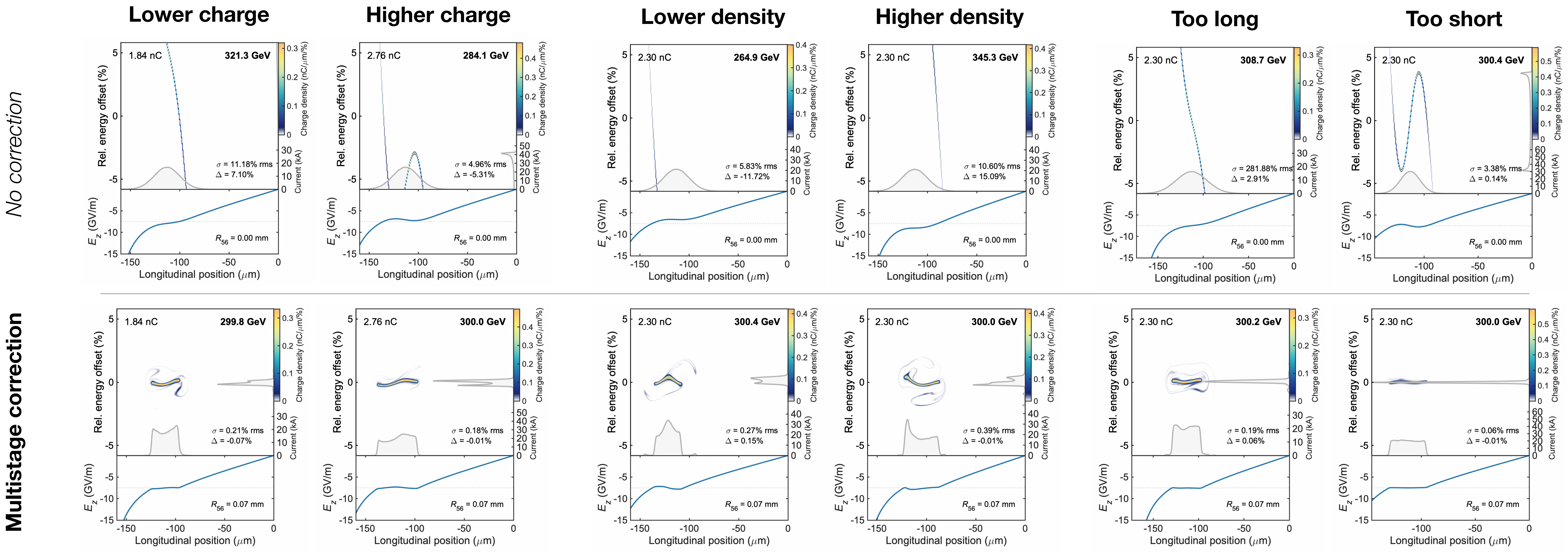

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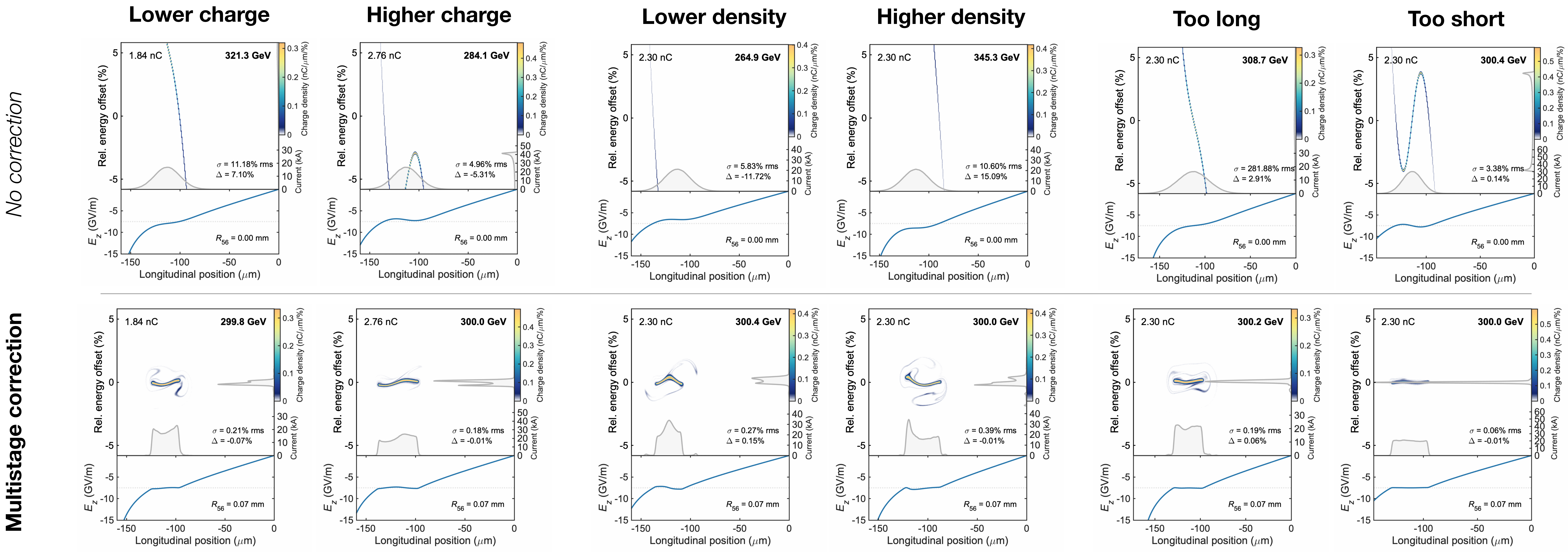
4 Self-stabilization solve staging problem #4:
Greatly reduced synchronization tolerances



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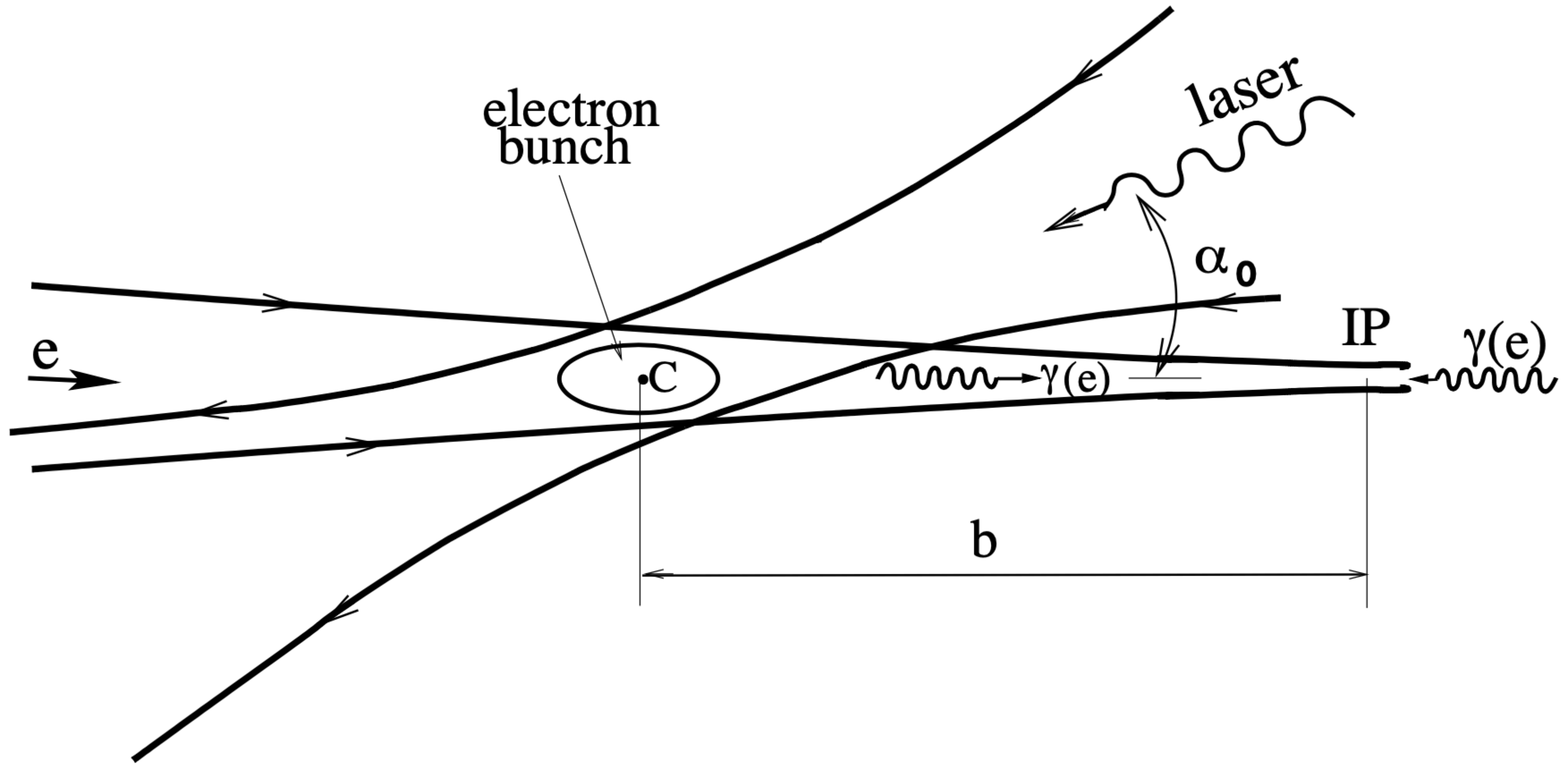
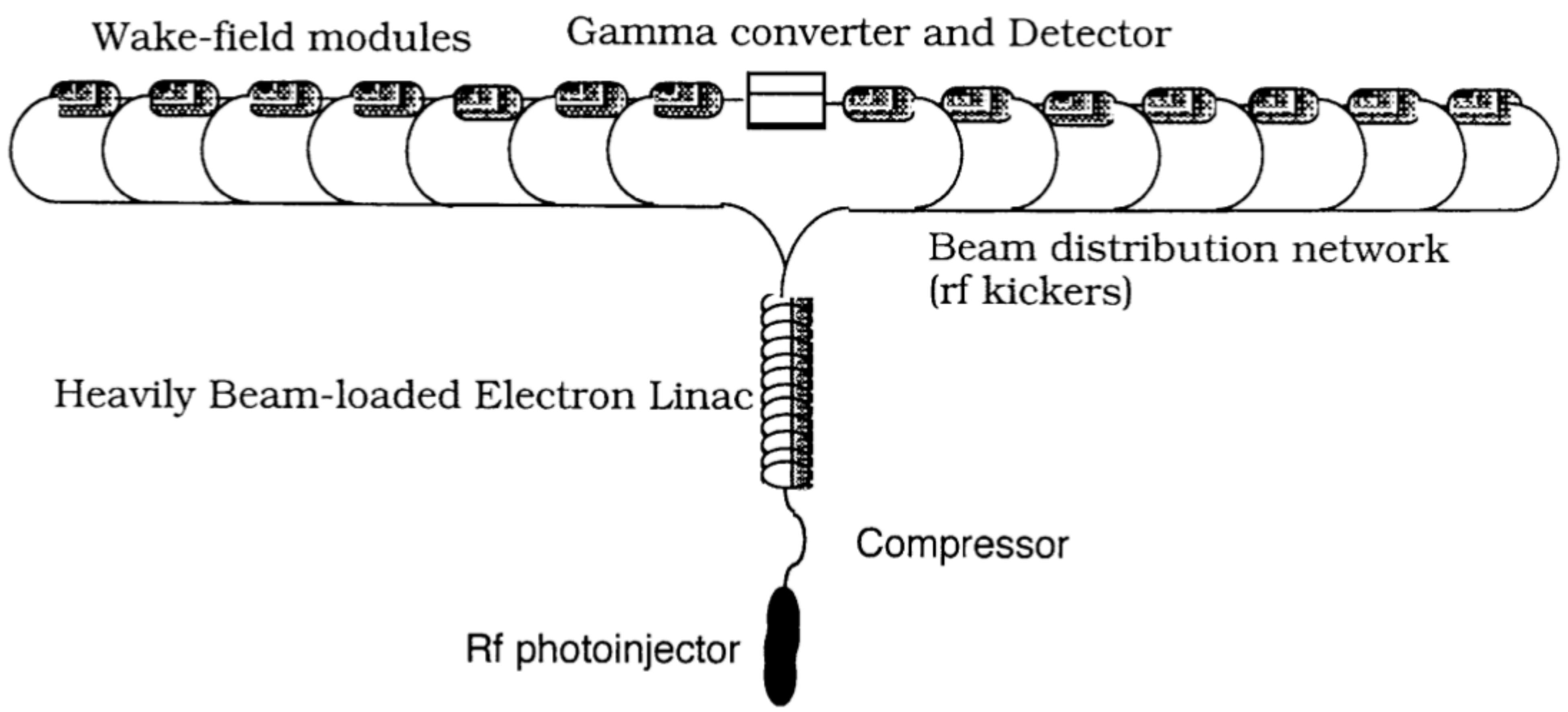
Assuming it exists… now what?

Plasma-based photon collider—a cheap Higgs factory?

- Plasma accelerators can likely provide high energy, beam quality and rep. rate for **electrons**, but maybe **not positrons.**
- Photon colliders can function with electron bunches only:
  - **Generate gamma-beams by inverse Compton scattering** of laser photons off high-energy electrons.
    - The gamma-beam takes the properties of the electron beam (e.g., emittance)
  - Advantage: gamma–gamma Higgs factory can operate directly at the Higgs resonance (125 GeV) instead of at Higgs+Z (~250 GeV)—large cost reduction.
  - Disadvantage: Powerful colliding laser requires R&D.
- Plasma-based photon collider **proposed already in 1998**.
  - Now we have may have the tools to realize it!



From: Badelek et al., TESLA Technical Design Report, Part VI (2001)



From: Rosenzweig et al., NIM A 410, 532 (1998)

Plasma-based photon collider — a cheap Higgs factory?

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> > **Generate gamma-beams by inverse Compton scattering** of laser photons off high-energy electro…

> > > The gamm… electron b…

> > Advantage: ga… directly at the H… Higgs+Z (~250…

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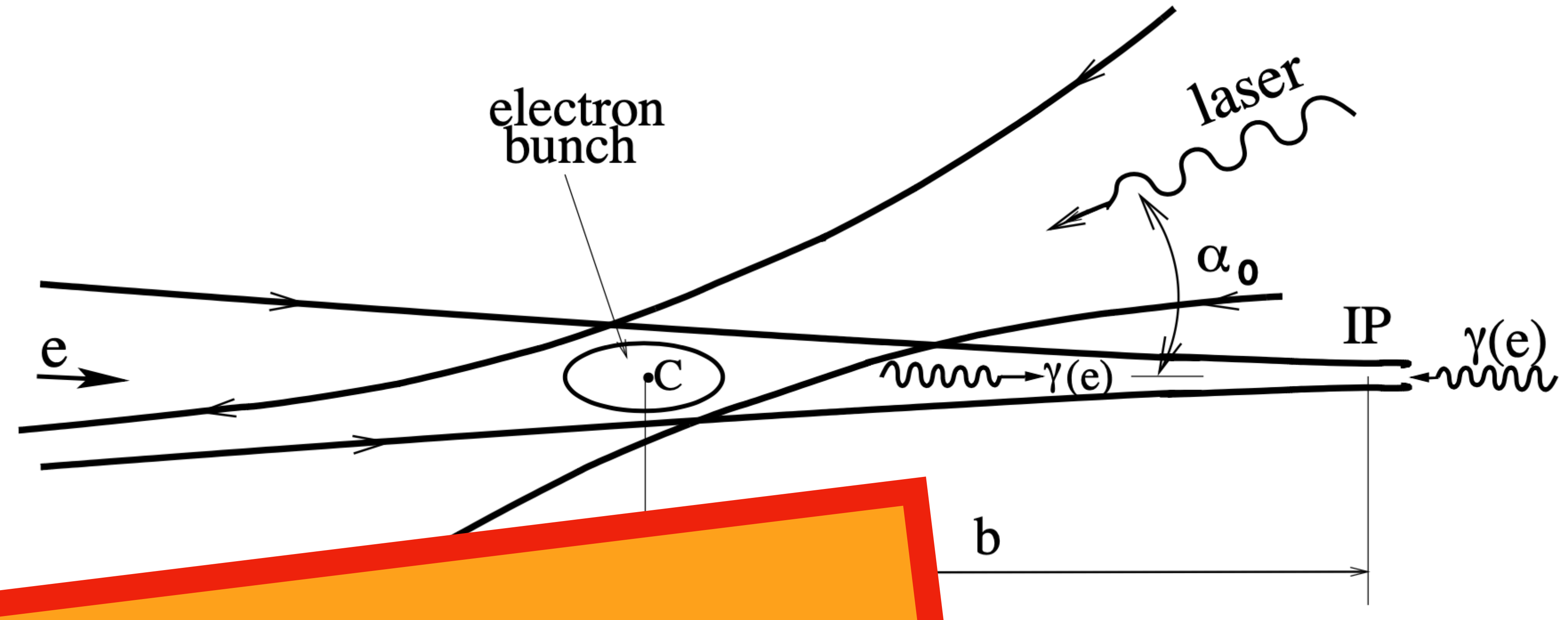
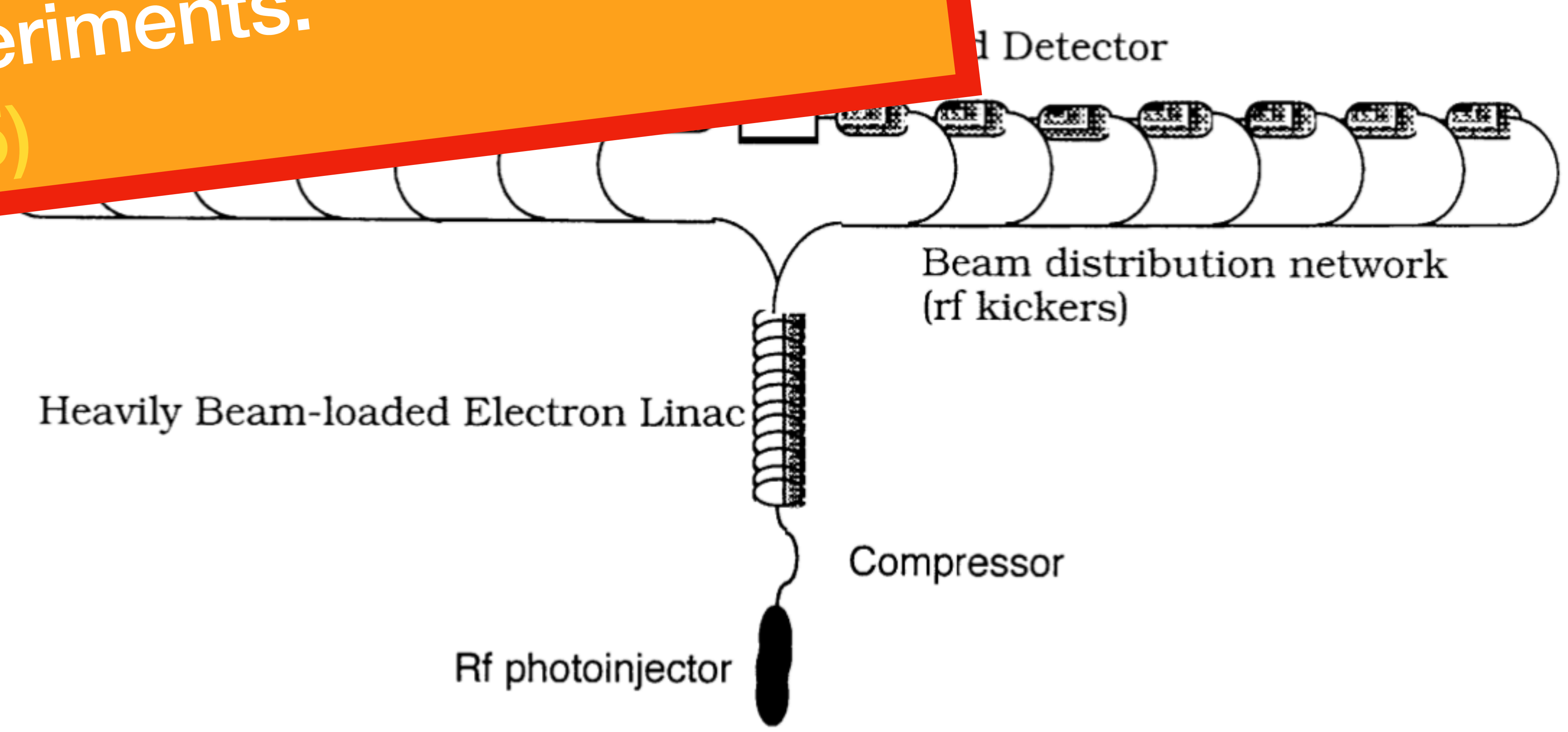


…ign Report, Part VI (2001)

Postdoc advertisement

Uni. Oslo is currently offering a postdoc position (link) to study challenges toward a plasma-based photon collider, theoretically and in experiments.

(Deadline: Oct 5)



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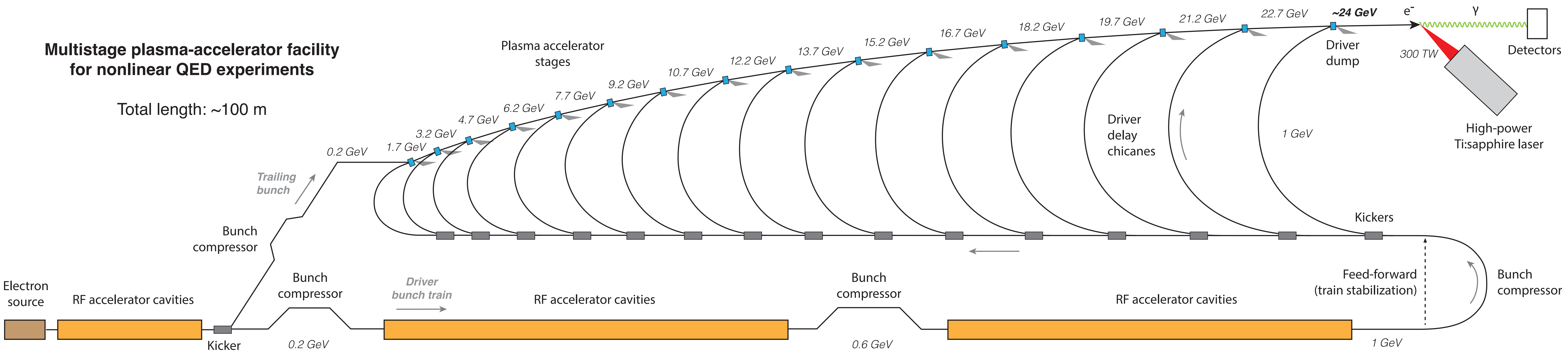
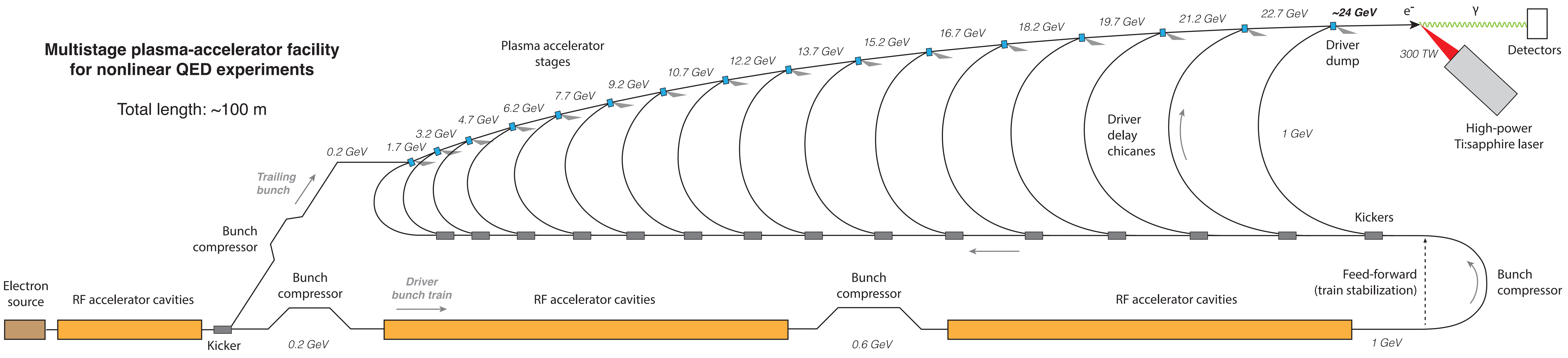
"Missing Middle": **A multistage facility for nonlinear QED**



Schematic cartoon of multistage plasma accelerator for strong-field QED experiments.

- **Nonlinear QED: reach Schwinger field** by colliding ultrarelativistic electrons and intense laser.
  - *Experiments at SLAC (E144) and RAL (Astra-Gemini): $\chi \approx 0.3$ (fraction of Schwinger field)*
  - *Planned experiments at SLAC (E320, $\chi \approx 1+$) and potentially EuXFEL (LUXE, $\chi \approx 0.5$–5)*
- **Needs high particle energy**, but **modest requirements on beam quality and rep. rate**.
  - Ideal **demonstrator facility** for staging: Stepping stone toward a gamma–gamma collider.

“Missing Middle”: A multistage facility for nonlinear QED



Schematic cartoon of multistage plasma accelerator for strong-field QED experiments.

- **Nonlinear QED: reach Schwinger field** by colliding ultrarelativistic electrons and intense laser.
  - *Experiments at SLAC (E144) and RAL (Astra-Gemini): $\chi \approx 0.3$ (fraction of Schwinger field)*
  - *Planned experiments at SLAC (E320, $\chi \approx 1+$) and potentially EuXFEL (LUXE, $\chi \approx 0.5$–5)*
- **Needs high particle energy**, but **modest requirements on beam quality and rep. rate**.
  - Ideal **demonstrator facility** for staging: Stepping stone toward a gamma–gamma collider.

Conclusions

- Staging is likely required to reach high energies, efficiently.
- Four staging problems:
  - *Compactness*
  - *In- and out-coupling of drivers*
  - *Emittance growth from chromatic mismatching*
  - *Tight synchronization tolerances*
- **Nonlinear plasma lenses can *potentially* solve all the above problems.**
- Future work:
  - How do we **realize this nonlinear plasma lens**?
  - What is the **6D dynamics** of multiple plasma accelerators + nonlinear plasma lenses?
  - Can we use this to **design compact high-energy facilities**—for nonlinear QED or a Higgs factory?