DIRECT MEASUREMENTS OF EMITTANCE GROWTH FROM COULOMB SCATTERING ON NEUTRAL GAS ATOMS IN A PLASMA LENS

Efforts towards quantifying fundamentally limiting factors of plasma-based particle-beam optics

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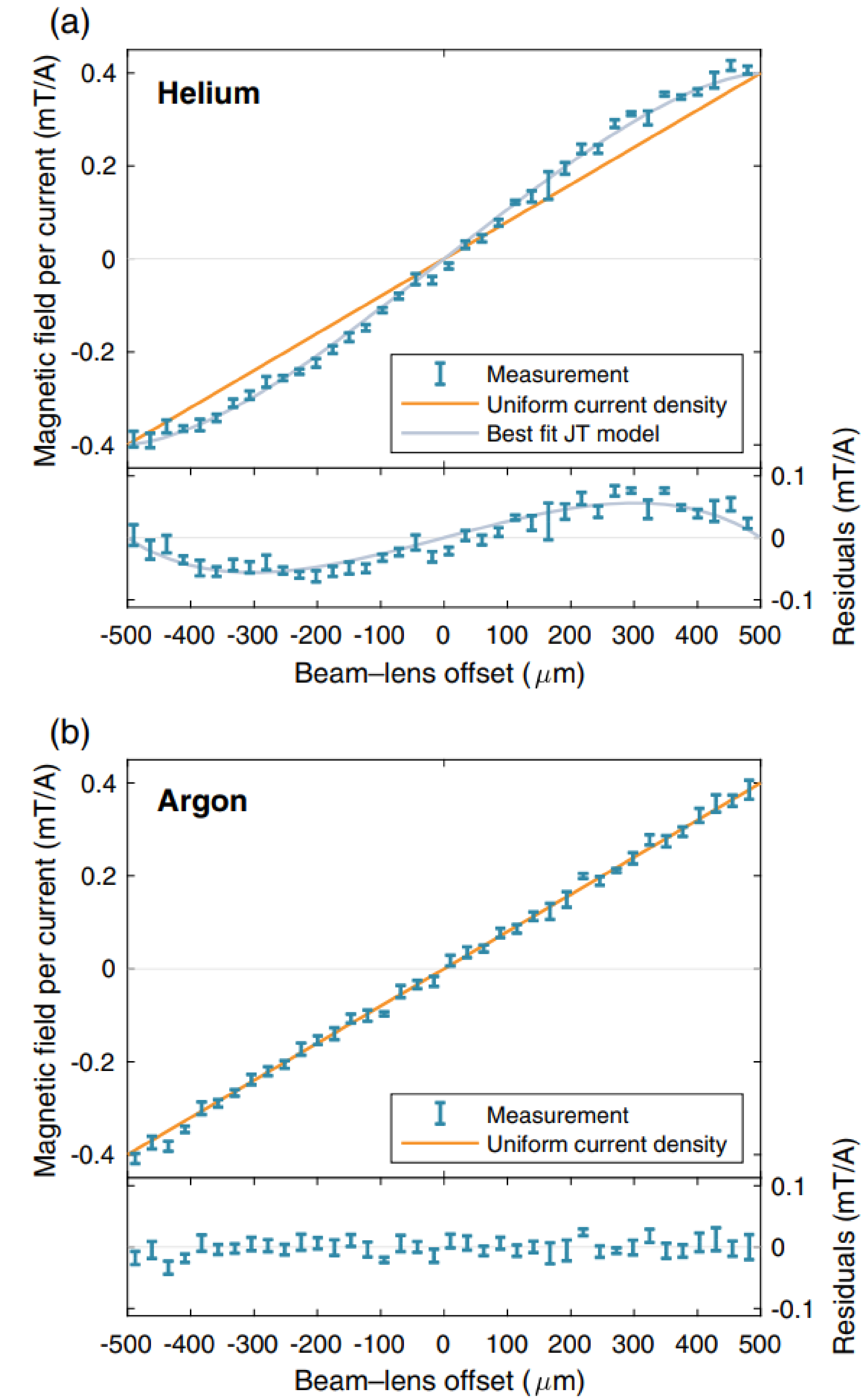
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Background

- Plasma lenses (PLs) a promising technology
  - Very strong, axisymmetric focusing
  - Compact optics (1 PL replaces multiple quadrupoles)
    - Capture/focus divergent beams close to target
    - Reduces chromatic emittance growth

- *Active* plasma lenses (APLs) shown to preserve beam quality [1] … →
  - … under certain conditions
  - Not necessarily compatible with high-brightness / -luminosity beams
    - Other limitations not yet quantified



[1] C. A. Lindstrøm *et al.*, "Emittance Preservation in an Aberration-Free Active Plasma Lens", Phys. Rev. Lett. **121**, 194801 (2018)

Background

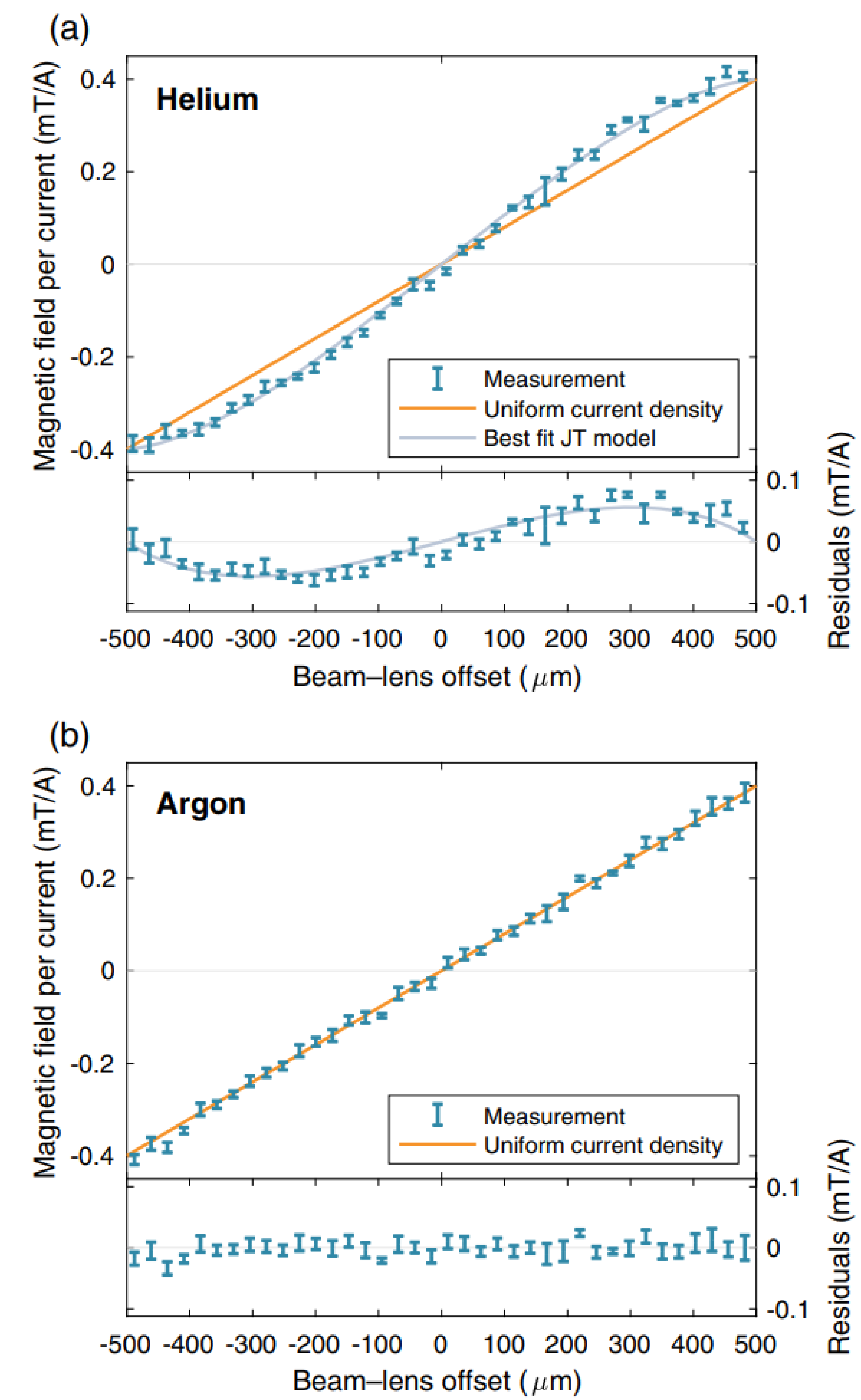
> Unlike in “conventional” accelerators, beam traverses matter
  > Interactions such as Coulomb scattering on
    > Plasma electrons + ions
    > Neutral atoms
  > Causes emittance growth – depends on beam and gas:

$$\frac{d\epsilon_{\mathrm{n}}}{ds} \propto \frac{\beta}{\gamma_{\mathrm{b}}} n_0 Z(Z+1)$$

> High-*Z* gases – linear focusing gradients [1] →

> Wake excitation must be suppressed in APLs
  > Large bunch-plasma mismatch
  > Low bunch + high plasma density
    > Low bunch current and large size (far from beam waist)

> When can and can’t we use these devices?



[1] C. A. Lindstrøm *et al.*, “Emittance Preservation in an Aberration-Free Active Plasma Lens”, Phys. Rev. Lett. **121**, 194801 (2018)

THE STUDY

- Experimental quantification of limitations of APLs for high-brightness beams
  - Wake excitation
  - Scattering
  - Gradient linearity

Focus of this talk: neutral-gas Coulomb scattering

- Figures of merit:
  - Projected beam normalized emittance
  - Beam optics distortion

Ultimately: *can we expect to use APLs for high-brightness / -luminosity beams*?

Initial analytical estimations

- Normal parameters for FLASHForward:
  - Beam energy: 1 GeV
  - Normalized emittance: 2 mm mrad
  - Beam size: 150 µm rms $\rightarrow$ $\beta = 22$ m
    - Fit beam inside capillary (1.5 mm diameter) with 5 stdevs
  - Gas pressure in 50-mm capillary: 1-15 mbar $\rightarrow$ $n_0 \approx 2 - 40 \times 10^{16}$ cm^{-3}

- "Regular" multiple-scattering emittance growth

$$\Delta\epsilon_\mathrm{n} = \frac{4\pi r_\mathrm{e}^2 n_0 \beta}{\gamma_\mathrm{b}} L \cdot 1.64\, Z(Z+1) \ln\left(\frac{287}{\sqrt{Z}}\right) \approx \begin{cases} 50 \text{ mm mrad} & (\mathrm{Ar}) \\ 20 \text{ mm mrad} & (\mathrm{N_2}) \\ 0.8 \text{ mm mrad} & (\mathrm{H_2}) \end{cases}$$

!

Initial analytical estimations

- But wait a second…
  - Estimated emittance growths much larger than seen in [1]
    - Using parameters from [1], expect ~4 mm mrad growth
    - Observed emittance growth <0.25 mm mrad at 90 % confidence

- Turns out: far from multiple scattering

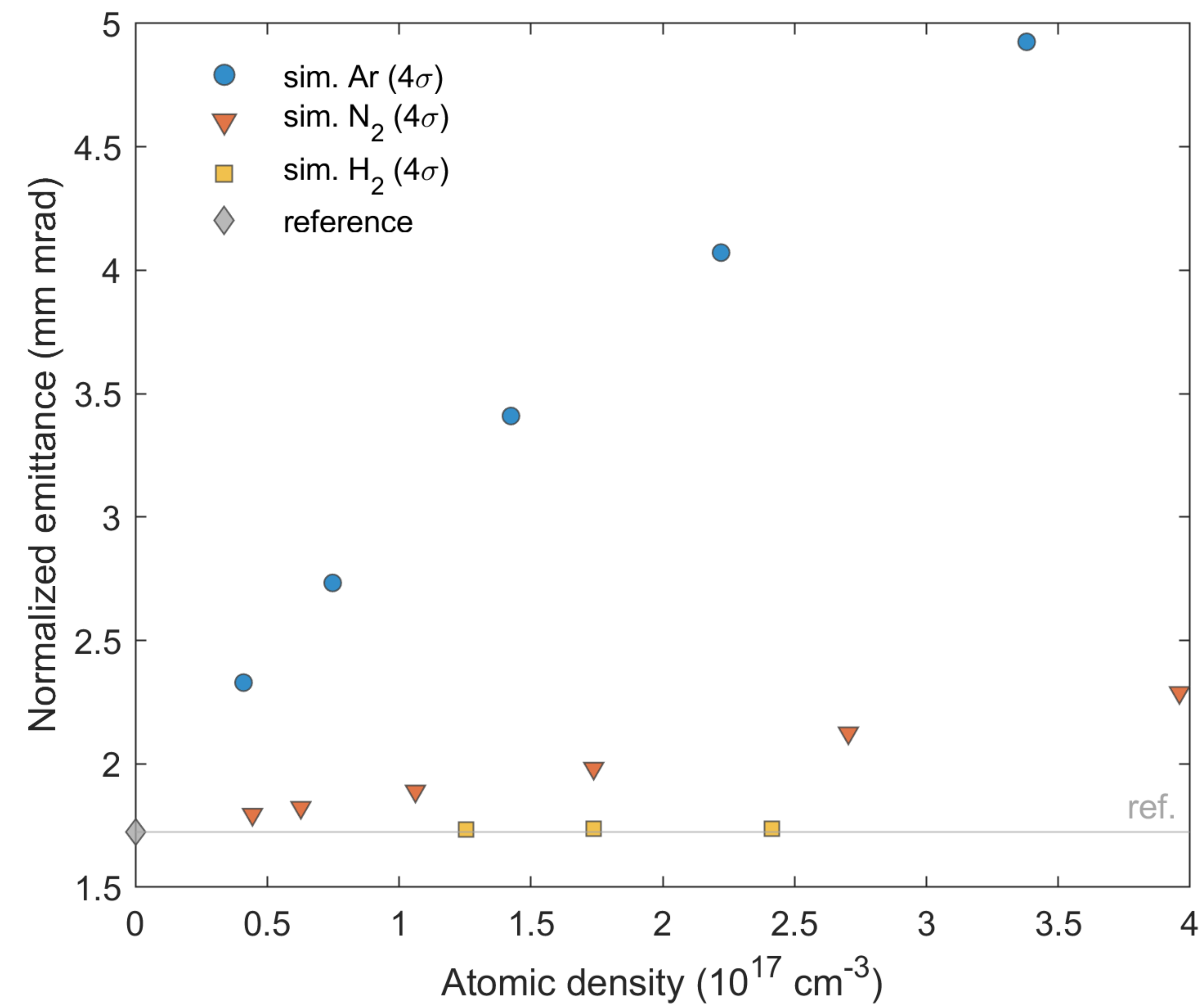
$$N_s = n_0 \cdot \sigma_s^{\mathrm{tot}} \cdot L \leq \begin{cases} 3 \text{ (Ar)} \\ 1 \ (N_2) \\ 0.05 \ (H_2) \end{cases}$$

- Estimated number of scattering events <1 – *not even single-scattering*
- No analytical emittance growth formula for this regime
  - Monte Carlo simulations in GEANT4 [2]

[2] https://geant4.web.cern.ch/

Comparison with simulations

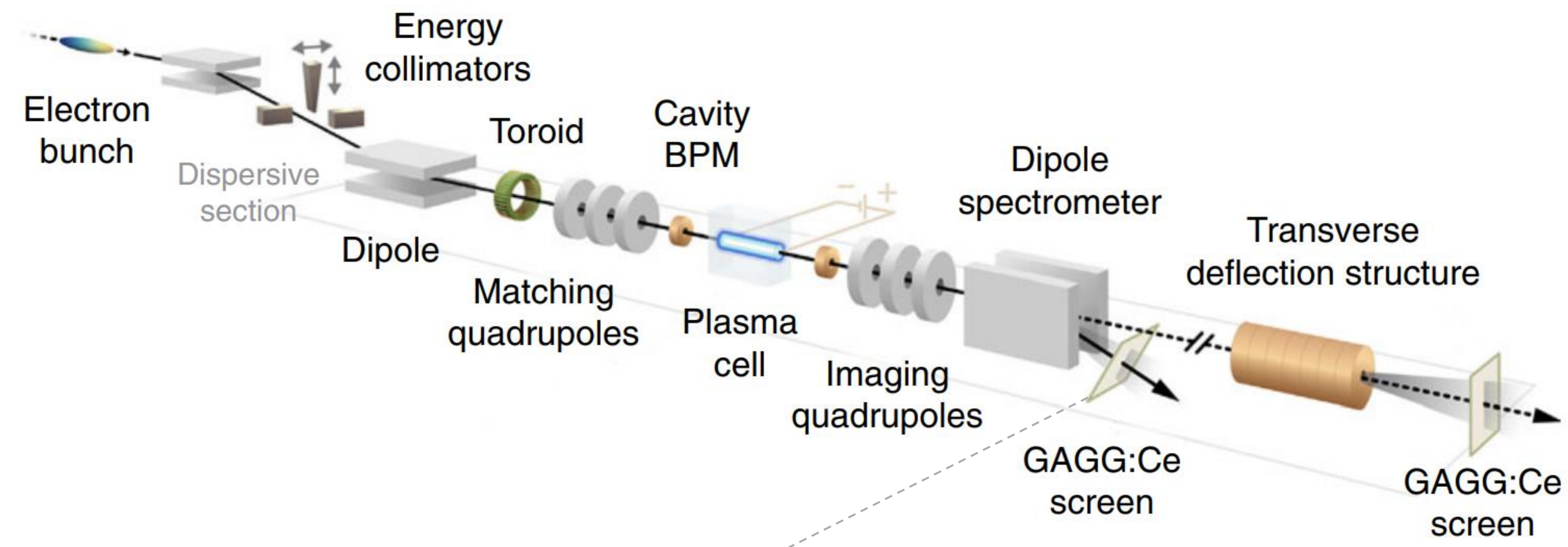
- Initial bunch:
  - Gaussian transverse profiles
    - Matching beam parameters from experiment
    - Close to parameters on p. 5
  - Single-scattering module
  - 1M particles
- “Cleaned” data – full beam larger but more erratic for N_2
  - Keep particles within 4σ
- More realistic expectations for the experiment

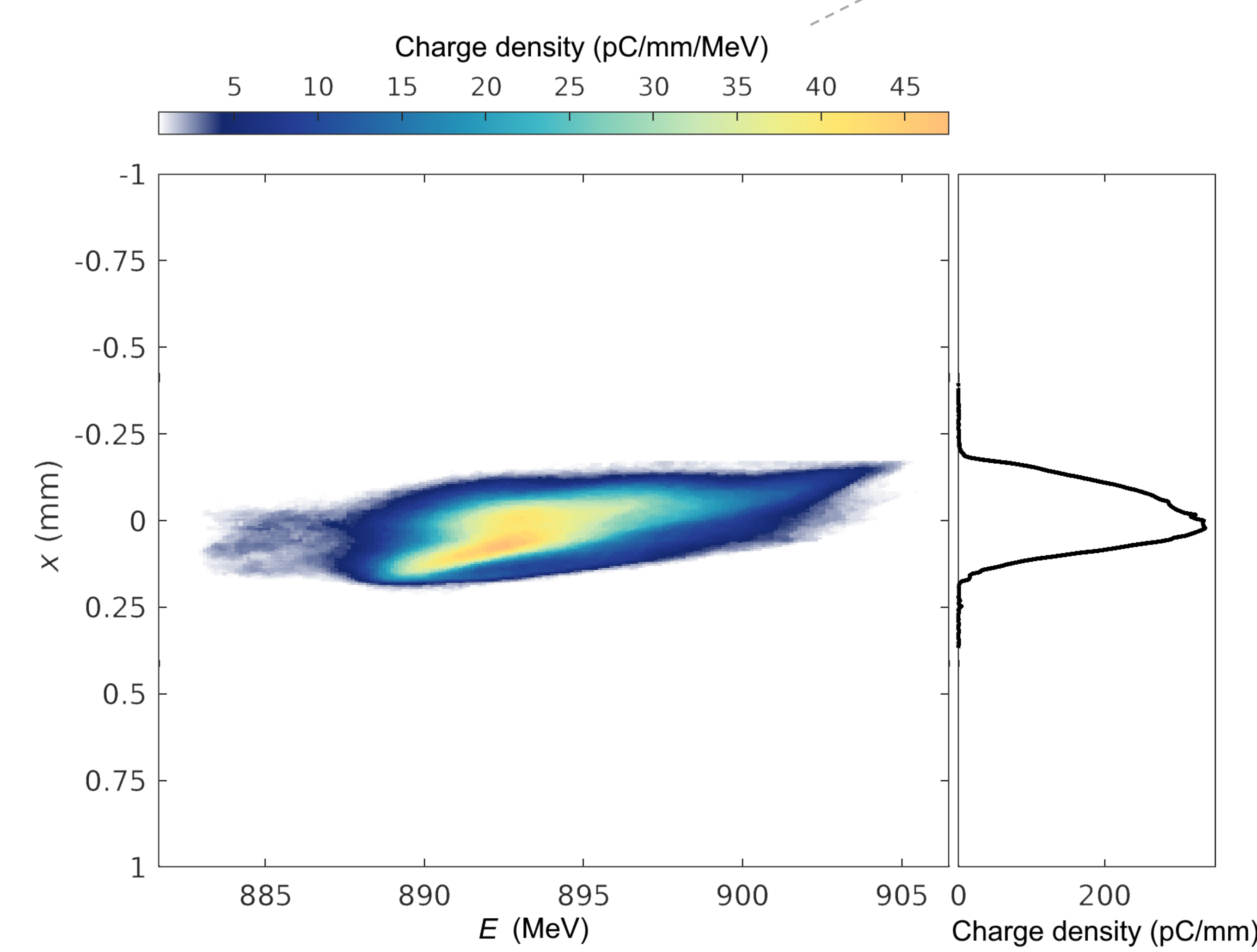


EXPERIMENTAL SETUP

- Using bunches from the FLASH linac:
  - 890 MeV, 0.5 % fwhm energy spread
  - 115 pC
  - 750 fs fwhm (~100 A peak)
  - 1.75 mm mrad
- Beam optics at lens relevant for APL use:
  - $\beta_0 \approx 17$ m (same as 41 cm away from 10-mm waist)
- "Repurposed" accelerating cell as APL
  - Sapphire HV discharge capillary
  - 50 mm long, 1.5 mm diameter

[3] C. A. Lindstrøm *et al.*, "Energy-Spread Preservation and High Efficiency in a Plasma-Wakefield Accelerator", Phys. Rev. Lett. **126**, 014801 (2021)

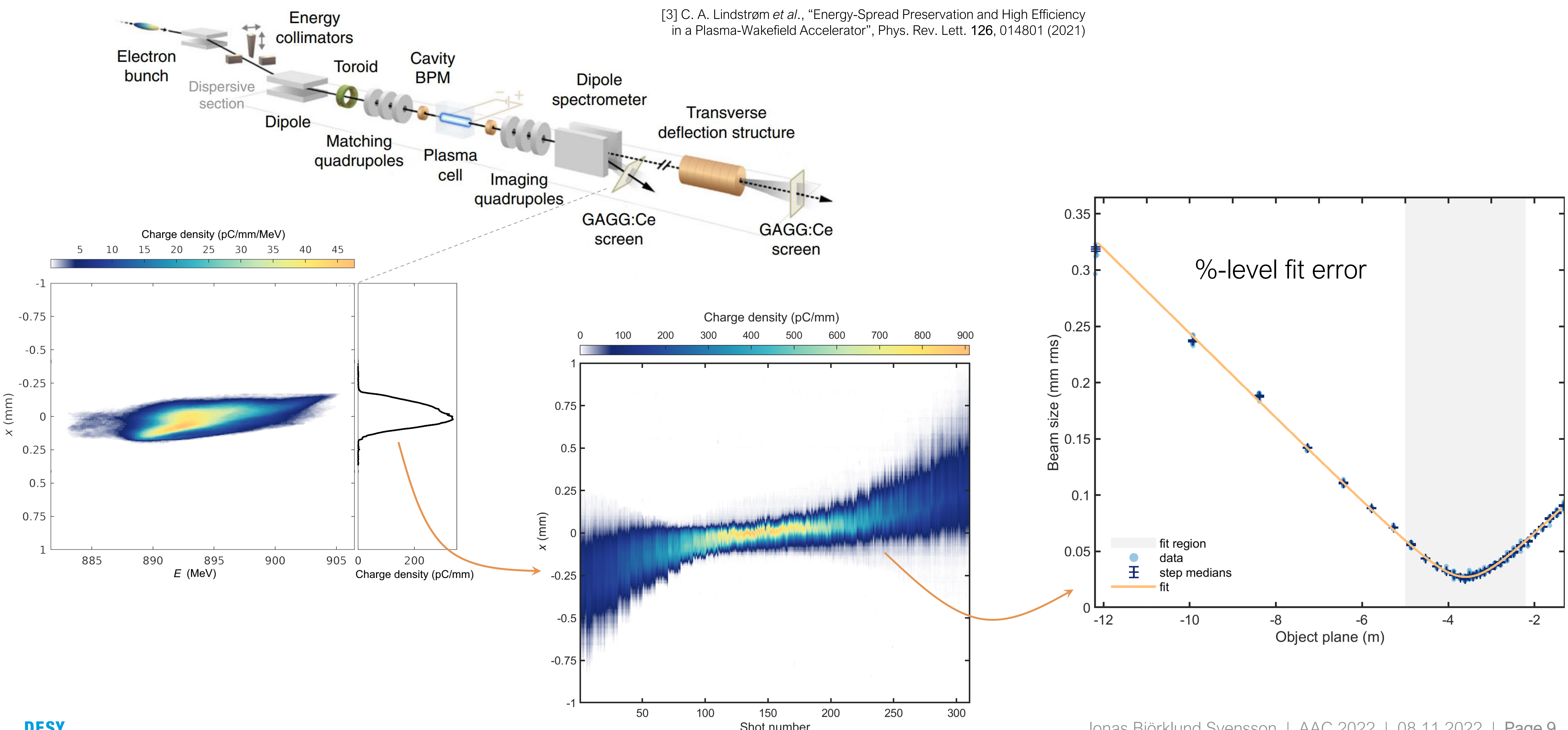




EXPERIMENTAL SETUP

- Emittance measurements through quad scans

[3] C. A. Lindstrøm *et al.*, “Energy-Spread Preservation and High Efficiency in a Plasma-Wakefield Accelerator”, Phys. Rev. Lett. **126**, 014801 (2021)

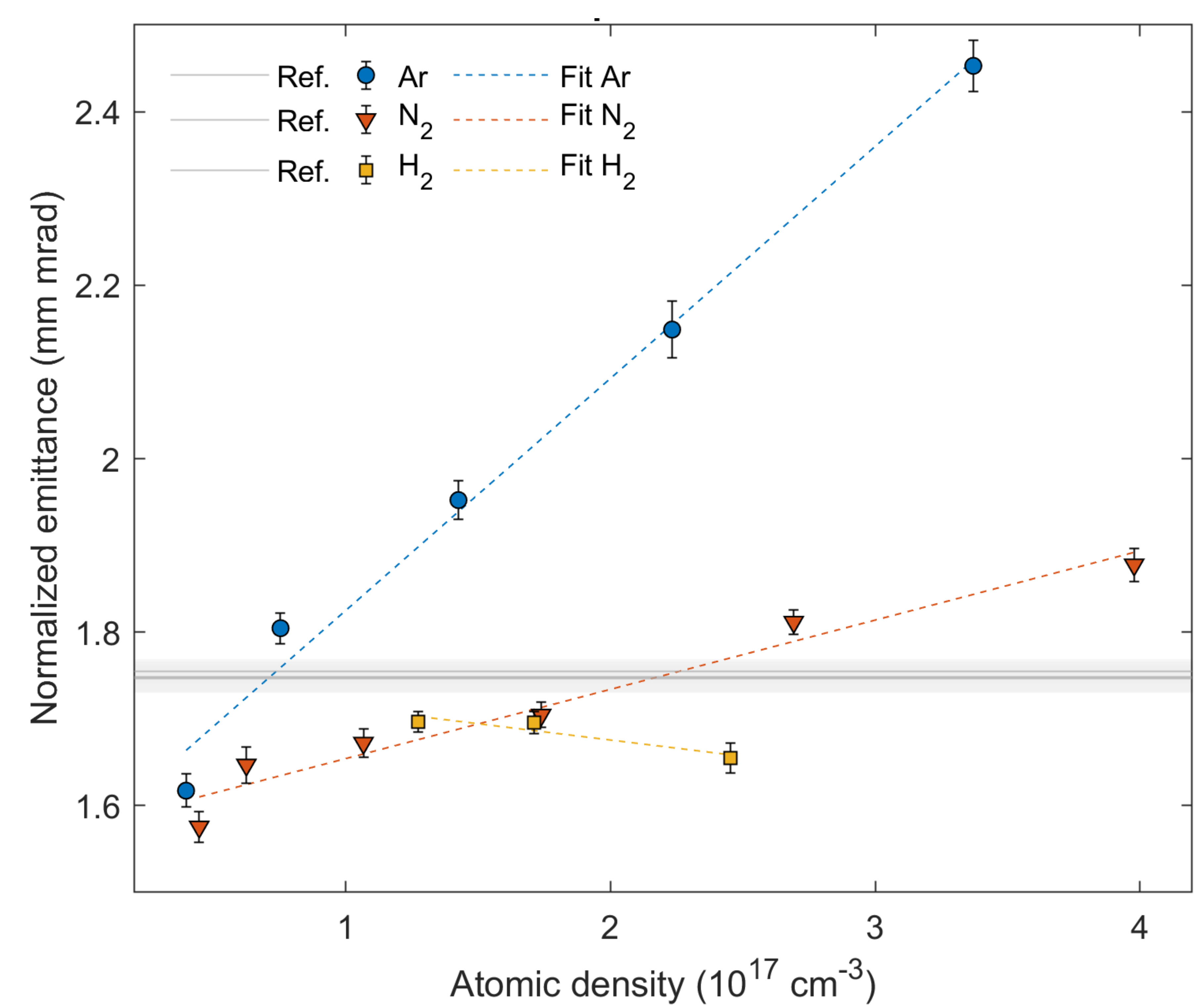


Experimental results

- Scanned gas densities for argon, nitrogen and hydrogen
  - Neutral gas
  - Capillary gas pressures in 1-15 mbar range
    - Limited by discharge (lower) and vacuum pumps (upper)

- Emittance trends similar to simulations, but…
  - Small max values – particularly for argon
  - Several data points shows emittance *de*-crease

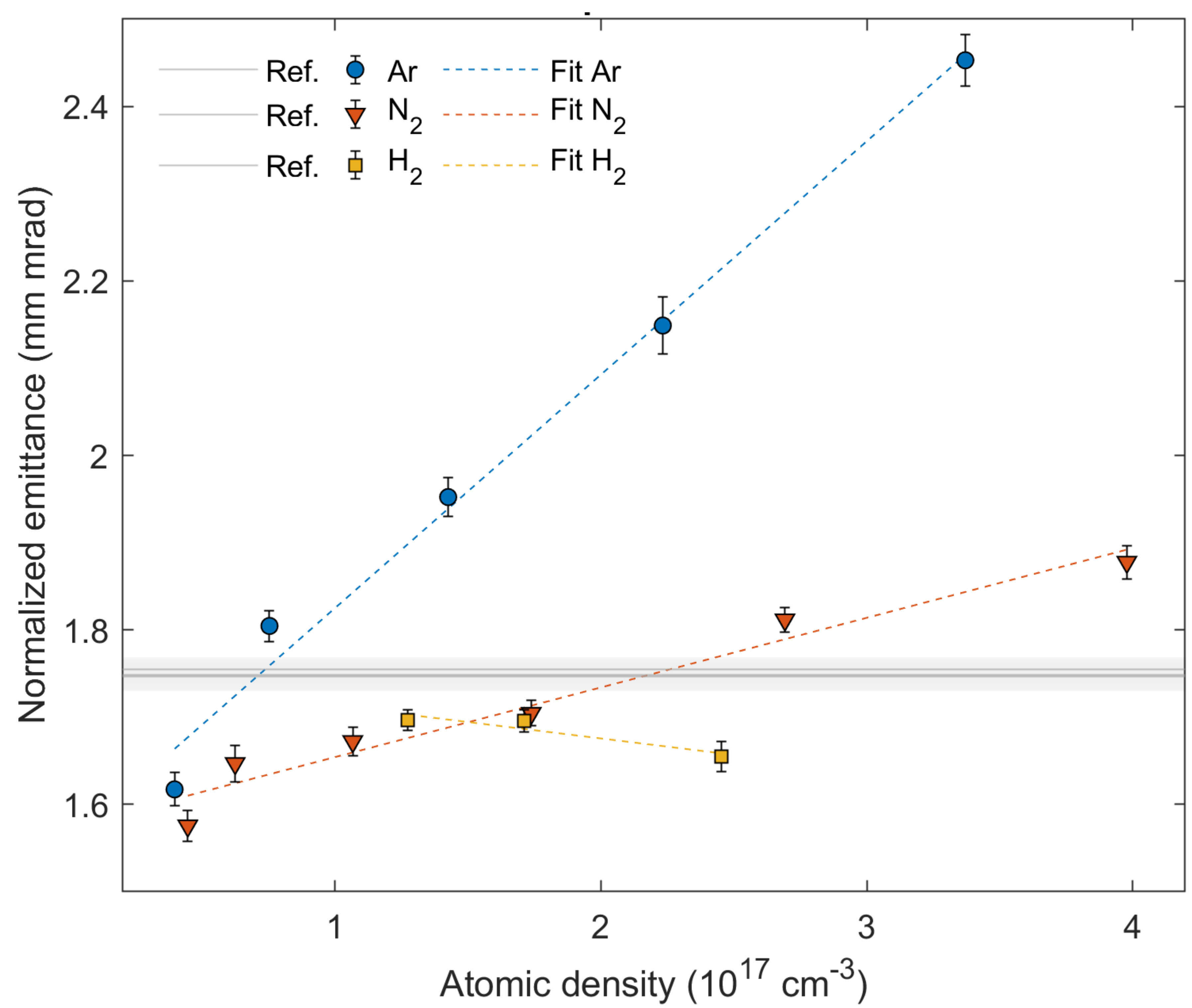
> *Why this discrepancy?*



Experimental results

Some potential sources of emittance decrease

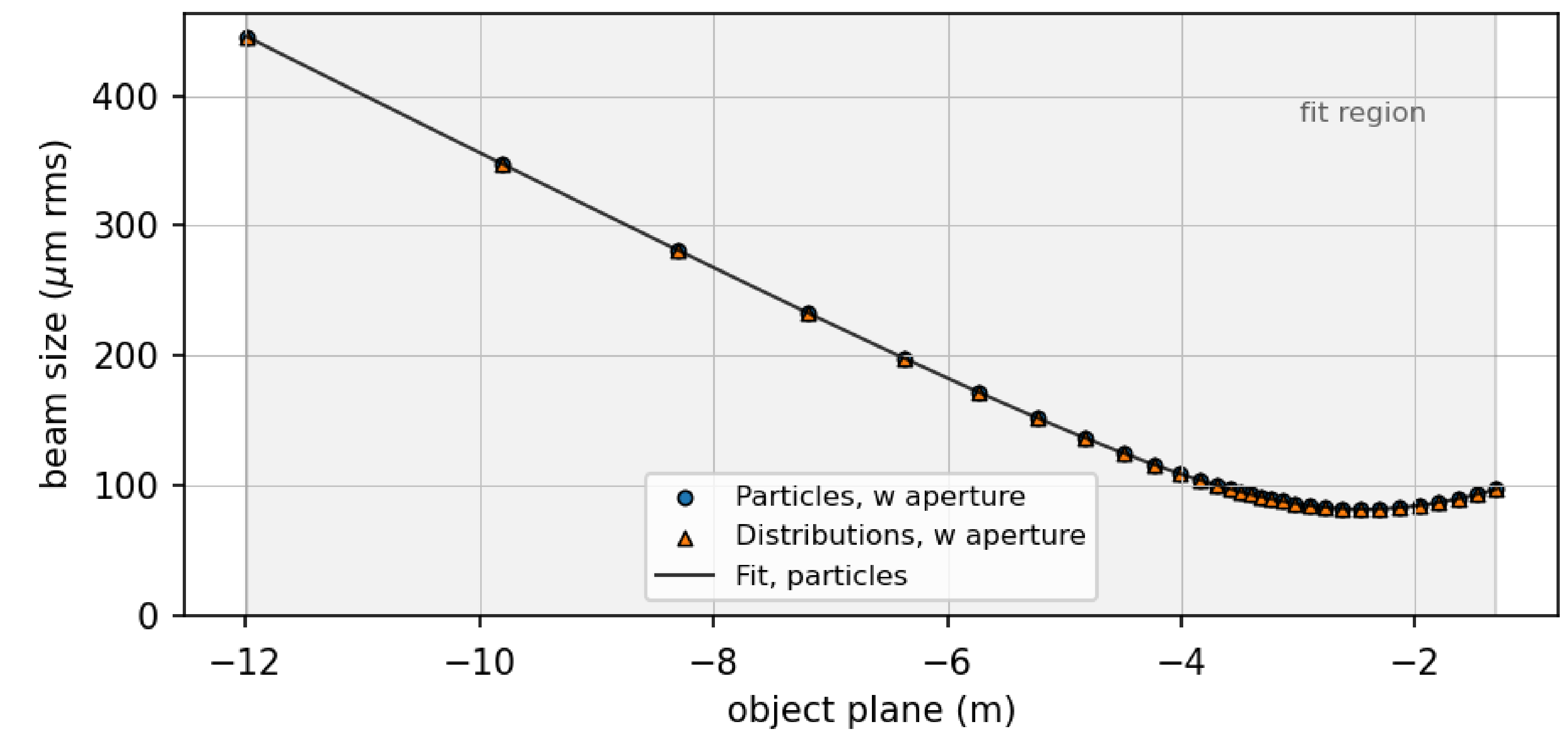
- Machine drifts
  - Affect reference optics (more) and emittances (less)
- Charge loss through beamline
  - Scraping removes outliers
    - Smaller measured RMS size
- Detector limitations
  - Wings in distribution potentially “hidden”
- Assuming charge loss is main contributor
  - Model charge loss to learn more

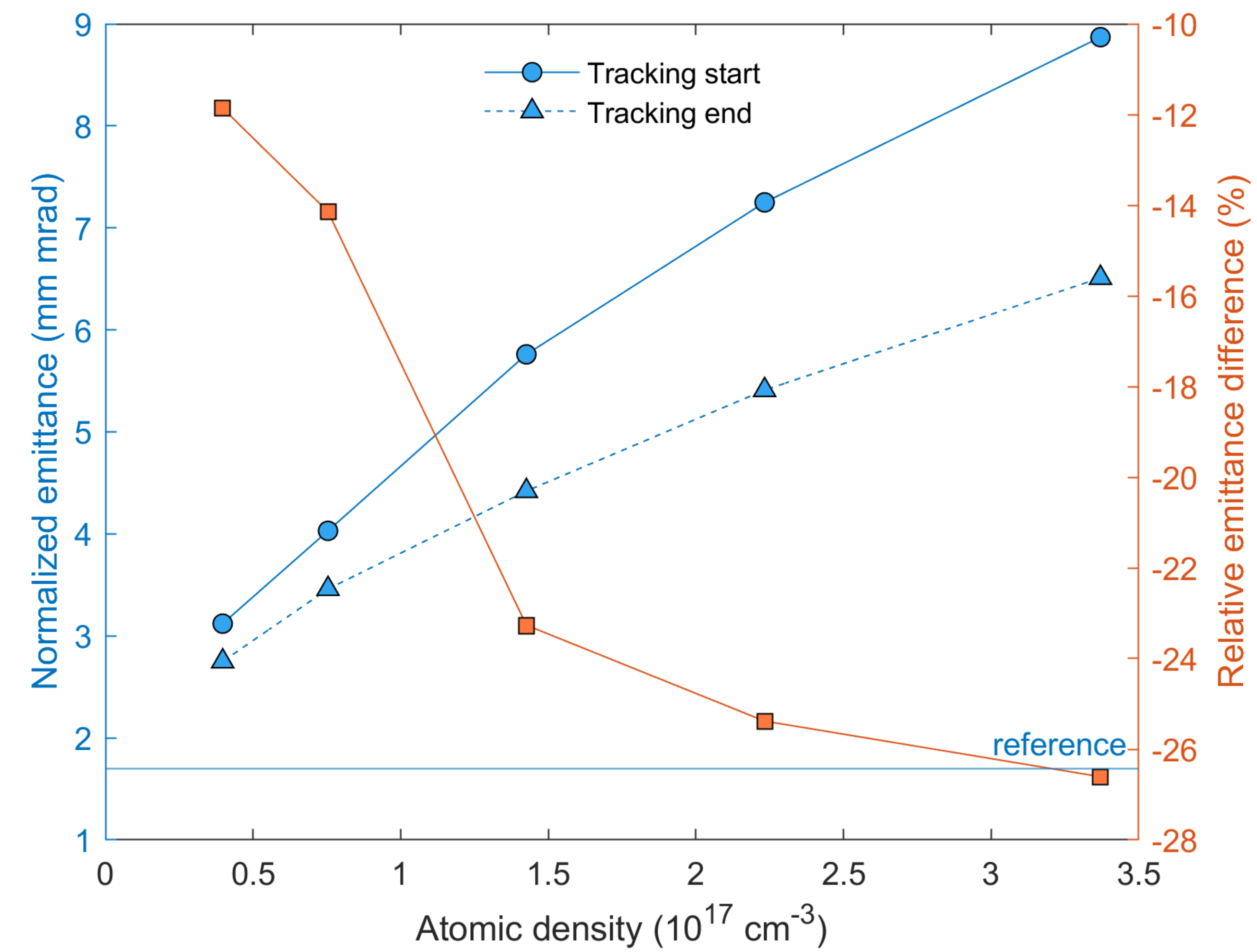


Comparison with simulations, part II

[4] S. Tomin *et al.*, "OCELOT as a framework for beam dynamics simulations of X-ray sources", in Proc. of IPAC'17, p. 2642 (2017)
https://github.com/ocelot-collab/ocelot

- Virtual emittance measurements
  - Particle tracking from PL exit to screen using OCELOT [4]
  - *Full* GEANT4-beams from argon scattering as input
- Fit emittance equal to particle emittance
  - Good measure of emittance at screen
    - … but not good measurement of the original!
- Large emittance decrease during propagation
  - Highest-emittance beams decrease most
  - Less charge loss than experiment
    - Not yet good match with vertical optics





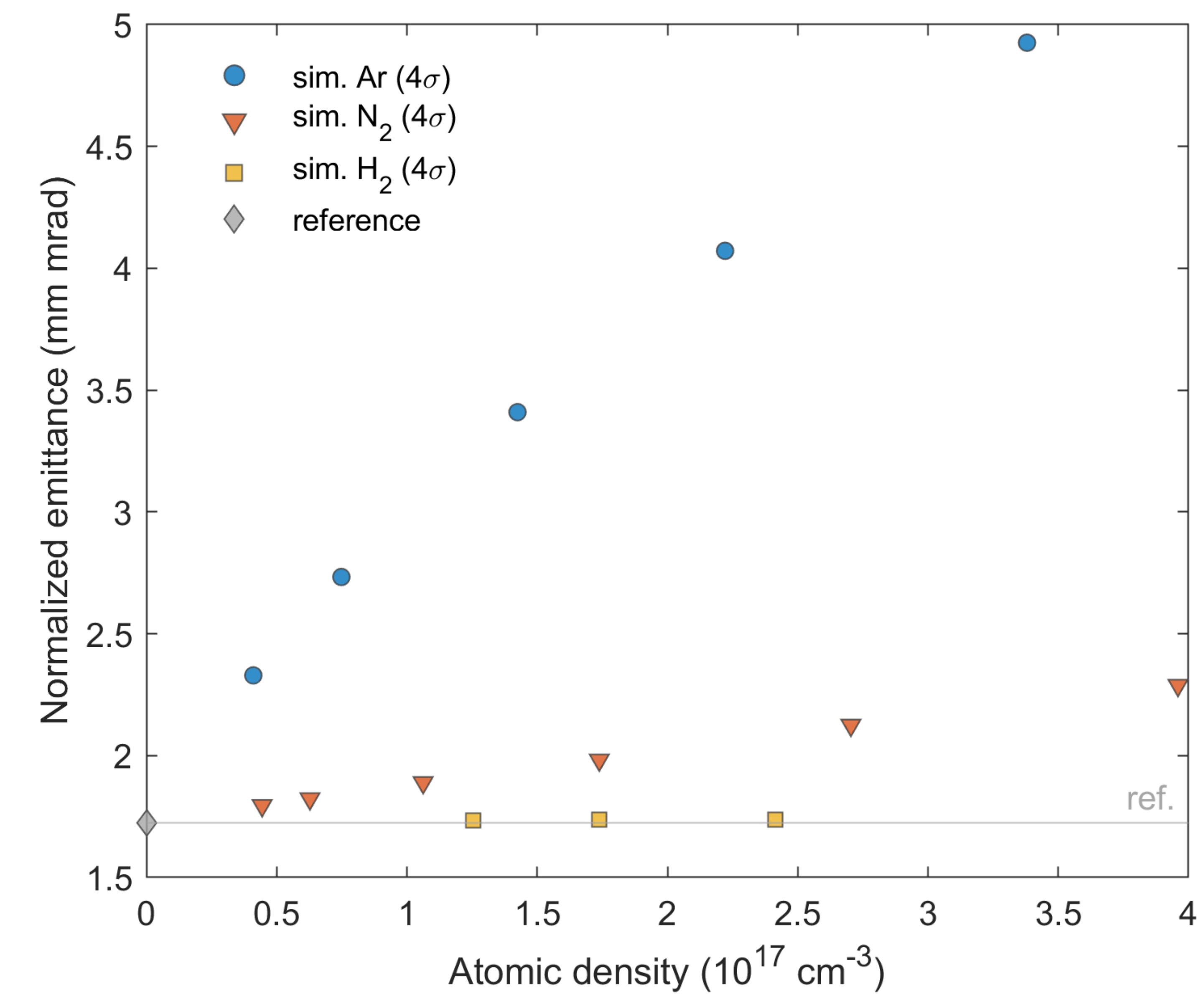
Conclusions

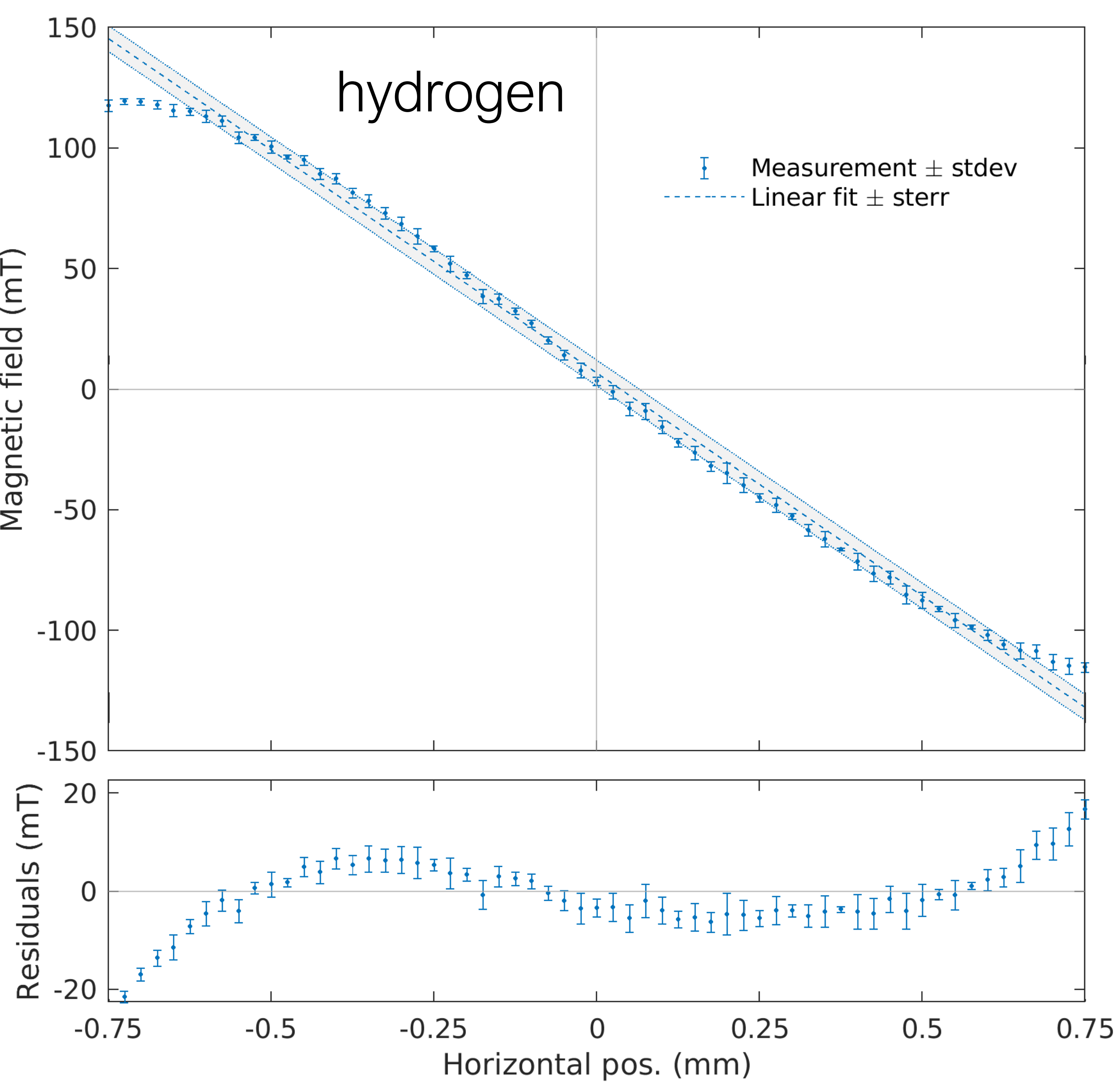
- Measurement flawed but still gives insight
  - Short devices and low gas densities – *not in multiple-scattering regime*!
    - Smaller emittance growth than analytic theory
    - Still – simulations suggest noticeable increase even for low gas densities
    - Lower limit on gas density: *discharge must work*

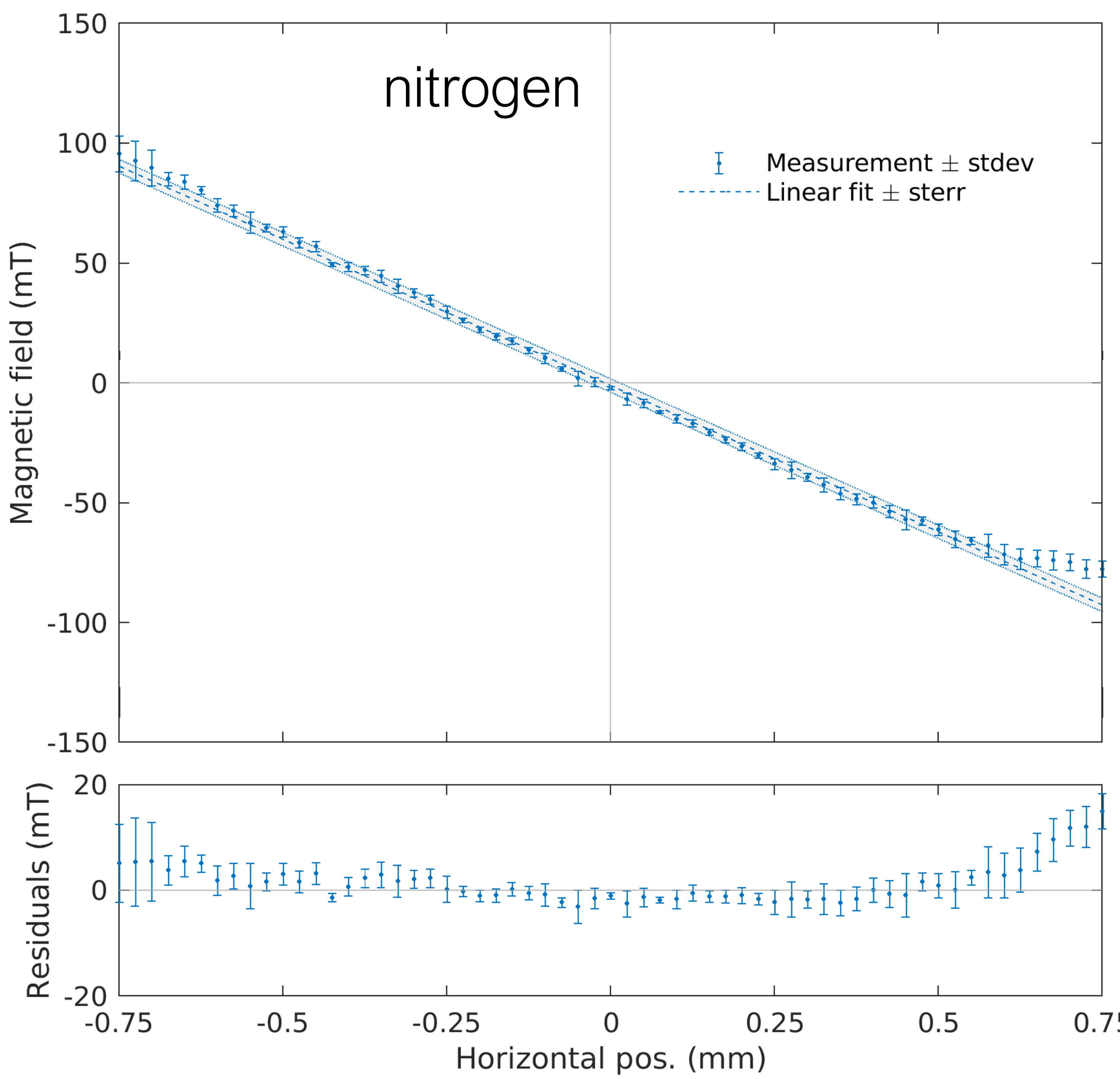
- So: does this rule out using APLs for high-brightness / -luminosity beams?
  - Not quite – circumstances matter
  - Many things still unknown
    - E.g. scattering contribution *during* discharge
      - Electrons, ions, near-neutrals (i.e. Ar^{2+}), …

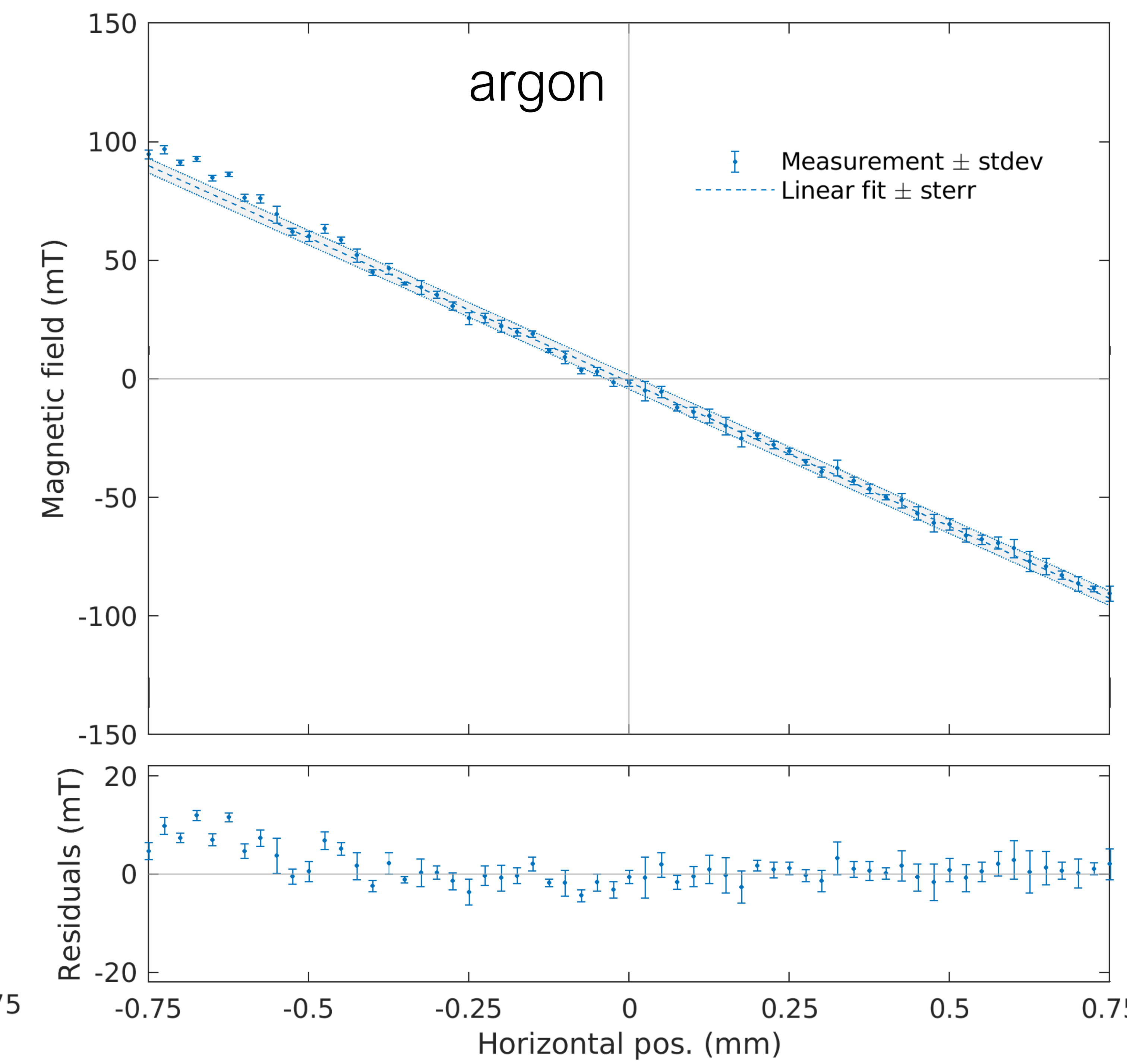
Conclusions – Bonus data

- If an APL is to be used, nitrogen *likely* better than argon
  - Very early analysis – nearly raw data
  - ~120 T/m for Ar, N_2 – consistent with 340 A discharge current
    - Gradient enhancement *only* in H_2
  - More analysis and data needed for final verdict









Outlook

- More to come
  - Refinement of experiment
    - Upgraded experimental setup – larger beam pipes
    - Upgraded diagnostics – measure both transverse planes
  - Take care not to lose *any* charge
    - Careful optics setup
  - Extended simulations of scattering and transport
    - More particles = ‘more better’
    - Model vertical optics more accurately
      - If necessary include measured magnet misalignments, etc.

THE END

Thanks for your attention!

Questions, comments, …