Slice Emittance Preservation and Focus Control in a Passive Plasma Lens

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EAAC2025

FLASHFORWARD

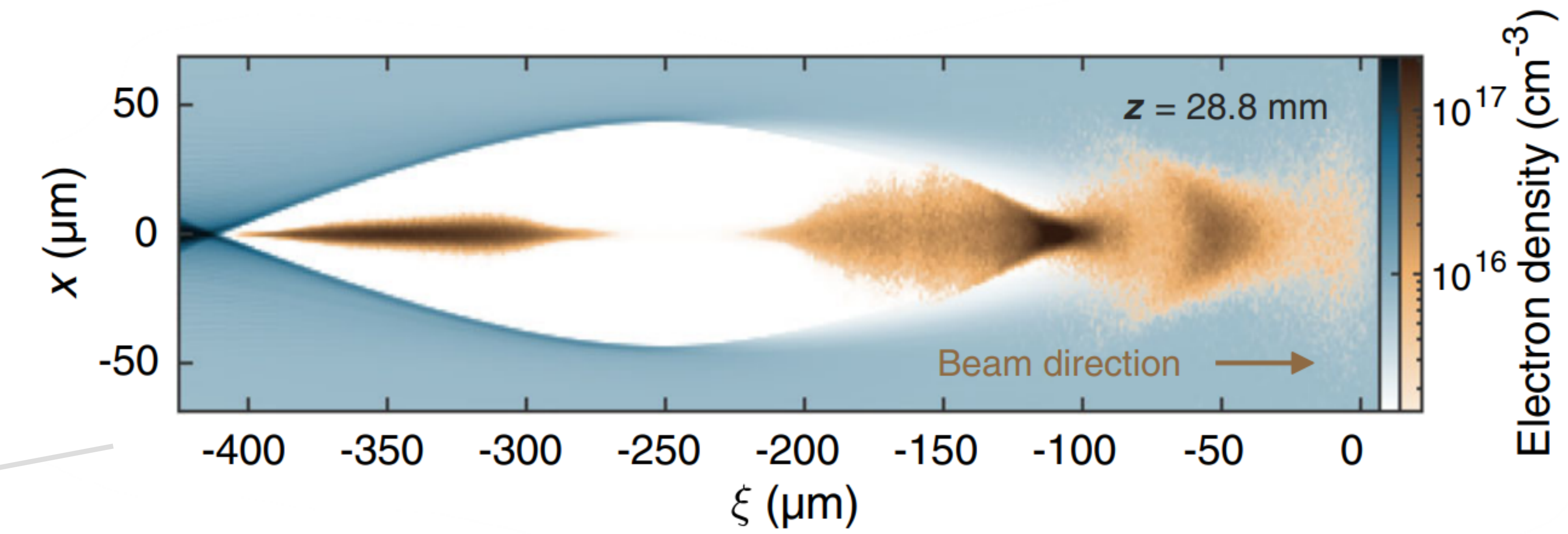
DESY.

Small beams and Matching

> Some applications operate with (transversely) small particle beams

> > Particle colliders

> > **Plasma-based accelerators (PBAs)**



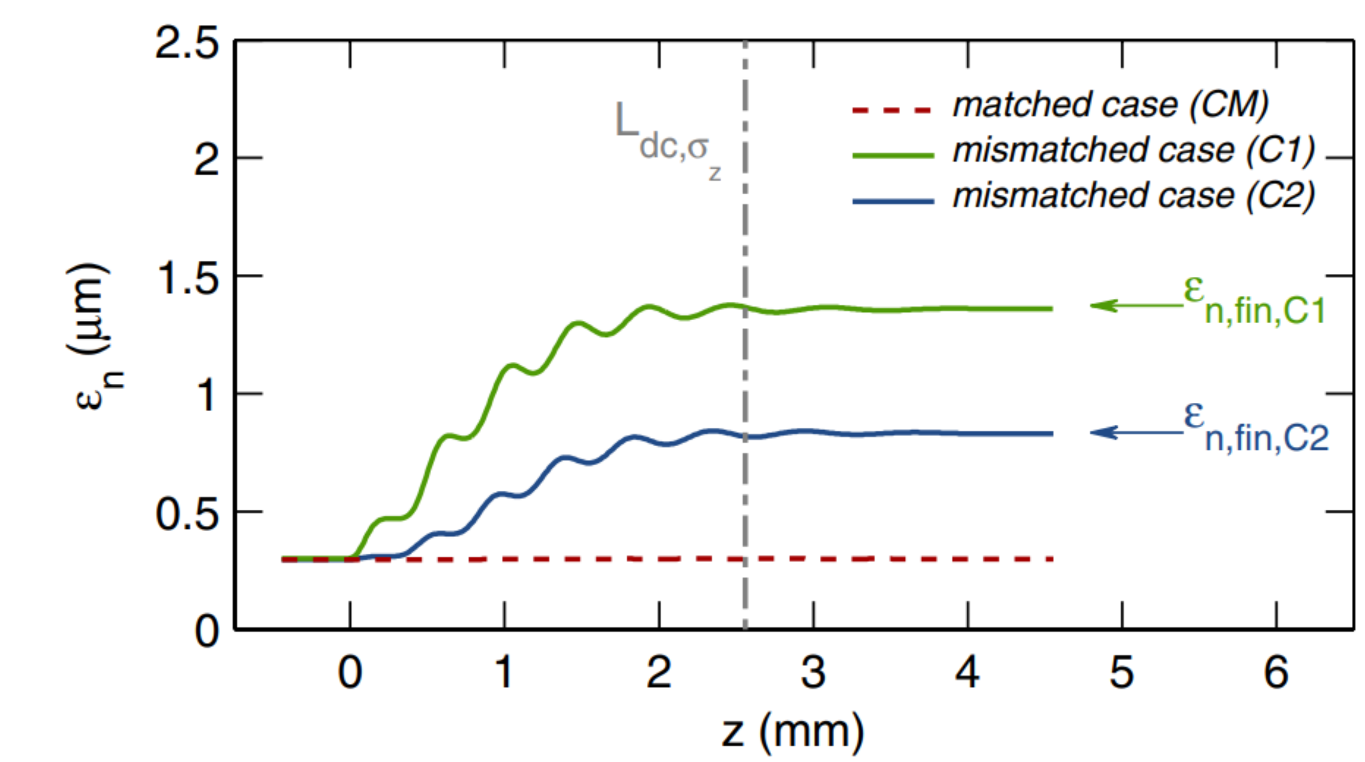
C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)

> Matched beams important for emittance preservation in PBAs

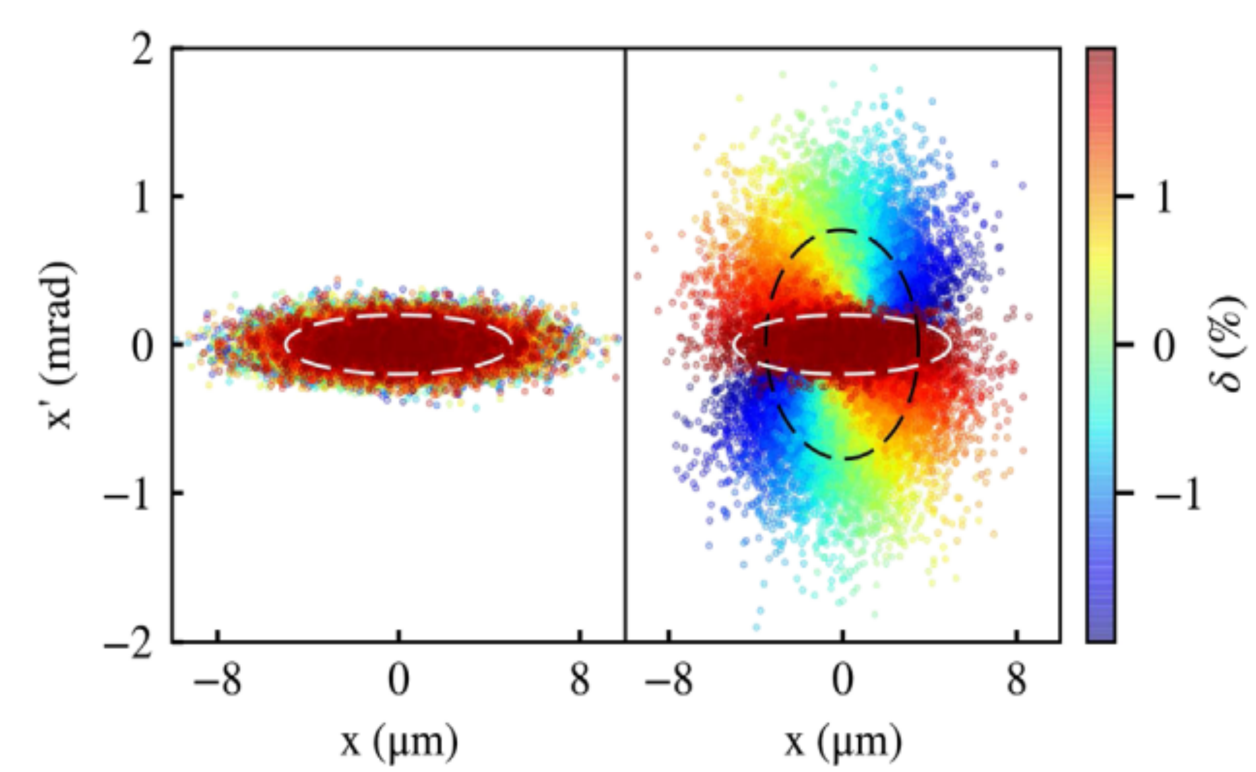
> > Mismatched → chromatic betatron decoherence

> > Matched beta function in the mm range, $\beta_\mathrm{m} \propto \sqrt{\frac{\gamma_\mathrm{e}}{n_\mathrm{p}}}$

> > > **Difficult to transport**



T. Merhling *et al.*, Phys. Rev. ST Accel. Beams **15**, 111303



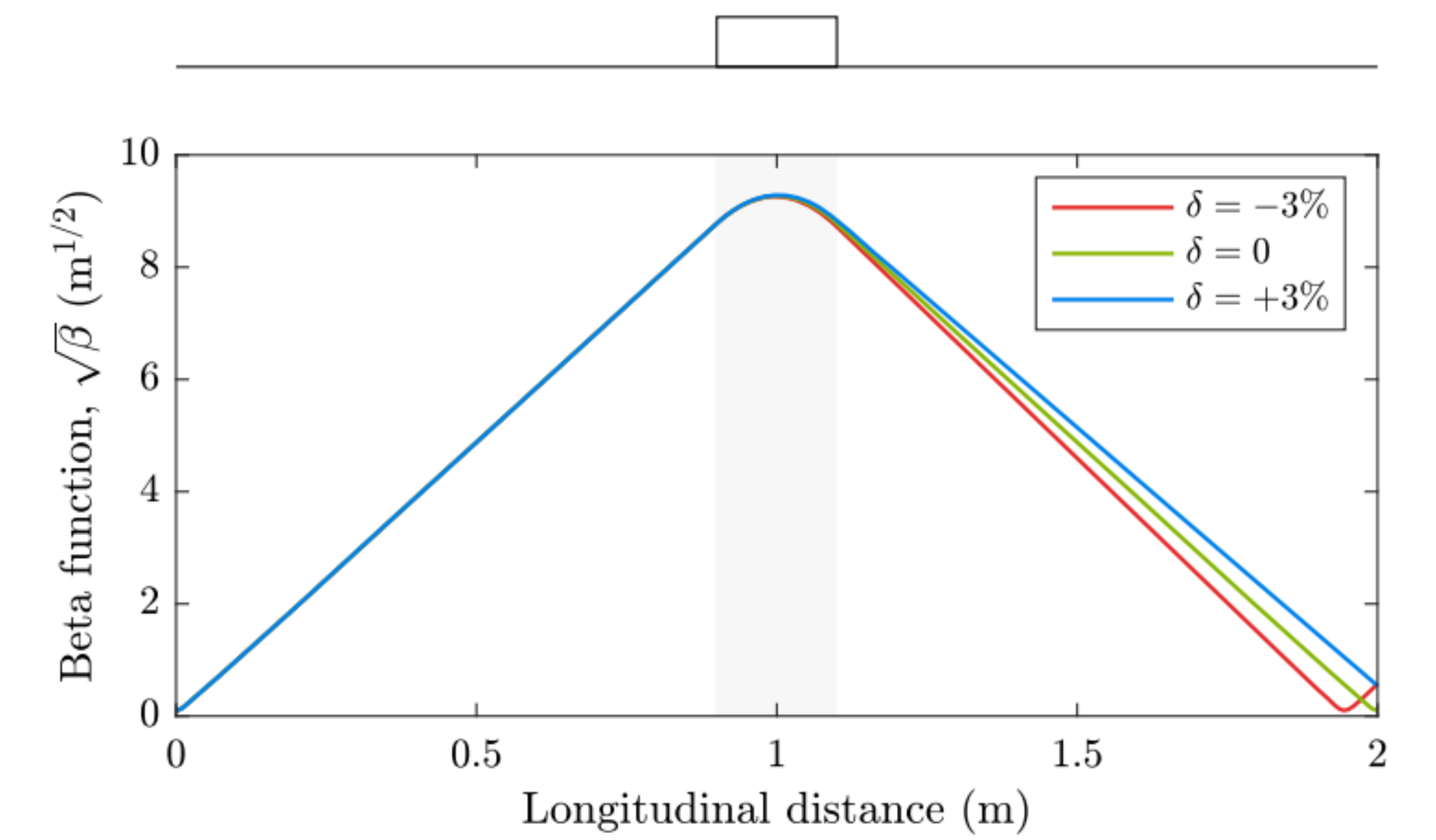
R. Ariniello *et al.*, Phys. Rev. Accel. Beams **22**, 041304 (2019)

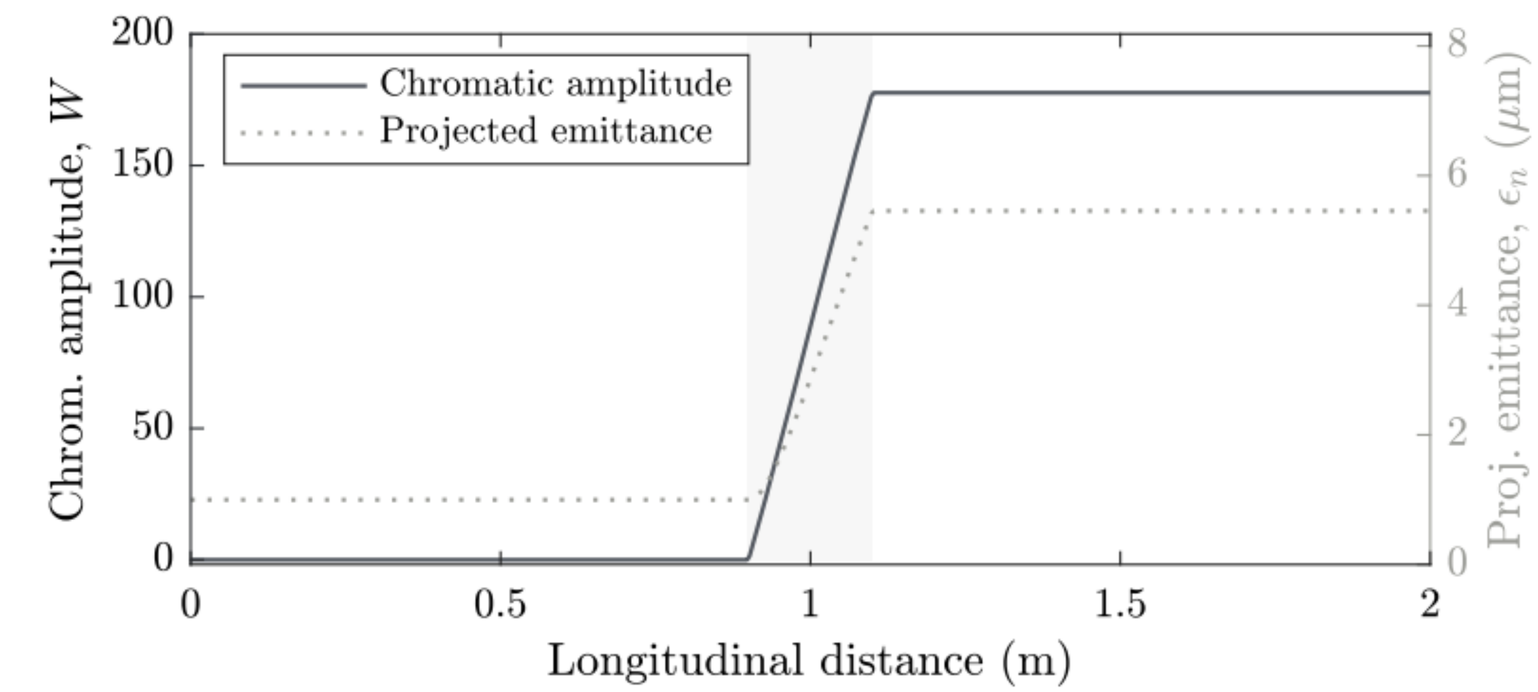
Strong Focusing and Chromaticity

> Strong focusing required to reach/capture small beam sizes
  > Any single optic is chromatic

> Chromaticity increases for smaller foci and longer focal lengths
  > Associated emittance growth

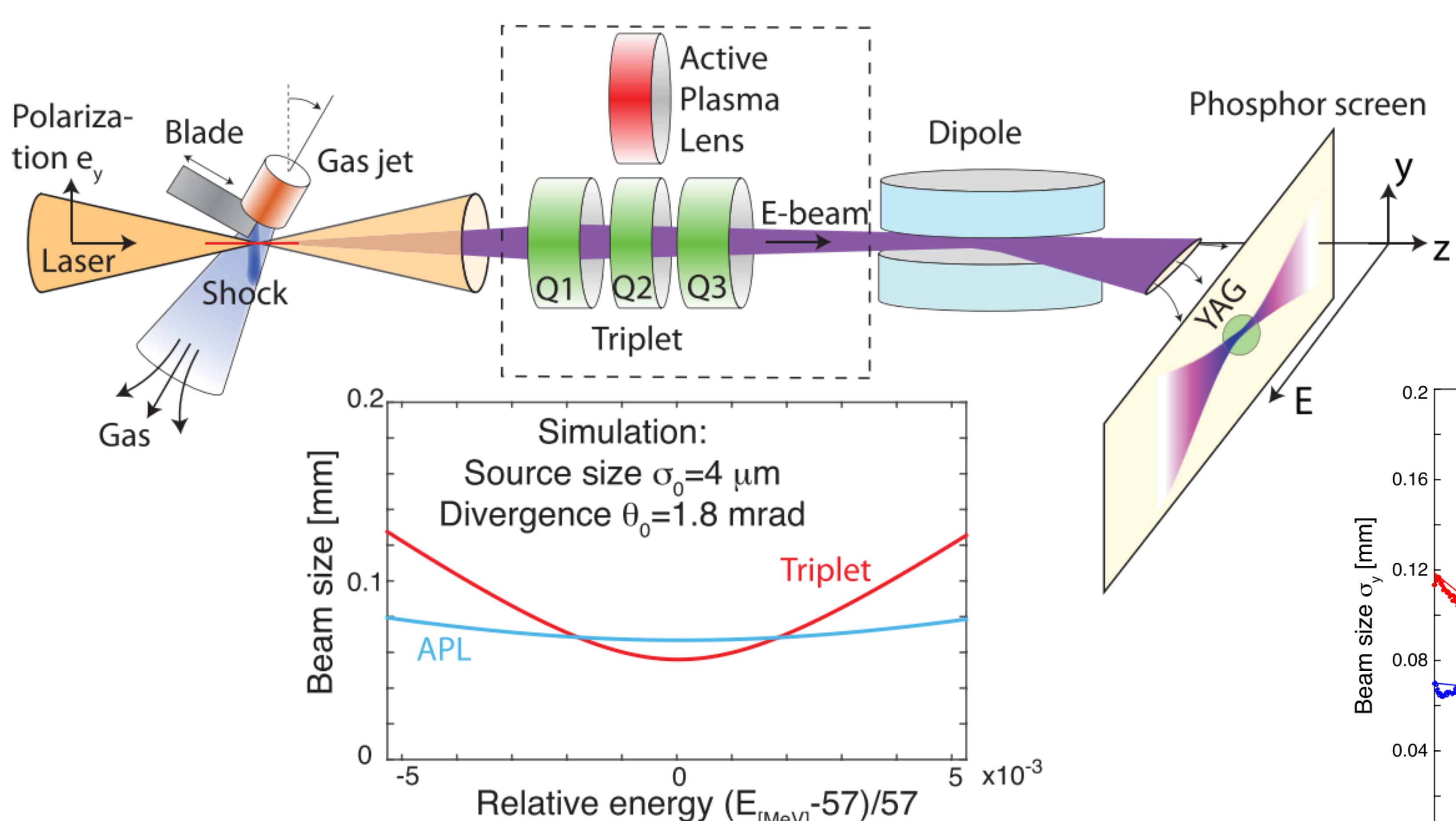
> Minimum number of focusing elements
  > Quadrupoles: 2 (3)
  > Plasma lenses: 1

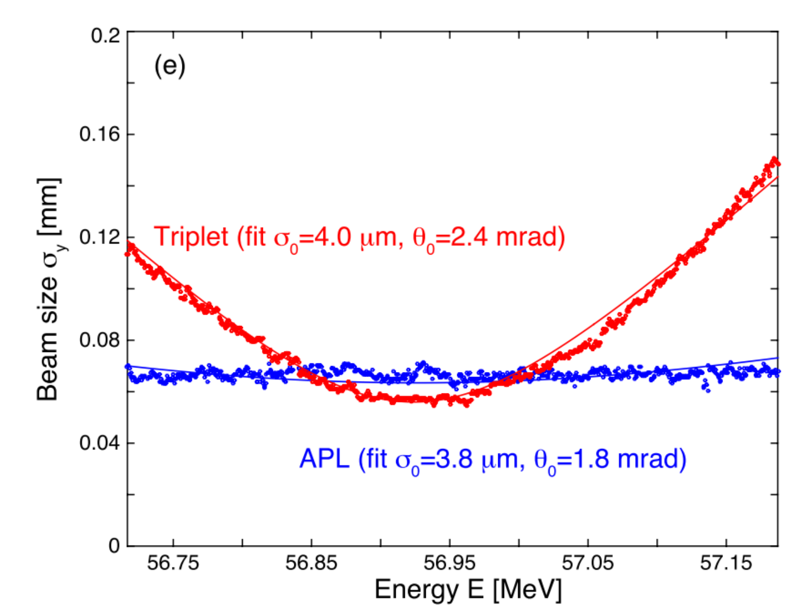




C. A. Lindstrøm, Phys. Rev. Accel. Beams **24**, 014801 (2021)

$$\frac{\Delta\varepsilon}{\varepsilon_0} \propto \frac{L^{*2}}{\beta^{*2}}\sigma_\delta^2$$



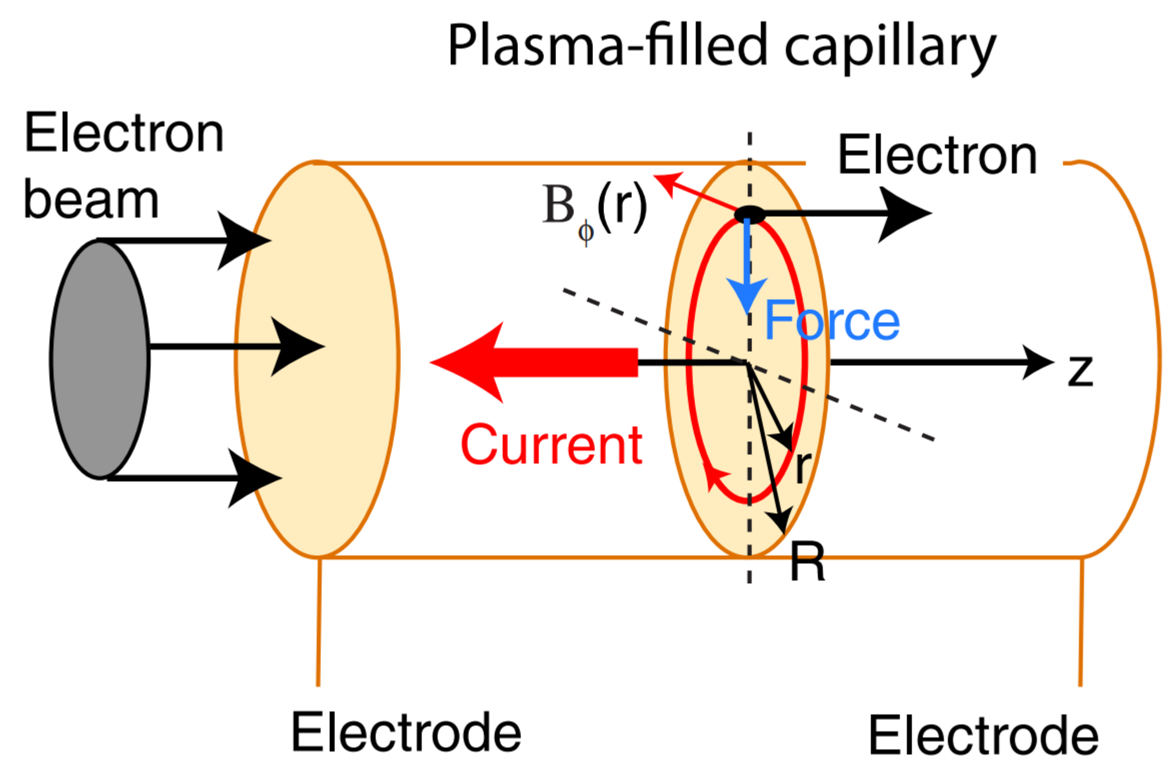


J. van Tilborg *et al.*, Phys. Plasmas **25**, 056702 (2018)

Plasma Lenses

Two types of plasma lenses:

> **Active plasma lenses (APLs)**
  > Discharge current produces (de-)focusing B-field
  > ~0.1's – 1's kT/m focusing gradient
  > Focusing (ideally) independent of beam

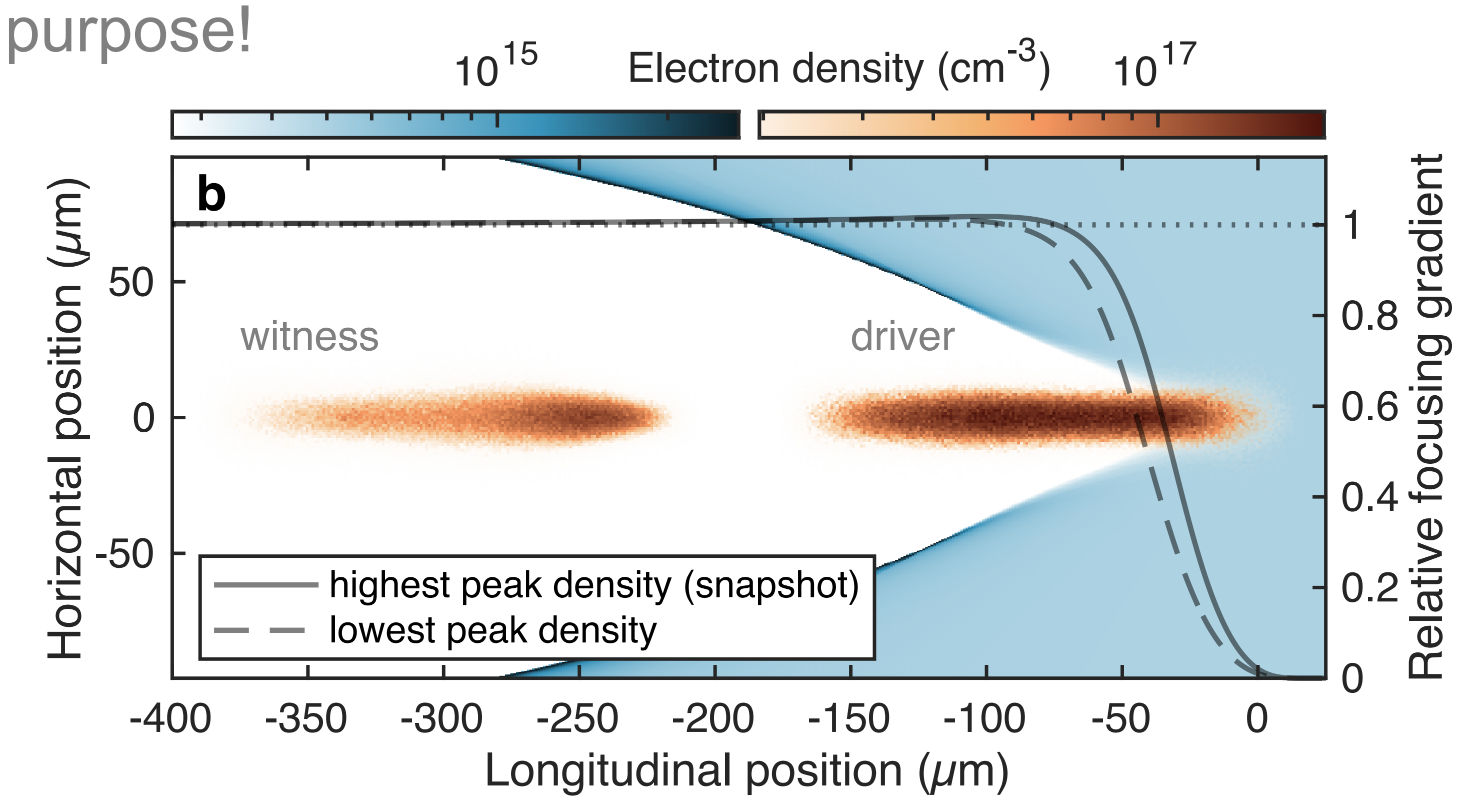


J. van Tilborg *et al.*, Phys. Rev. Lett. **115**, 184802 (2015)

> **Passive plasma lenses (PPLs)**
  > Plasma wake produces focusing wakefield*
  > 1's – 1000's kT/m focusing gradient
  > Requires driver (bunch/laser)

*Assuming an underdense lens

Same physics in a PPLs and PBAs, but different purpose!



> **For reference:** quadrupole magnets <~0.1 kT/m

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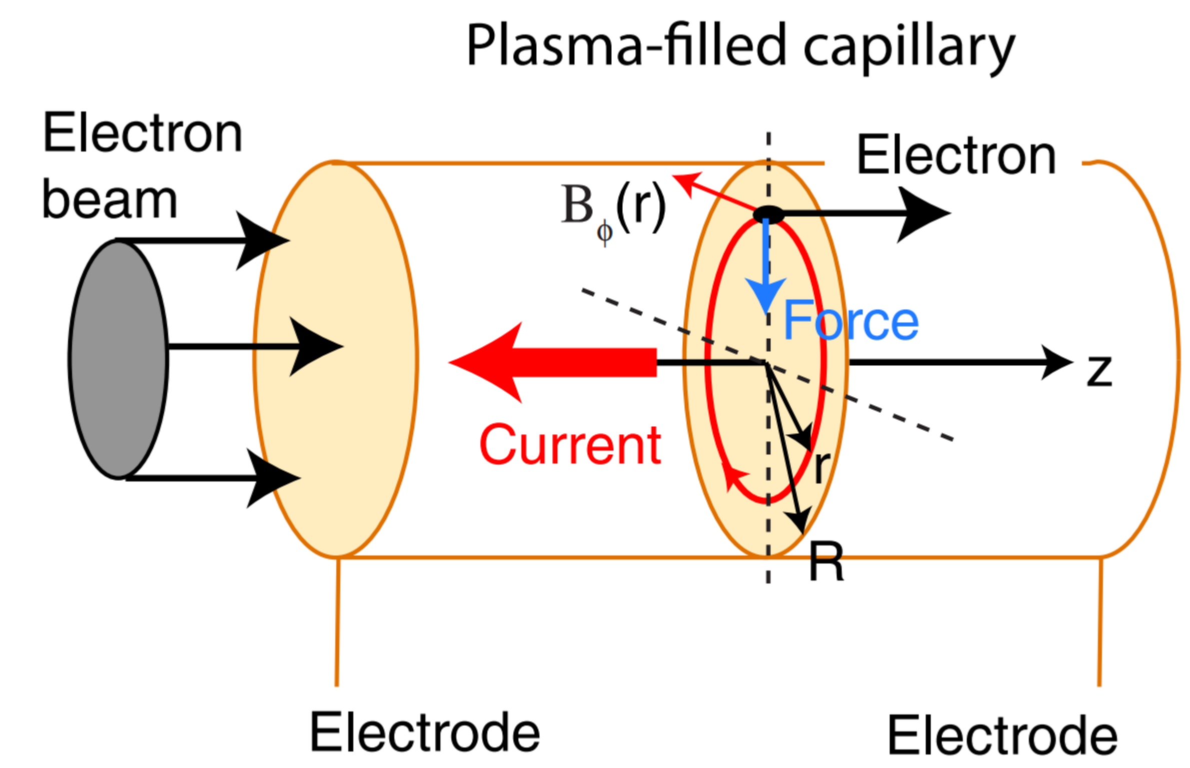

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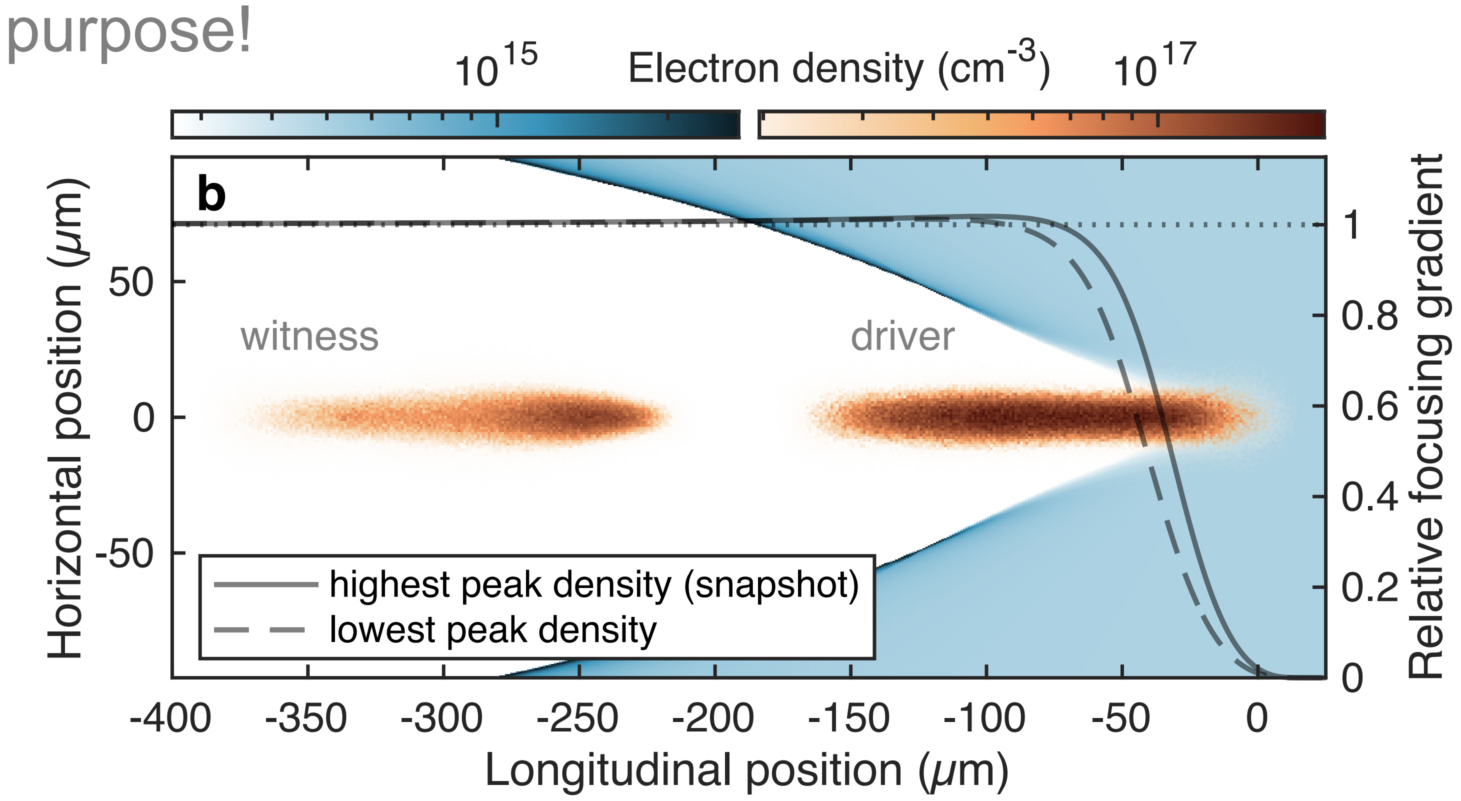

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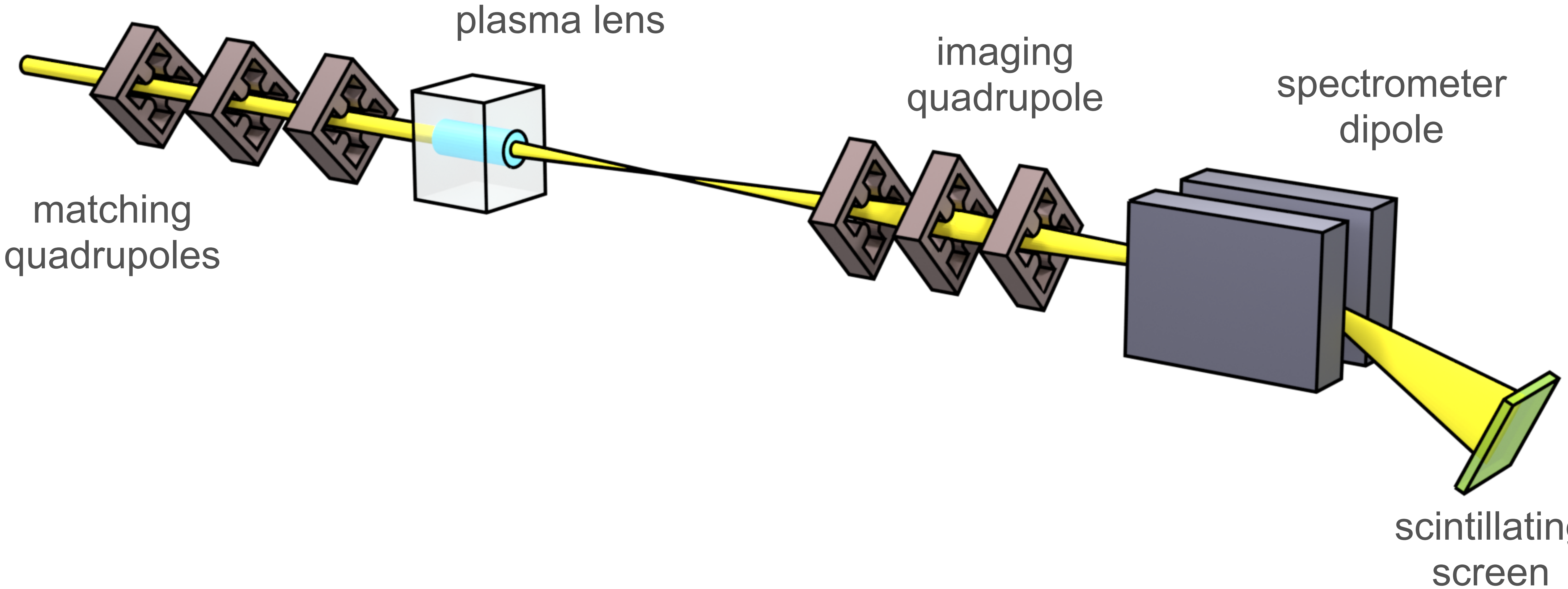
Big question:
Can they be used with high-brightness beams?

The experiment

- Experiment performed at FLASHForward

- Bunch pair from single FLASH bunch
  - Typical FFWD PWFA-beam

- HV discharge plasma
  - 15-mm x 1.5-mm sapphire capillary
  - Nitrogen, Z = 7
  - Argon, Z = 18



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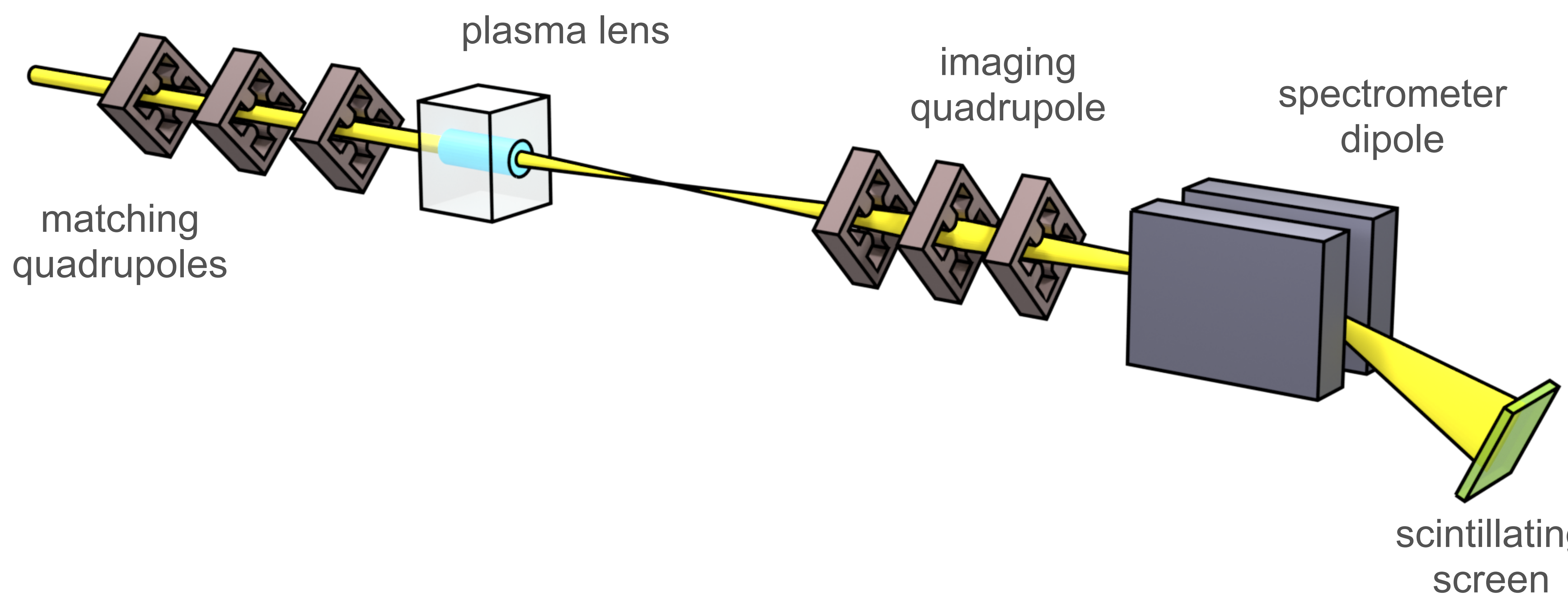
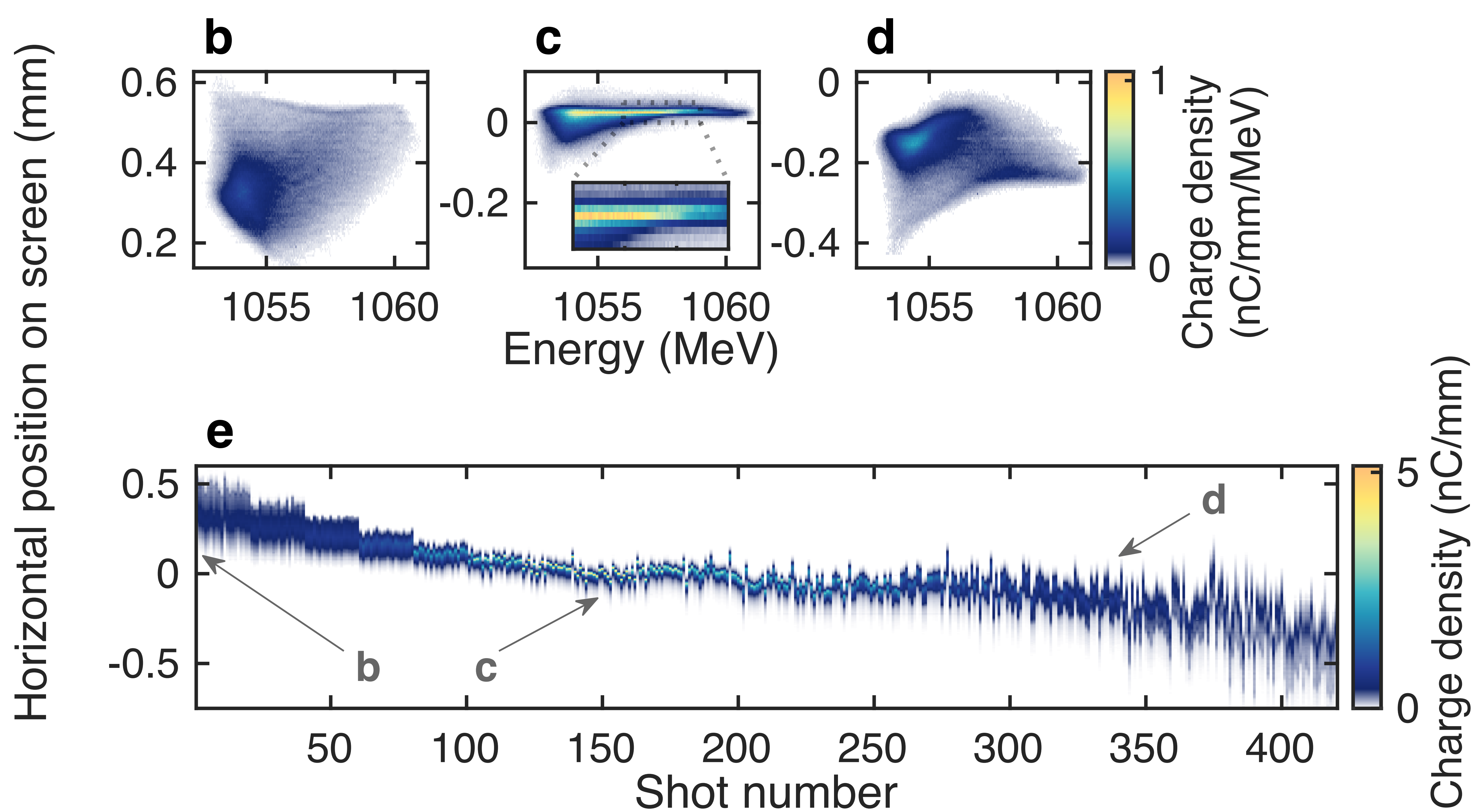
- Concept: use the PPL as a final-focusing element
  - Quadrupole magnets to set a modest focus into PPL
  - Driving bunch excites wake, witness samples it
  - Bunch(es) focused tightly

- Goal: emittance-preserving tight focusing with a PPL
  - Ideally tunable focal parameters



Experimental results: nitrogen plasma

- Main method: object plane scans on high-resolution electron spectrometer
  - Variation of multi-quad scan
  - Point-to-point imaging a range of longitudinal positions
  - Fit to beam sizes to get emittance, waist beta, waist location



Experimental results: nitrogen plasma

Beam propagation around a waist

$$\sigma(s) = \sqrt{\varepsilon_g \beta} = \sqrt{\frac{\varepsilon_n}{\gamma_b}\left[\beta^* + \frac{(s-s^*)^2}{\beta^*}\right]}$$

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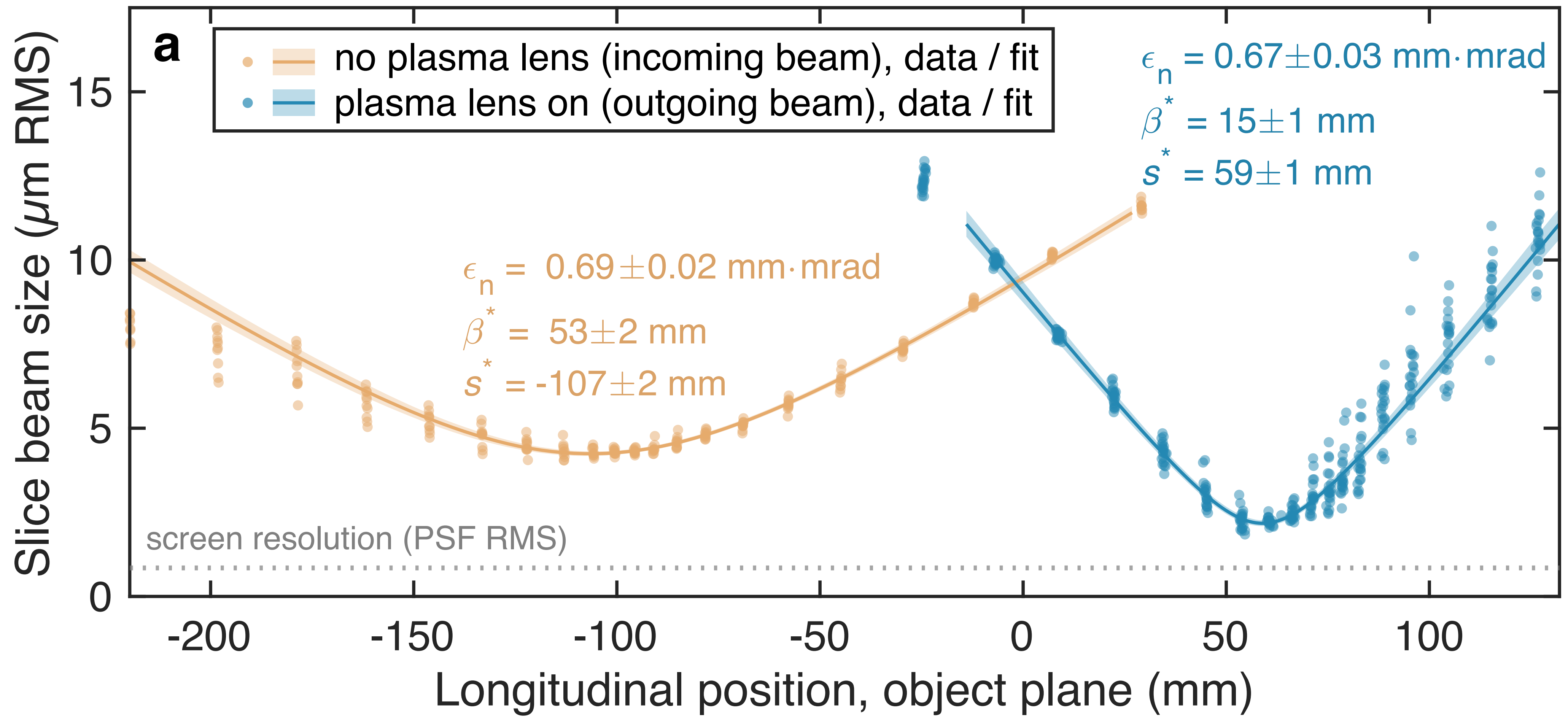

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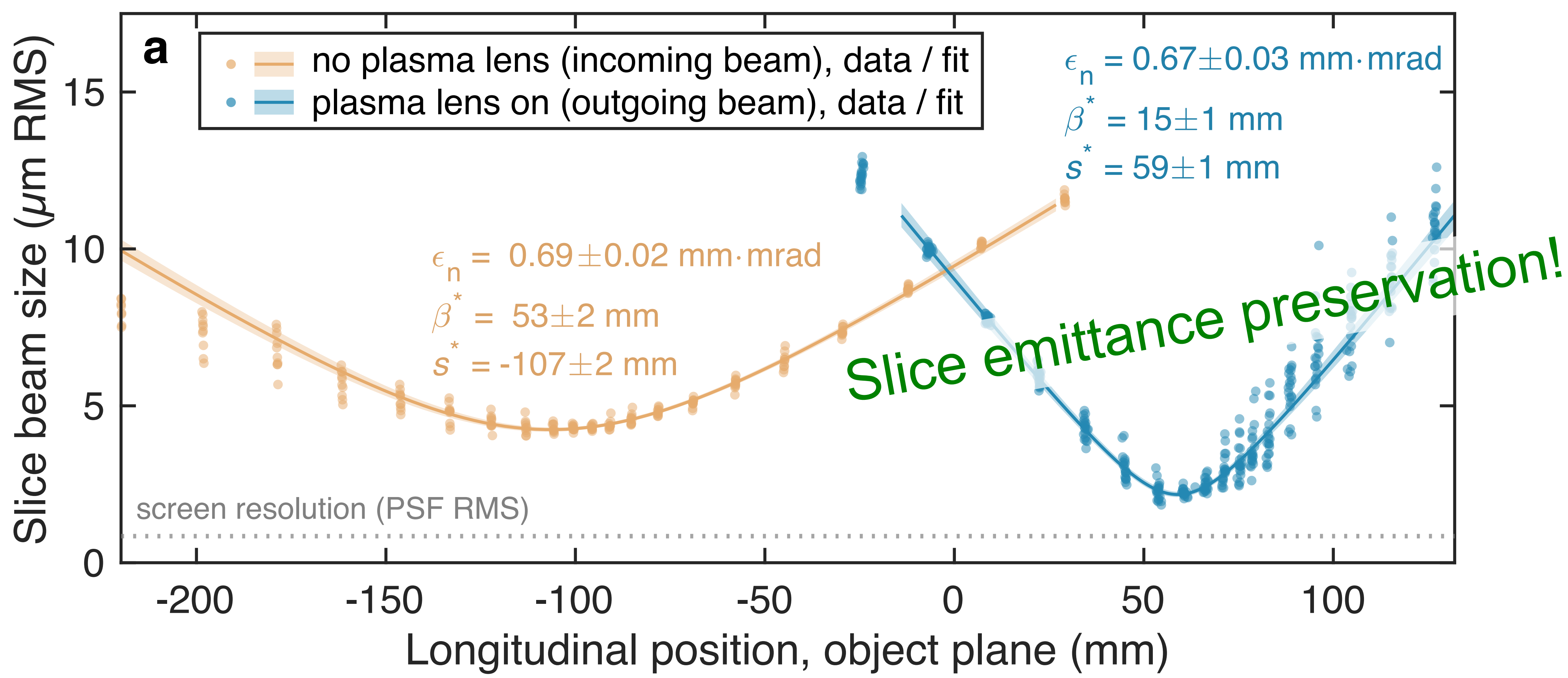

Emittance in: 0.69 ± 0.02 mm·mrad

Emittance out: 0.67 ± 0.03 mm·mrad

EXPERIMENTAL RESULTS: NITROGEN PLASMA

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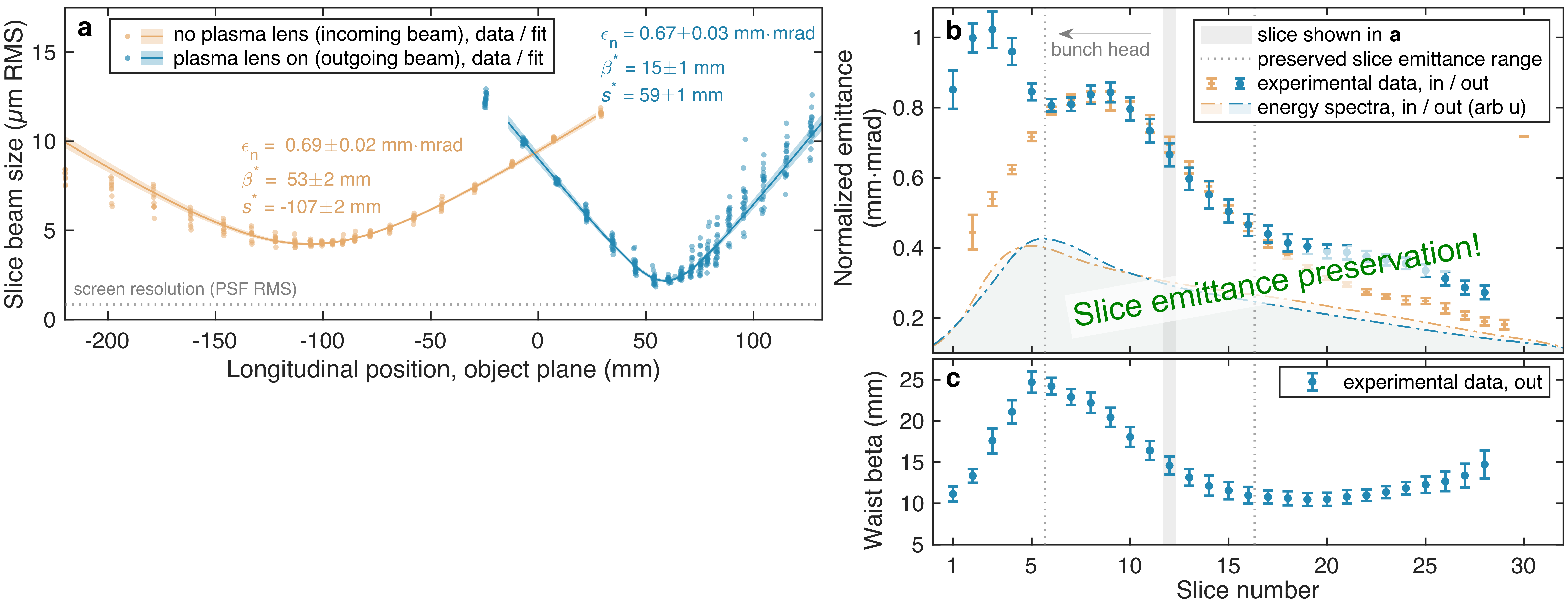

Experimental results: nitrogen plasma

- Small change in energy: assume idealized slice propagation
  - Assume Gaussian focusing channel (plasma redistribution)
  - Predicts smaller waist betas for tail slices
  - Resolution limited!

Beam propagation around a waist

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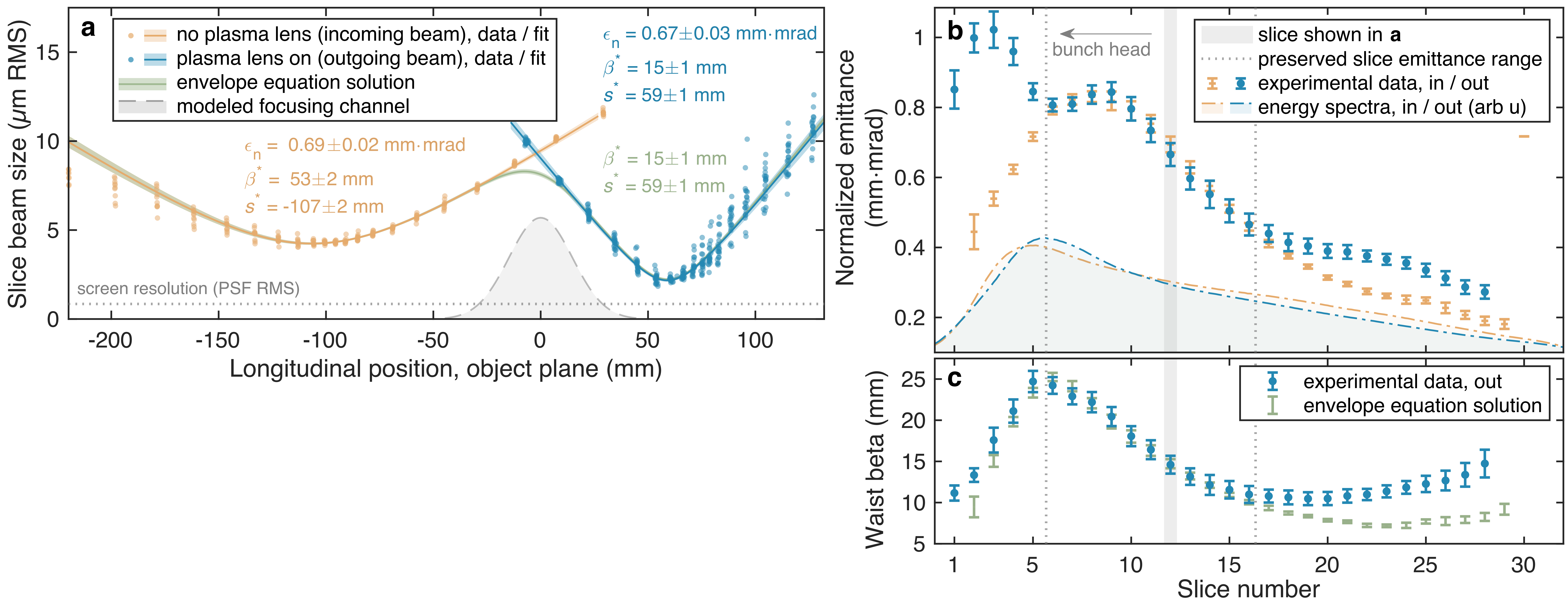
Betatron envelope equation

$$\frac{1}{2}\beta'' + \kappa\beta - \frac{1}{\beta}\left[1 + \left(\frac{\beta'}{2}\right)^2\right] = 0$$



Experimental results: nitrogen plasma

Beam propagation around a waist

$$\sigma(s) = \sqrt{\varepsilon_g \beta} = \sqrt{\frac{\varepsilon_n}{\gamma_b}\left[\beta^* + \frac{(s-s^*)^2}{\beta^*}\right]}$$

Betatron envelope equation

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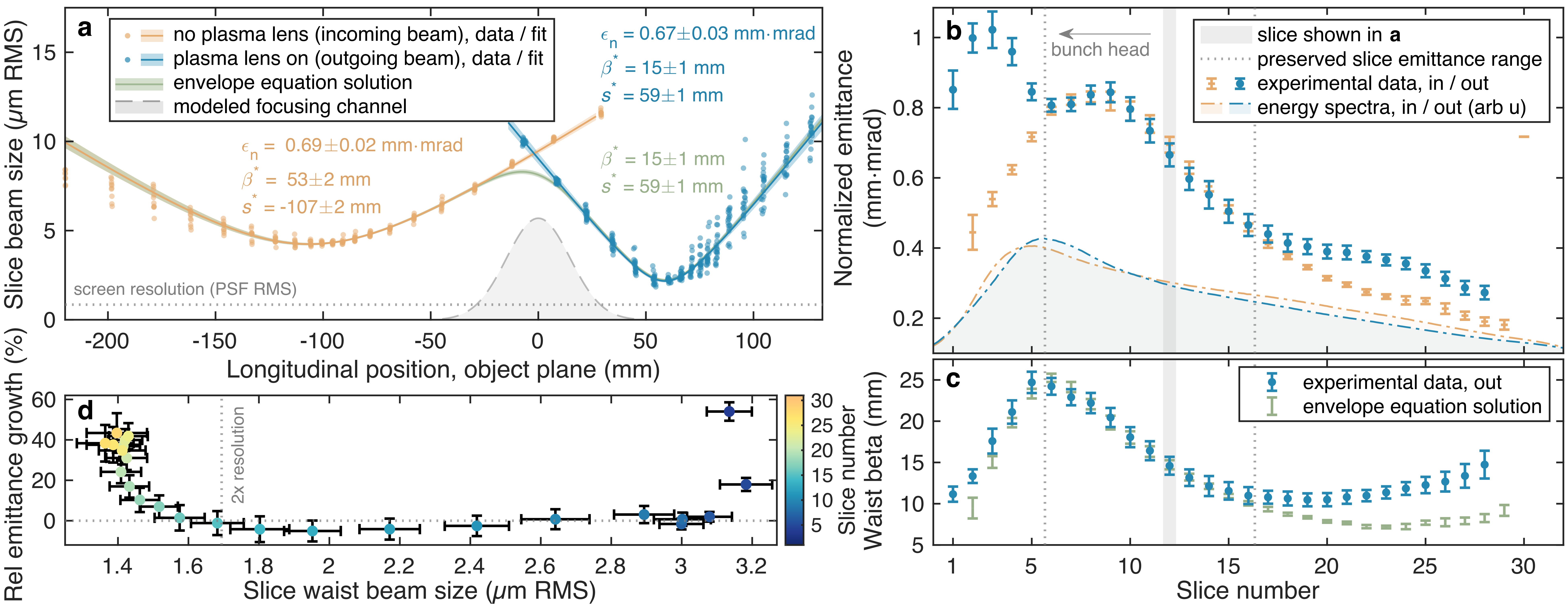

Experimental results: nitrogen plasma

- Particle-in-cell simulations agree with measurements and model
  - *Slice + projected emittance preservation*
  - Tight focusing

Beam propagation around a waist

$$\sigma(s) = \sqrt{\varepsilon_g \beta} = \sqrt{\frac{\varepsilon_n}{\gamma_b}\left[\beta^* + \frac{(s-s^*)^2}{\beta^*}\right]}$$

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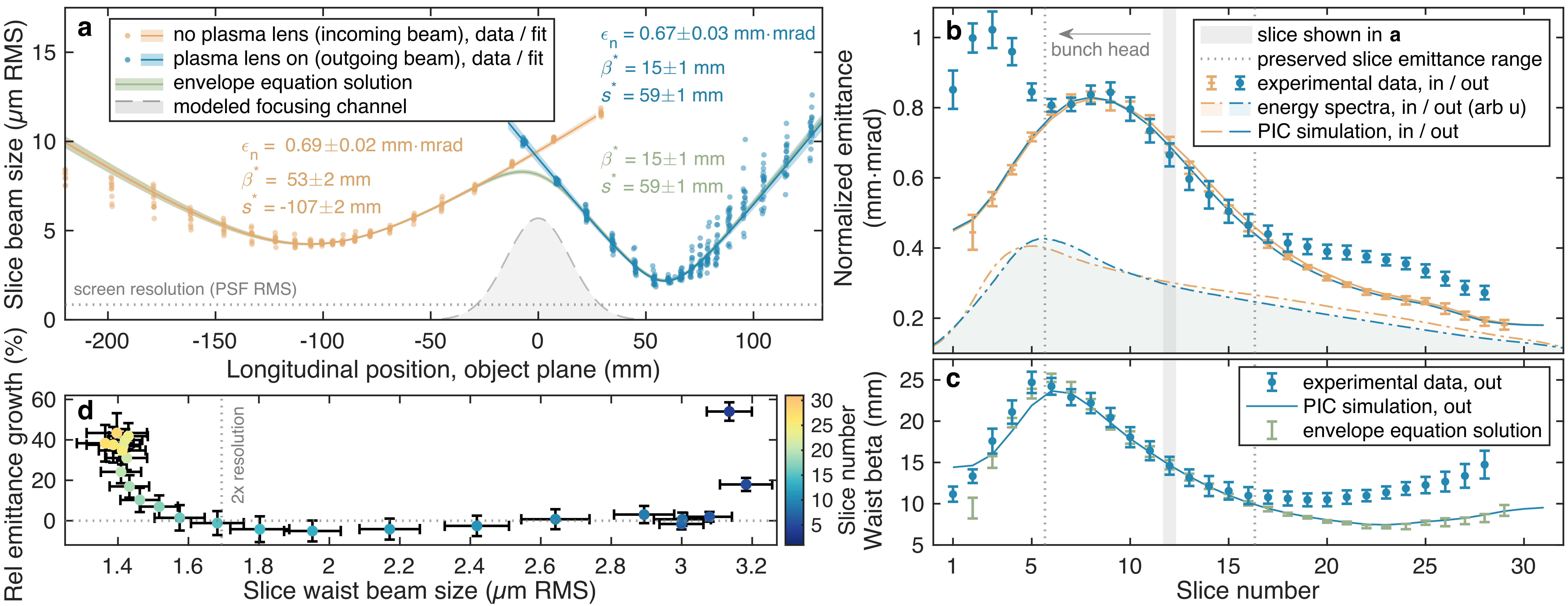
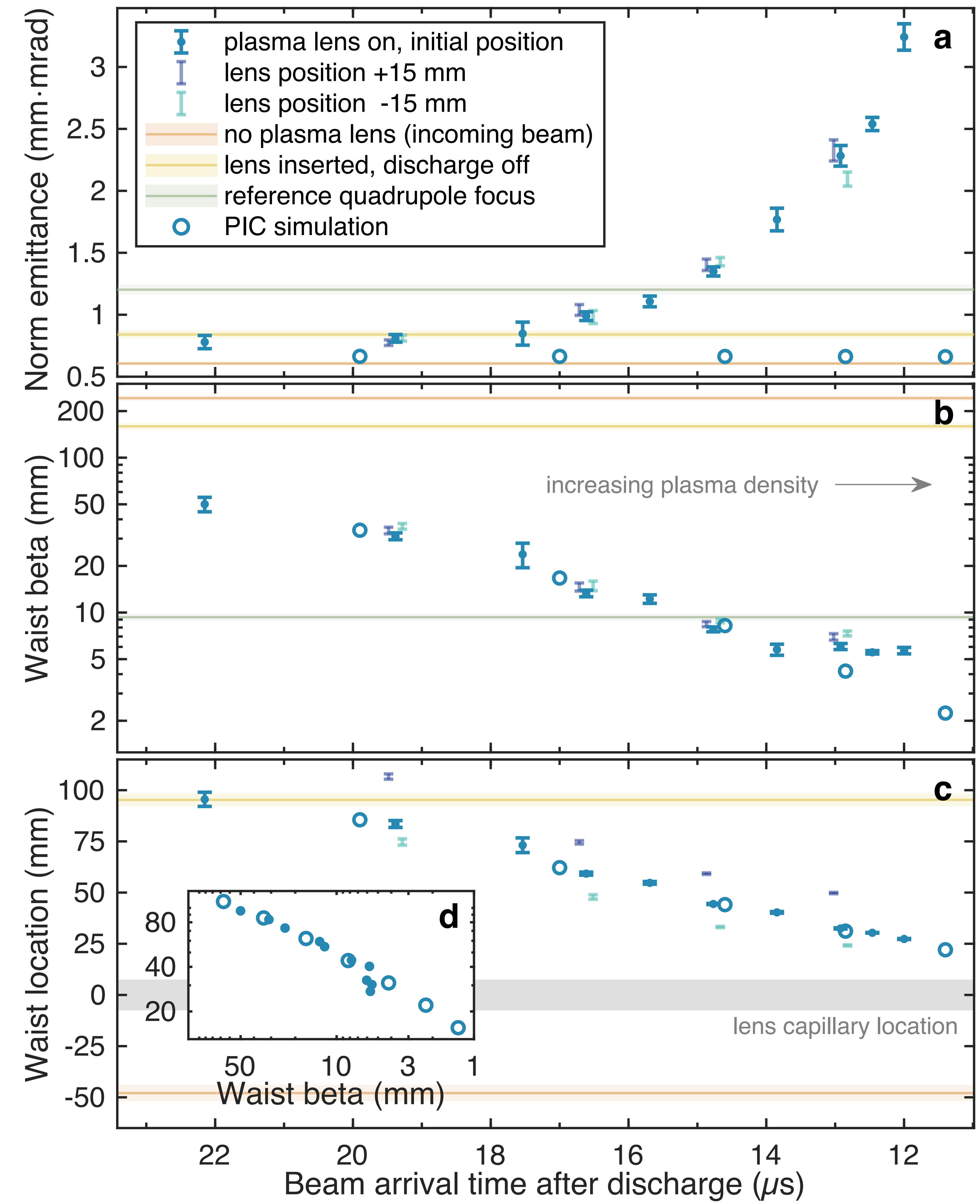


Experimental results: argon plasma

- Capillary degraded while taking data with nitrogen
  - Unstable discharge
  - Higher-pressure argon stabilized the discharge
  - Detrimental effects…

- Not emittance preserved
  - Coulomb scattering from argon
  - Resolution limit again (c.f. quad focus)
  - Small measured waist betas
    - Projected: 6 mm
    - Slice: 1.6 mm
    - Likely smaller in reality

- PIC simulations reproduce focusing - *no emittance growth*
  - Neutral Coulomb scattering not implemented
  - No measurement resolution limitation

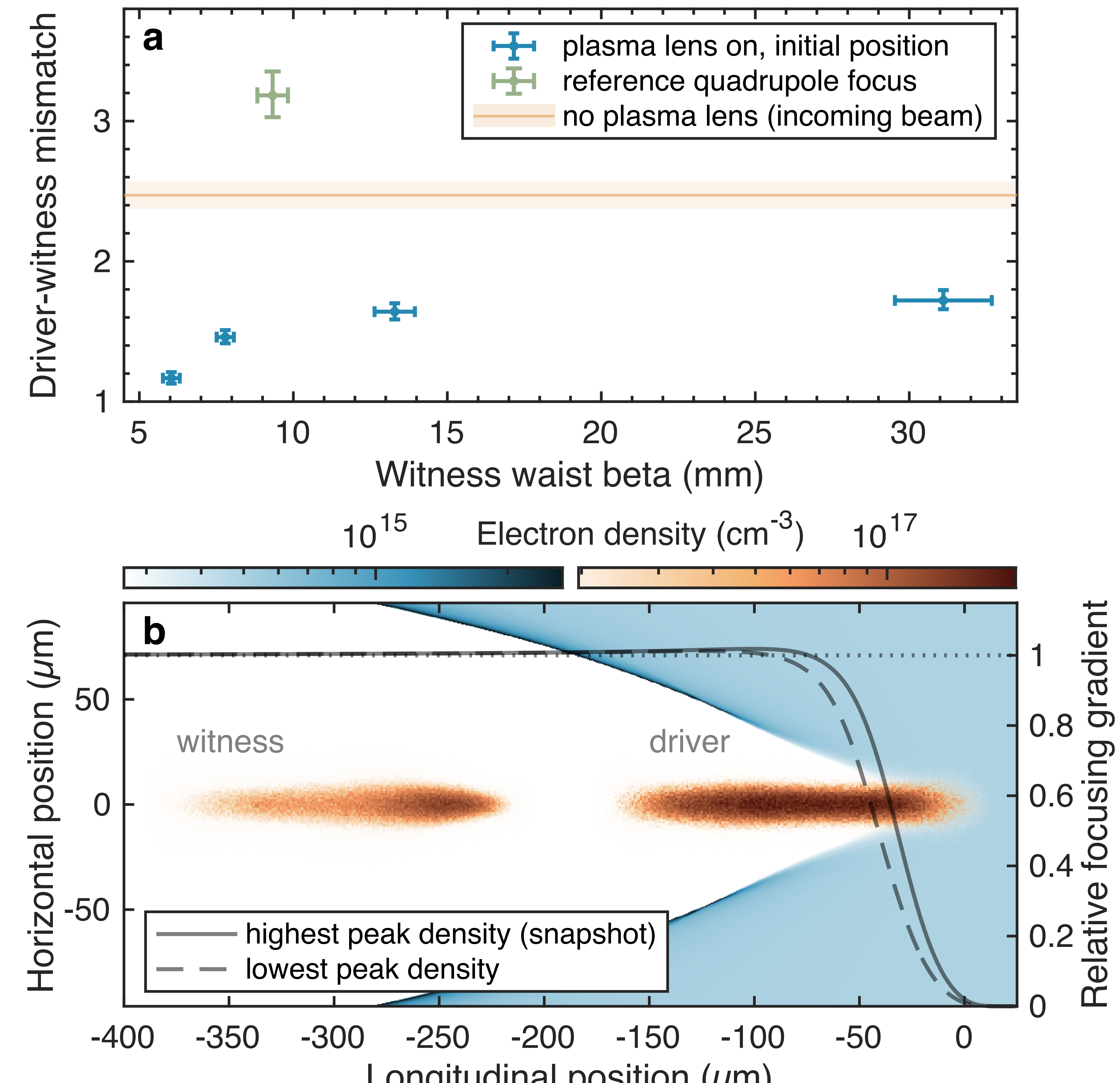


Experimental results: argon plasma

$$\mathscr{M}_{\mathrm{D-W}} = \frac{\left(\beta_{\mathrm{D}}^{*2} + \beta_{\mathrm{W}}^{*2} + \left(s_{\mathrm{D}}^{*} - s_{\mathrm{W}}^{*}\right)^2\right)}{2\beta_{\mathrm{D}}^{*}\beta_{\mathrm{W}}^{*}}$$

- Driver and witness more equal with lens on
  - M = 1 means identical beam optics
  - Leftmost points strongly affected by resolution limit

- Most of the driver focuses too - can be optimized
  - Optimal plasma density exists for a given driver current
  - Potentially ideal for PWFA
    - Driver head focuses similarly in PPL and PWFA
    - Minimize driver evolution?
    - Transverse stability?



CONCLUSIONS

- PPLs can work, potentially even better than quadrupole magnets
  - (Slice) emittance preserved with the right choice of gas
  - PBA-relevant waist betas achievable
  - Tunable focus - matching can be optimized

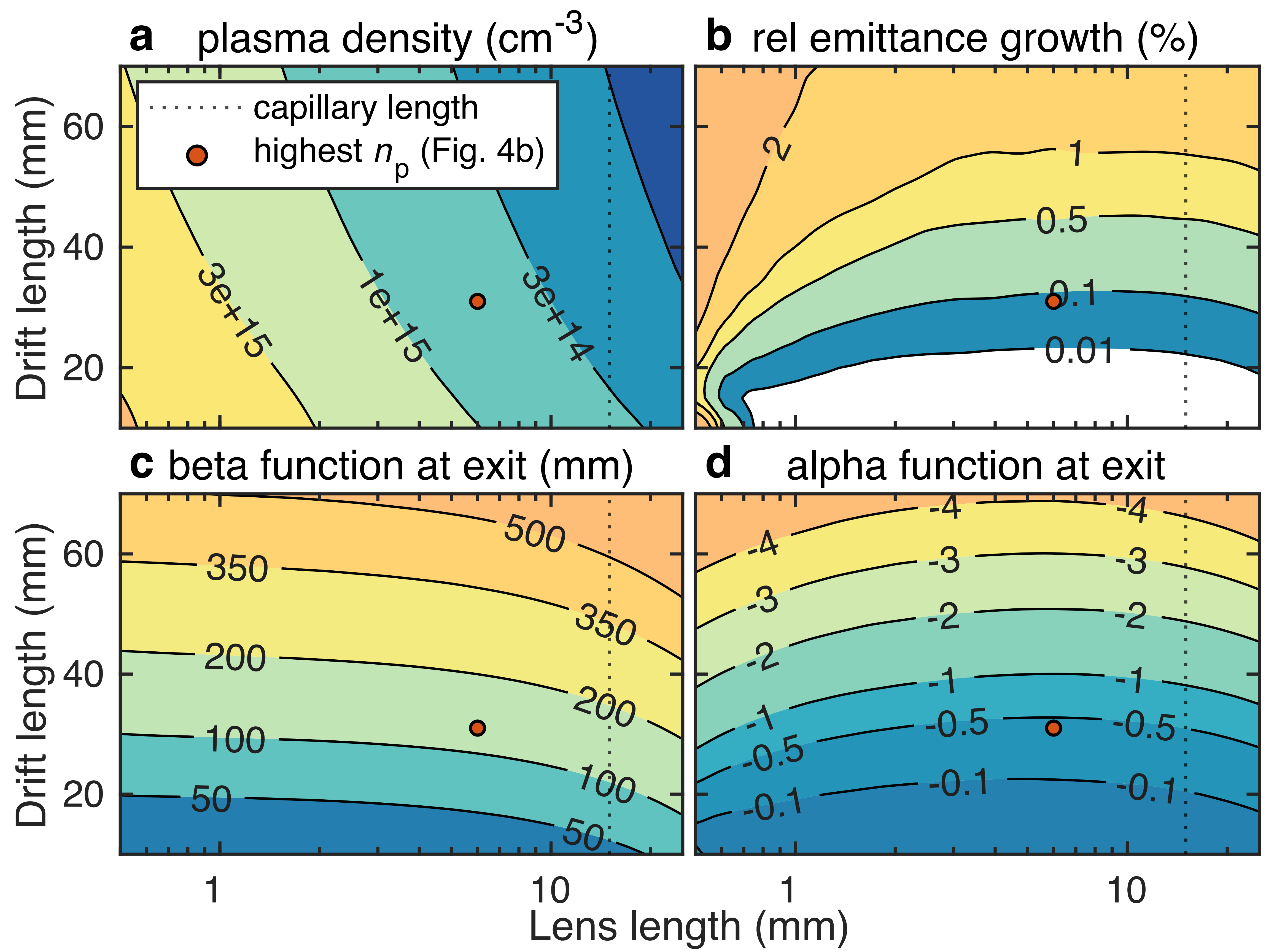
- … and they could work for the driver too
  - Subject of further study
  - Capturing PPL can “disregard” driver

See manuscript on **https://arxiv.org/abs/2509.08420**

Thank you!

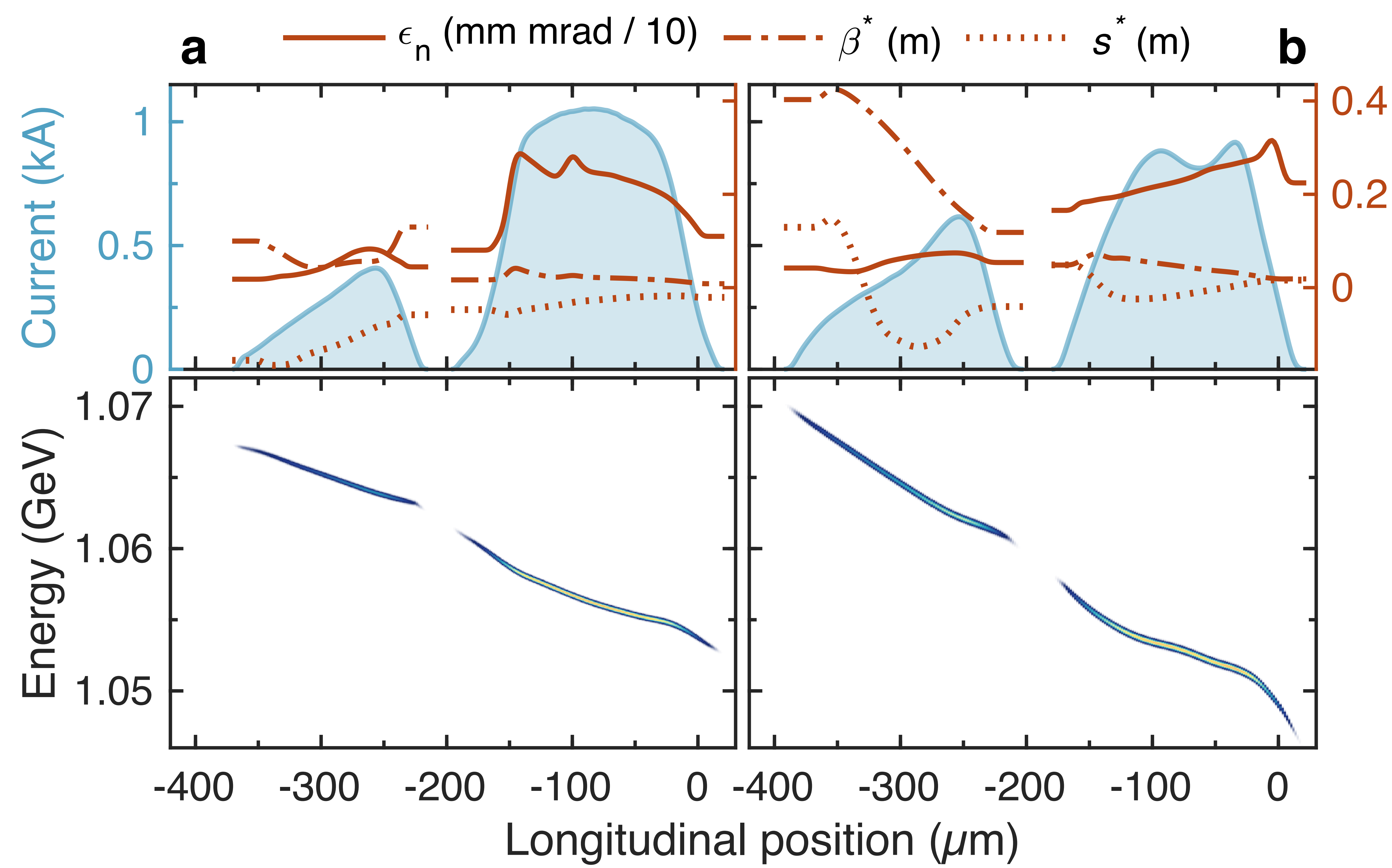
Extra 1: Preparatory simulations

- 2D scan of lens length and lens-waist distance (drift length)
  - Simulations of *capturing / collimating* PPL
    - Easier to interpret
- Gaussian bunches
  - FLASHForward-like parameters
  - Higher driver emittance
    - Find wake-excitation limitations
- All plotted beam values are averaged slice parameters
  - Highlight wake excitation limit, suppress chromatic effects



Extra 2: Longitudinal phase spaces and slice parameters

- Longitudinal phase spaces and slice waist parameters for the different working points
  - **a**: nitrogen
  - **b**: argon



Extra 2: Plasma density measurements

> Plasma densities measured with optical emission spectroscopy (OES)
  > Relevant densities for focusing at >4 us
  > Could not retrieve plasma densities from OES measurements, had to infer from beam optics