

Direct Observation of electron shedding from a laser driven wakefield accelerator

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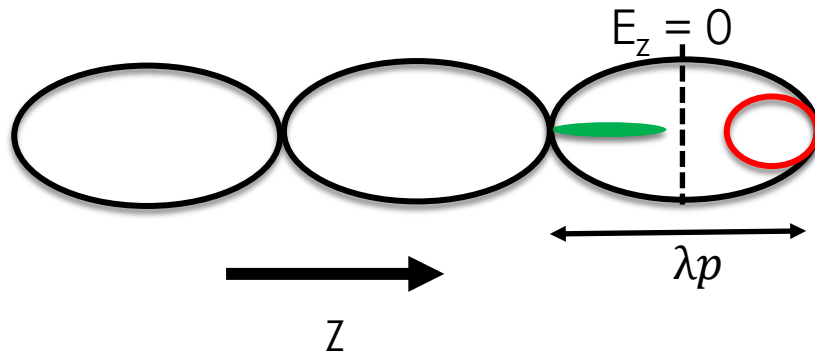
- *Introduction to electron shedding*
- *Measurement of electron beams*
- *Femtosecond relativistic electron microscopy*
- *Experimental Results*
- *Model for long beams*
- *Simulations showing electron shedding*



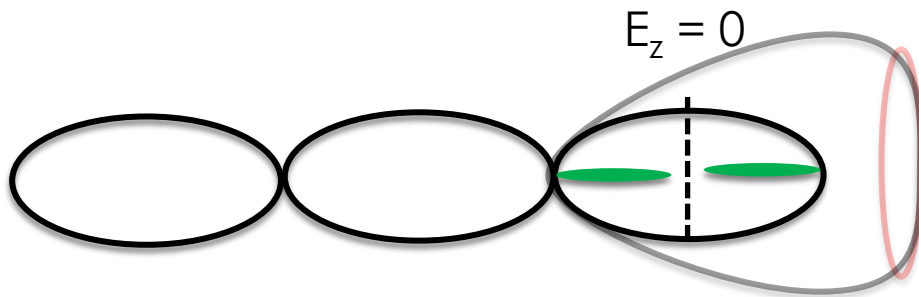
What is Electron Shedding



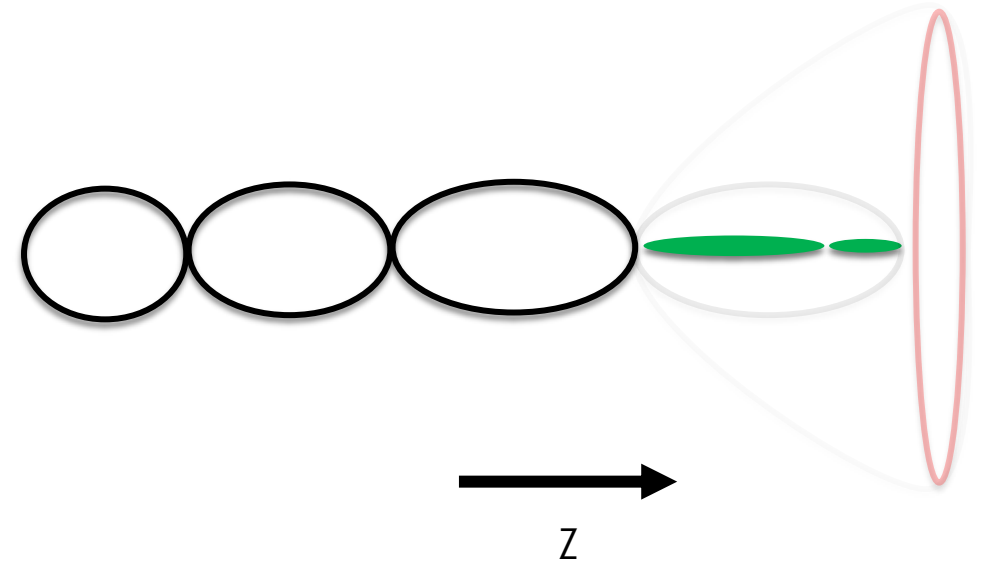
Ideally:



*Electrons present half λ_p away
with a bunch length at most the $\lambda_p/2$*



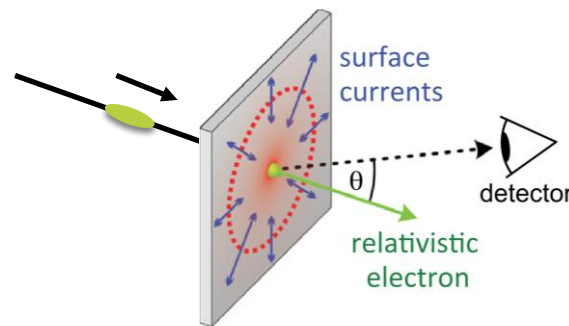
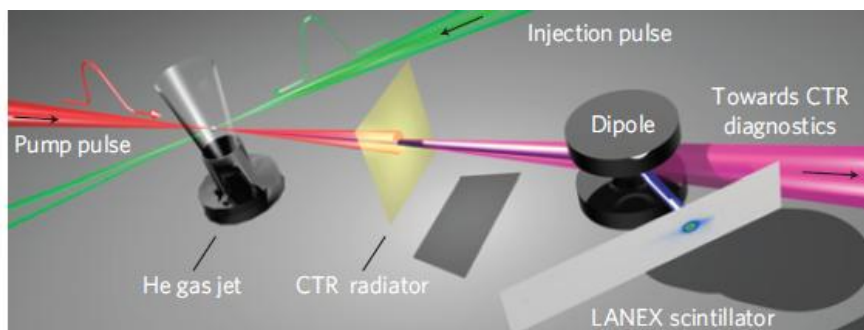
*Upper limit of bunch length is $\sim \lambda_p$ @local plasma
density*



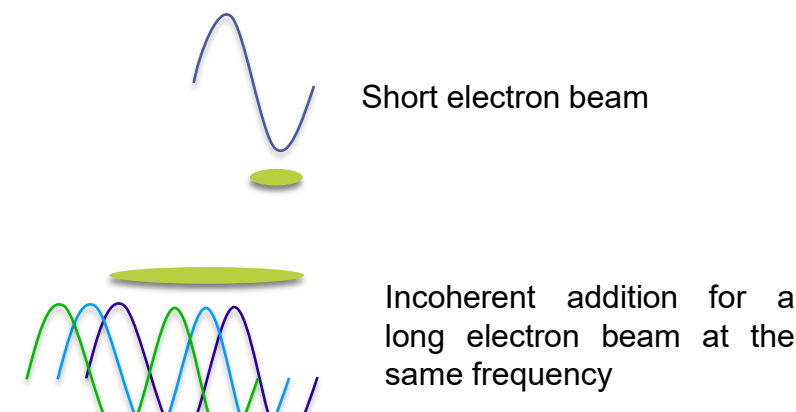
*Lengthening and loss of a beam
Electron Shedding*

How do we measure such an effect?

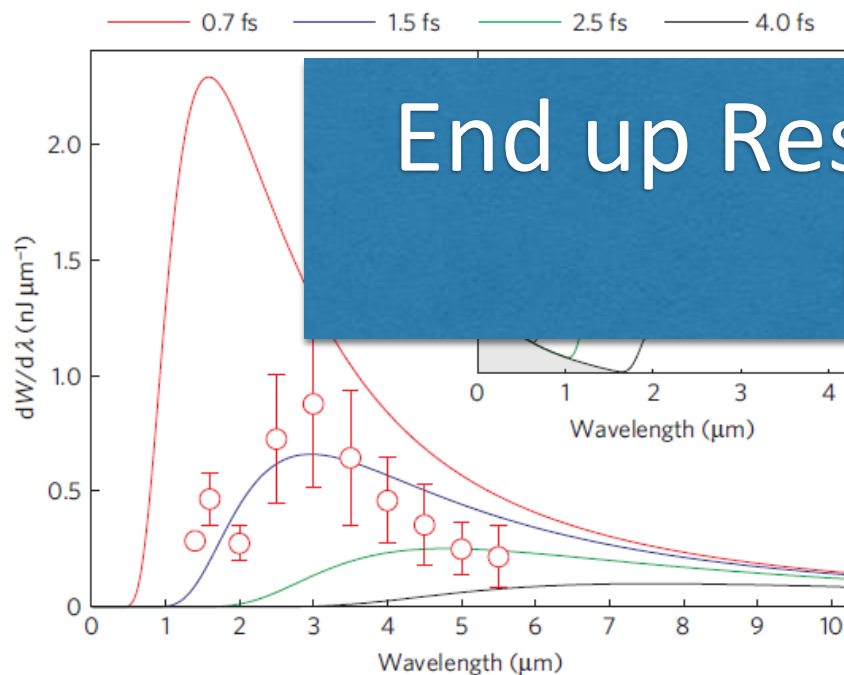
Measurements of electron beams from LPA's



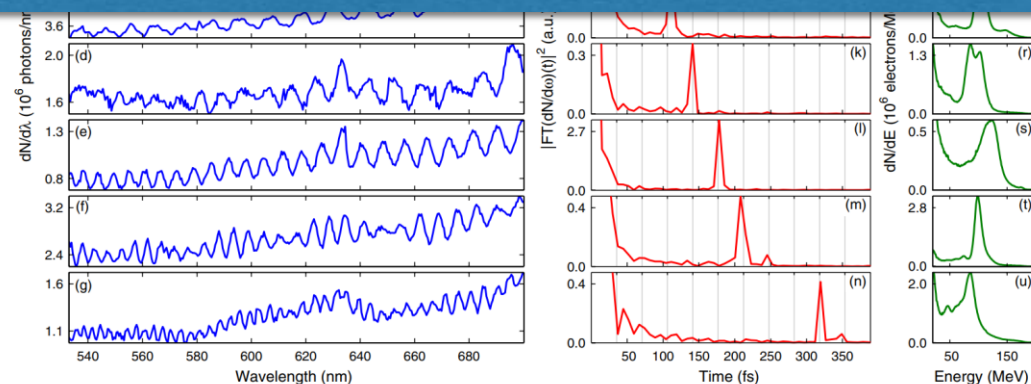
M. C. Downer, et al. Rev. Mod. Phys. **90**, 035002



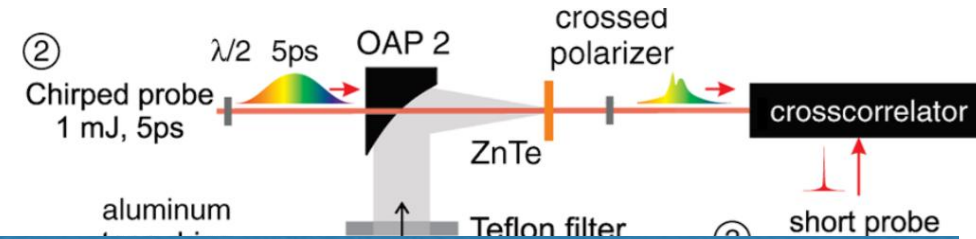
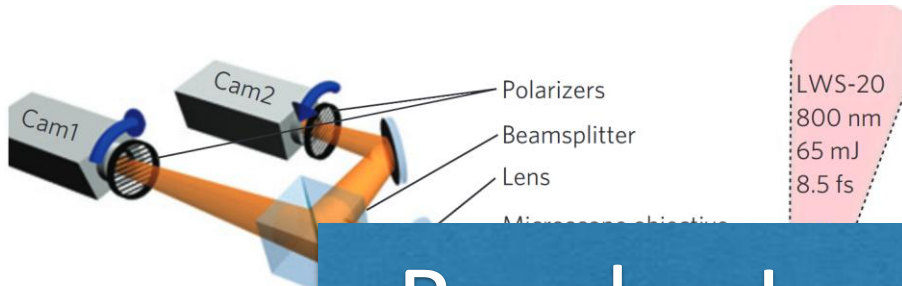
End up Resolving Finer structures but no long scale evolution



O. Lundh, et al. Nat. Phys. **7** (2011): 219-222.



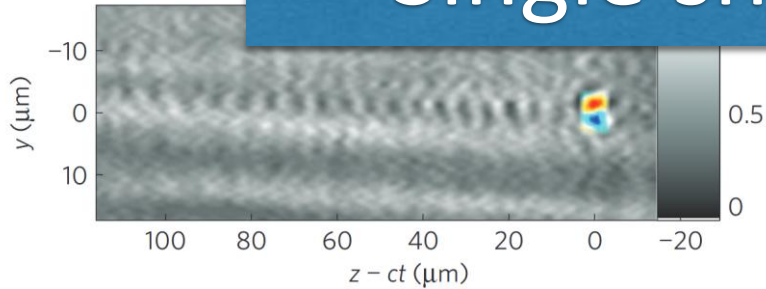
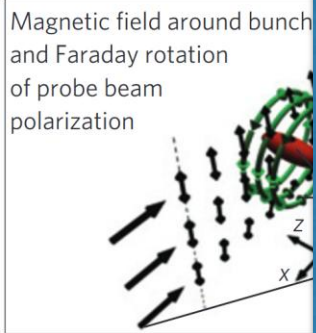
O. Lundh, et al. PRL. **110** 065007 (2013)



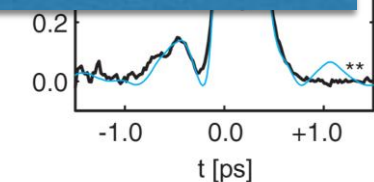
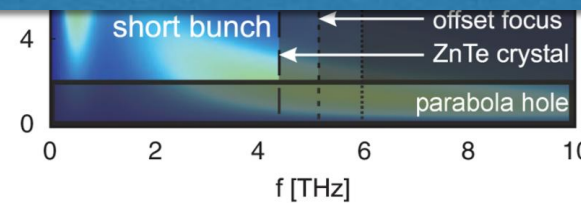
Resolve Long structures but no evolution

We require:

Single shot probing of electron beams

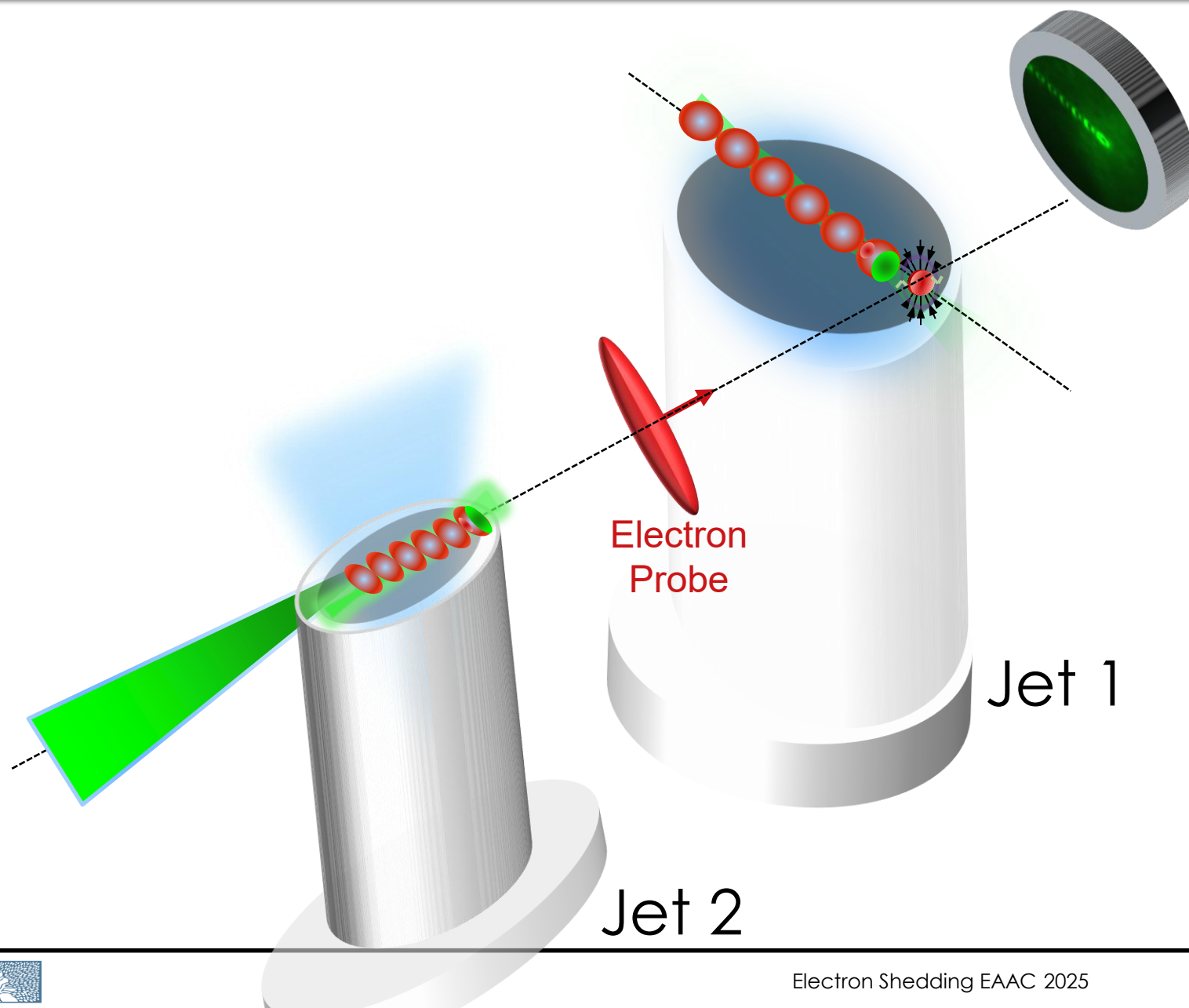


A. Buck, et al. *Nat. Phys.* **7**, pages 543 (2011)



A.D. Debus, et al. *Phys. Rev. Lett.* **104**, 084802

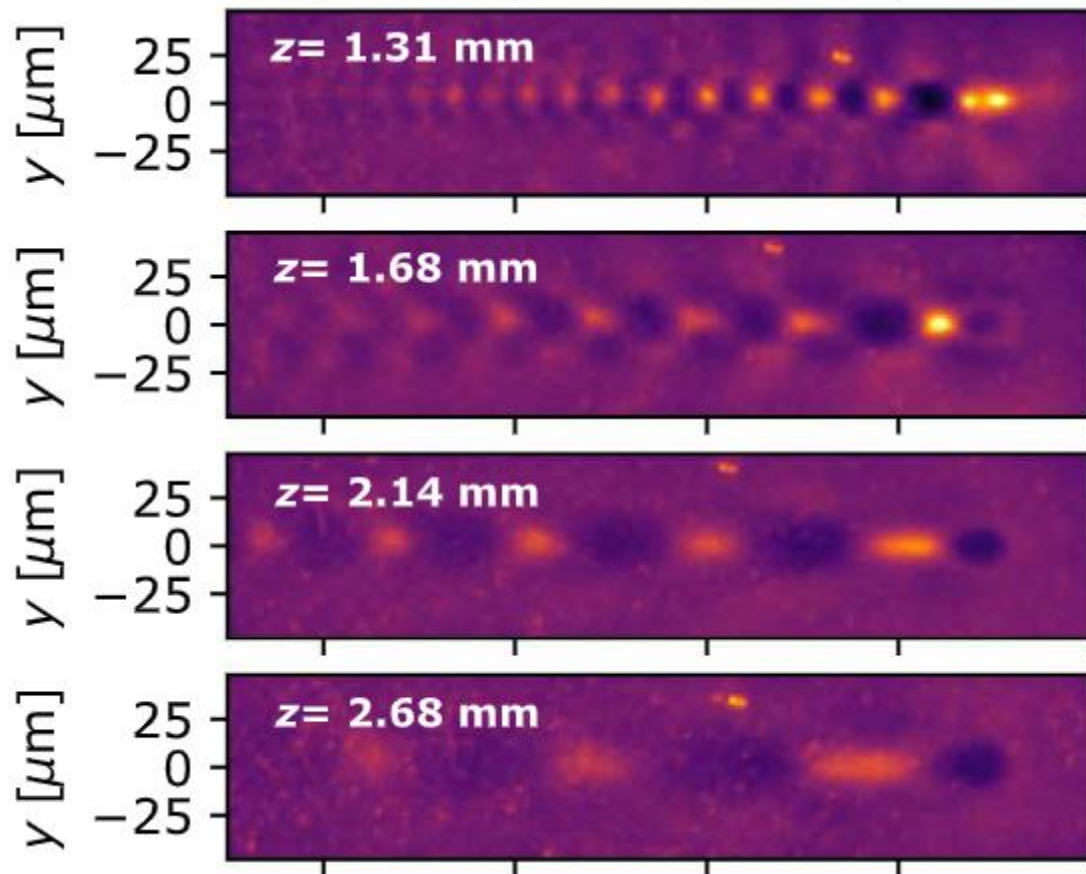
Femtosecond Relativistic Electron Microscopy



What we observed in the past

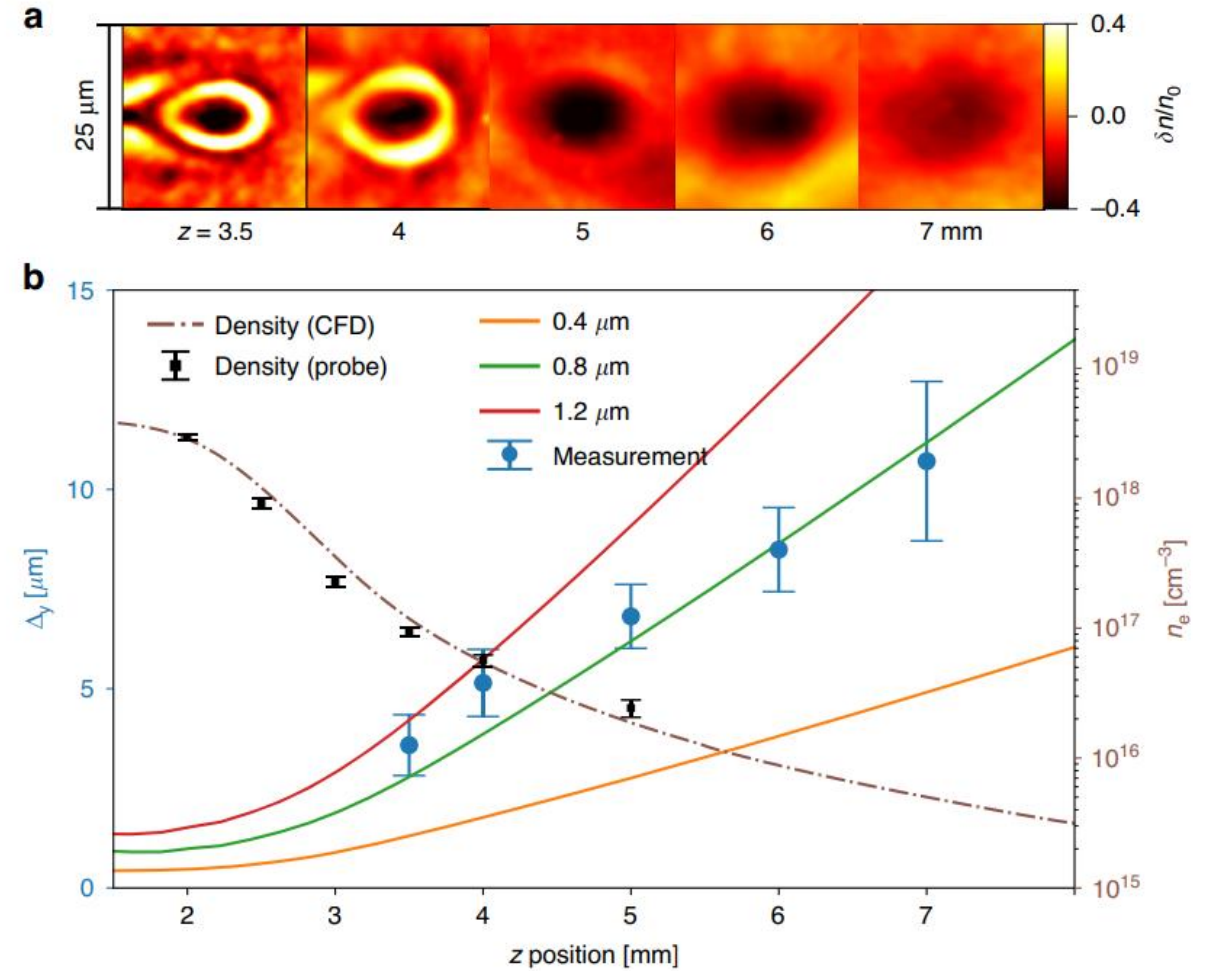


Downramp injection



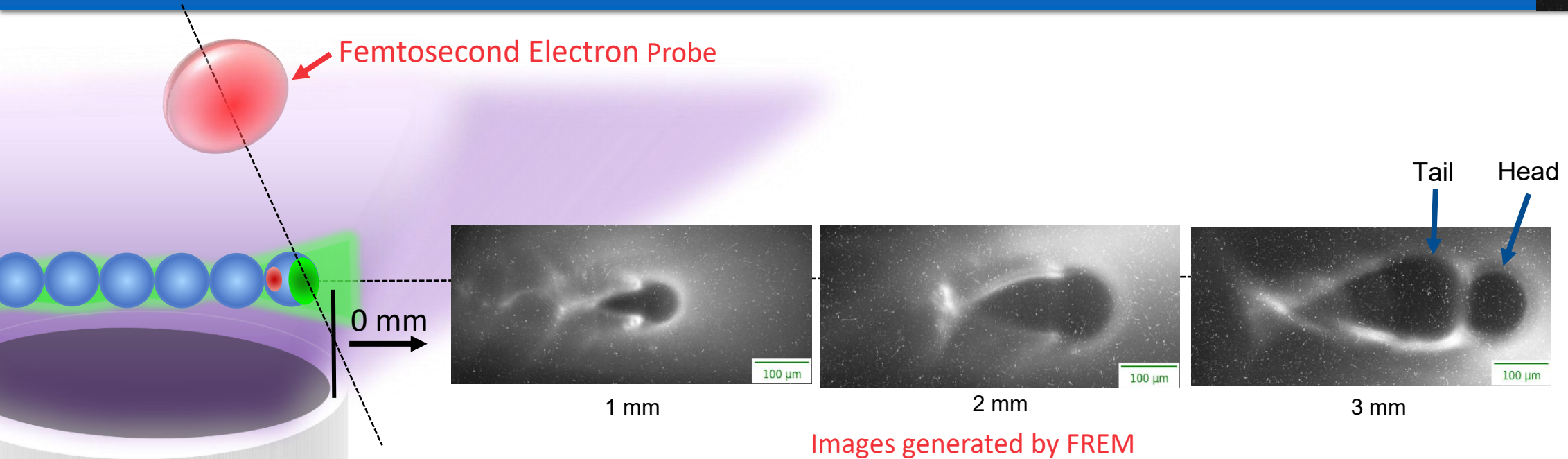
Y. Wan, et. al Science advances, **10**, eadj3595. (2024)

Electron beam exiting an LWFA



Y. Wan et al. Light: Science & Applications 12:116 (2023)

Unexpected Experimental Results



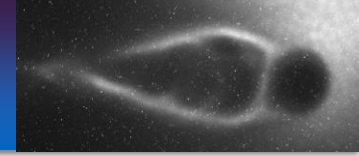
Images generated by FREM

Trying to obtain beams to drive a PWFA stage

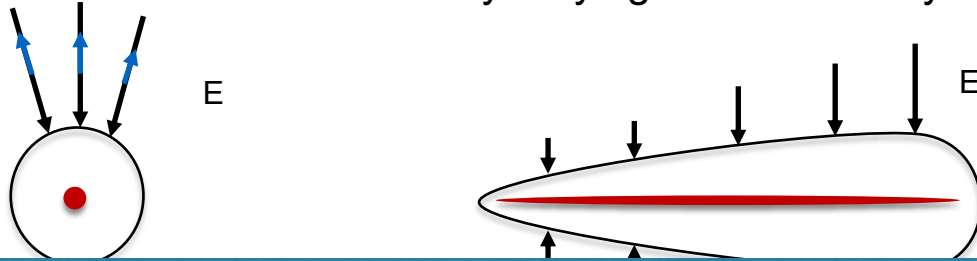
Experimentally we measure between 500 to 700 pc above 100 MeV

A long extending structure unlike what we observed in the past

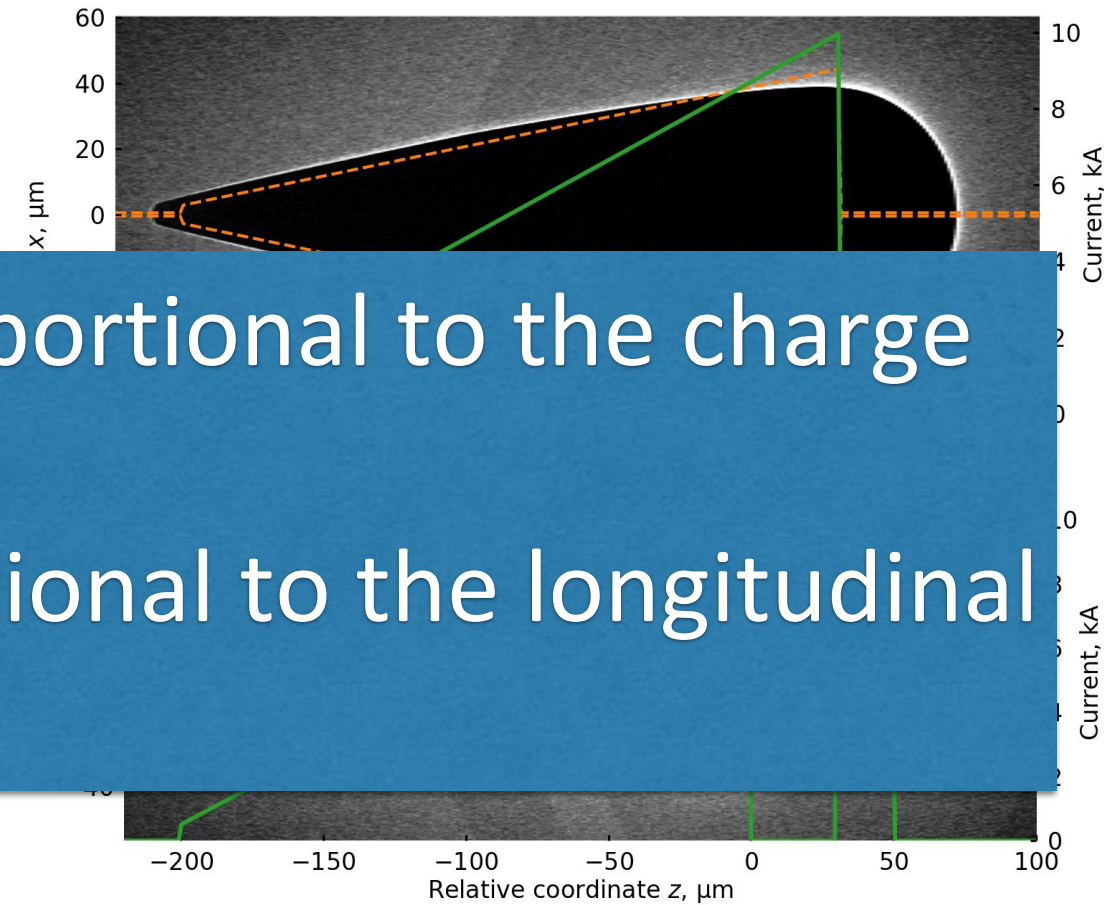
Model to probe the longitudinal current density



Slowly varying current density and a long beam



An analytical model with a relativistic beam



For a short beam width is proportional to the charge

Long beam the width is proportional to the longitudinal current

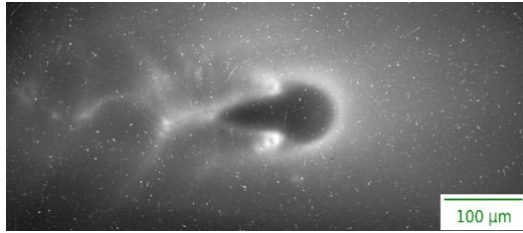
Imprints a circular spot
on the probe

B fields cancel out as the beam propagates

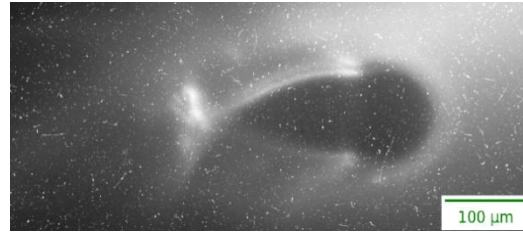
Mapping the longitudinal charge density

The width of the distribution is proportional to the
longitudinal current for a long relativistic beam

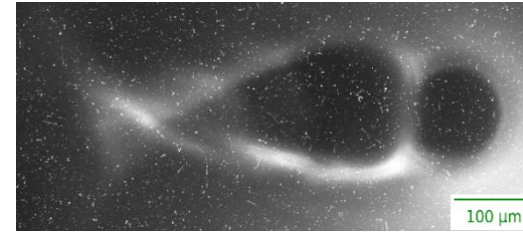
We see the formation of a long tail and its loss: shedding



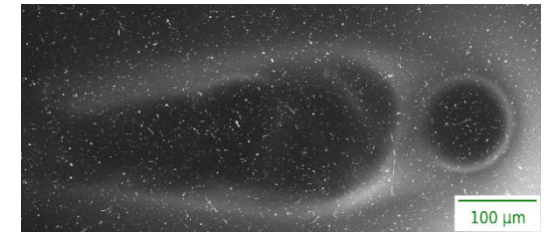
1 mm



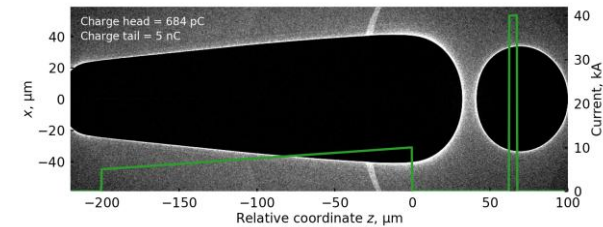
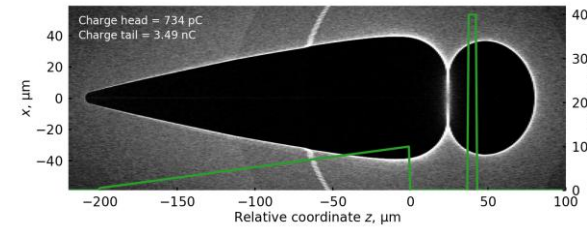
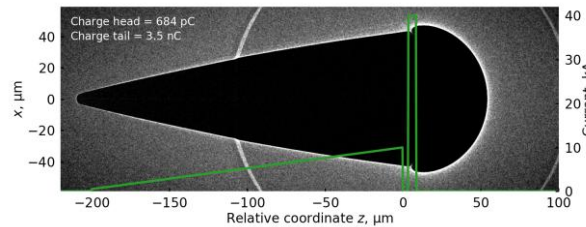
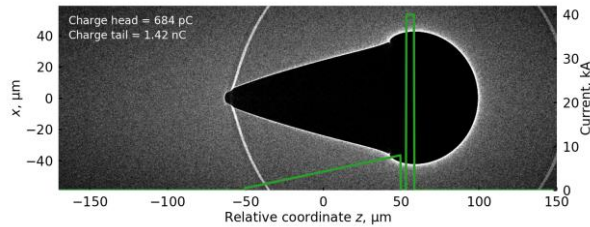
2 mm



3 mm



4 mm



We see a beam with 2 distributions of current lengthening as the beam exits the LWFA



8 mm

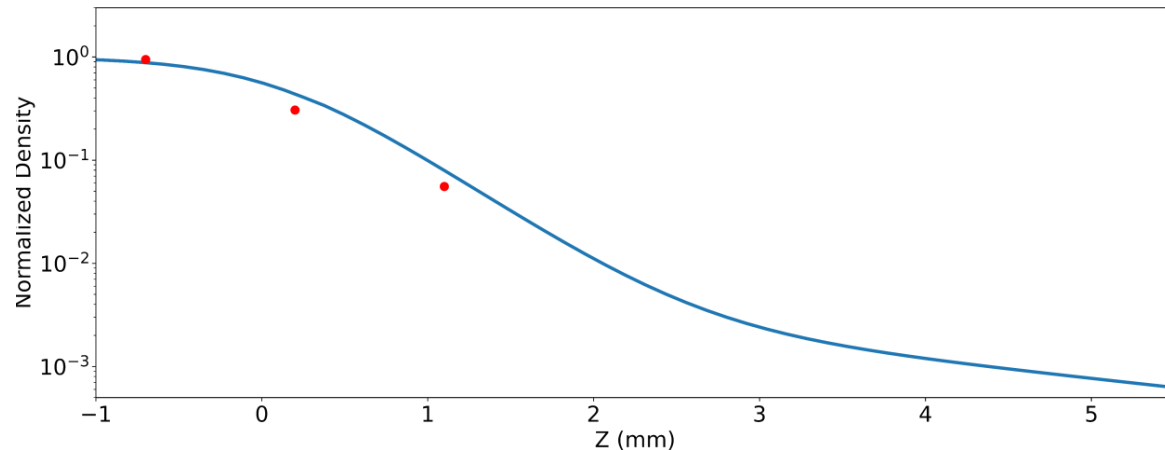
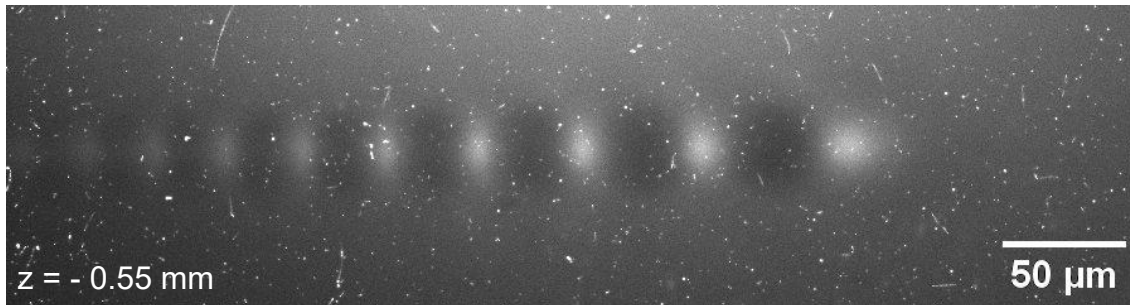
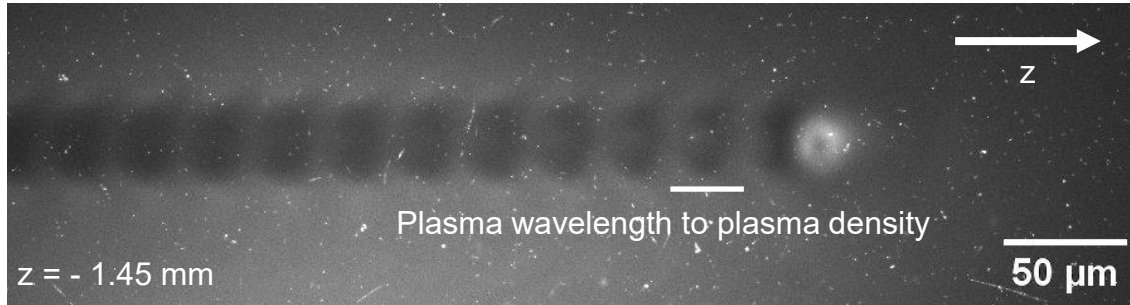
Far away we lose the tail

Where do all these particles go and how are they generated?

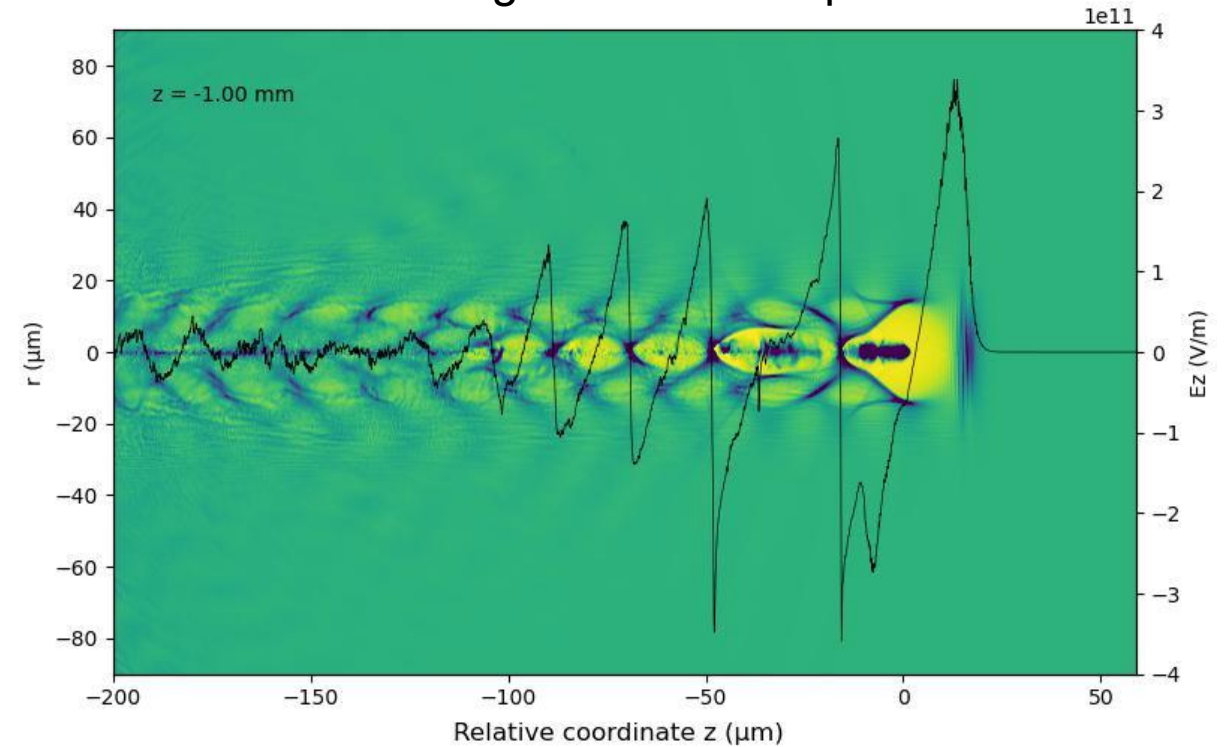
What causes electron shedding



Mapping the down-ramp of the density profile



FBPIC to look at the evolution of the beam during the down-ramp

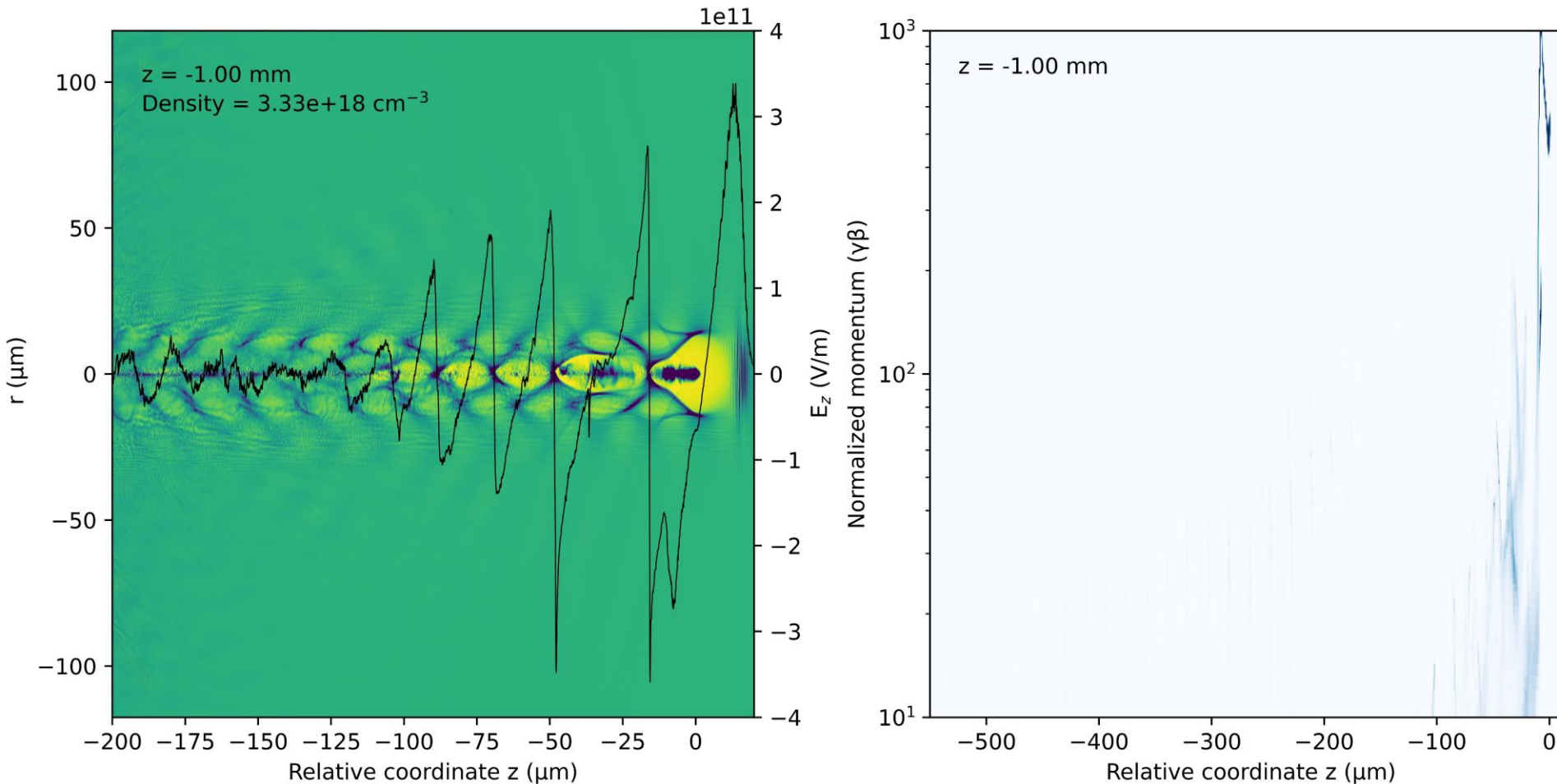


Ionization injection with 2 modes

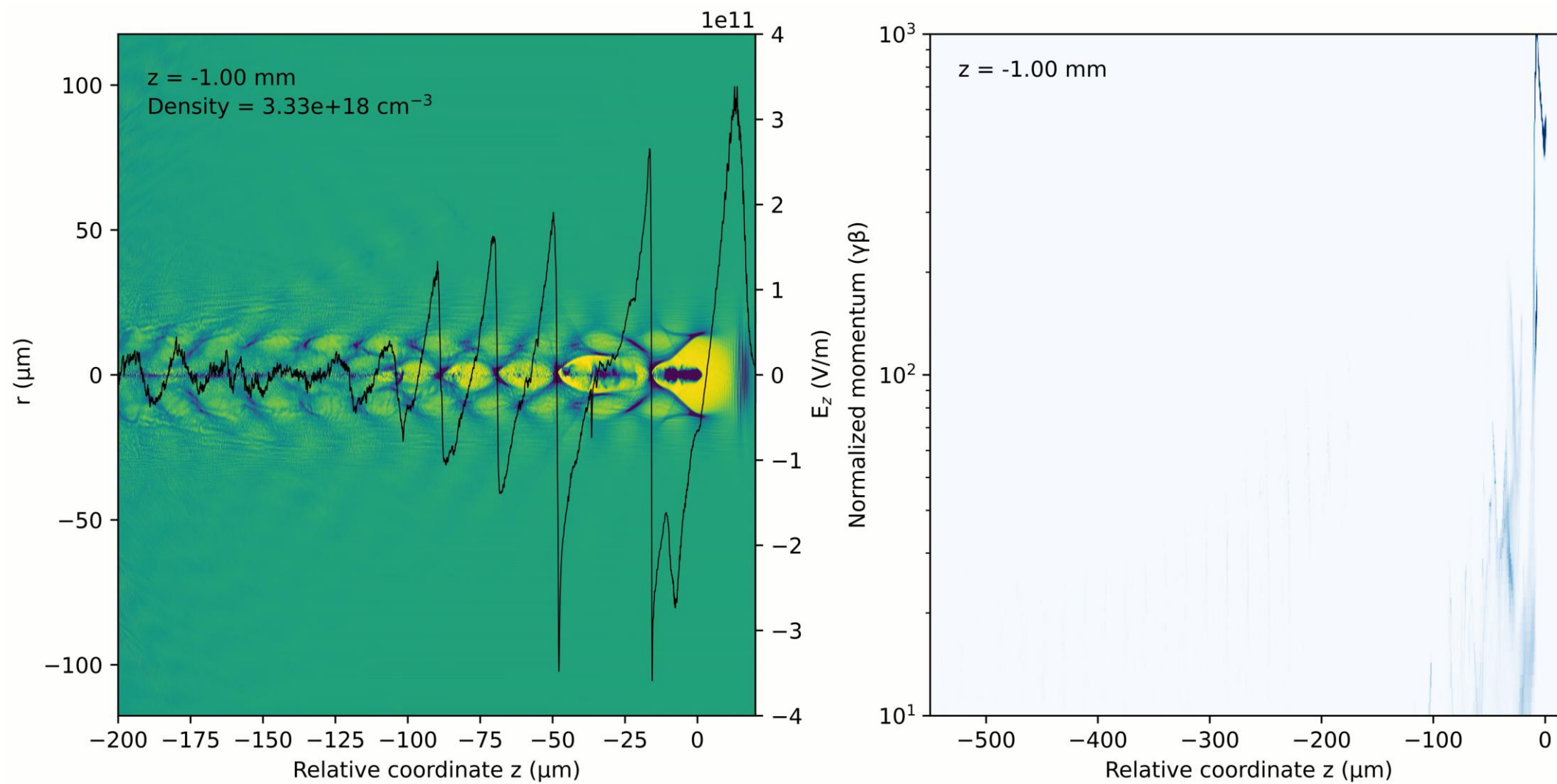
$a_0 = 2$, $w_0 = 27 \mu\text{m}$

Density of plateau: $3.5 \times 10^{18} \text{ cm}^{-3}$ modeled with tanh functions
780 μm x 270 μm moving window decomposed on 4 GPU's

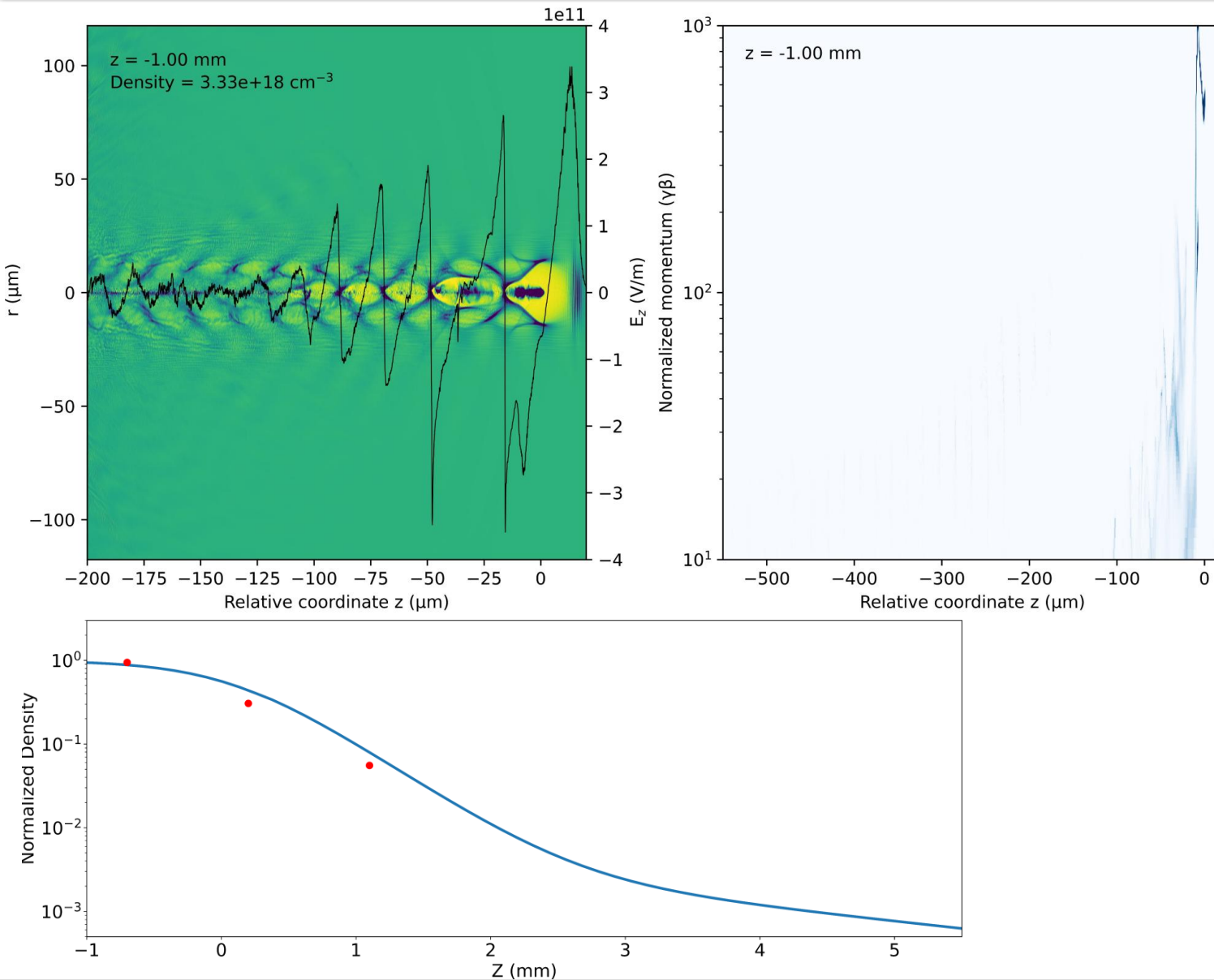
What causes electron shedding



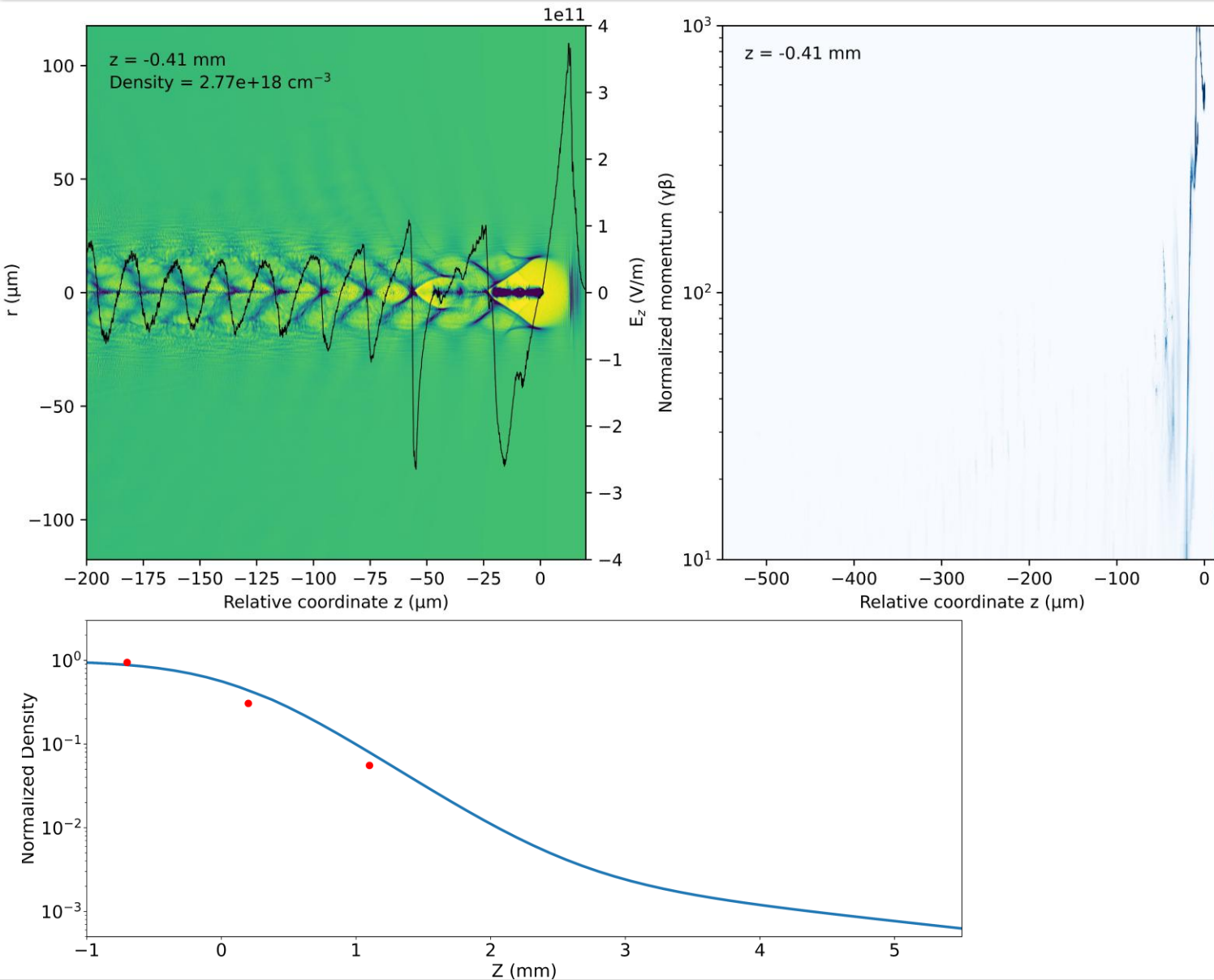
- Electrons accelerated to about 500 MeV
- A charge of 950 pc (>50 MeV) around the down-ramp
- 680 pc above 100 MeV



Simulations: key processes



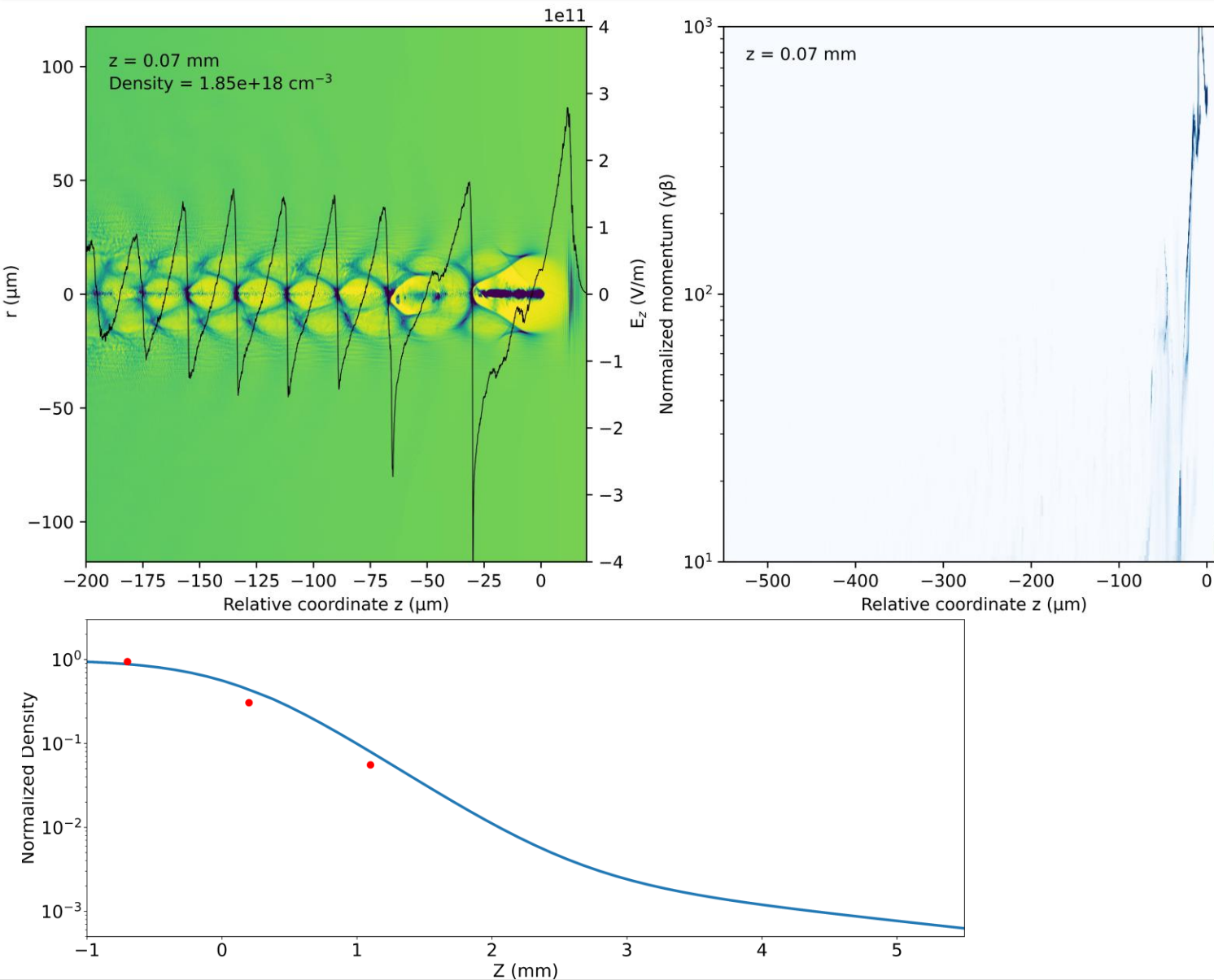
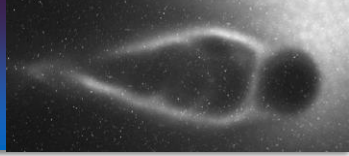
Simulations: key processes



Plasma wavelength increases and electrons start to enter the decelerating phase

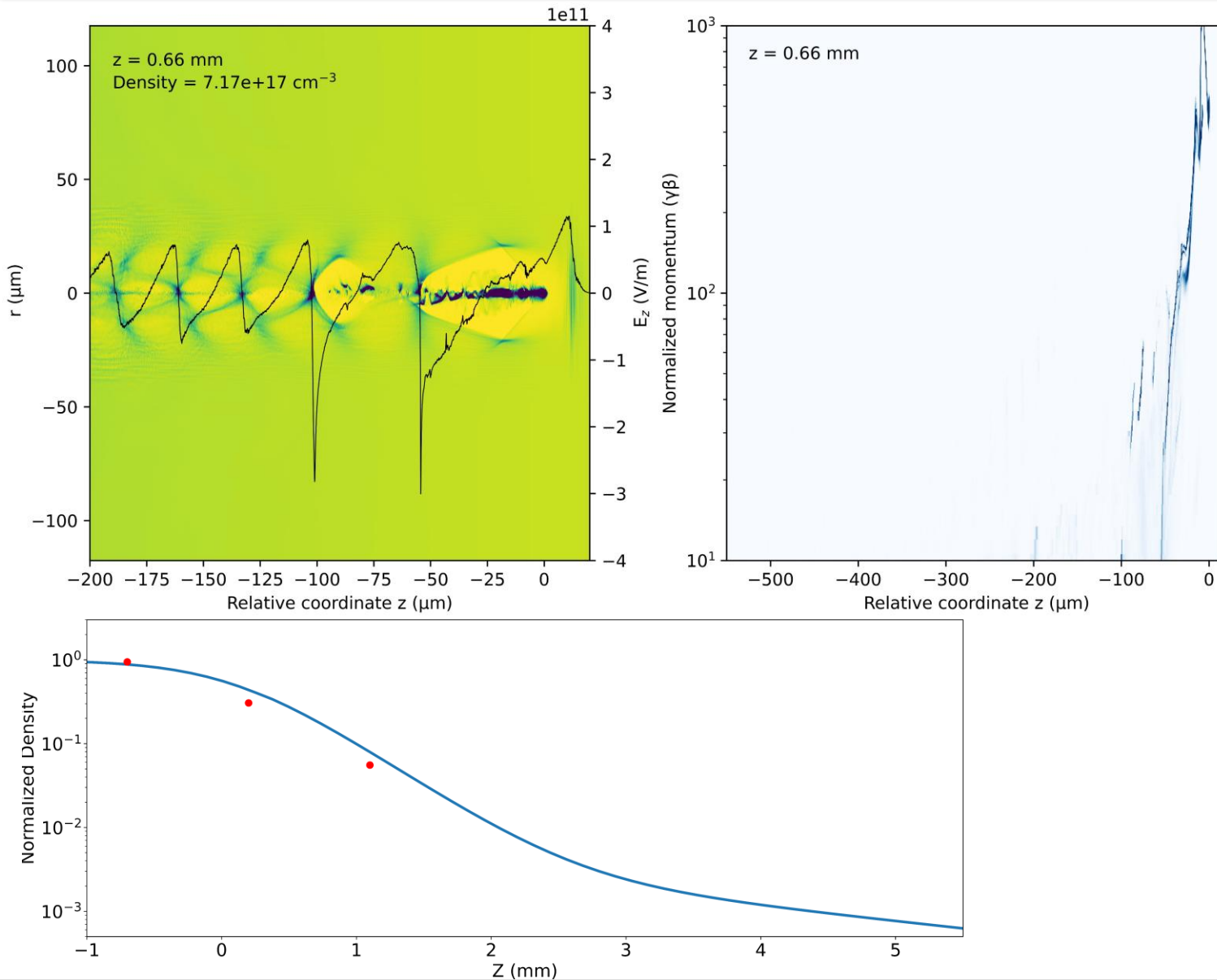
Down ramp injection contributes to a small part of the spectrum

Simulations: key processes



A combination of the laser and the beam drives the wake increasing its strength assisting injection at the down ramp

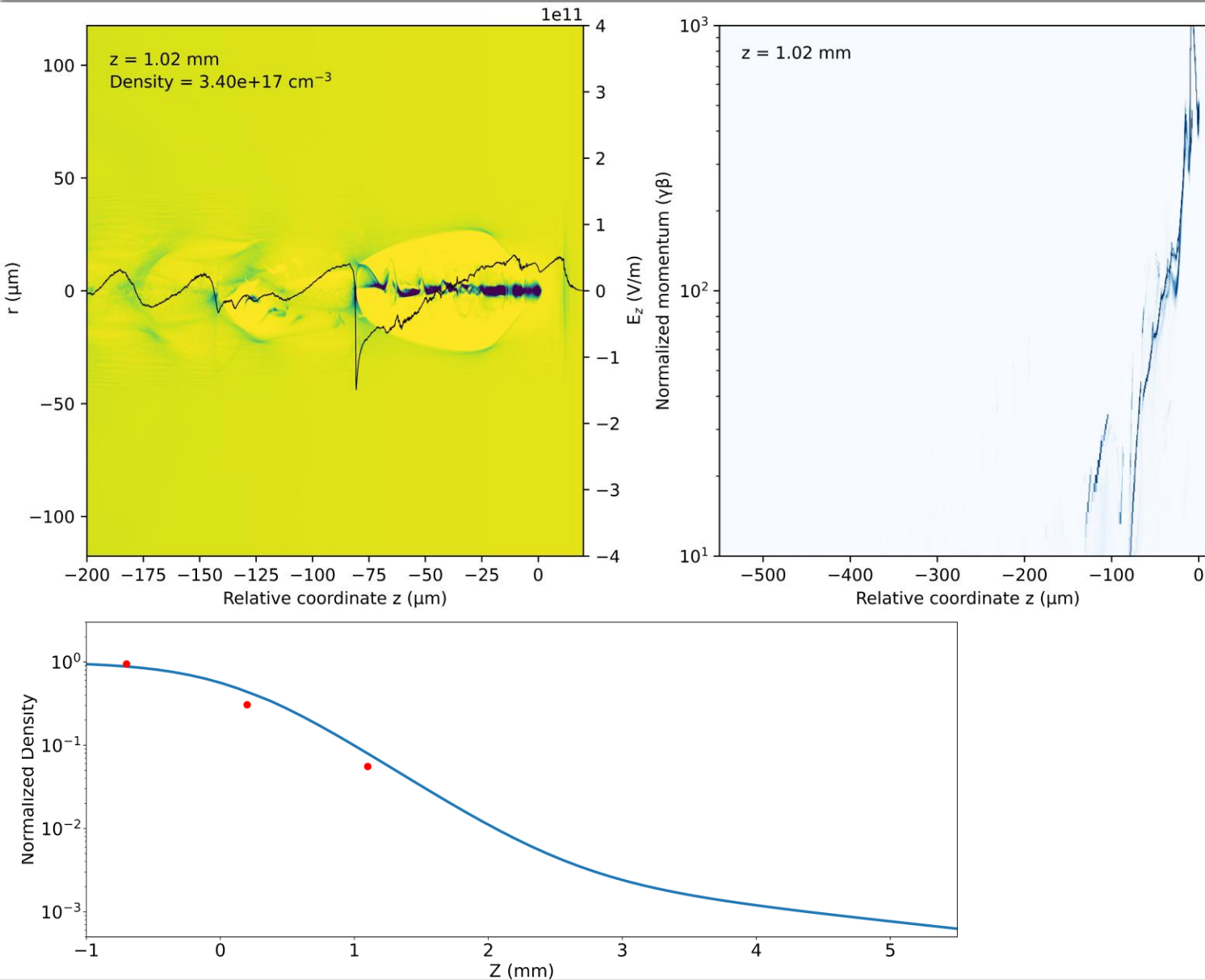
Simulations: key processes



A strong beam driven wakefield moves the wake phase further backwards assisting injection further



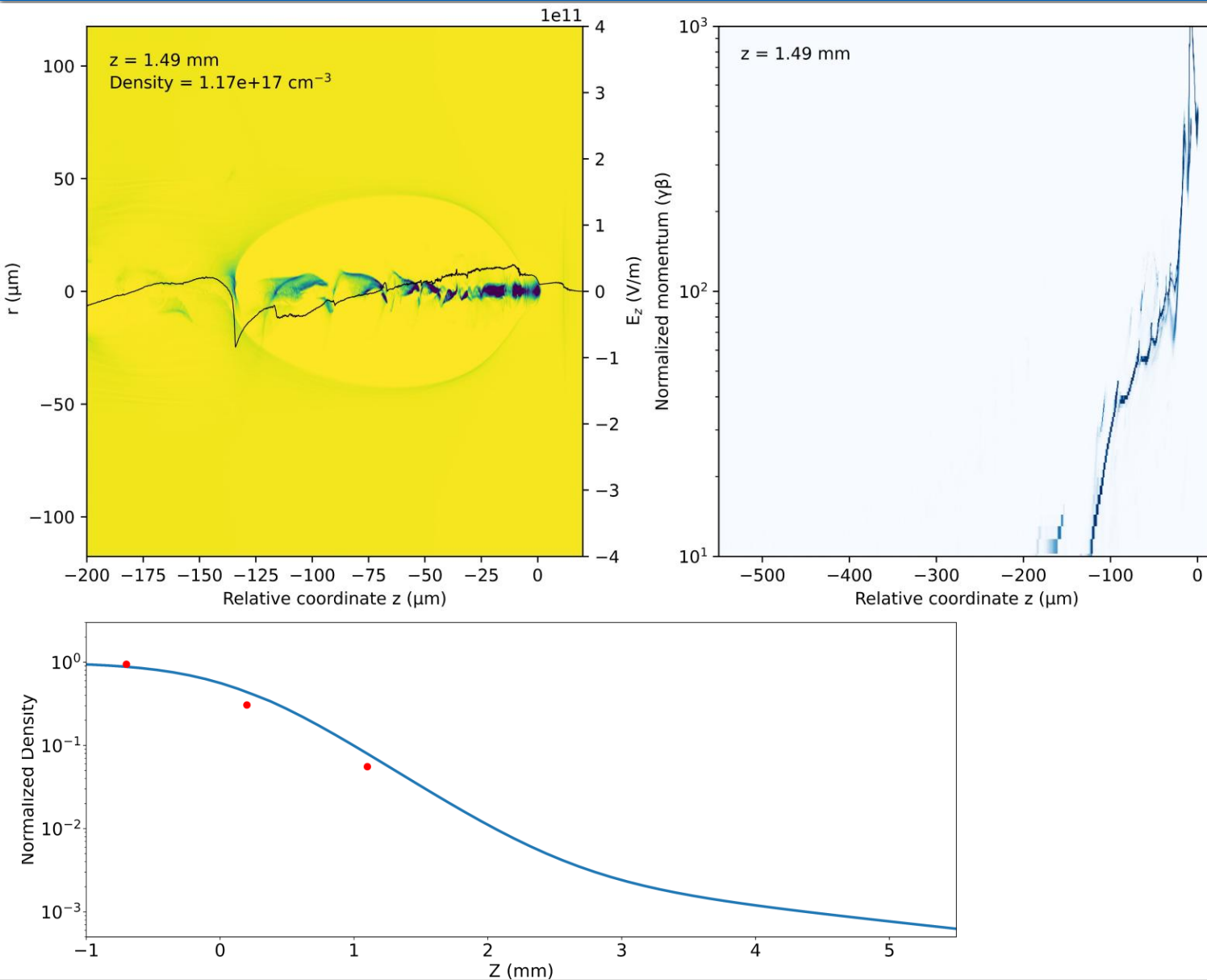
Simulations: key processes



Beam driven wake dominates promoting subluminal injection during the transition

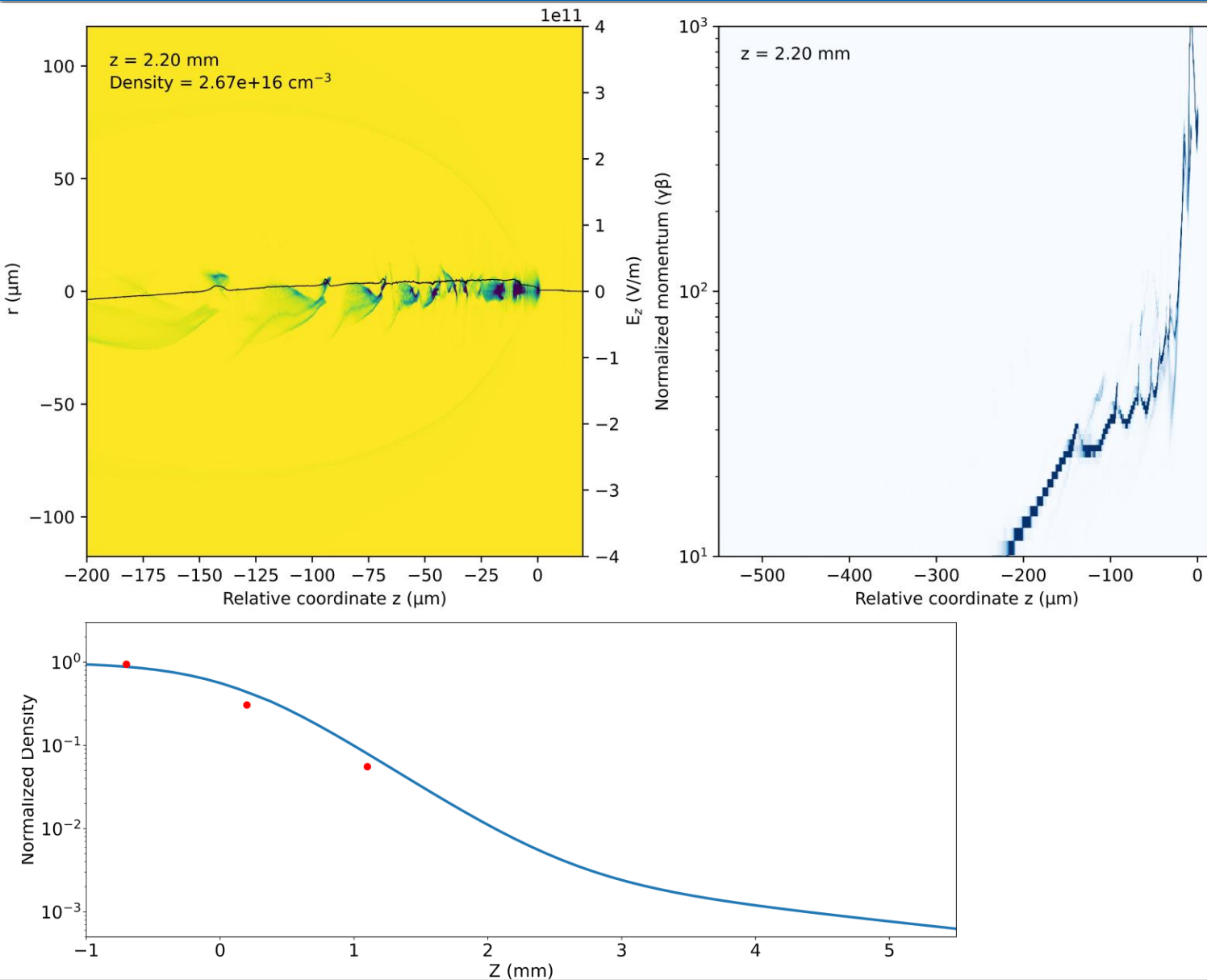
A part of the beam is decelerated while the other part undergoes injection and acceleration along with betatron oscillation

Simulations: key processes



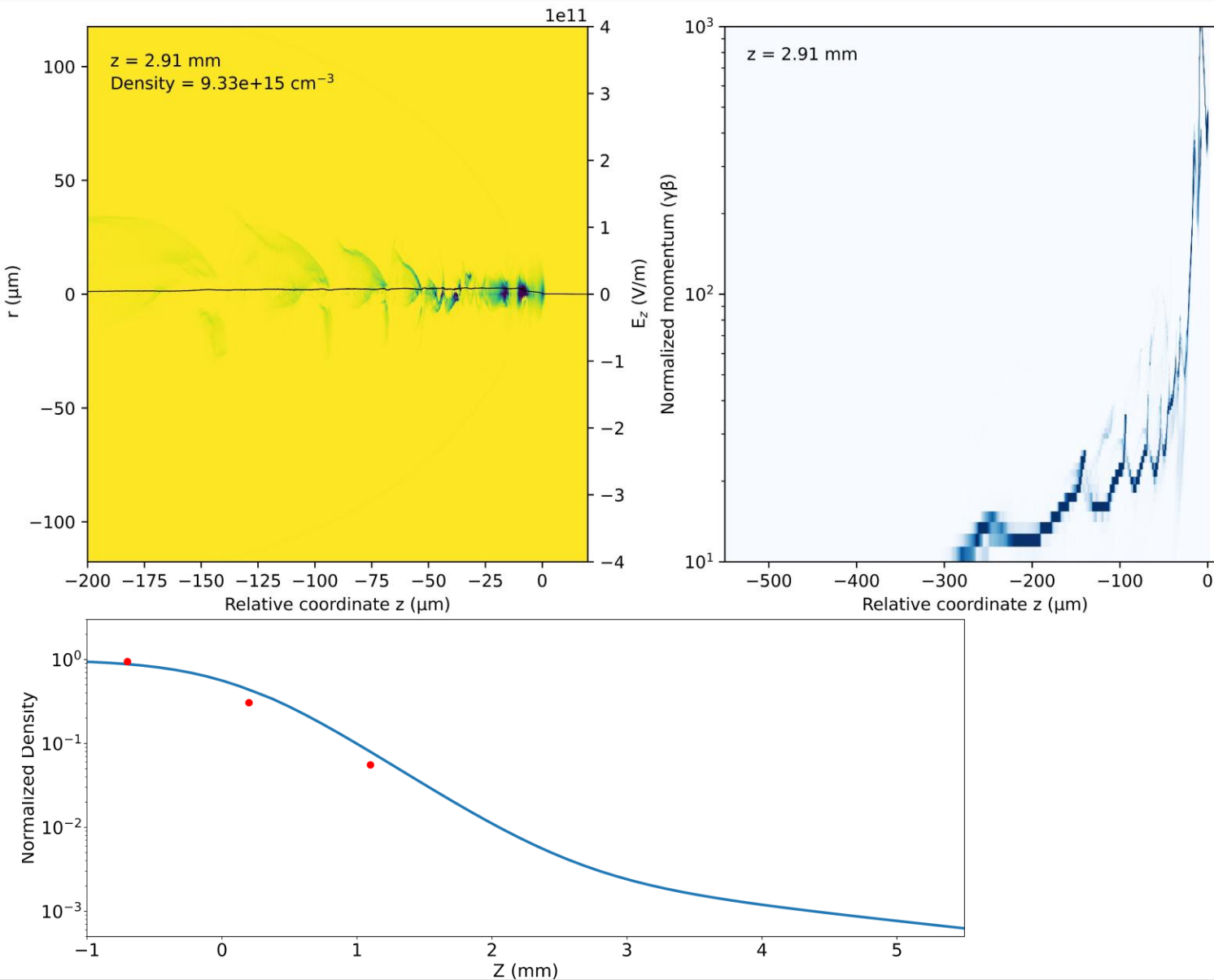
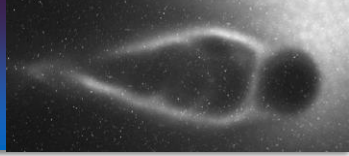
Injection continues as the wake strength decreases

Simulations: key processes



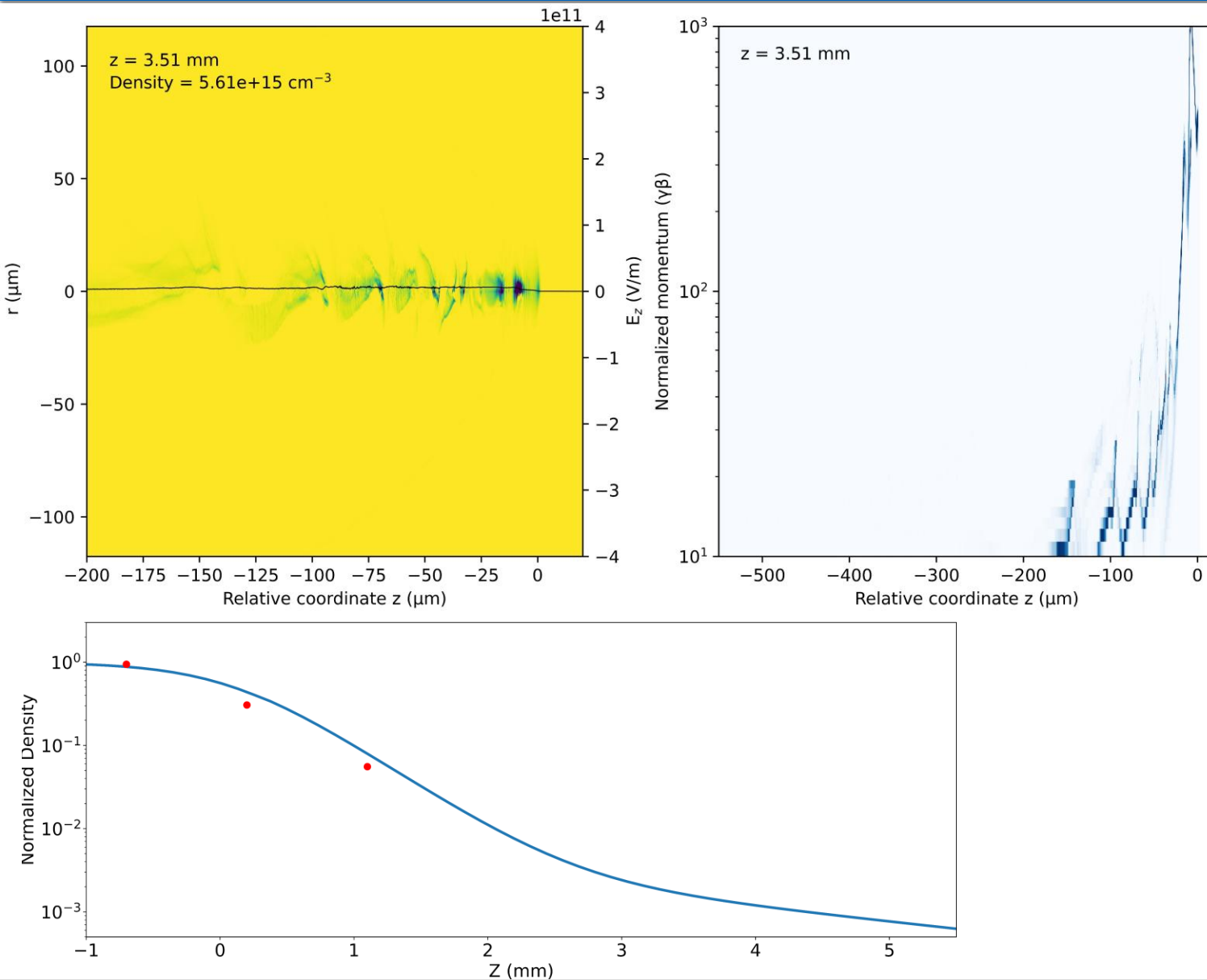
Until a point of maximal injection

Simulations: key processes



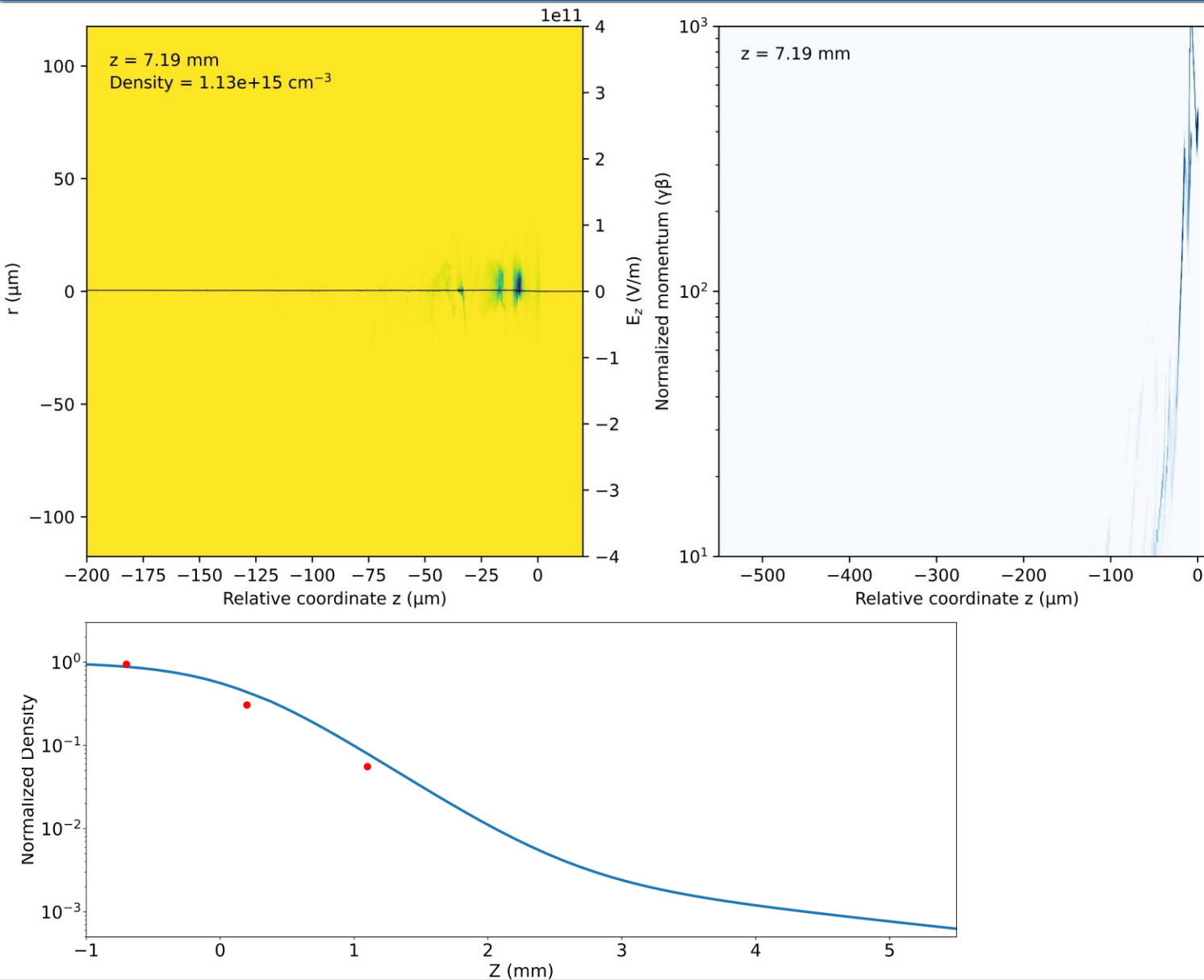
All the particles enter the decelerating point of the wake and energy is lost leading the electron shedding

Simulations: key processes



Loss of the beam

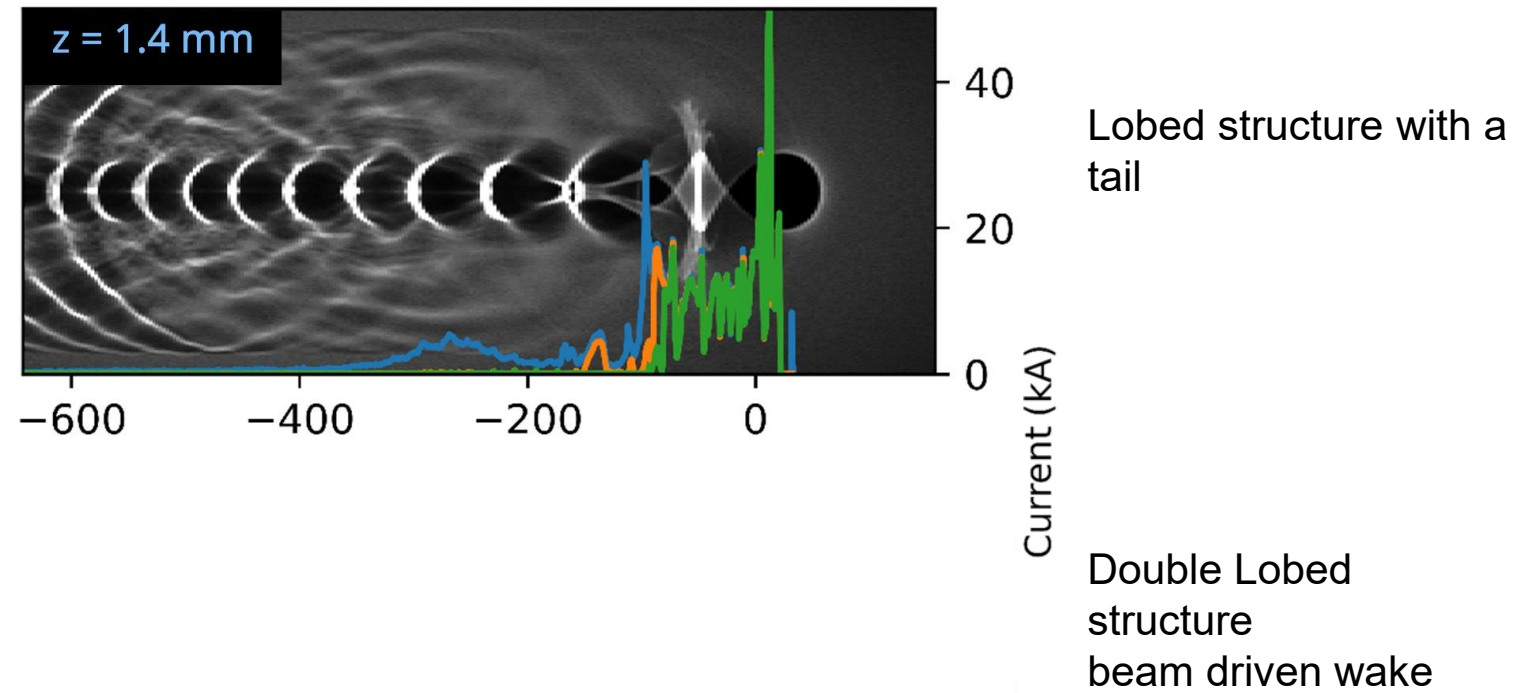
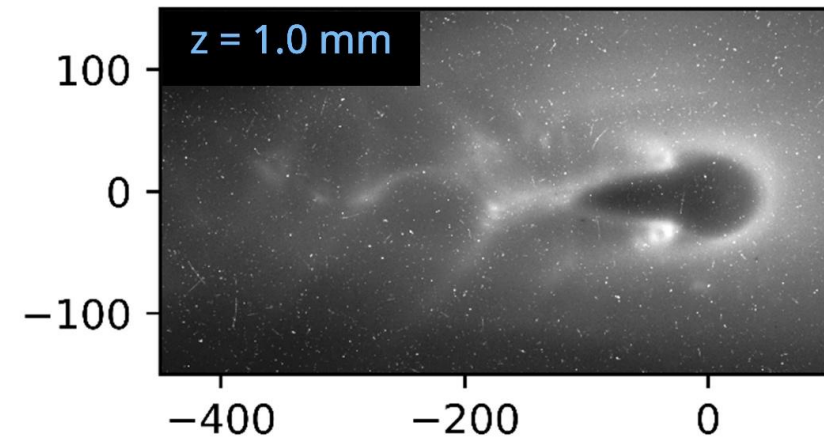
Simulations: key processes



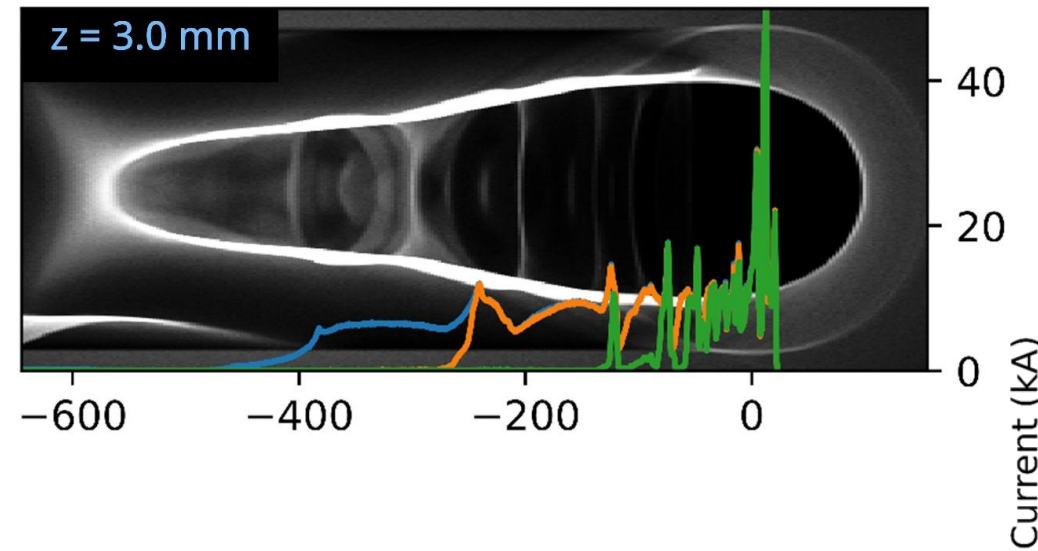
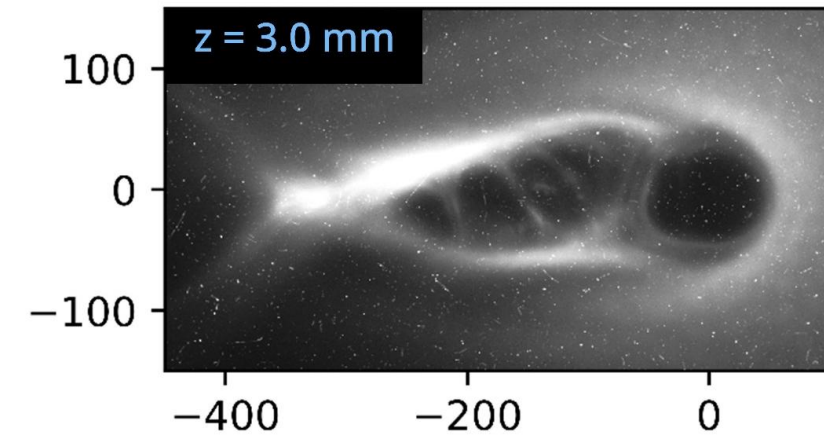
Finally back to a single beam propagating into vacuum

We compare the probe images generated

Experiments to simulations



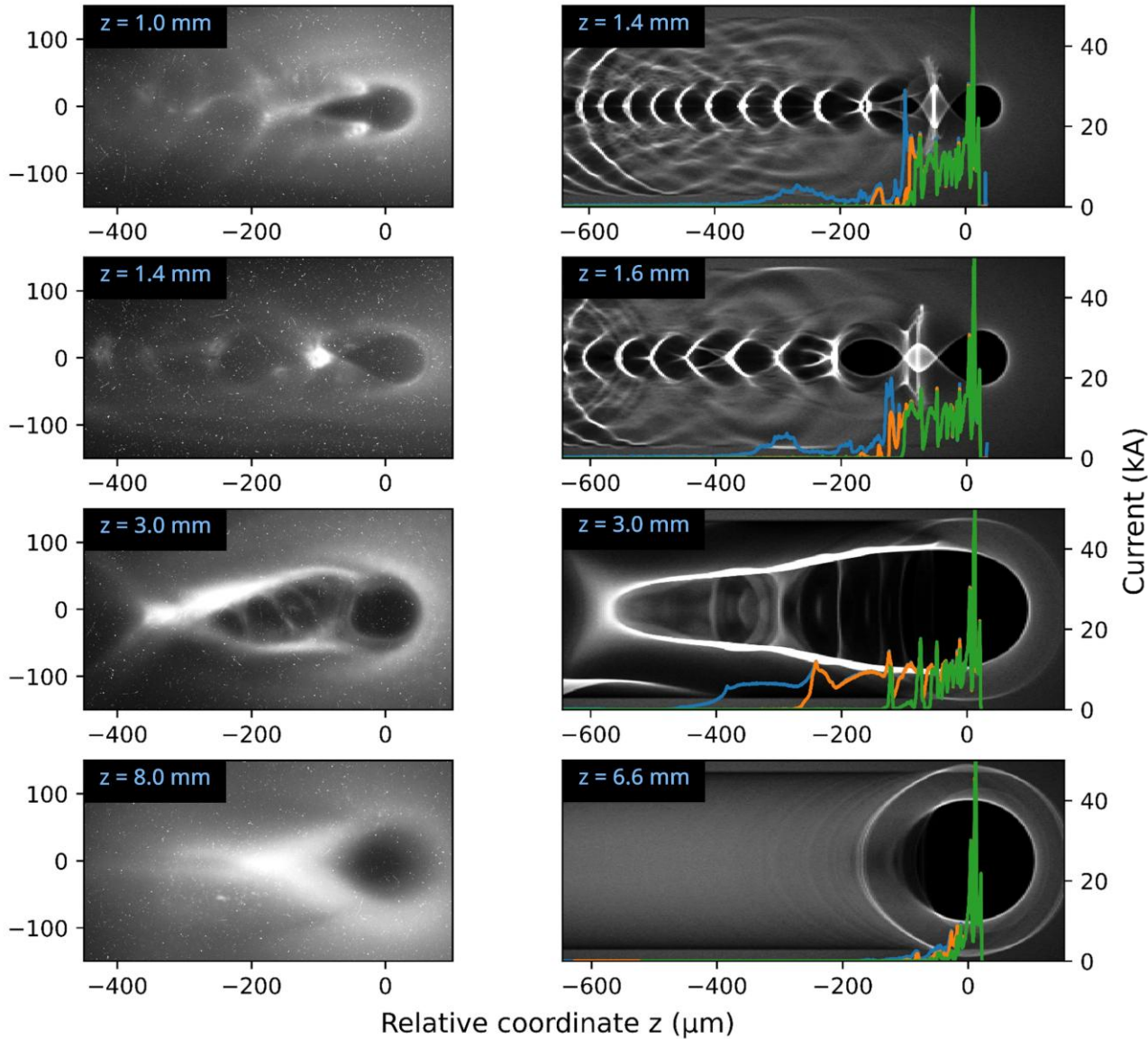
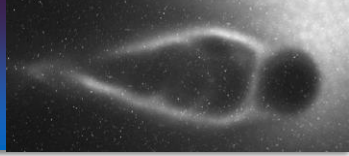
Experiments to simulations



Long beam with a tail
Low energy electrons
predominantly at the
back

Nearly a single beam in
vacuum

Experiments to simulations



Lobed structure with a tail

Double Lobed structure : beam driven wake

Long beam with a tail : Low energy electrons are predominantly at the back

Nearly a single beam in vacuum



- *Coupling high charge beams out of an LWFA*
- *Injection enhanced at the downramp accelerates particles to nearly 50 MeV*
- *As density reduces, transition into a PWFA causes loss of the energy gained*
- *Beam lost due to divergence and oscillation around axis and energy loss*
- *Far away a single beam is seen: Electron shedding*

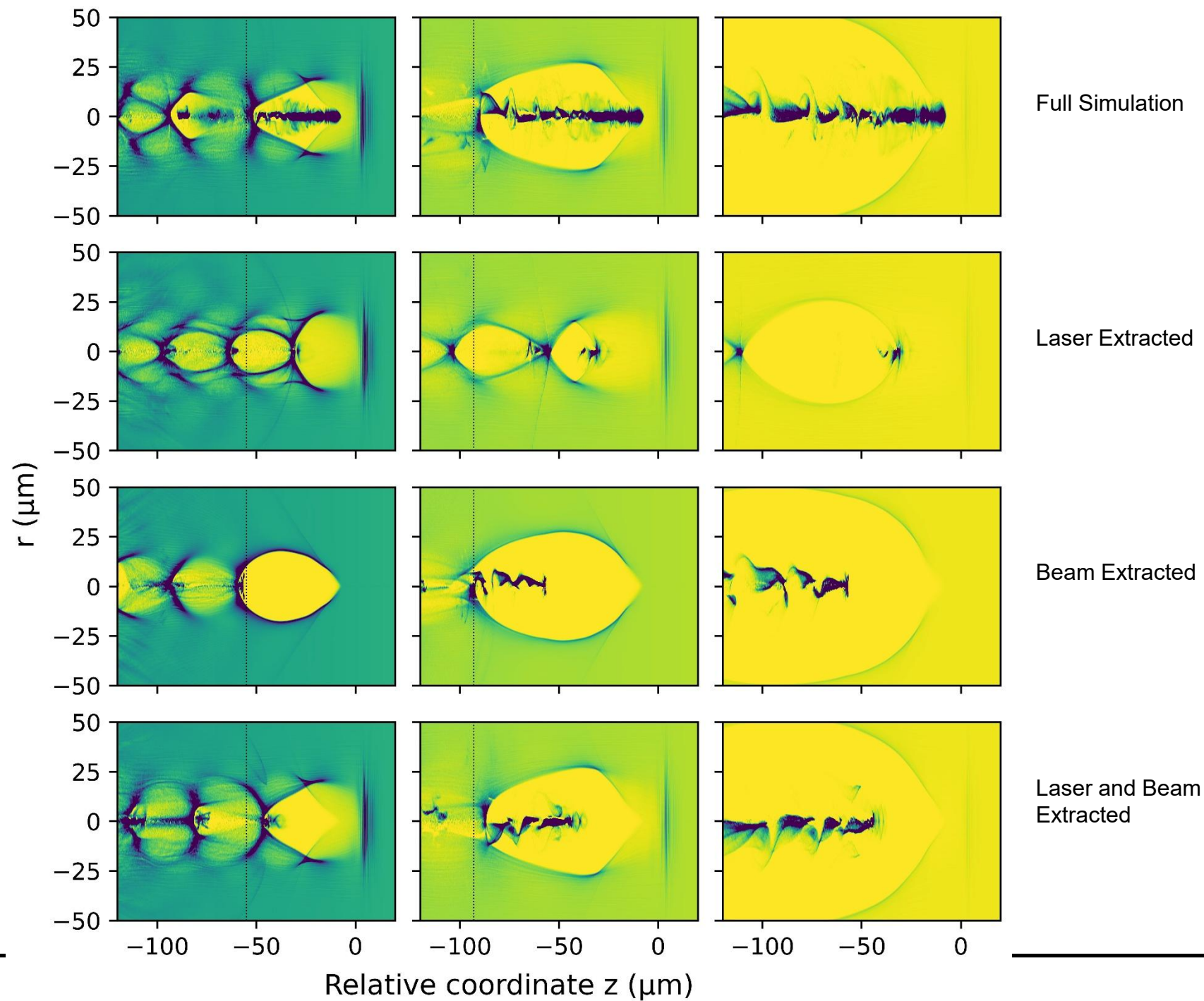


Thank you

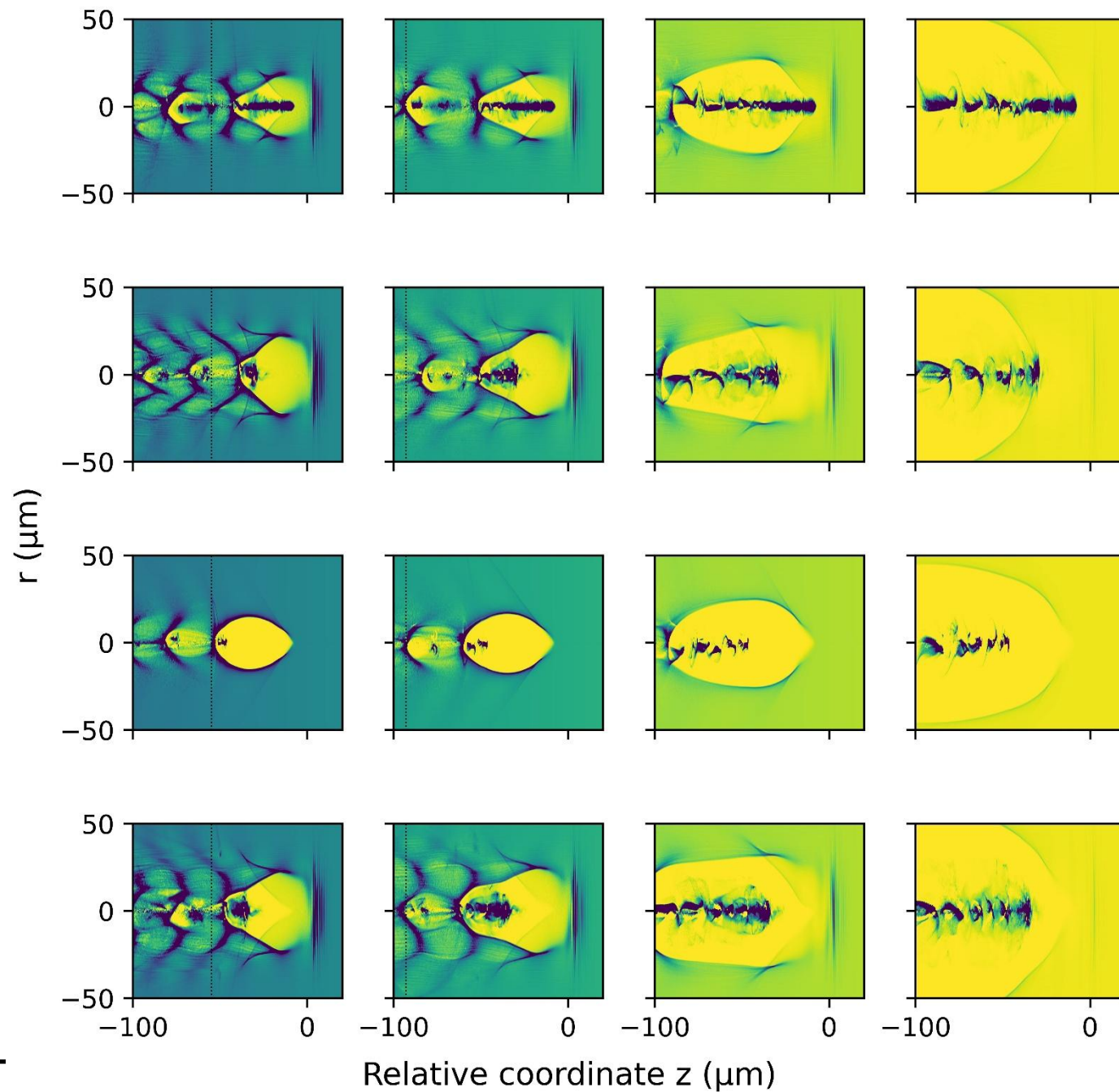


QUESTIONS ?







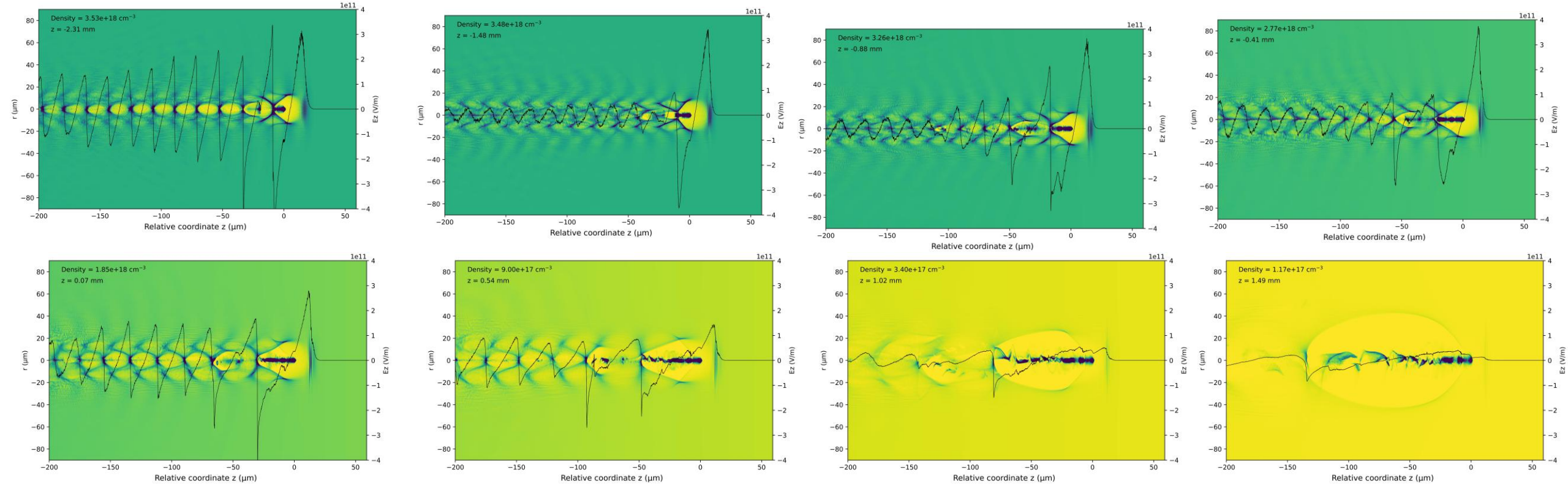


Z max _ init beam 102500

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 5.424833923333211
 5.424833923333211
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 5.661650329583787
 5.661650329583787
 5.661650329583787
 6.215071960436125
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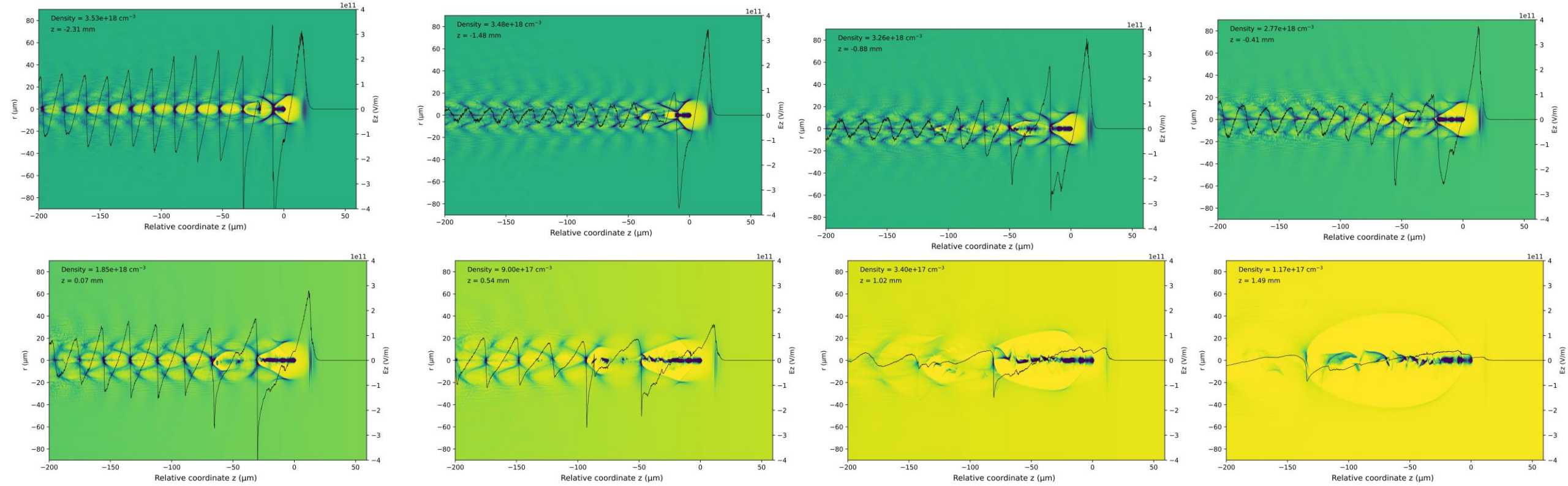


What causes electron shedding



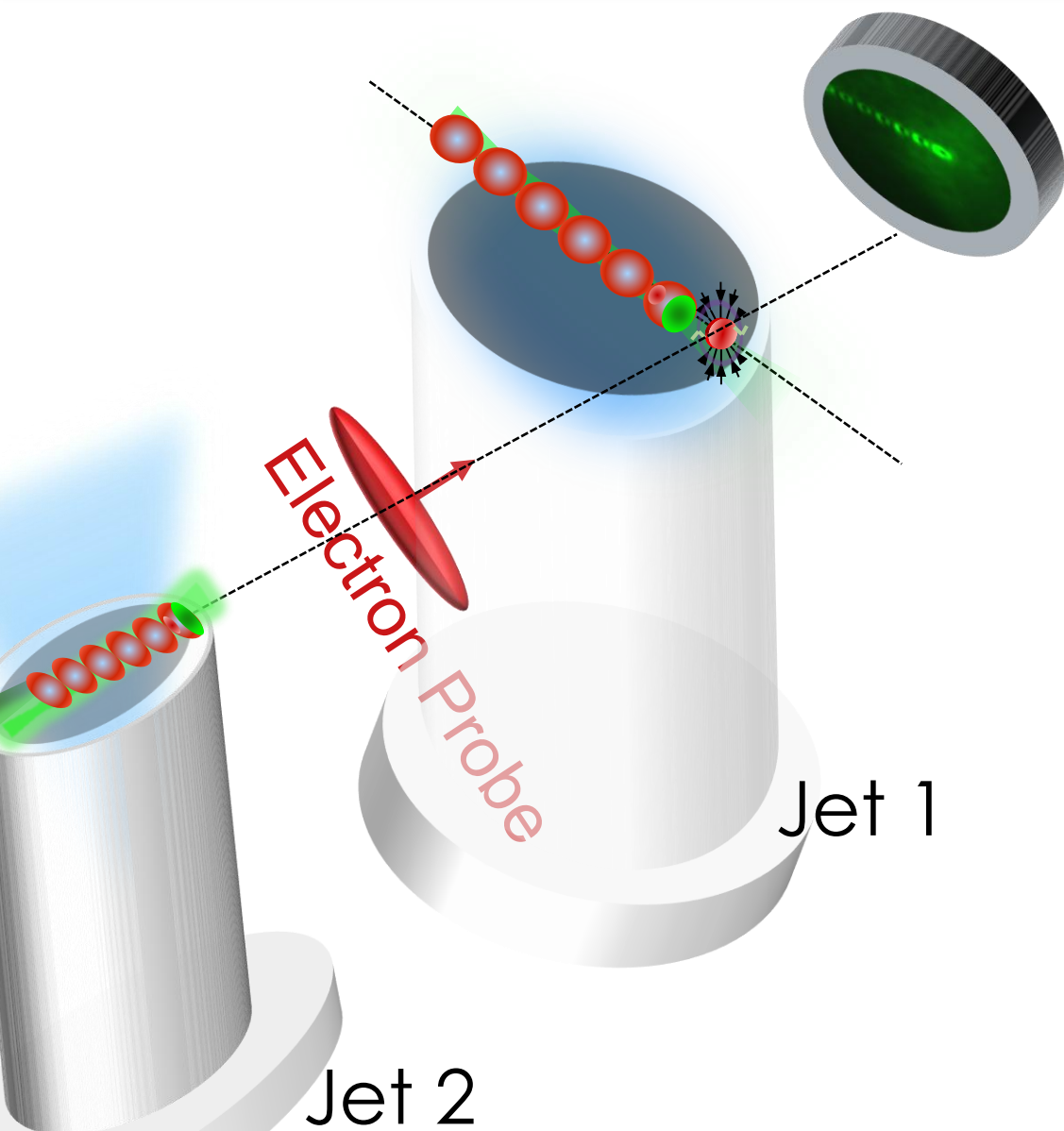
- High charge beams exiting an LWFA
- Transition from a laser driven into a beam driven wake
- Wake phase moves back, assisting down ramp injection
- Injected particles have larger divergence as they oscillate in the tail shedding electrons on the way
- Energy of these particles comes from the accelerated beam itself

What causes electron shedding

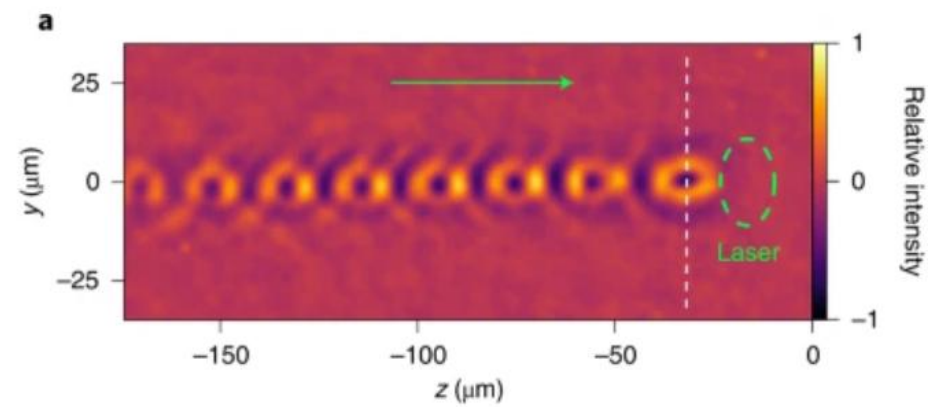


- High charge beams exiting an LWFA
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Femtosecond Relativistic Electron Microscopy



Need a good way to explain the fields

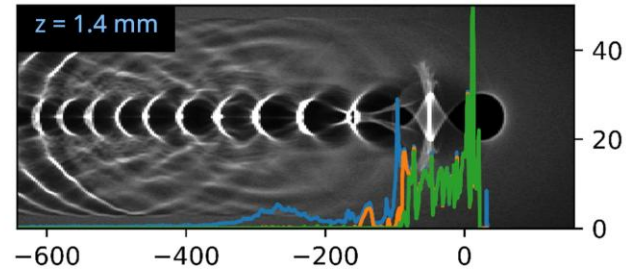
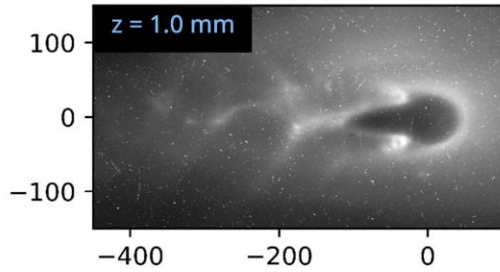
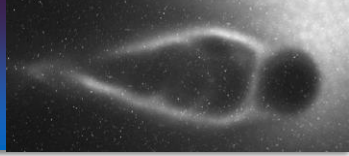


Y. Wan, et. al, *Nat. Phys.* **18**, 1186–1190 (2022)

LPA + ionization inj, downramp injection



Experiments to simulations



Lobed structure with a tail

Double Lobed structure : beam driven wake

Long beam with a tail : Low energy electrons are predominantly at the back

Nearly a single beam in vacuum