Driver energy depletion

Large energy depletion of a beam driver in a plasma-wakefield accelerator

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

EUROPEAN NETWORK FOR NOVEL ACCELERATORS
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IFAST

DESY.

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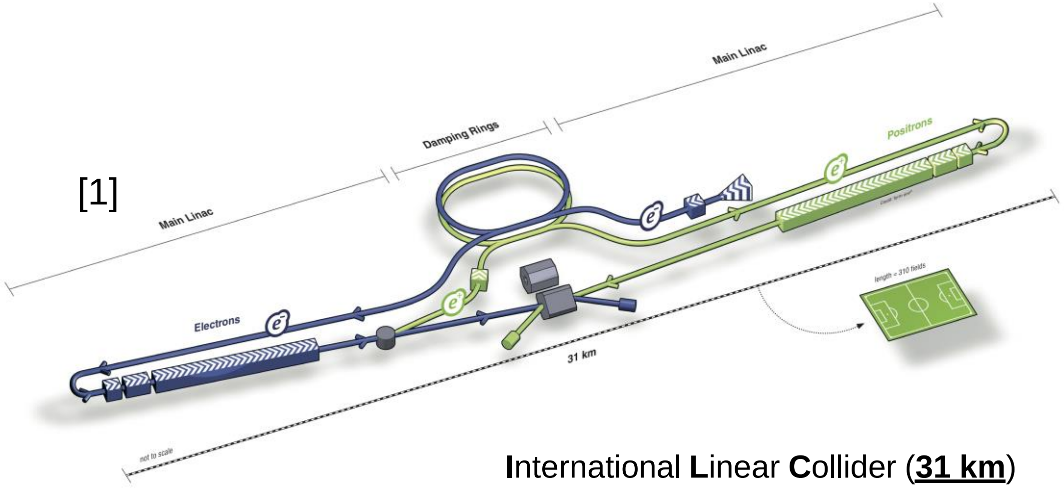
Plasma-wakefield accelerators promise compactness

- Accelerating gradient
  - State-of-the-art radiofrequency 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 **L**inear **C**ollider (**31 km**)

[2]

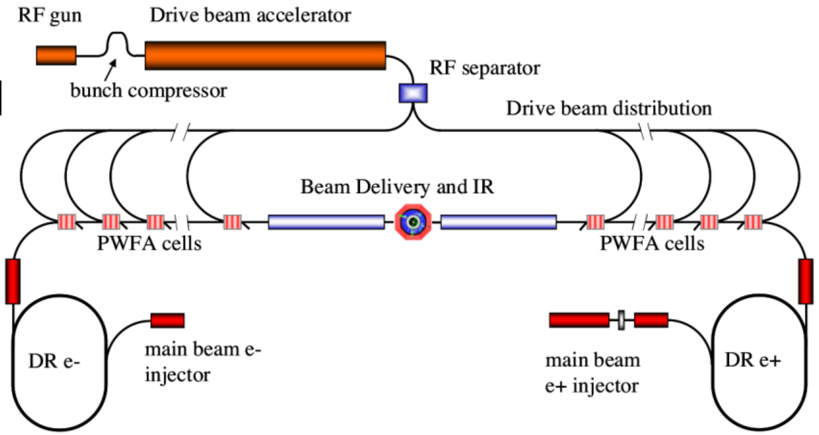


Fig. 1: Concept for a multi-stage PWFA Linear Collider. (**4 km**)

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

Driver energy depletion is key component for efficiency

> Path to high total efficiency is a product of:

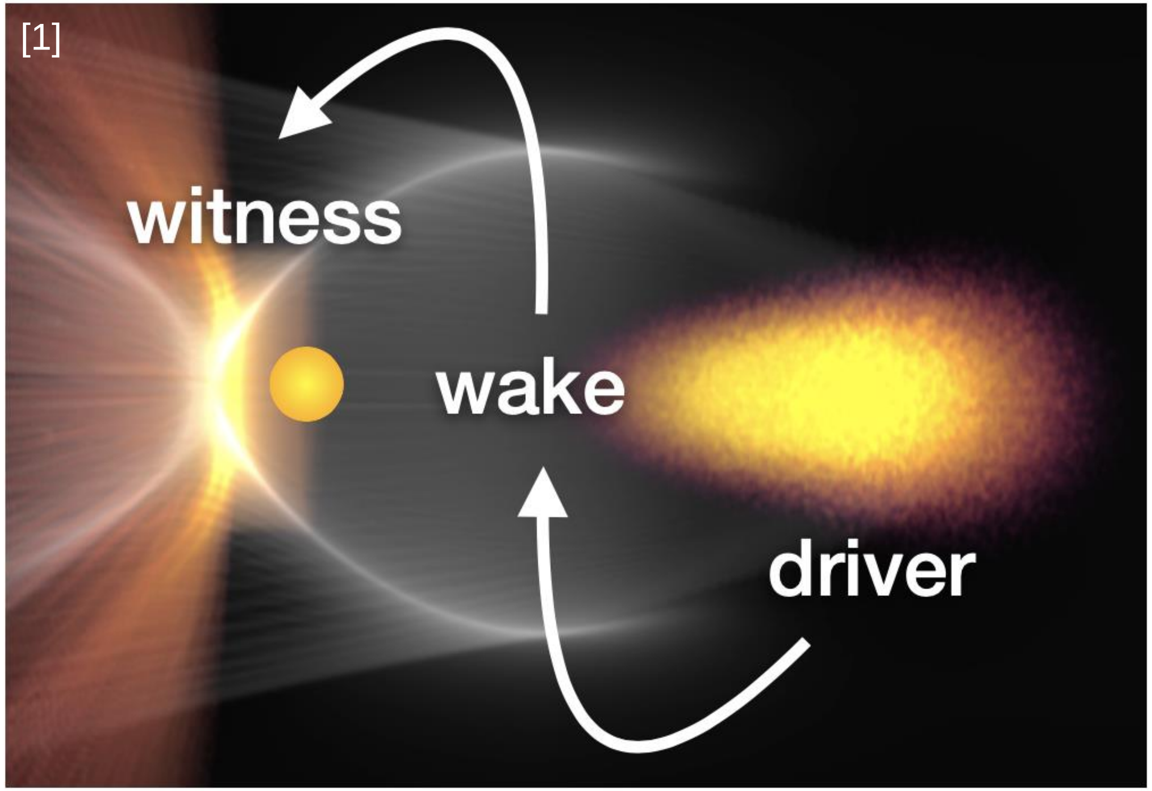
1. Driver production efficiency ✓ (beam driven)

   CLIC: [2] η = 55 % (excluding facility power)
   Ti:Sapphire laser: η < 1 %

2. Driver energy depletion ← **This talk**

3. Driver to witness energy transfer efficiency ✓

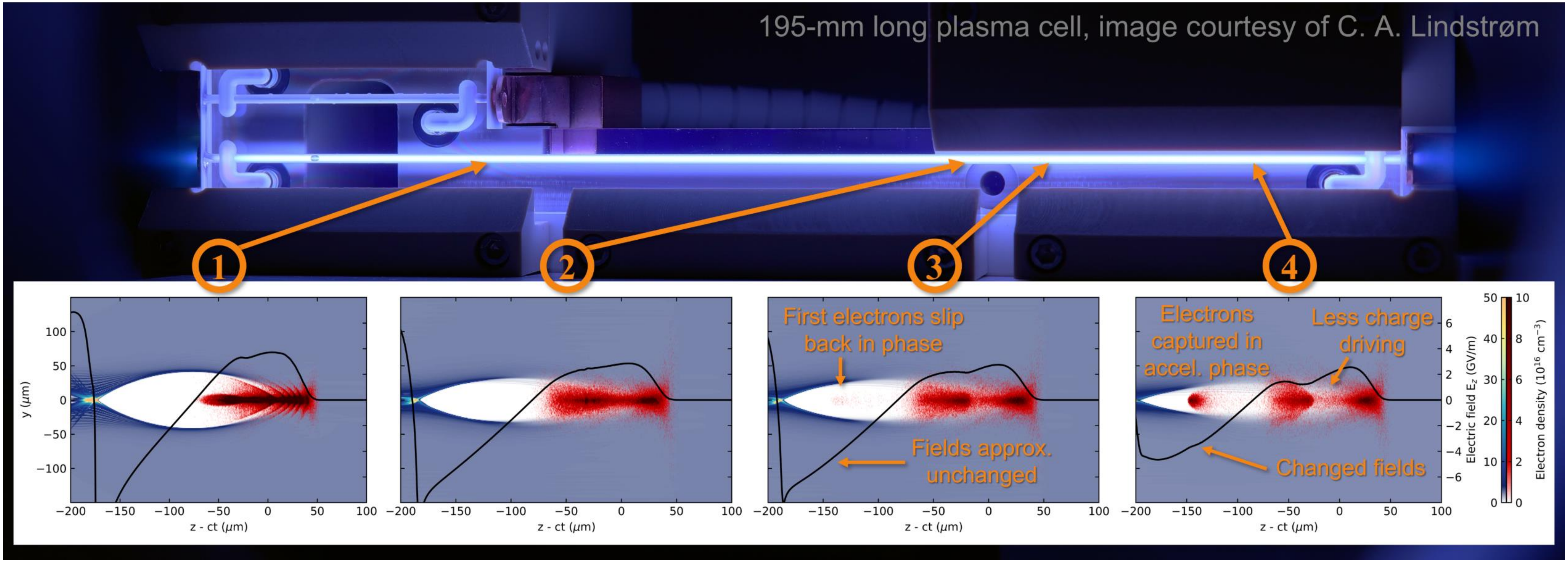
   [3]: η = 30 %
   [4]: η = 42 %



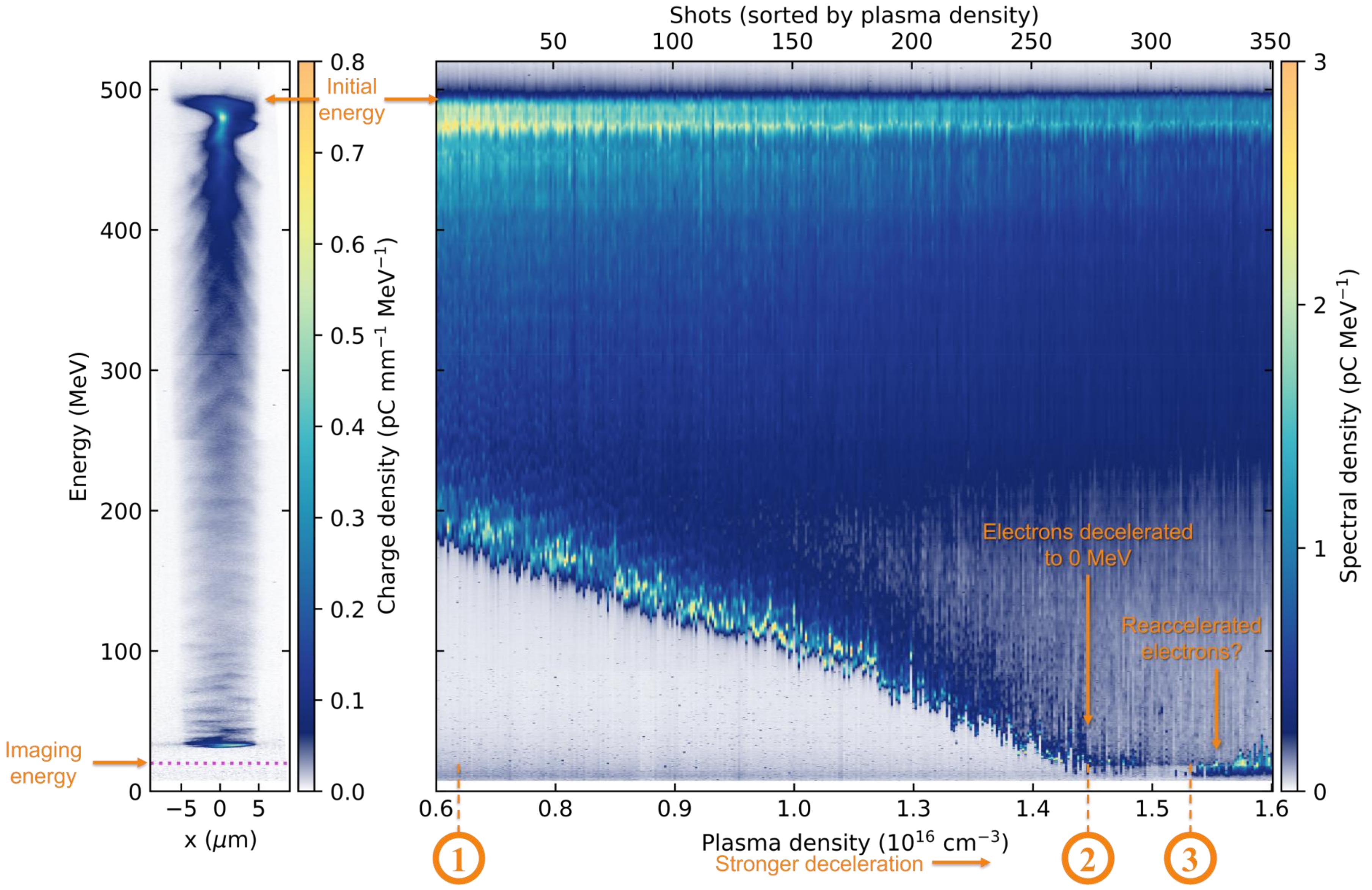
[1] Courtesy of R. D'Arcy
[2] CLIC CDR 2012
[3] M. Litos et al. (Nature 515, 92-95) 2014
[4] C. A. Lindstrøm et al. (PRL 126 , 014801) 2021

Electron reacceleration is the limit of depletion

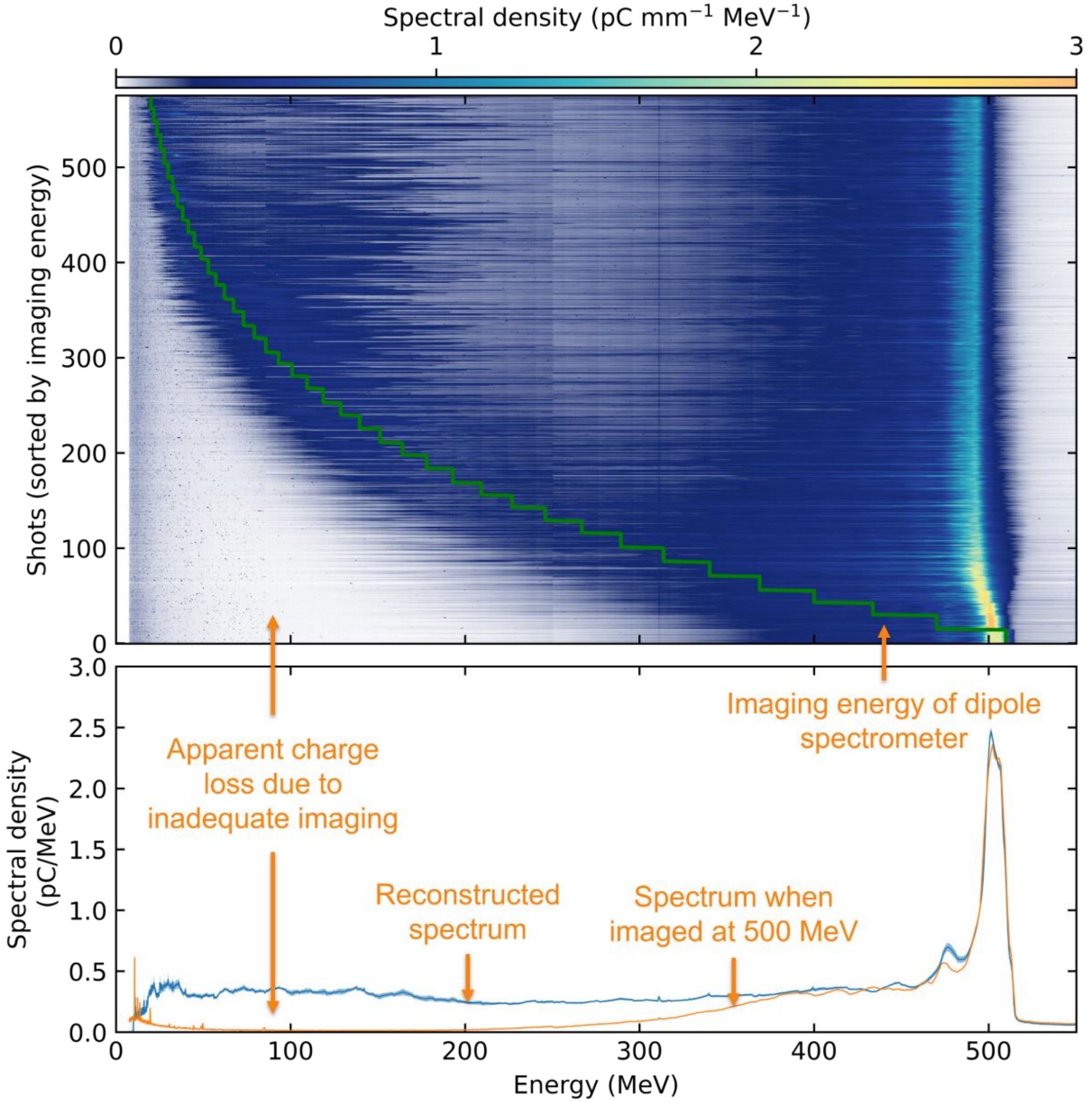
HiPACE++ simulations show reacceleration of energy depleted electrons

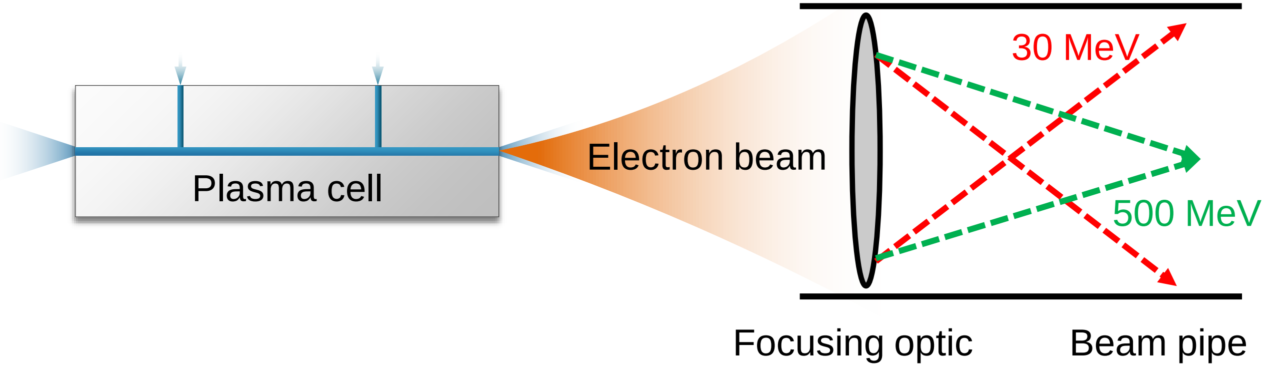


Energy spectrum of a strongly decelerated drive bunch



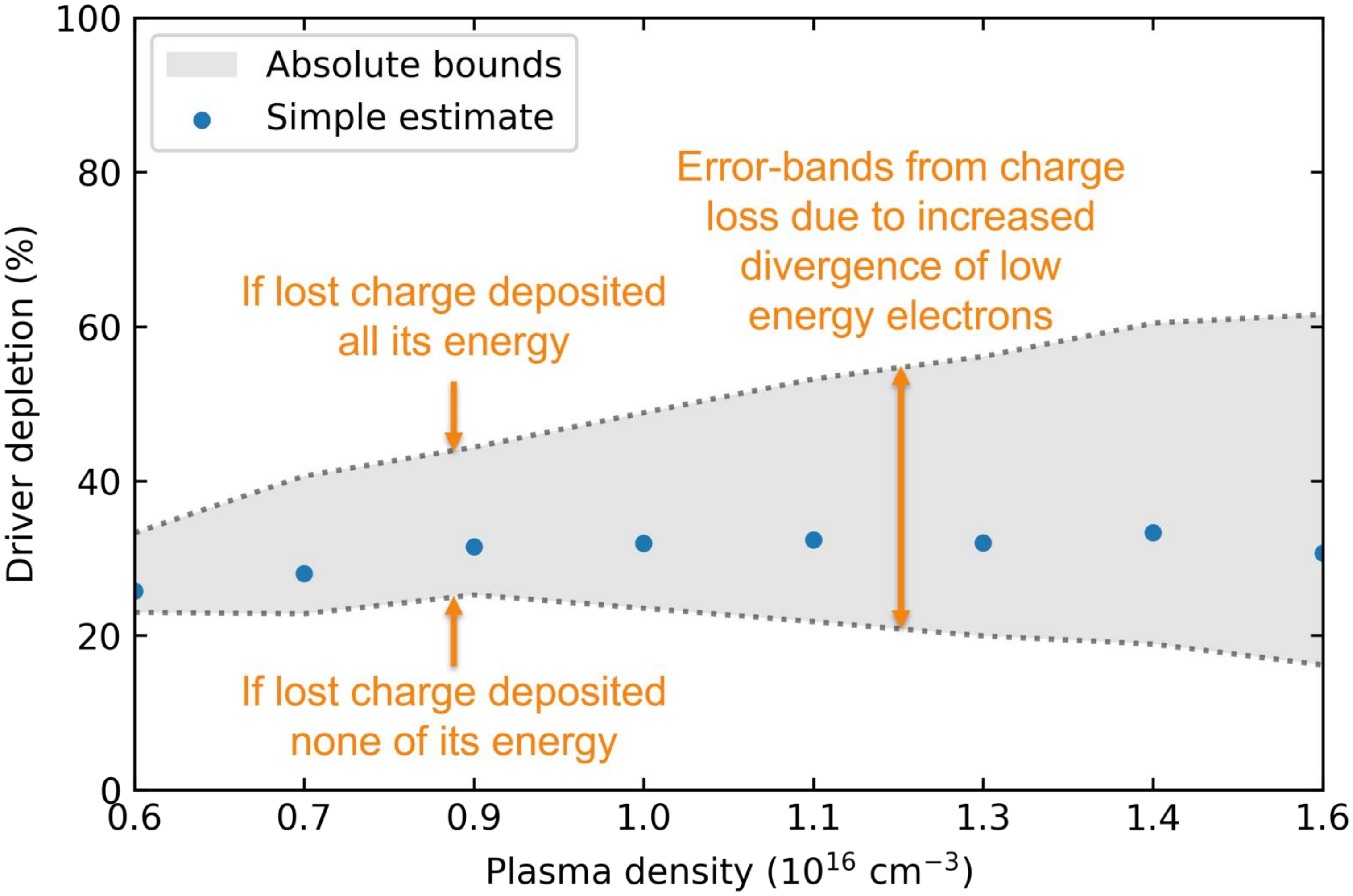
Imaging energy scan needed to properly characterize energy spectrum





- 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**

Drive bunch energy depletion of 20-60%



- We expect larger divergence at lower energies due to:
  - Increase in geometric emittance
  - Smaller matched beta function
  - Possible emittance growth due to interaction with the plasma
- Develop charge loss model to correct for additional sources of charge loss

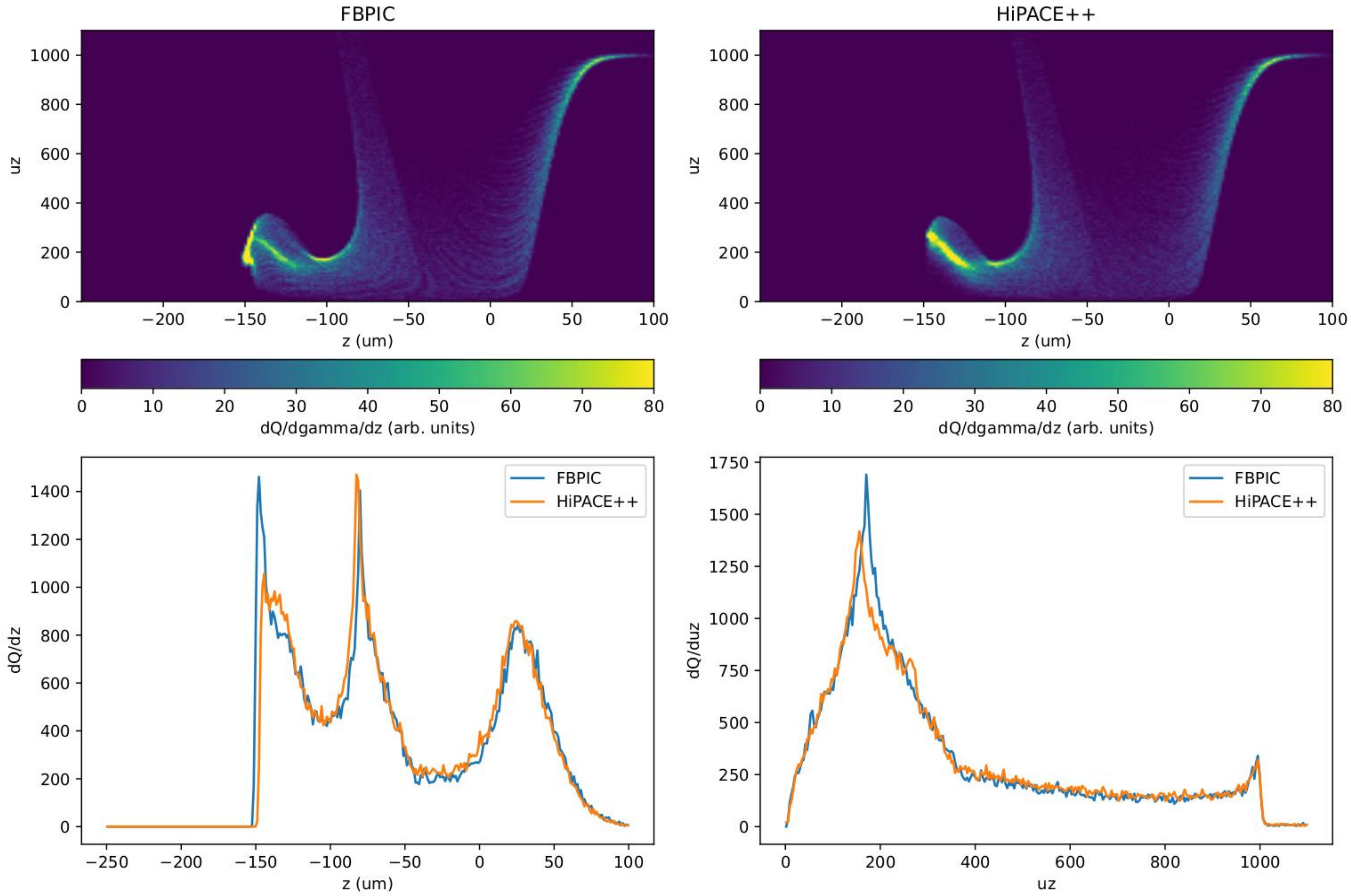
Conclusions

- Electron reacceleration
  - **Limit of** driver energy depletion and thus **overall energy efficiency** in beam-driven PWFA
  - ‘Avoidable’ by shaping the drive bunch current
- Charge loss needs to be modelled to **better estimate** drive bunch energy **depletion**
- Next steps:
  - Combining all independent record-efficiencies:
    - 55% RF to driver (CLIC) · 20-60% driver to wake · 42% wake to beam → 5-13 % overall efficiency
  - Do it!

Thanks to all involved

Backup Slides

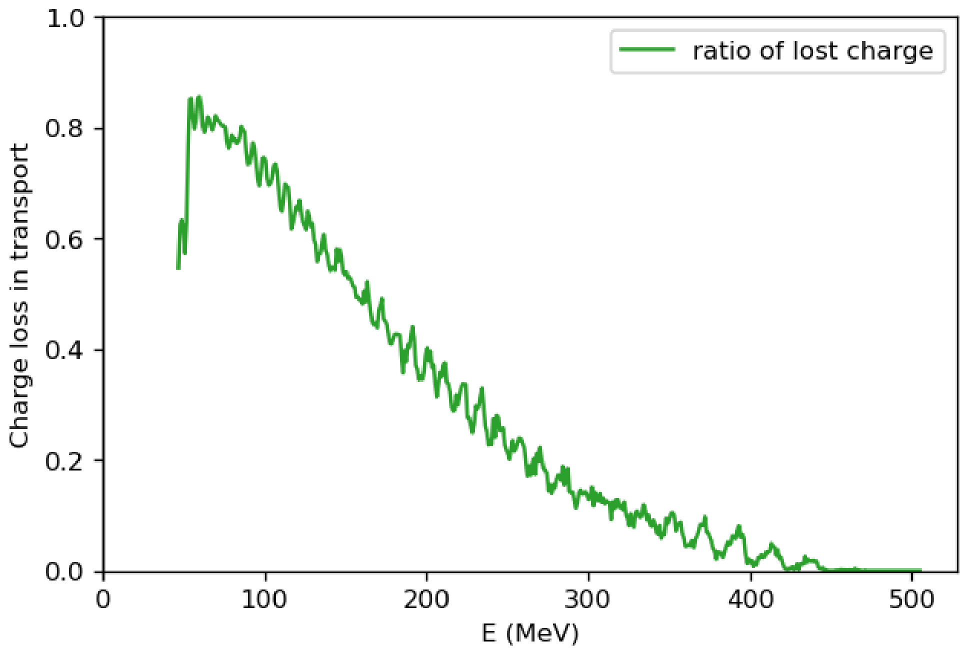
Quasistatic check

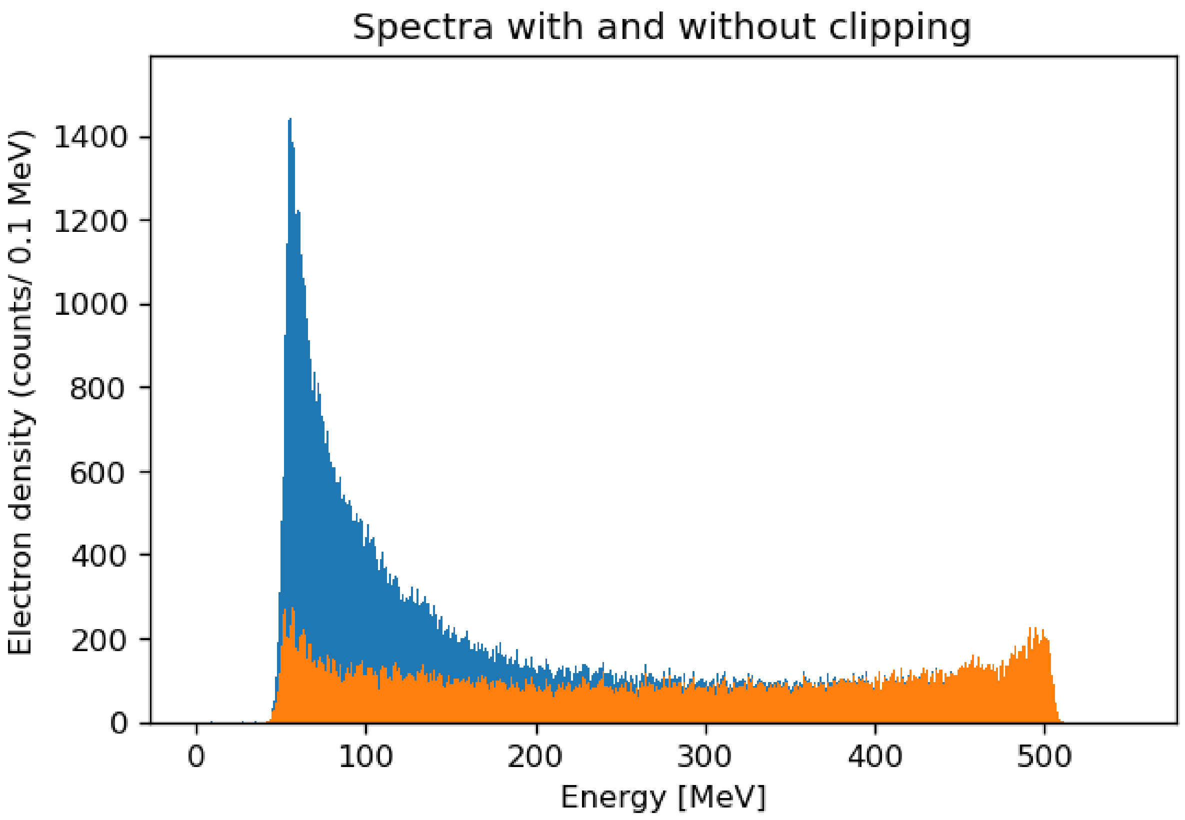


Charge loss in simulations

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

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





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

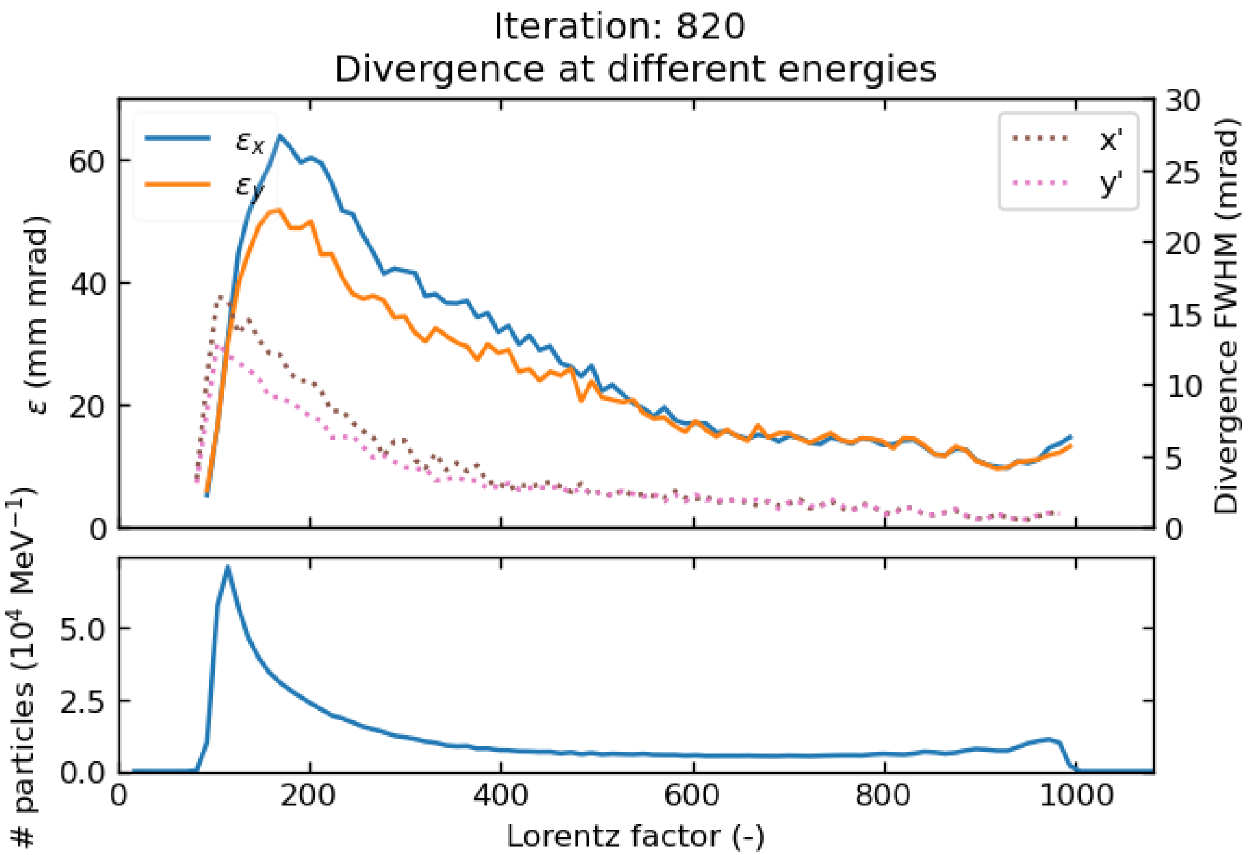
$$\sigma_x'^2 = \frac{\epsilon_g}{\beta*} = \frac{\epsilon_N}{\gamma}\frac{k_p}{\sqrt{2\gamma}}$$

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

- Decreasing energy → larger divergence

Large emittance at low energies → large divergence

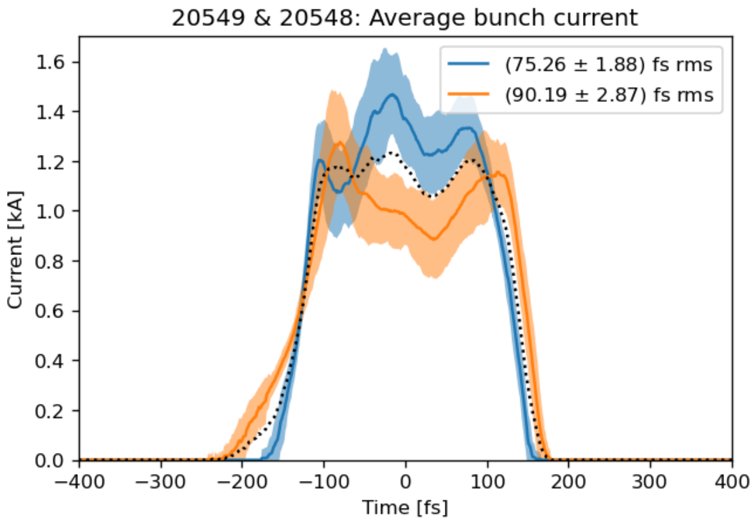
$$\sigma'_x = \sqrt{\frac{\epsilon_N(\gamma)k_p}{\sqrt{2\gamma^3}}}$$

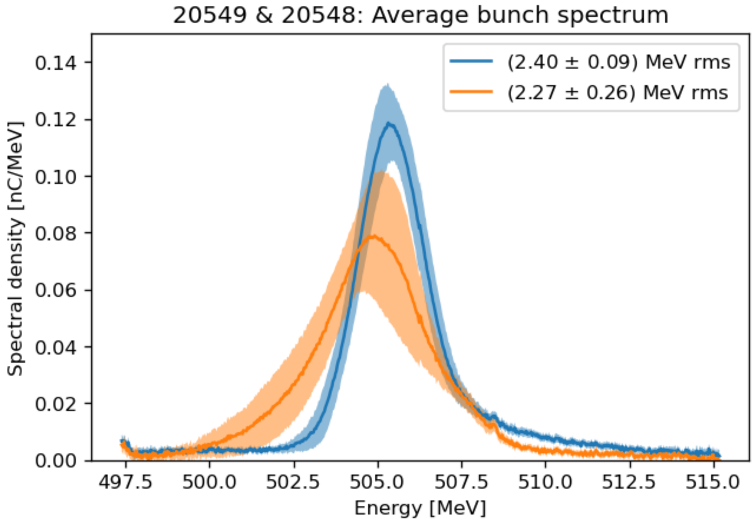


Measured simulation input parameters

- 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.

Plasma density

- Our measurements 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

NO MORE BACKUPS :)