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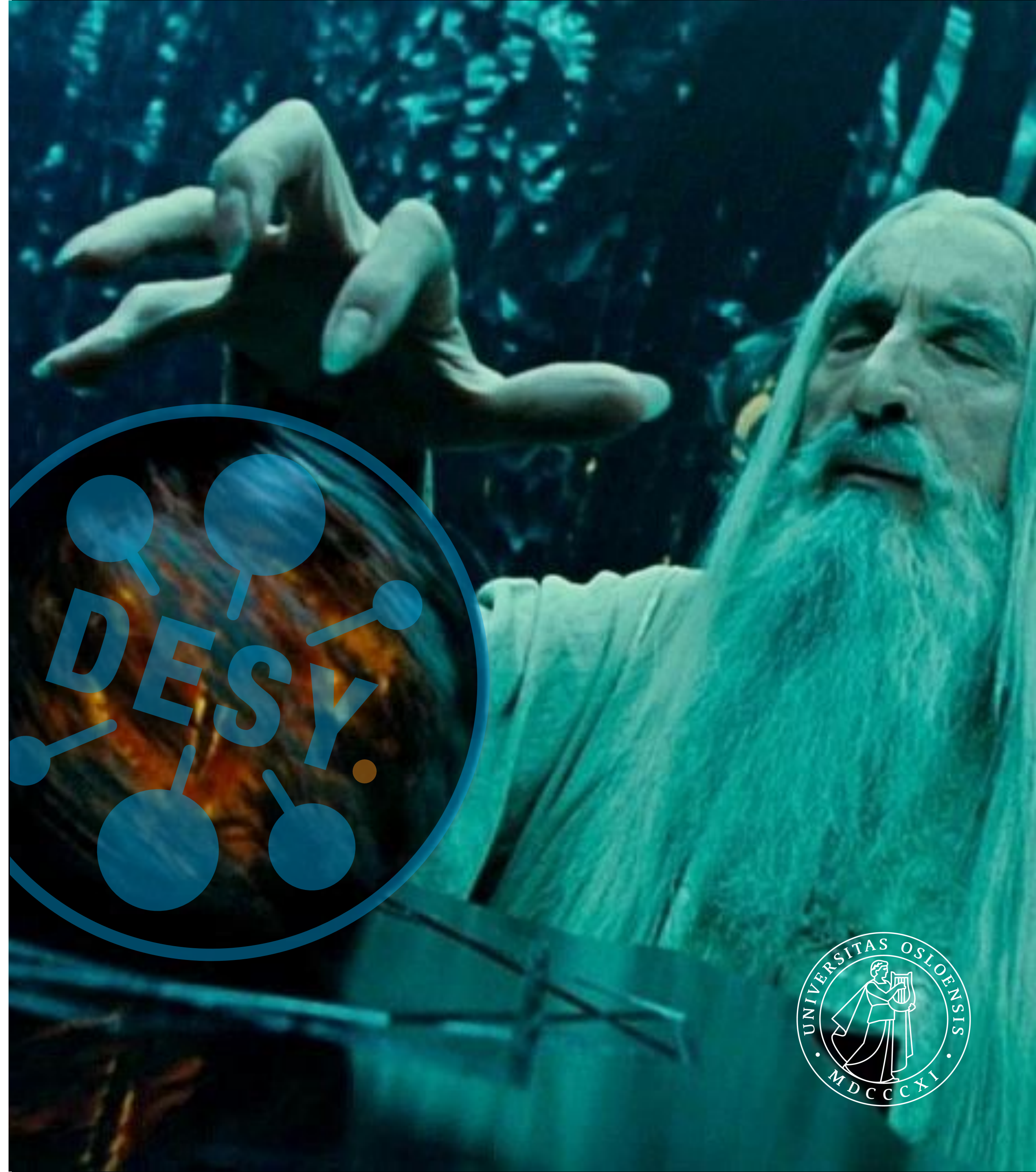


Lessons learned at FLASHForward: From 50 MeV to 10 GeV energy gain

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Background



- > **FLASHForward is a plasma-accelerator facility at DESY.**
 - > 1 GeV beams (much lower than FACET-II).
 - > Focus on beam quality, stability and high rep. rate
- > Several experiments:
 - > X-1 (internal injection) – Alex Knetsch was the PI.
 - > **X-2 (external injection) – I was the PI (2019–2022)**
 - > X-3 (high rep. rate)
 - > etc.
- > All work and figures are part of a big collaborative effort.

Disclaimer

“That’s like, just your opinion, man.”



**Not all conclusions will be transferrable
from FLASHForward to FACET-II,**
but hopefully something is useful.

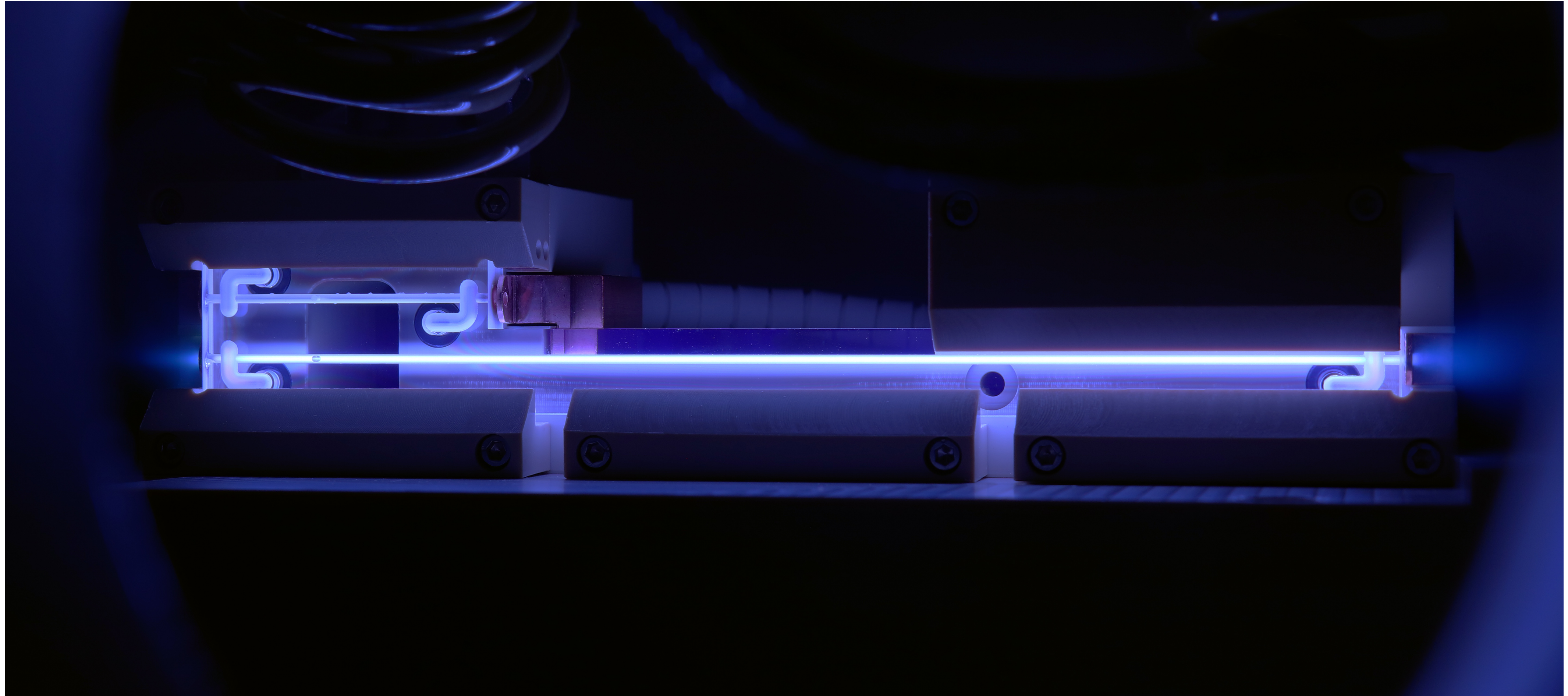
Take it with a pinch of salt.

Main take-home message:
Beam-quality preservation is a precision game

Want to preserve to the %-level?

Then you have to **measure, control, and stabilize**
everything to the %-level (and often 0.1%-level)

Maintaining control: **Start short, but controlled, then extend**



Source: Lindstrøm et al., Proc. EPS-HEP2021, 880 (2021).

An important compromise: Gradient or Quality?

High total efficiency

Higher gradient

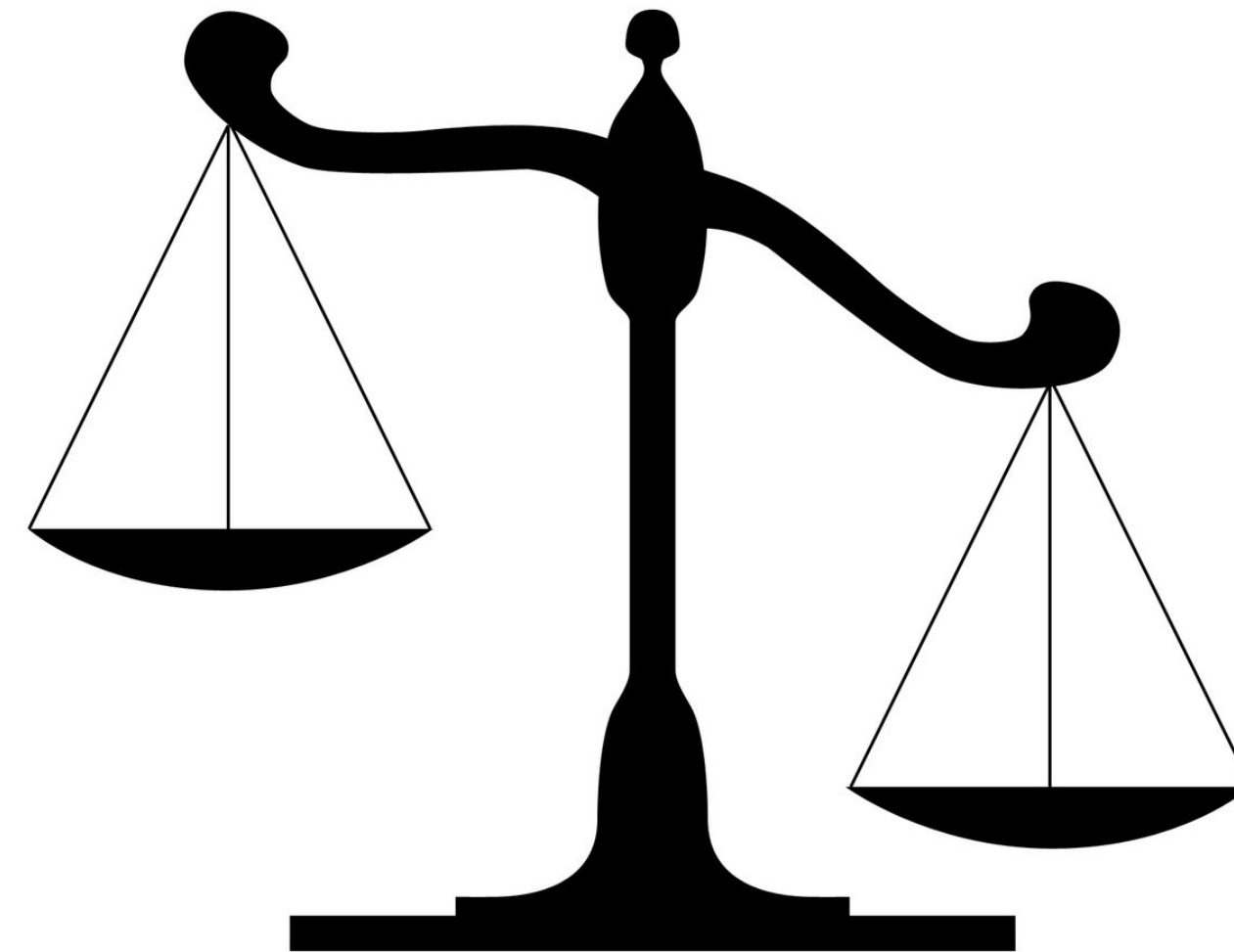
Shorter bunches
More CSR

–

Complex bunches
Smaller matched beta
Smaller tolerances

+

More gain



Lower gradient

Longer bunches
Less CSR

+

Straighter bunches
Larger matched beta
Larger tolerances

–

Less gain

Beam-quality preservation

Our minimum:
~1 GV/m

Charge preservation should be priority number one

> Order of business:

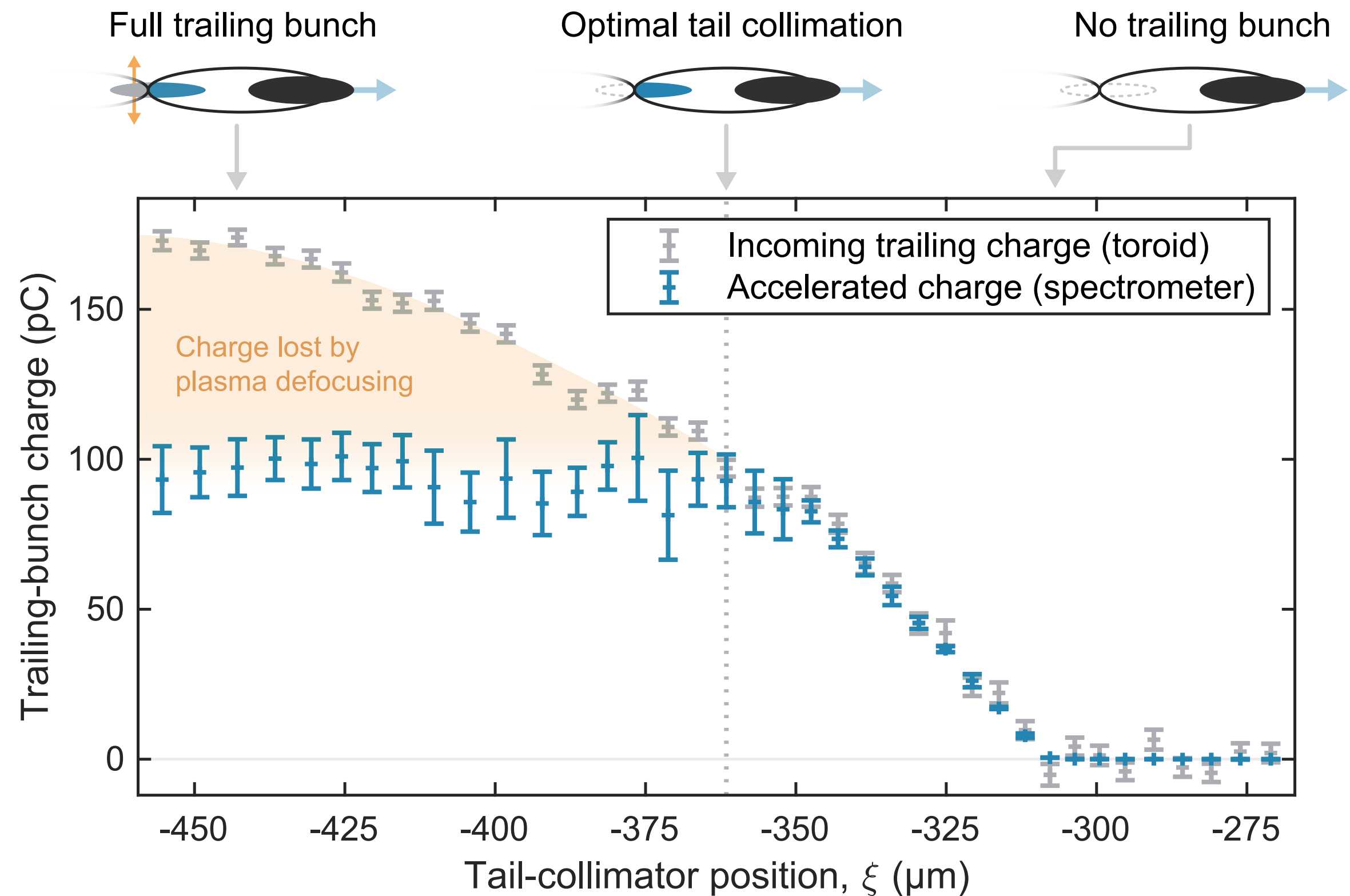
- > 1. Charge preservation
- > 2. Energy-spread preservation
- > 3. Emittance preservation

> Energy-spread and emittance preservation is **meaningless without charge preservation.**

> Reaching 100% charge coupling takes **a lot of effort**, is necessary for all later steps, but should be obtainable.

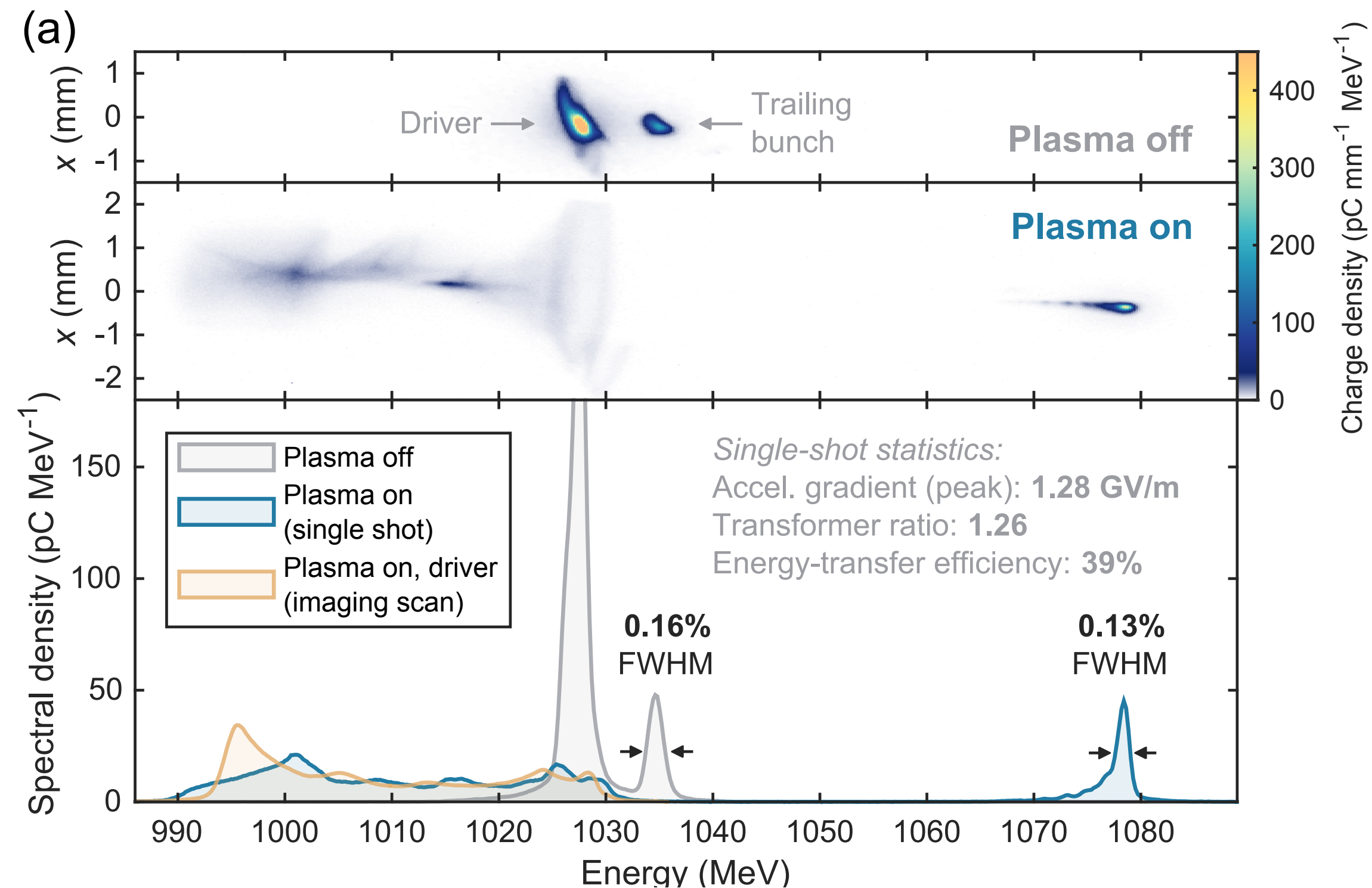
> Ideally, start in a short plasma, then extend.

> Establishing charge preservation requires an online, calibrated reading of the accelerated charge (a well-calibrated screen).



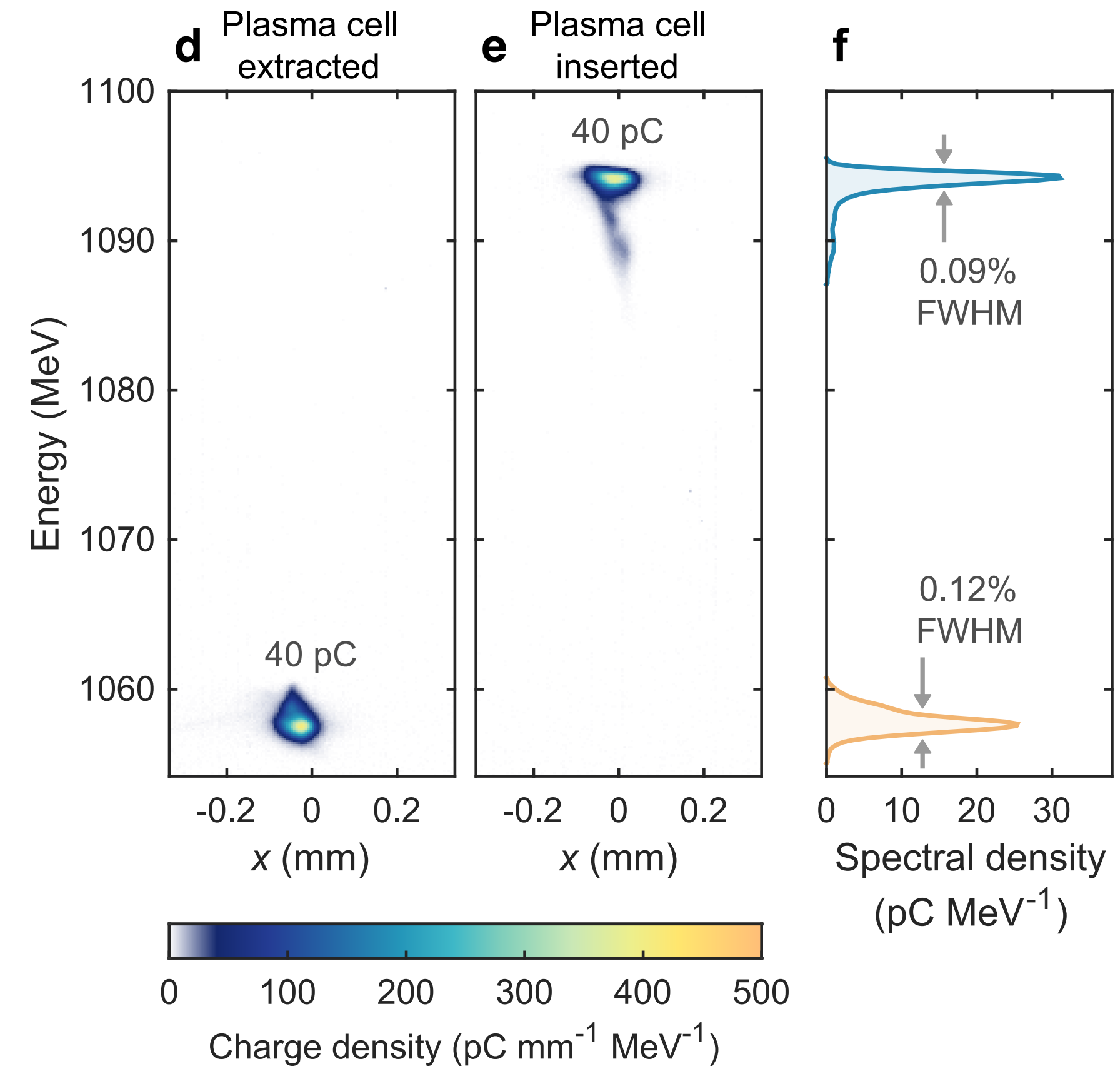
Source: Lindstrøm et al., PRL 126, 014801 (2021)

Energy-spread preservation *is possible* (at least in a short PWFA)



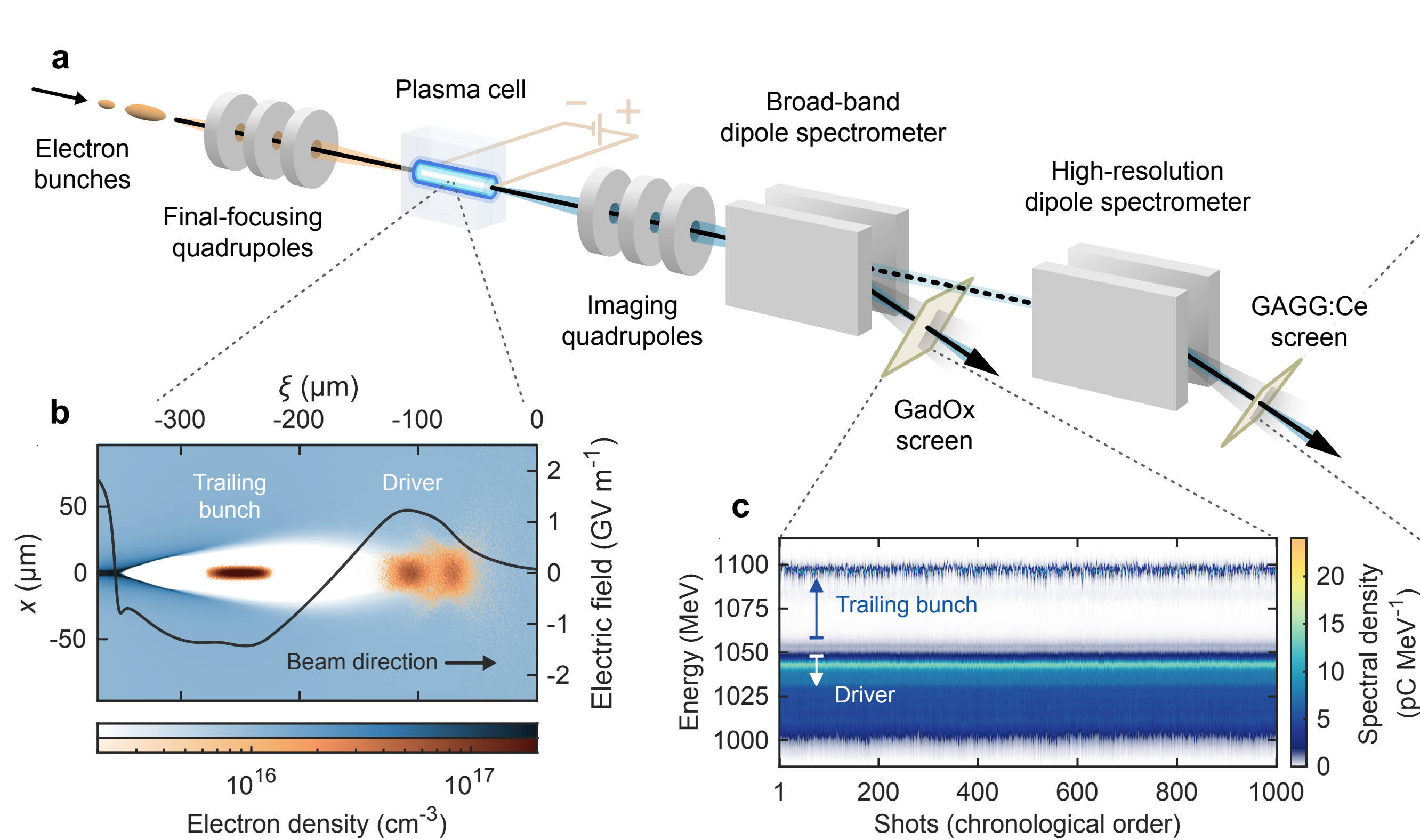
Source: Lindstrøm et al., PRL 126, 014801 (2021)

- > Energy-spread preserved at 0.1%-level.
- > Energy-spread-to-gain ratio was at ~3% (represents the wakefield flatness)



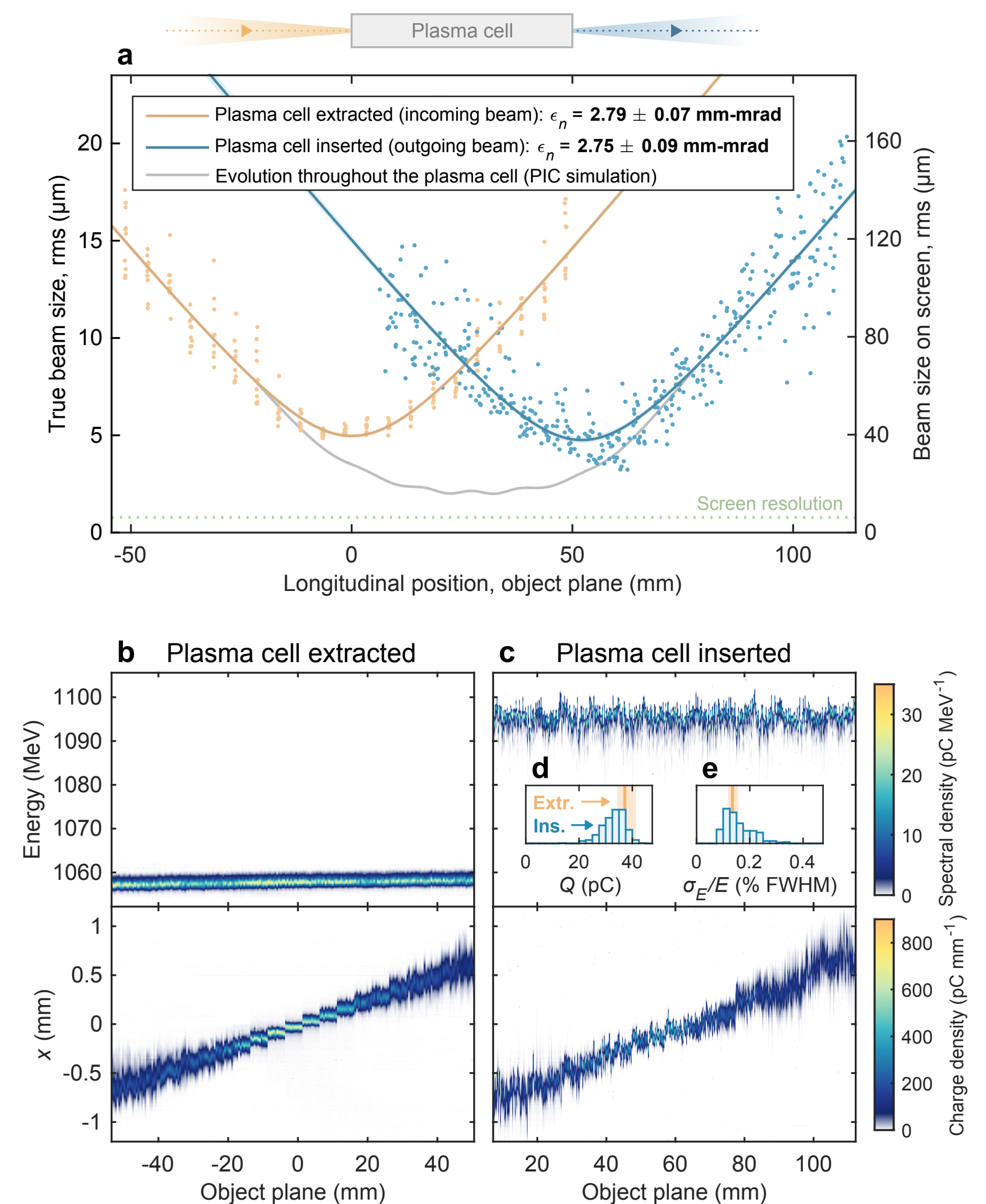
Source: Lindstrøm et al., submitted (2022)

Emittance preservation *is* possible (at least in a short PWFA)

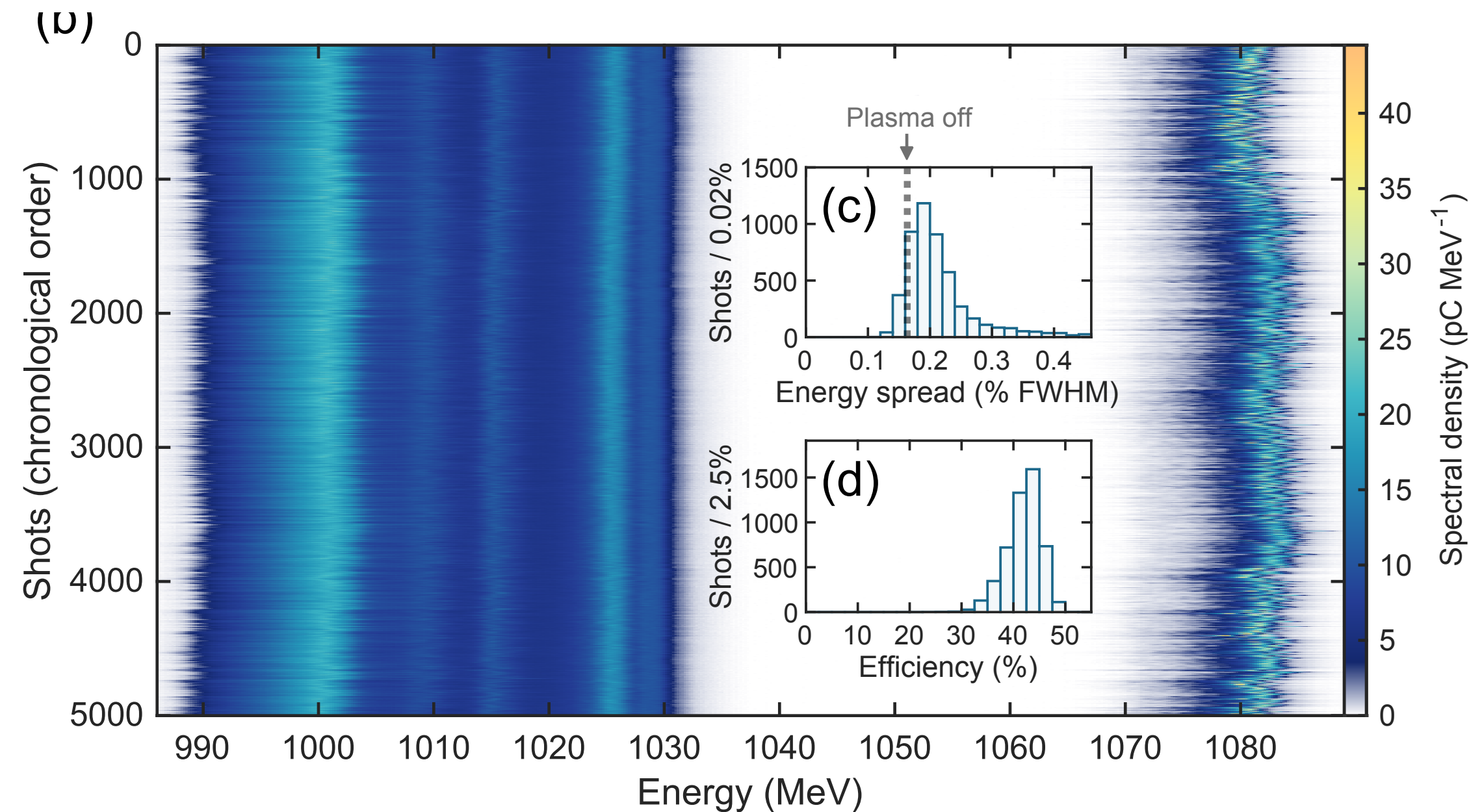


Source: Lindstrøm et al., submitted (2022)

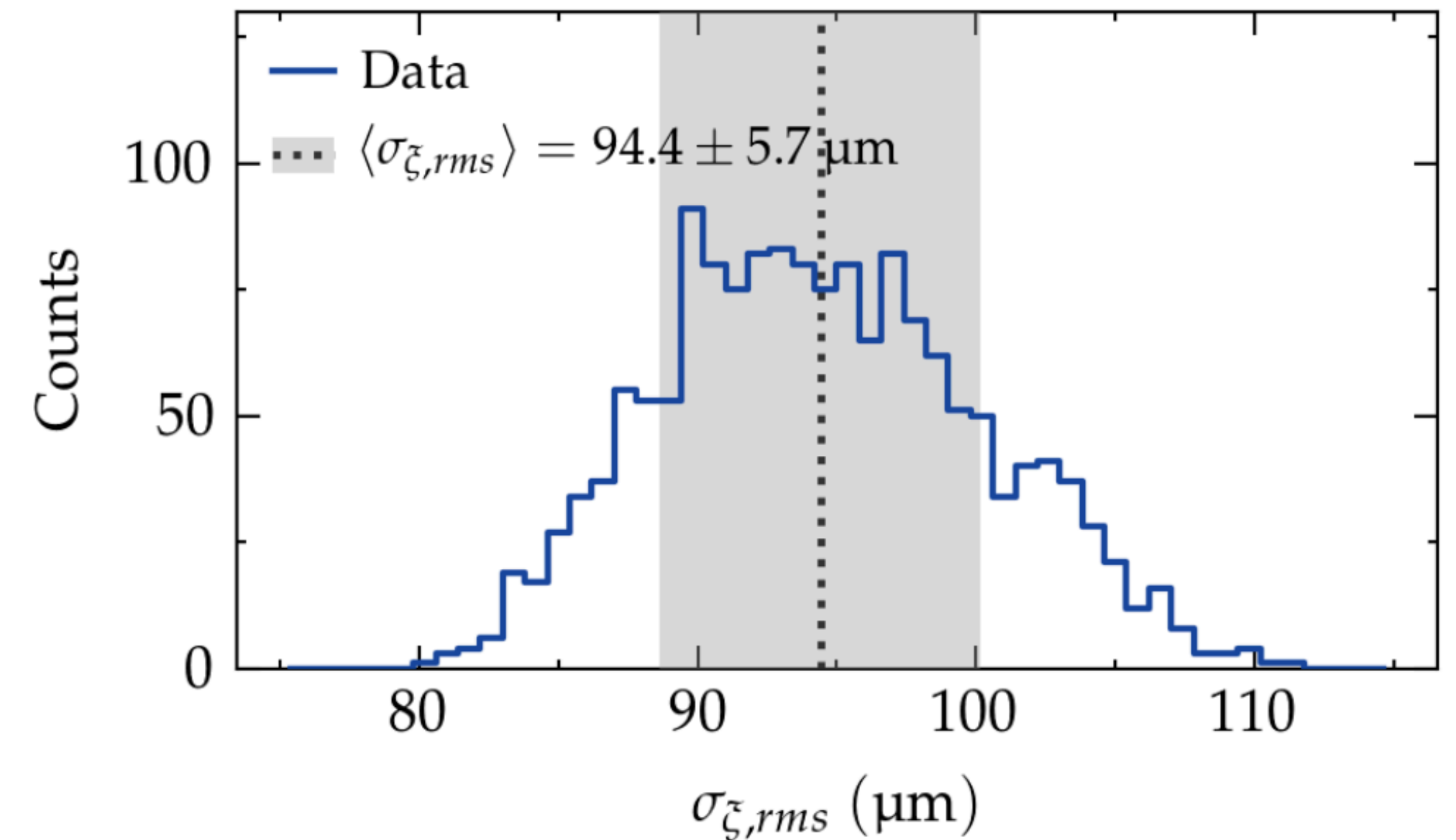
- > Emittance preserved (at 2.8 mm mrad) within 3% measurement error
- > Promising starting point for combining with high total efficiency (E300)



Stability is the main challenge



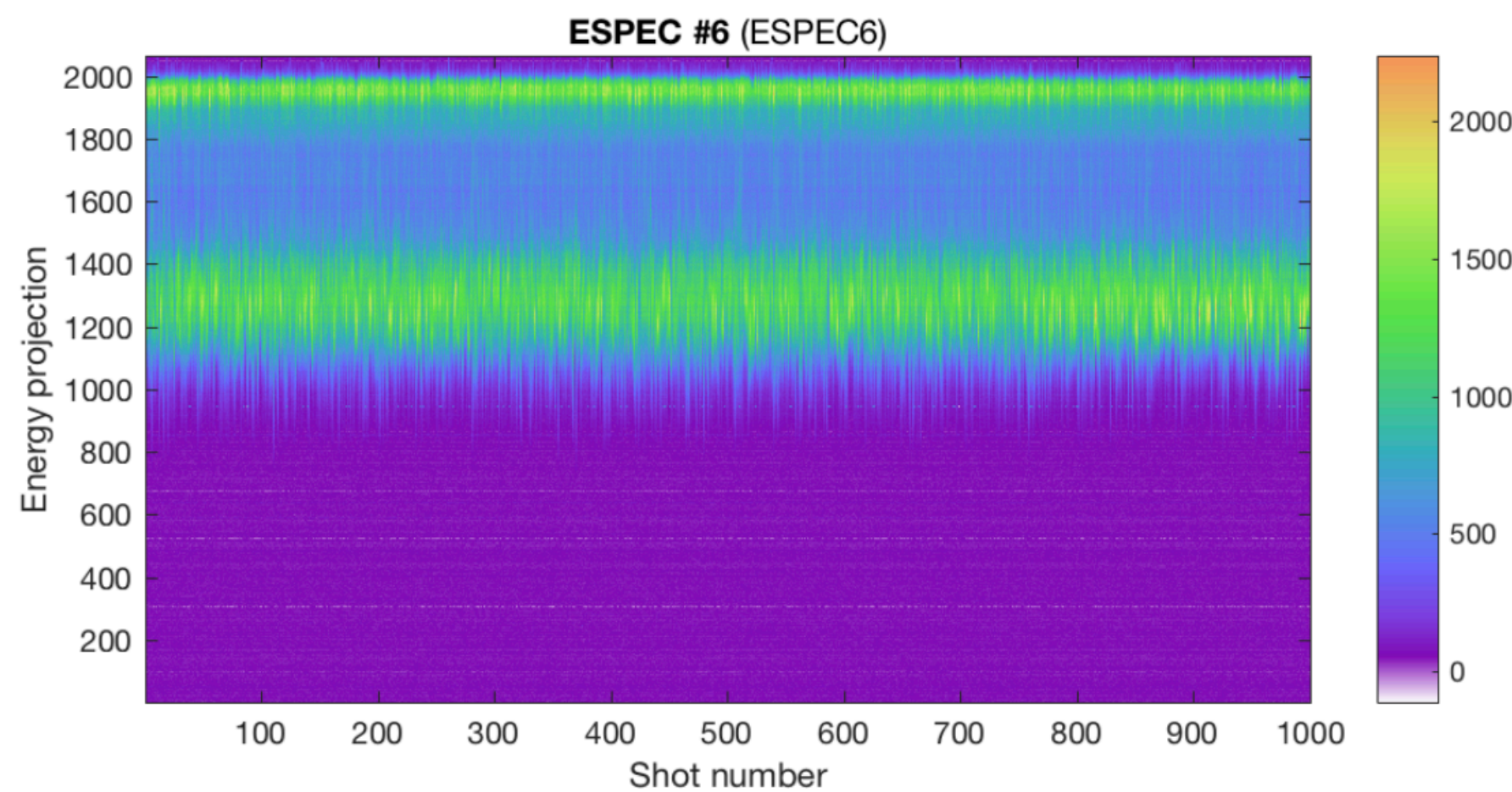
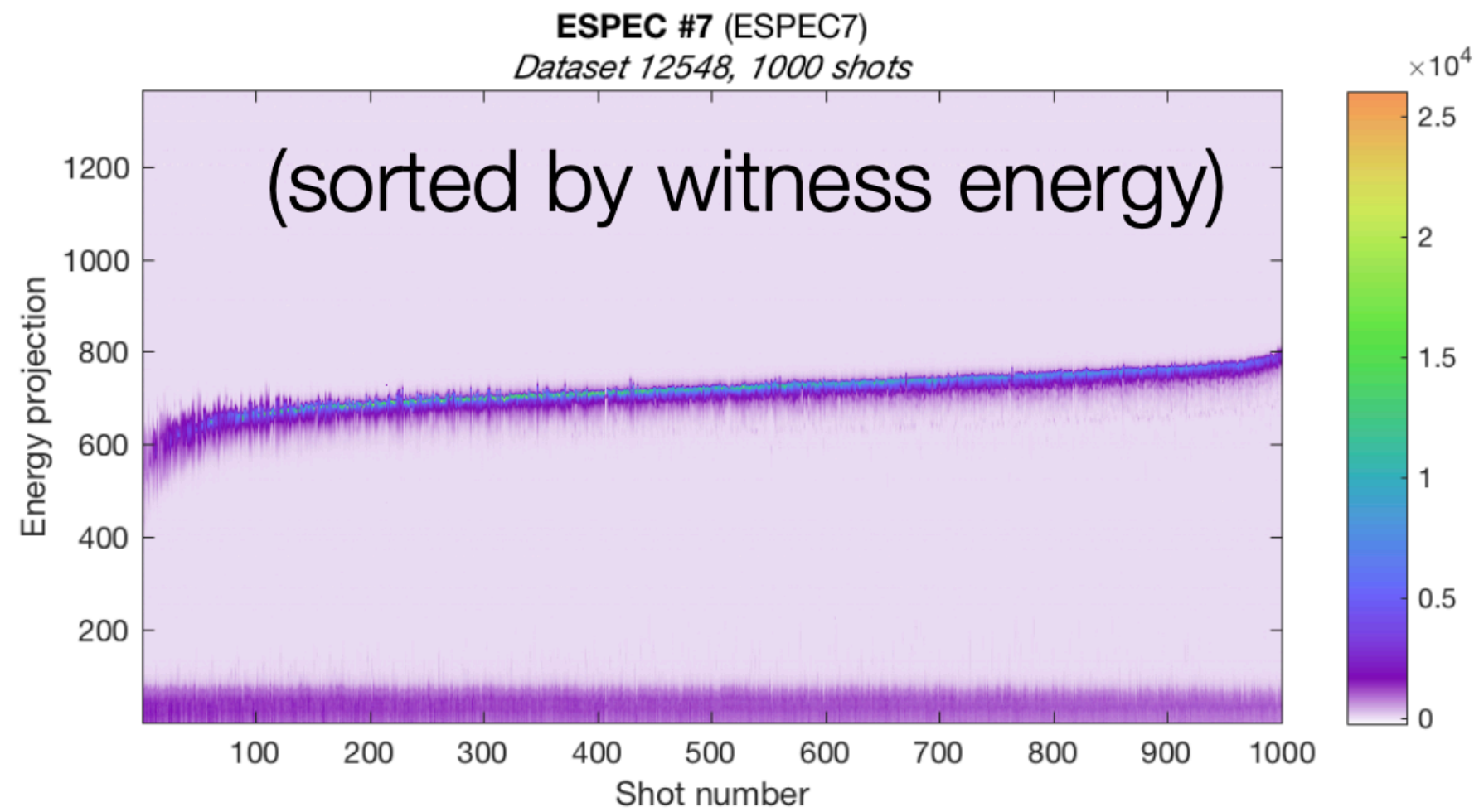
Source: Lindstrøm et al., PRL 126, 014801 (2021)



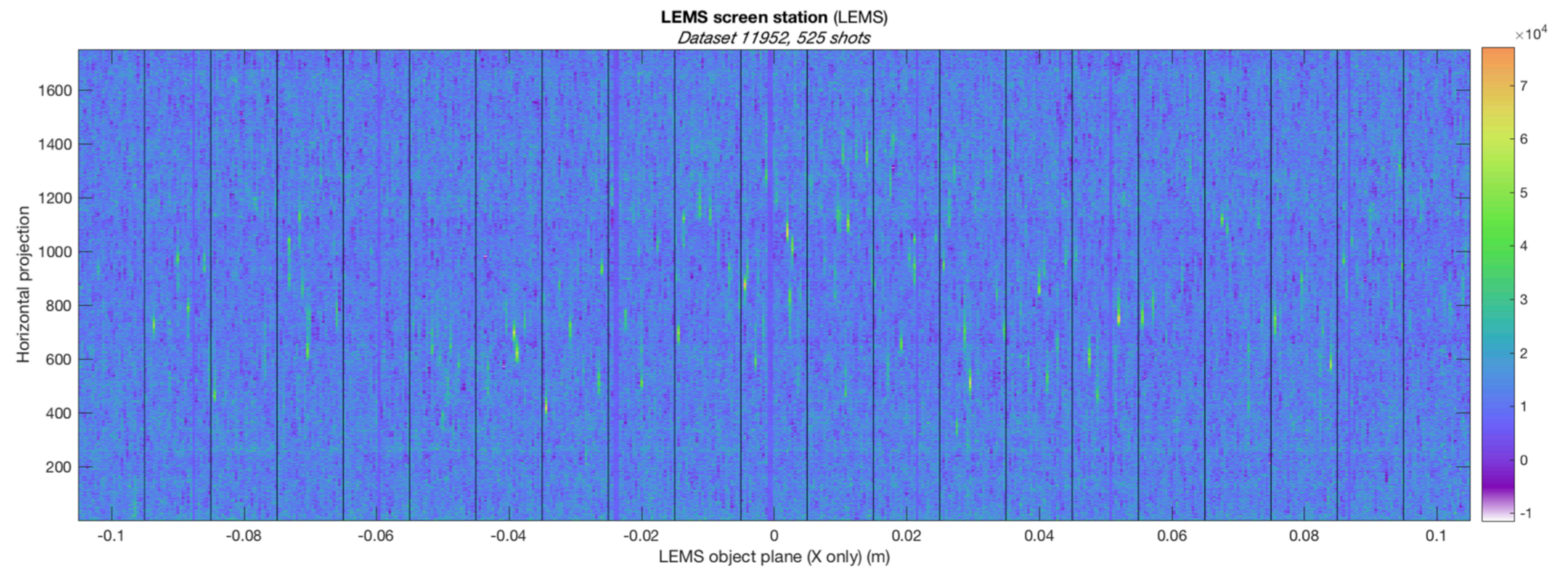
Source: Pau Gonzalez (PhD thesis, Uni. Hamburg, 2022)

- > Transverse jitter is semi-acceptable ($\sim 10\%$ of the beam size — “jitter emittance” ~ 0.2 mm mrad)
- > Bunch length jitter of $\sim 6\%$ (mainly due to a **0.01–0.1 degree-level RF phase jitter** before the first compressor, plus CSR)
 - > **This is the main limitation to extending to results to higher energy gains—much ongoing work to improve it.**
- > Plasma density (here: argon discharge) jitters on the %-level (below our measurement capability)

Stability is the main challenge

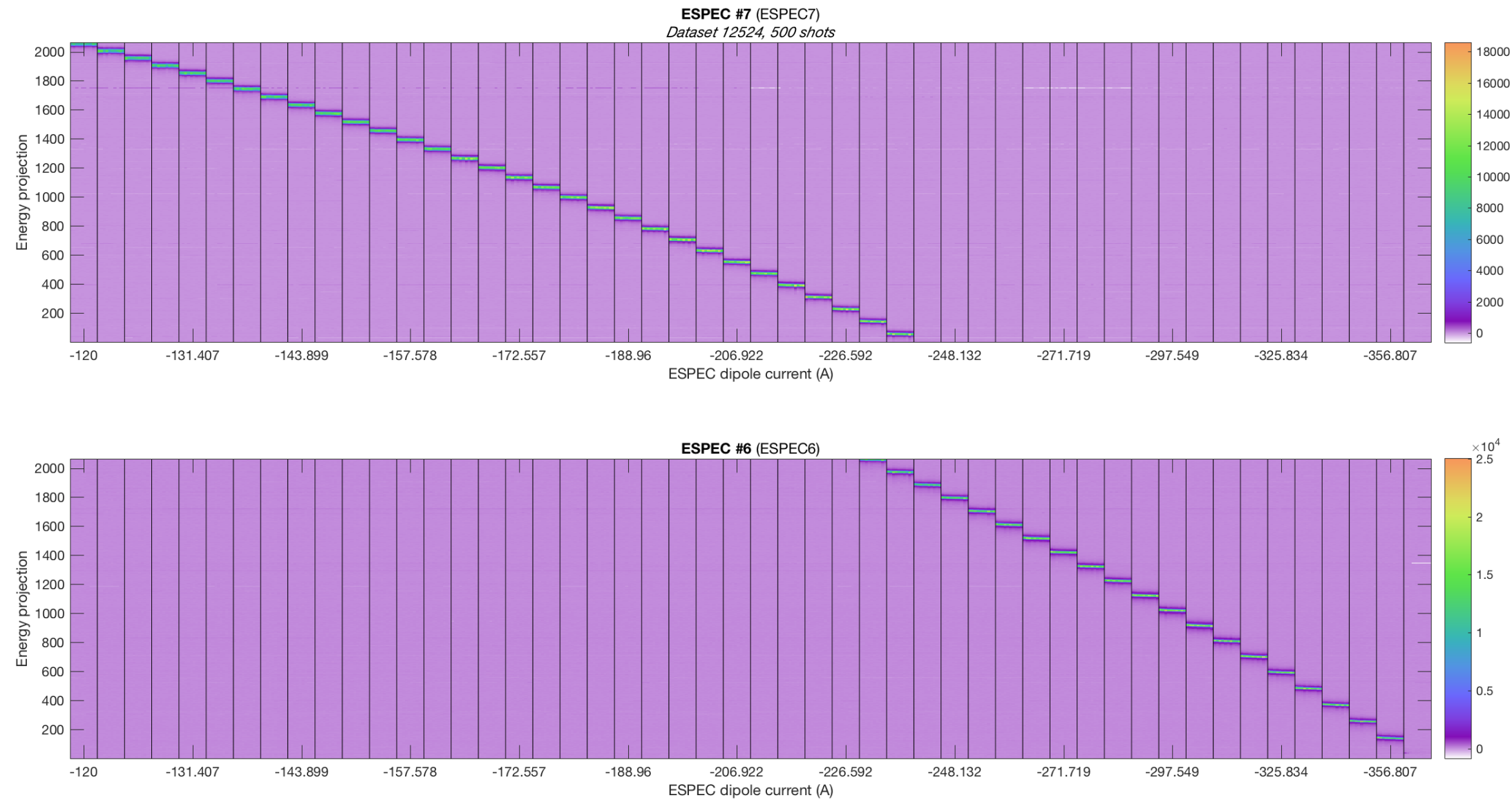


High energy-gain on a high-resolution screen
= very unstable (near impossible to measure emittance)

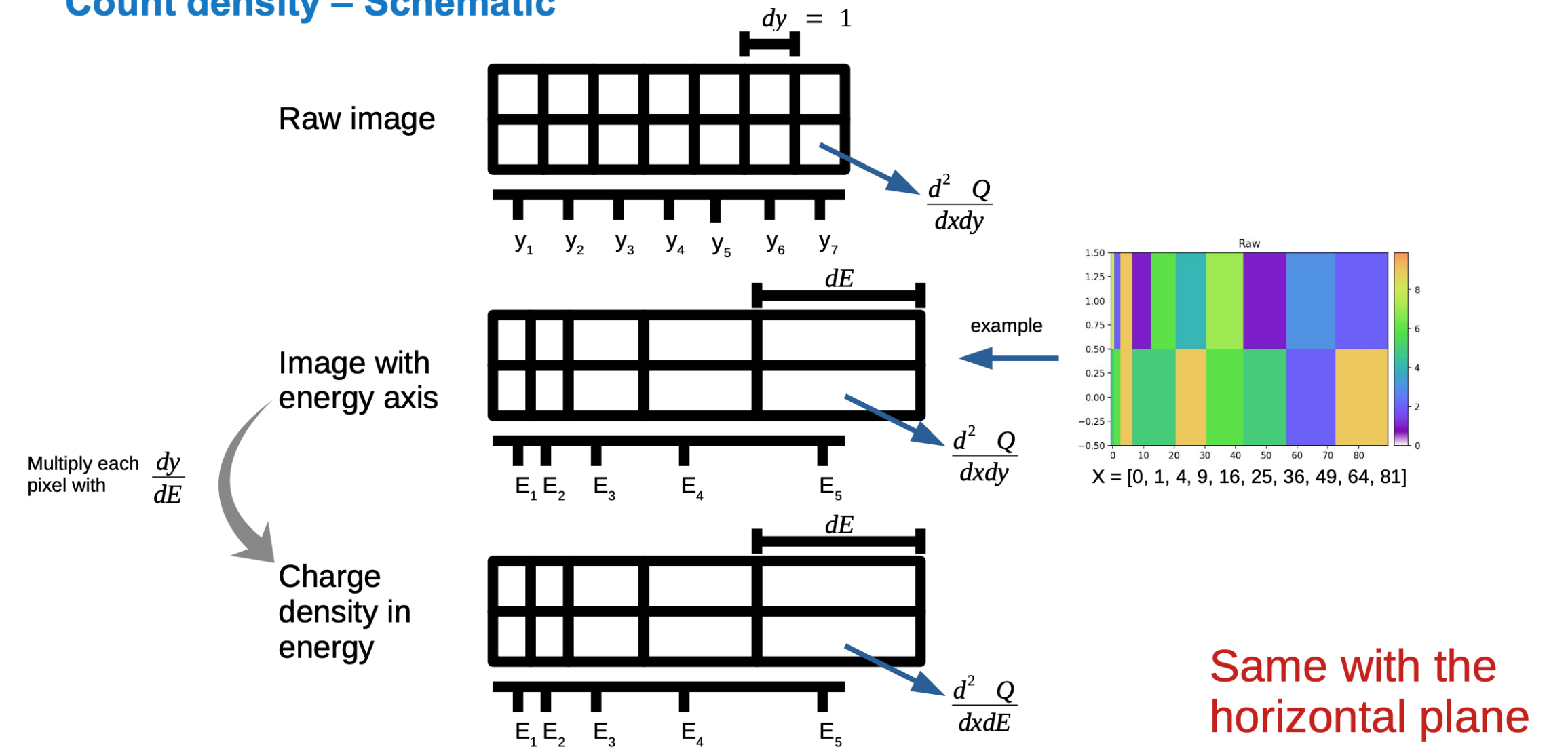


- > High-res screen (for emittance meas.): 6 μm rms, 10x10 mm FOV only.
- > **Practical problem: Larger energy gain -> larger energy fluctuation -> difficult to keep the beam on a high-resolution screen**

Calibrate the spectrometer very carefully

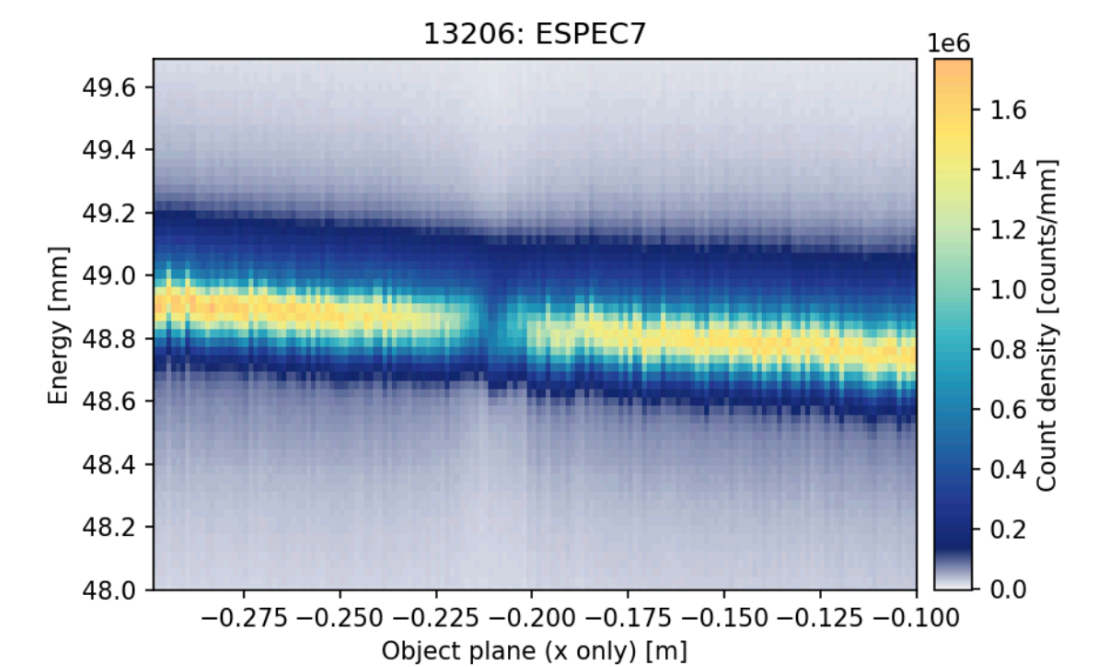


Count density – Schematic



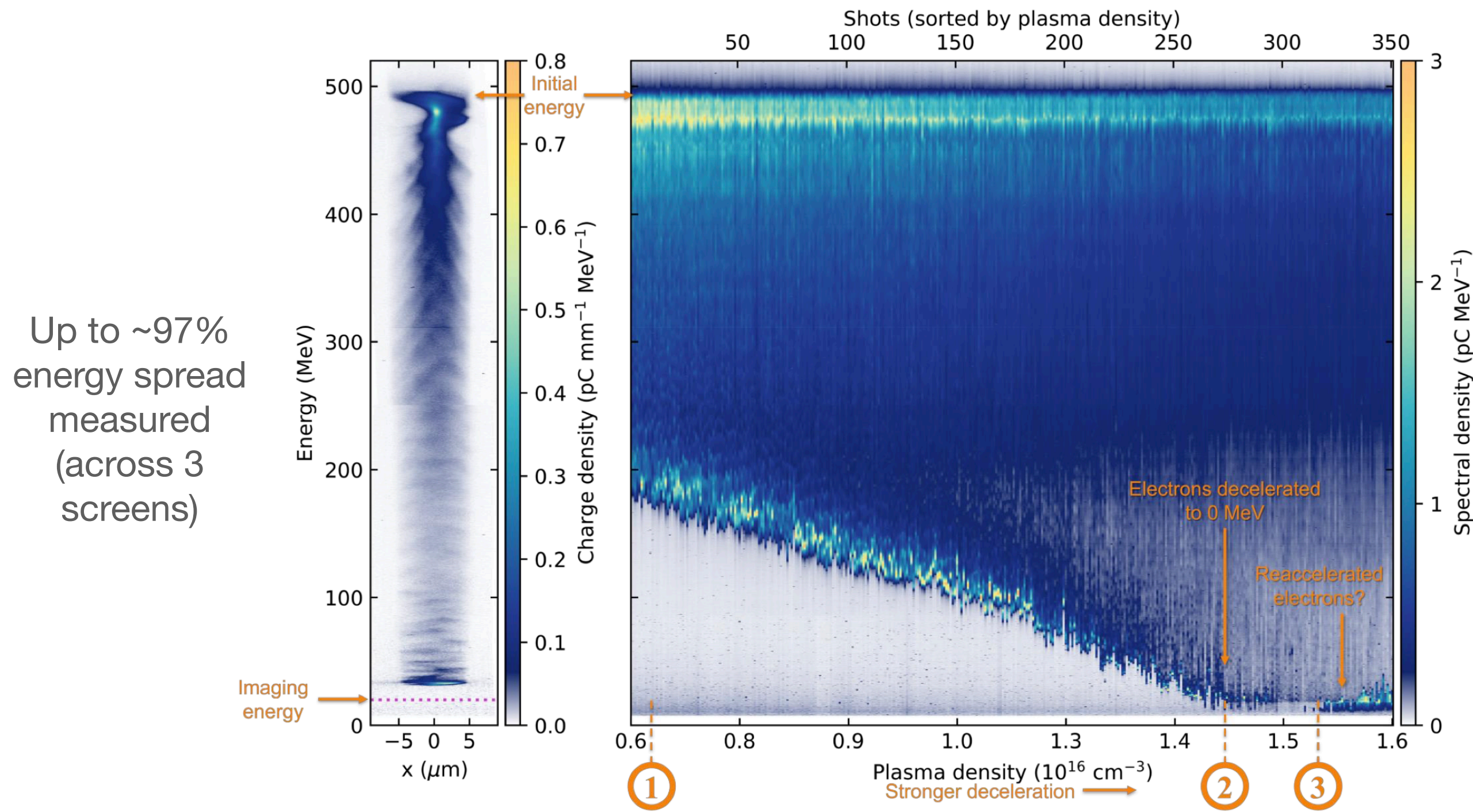
Slide by Felipe Pena.

- > Dipole scan: Gives energy calibration (through $B/E = B\text{-field}/\text{Energy}$)
 - > Gives charge calibration curve (pC/count for each point along the curve)
- > For high-accuracy, cannot assume that the charge-calibration curve is uniform (also, it changes with camera settings).
- > Any saturation => invalid
- > Must correct for screen saturation (Birks' law), especially in GadOx (LANEX), but also in YAG/GAGG.
 - > Must avoid scintillator quenching — impossible to reconstruct (information is lost).



Observation of quenching when focusing too strongly.

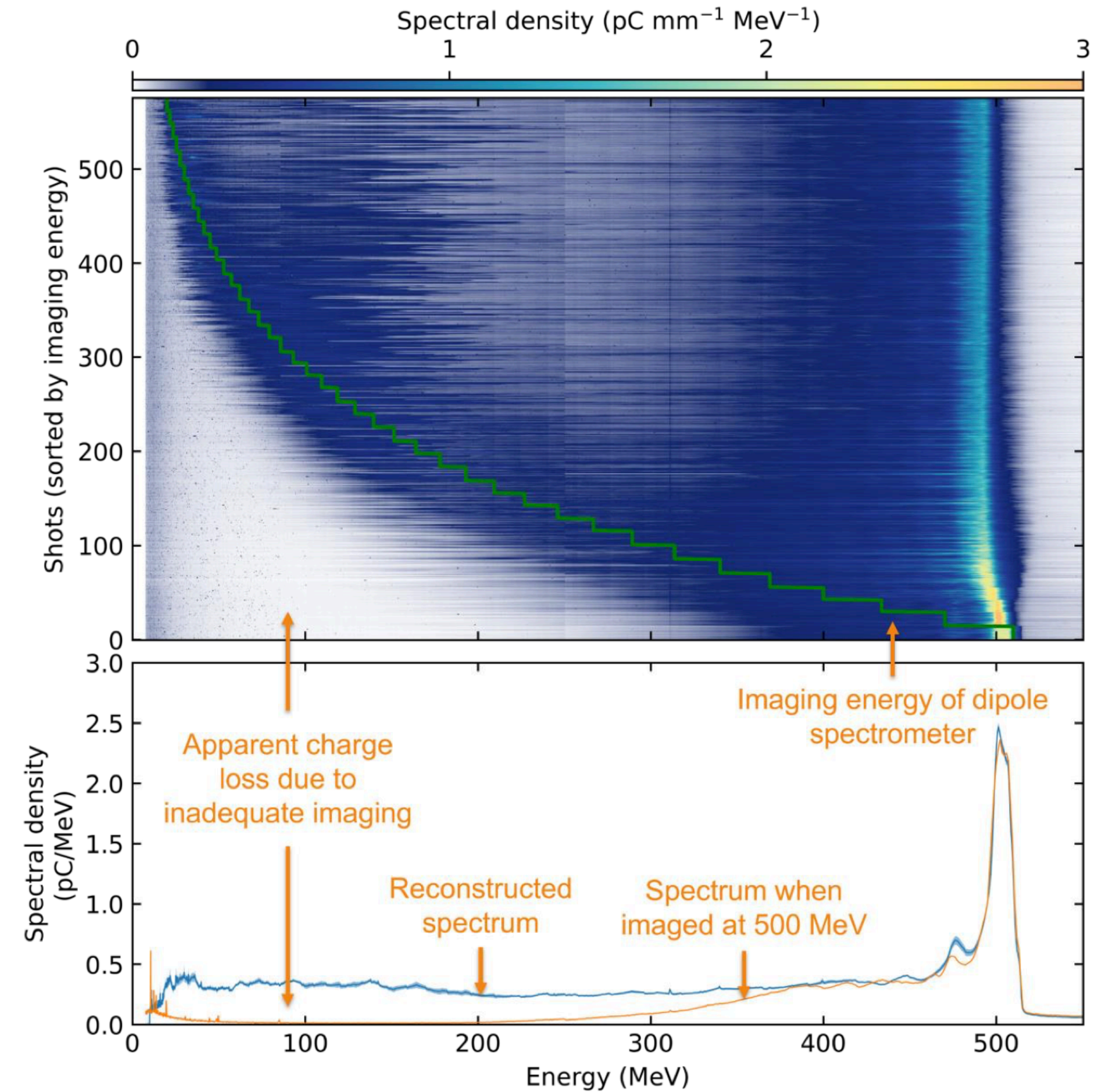
Spectrum reconstruction is tedious, but important



Up to ~97%
energy spread
measured
(across 3
screens)

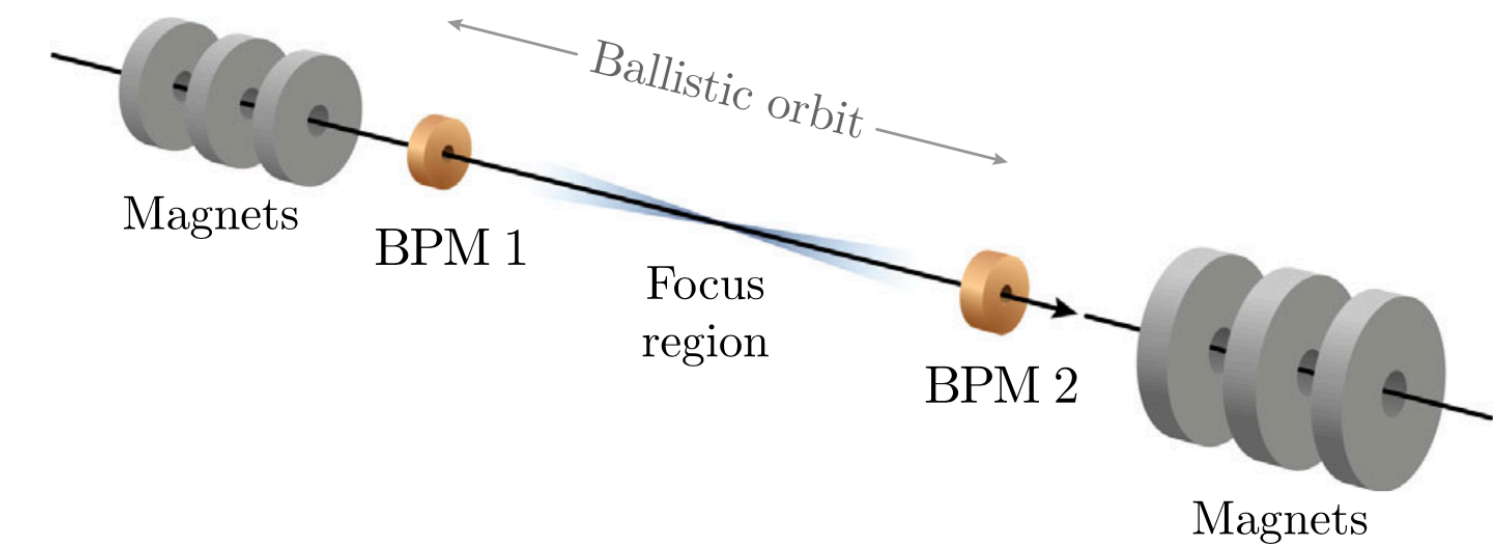
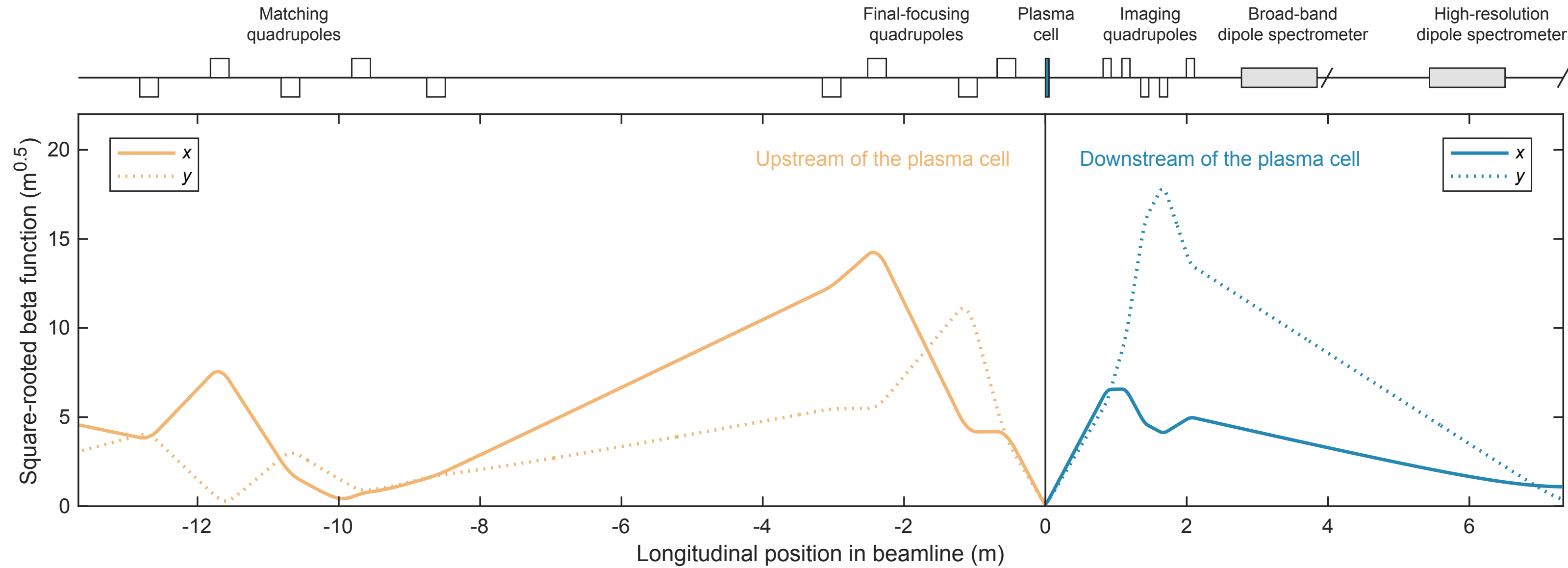
> Three parts:

- > Spectrometer calibration
- > Imaging energy scan [like in Corde et al., Nature 442, 524 (2015)]
- > Charge may still be missing (lost in plasma or clipped in transport)



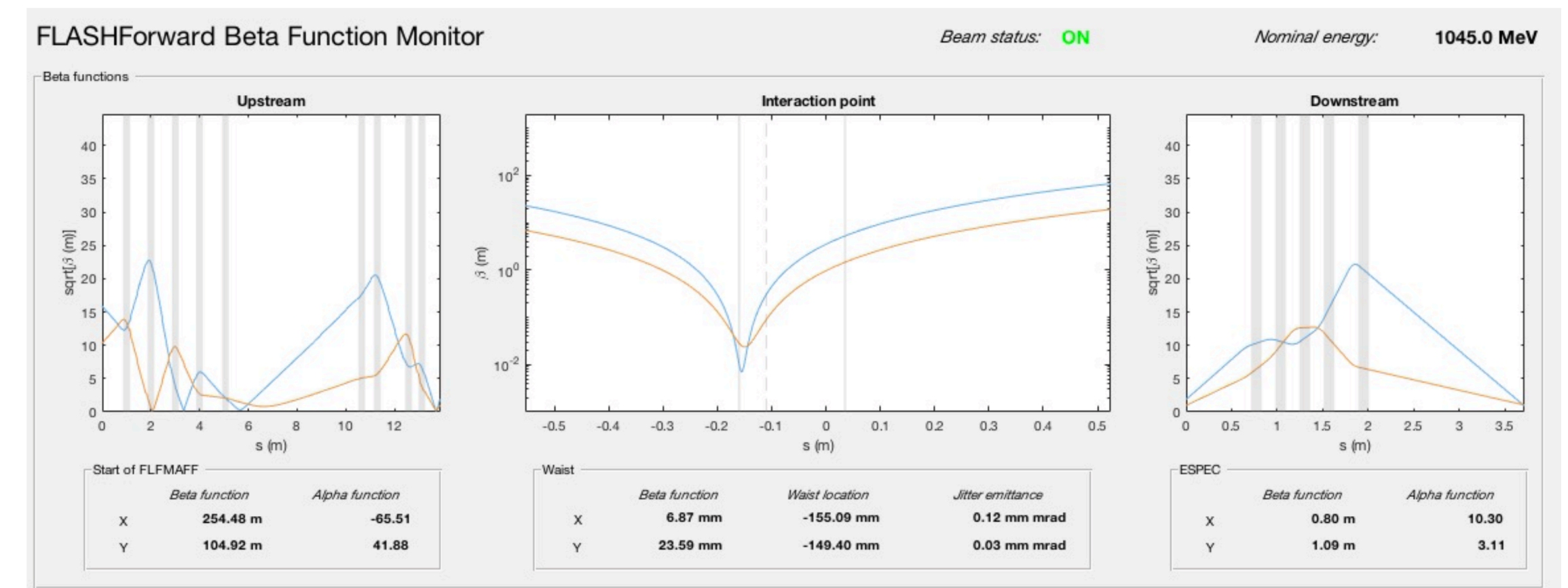
Source: Felipe Pena, poster/presentation at EuroNNAc 2022.

Understand the beam optics with per-mille-level accuracy



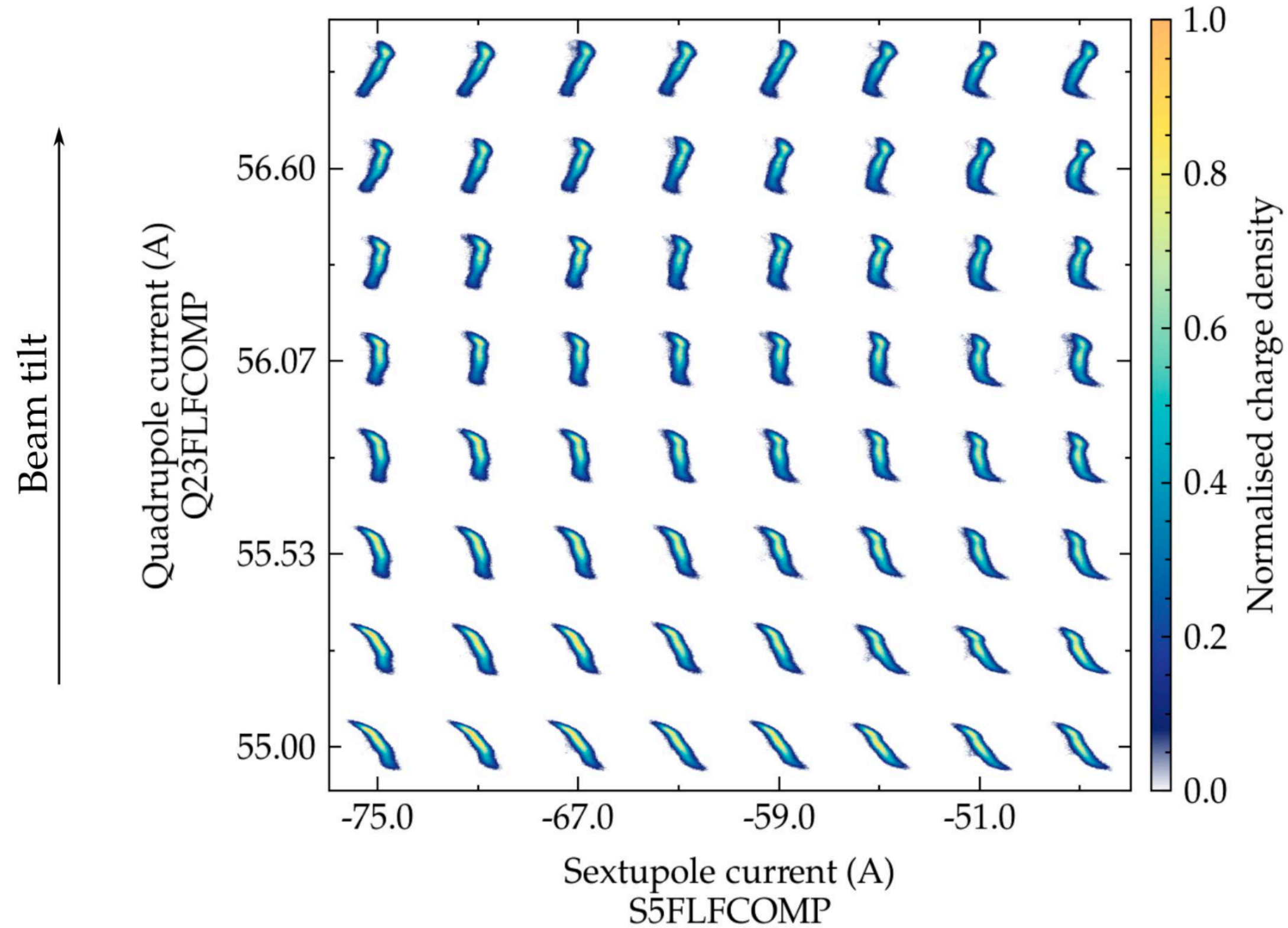
Source: Lindstrøm et al., PRAB 23, 052802 (2020).

- > **The waist beta function is ~10 x 10 mm.**
- > mm-level movements required 0.1%-level changes in quad currents.
- > Online beta-function monitor (Hz updates) using two BPMs.
 - > ~mm precision in placing the beta function.
- > Online tool was crucial in placing the focus precisely (no time for quad scans for every 0.1% change in final-focus quads.)
- > We never used in-waist screens (CTR makes it impossible to use).



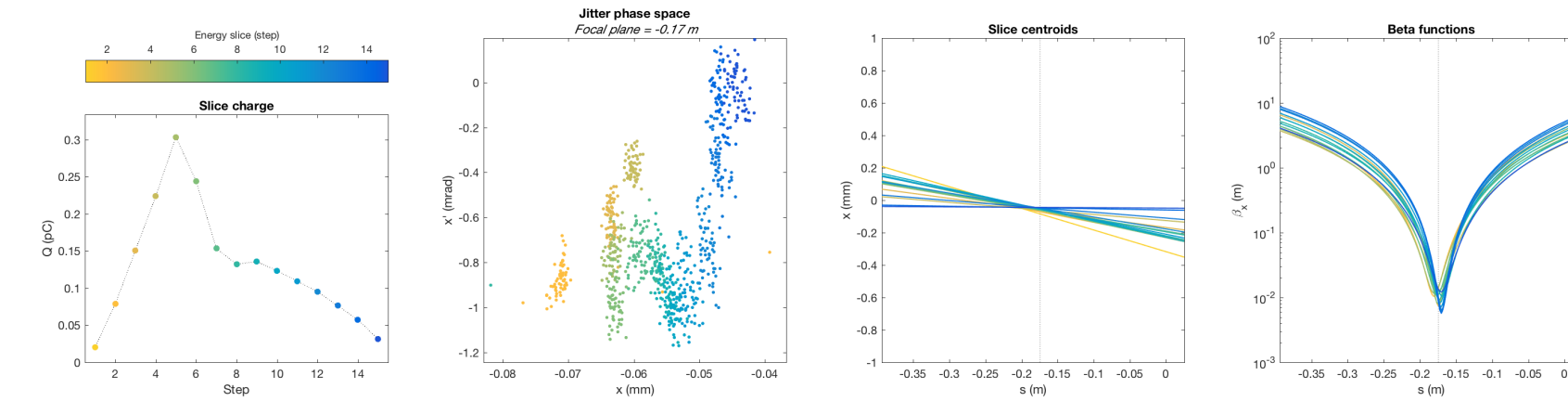
Online beta-function GUI (measured live with 2-BPM technique)

Straighten those bunches, also to higher order (sextupoles)

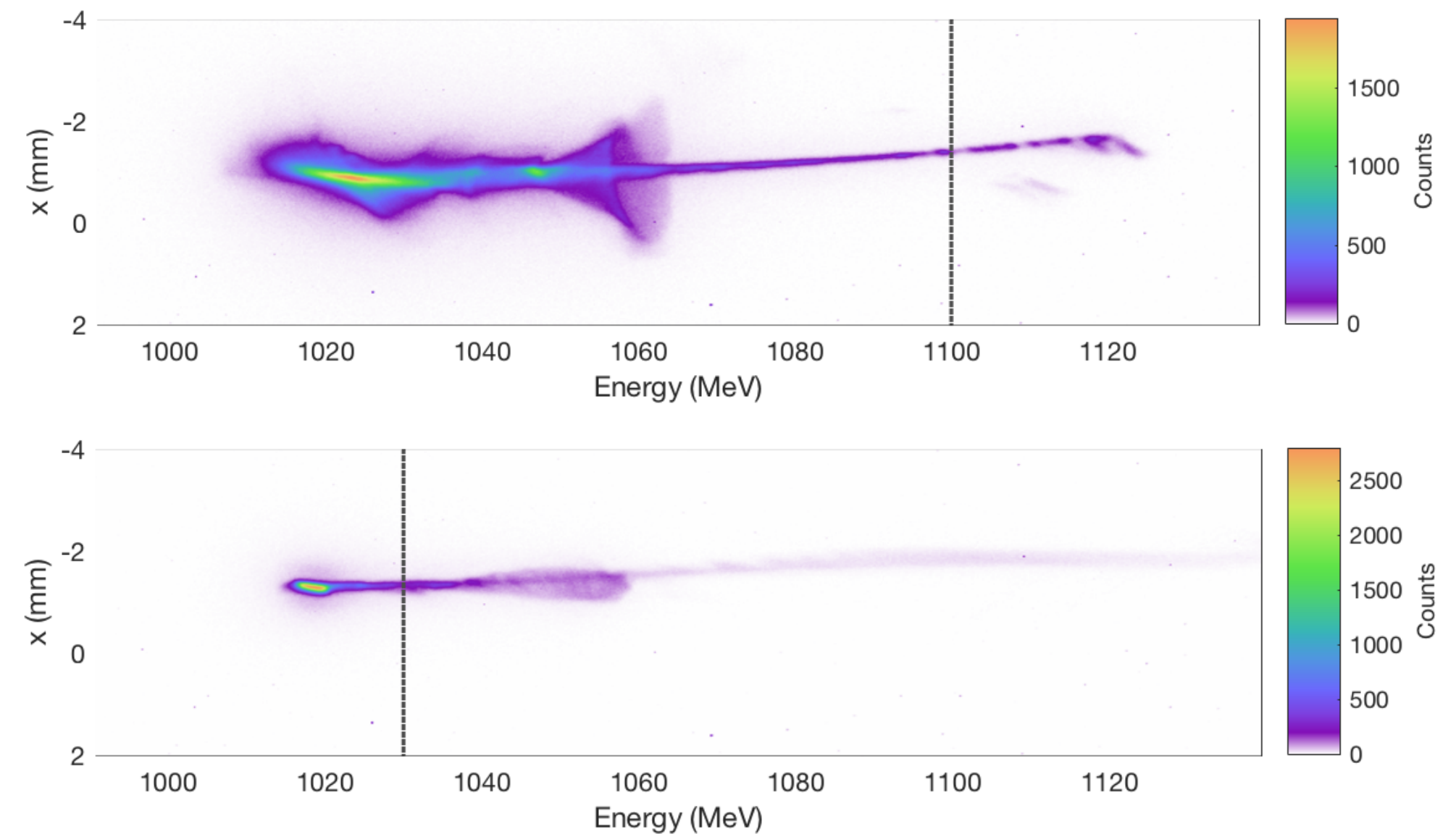


Source: Pau Gonzalez (PhD thesis, Uni. Hamburg, 2022)

> Measured on a TDS / TCAV. Changing a quad and a sextupole in a dispersive section.

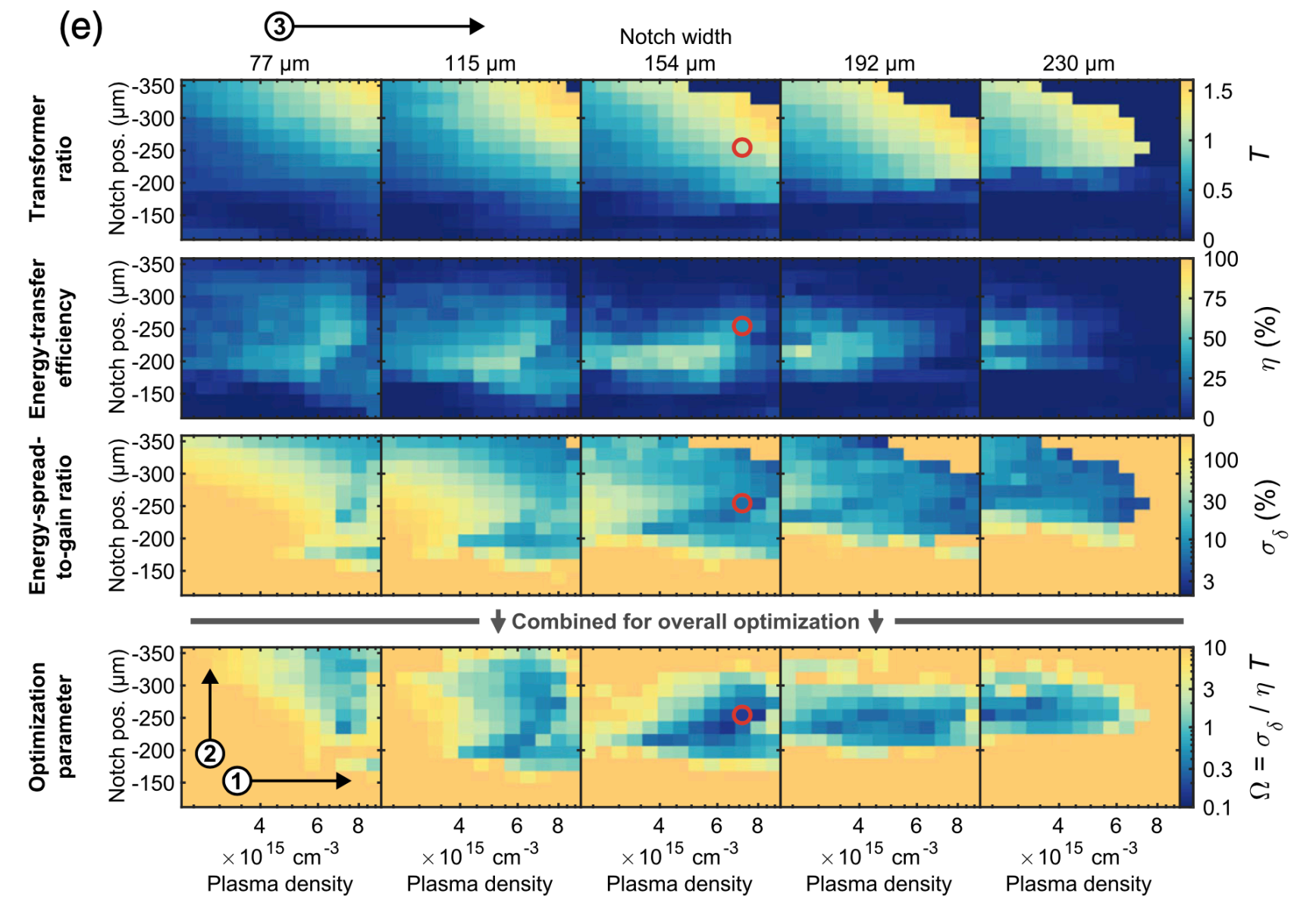
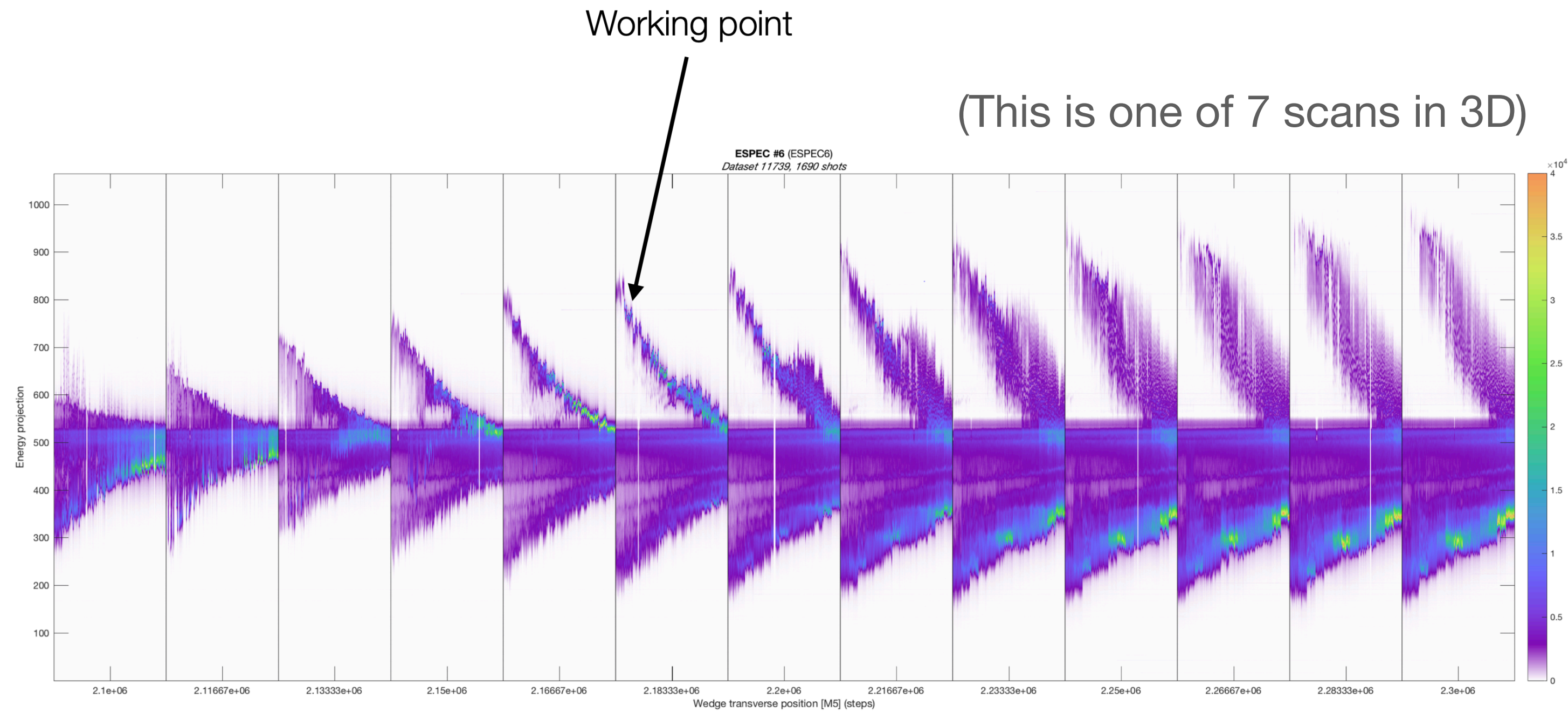


Measured with 2-BPM technique (slice-by-slice)



> In the end, the plasma tells you if the bunch was straight or not (final straightening is in-situ).

Optimal beam loading — finding a needle in a hay stack



Source: Lindstrøm et al., PRL 126, 014801 (2021)

> The “optimal beam loading scan”: 3D scan of:

- > Plasma density
- > Bunch separation (notch-collimator width)
- > Driver/trailing bunch charge ratio (notch-collimator position)

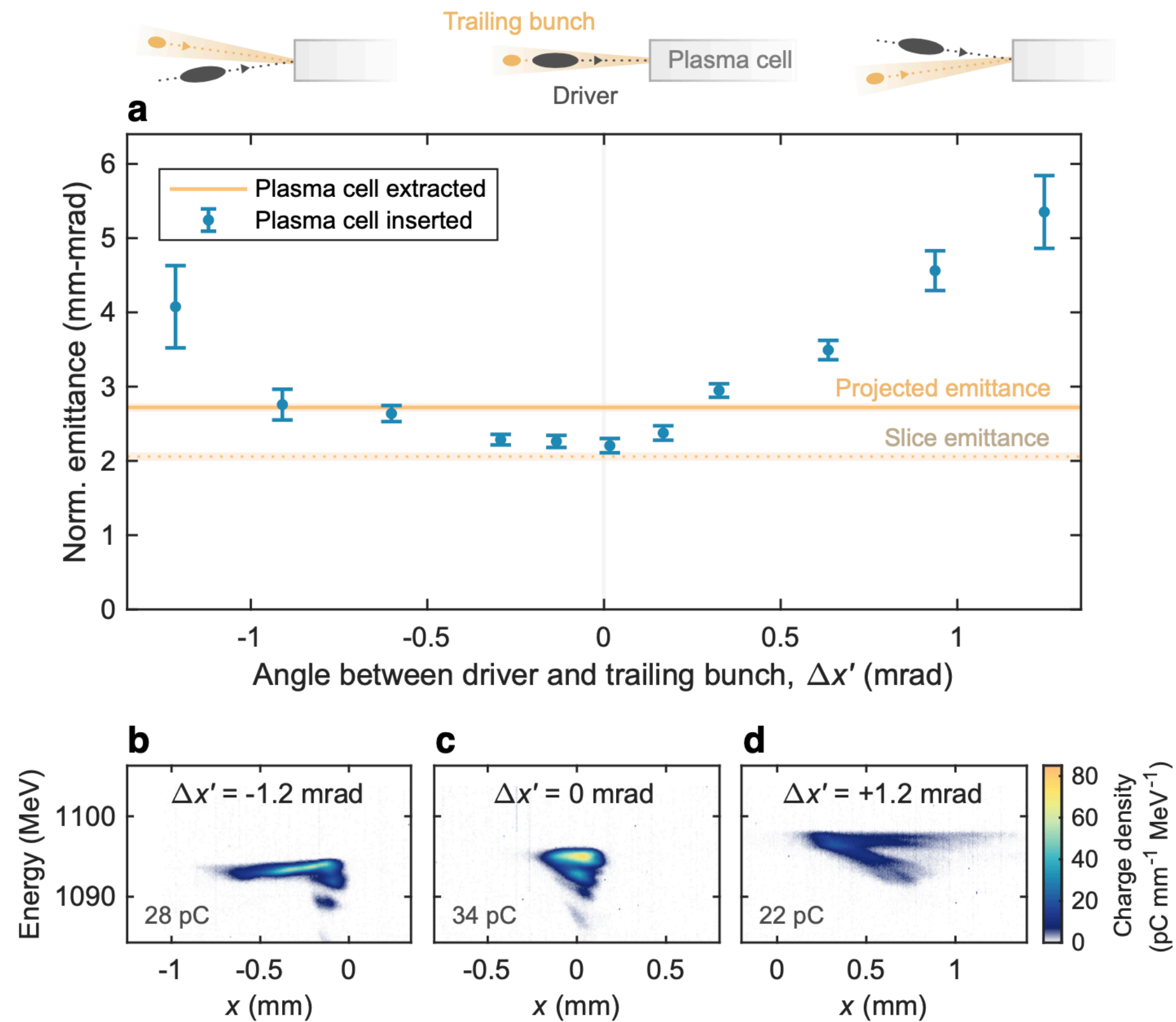
A useful, dimensionless, and length-independent quantity to minimize

$$\Omega = \frac{\sigma_\delta}{\eta T}$$

Matching/aligning the trailing bunch — **threading that needle**

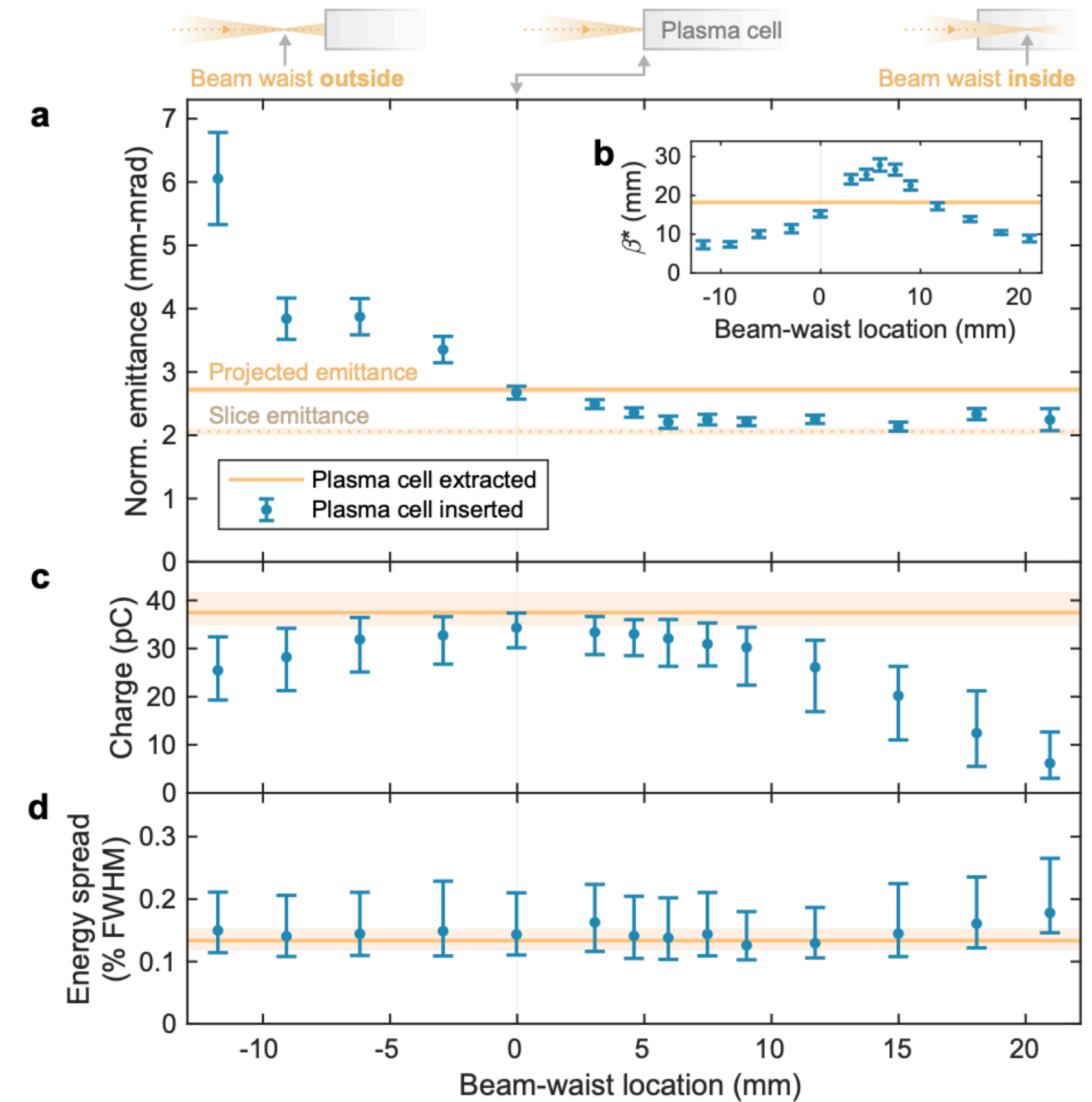
Alignment

0.1% adjustments of a dispersive quad



Matching

0.1% adjustments of a final-focus quad



Source: Lindstrøm et al., submitted (2022)

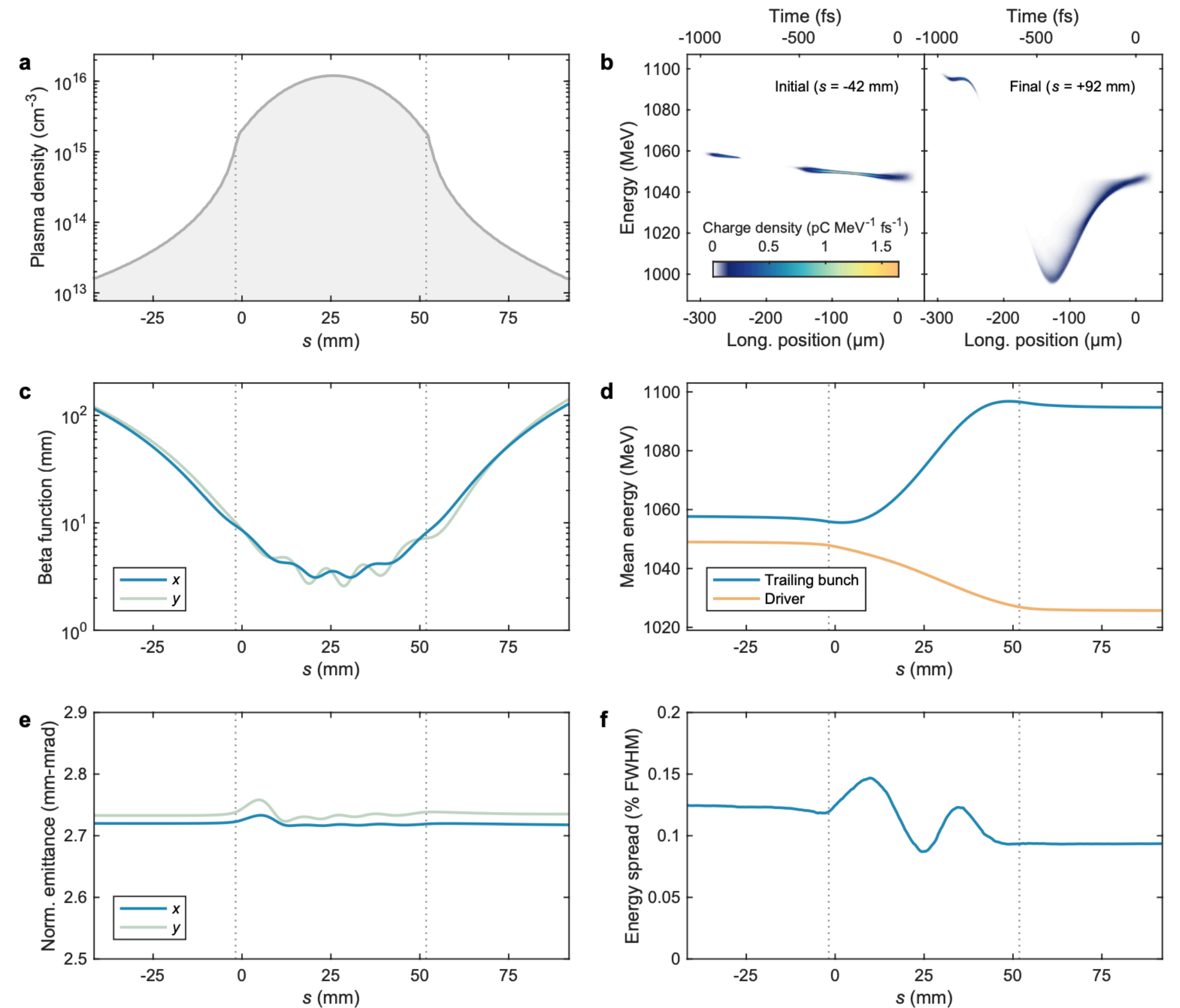
Characterize beam + plasma for a meaningful PIC comparison

> If you want to compare to PIC simulations with %-level accuracy, you must reconstruct everything with %-level accuracy:

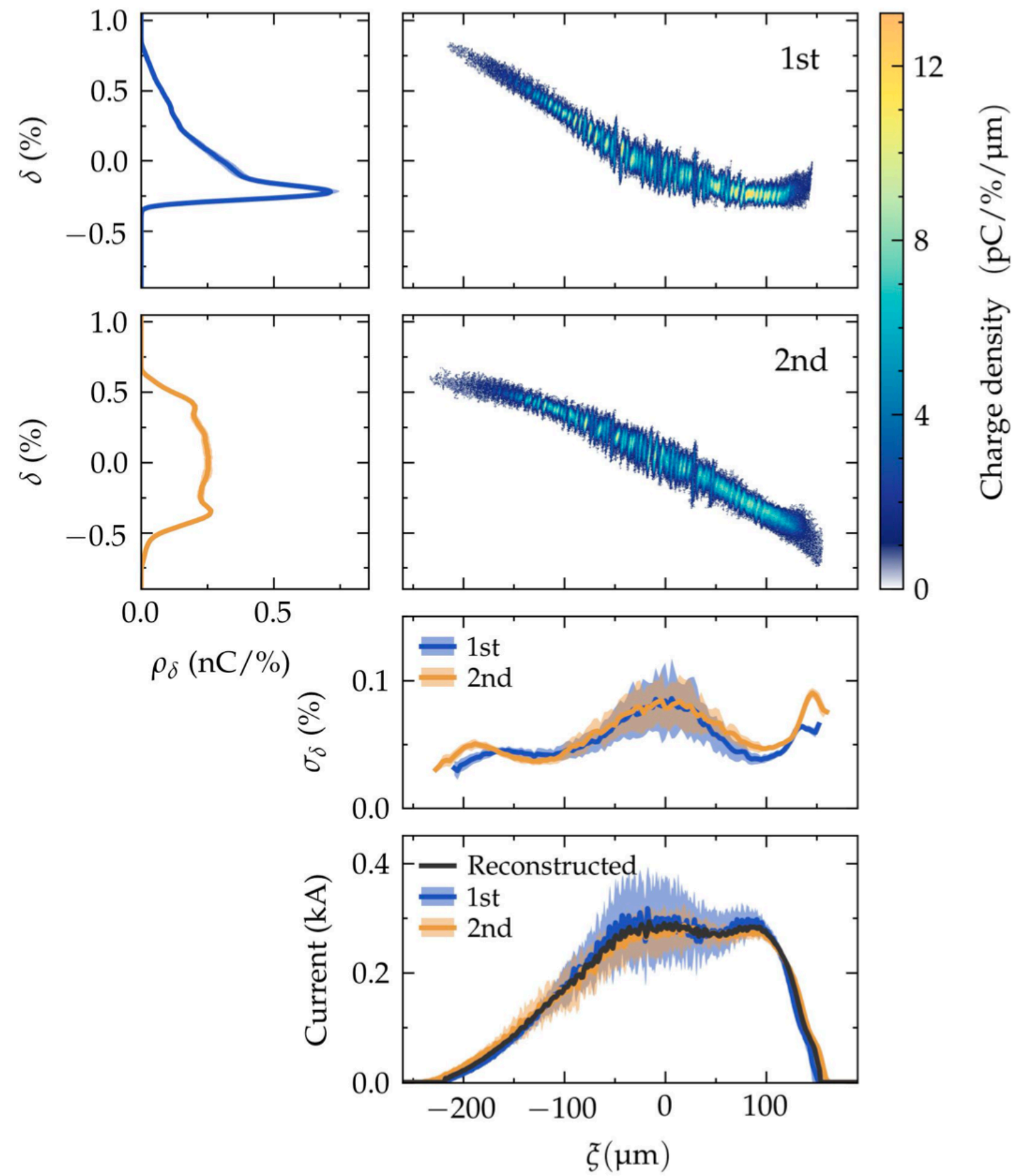
- > 6D phase space of the driver and trailing bunch (2D + 2D + 2D is sometimes enough)
- > Plasma density profile

> This means that every “interesting working point” must be characterized by a laundry-list of scans:

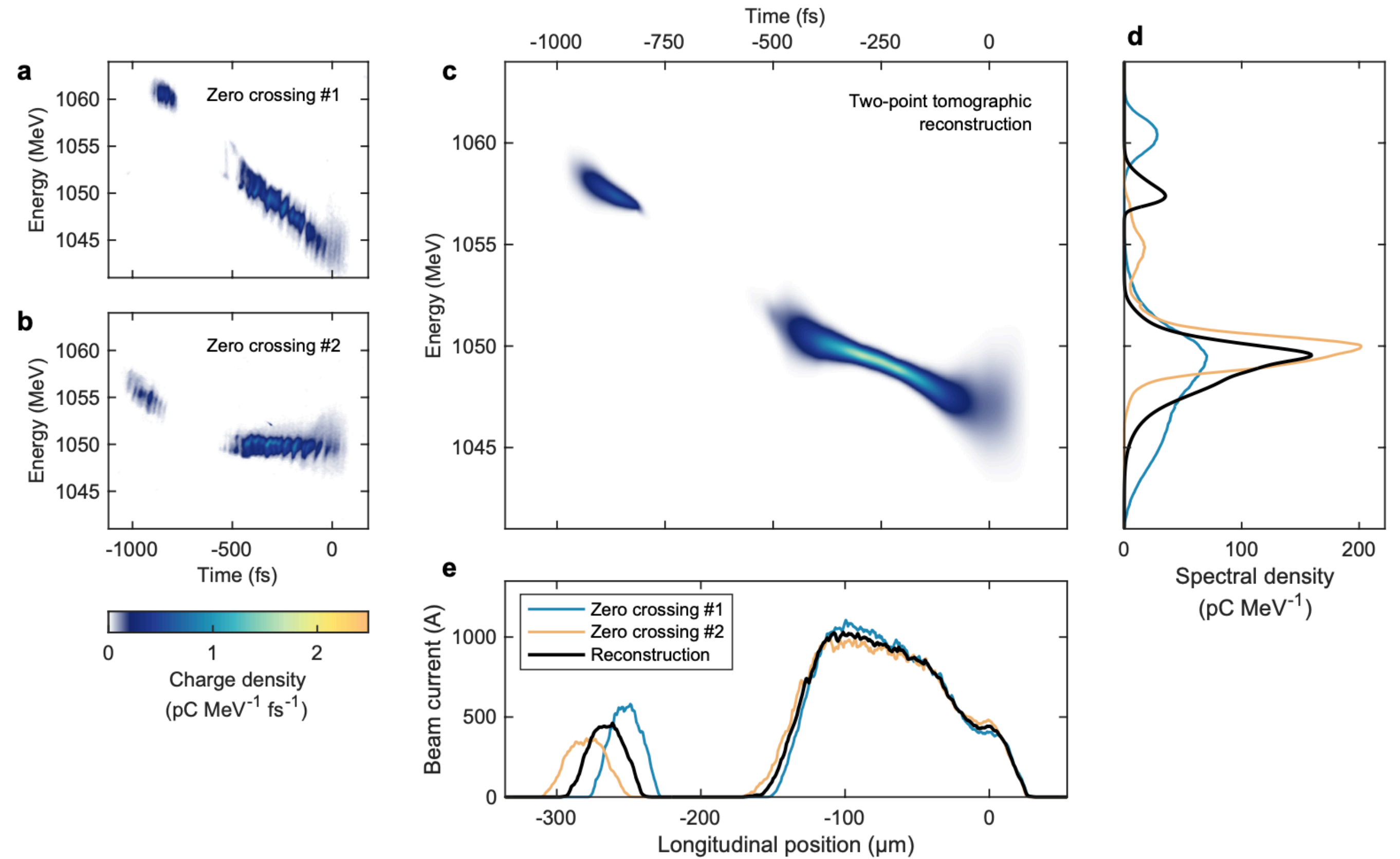
- > Longitudinal phase space (plasma off)
- > Object-plane scans (plasma off/on, x/y, driver/trailing bunch) for *betas*, *waist locations*, *emittances*
- > Imaging energy scans (plasma off/on) for *spectrum*
- > Plasma density (profile, ideally in longitudinal and radial)



Two-point tomography is required for accurate TCAV data

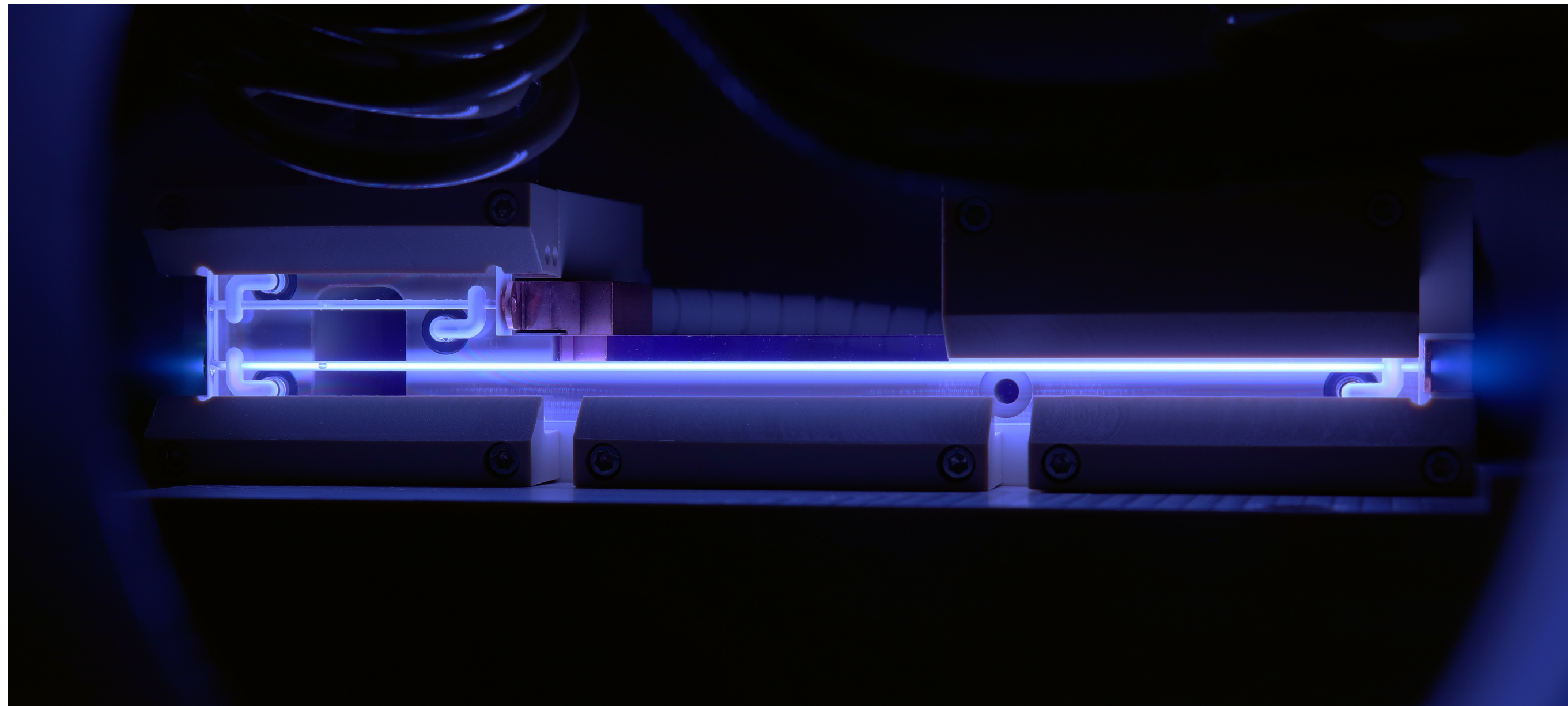


Source: Pau Gonzalez (PhD thesis, Uni. Hamburg, 2022)



Source: Lindstrøm et al., submitted (2022)

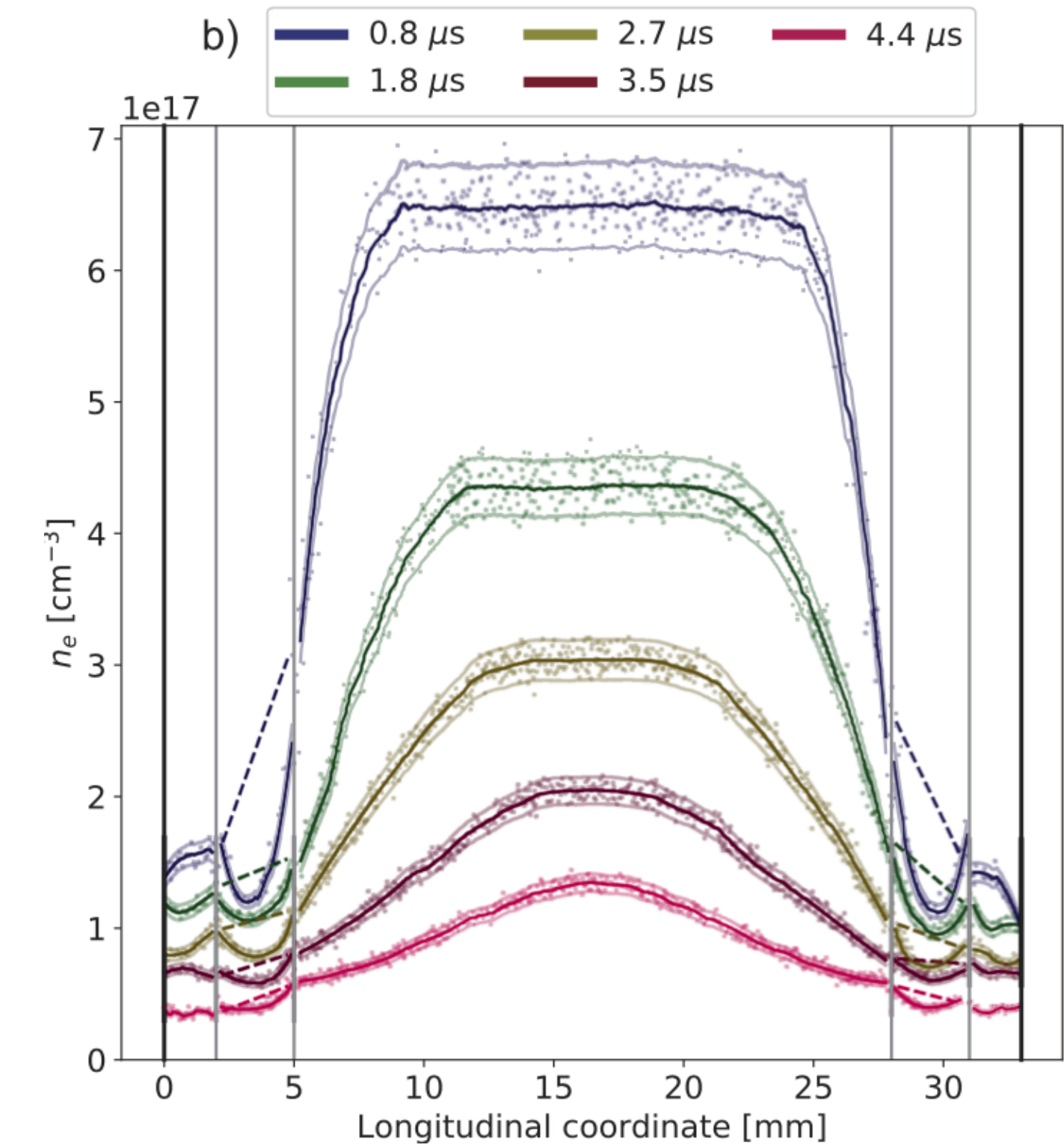
Lastly: Discharges – rock solid, can be long, easy to characterize



Source: Lindstrøm et al., Proc. EPS-HEP2021, 880 (2021).

One less laser – always a good thing

H-alpha spectral line broadening measurement



Source: Garland et al.,
Rev. Sci. Instrum. 92, 013505 (2021)

Thanks