# Driver energy depletion

## Large Energy Depletion of a Beam Driver in a Plasma-Wakefield Accelerator


**Felipe Peña**, C. A. Lindstrøm, J. Beinortaite, J. Björklund Svensson, L. Boulton, S. Diederichs, J. M. Garland, P. González Caminal, G. Loisch, S. Schröder, M. Thévenet, S. Wesch, J. Wood, J. Osterhoff, and R. D’Arcy



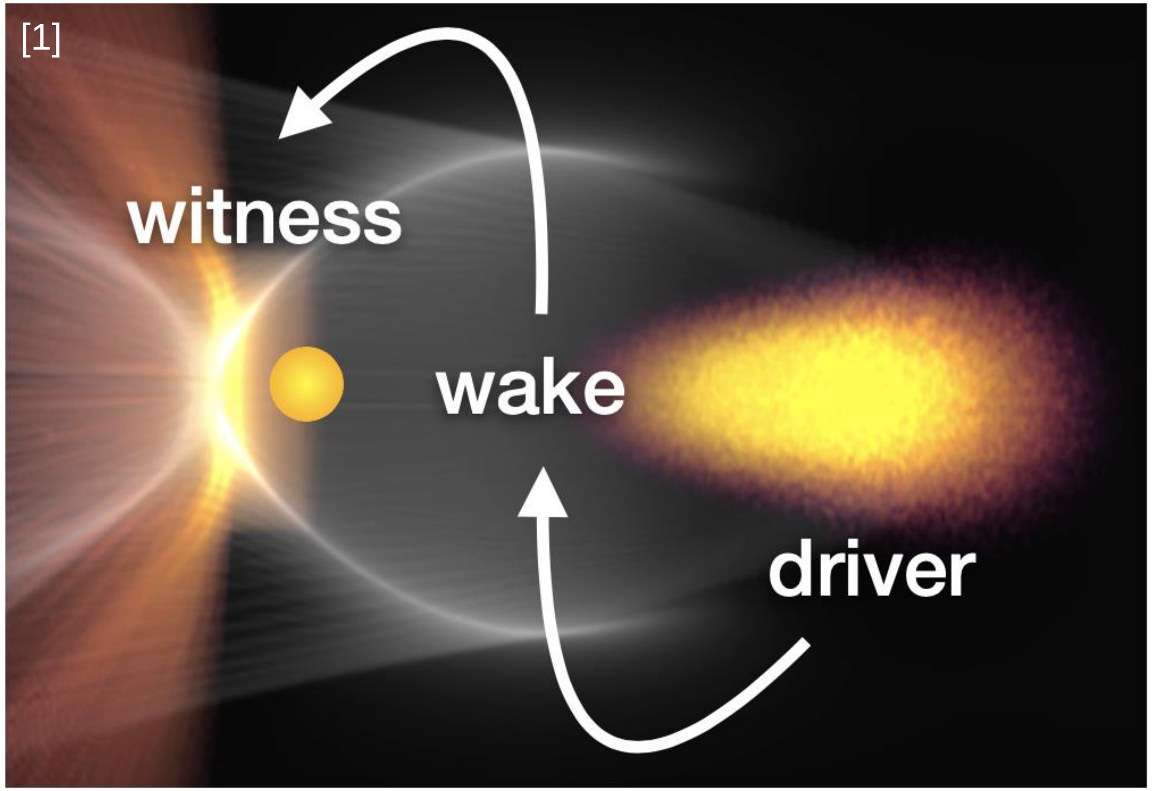
20th Advanced Accelerator Concepts Workshop
6-11 November 2022
New York, US


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

# Driver energy depletion is key component for efficiency

> Wall-plug-to-witness efficiency is a product of:




[1] Courtesy of R. D'Arcy
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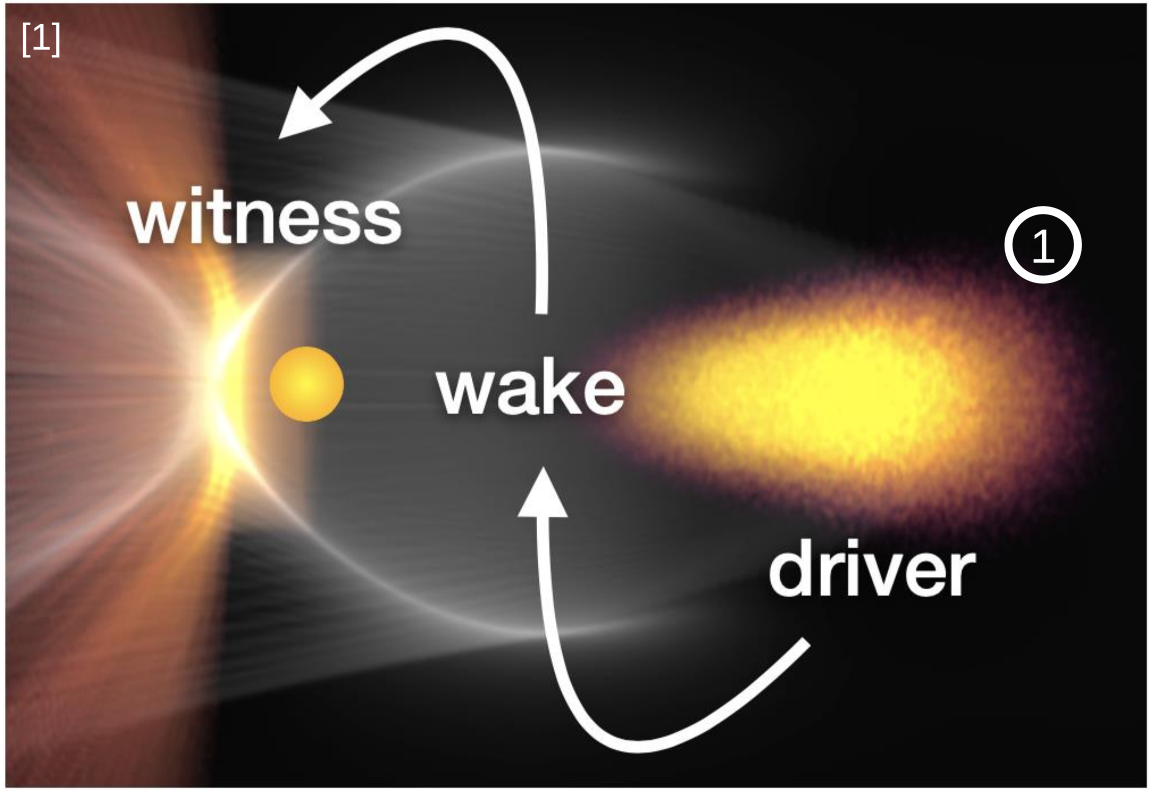


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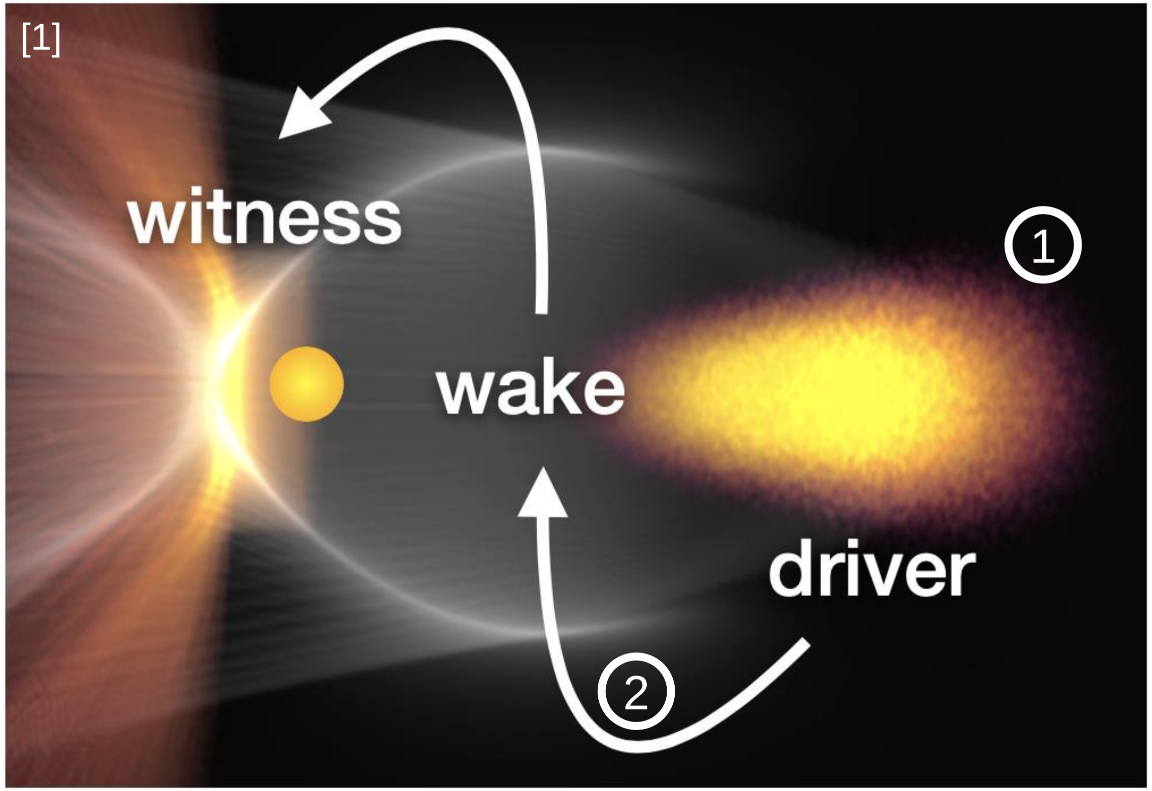



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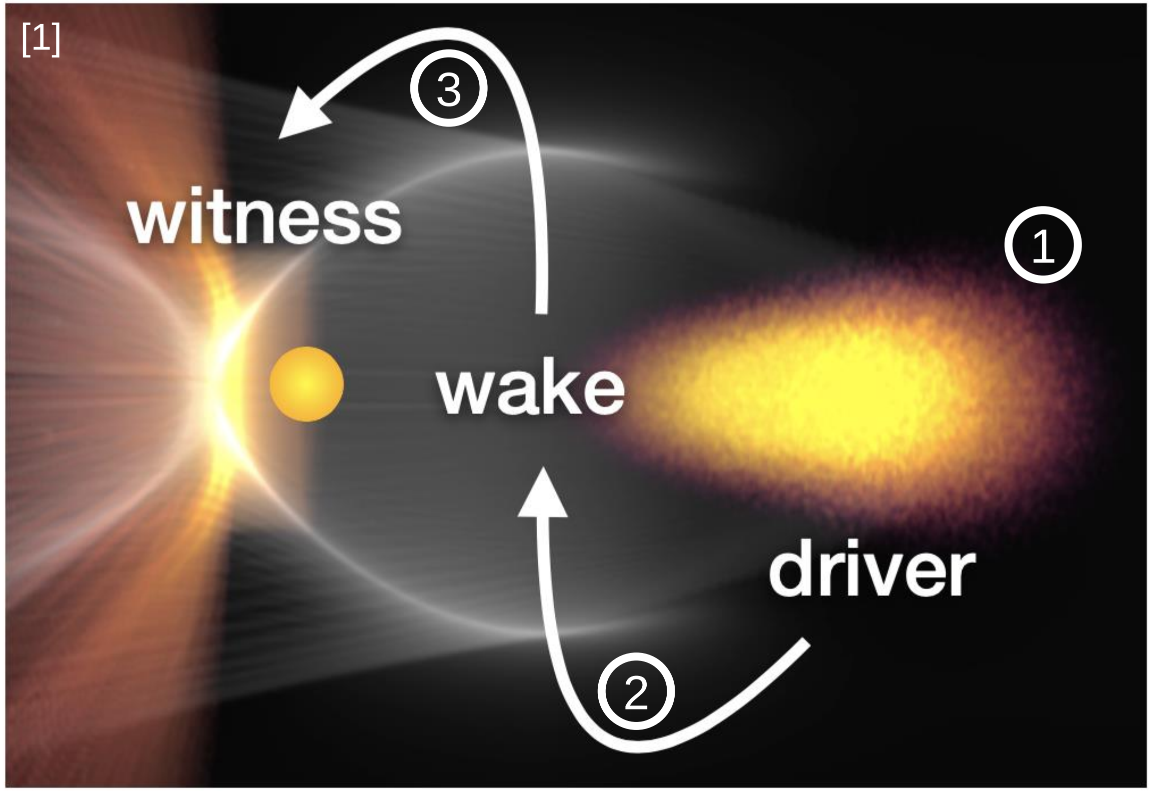



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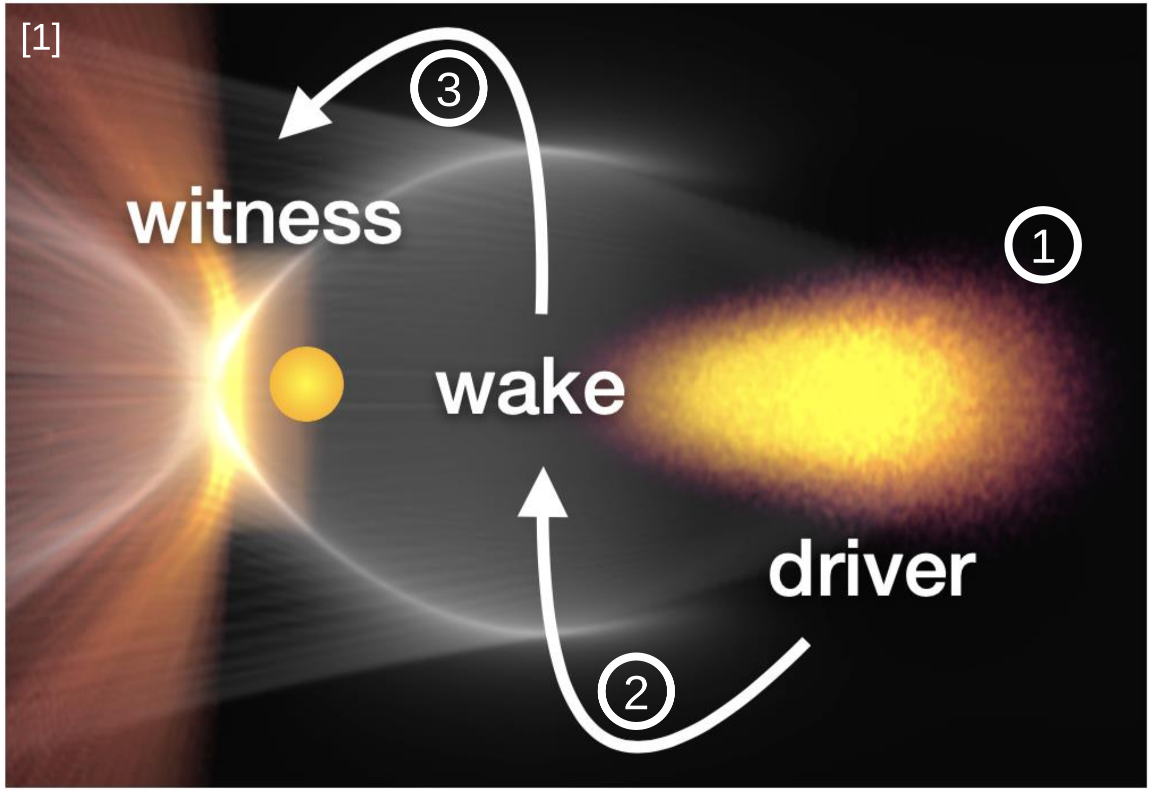


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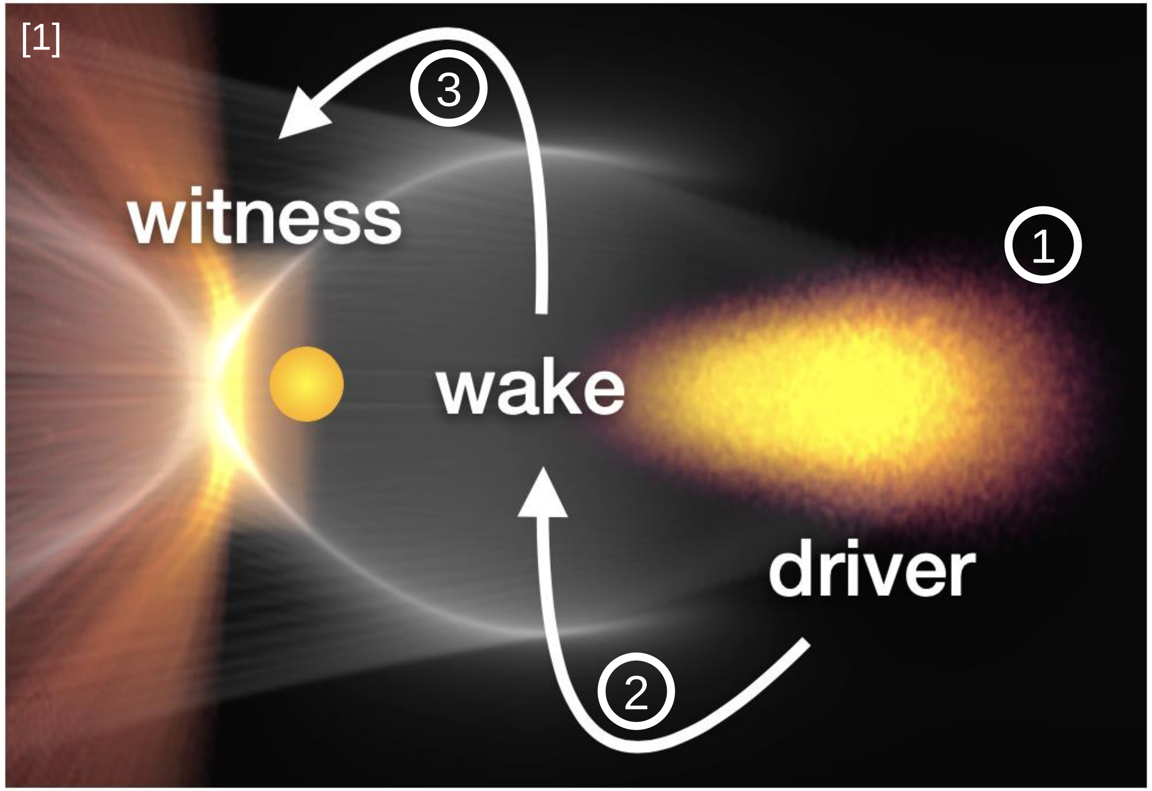
   [5]: η = 42 %





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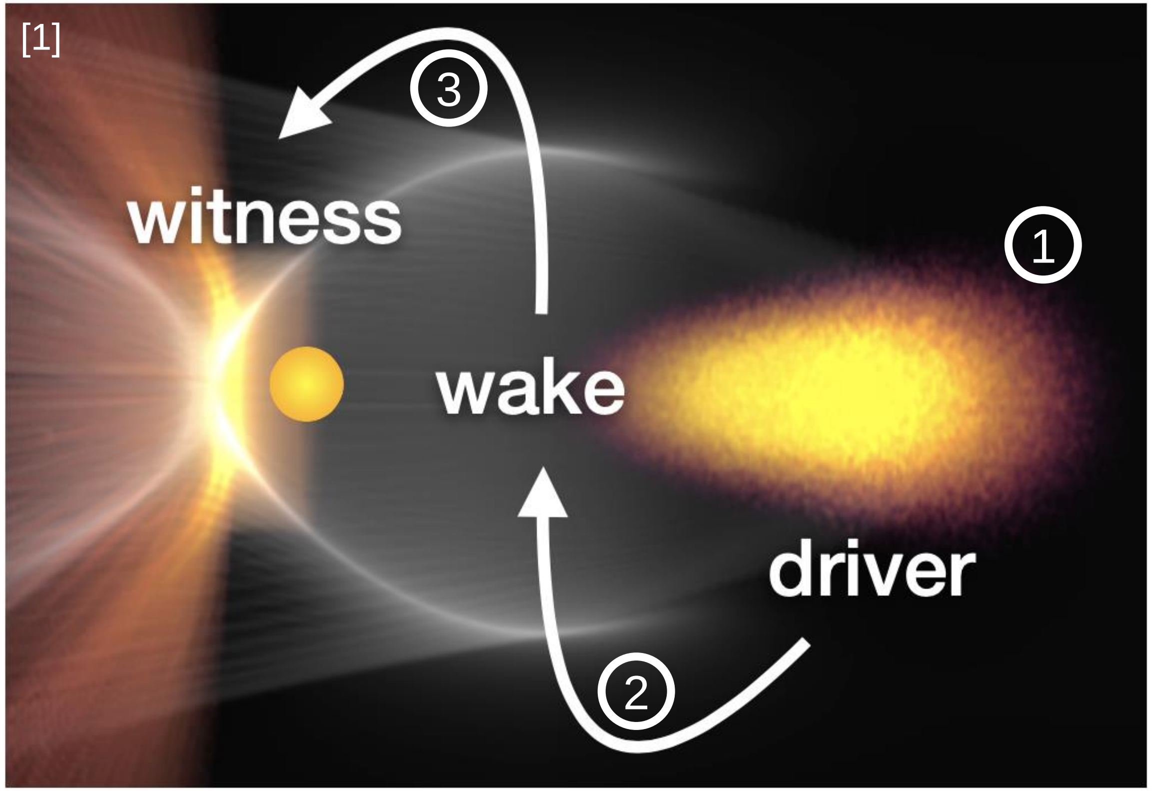


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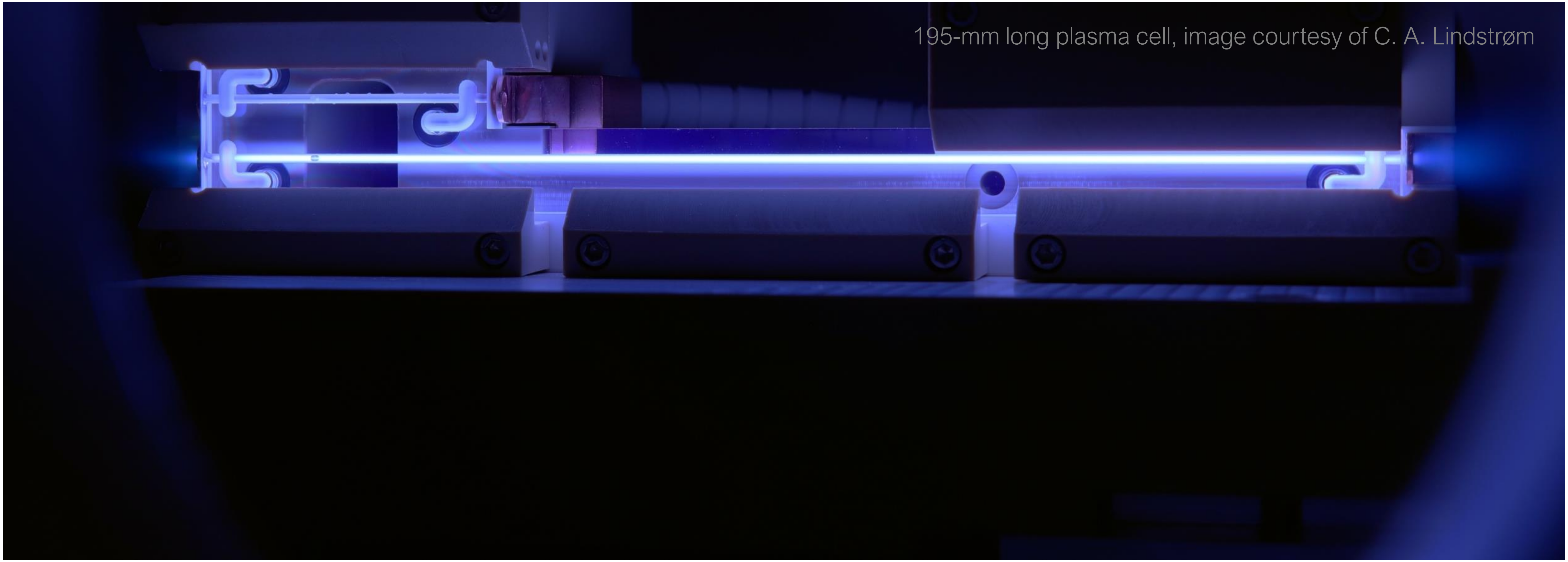
# Electron reacceleration is the limit of depletion

## HiPACE++ simulations show reacceleration of energy depleted electrons



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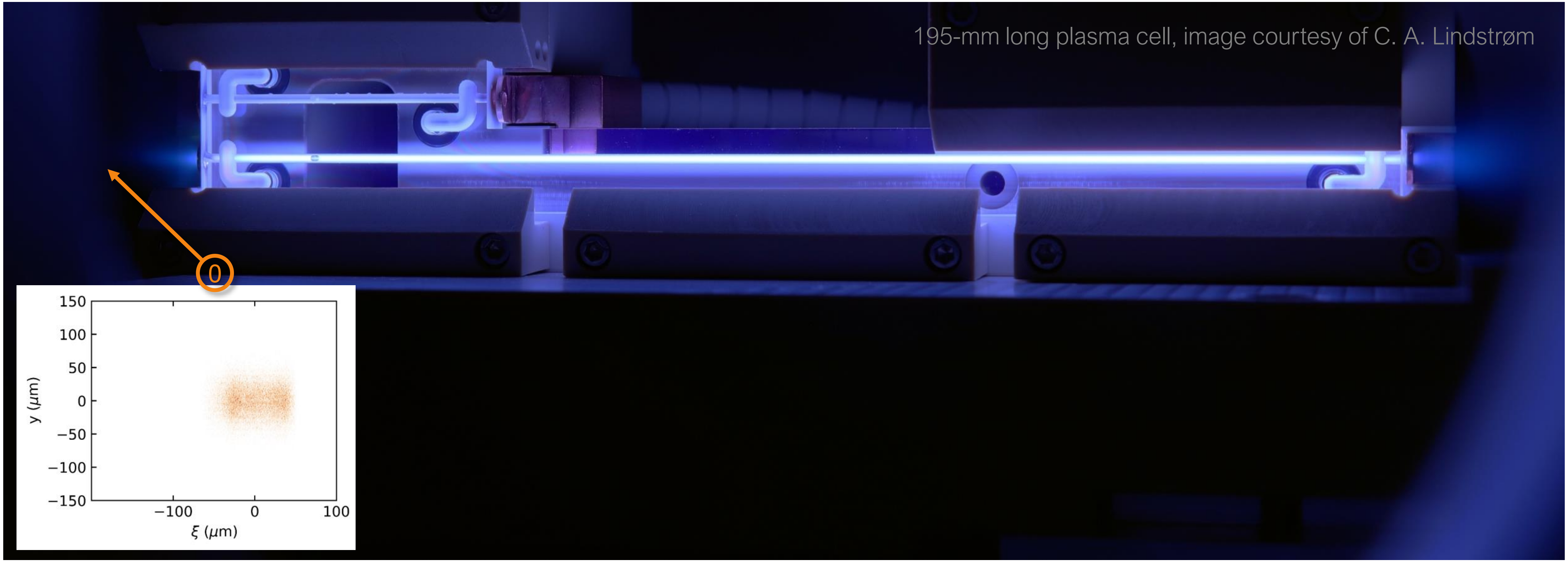

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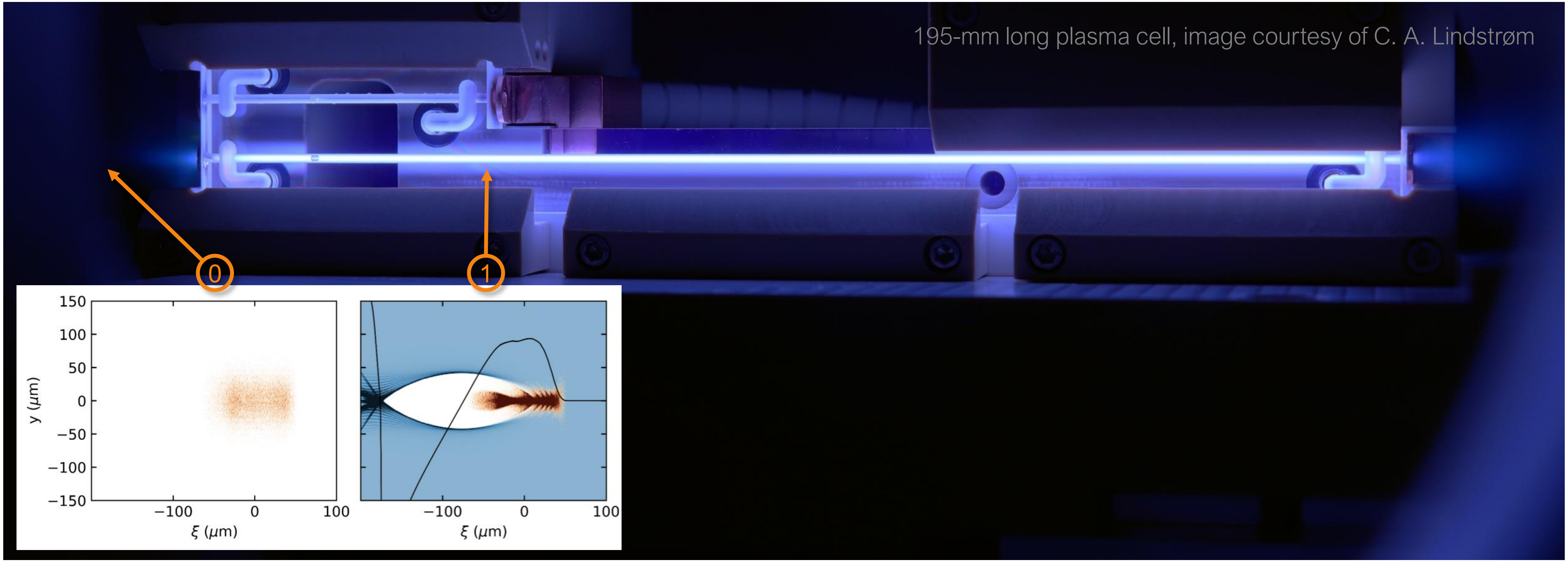

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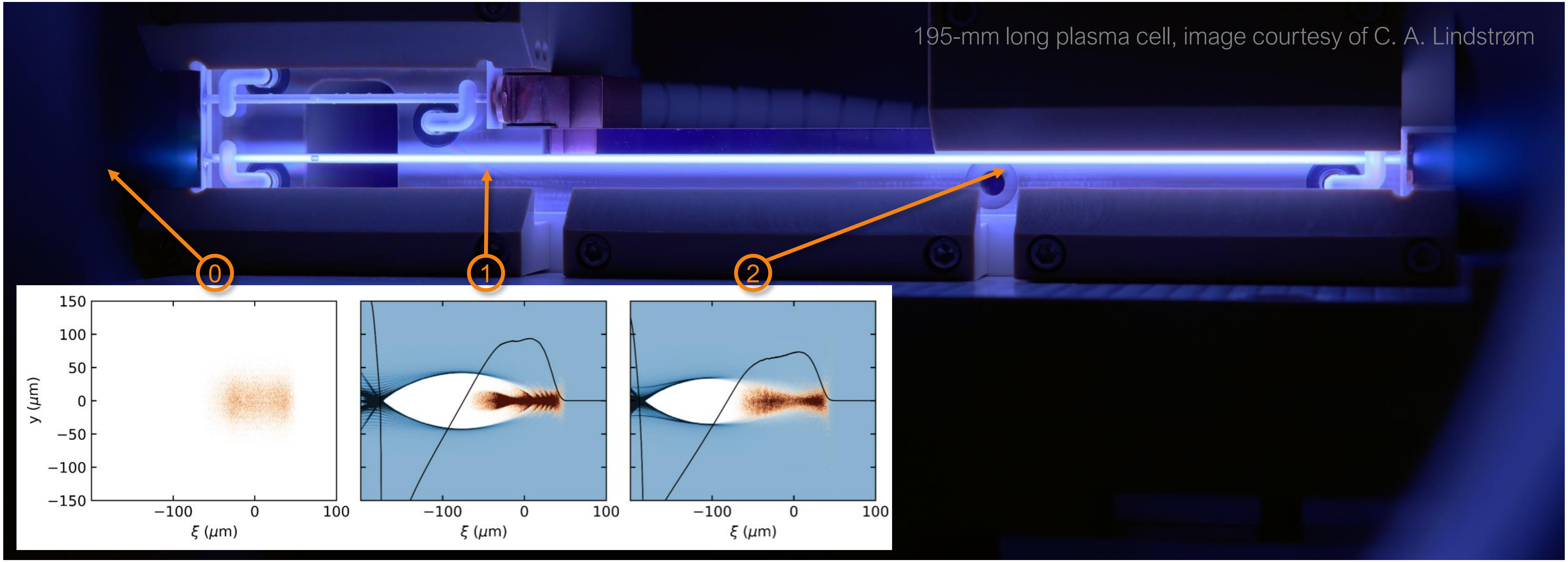

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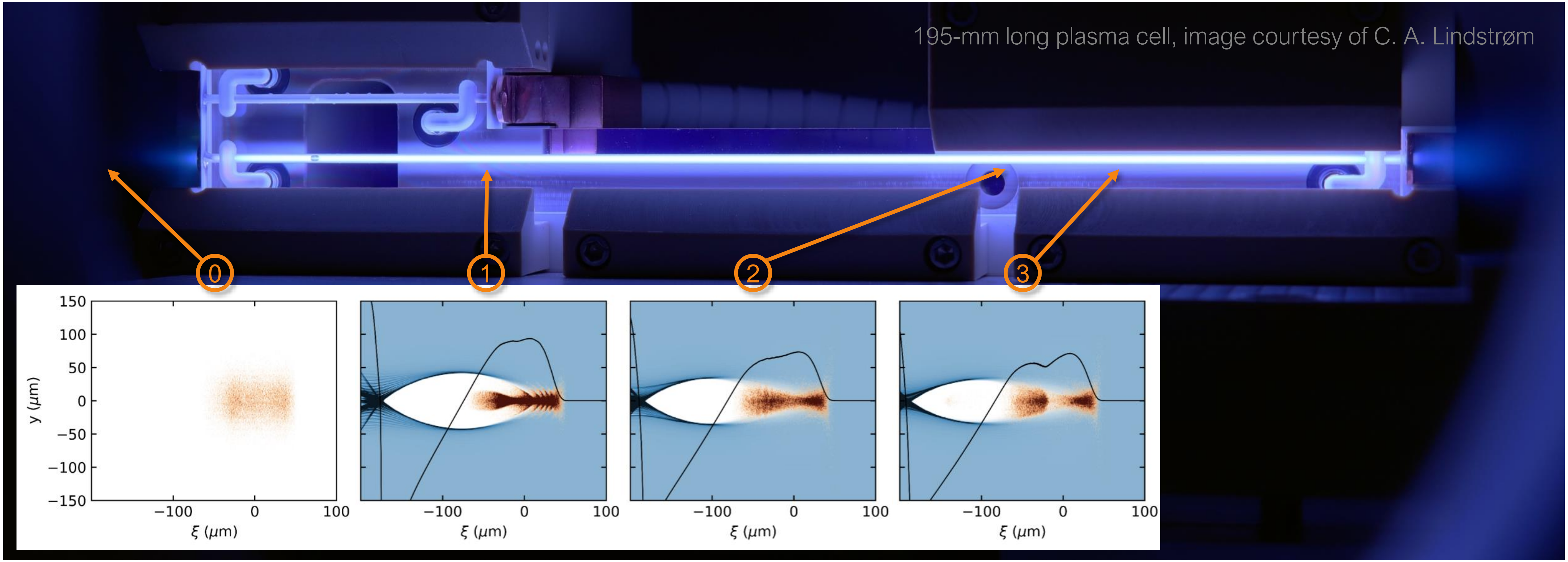

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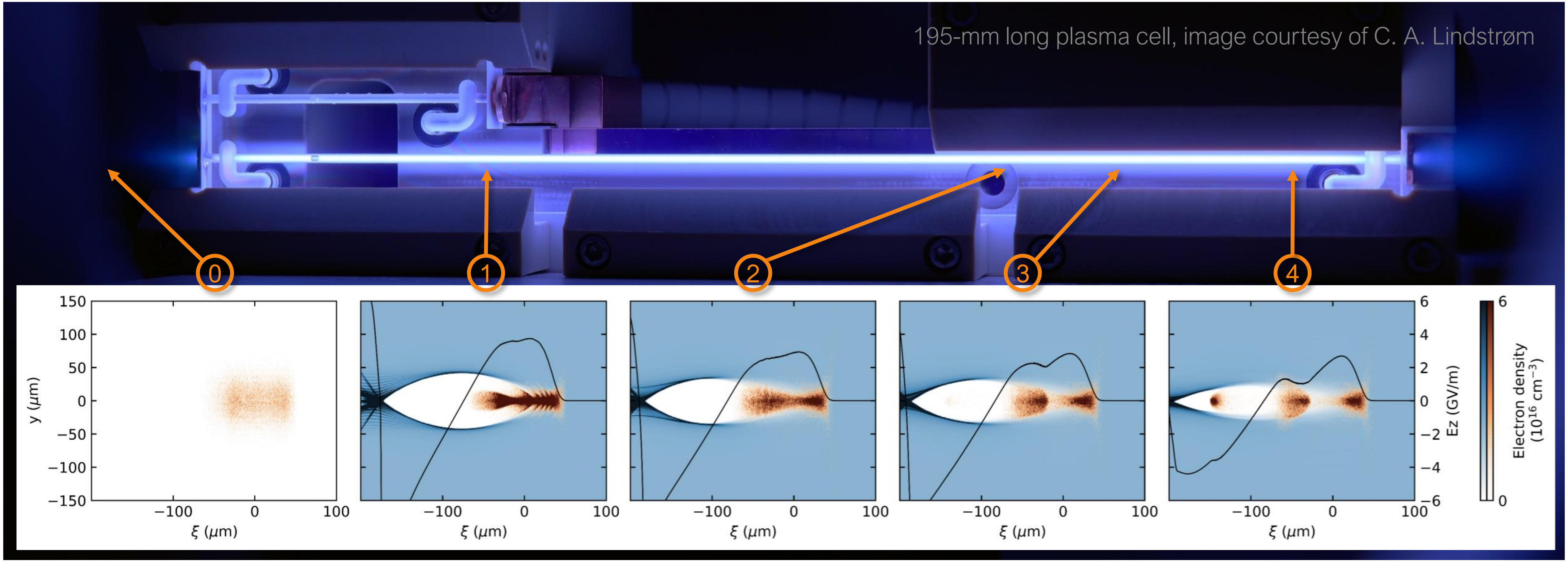
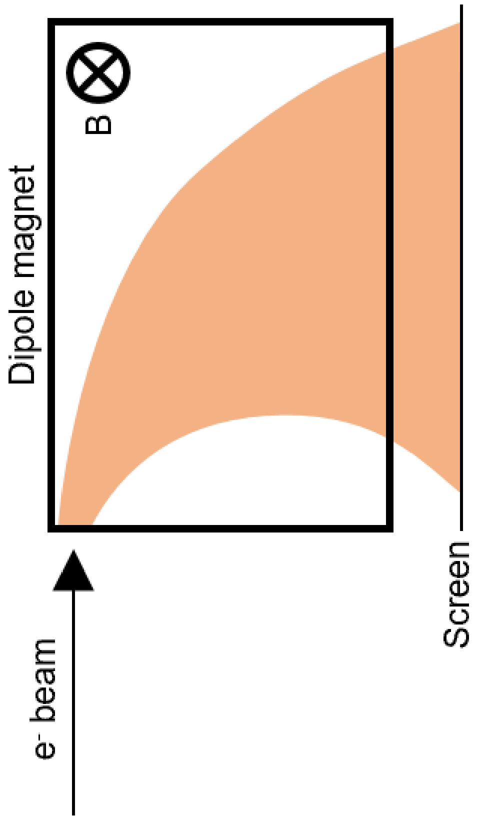


# Energy-depleted electrons are measured down to 2% of the initial energy



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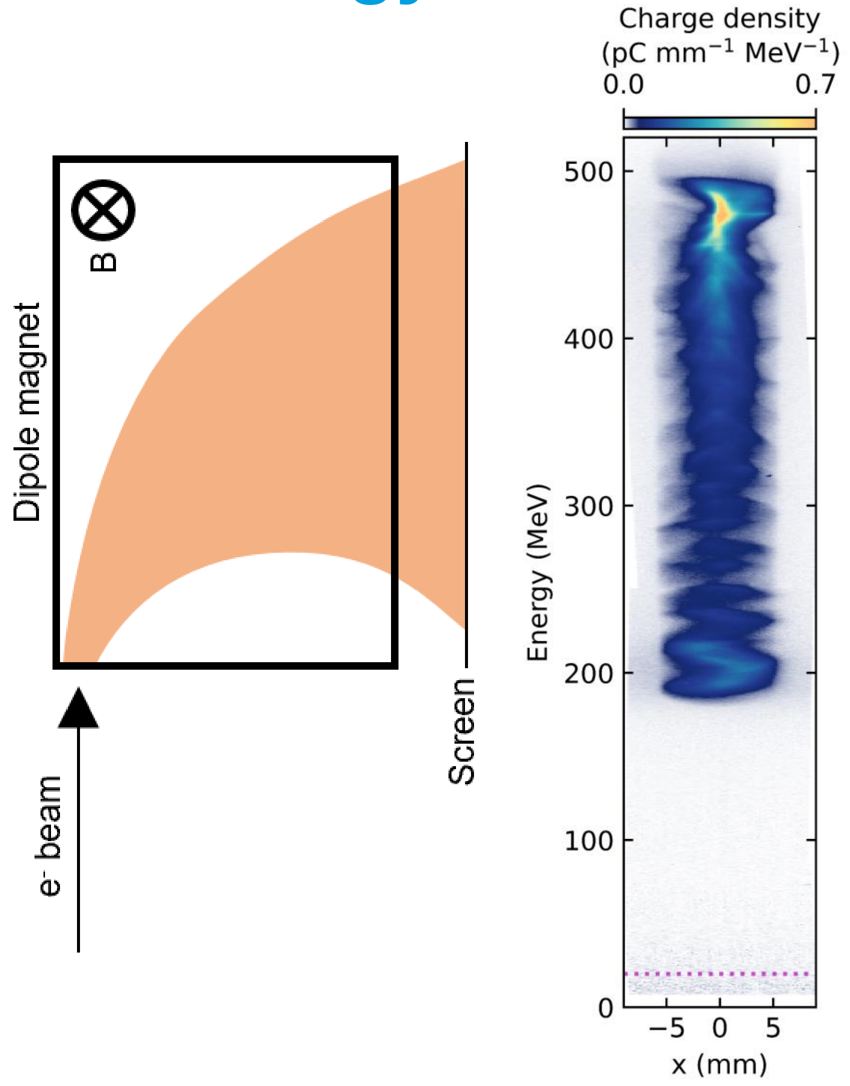

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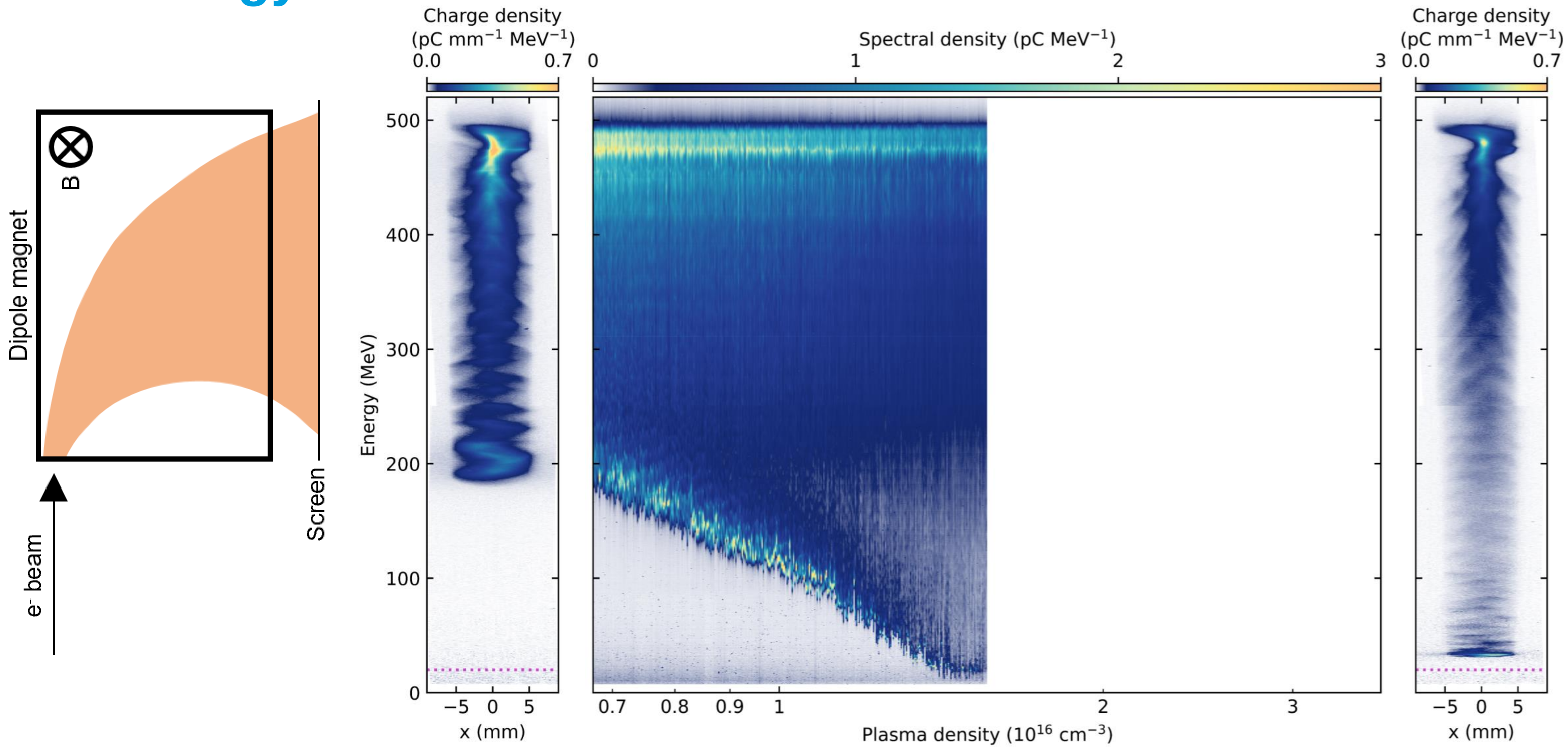

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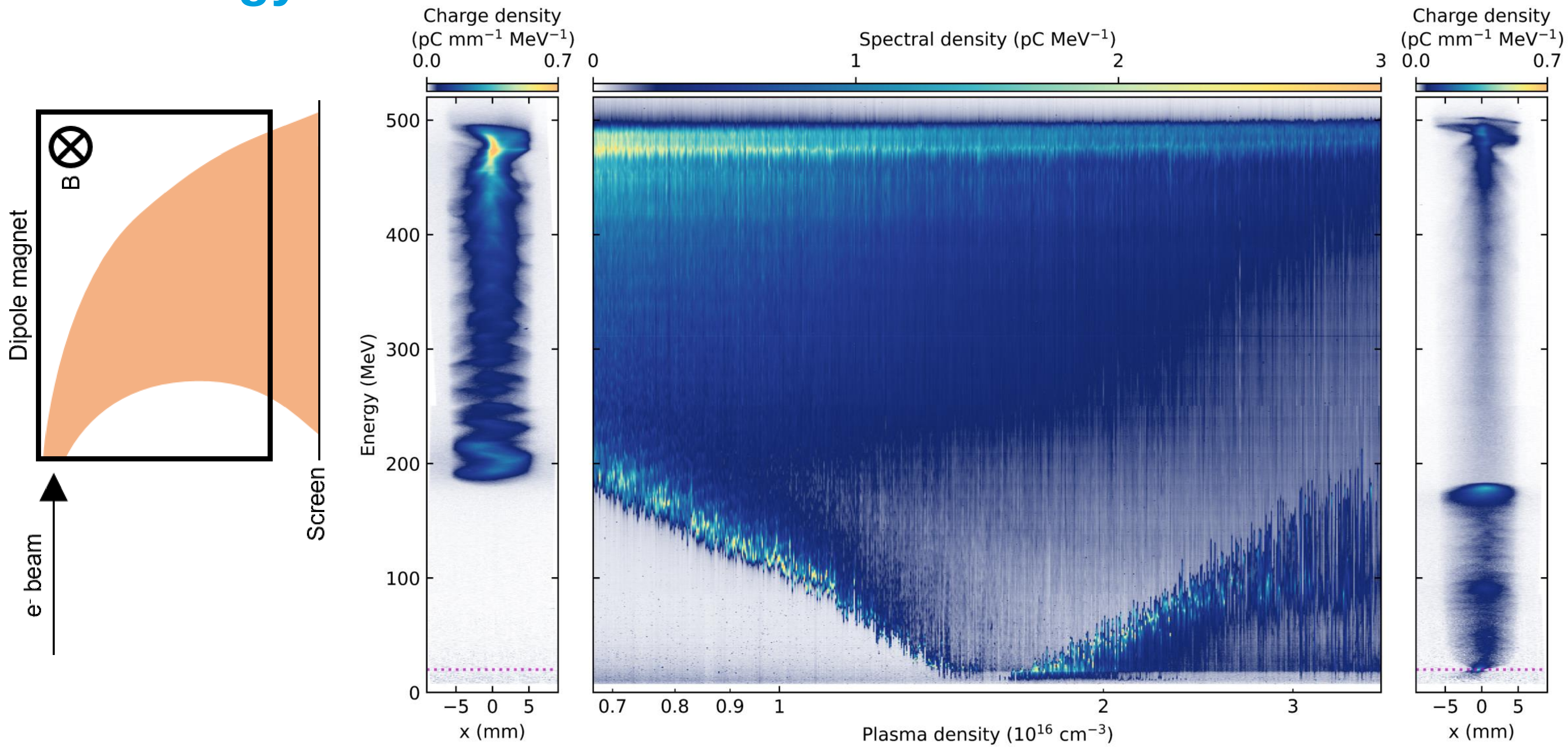

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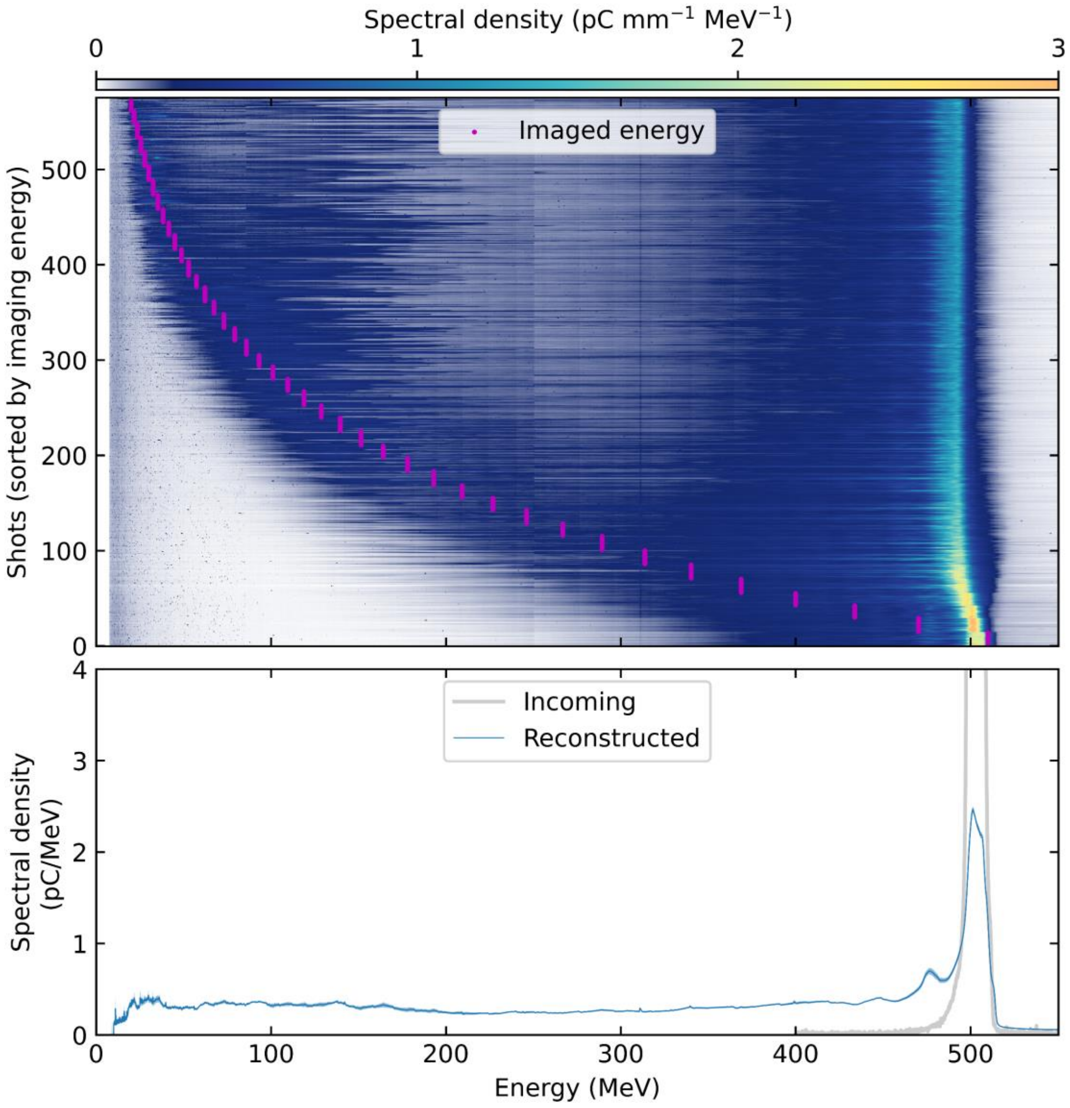

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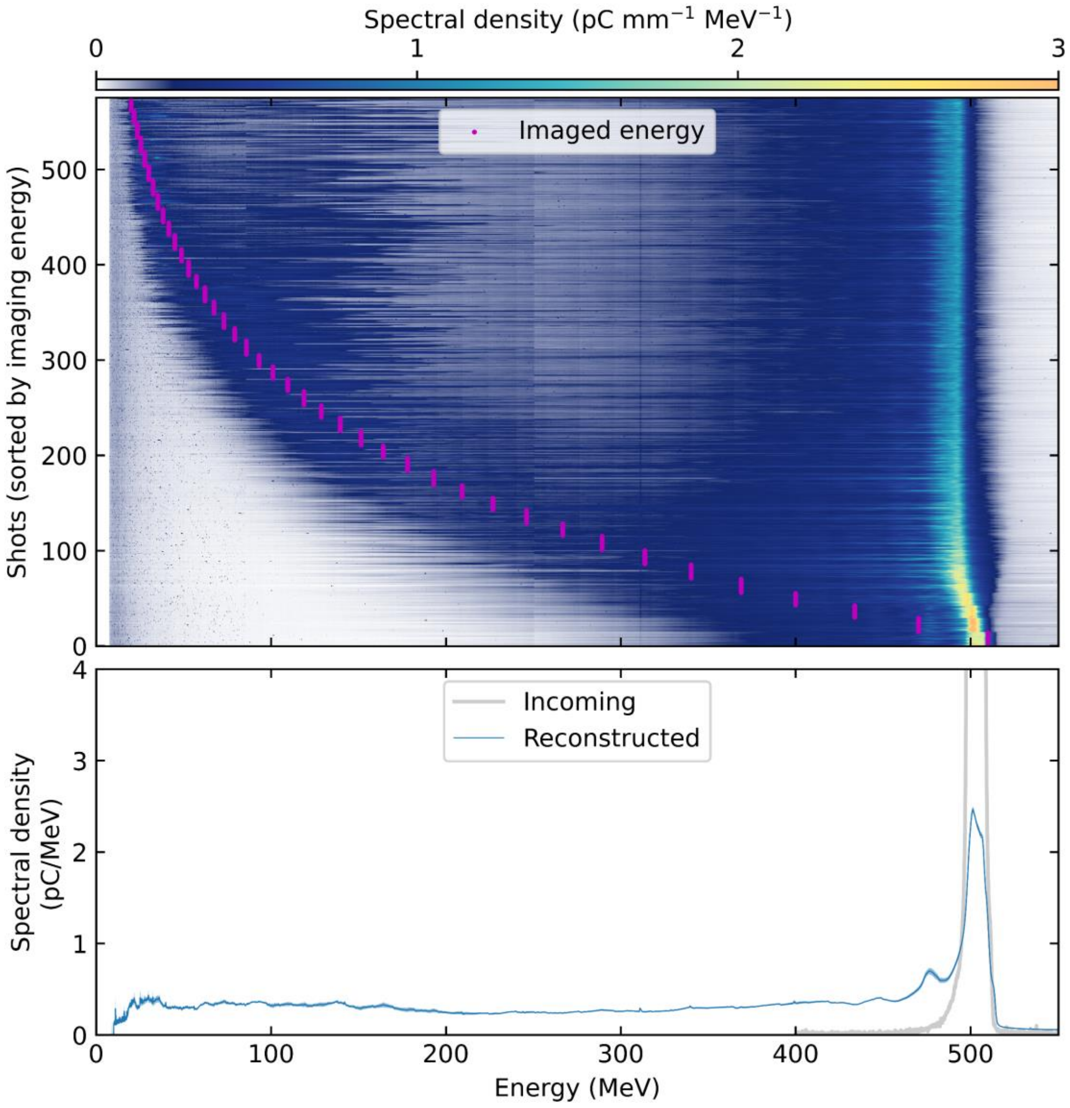


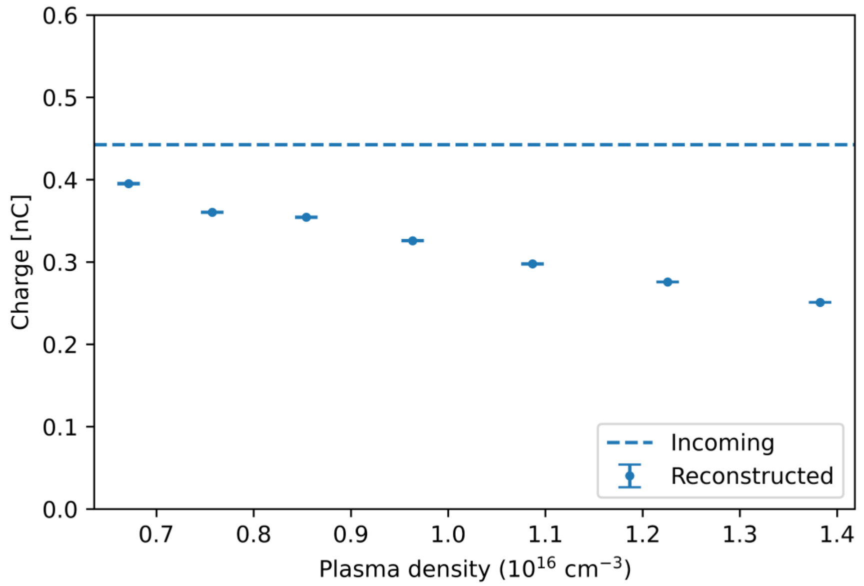

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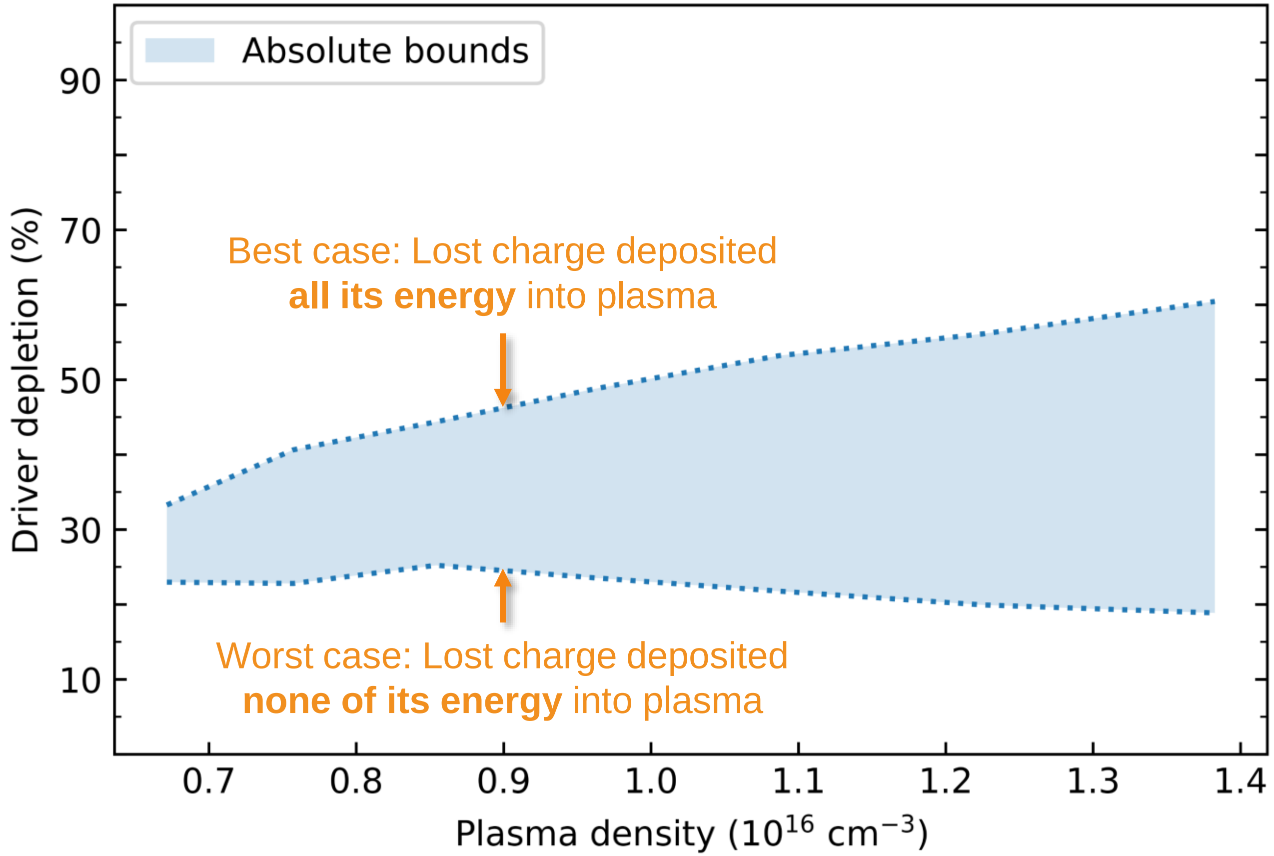


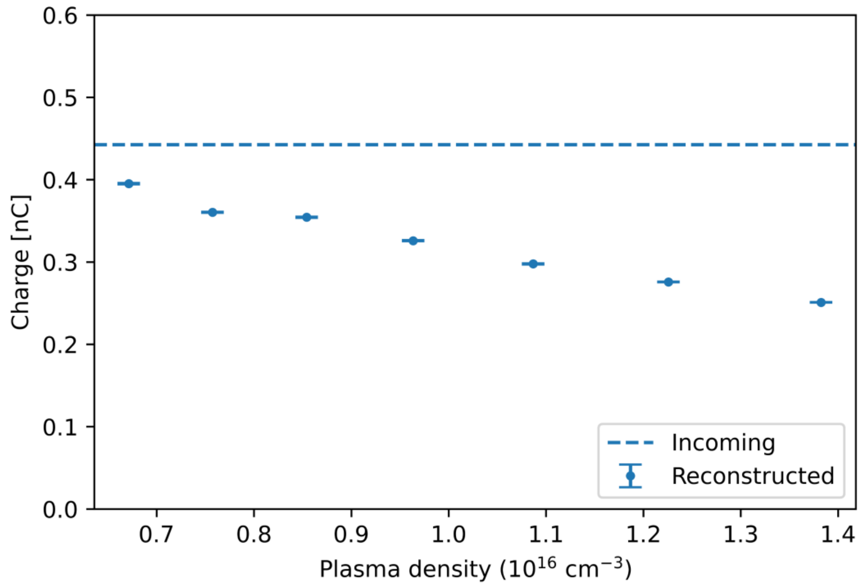

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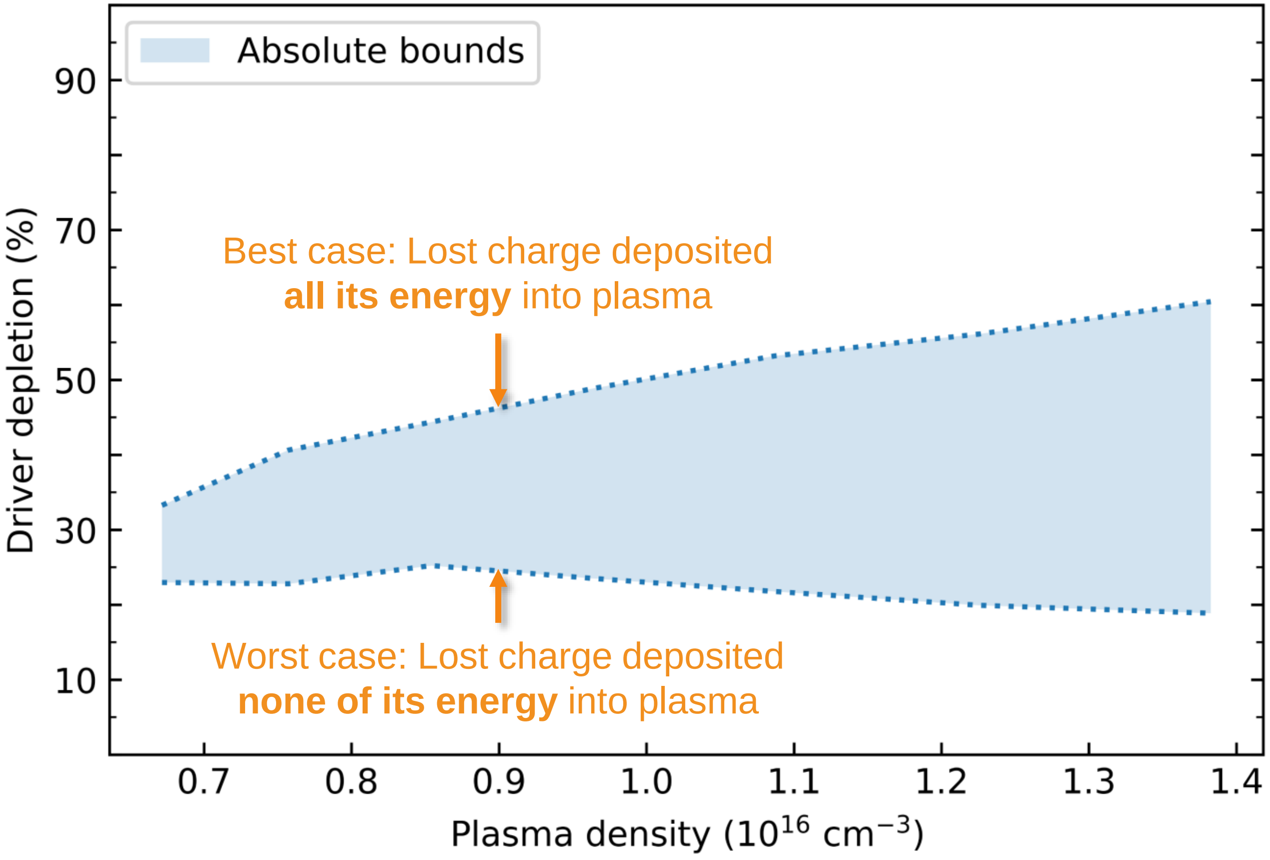
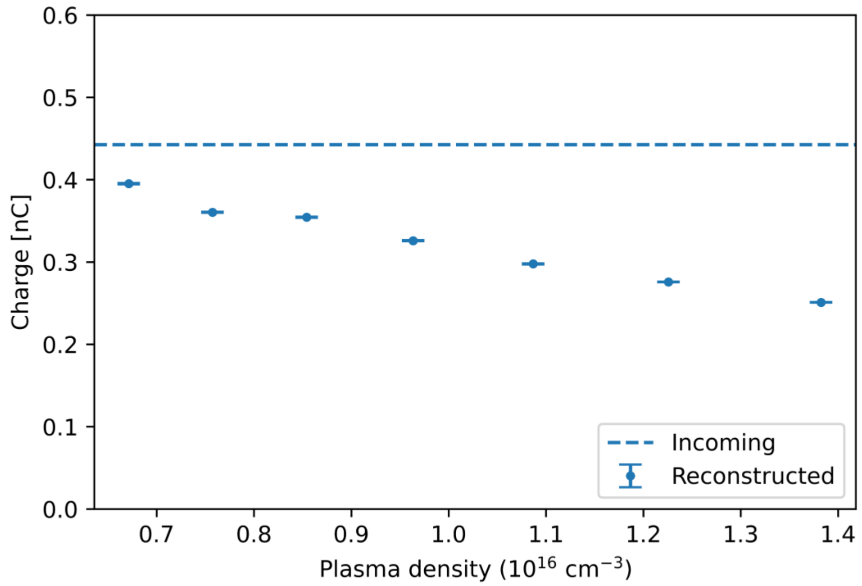
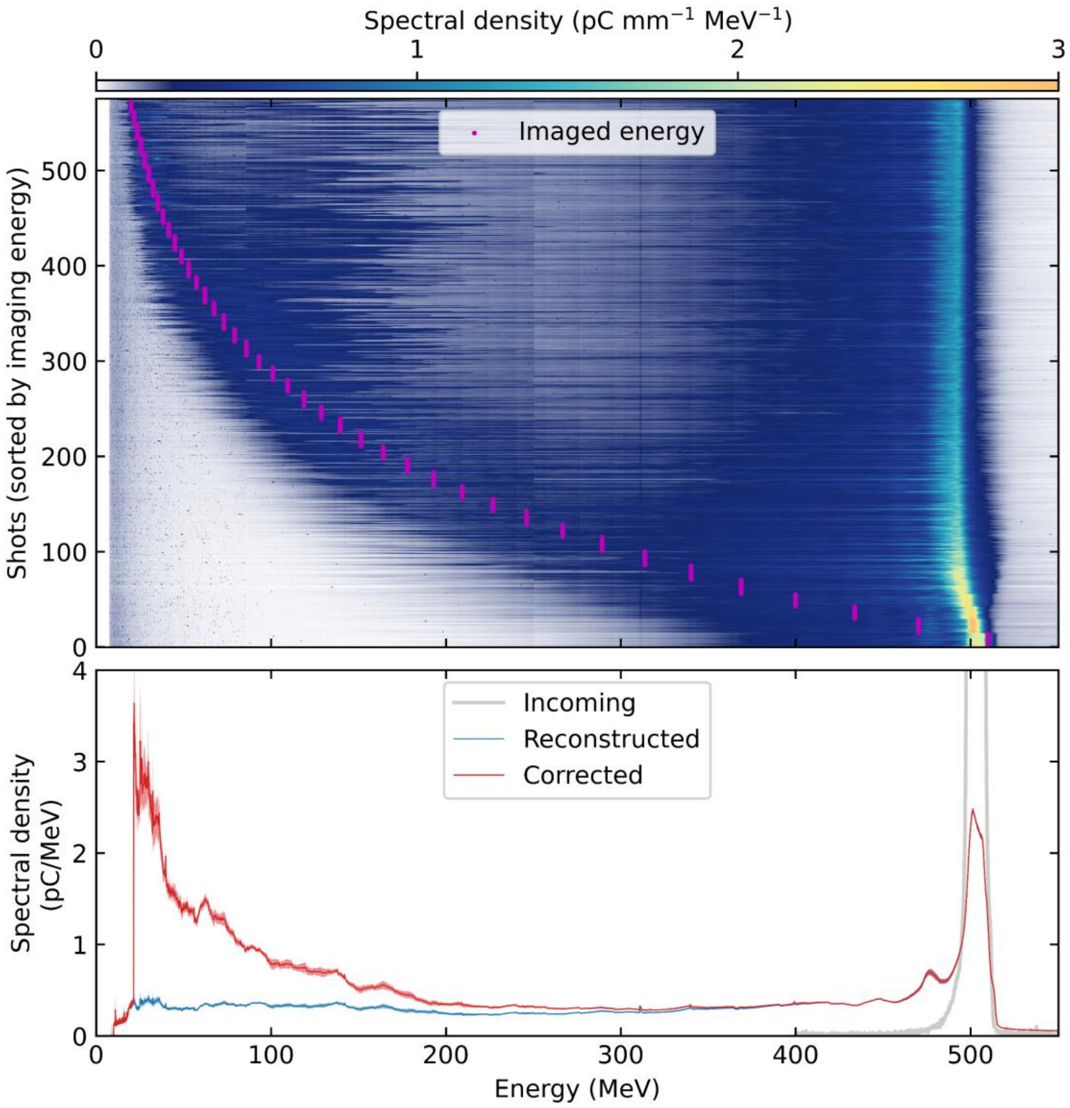



- Simulations show: Charge loss in transport to the diagnostic, **not** in the plasma
- Understand the charge loss
  → construct a model
    → correct the measurement

# Corrected energy spectra are closer to incoming charge

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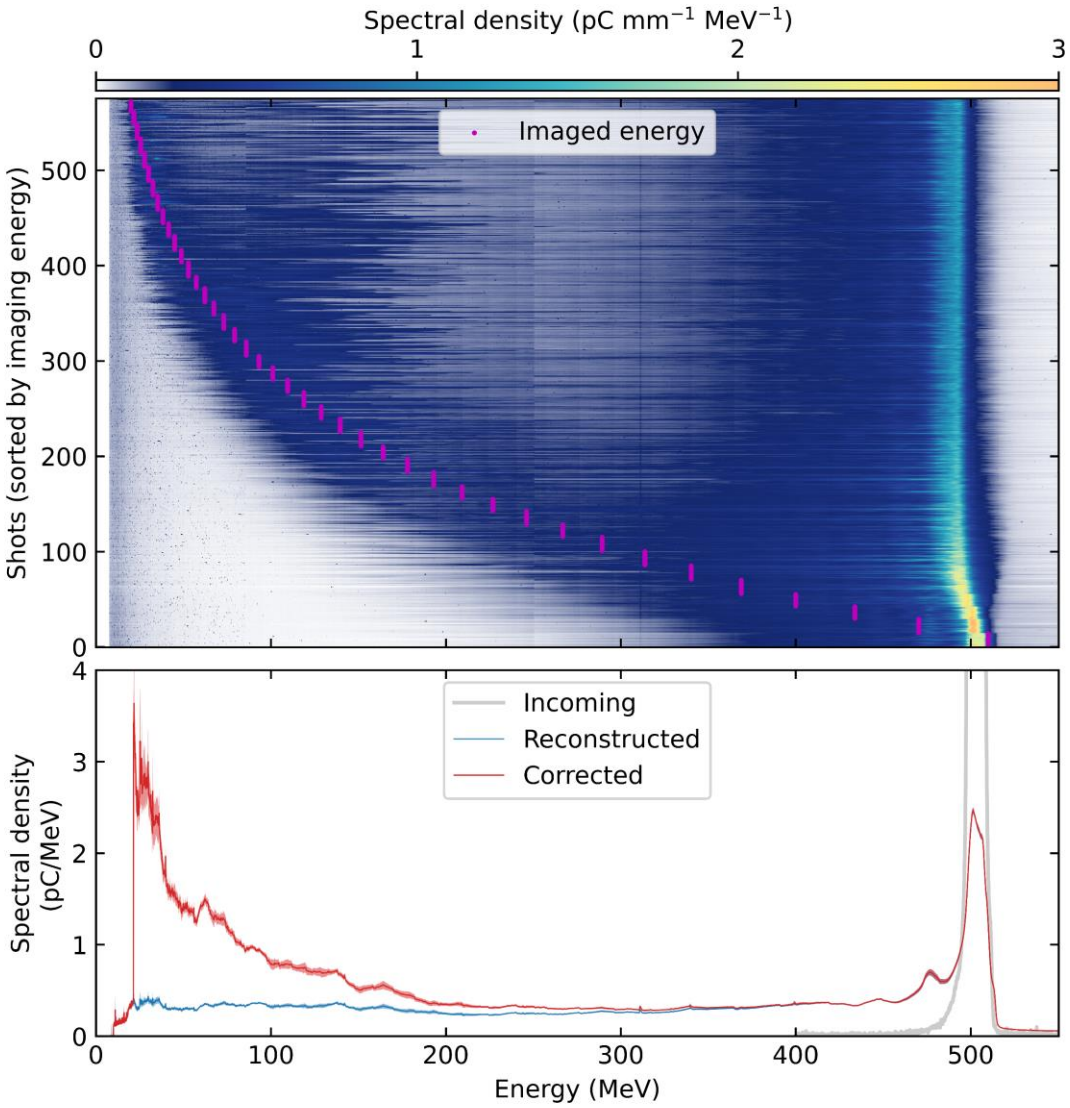


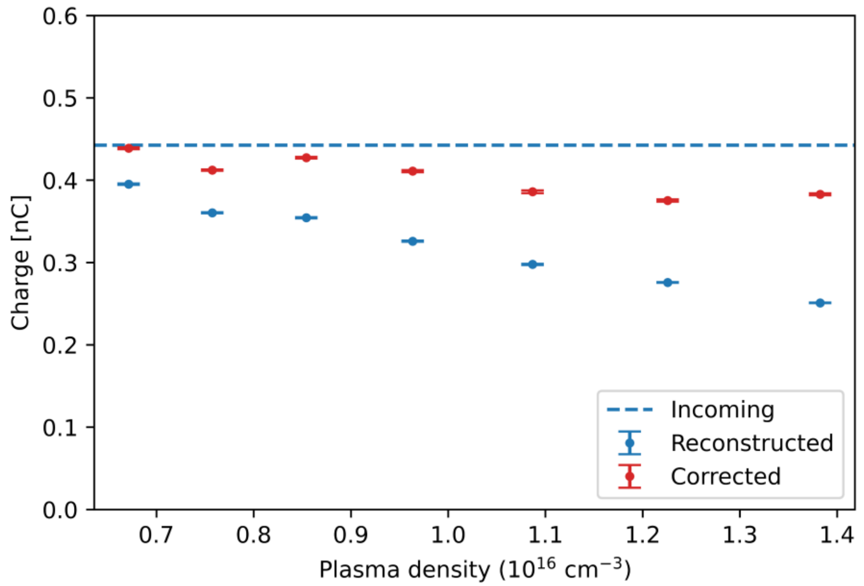


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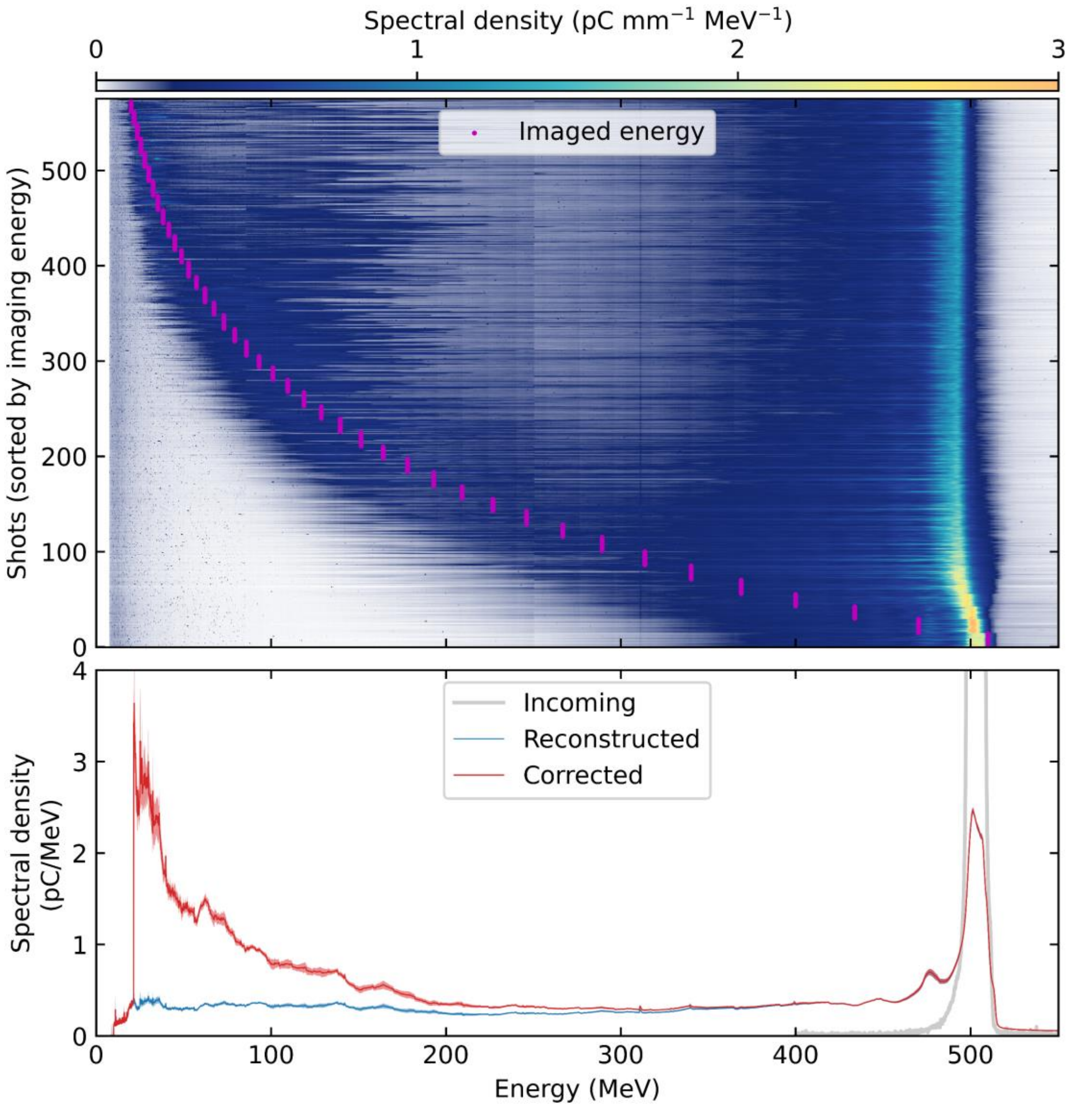


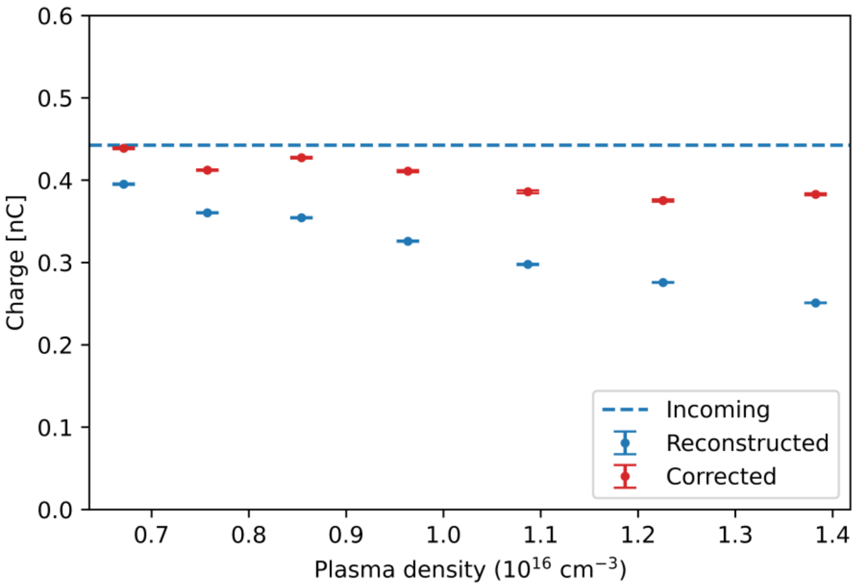


> Simulations show: Charge loss in transport to the diagnostic, **not** in the plasma

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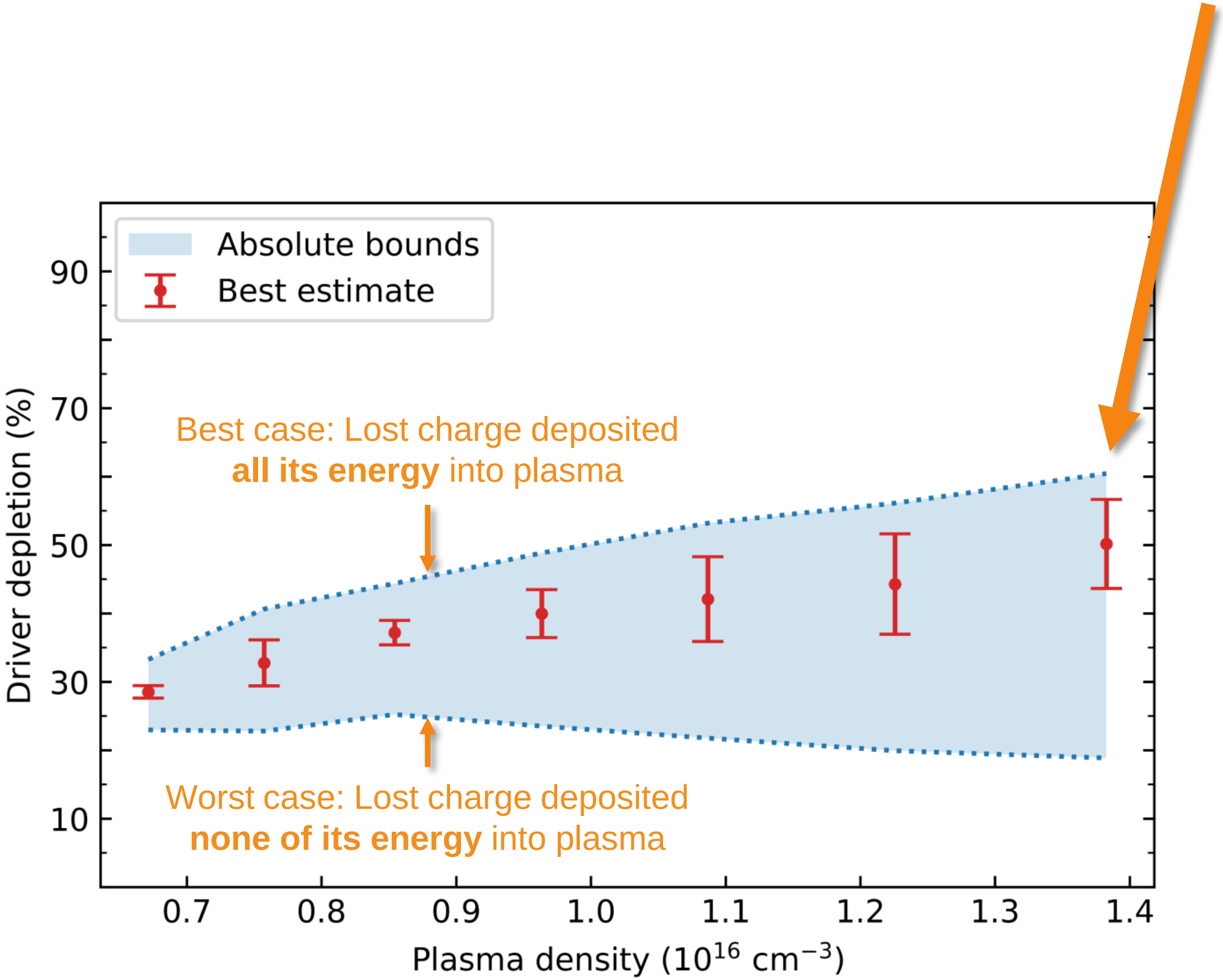
> Model does not include incoming beam angles and approximates long. plasma density ramps

# Drive bunch energy depletion by (50±7) %



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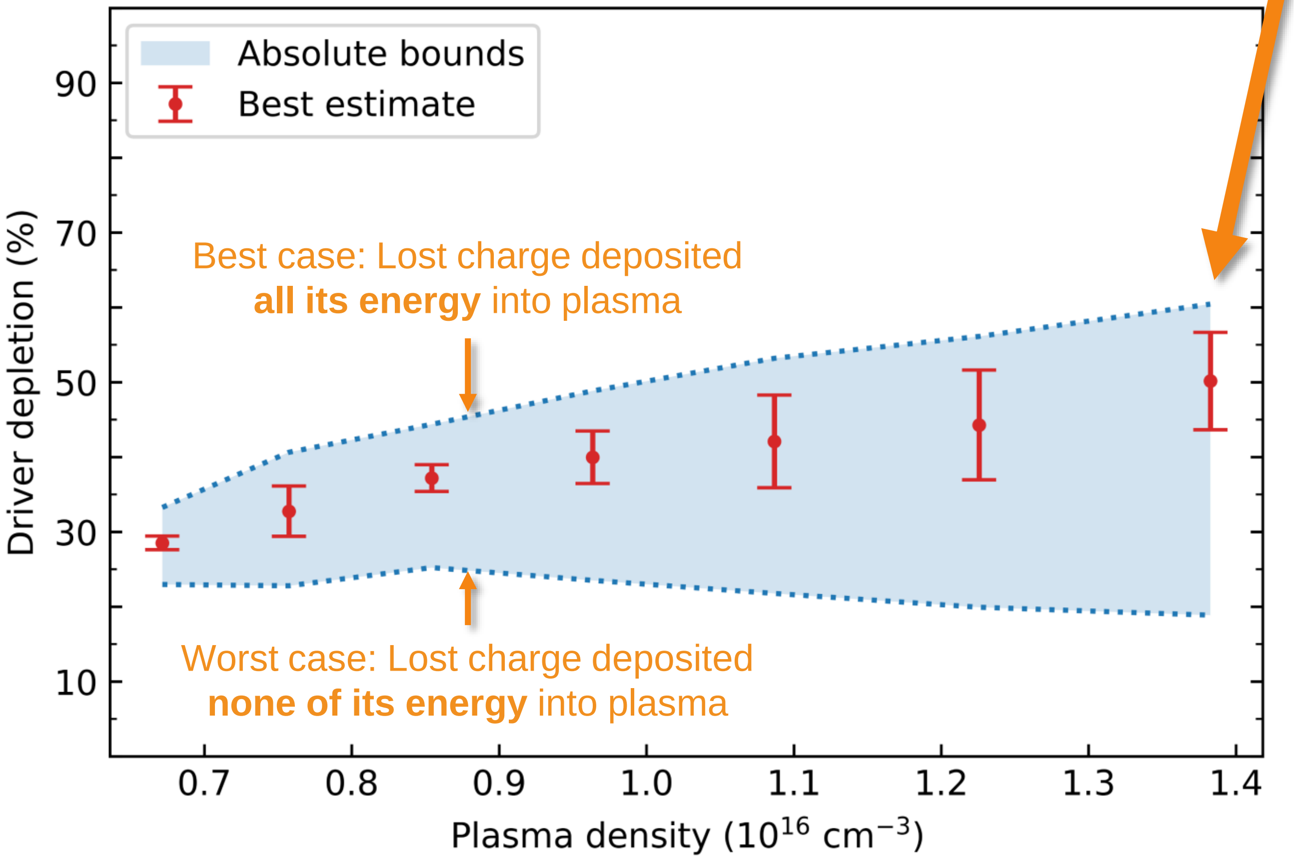



- Uncertainty from
  - Remaining charge loss
  - Statistical error from reconstructed spectrum

# Conclusions

> Electron reacceleration is a limit of overall energy efficiency in beam-driven PWFA

> Drive bunch energy depletion measured up to (50±7) %

# Conclusions

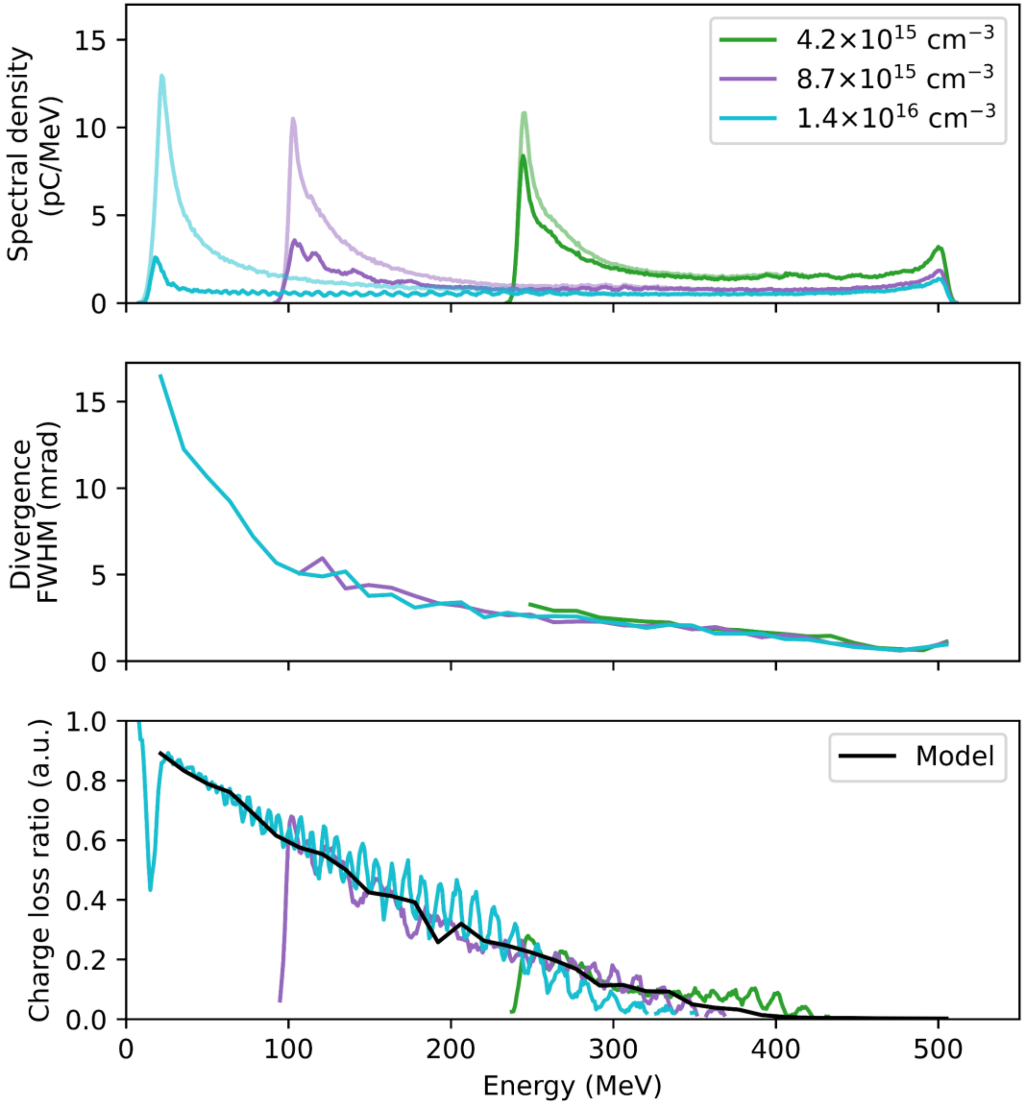
- Electron reacceleration is a limit of overall energy efficiency in beam-driven PWFA
- Drive bunch energy depletion measured up to (50±7) %
- Next steps:
  - Improve depletion by optimizing bunch current [1, 2]
  - Combine all independent record-efficiencies experimentally
    - 55% wall-plug-to-driver [3] · 50% driver-to-wake · 42% wake-to-trailing-bunch [4]

      → **12 % wall-plug-to-trailing-bunch efficiency**

[1] G. Loisch et al., Phys. Rev. Lett. **121**, 064801 (2018)
[2] R. Roussel et al., Phys. Rev. Lett. **124**, 044802 (2020)
[3] M. Aicheler *et al.*, CLIC Conceptual Design Report (2012)
[4] C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126** , 014801 (2021)

# Backup Slides

# Charge loss is only dependent on the energy




Higher charge loss at lower energy

Larger divergence at lower energy

**Charge loss is density independent**

Higher divergence particles clipped in transport

Divergence increase due to:

> Increasing geometric emittance

> Emittance growth from nonlinear fields

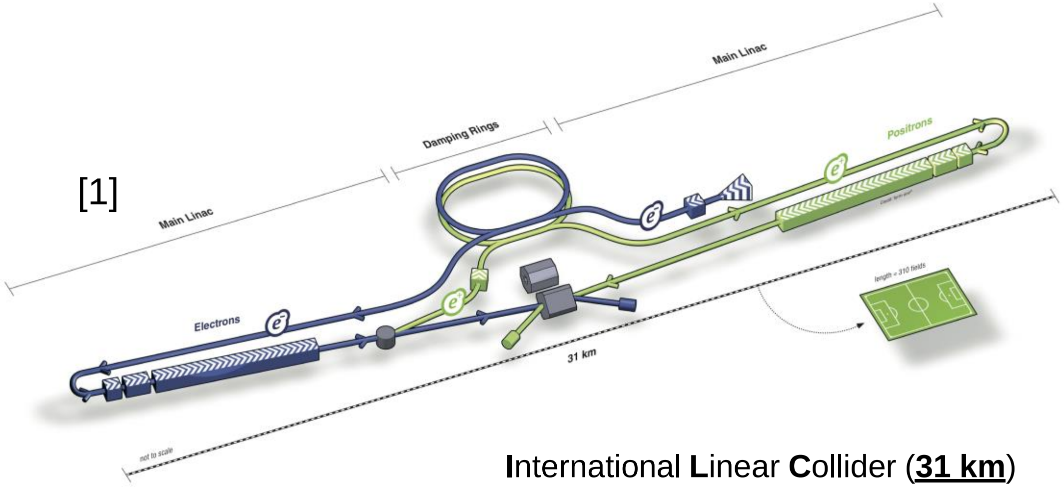
# Plasma-wakefield accelerators promise compactness

- Accelerating gradient
  - State-of-the-art RF accelerators: 100 MV/m
  - Plasma-Wakefield Accelerators: 10 GV/m

- **Construction costs** can be **greatly reduced**

- For high-power beam delivering accelerators:
  - e.g., hard X-ray FELs and colliders
  - Goal: Keep running costs low
    - **High total energy transfer efficiency needed**

[1]




International Linear Collider (**31 km**)

[2]

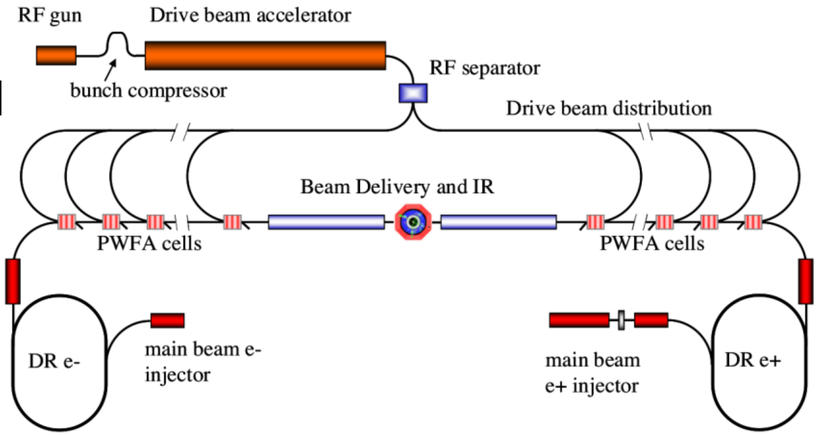
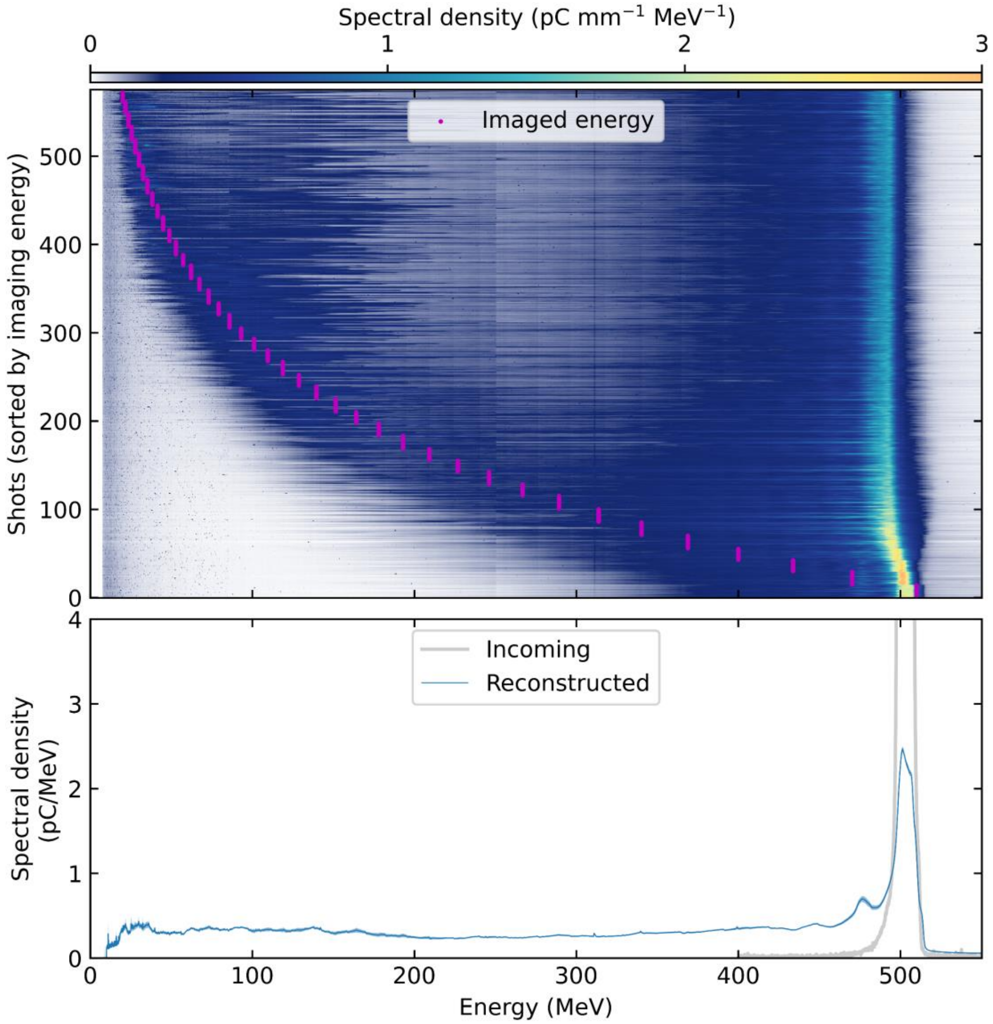
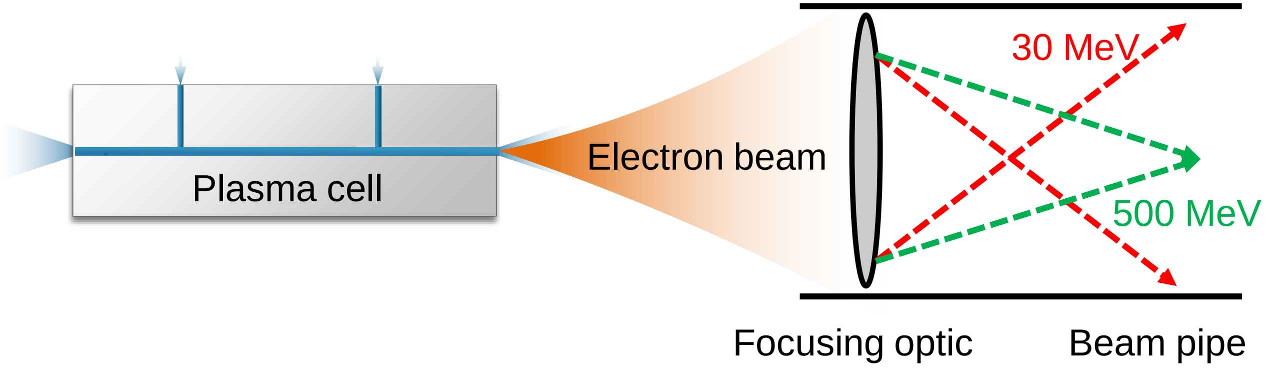



Fig. 1: Concept for a multi-stage PWFA Linear Collider. (**4 km**)


[1] ILC Technical Design Report (2013)
[2] Pei *et al.*, Proc. PAC'09 **p.2682** (2009)

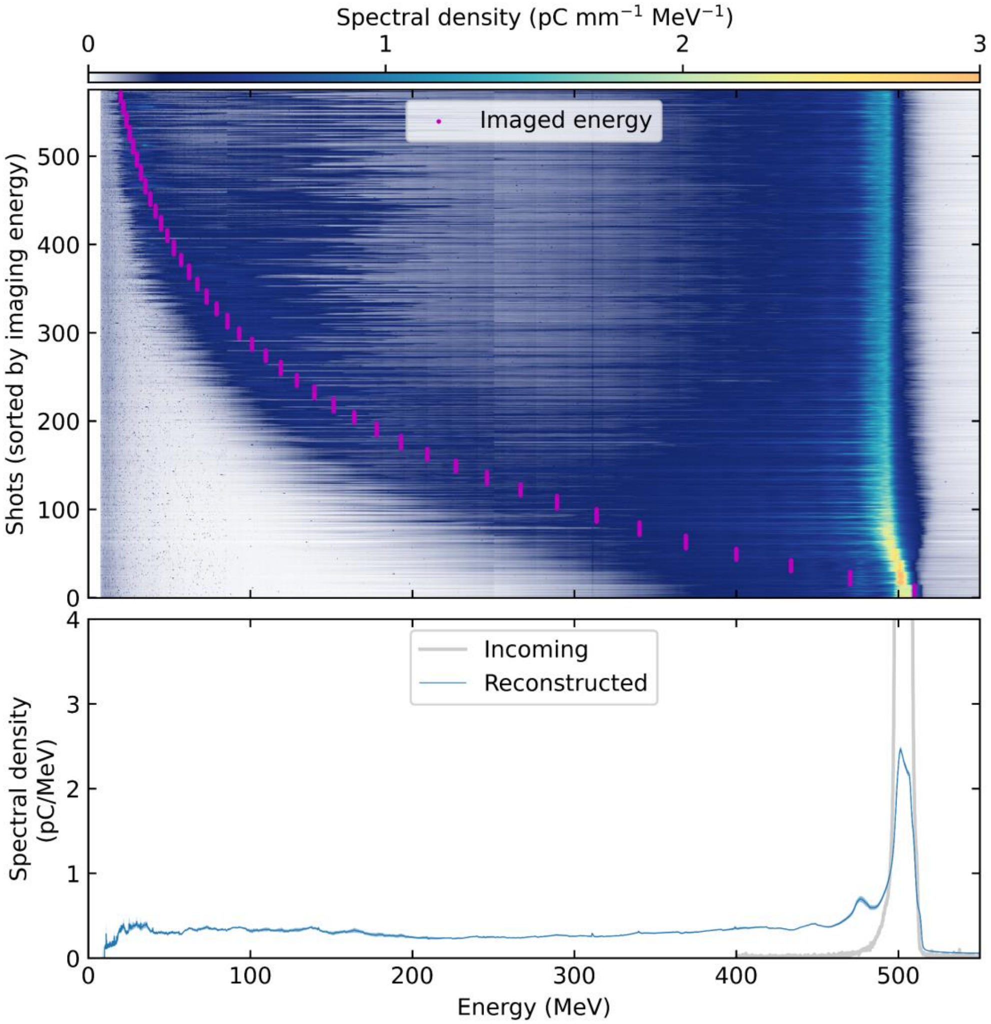
# Spectrum reconstruction is required for accurate measurement

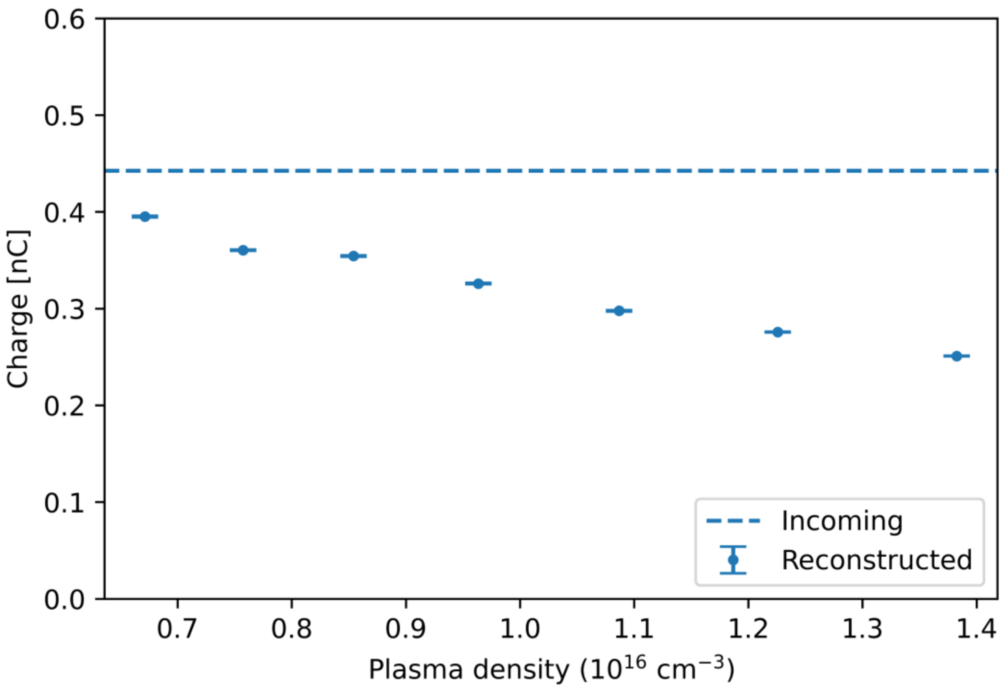


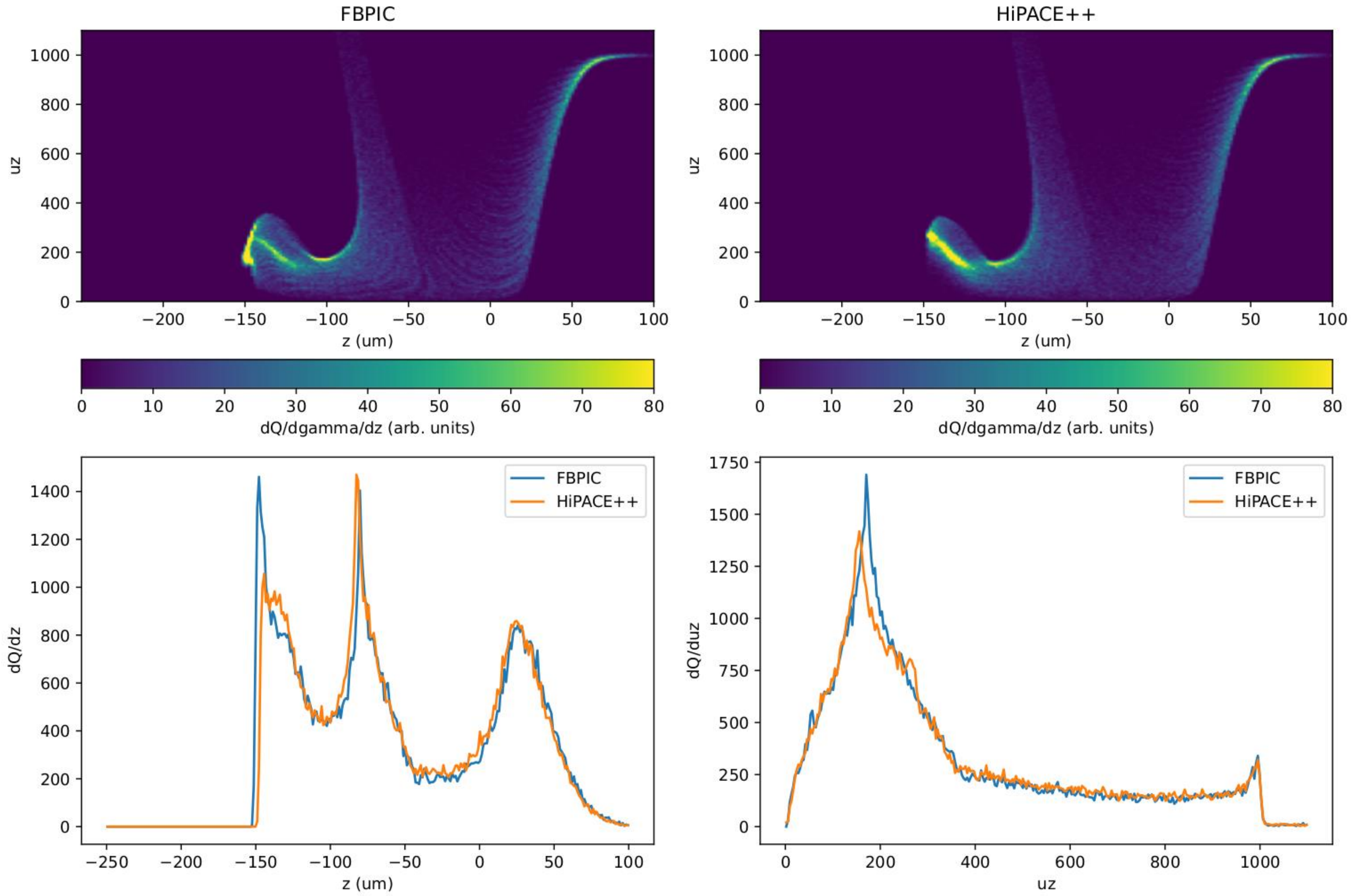

- Imaging energy scan required to reconstruct the 'true' energy spectrum of the beam to counteract charge loss due to under/overfocusing
- Reconstruction **only possible with high stability**

# There is still charge loss when reconstructing the spectrum



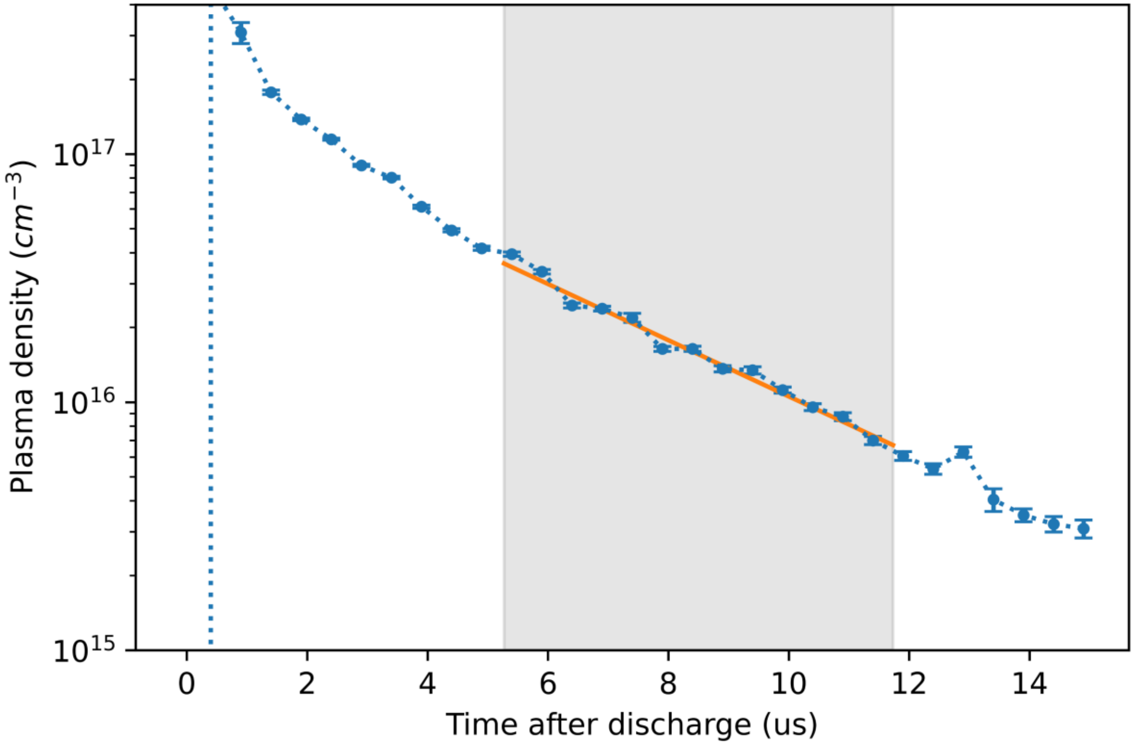
# Quasistatic check



# Plasma density

> Measured with an optical spectrometer averaging radially
>
> - We probably have higher density on axis

> We adjust the density by moving the discharge in time



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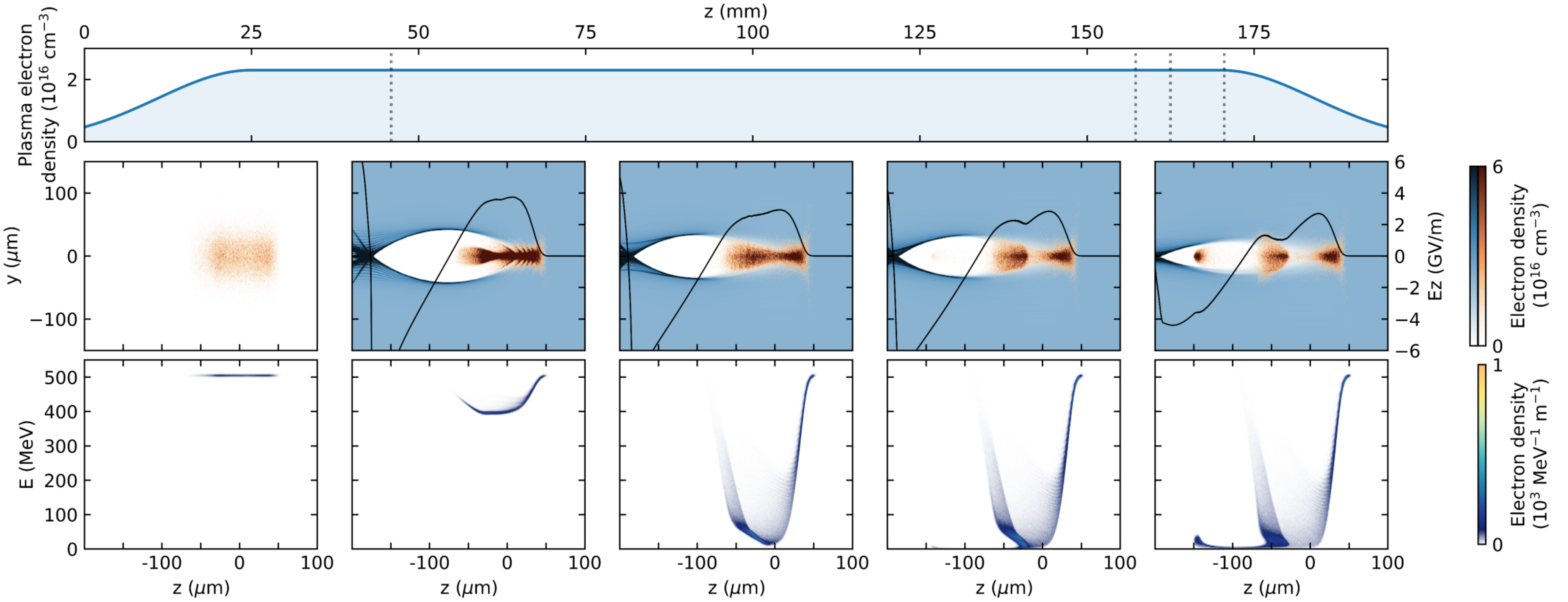
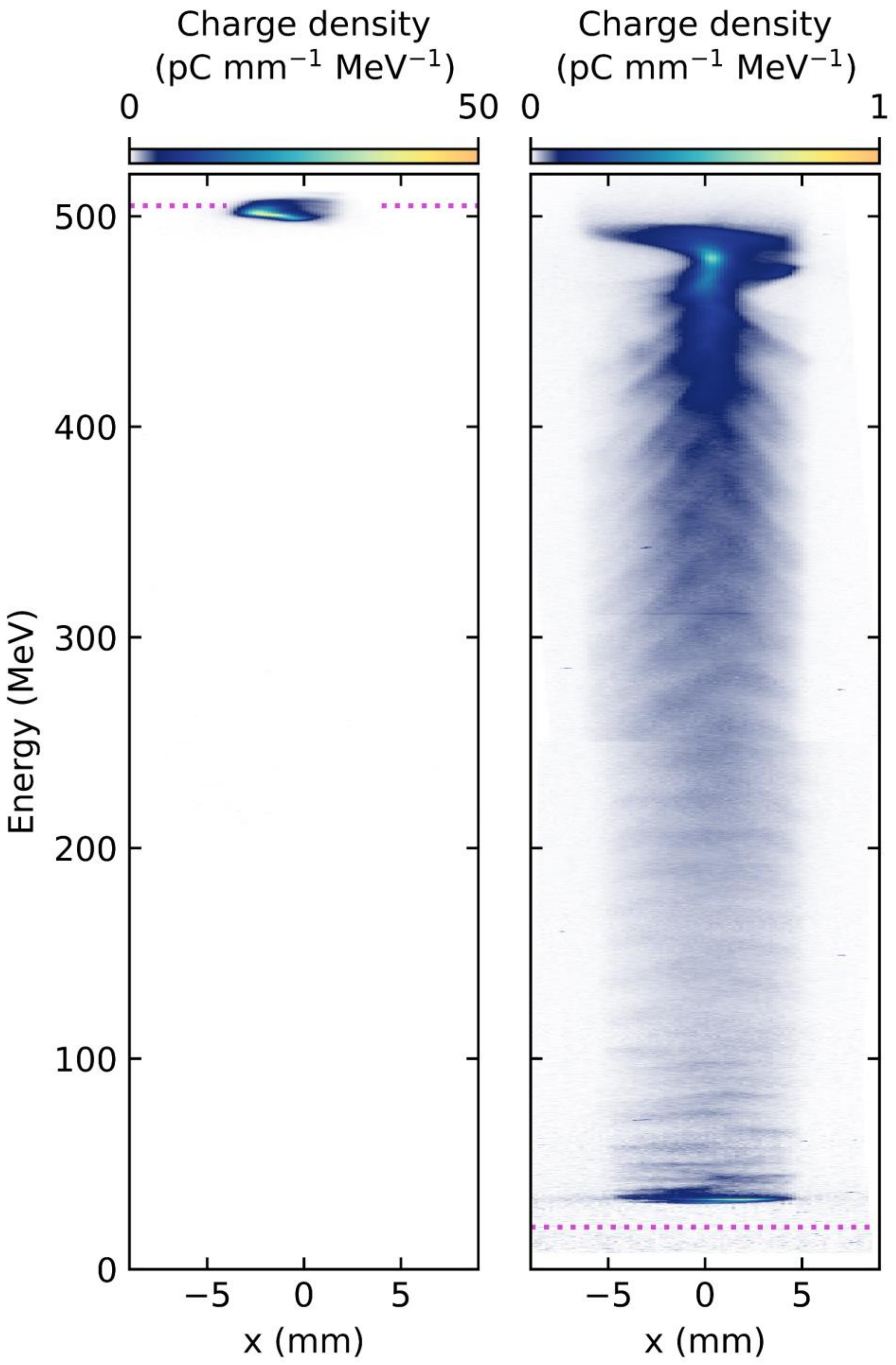


# Sample images



# What is the divergence of the beam?

> With $\beta_m = \beta^* = \frac{\sqrt{2\gamma}}{k_p}$ and $\epsilon_g = \frac{\epsilon_N}{\gamma}$ we can have

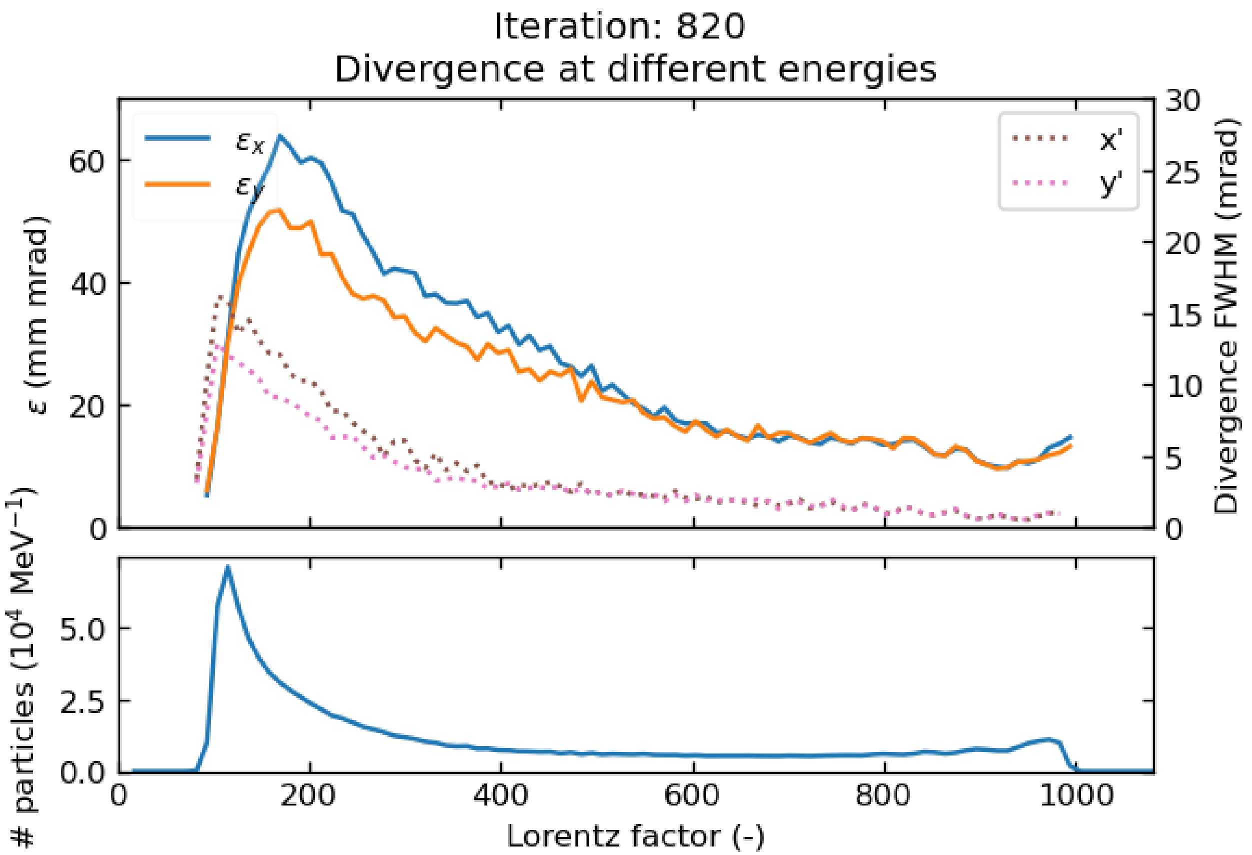
$$\sigma_x'^2 = \frac{\epsilon_g}{\beta^*} = \frac{\epsilon_N}{\gamma}\frac{k_p}{\sqrt{2\gamma}}$$

$$\boxed{\sigma_x' = \sqrt{\frac{\epsilon_N(\gamma)k_p}{\sqrt{2\gamma^3}}}}$$

> Decreasing energy → larger divergence

# Large emittance at low energies → large divergence

$$\sigma'_x = \sqrt{\frac{\epsilon_N(\gamma)k_p}{\sqrt{2\gamma^3}}}$$



# Plasma density

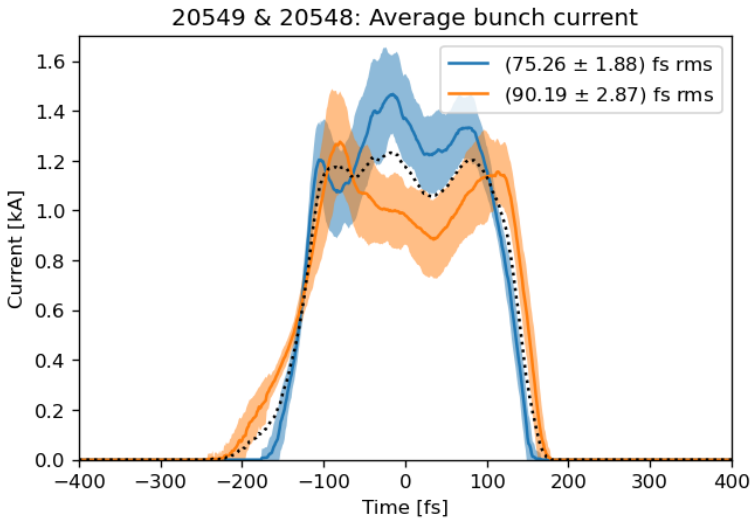
- Our measurement with the optical spectrometer averages radially
    - We probably have higher density on axis, by possibly 50%
- Other diagnostics also hint to higher densities

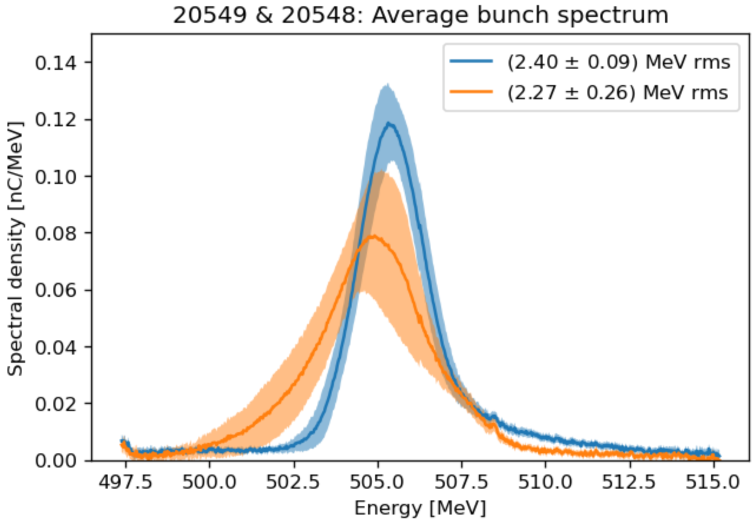
- We use the measured densities + 50%
  - Need to point out the large uncertainty in density

# Measured simulation input parameters

> Beam
  - Beam **current** measured at TDS scaled in charge
  - **Energy** & **energy spread** at TDS
  - **Twiss parameters** measured with 2-BPM tomography
  - Incoming **charge** (BPM)

> **Plasma** density
  - Flattop **density** from optical spectrometer
  - Long. **density profile** shape from previous experience



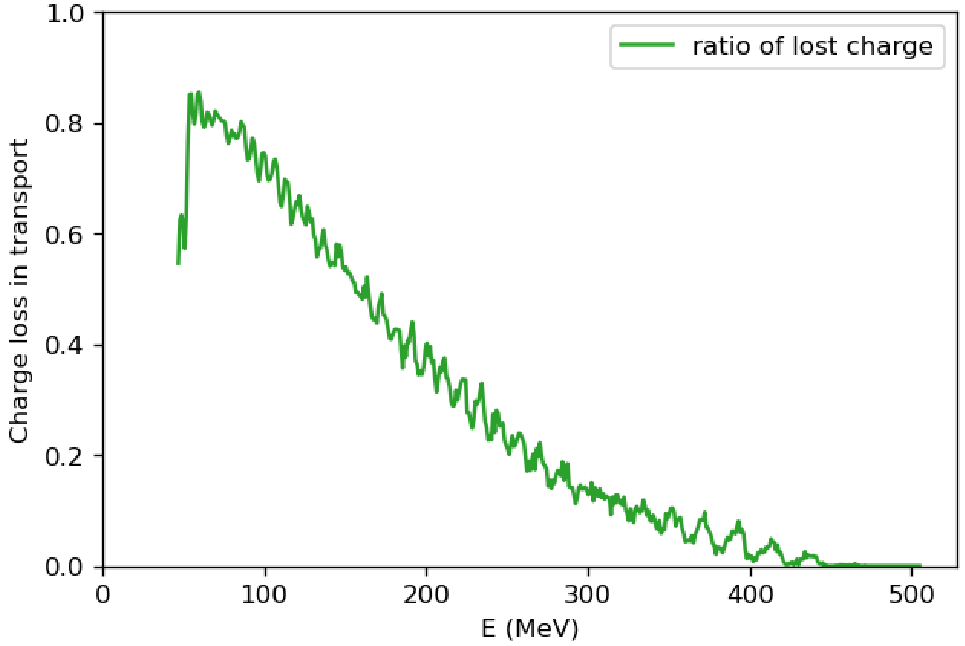



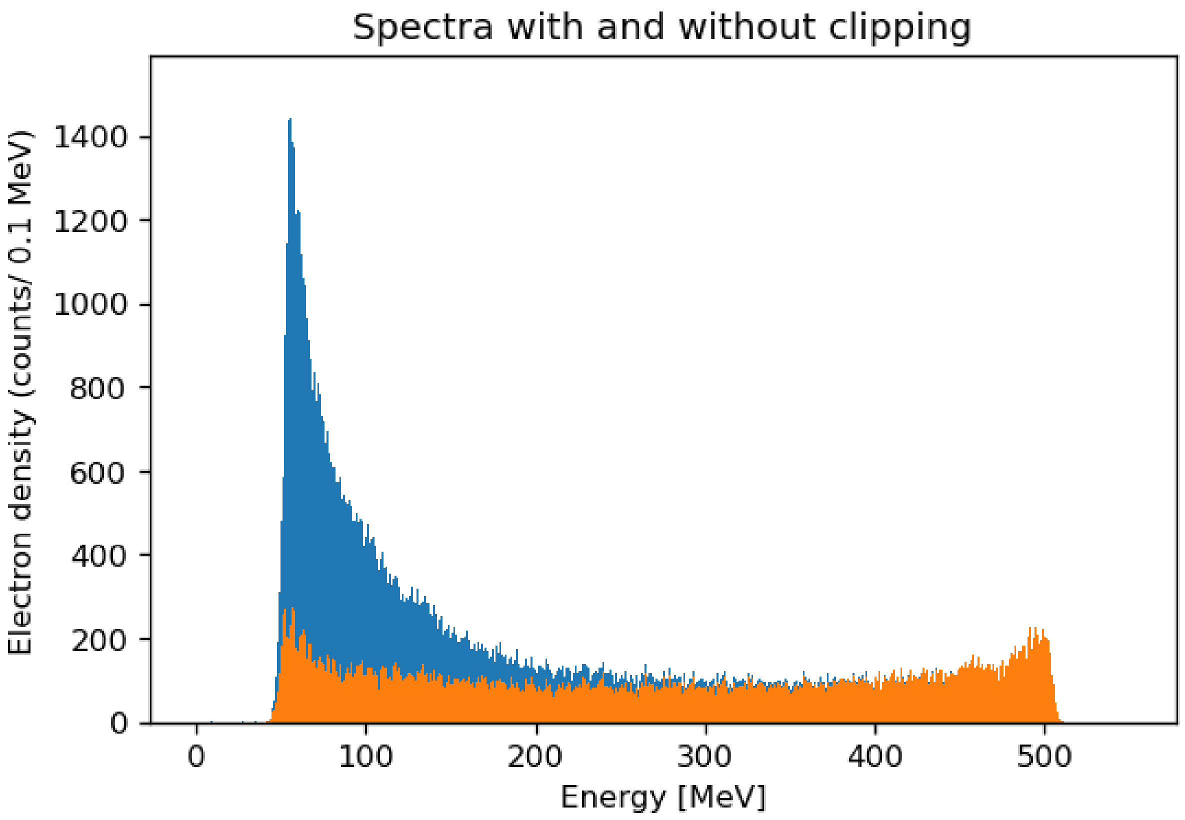

2 BPM-Tomography
X-Plane:
Beta function at waist: 32.98 mm.
Waist location: 30.18 mm.
Y-Plane:
Beta function at waist: 53.11 mm.
Waist location: -10.13 mm.

# Charge loss in simulations

> Hypothesis: Low energy electrons have large divergence and clip in transport

- Charge loss is after plasma
- Charge loss is predominantly at low energies



# NO MORE BACKUPS :)