BEAM REPRODUCIBILITY IN A DENSITY-DOWNRAMP PLASMA WAKEFIELD ACCELERATOR.

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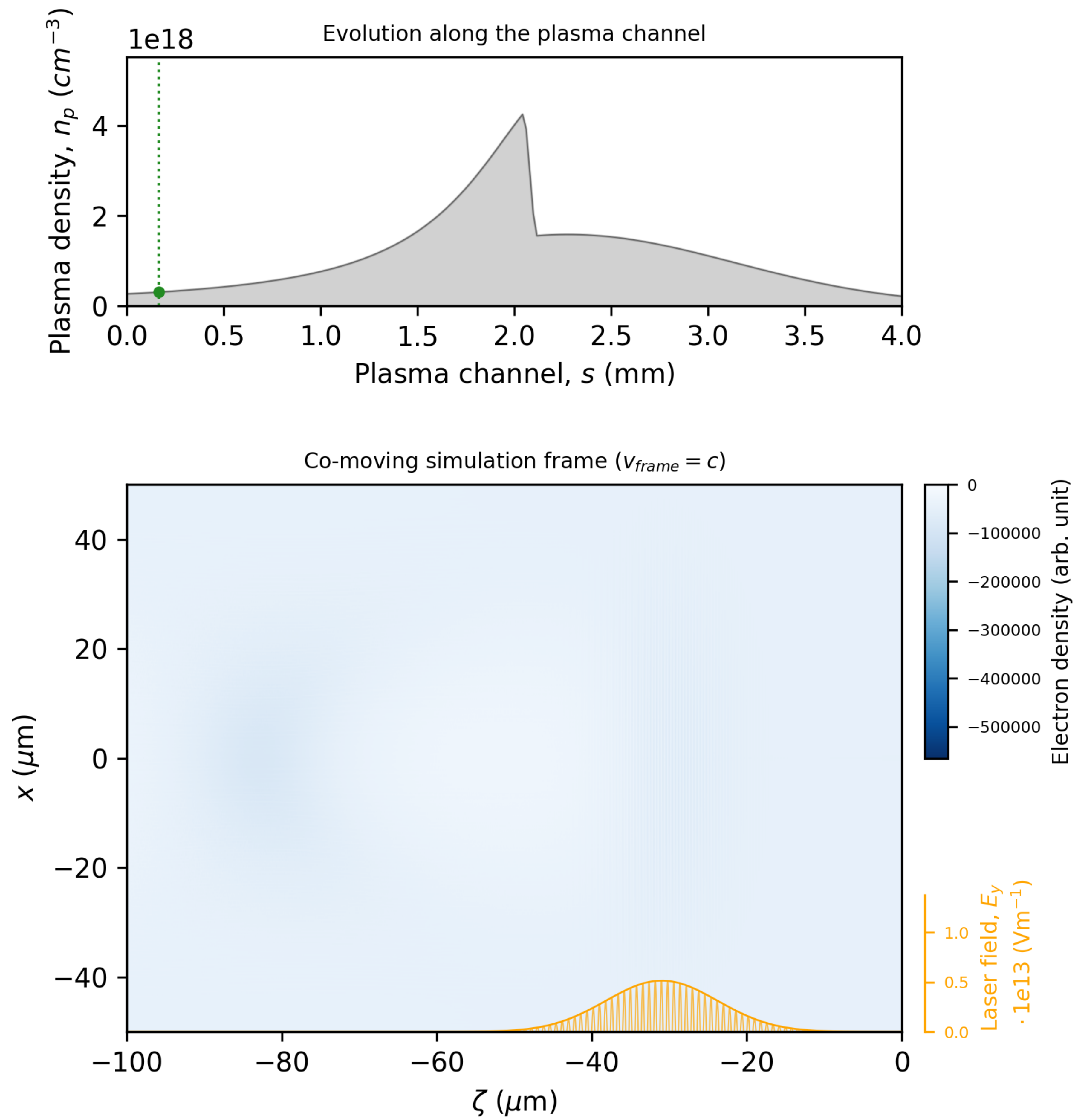

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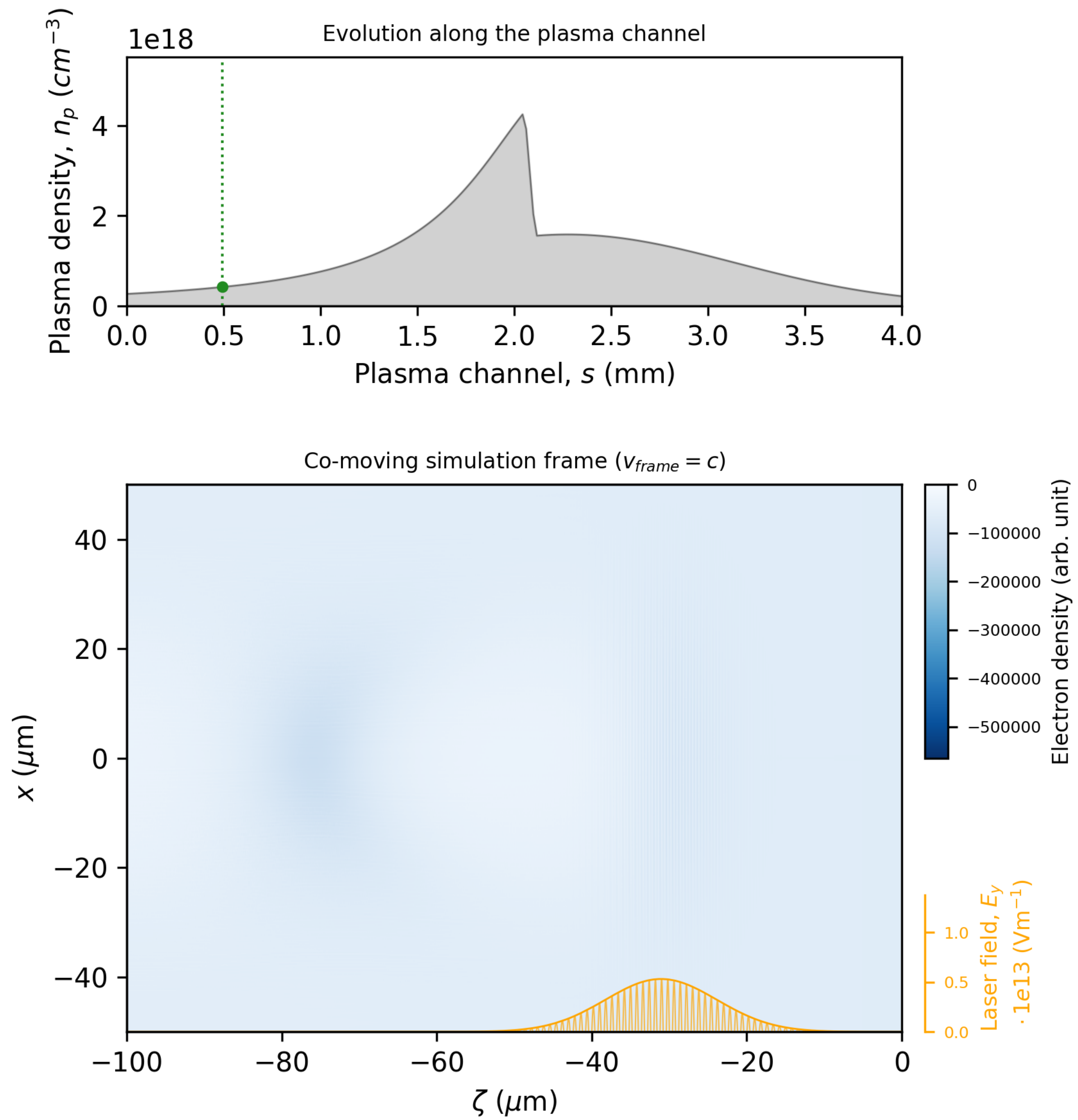

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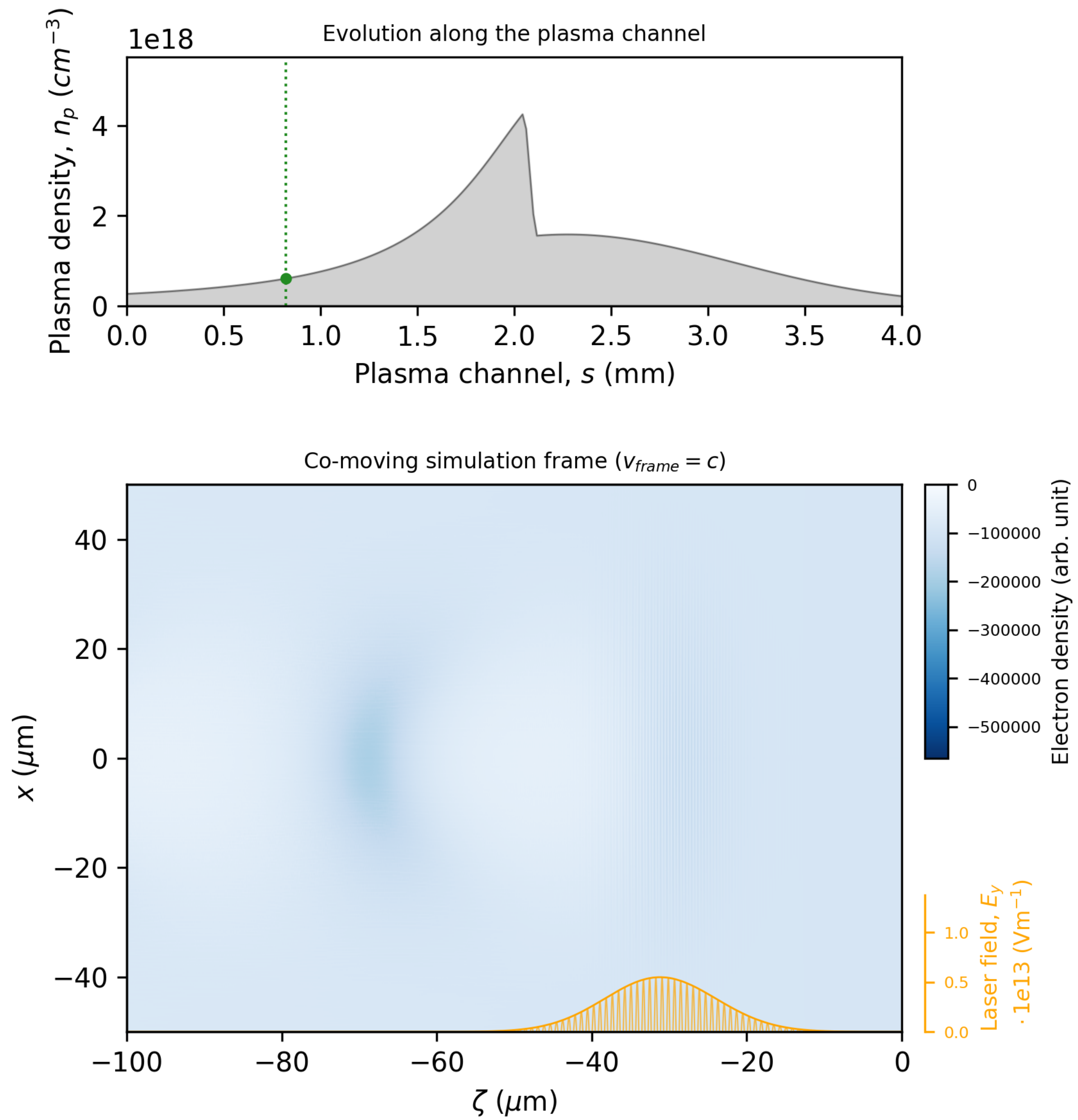

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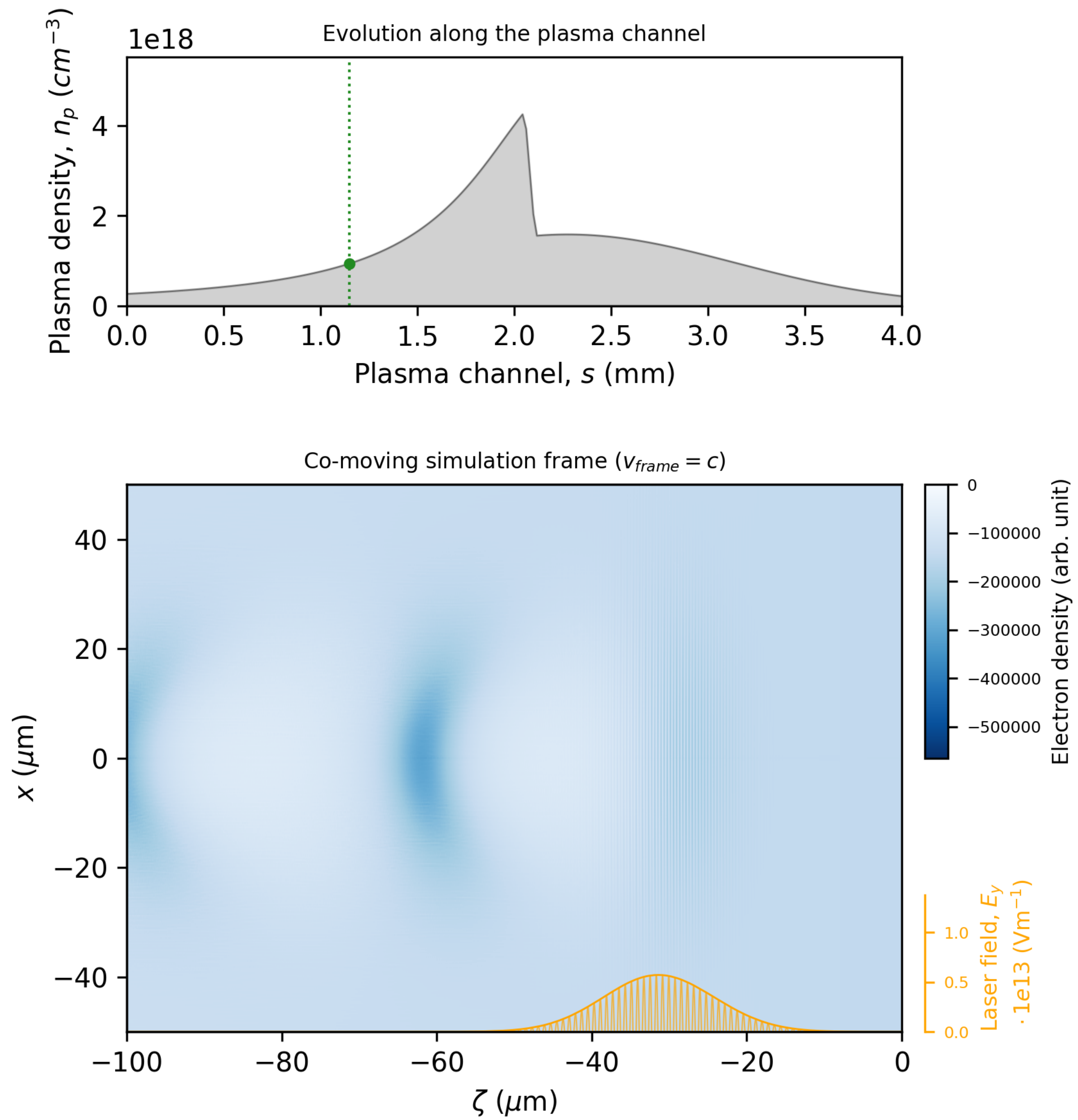

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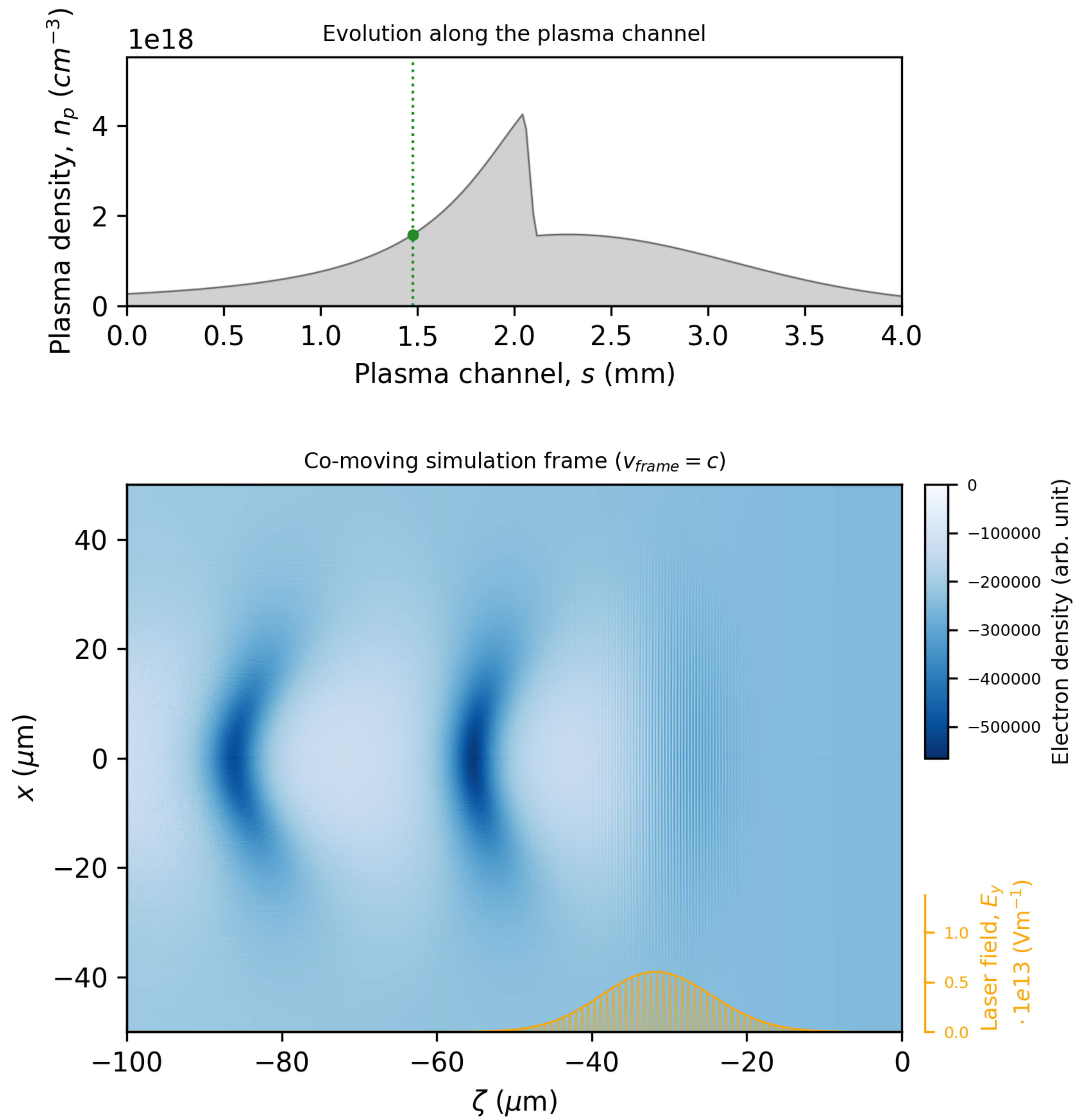

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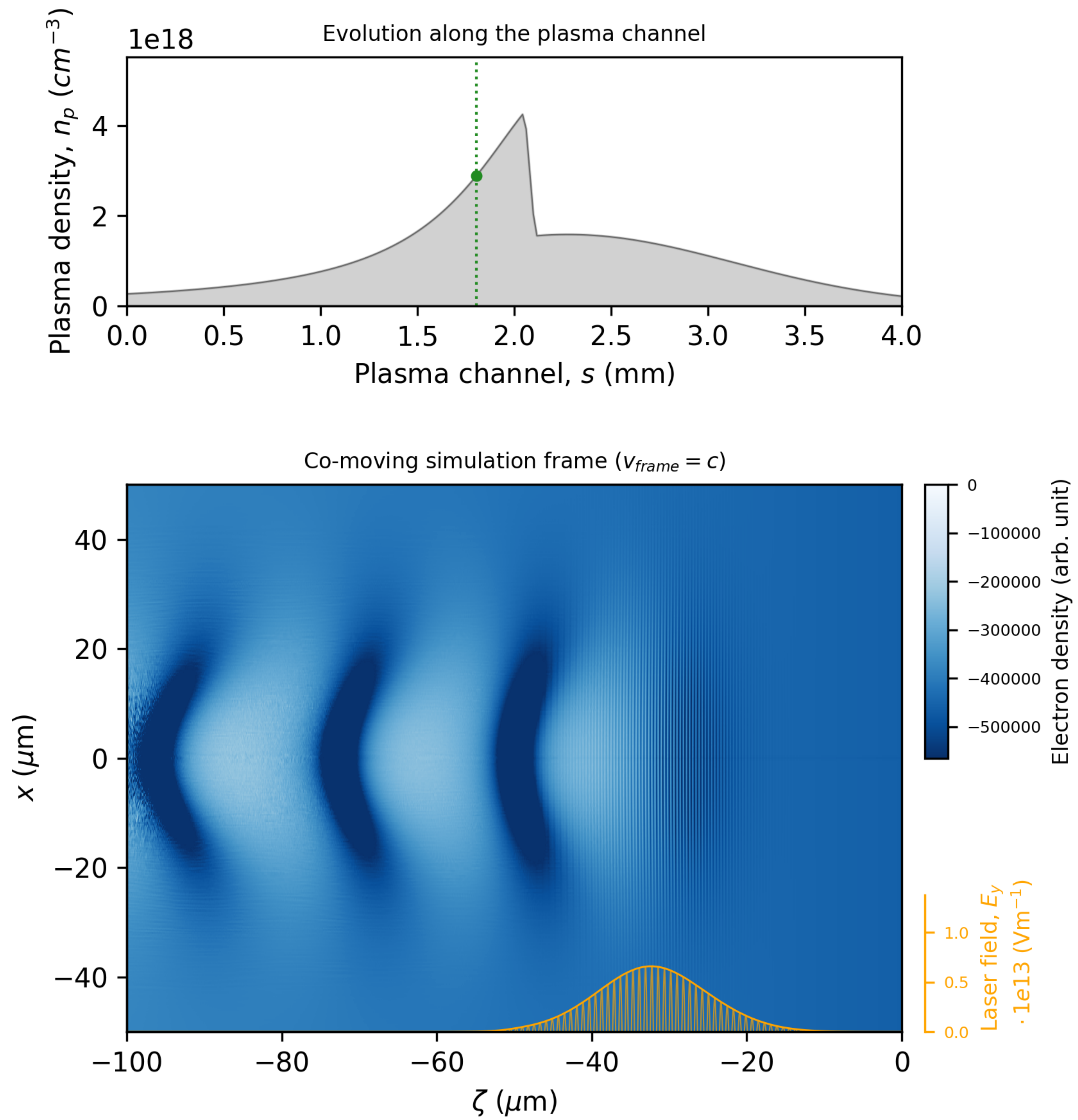

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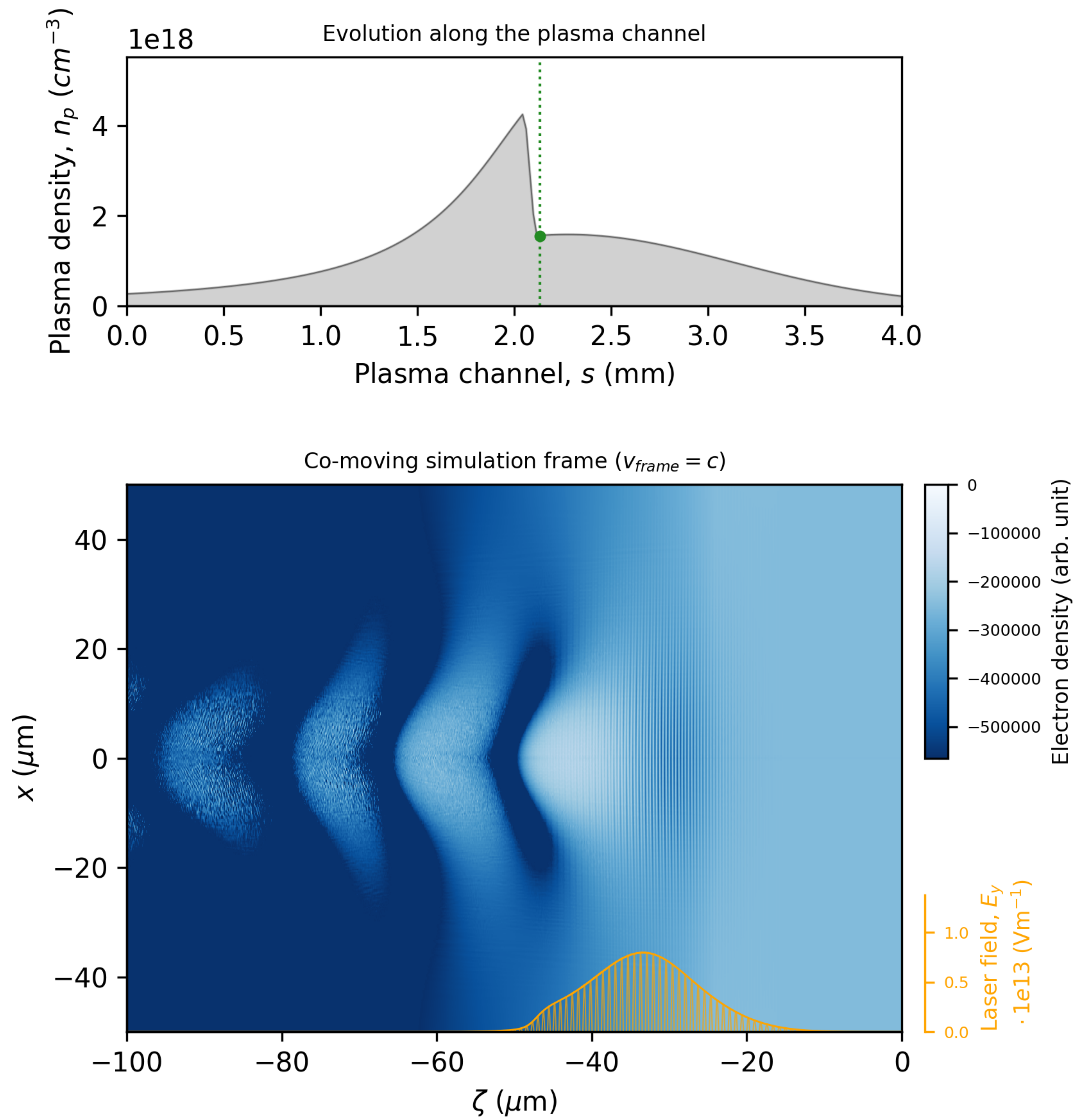

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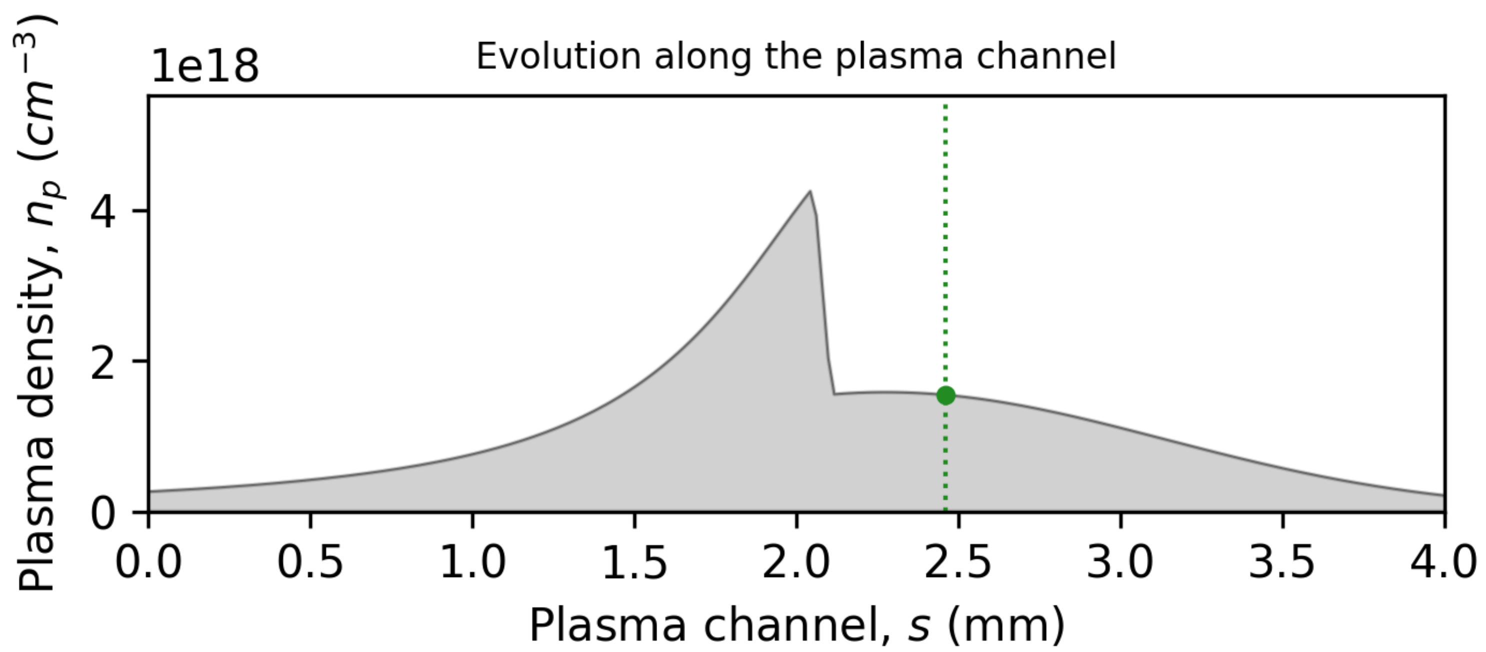

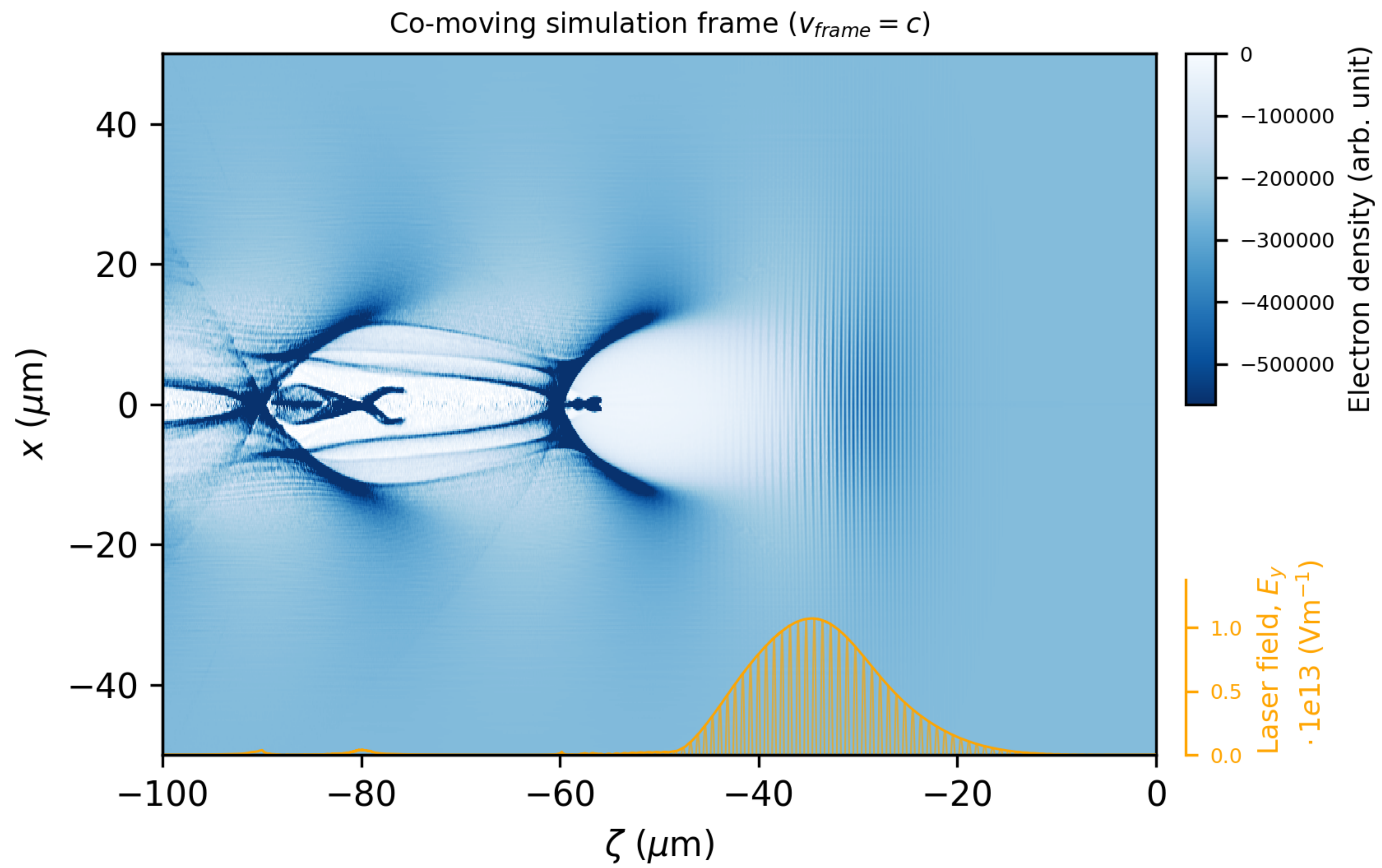

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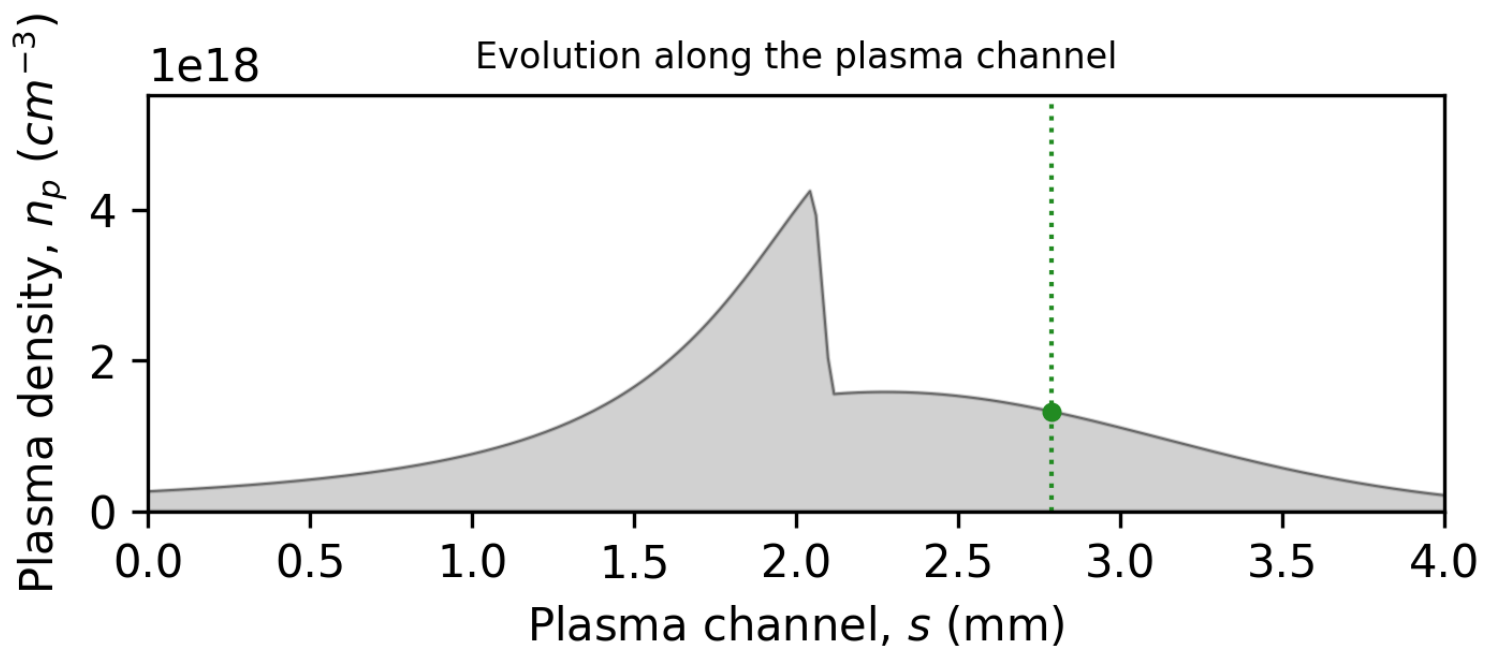

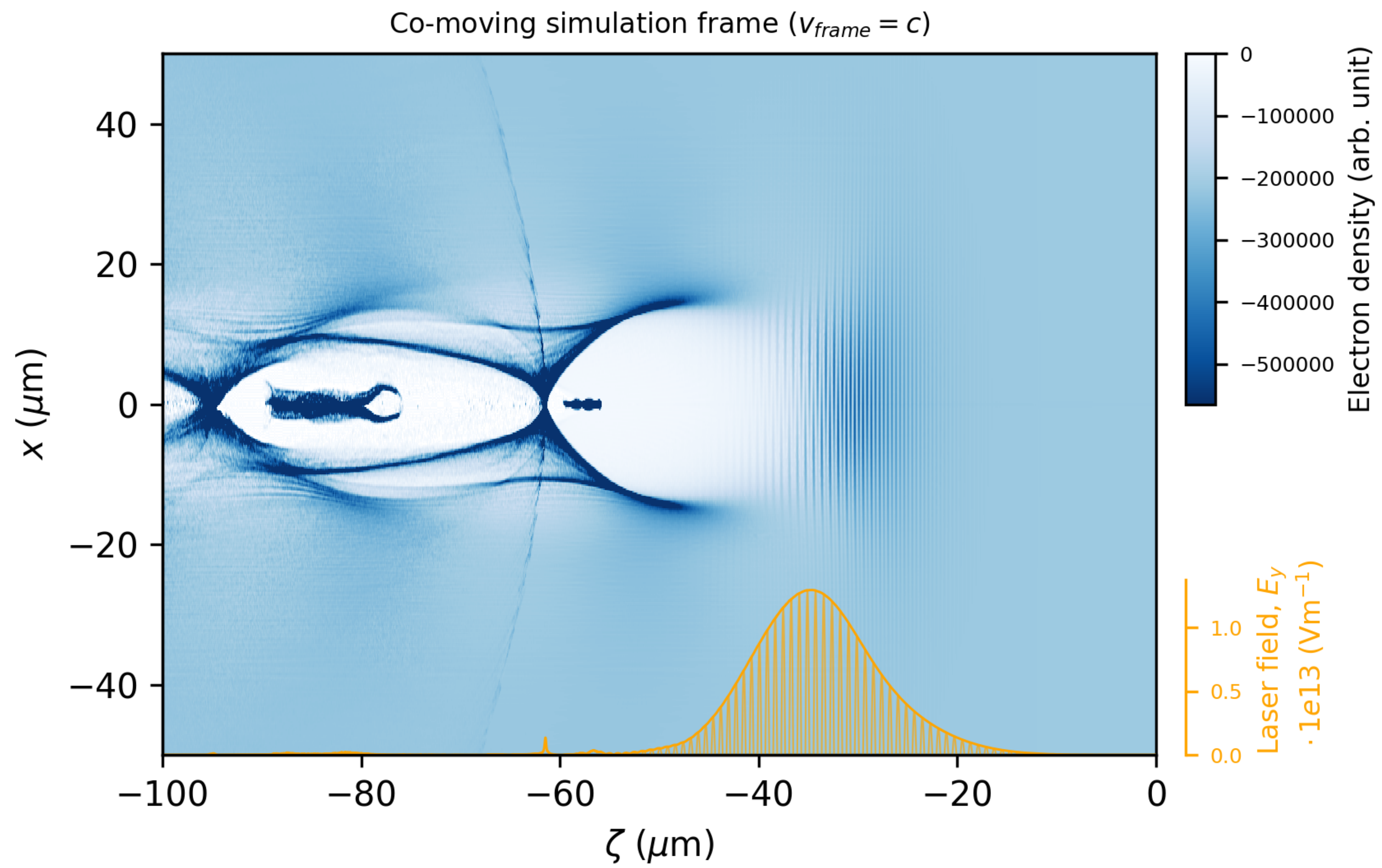

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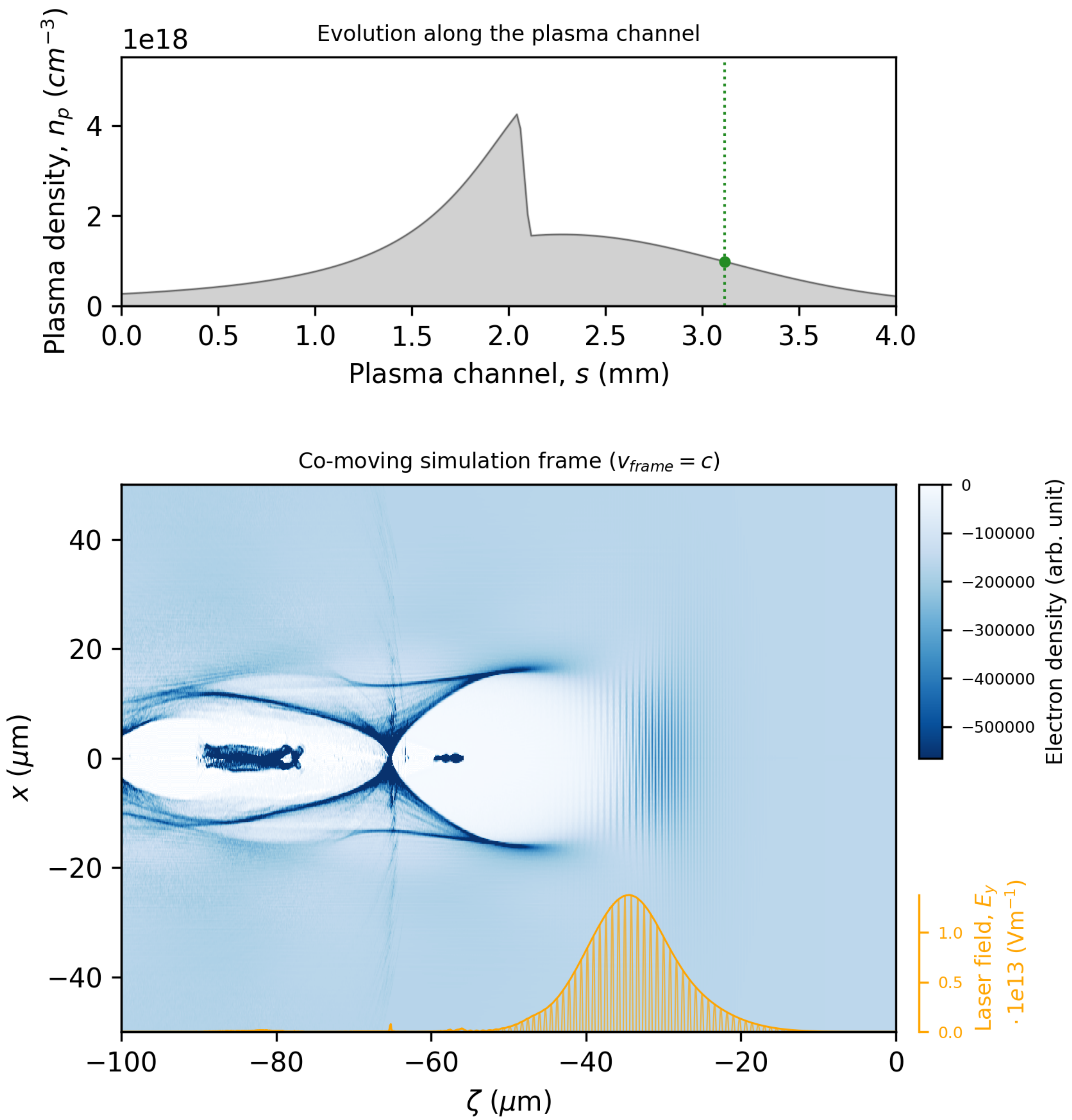

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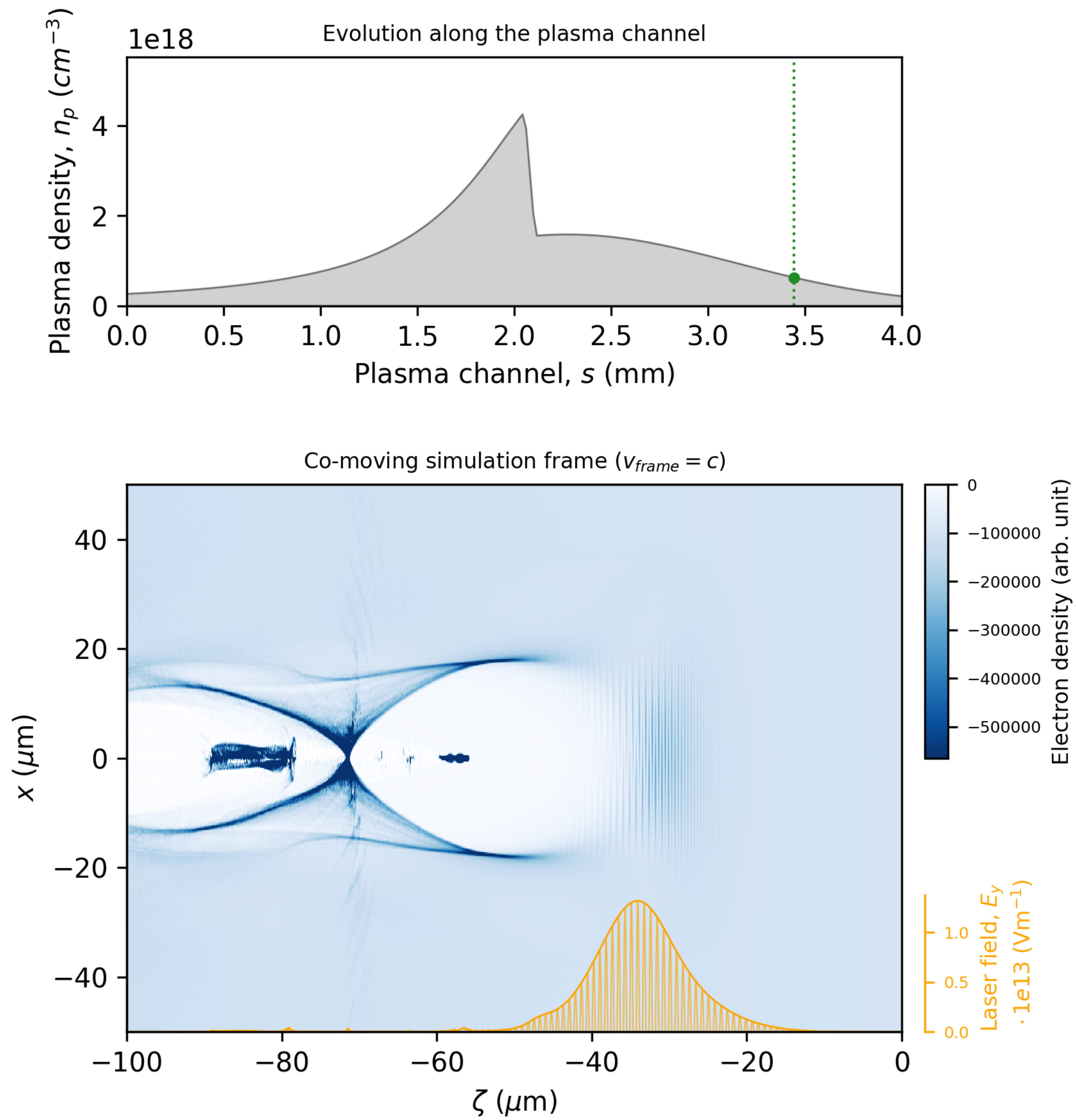

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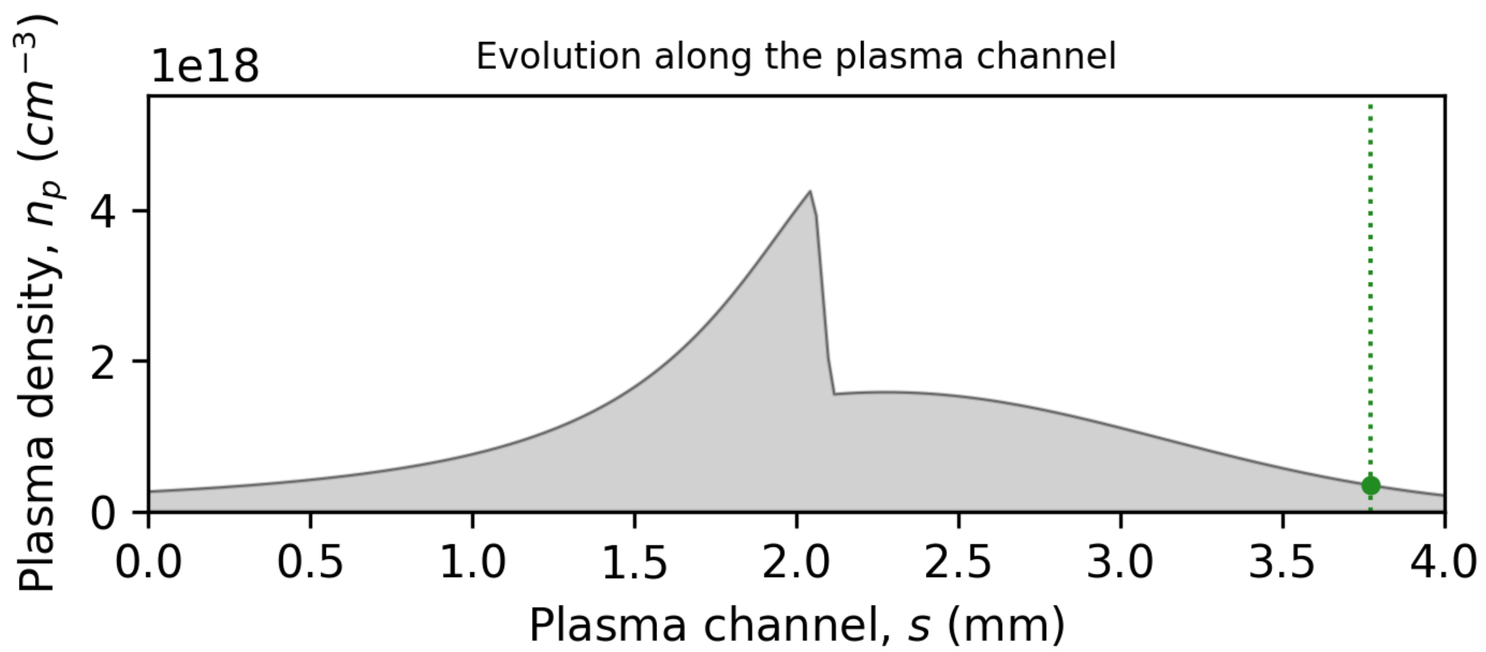

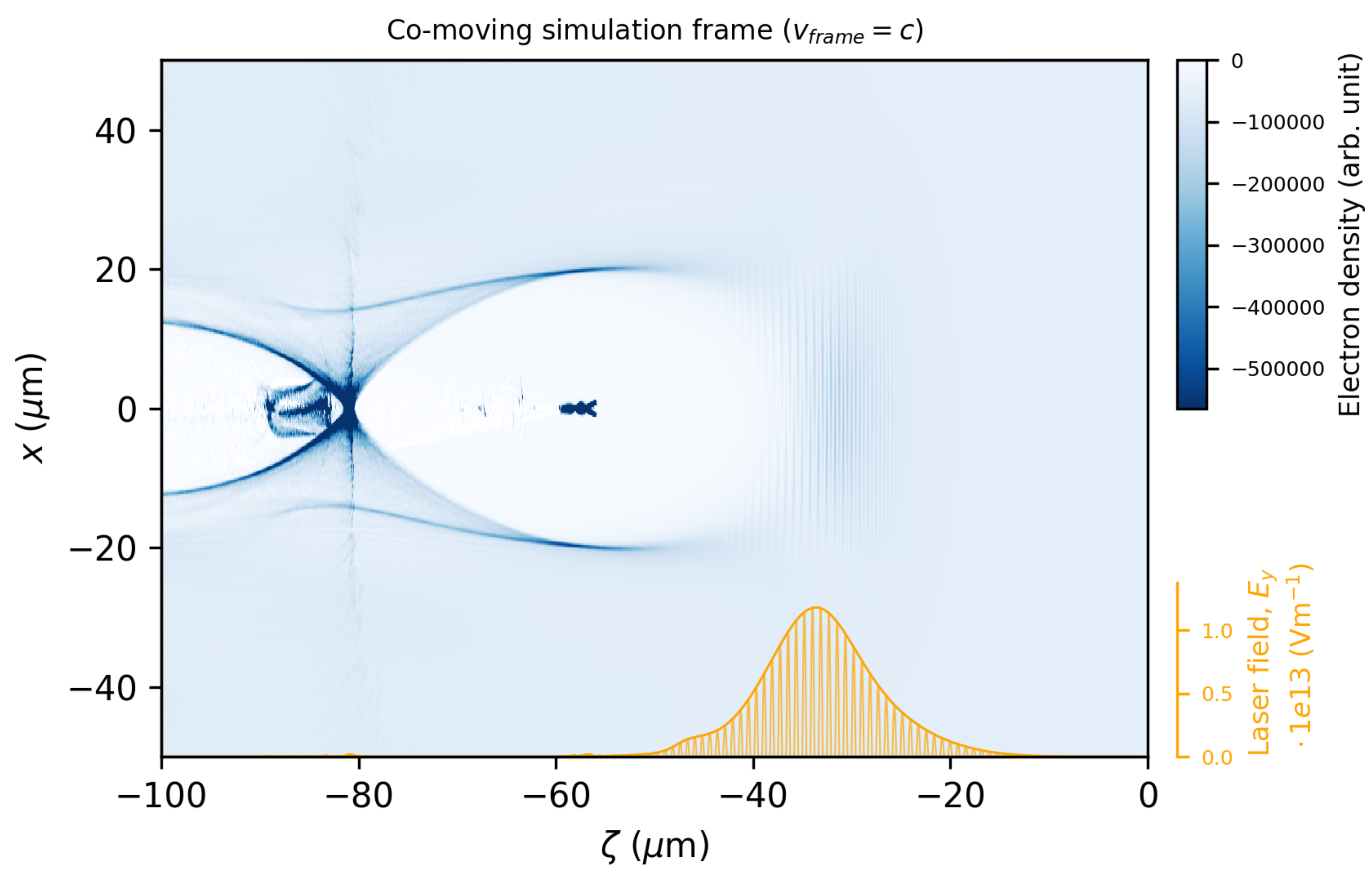

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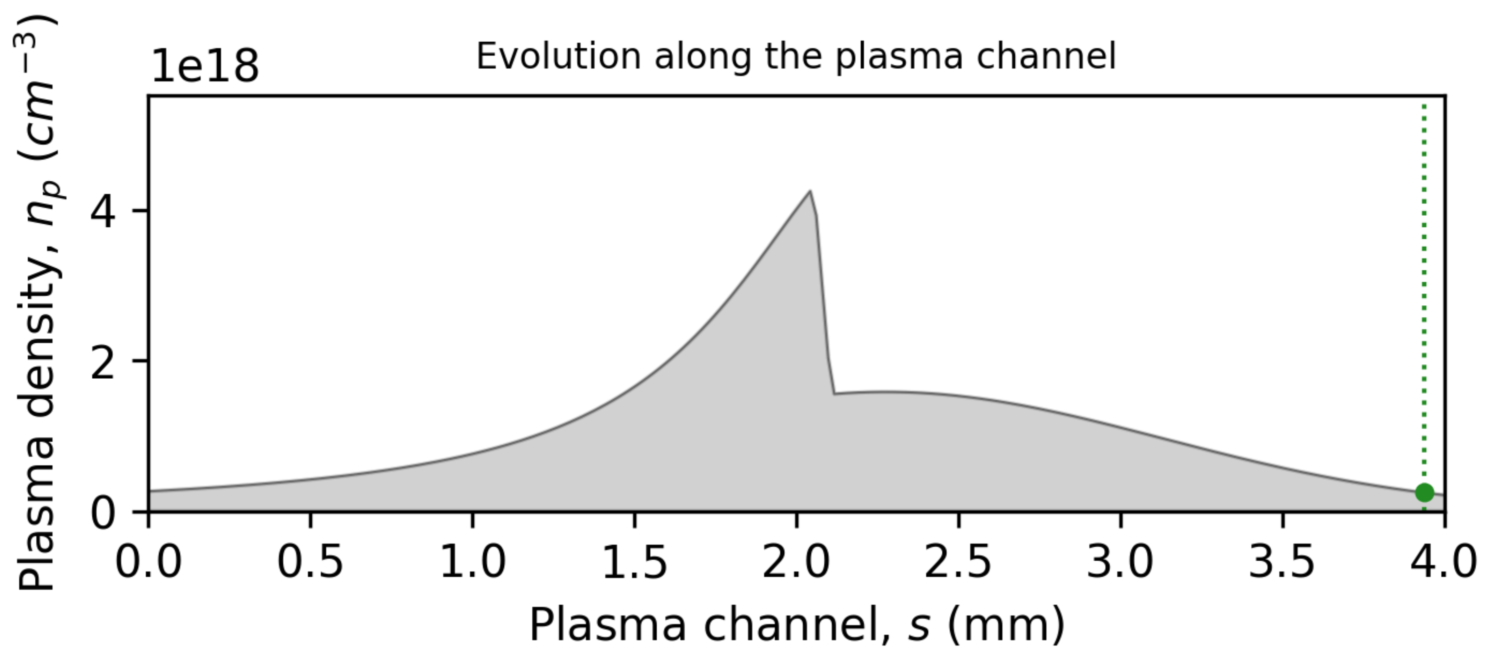

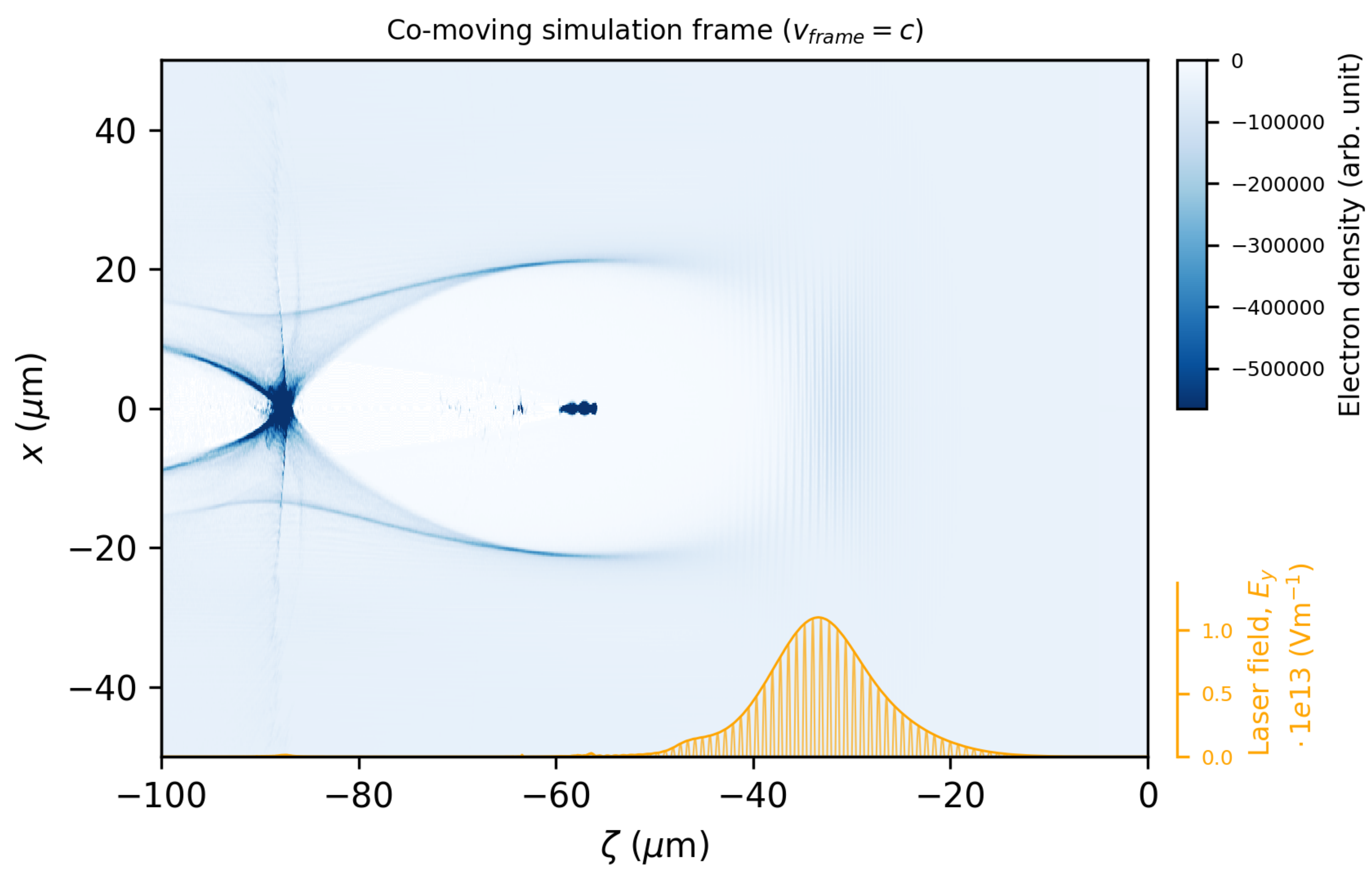

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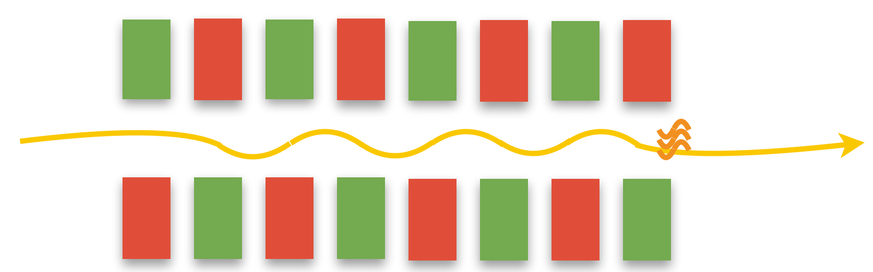
Beam brightness and stability — the holy grail of FEL operation.

- Lasing medium in a free-electron laser: electron beam travelling through alternating magnetic field.

$$\lambda_r \simeq \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



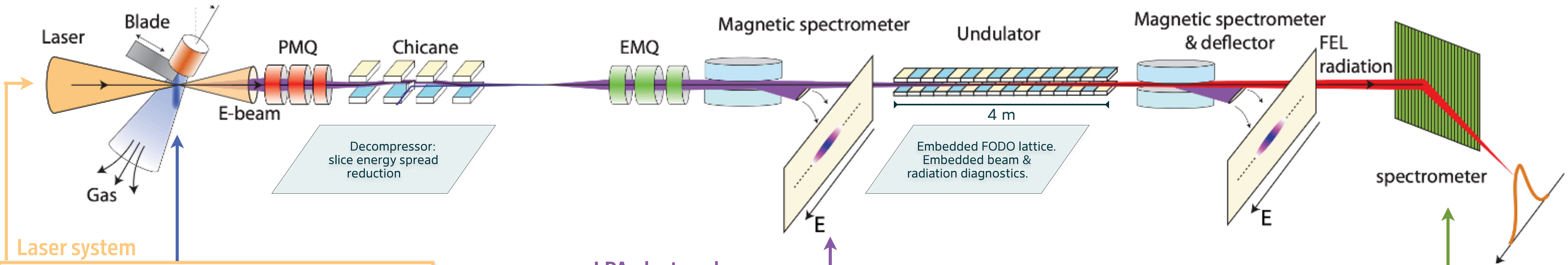
- Transverse motion of the electrons couples to the horizontal component of the radiation field.
  - Excellent beam matching required.
  - Excellent beam alignment required.

- High phase space density of an electron bunch establishes the FEL instability (SASE) in a single pass through the undulator.

$$B_{6D} \propto \frac{I}{\epsilon_x \epsilon_y \epsilon_z}$$

- ‰-level energy spread.
- µm-level emittance.
- kA-level peak currents.

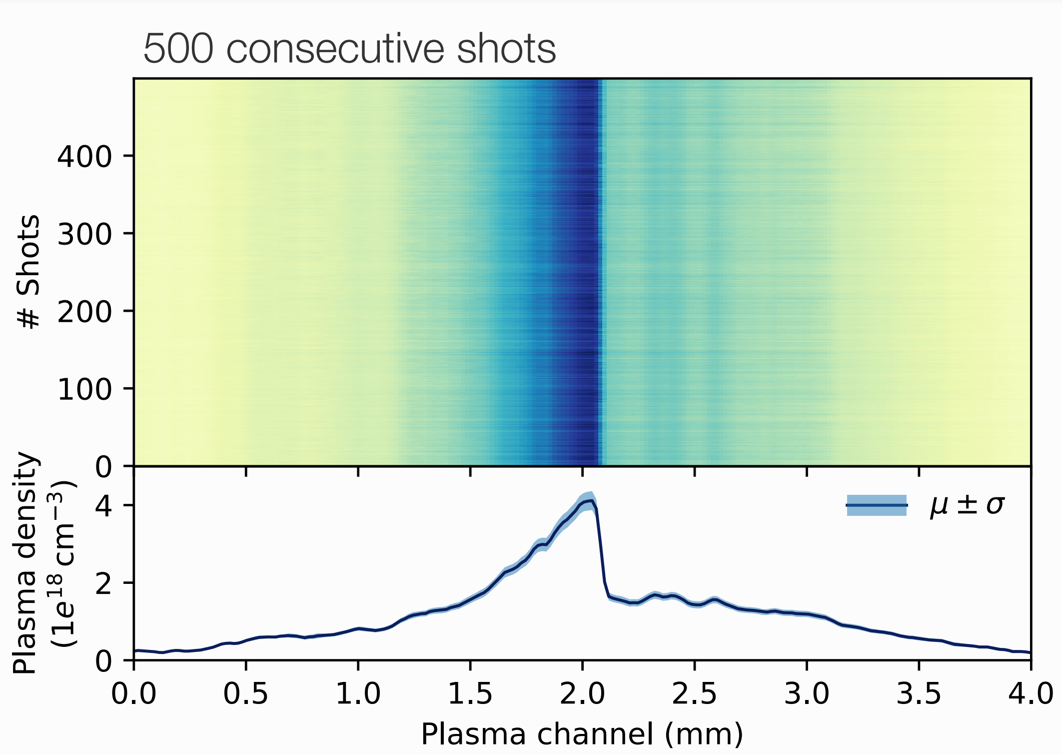
Building a reliable LWFA-based free-electron laser prototype @BELLA.



Laser system

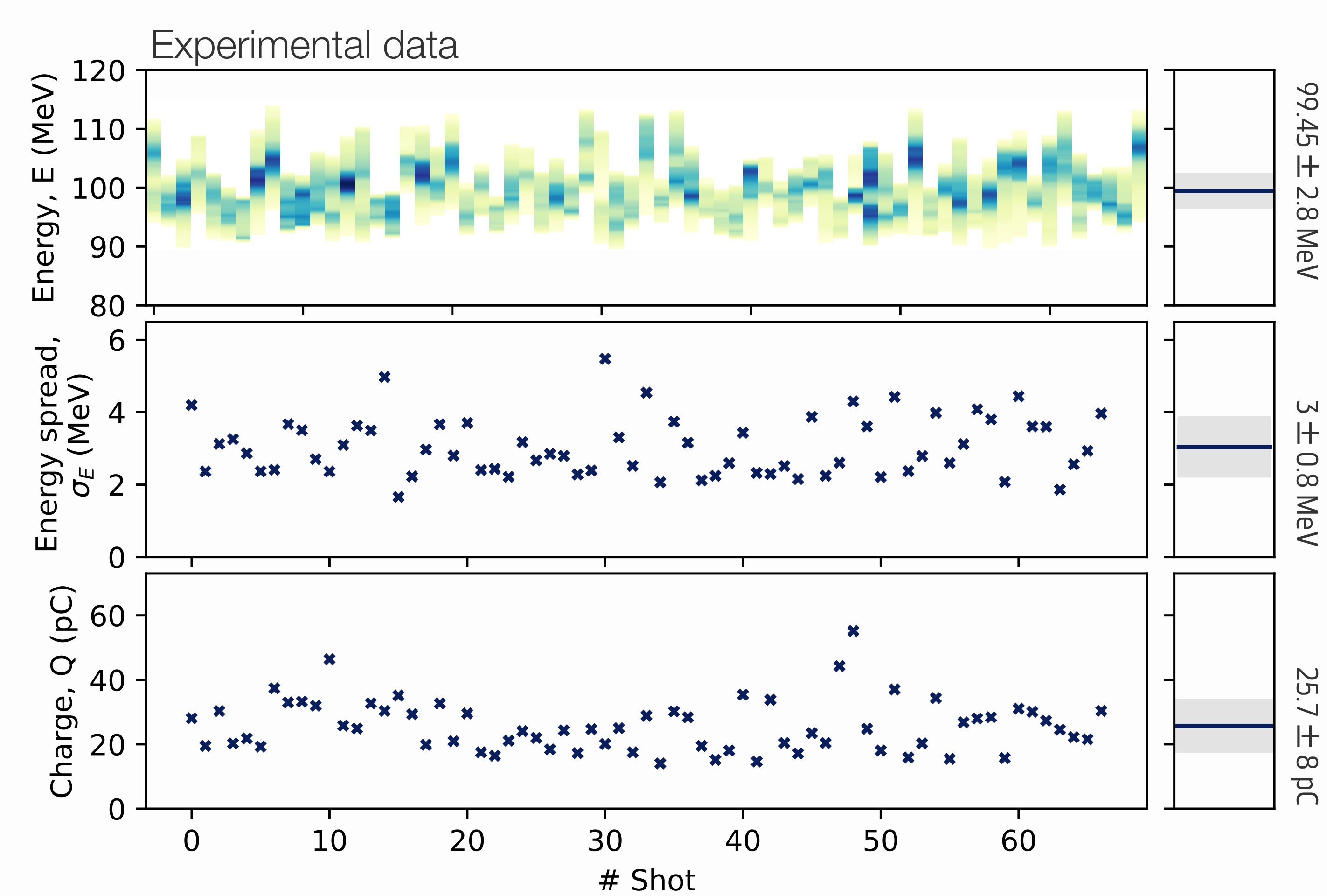
- 100TW, 5Hz, 0.8 µm
- At full capacity: 2.5 J, w_0: 38 µm, σ_t: 37 fs.
- Active stabilisation systems.

Plasma source



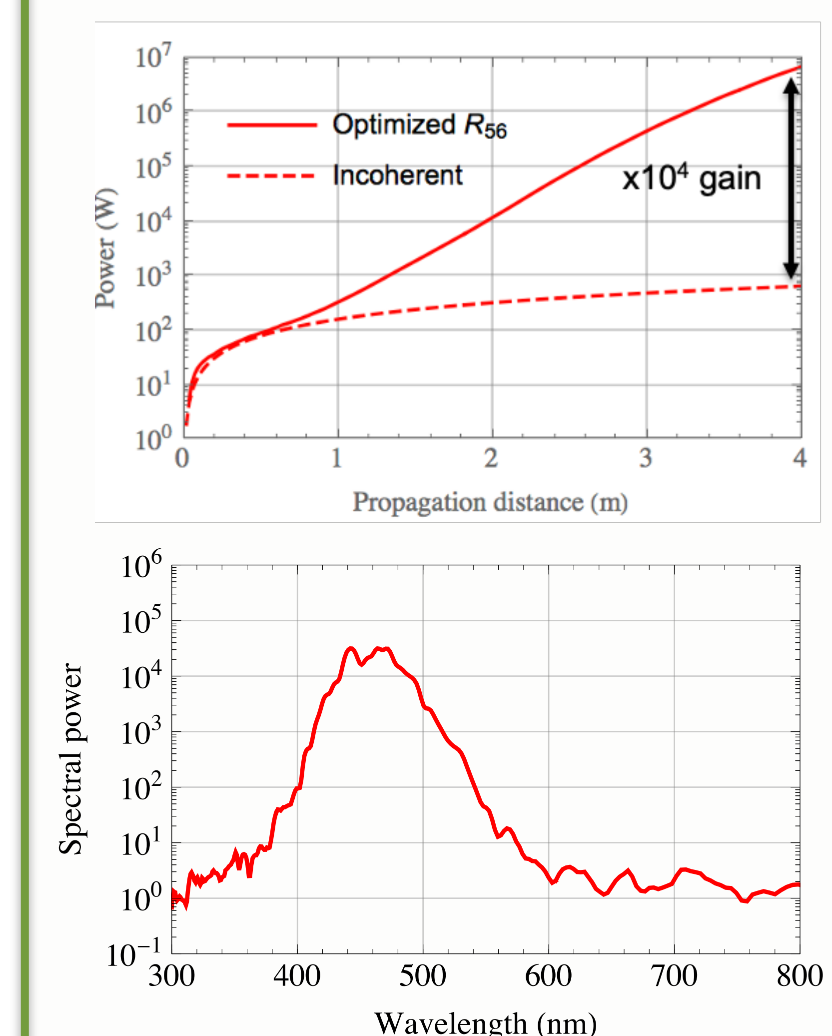
- Supersonic jet with adjustable blade system.
- On-axis density measurement via phase modulation of a transverse probe.

LPA electron beam



- 30 pC @ 100 MeV beams are routinely achieved.
- 3% mean energy jitter.
- 20% charge jitter.

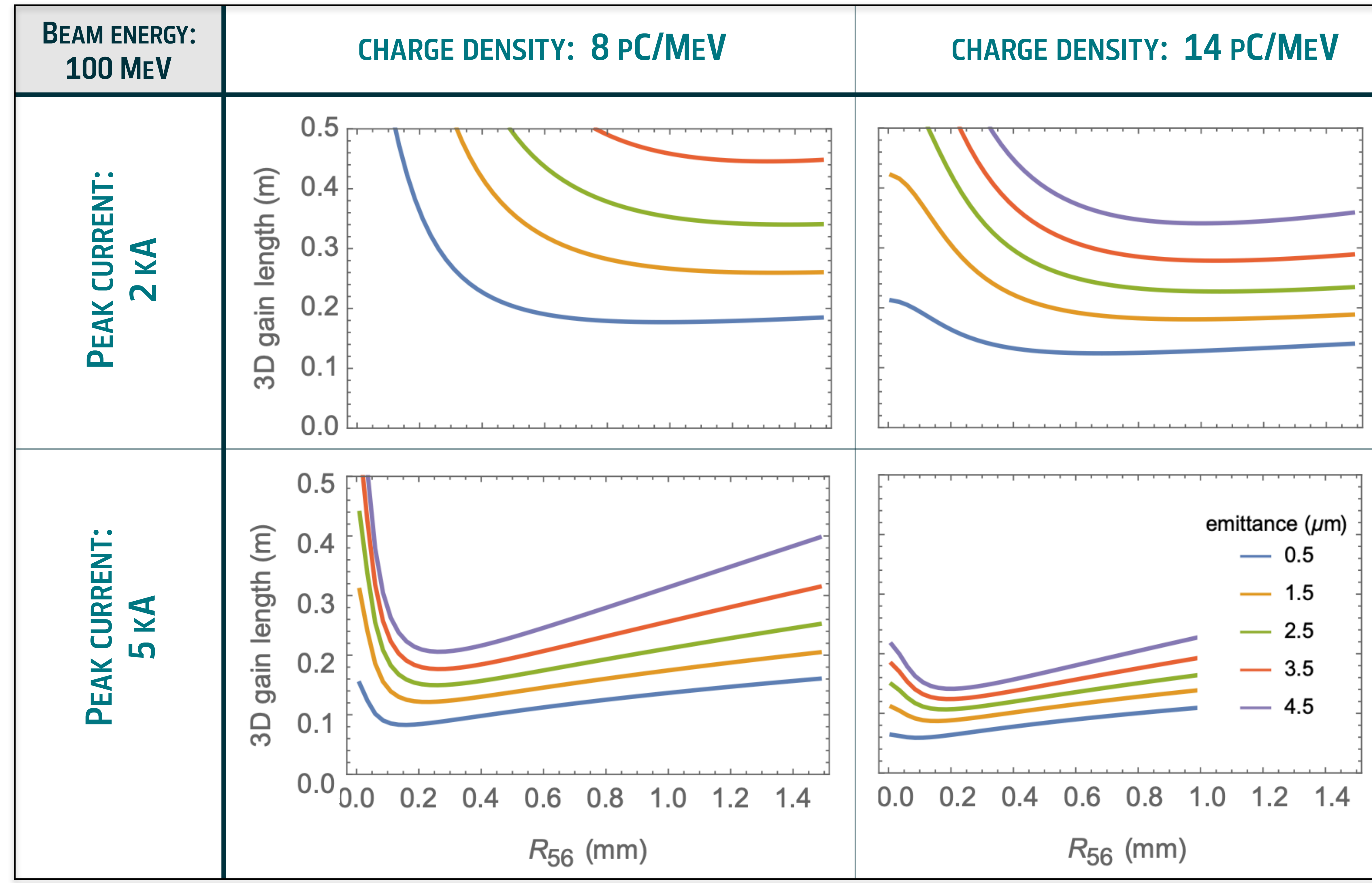
Undulator radiation



PI & Material Courtesy: Sam Barber

Experiment design considerations for lasing conditions.

- Slice energy spread reduction via bunch decompression in a magnetic chicane.
  A. R. Maier et al, PRX 2, 031019 (2012).
  - Tunable R56: 0 — 1.5 mm
- Undulator length: 4 m.
- Assumptions for calculations:
  - Transversely matched beam.
  - Good alignment to undulator axis.



Experimental design covers large to-be-expected phase space of LPA beam parameters.

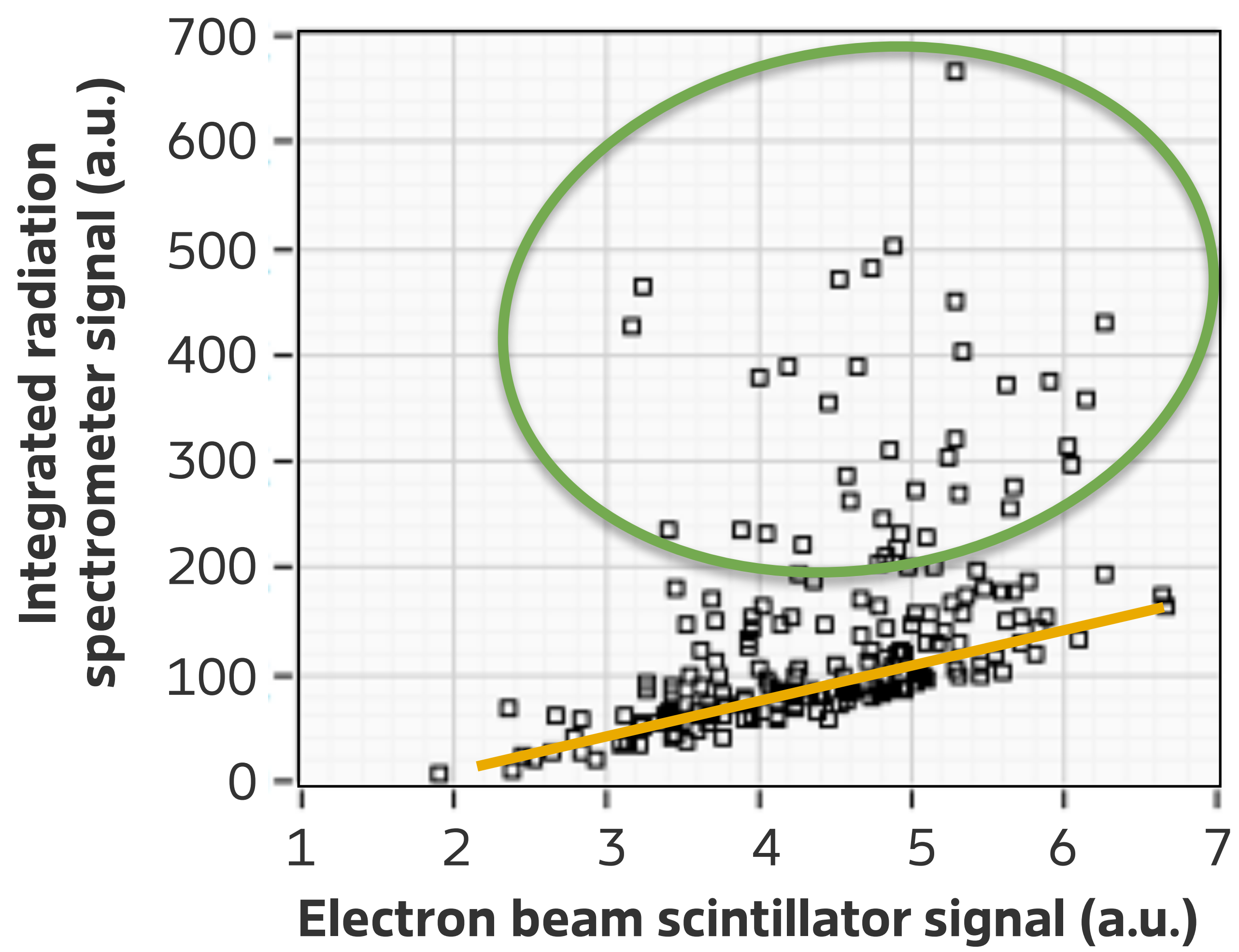
PI & Material Courtesy: Sam Barber

Evidence of coherent undulator radiation enhancement.

Data taken in partnership with TAU Systems Inc.

> Simultaneous measurement of:

1. Electron beam profile at dipole spectrometer. (Integrated signal intensity ∝ **beam charge**.)
2. **Undulator radiation** at the end of the undulator.



Enhanced radiation intensity by a factor of up to ~10.

≙ **Coherent** undulator radiation enhancement.

Linear trend of radiation intensity.

≙ **Incoherent** spontaneous undulator radiation.

> Measurements at 50% of the undulator length show only linear intensity growth with beam charge.

Optimisation and stabilisation of the beam generation and acceleration process needed.

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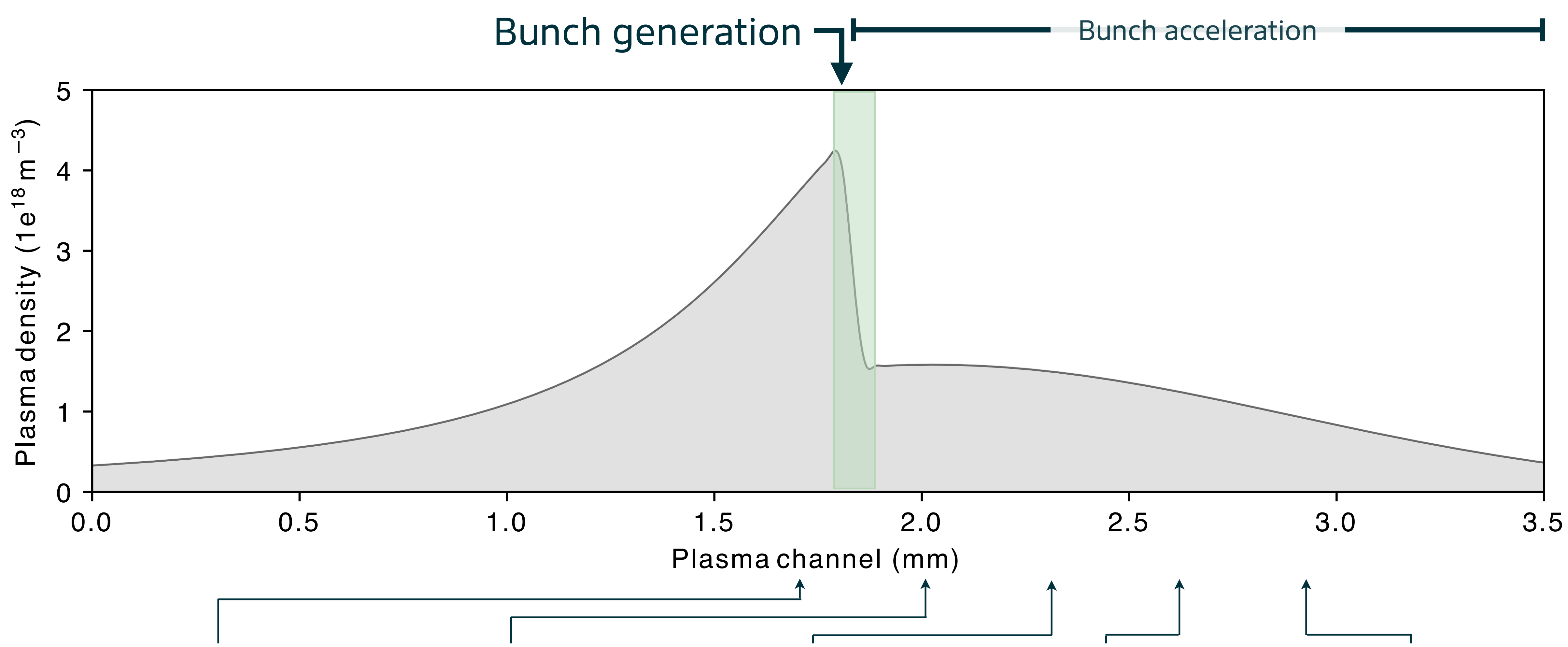
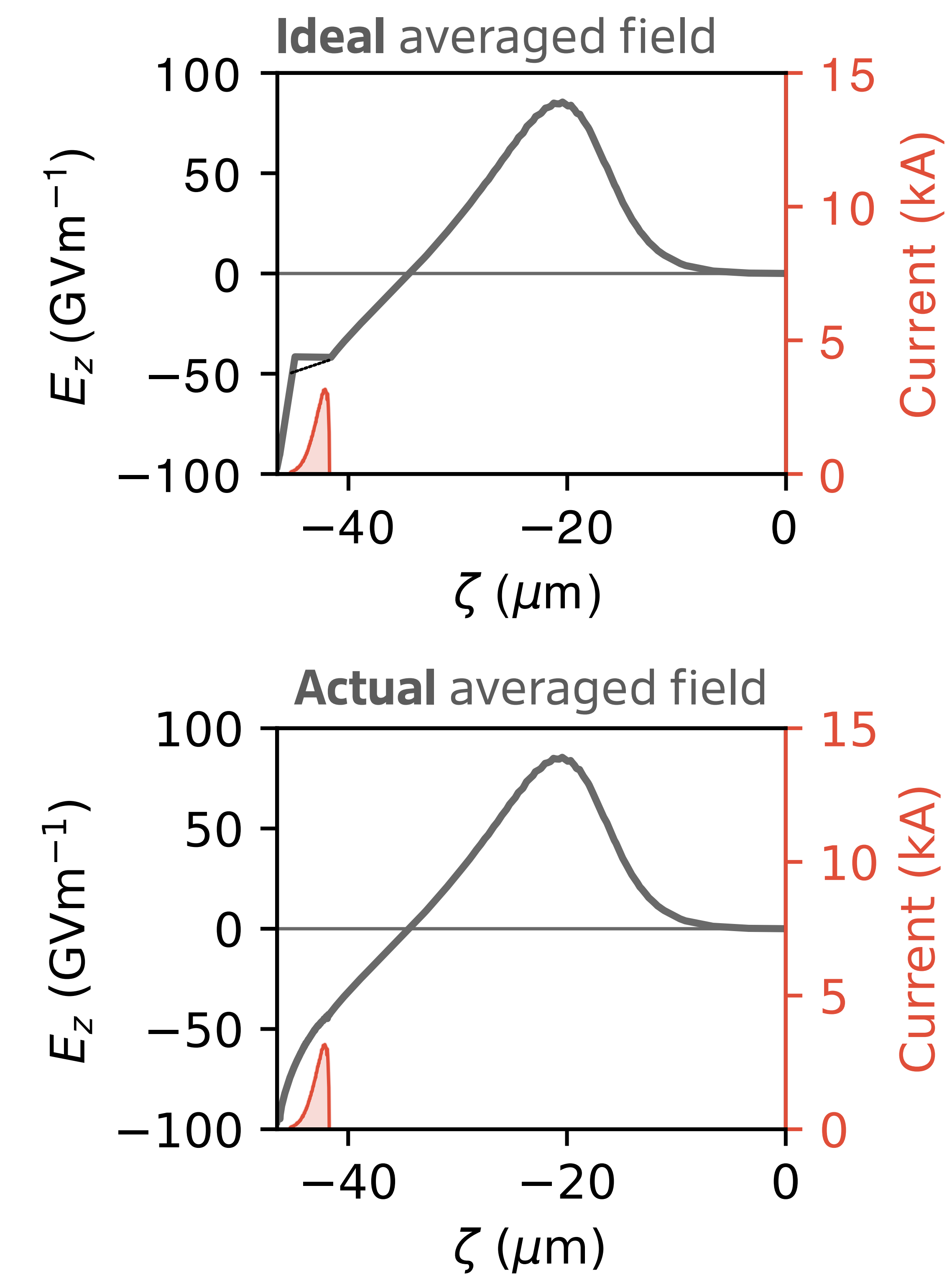
THE BEAM-QUALITY CHALLENGE IN A DENSITY-DOWNRAMP PLASMA ACCELERATOR.





- Bunch generation is determined by:
  - Laser parameters at plasma ramp.
  - Ramp profile.
- Acceleration process is determined by:
  - Plasma density profile.
  - Laser evolution.
  - Beam loading.

HIGH-DIMENSIONAL OPTIMISATION PROCESS:
GUIDANCE FROM SIMULATIONS NEEDED.

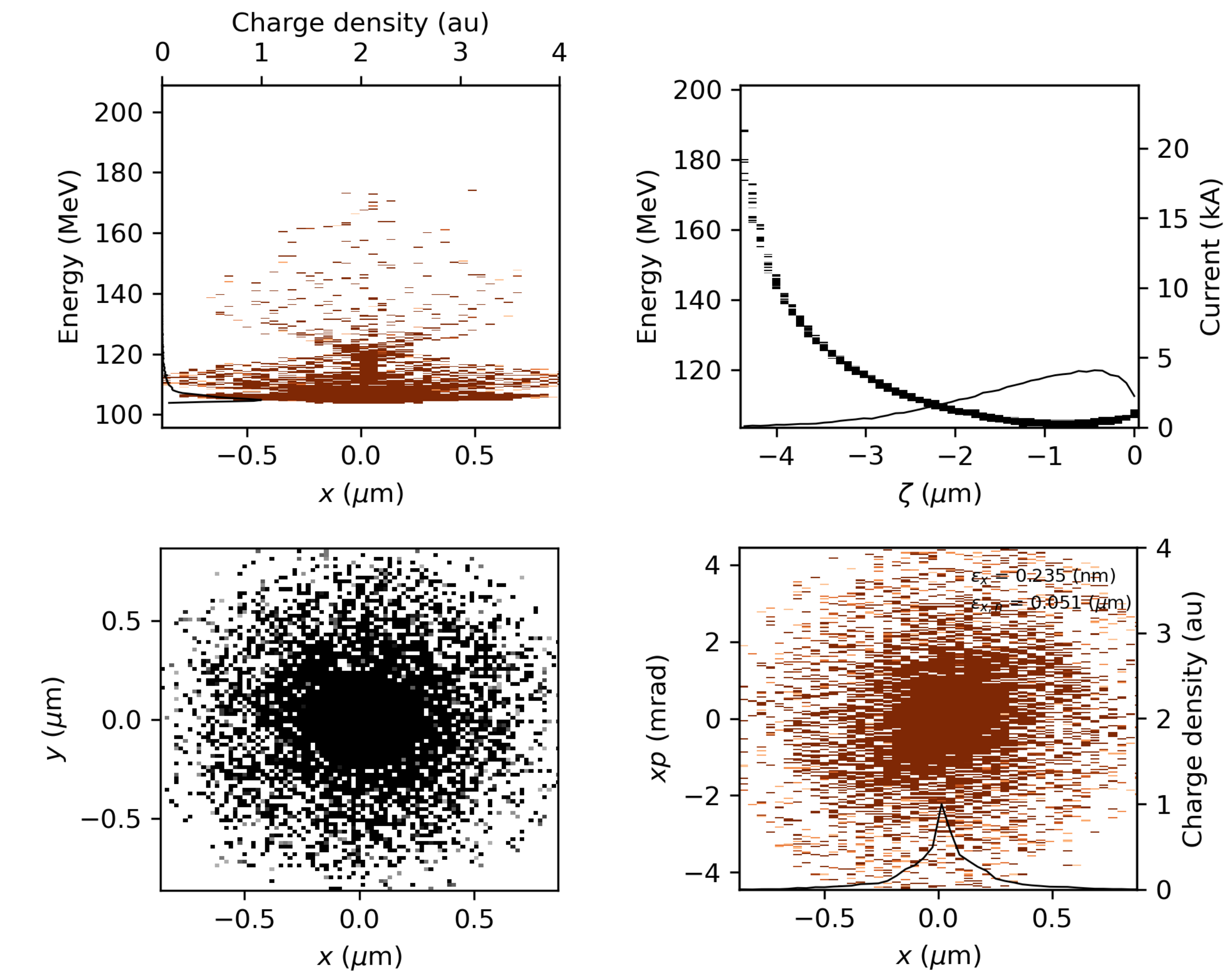
F. Massimo et al Plasma Phys. Control. Fusion 60 034005 (2018).
C. S. Hue et al., Matter Radiat. Extremes 8 (2): 024401 (2023).

SIMULATION SETUP.

- Plasma density profile:
  - Longitudinal: fit on experimental data.
  - Transverse: constant.
- Laser parameters:
  - Bi-Gaussian intensity profile.
  - Energy: 2.45 J.
  - Waist: 38 μm.
  - Duration: 37 fs.
  - Wavelength: 0.8 μm.
- Computational specifications:
  - PIC code: FBPIC.
  - EM solver: Pseudo Spectral Analytical Time Domain (PSATD).
  - Geometry: cylindrically symmetric (RZ, quasi-3D).
  - Lorentz boosted frame: $\gamma = 2$.
  - Resolution:
    - $N_r/\lambda_0 = 8 \triangleq \Delta r = 0.1$ μm
    - $N_z/\lambda_0 = 150 \triangleq \Delta z = 0.006$ μm
  - 4 hours on 8 GPUs (Nvidia A100).

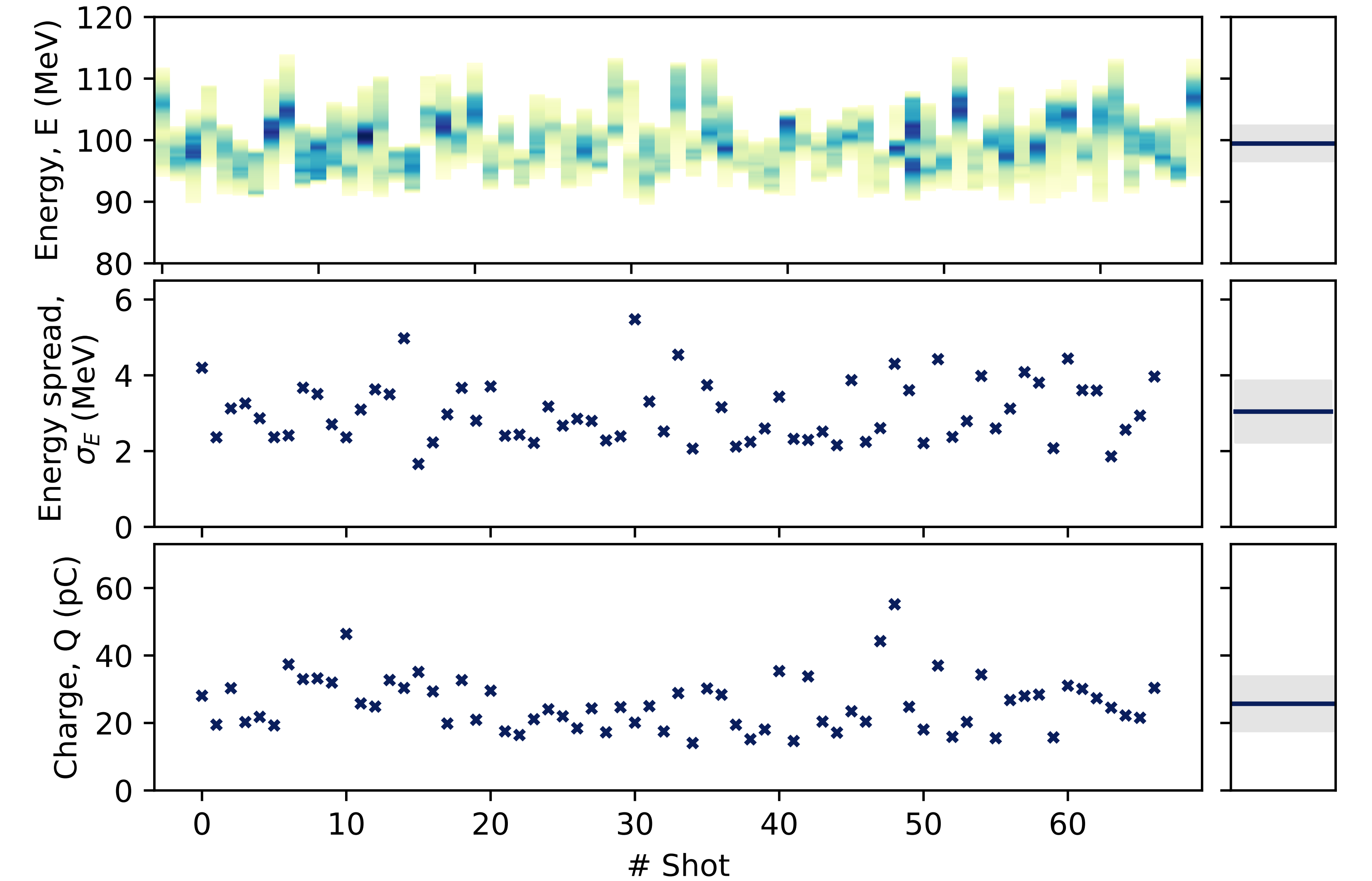
SIMULATIONS SHOW GOOD AGREEMENT WITH EXPERIMENTS

SIMULATIONS



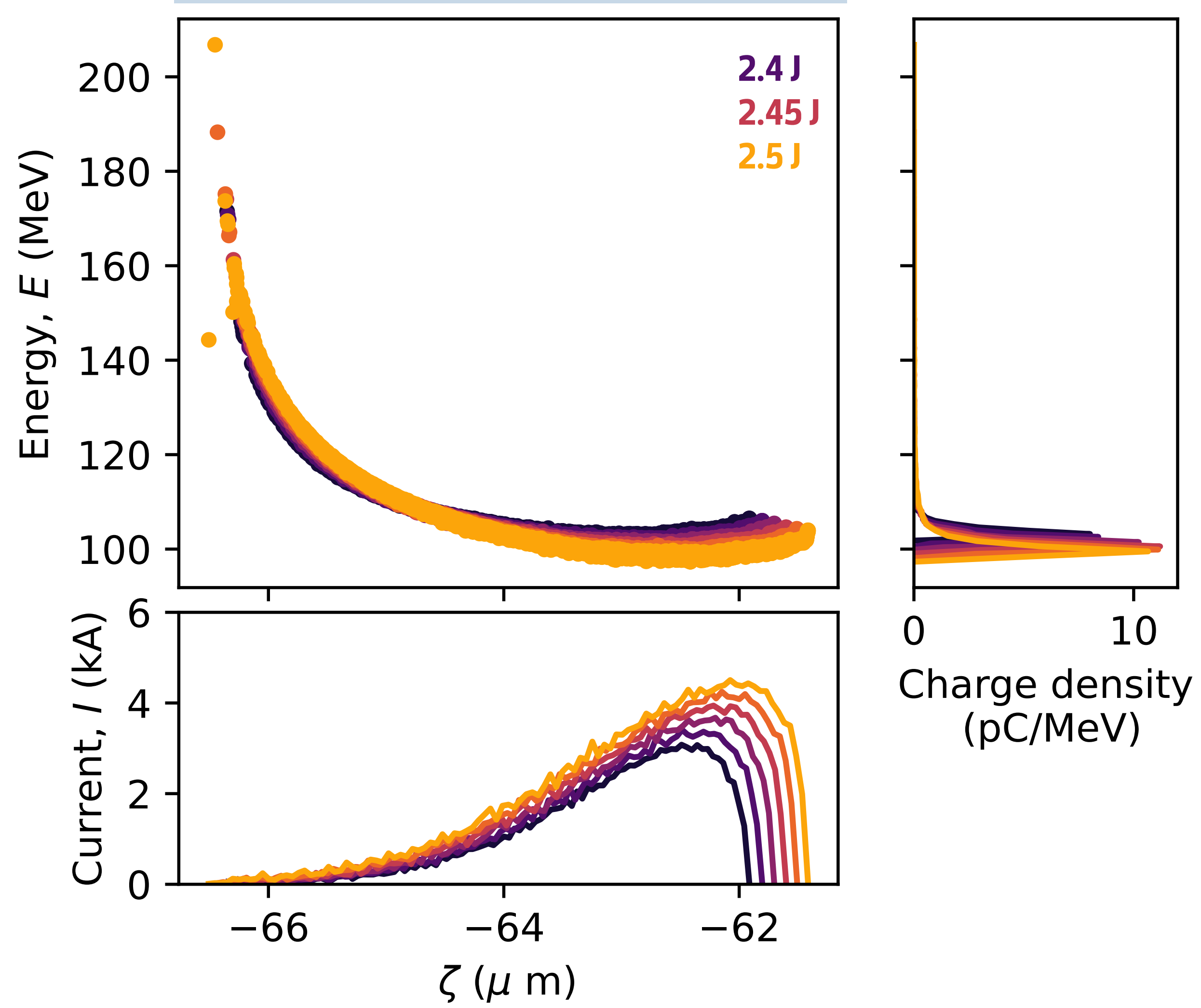
Q: 27.19 pC
<E>: 107.5 MeV
δ_E: 5.3 %

EXPERIMENTAL DATA



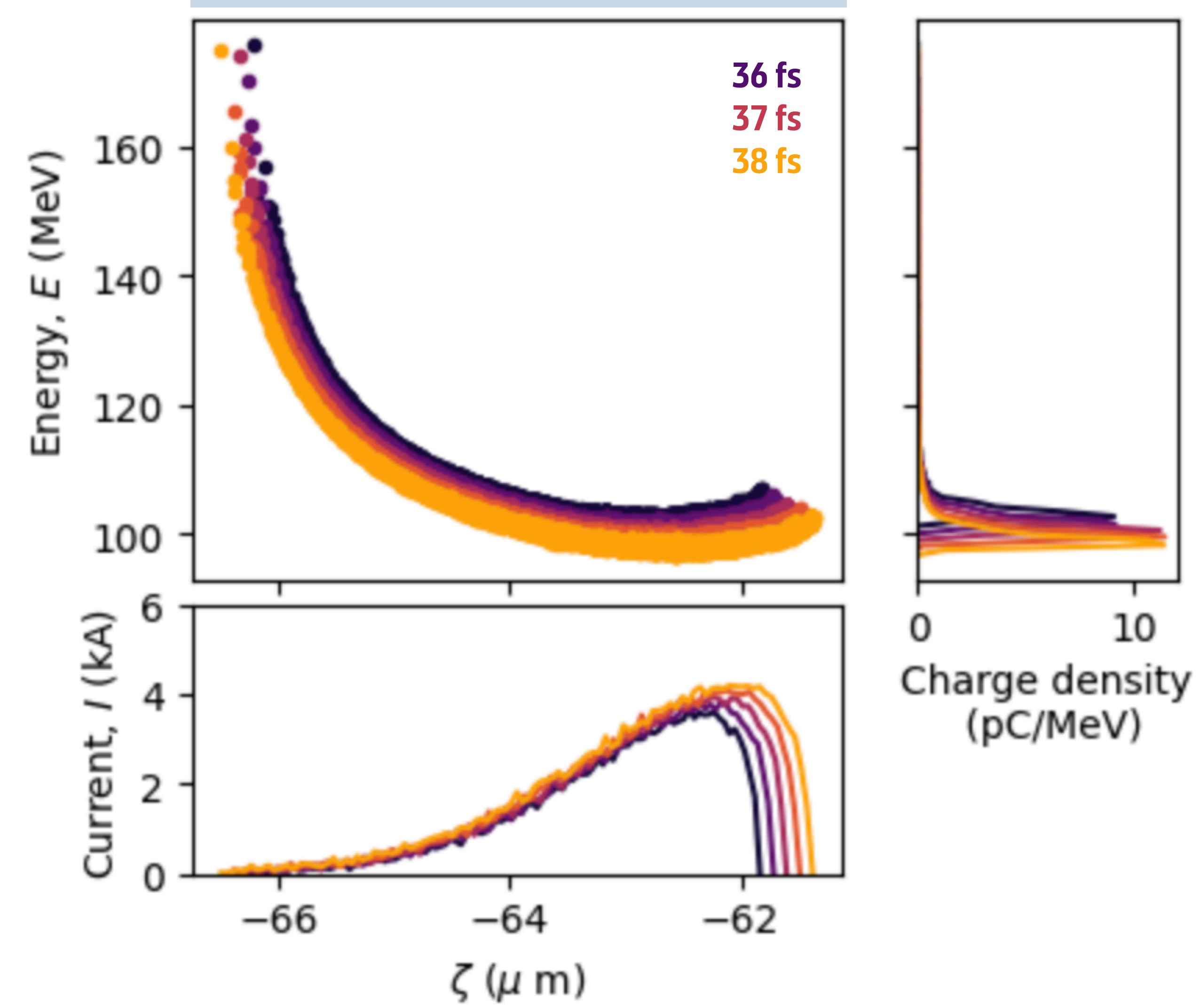
BEAM PROFILE DEPENDENCIES — A QUALITATIVE VIEW.

LASER ENERGY



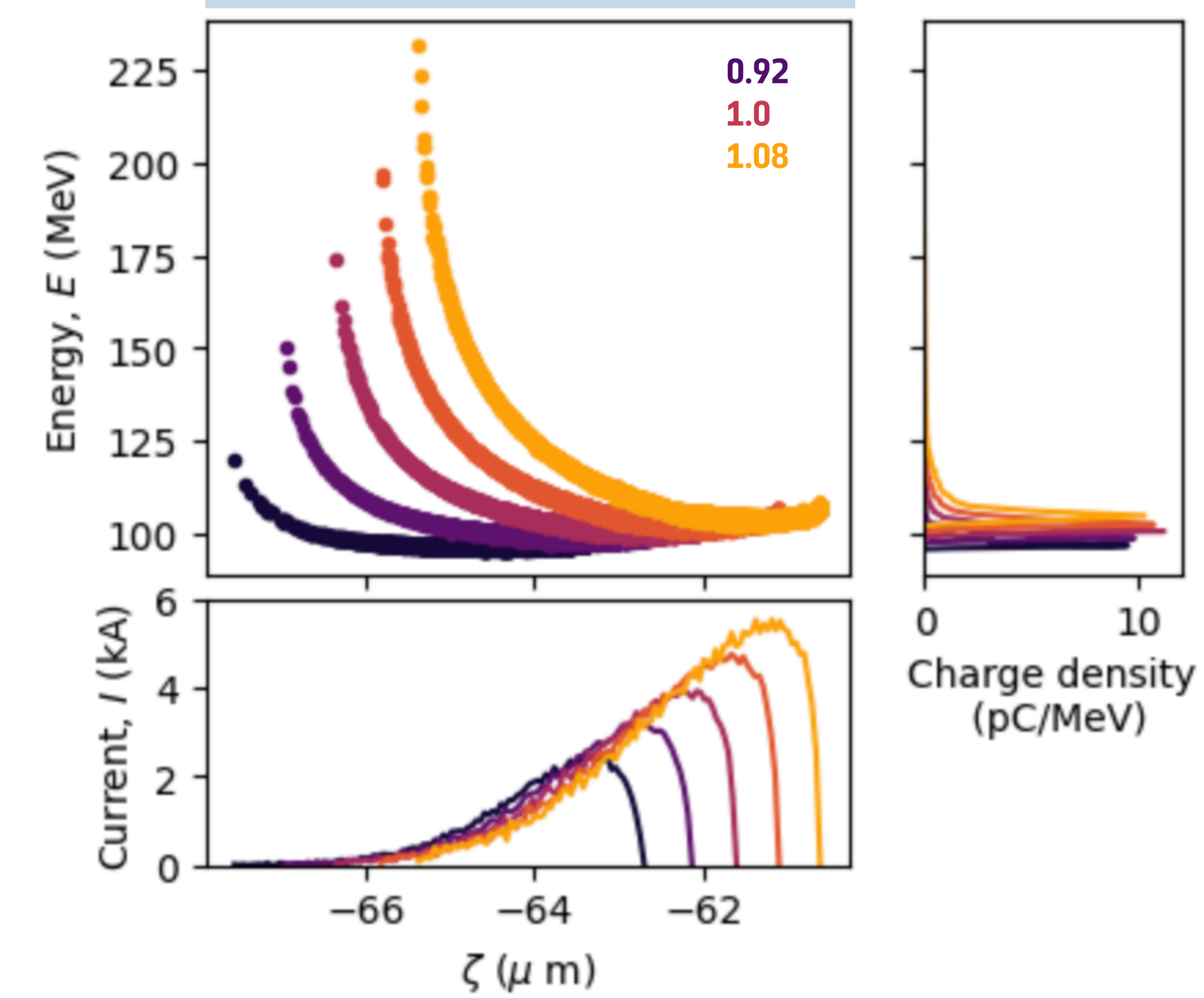
- Bunch length modification.
- Peak current modification.
- **Longitudinal phase-space rotation.**

LASER DURATION



- Bunch length modification.
- Peak current modification.
- **Energy shift.**

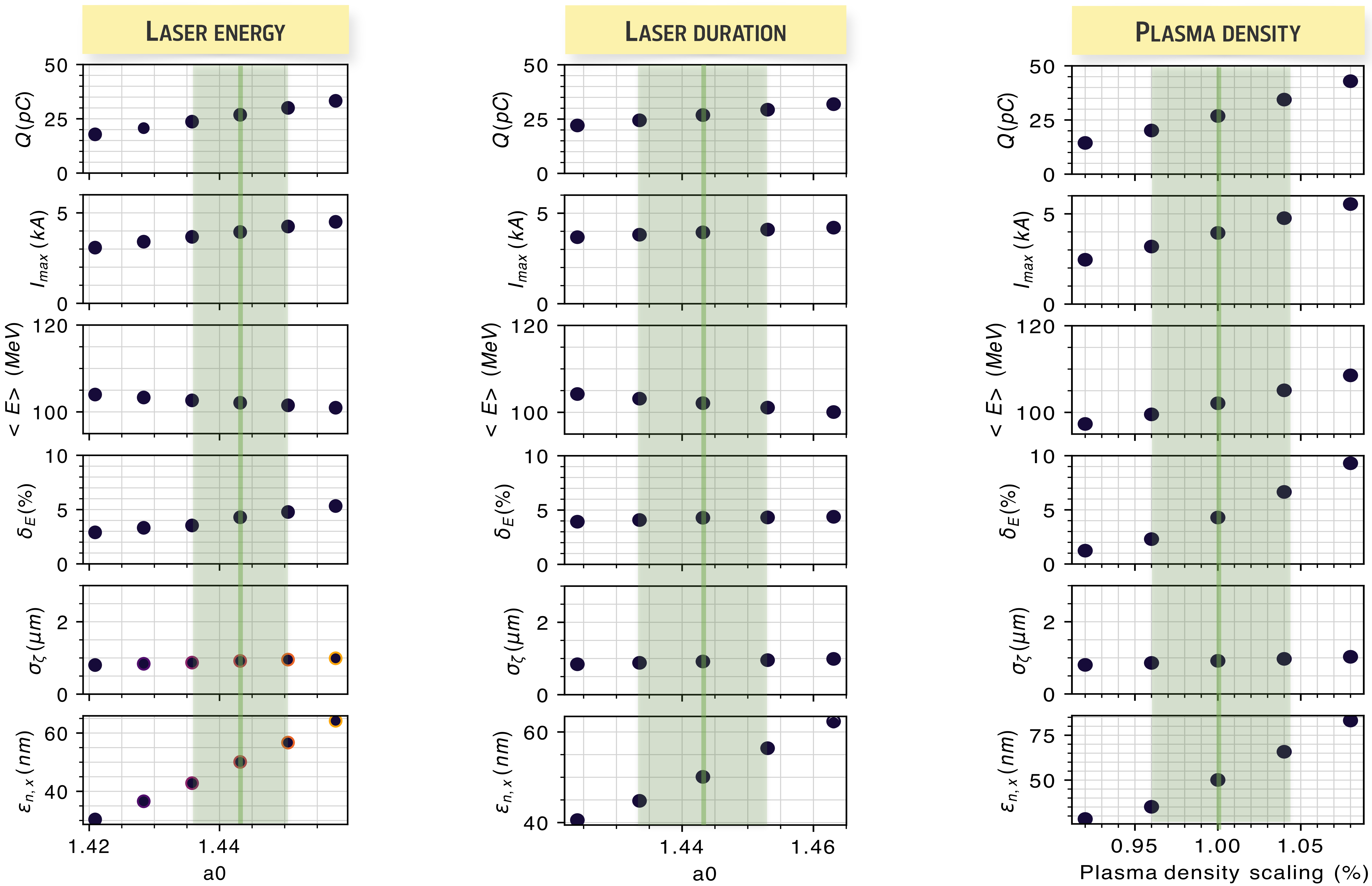
PLASMA DENSITY



- Bunch length modification.
- Peak current modification.
- **Tail dechirping.**

Beam parameter dependencies.

± experimental jitter



Major source for charge jitter

Major source for peak current jitter

Major source for energy spread jitter

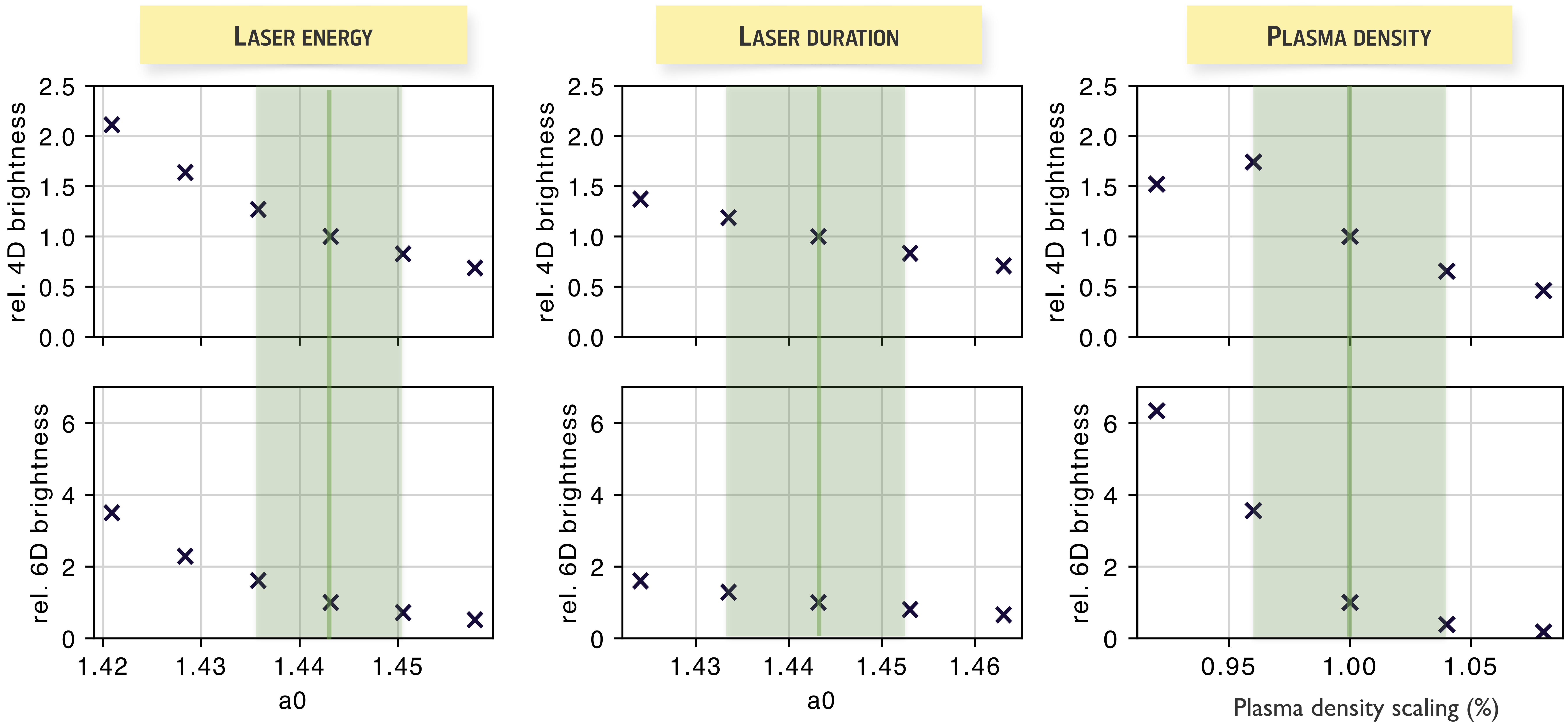
$\sigma_{exp} = 0.025\,J$ $\sigma_{exp} = 0.5\,fs$ $\sigma_{exp} = 4\,\%$

BEAM BRIGHTNESS VARIANCE.

± experimental jitter

$$B_{4D} \propto \frac{I}{\epsilon_x \epsilon_y}$$

$$B_{6D} \propto \frac{I}{\epsilon_x \epsilon_y \epsilon_z}$$



SUMMARY AND OUTLOOK.

- BELLA is working towards a reliable LWFA-based FEL facility.
  - 30 pC @ 100 MeV beams are routinely achieved.
  - Experiments show evidence for coherent undulator radiation.
- The bunch generation and acceleration process can be accurately modelled with PIC simulations.
  - Simulations are computationally expensive.
  - A detailed tolerance study may require a different simulation setup.
- Simulations unlock most relevant dependencies for guiding the process of experiment optimisation.
- Plasma density jitter seems to be a major source of beam parameter jitter — to be confirmed with experiments.

Thank you!

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