Staging of plasma accelerators

For high energy, stability and beam quality

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Motivation: Requirements for a HEP collider

> High-energy physics colliders require both **high energy** and **high luminosity**.

High energy

High repetition rate

High efficiency

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

Low energy spread
High energy stability
(luminosity spectrum, final focusing)

Low emittance

> The accelerator must provide:

> High acceleration gradient ← Motivates use of plasma accelerators

> High beam quality and wall-plug-to-beam efficiency ← Current R&D topics

> **High beam power** (i.e., simultaneous *large energy gain* and *high repetition rate*) ← Next R&D topics

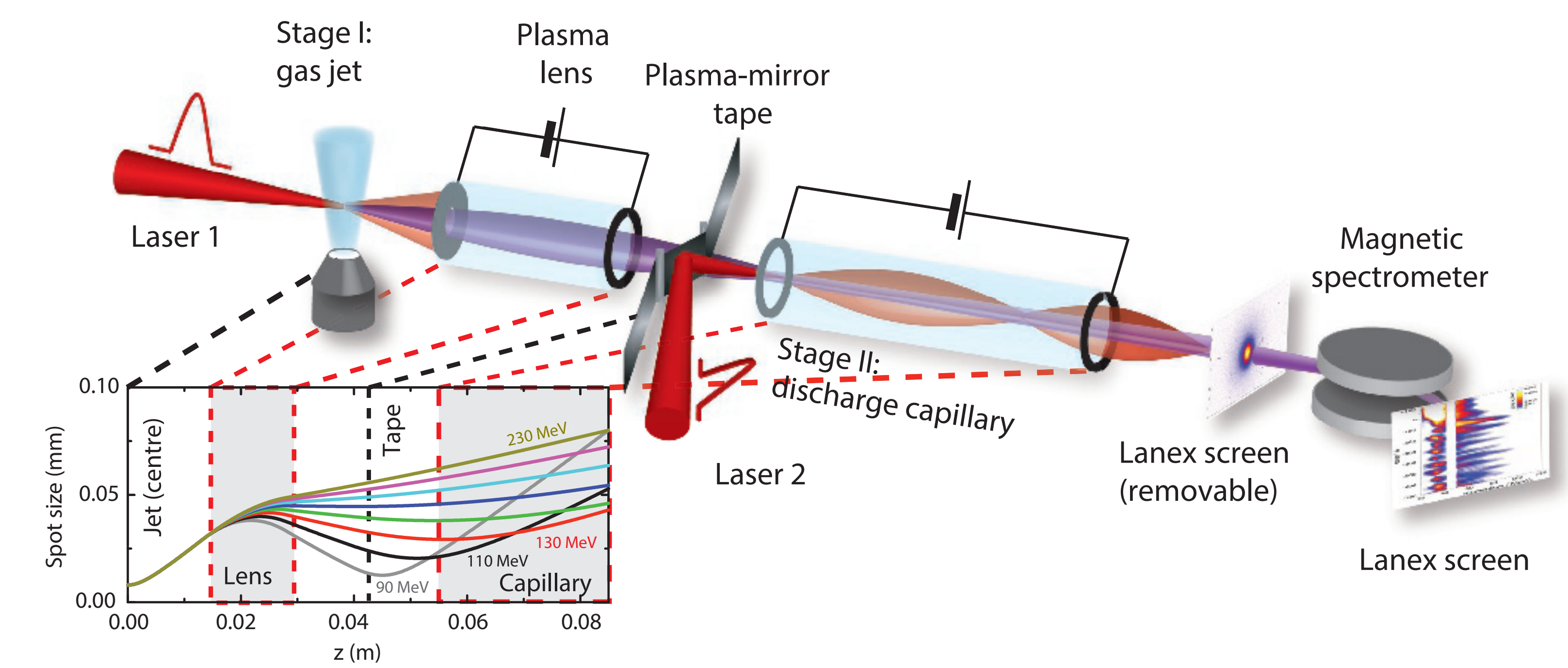
CHALLENGE: STAGING OF PLASMA ACCELERATORS IS NON-TRIVIAL

Review Article: Lindstrøm, Phys. Rev. Accel. Beams 24, 014801 (2021)

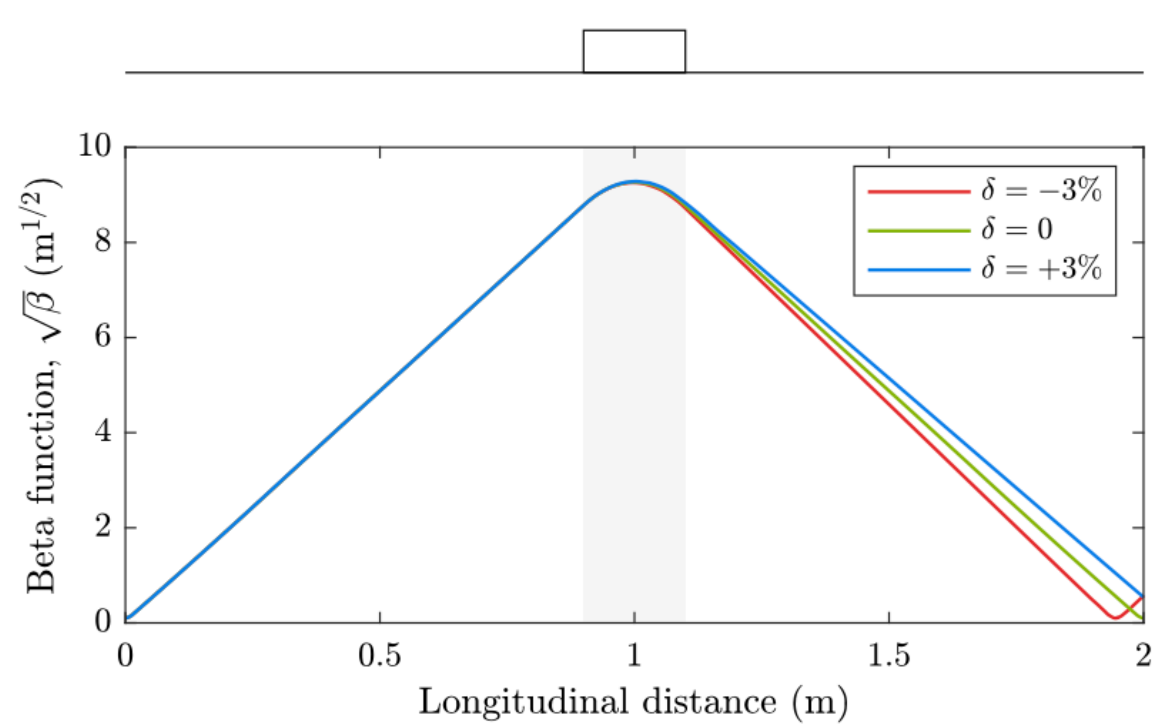
> **Staging is likely necessary to reach high beam power**
>> *Allows high-repetition-rate (medium-energy) drivers*
>> *Allows high efficiency (i.e., driver depletion)*

> Proof-of-principle demonstration at LBNL using plasma lenses.

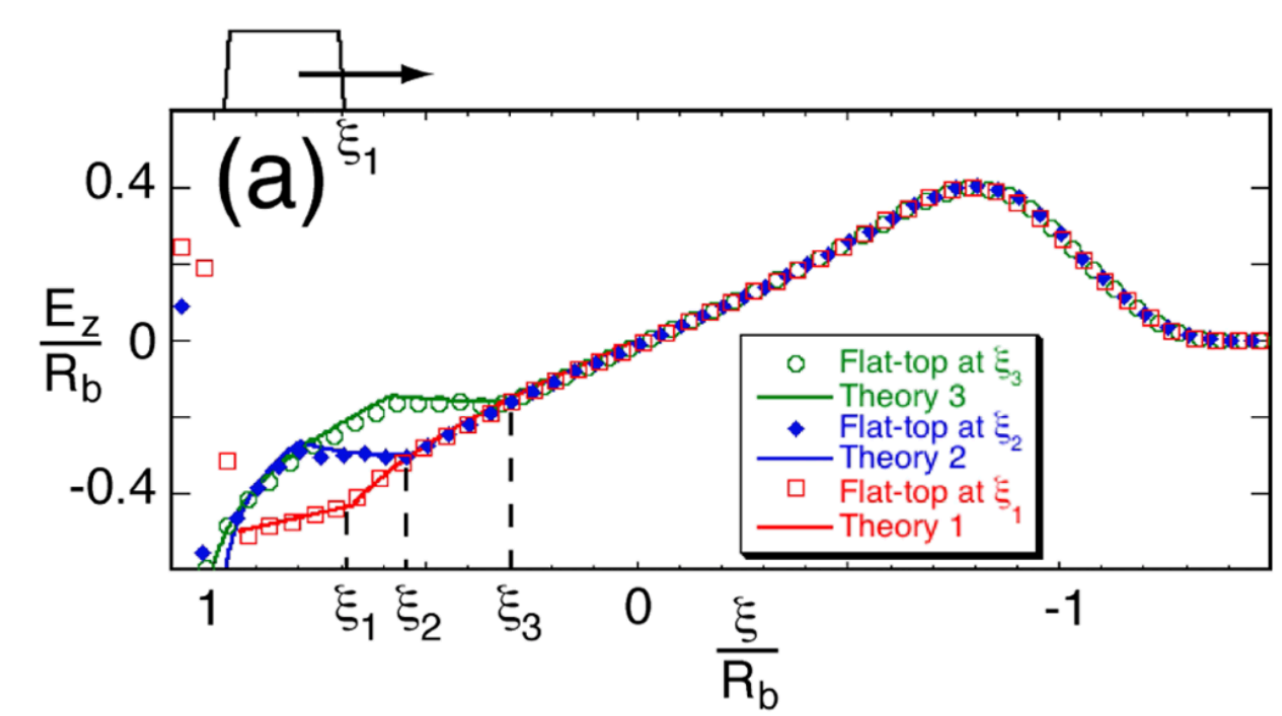
> **Beam-quality preservation is challenging**
>> (1) Emittance growth due to strong chromaticity
>> (2) Tight synchronization and misalignment tolerances



Proof-of-principle demonstration of staging.
Source: Steinke et al. [Nature 530, 190 (2016)]



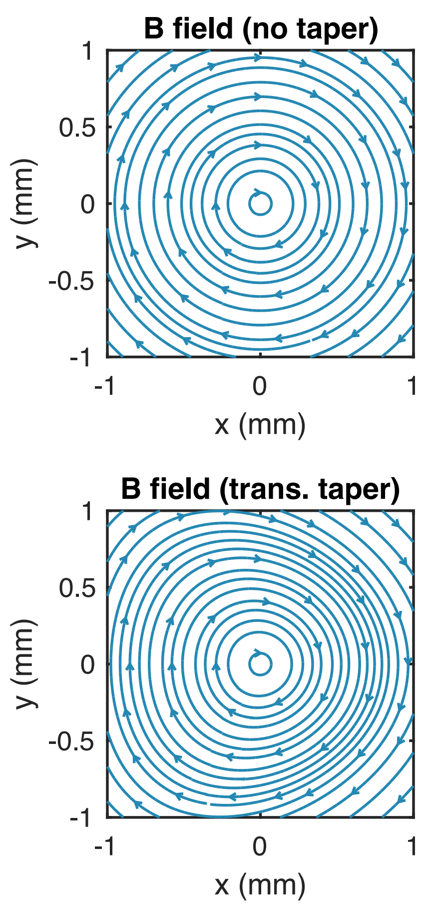
(1) **Energy-dependent mismatching due to chromaticity between stages.**
Source: Lindstrøm [PRAB 24, 014801 (2021)]

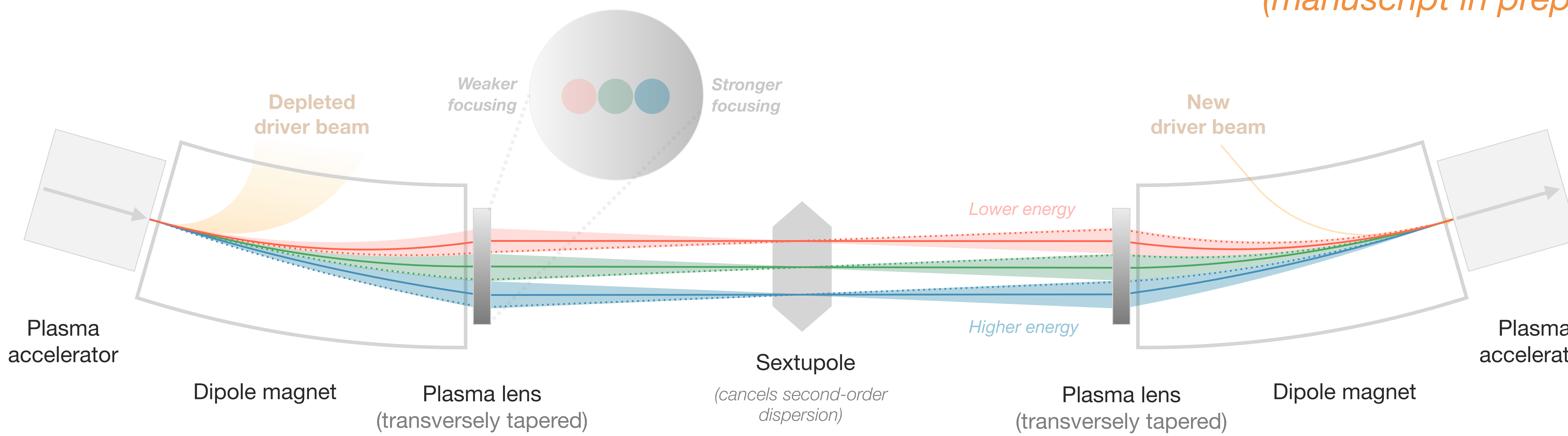


(2) **Energy spread and offset highly sensitive to timing jitter.**
Source: Tzoufras et al. [PRL 101, 145002 (2008)]

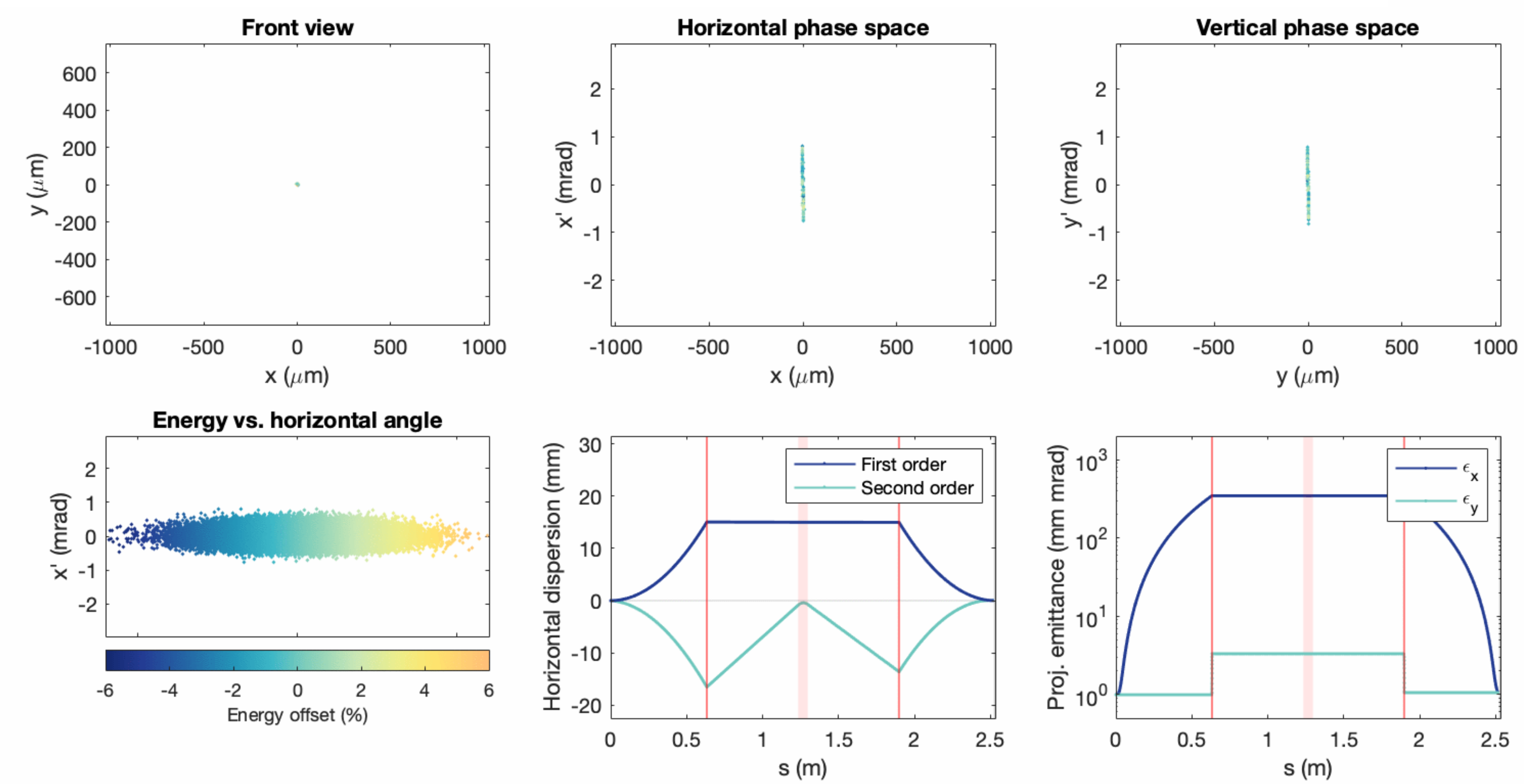
NEW CONCEPT #1: ACHROMATIC TRANSPORT WITH TRANS. TAPERED PLASMA LENSES

(manuscript in preparation)



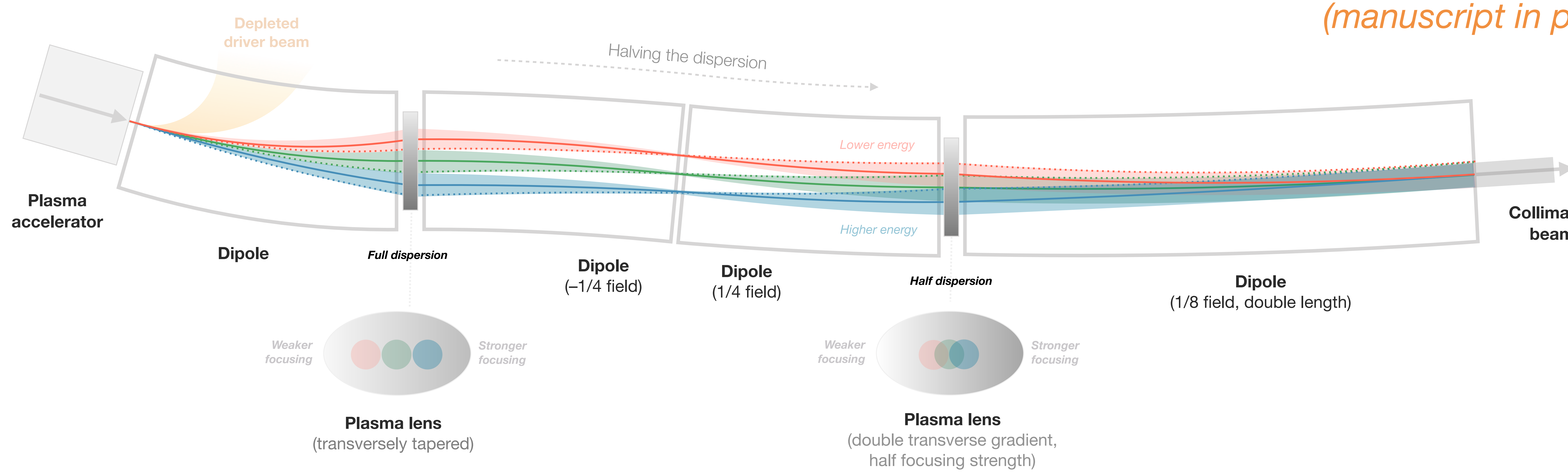


- **<u>Transversely tapered</u> plasma lenses (APL/PPL)**
  - *Disperse the bunch into the PL with a dipole, match the focusing of each energy with a transverse taper.*
- **Local chromaticity correction*** (used in final focus systems) ** Raimondi & Seryi, Phys. Rev. Lett. 86, 3779 (2001)*
- Simple in/out-coupling of laser and beam drivers.
- Large, dispersed beams in the plasma lenses ⇒ minimal wakefield-distortion in APLs.



New concept #1: Achromatic transport with trans. tapered plasma lenses

(manuscript in preparation)

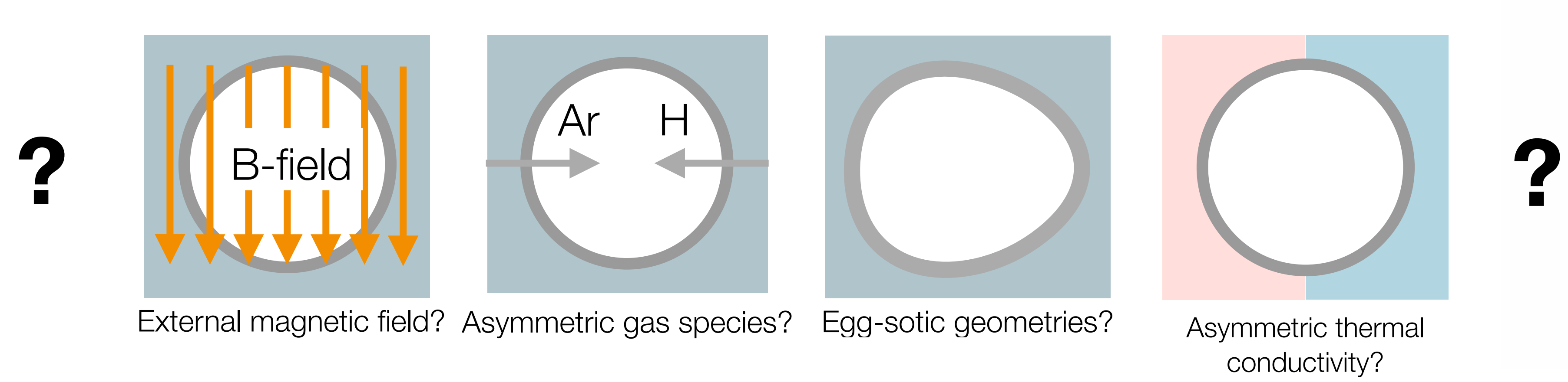


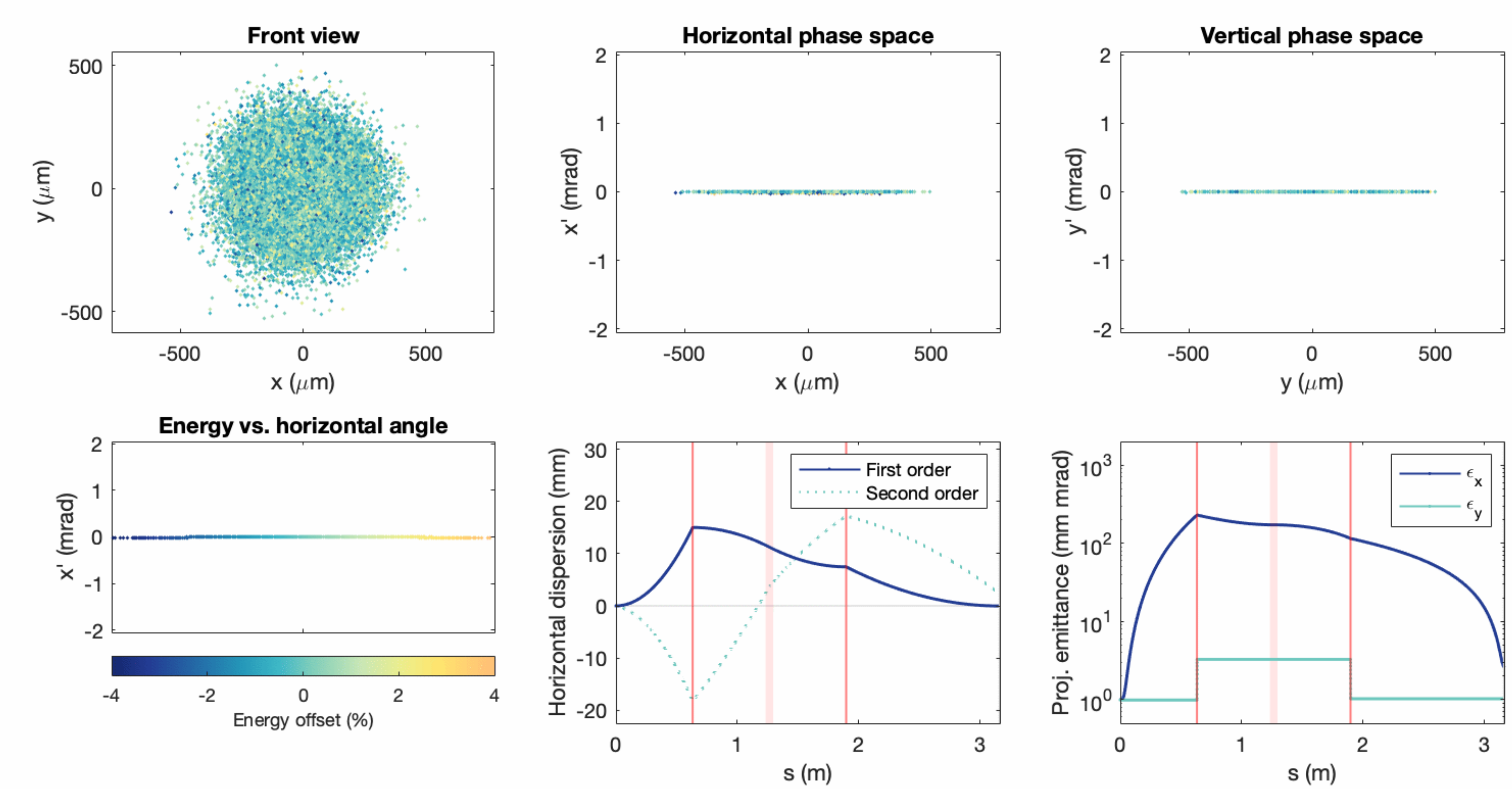
> Can also be asymmetric (beam telescope):

> Coupling to applications (e.g., undulators)

> Inverted: Beam-driver in-coupling, final focusing.

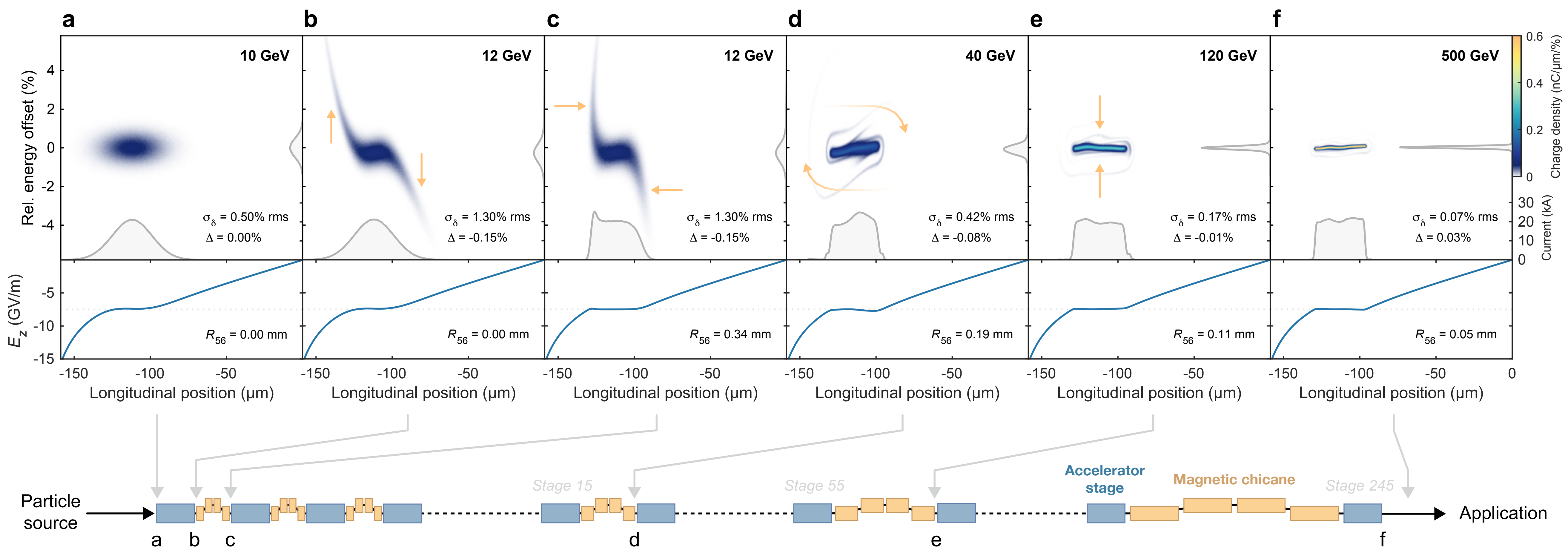
> **R&D required for demonstration of transversely tapered (active or passive) plasma lenses**





New concept #2: Self-correction for stability and energy-spread damping

Preprint: Lindstrøm, arXiv:2104.14460 (2021)



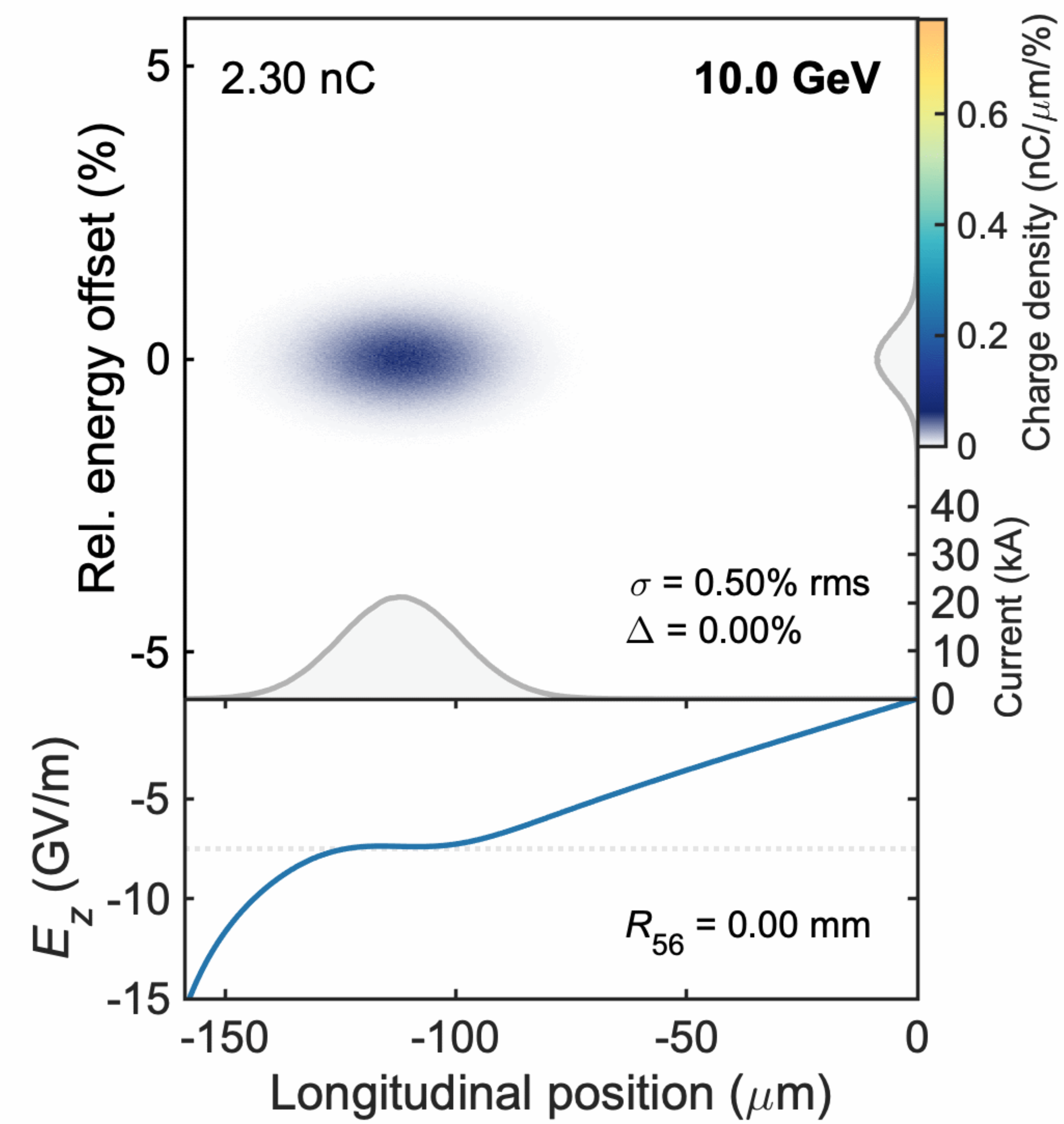
> **Introduce a small compression** between stages (magnetic chicane; R_{56})

> (1) Synchrotron oscillations of the centroid ⇒ **phase stability.**

> (2) Feedback between beam loading and shape of current profile ⇒ **automatic wakefield flattening** (optimal beam loading).

> Self-correcting long. phase space: **Damps energy spread** and **energy offset**

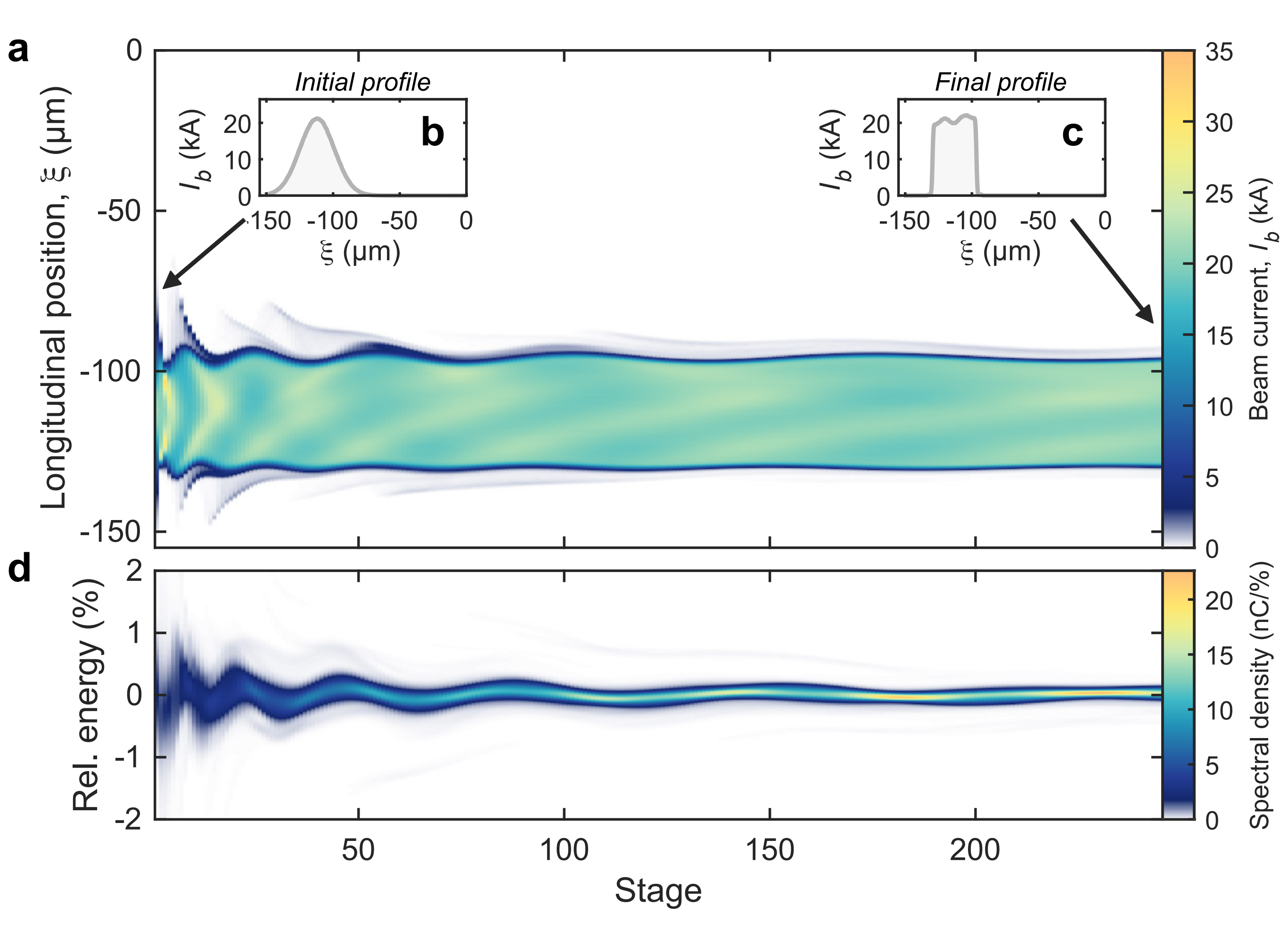
> Robust mechanism: specific wakefield regime or exact R_{56} not critical.

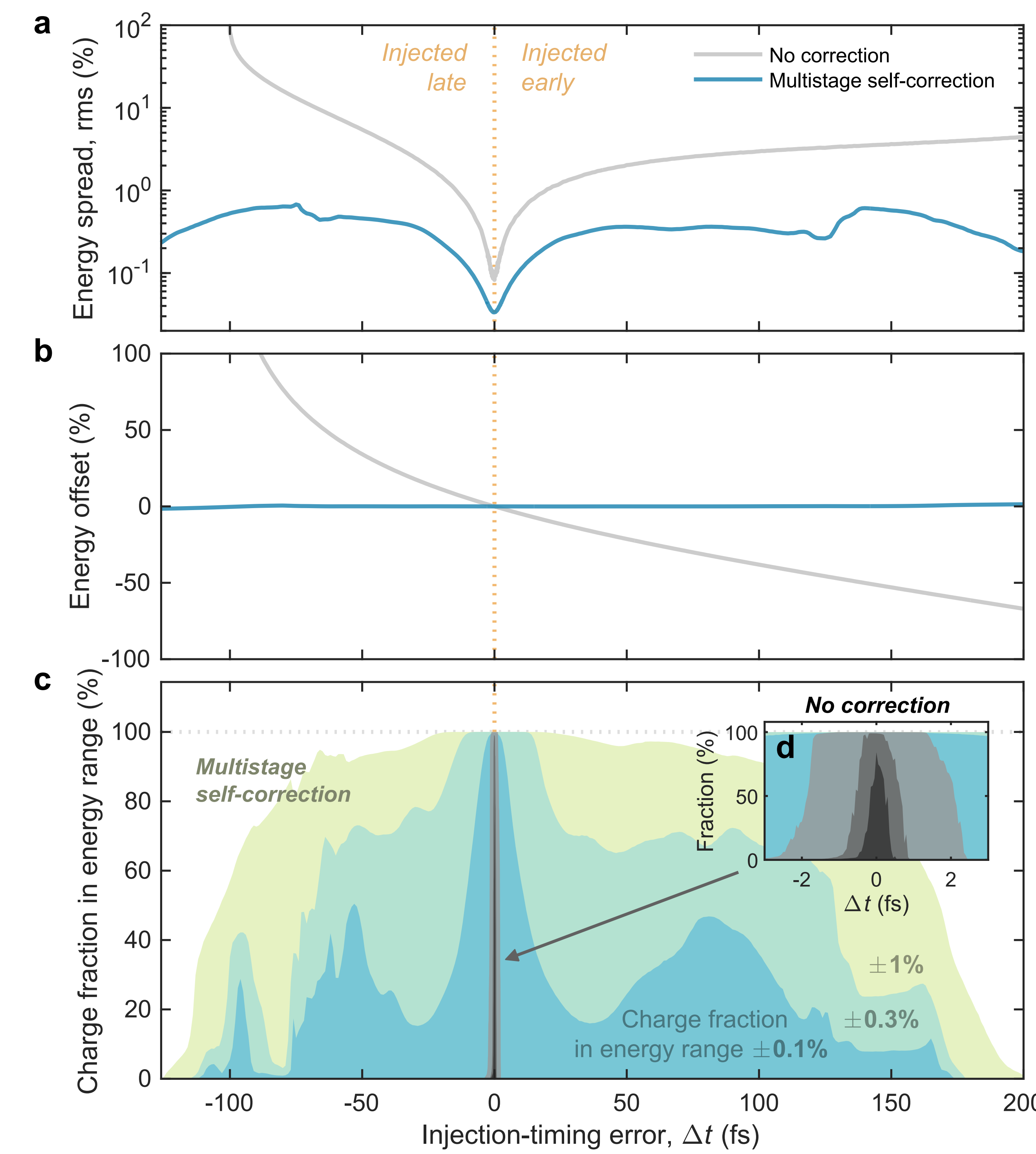


Self-correction (animation)

NEW CONCEPT #2: SELF-CORRECTION FOR STABILITY AND ENERGY-SPREAD DAMPING

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





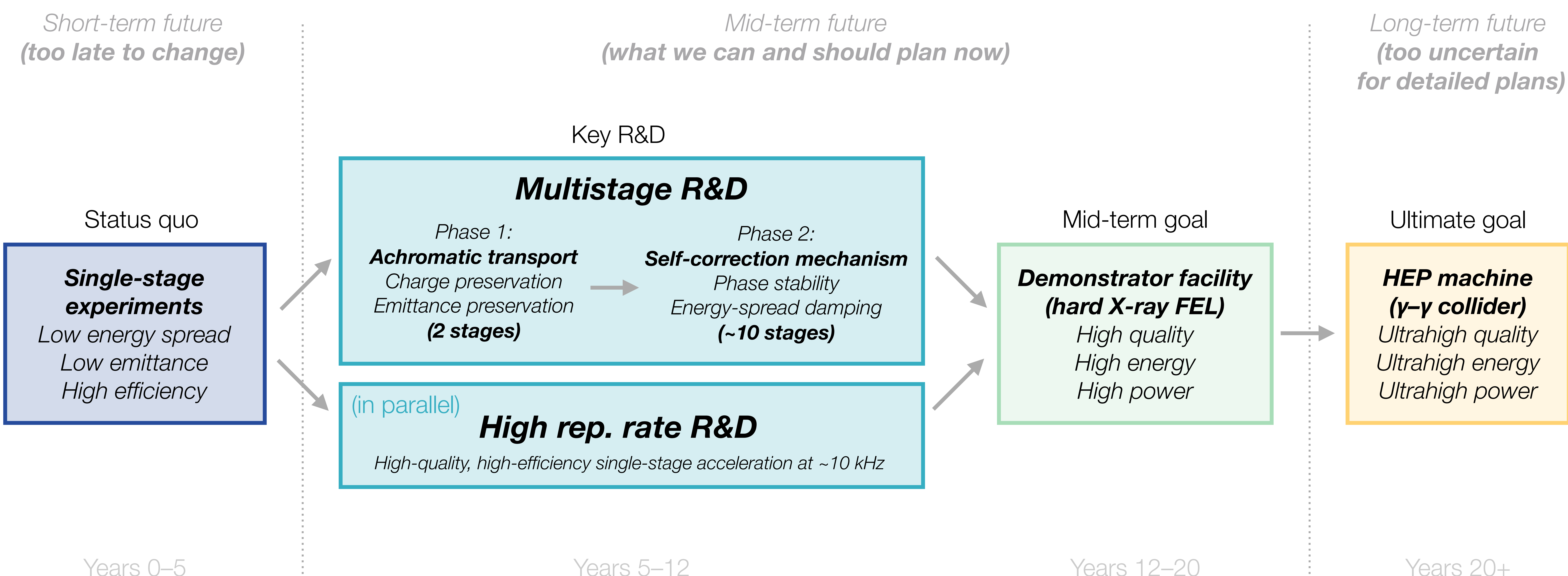
- No need for ultra-precise shaping of current profiles.
- **Improved synchronization tolerances** by several orders to magnitude.
- (Strong beam loading ⇒ natural high efficiency.)
- Implication: **Staging *not only* relevant to high energies**
  - Also beneficial for small-scale plasma accelerators.

- More R&D required to investigate…
  - …the coupling to the transverse phase space.
  - …the effect of CSR, betatron radiation, etc.

QUESTIONS, PART 1: **ROAD MAP TO A HEP COLLIDER**

- **1) Where do you see HEP applications of advanced accelerators in 30 years?**
  - γ–γ collider (the ideal starting point) — allows a "low-risk" path independent of e^+ success/failure.
  - e^+e^- collider (a potential upgrade) — important to continue e^+ plasma acceleration R&D (in parallel).
- **2) What intermediate physics applications/steps do you see until a HEP linear collider?**
  - Non-linear QED experiments — requires high energy, but moderate power.
  - Hard x-ray FEL — requires all the same properties as a HEP collider, but at a smaller scale.
- **3) What is the synergy with related fields?**
  - Staging can provide higher energy, higher stability and higher beam quality.
    - Can be applied to improve also small-scale plasma accelerators.
    - *Example: Direct injection into a storage ring (requires high energy stability, low energy spread)*
- **4) What is the role of your work here?**
  - Two new concepts that may enable staging:
    - *Achromatic emittance-preserving transport (with transversely tapered plasma lenses).*
    - *Self-correcting longitudinal phase space (small compression between stages).*

QUESTIONS, PART 1: ROAD MAP TO A HEP COLLIDER



Questions, Part 2: **Milestones**

- **1) What are the important milestones for the next 10 years to get there from today?**
  - Demonstrate self-correction in a multistage (10-stage) plasma accelerator
  - Demonstrate high-repetition-rate (single-stage) plasma acceleration
- **2) What additional support is needed to achieve these?**
  - 💸💸💸
- **3) What should be proposed as deliverables until 2026?**
  - The “ultimate” single-stage plasma accelerator (beam-quality preservation, high overall efficiency).
  - Demonstrate transversely tapered plasma lenses.
  - Theoretical investigations of staging concepts.
  - Identify scalable high-repetition-rate concepts (for plasma sources, drivers, etc.)
- **4) Is the R&D work for each of those deliverables already funded and, if not, what additional resources / support would be needed?**

QUESTIONS, PART 3: **FUNDING AND FACILITIES**

- **1) What key R&D needs can be achieved in existing R&D facilities?**
  - Single-stage plasma acceleration (high-quality, high-efficiency, high-gradient)
  - Demonstrating transversely tapered plasma lenses
  - High-repetition-rate plasma acceleration
- **2) What is the role of the already planned future facilities in Europe and world-wide?**
  - Staging not currently part of any planned facilities.
- **3) What can be done with the existing and planned funding base?**
  - 2 stages (for transport) may be possible, but ~10 stages (for self-correction, high energy) is not possible.
- **4) Is a completely new facility needed?**
  - Yes, and the facility should be scalable to become a high-rep-rate, multistage facility (a demonstrator facility).
- **5) Are additional structures needed beyond existing networks and projects, e.g. a design study for a collider or an advanced accelerator stage?**