A compact electron injector for the EIC based on plasma wakefields driven by the RHIC-EIC proton beam

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Outline

- Plasma wakefield acceleration
- Using a proton driver
- Proton beam self-modulation
- Longitudinal field evolution
- Experimental observation of self-modulation
- Electron injection & acceleration
- Using the RHIC-EIC proton beam as an injector

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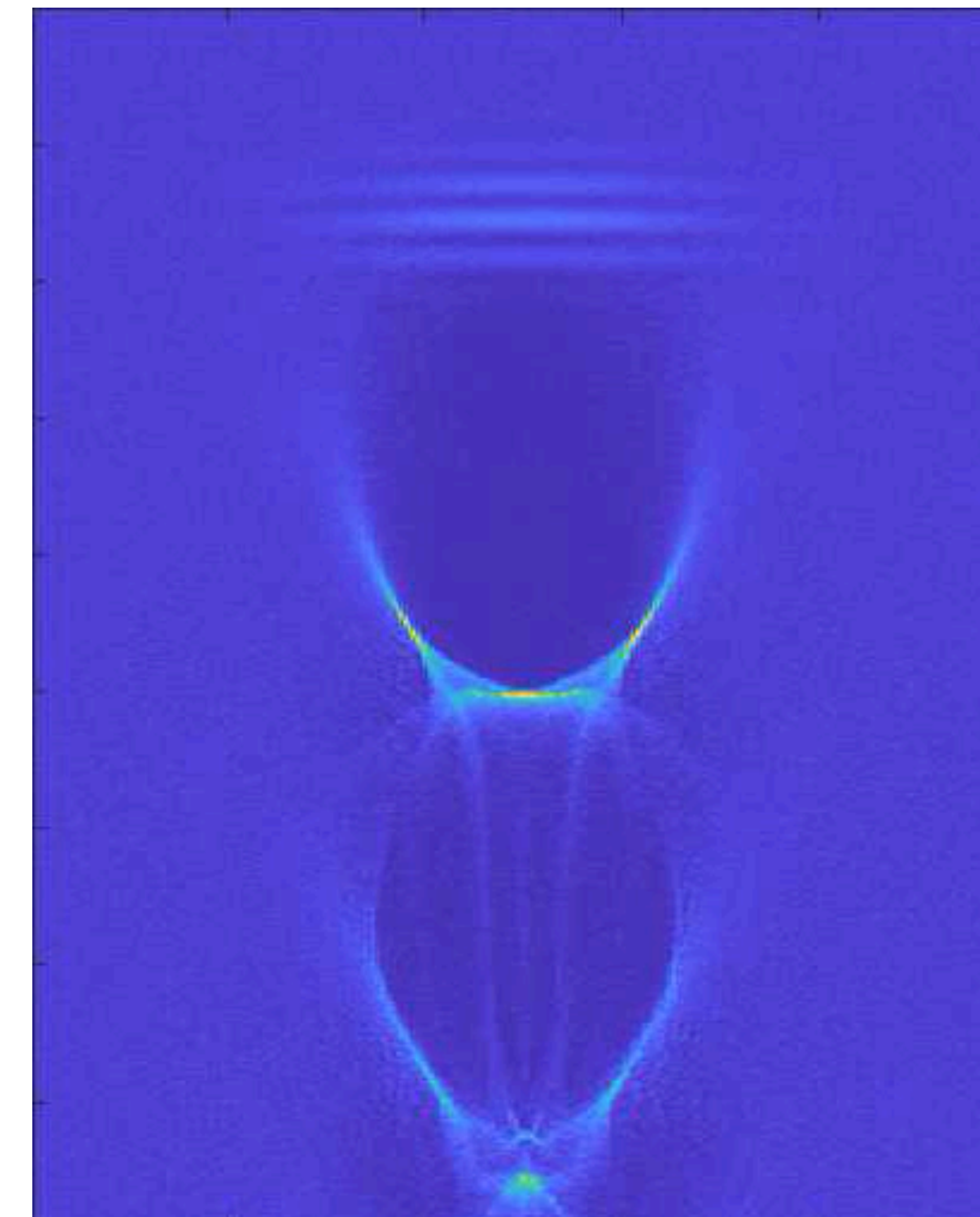
Plasma wakefield acceleration

- Plasma wakefield acceleration (PWFA) is a novel acceleration technique that can provide acceleration gradients more than two orders of magnitude larger than those produced by typical RF accelerators.
- It relies on plasma electron response to an ultra-relativistic, high density, charged particle beam.
- Electrons in the plasma move due to the space-charge force from the drive beam, while ions remain stationary on this timescale due to their larger mass, inducing a large charge separation.
- Electrons are attracted back to the axis by the ion channel but overshoot and begin to oscillate at a characteristic frequency. These oscillations excite a longitudinal electron density wave, inducing large electrostatic fields with gradients exceeding GVm^{-1}.
- Particles that are injected into the wakefields are accelerated by these fields, reaching high energies in much shorter distances than via traditional methods.

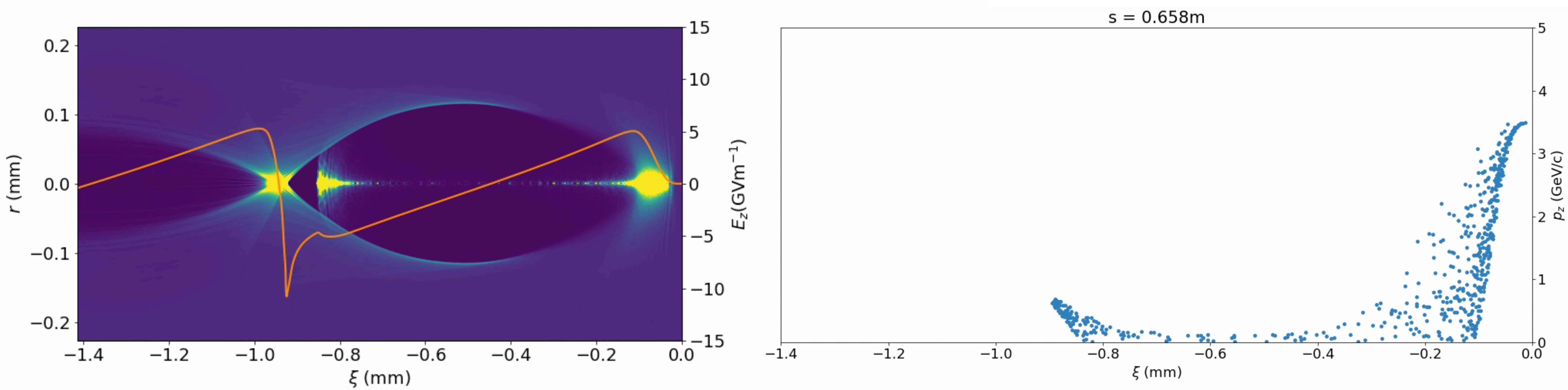


EPOCH particle-in-cell simulation of laser-driven PWFA.

Plasma wakefield acceleration

- Typical drivers used in PWFA are ultra-intense ($I > 10^{18}\ Wcm^{-2}$), short ($\tau \sim 30fs$), laser pulses or high peak current ($I >$ kA) electron beams.

- These typically have energies on the order of 10s of joules and lose energy while driving the plasma wakefield, becoming depleted over short distances (~ cm). This limits the final attainable energy of particles injected into the wakefield.



LCODE simulation demonstrating drive beam depletion.

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Using a proton driver

> Currently available proton beams have stored energies on the order of 10s kJ and so could drive wakefields over 100s of metres before becoming depleted.

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> **Difficulties:**

> The maximum field supported in a plasma scales with the density:

$$E_{max} \propto \sqrt{n_e}$$

> From linear theory, to efficiently drive a wakefield, the drive beam must have a certain size:

$$k_p \cdot \sigma_r \sim 1, \quad k_p \cdot \sigma_z \sim \sqrt{2}, \quad \text{where} \quad k_p \propto \sqrt{n_e}$$

➡ To drive larger fields, need a smaller beam.

Using a proton driver

> Currently available proton beams have stored energies on the order of 10s kJ and so could drive wakefields over 100s of metres before becoming depleted.

> **Difficulties:**

> Consider the SPS proton beam. $\sigma_r = 200\,\mu\text{m},\ \ \sigma_z \sim 8\text{ cm}$

> Choose the plasma density to match to the transverse size of the proton beam:

$$\sigma_r = k_p^{-1} = 200\ \mu\text{m} \ \Rightarrow\ n_e = 7\times 10^{14}\ \text{cm}^{-3}$$

$$k_p \cdot \sigma_z = \sqrt{2} \ \Rightarrow\ \boldsymbol{\sigma_z = 285\ \mu\text{m}}$$

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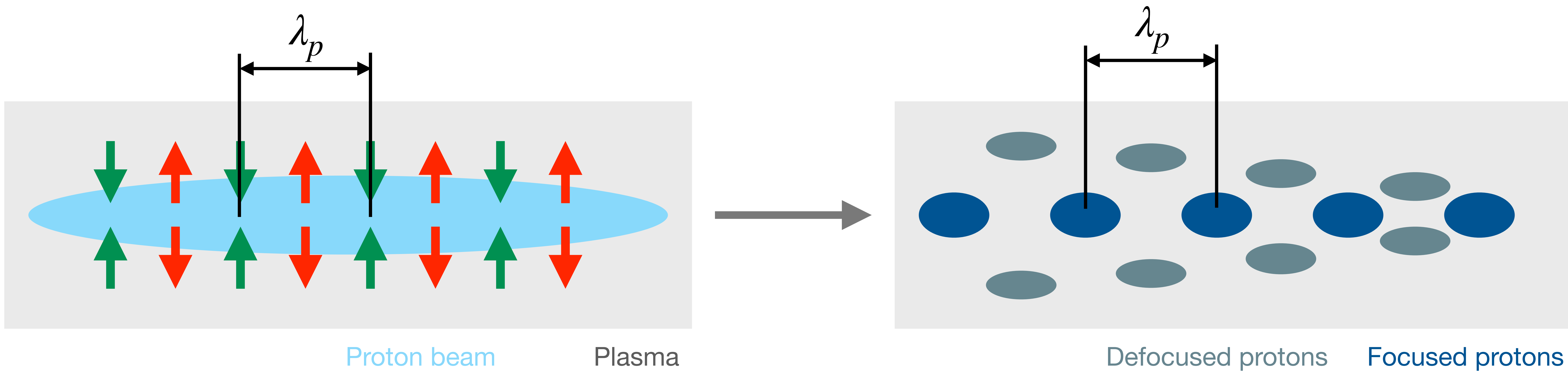
Using a proton driver: self-modulation

> It is still possible to use a proton beam to effectively drive a plasma wakefield by making using of an intrinsic plasma response to a long drive beam: ***self-modulation***.

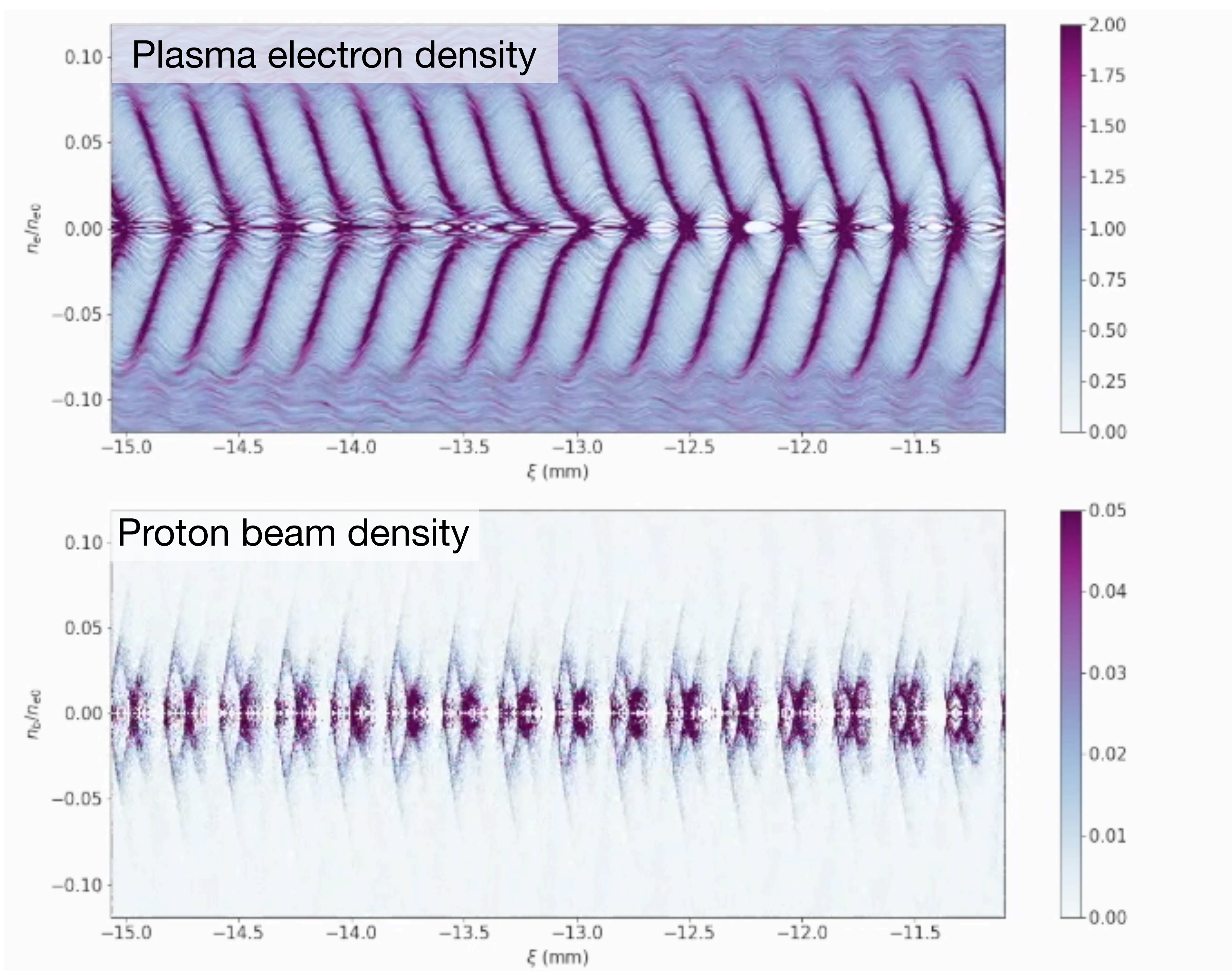
> During self-modulation, the initial transverse fields driven by the long bunch create regions of alternating focusing and defocusing fields, each separated by a plasma wavelength ($\lambda_p \propto 1/\sqrt{n_e}$), which act to split the long proton beam into small microbunches.

> Due to this being an intrinsic plasma response, it creates short microbunches at the correct frequency to resonantly drive a large amplitude wakefield.

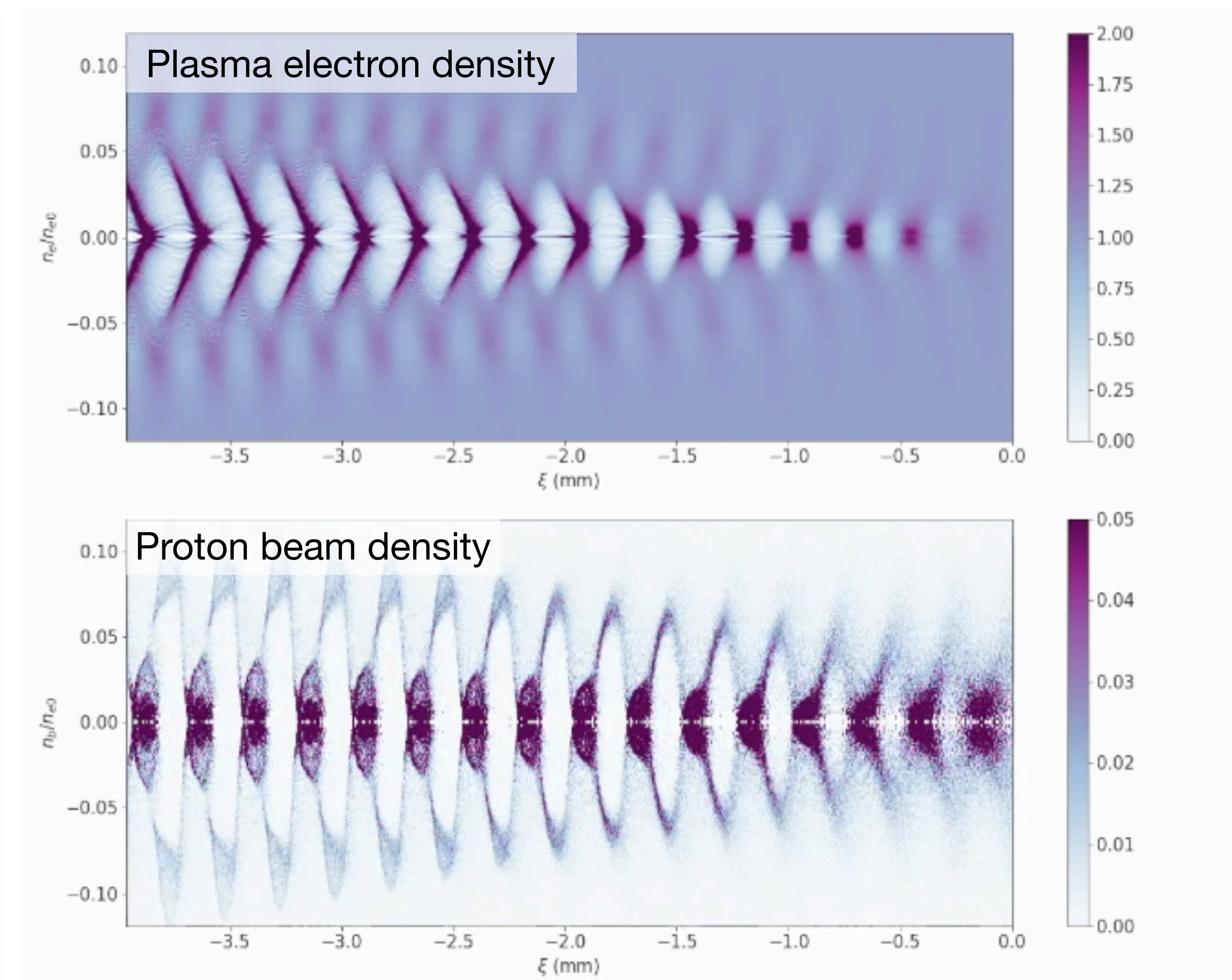


Using a proton driver: self-modulation

Middle of the beam



Front of the beam



LCODE simulation of proton beam self-modulation

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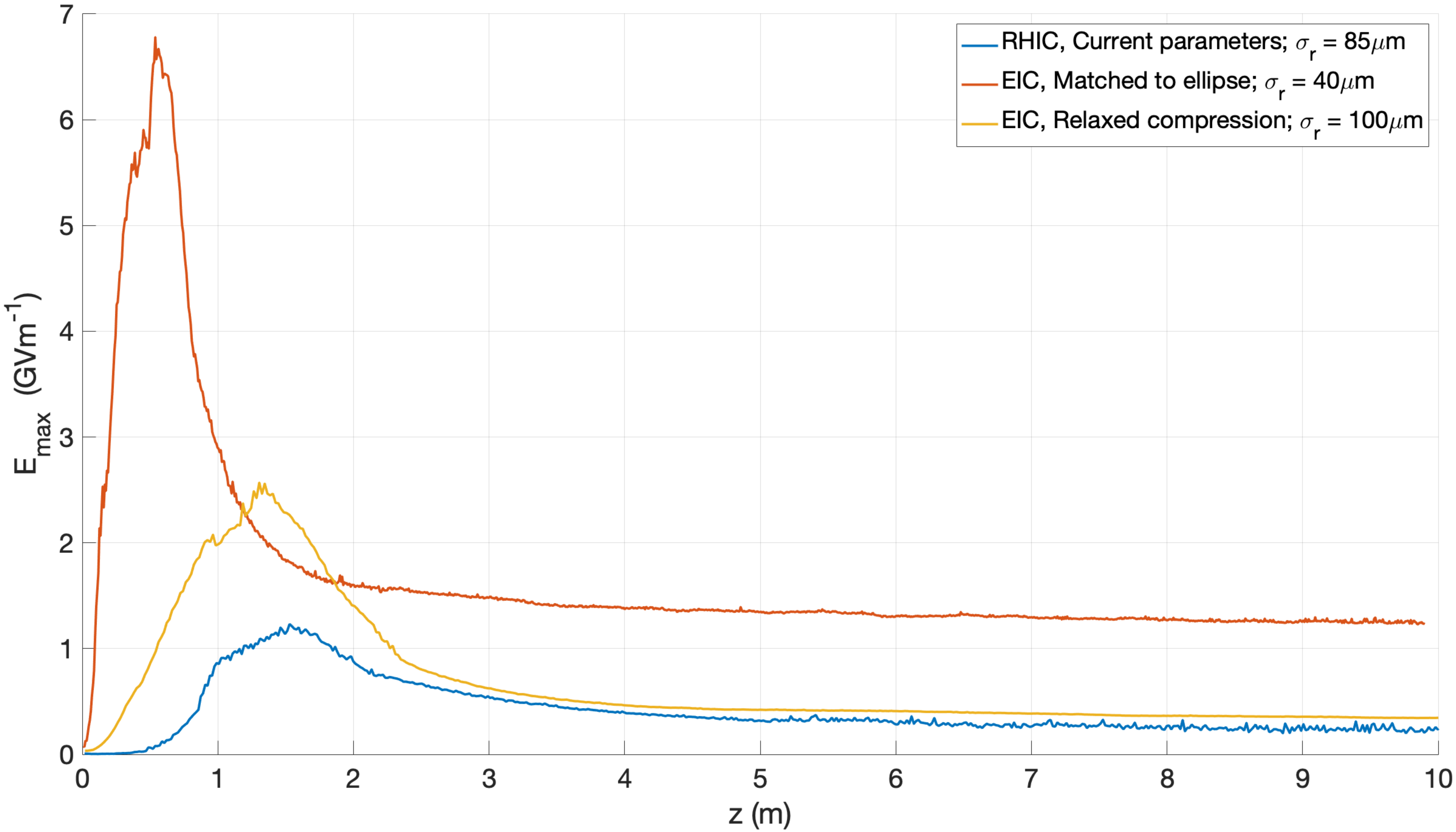
Longitudinal field evolution: RHIC-EIC

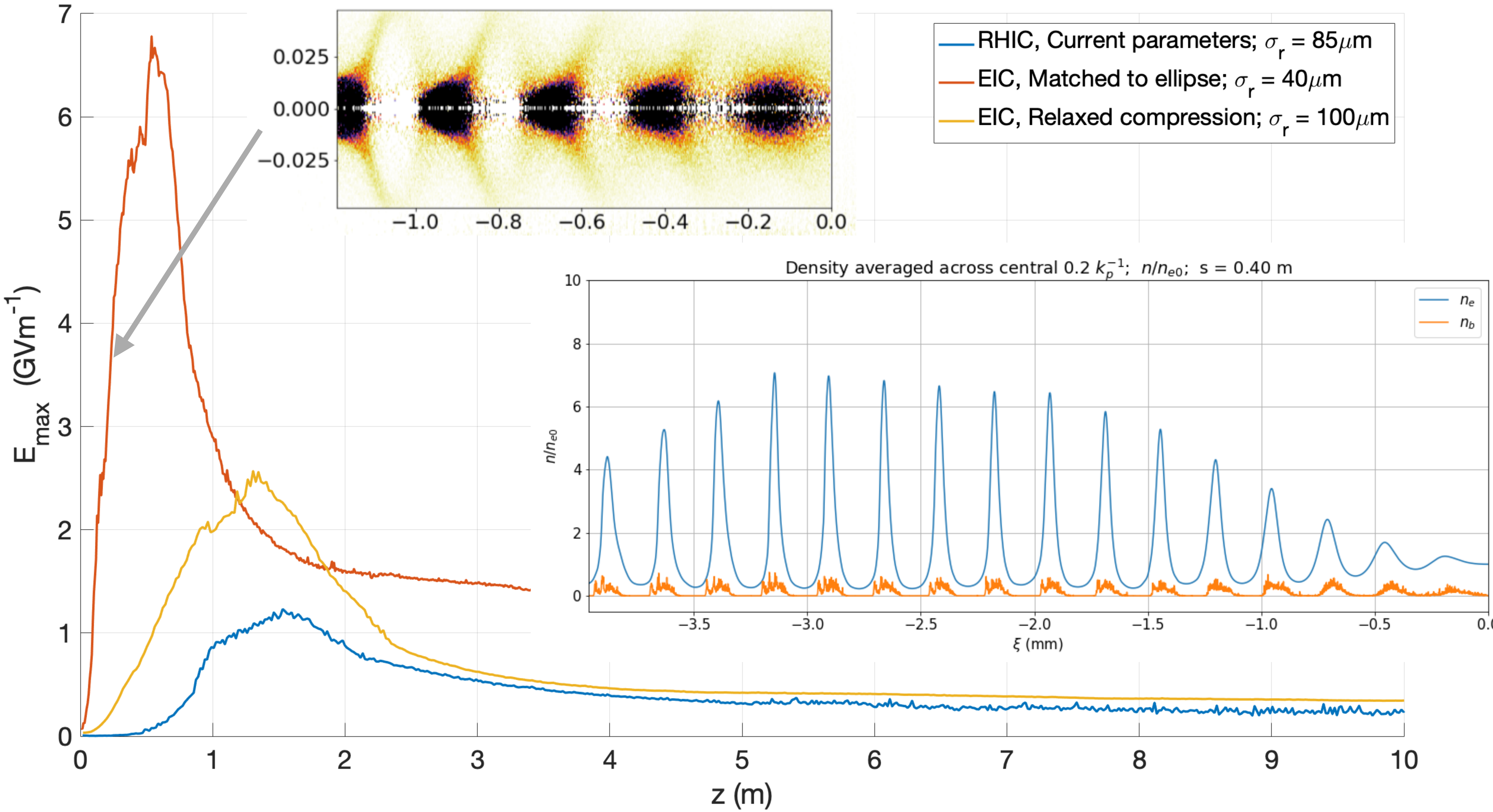
> **Assumed** beam parameters:

Parameter	EIC Matched to ellipse	EIC Relaxed compression	RHIC
N_p	2×10^{11}	2×10^{11}	2×10^{11}
E_p (GeV)	275	275	250
σ_r (μm)	40	100	85
σ_z (cm)	5	5	60
n_e (cm^{-3})	1.8×10^{16}	2.8×10^{15}	4×10^{15}

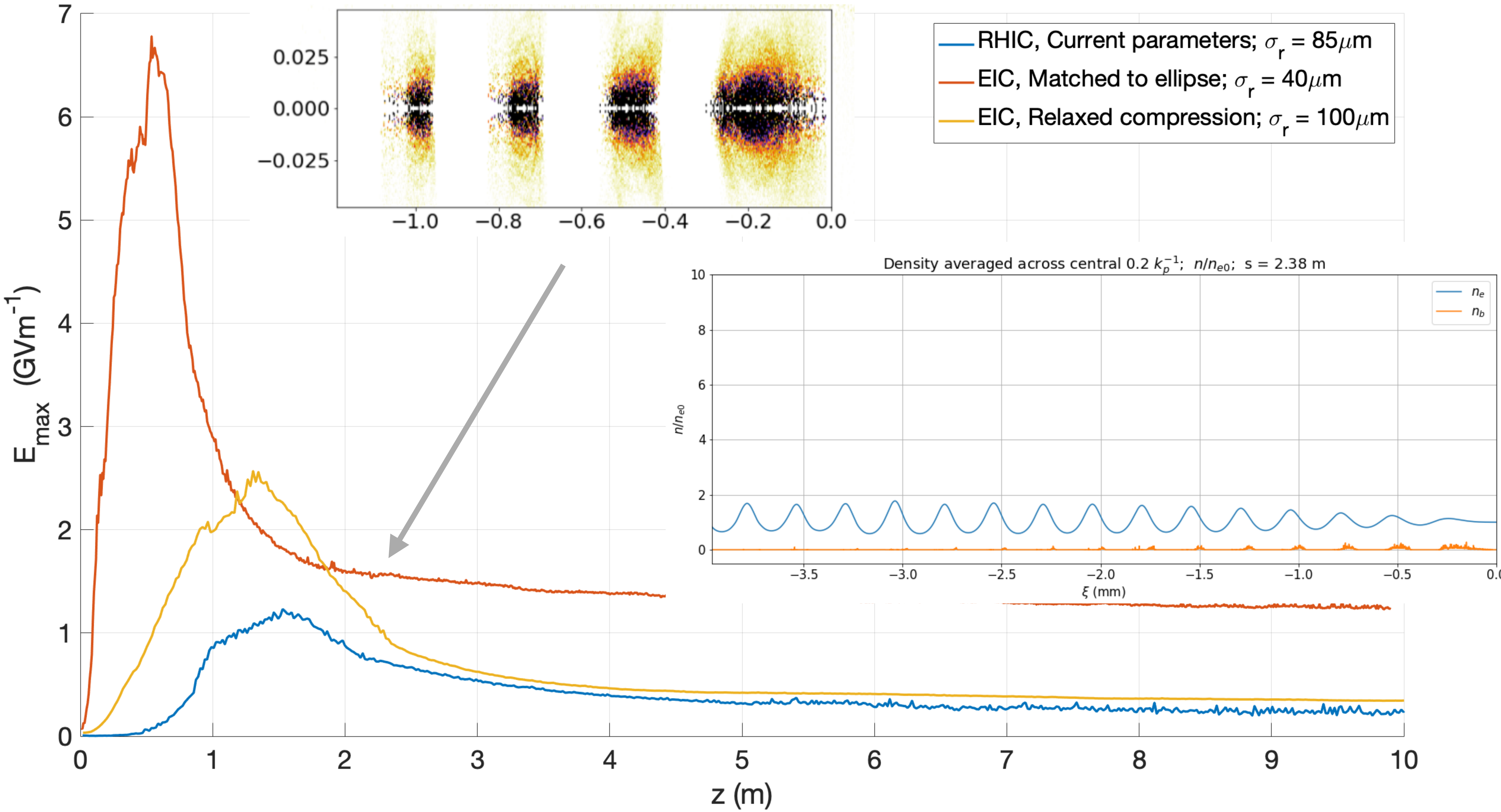
Longitudinal field evolution: RHIC-EIC



Longitudinal field evolution: exponential growth



Longitudinal field evolution: saturation

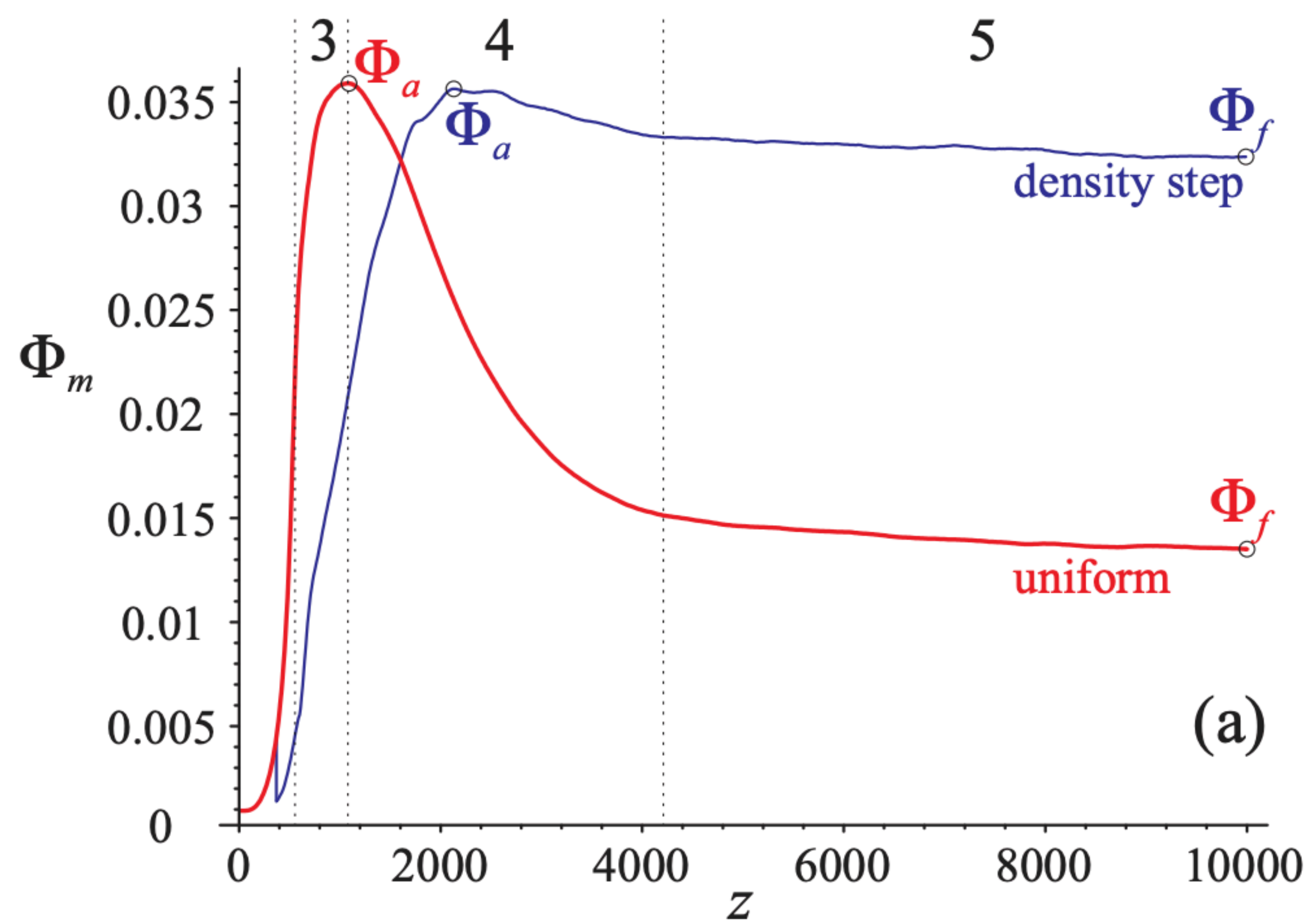


Longitudinal field evolution: density step

> By implementing a small increase (%-level) in the plasma density during the exponential growth of the longitudinal field, the structure of the microbunches can be preserved.

> The density step modifies the plasma wavelength, “freezing” the wakefield potential with respect to the microbunches.

> By varying the length and magnitude of the density step, an optimum condition can be reached where the maximum field is maintained over large distances.



Demonstration of effect of optimum density step for AWAKE parameters.

See K. Lotov, Physics of Plasmas ***22****, 103110 (2015)*

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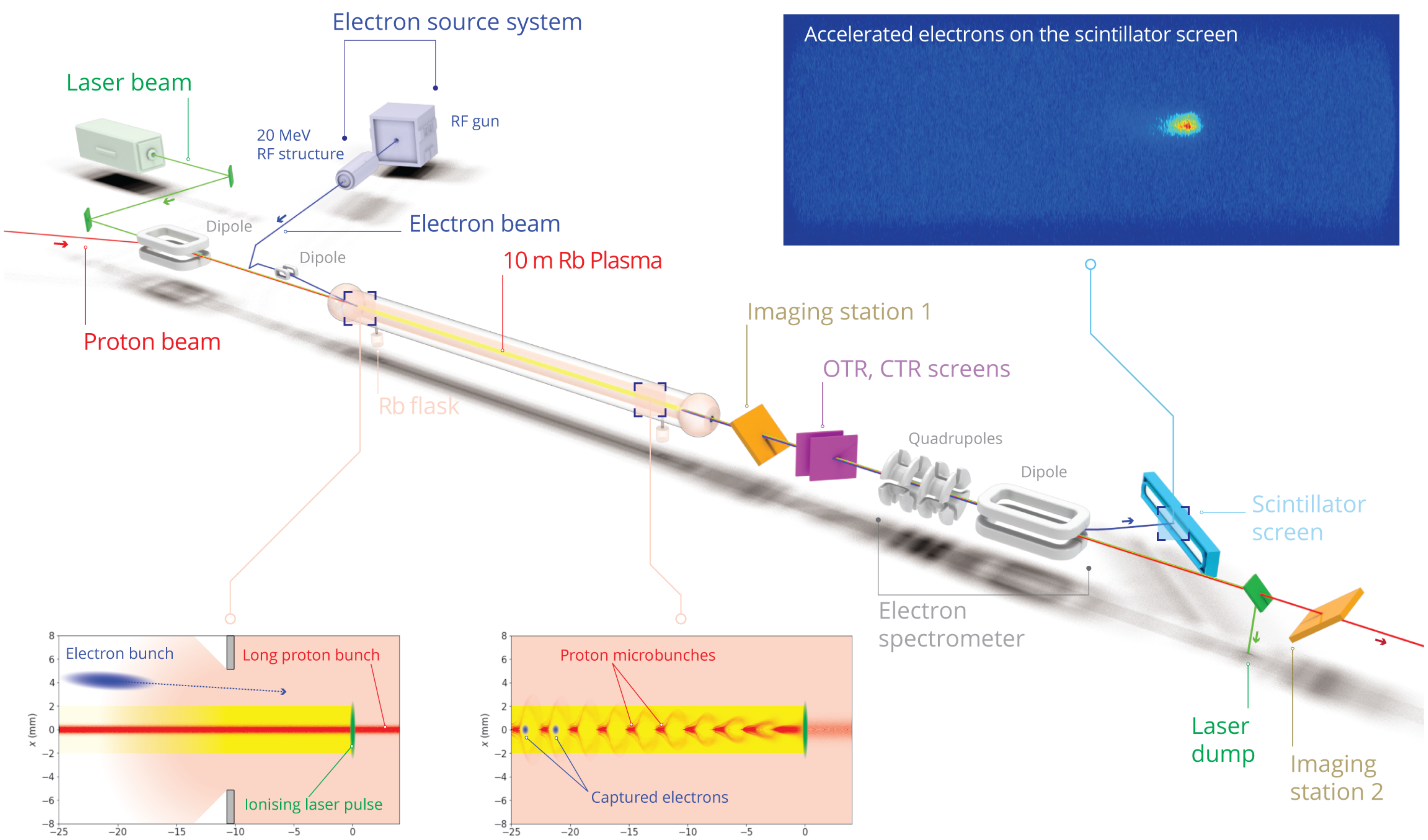
Experimental observation of self-modulation: AWAKE



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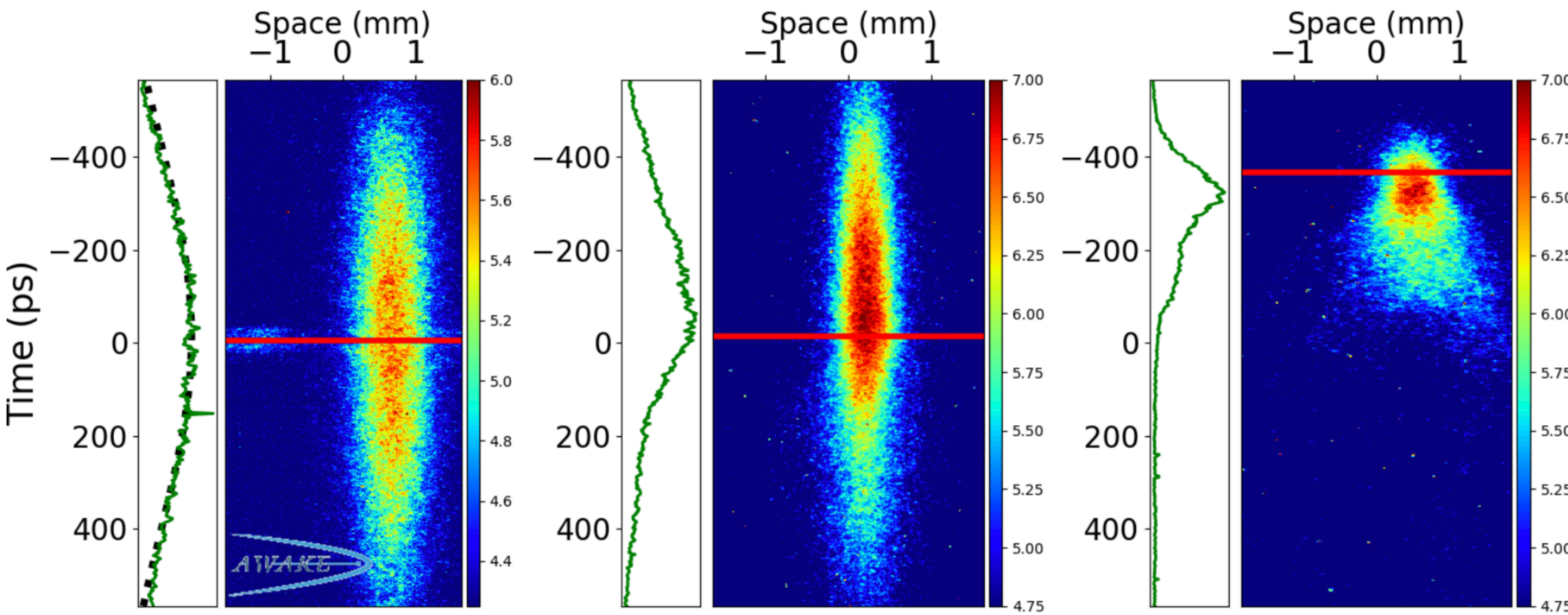

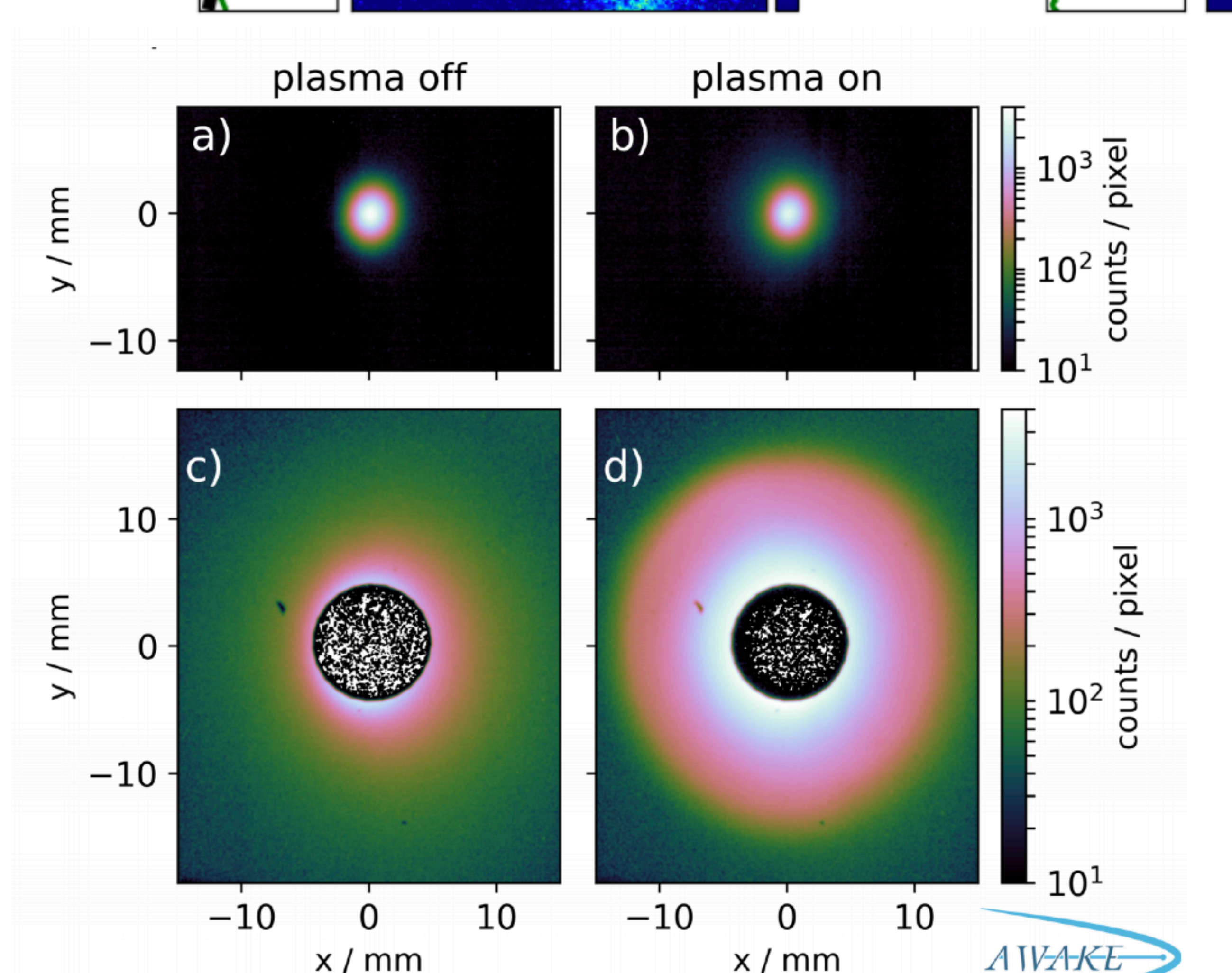

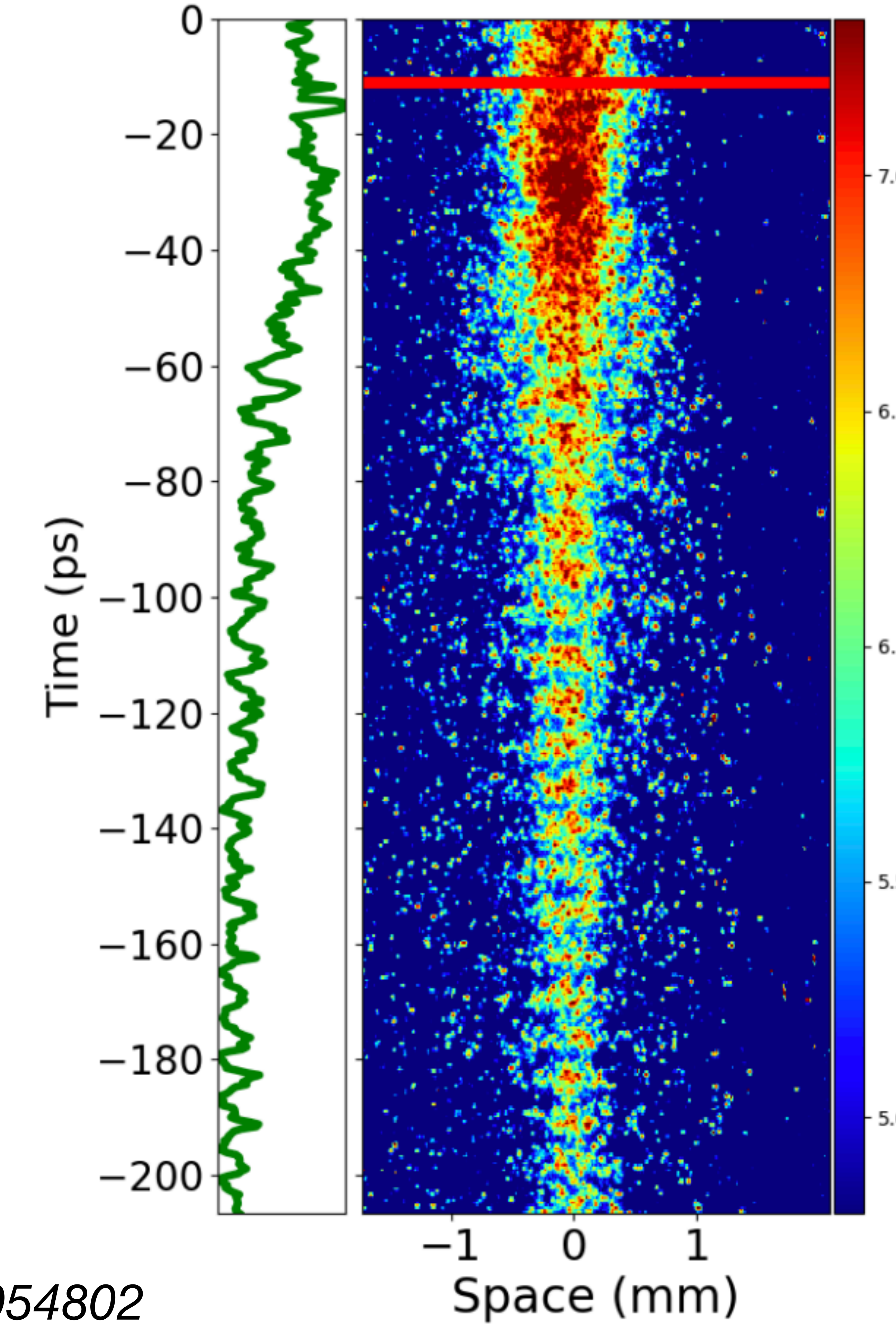

For more information see:
E. Adli et al. (AWAKE Coll.), Phys. Rev. Lett. ***122****, 054802*
M. Turner et al. (AWAKE Coll.), Phys. Rev. Lett. ***122****, 054801*

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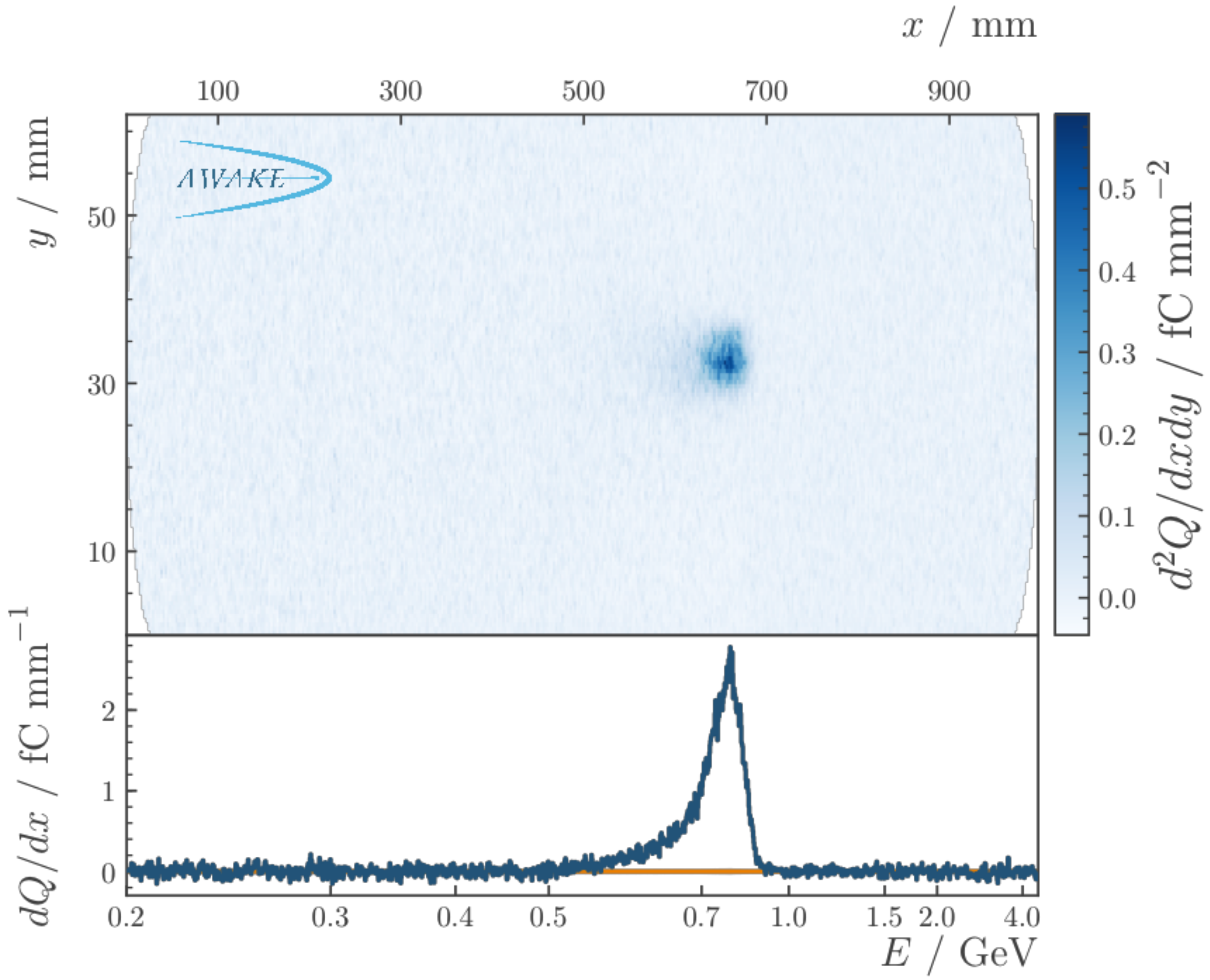
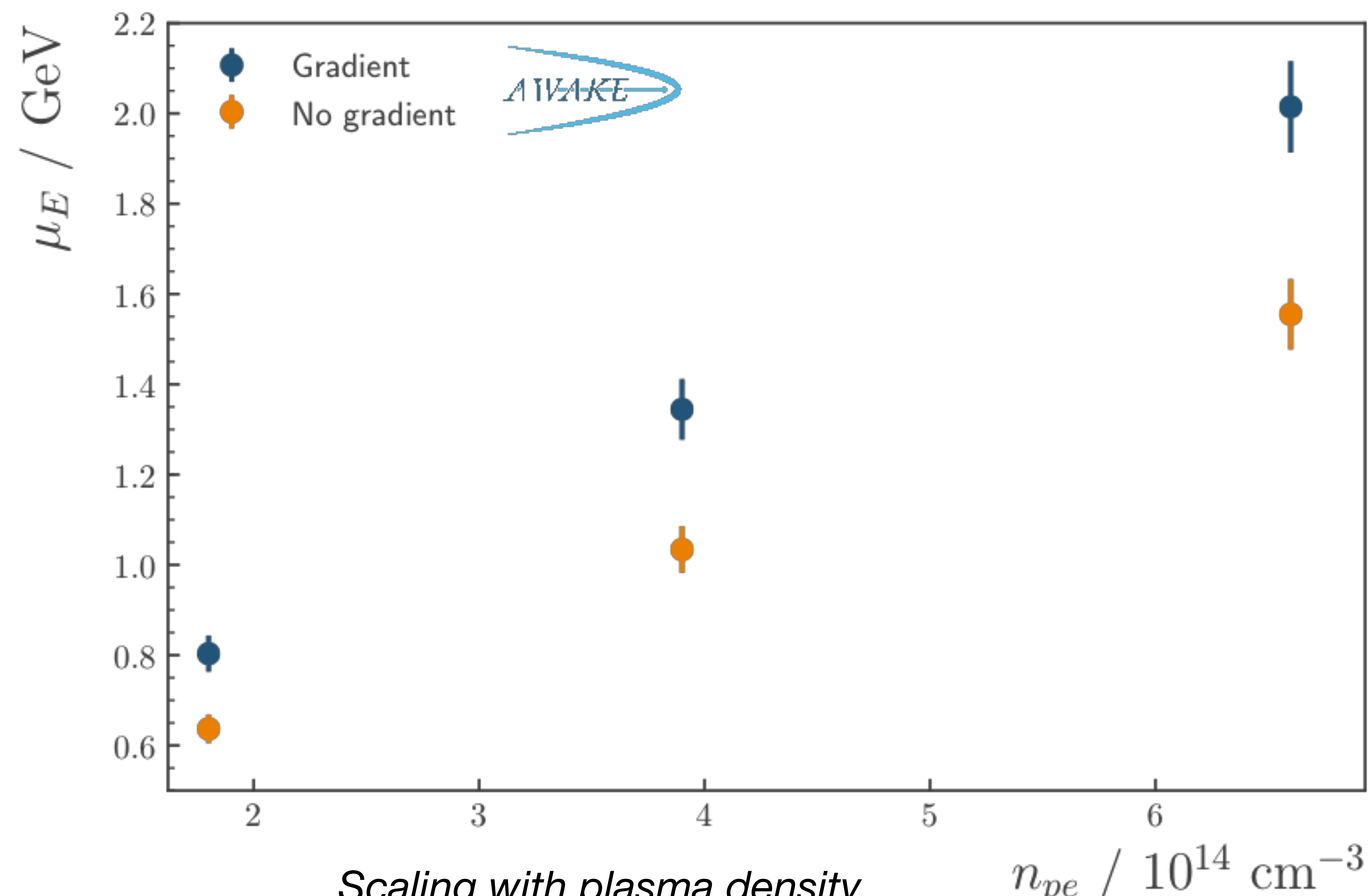
Electron injection & acceleration: AWAKE



Typical electron spectrometer image

For more information see:
*E. Adli et al. (AWAKE Coll.), Nature **561** (2018) 363*



Scaling with plasma density

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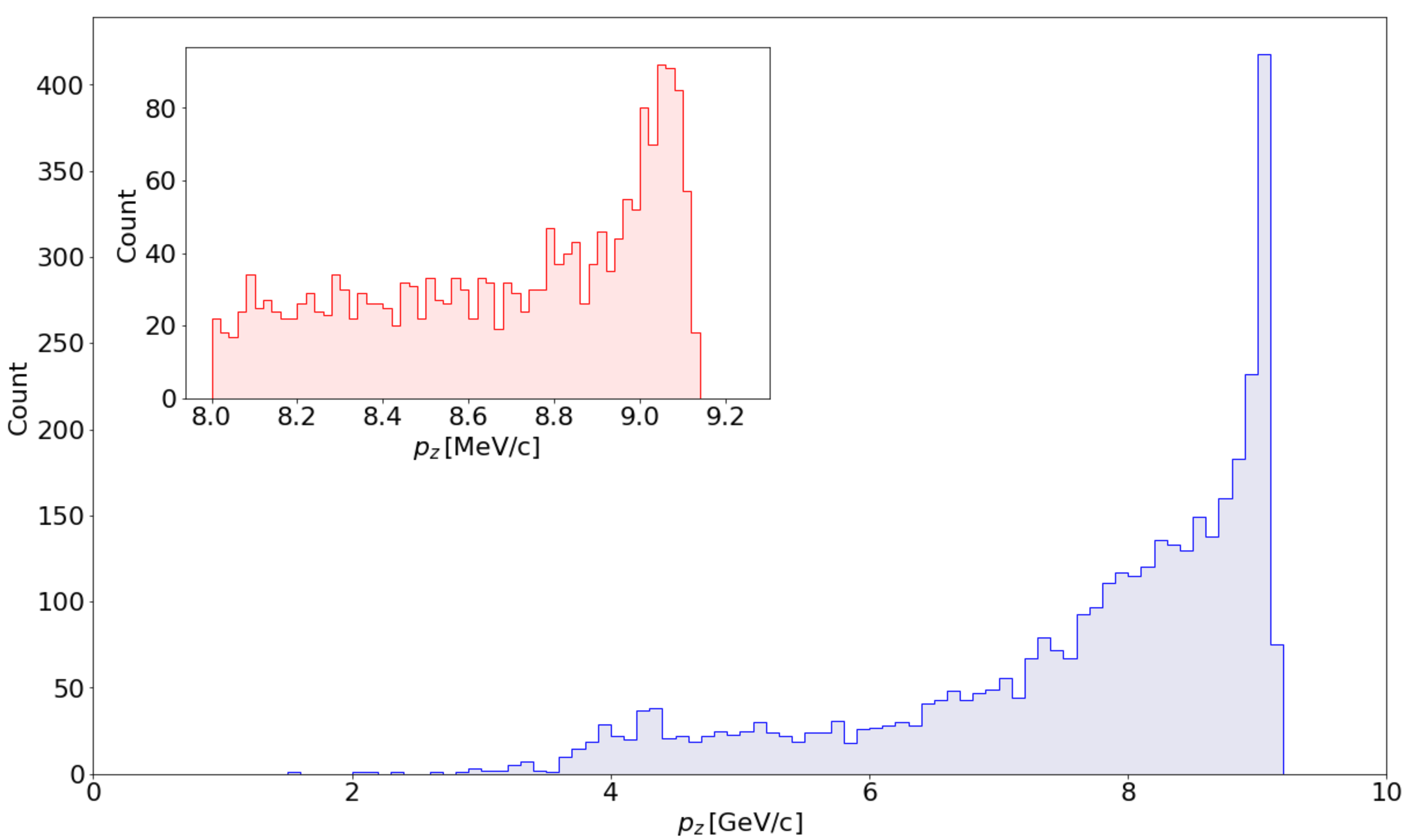
Using the RHIC-EIC proton beam as an electron injector

> The proposed RHIC-EIC proton beam would be ideal for use in driving wakefields due to its potentially small transverse size and high density.

> This means you could use plasma densities an order of magnitude higher than those used in AWAKE, with peak fields exceeding 6 GVm^{-1} and a field strength exceeding 1.2 GVm^{-1} post-saturation.

> Therefore, a plasma-based injector of length > 15 m driven by the proton beam could provide > 18 GeV electrons that would be injected into a storage ring before being used in electron-proton/ion collisions.



E.g. inject 5000 test electrons into wakefields driven by proposed RHIC-EIC proton beam with radius 40μm over 8m plasma length;

> 75.4% capture efficiency

> Peak energies exceeding 9 GeV (> 1.1 GVm^{-1} average gradient experienced by particles)

> Assuming an energy acceptance of 1% in the storage ring, 53% of electrons captured in the wakefields are captured in the storage ring.

> This can be improved via matching of the witness bunch to the wakefields e.g. see V. Olsen et al., Phys. Rev. Accel. Beams **21**, 011301

Conclusions

- The proposed RHIC-EIC proton beam could be used to drive strong wakefields with large acceleration gradients and thus provides an efficient way of accelerating electrons for use in the EIC collider.
- This scheme could reduce the build cost relative to an electron linac.
- The storage ring would only need to keep electrons at a constant energy rather than also accelerating them.
- Can change the energy of the electrons by tuning the plasma density.
- Optimisation of a plasma density step could provide even higher gradients after saturation, further reducing the required plasma length (see K. Lotov, Physics of Plasmas **22**, 103110 (2015)).
- Most of the technical challenges associated with the acceleration process (e.g. efficient capture in the wakefields, emittance preservation, energy spread preservation, density step effectiveness) should be demonstrated during AWAKE Run 2 (2021-2025).

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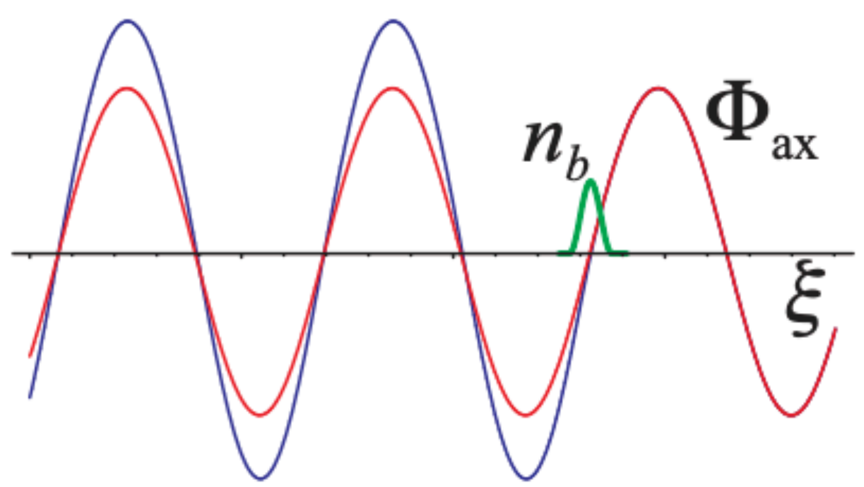
Thanks for your attention.

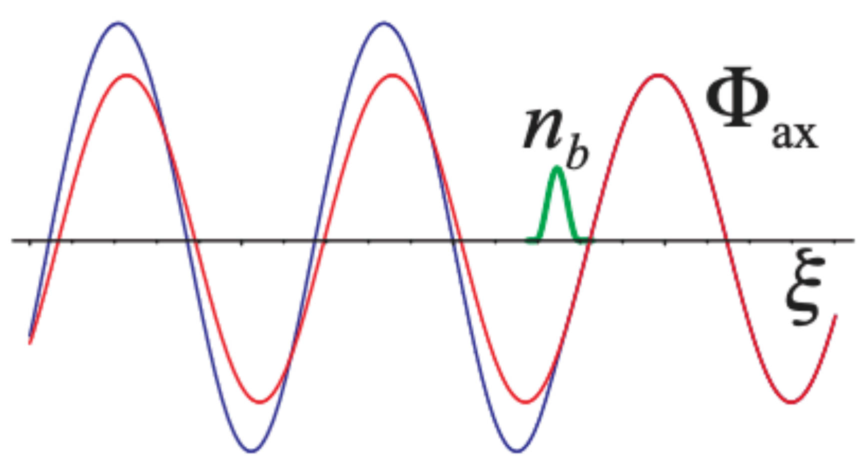
Extra

Longitudinal field evolution: wakefield phase shift



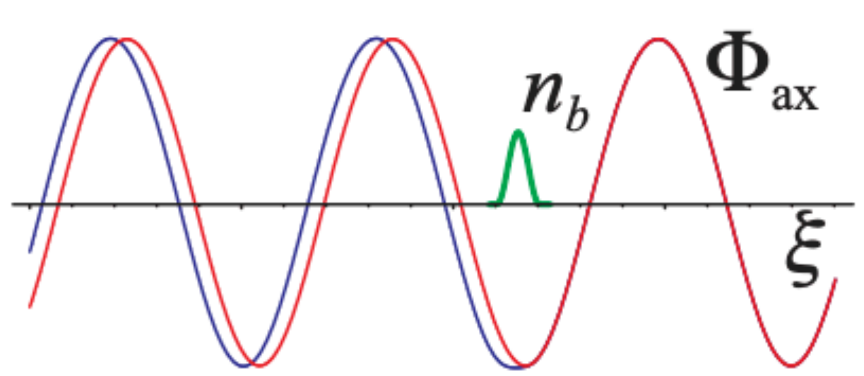
Microbunch perfectly in phase with the wakefield;

➡ amplifies the wakefield.



Microbunch π/4 phase shifted with respect to the wakefield;

➡ Simultaneously amplifies the wakefield and advances the phase.

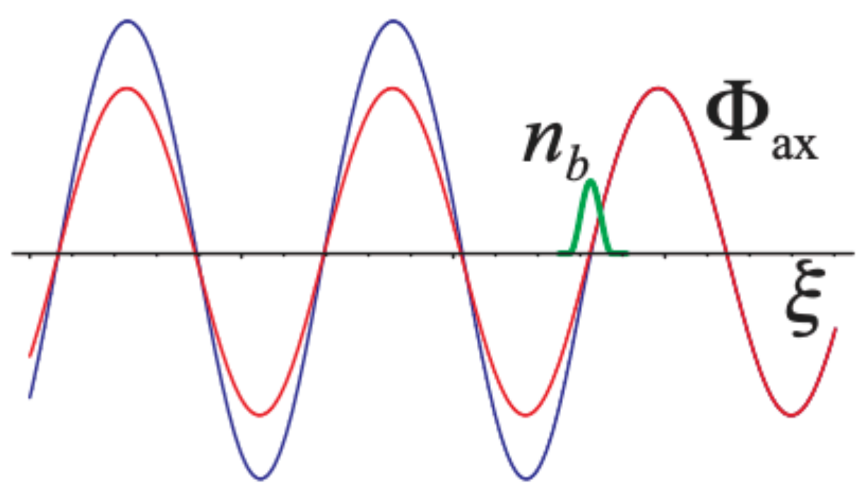


Microbunch exactly π/2 phase shifted with respect to the wakefield;

➡ amplitude remains unchanged, but phase advanced.

For more information see:
*K. Lotov, Physics of Plasmas **22**, 103110 (2015)*

Longitudinal field evolution: wakefield phase shift



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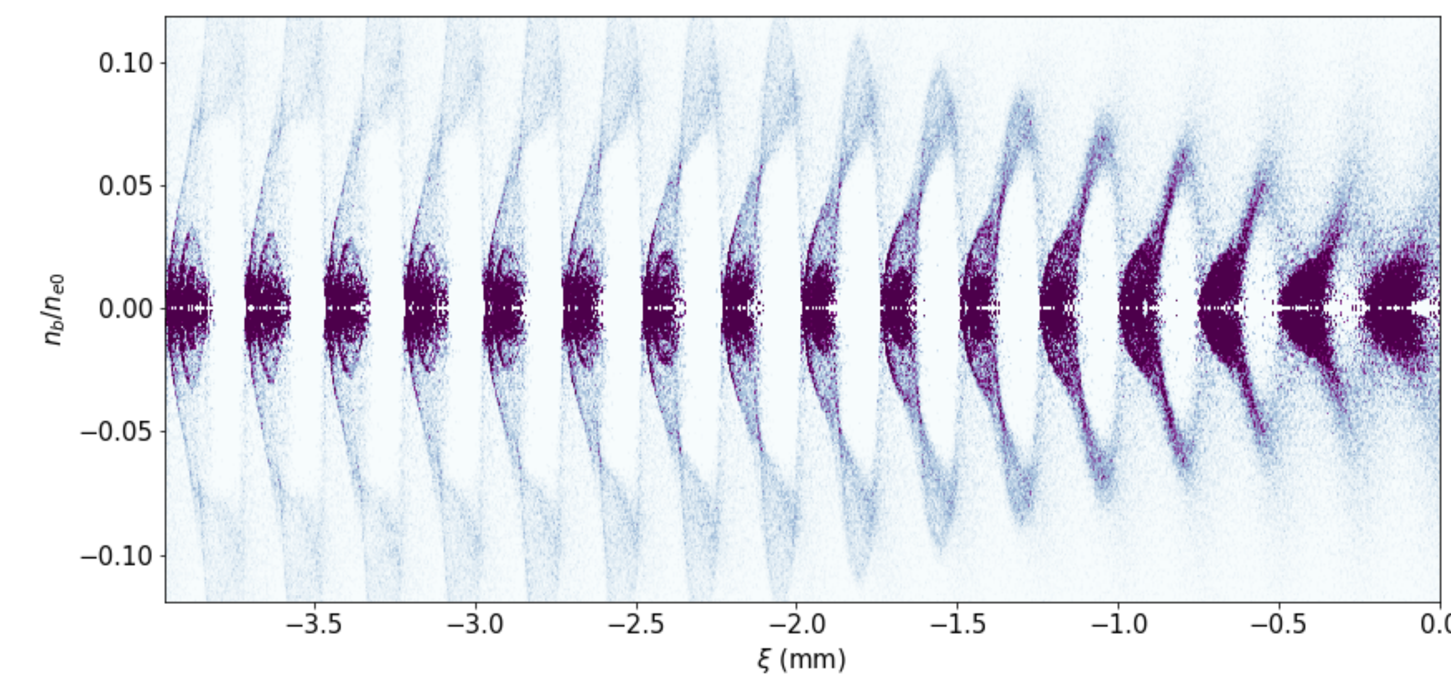

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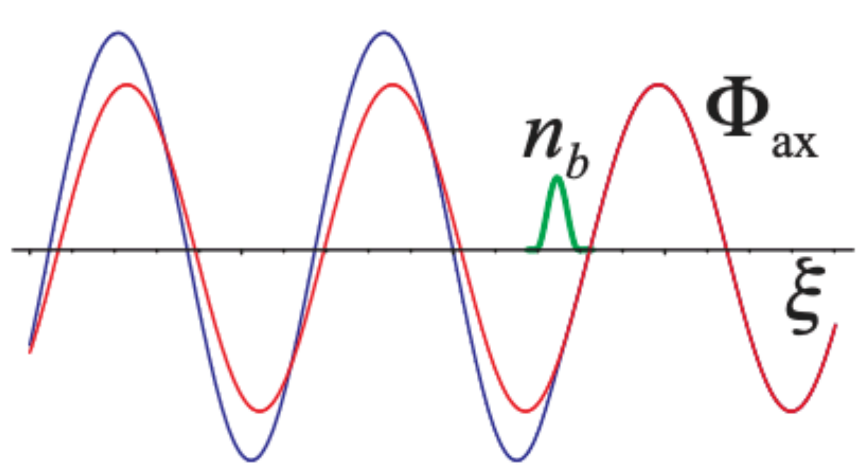

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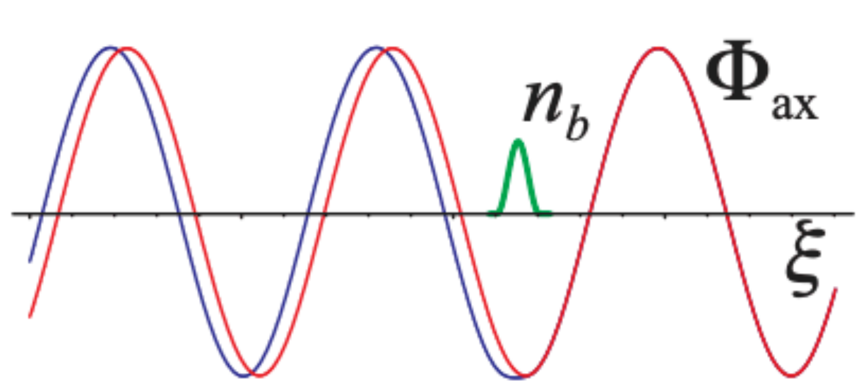

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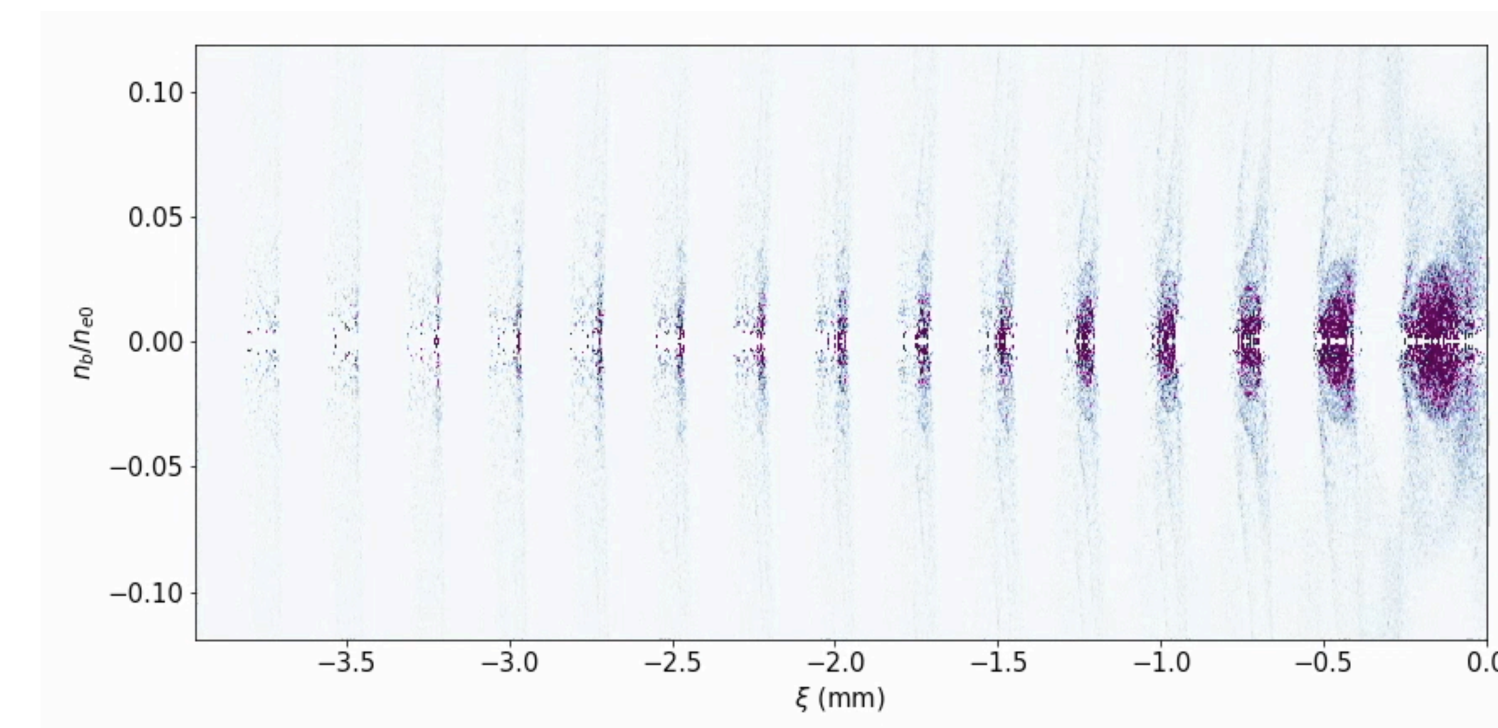

Front of the microbunches is in a defocusing region of the wakefield;

➡ Charge lost from the front of the microbunches.

➡ Centroid moves backwards with respect to the wakefield.

➡ Contribution to phase advance per bunch reduces, increasing the wakefield phase velocity with respect to the microbunches.

For more information see:
*K. Lotov, Physics of Plasmas **22**, 103110 (2015)*