Influence of proton bunch and plasma parameters on the AWAKE experiment

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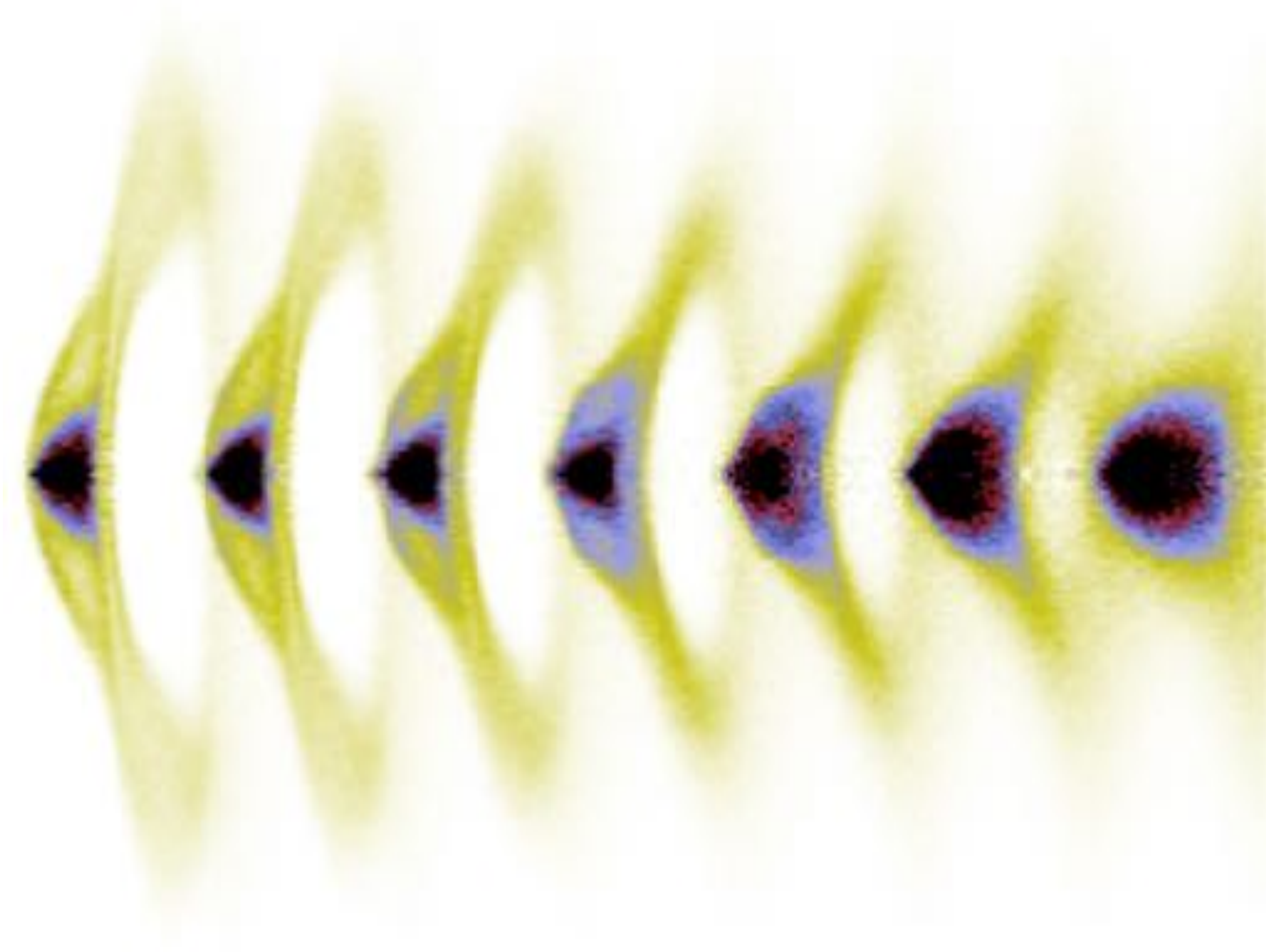

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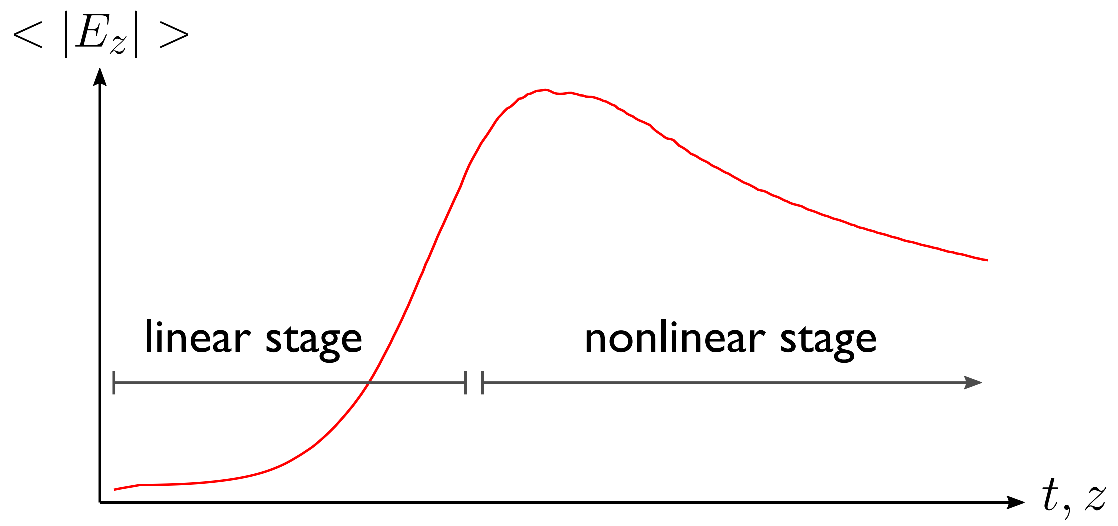
Beyond the linear stage of the SMI



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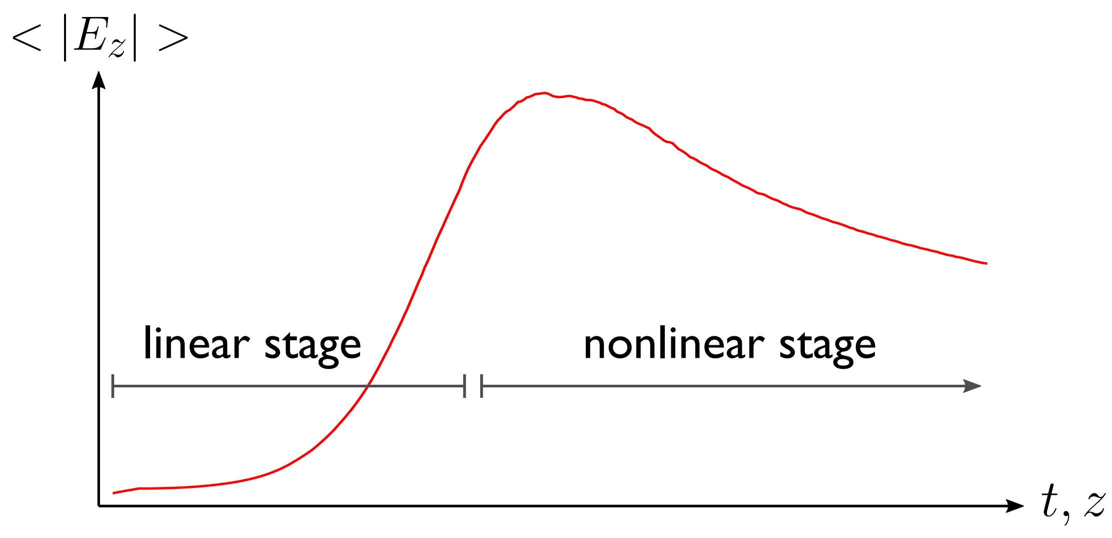

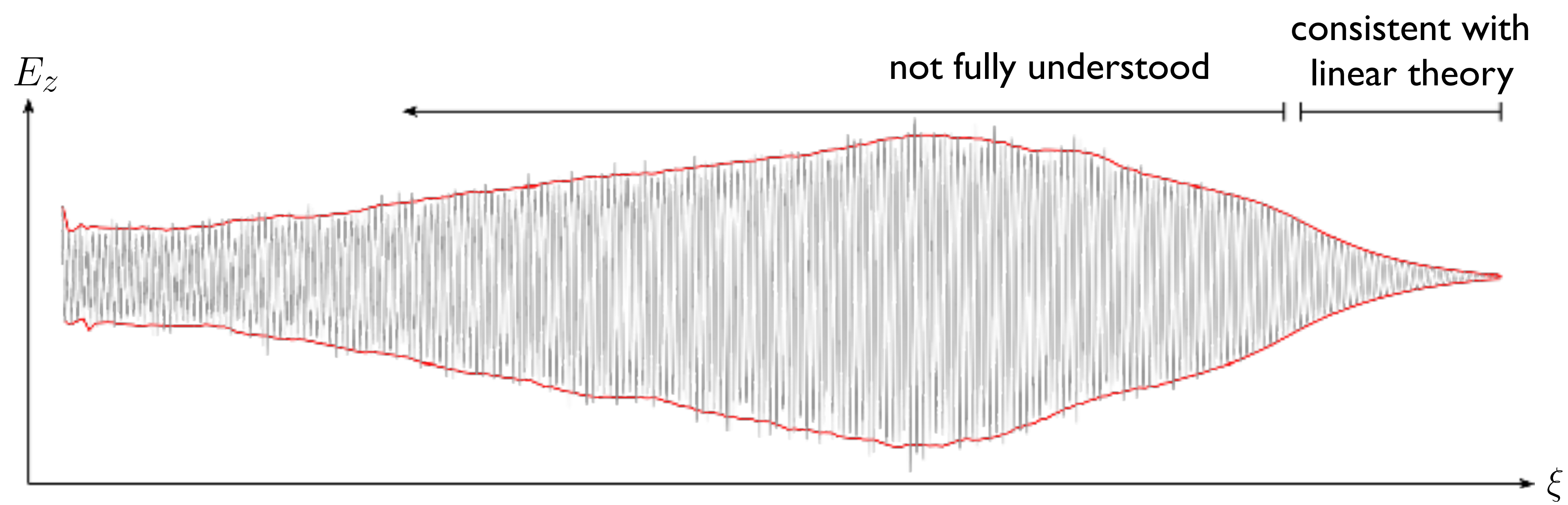

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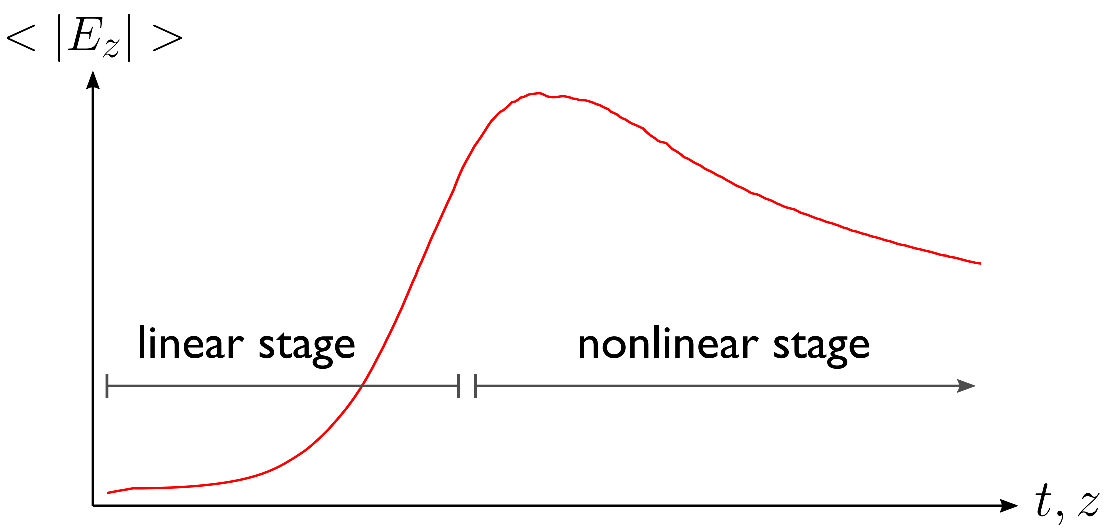
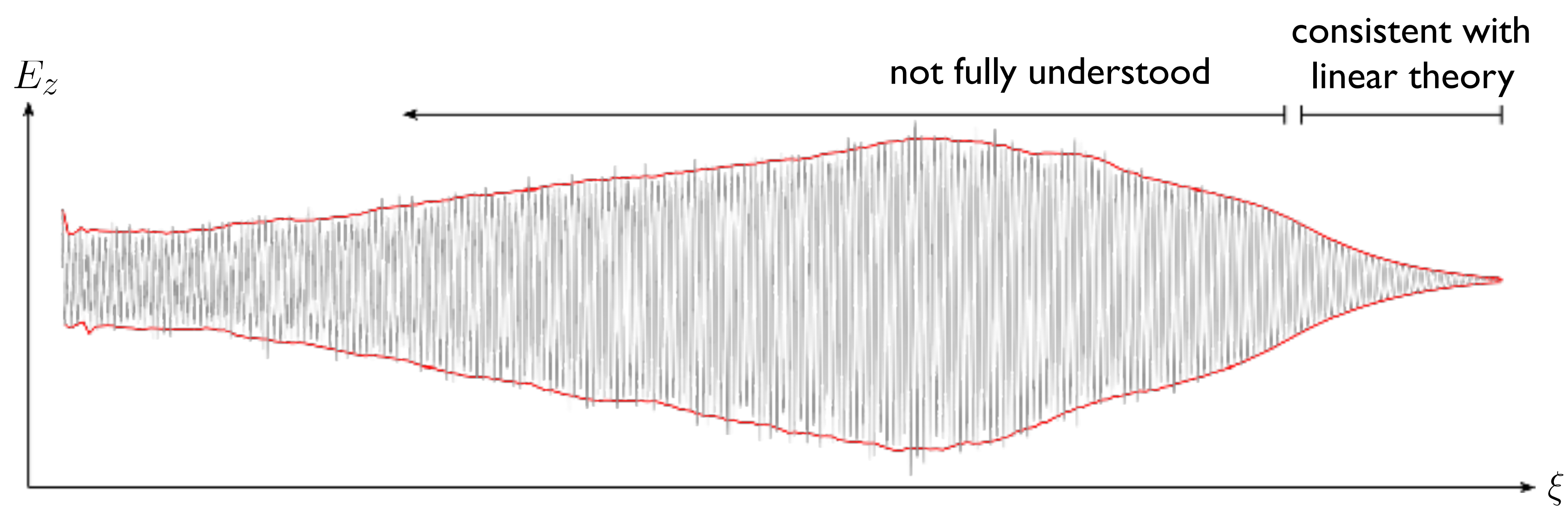


temporal decline

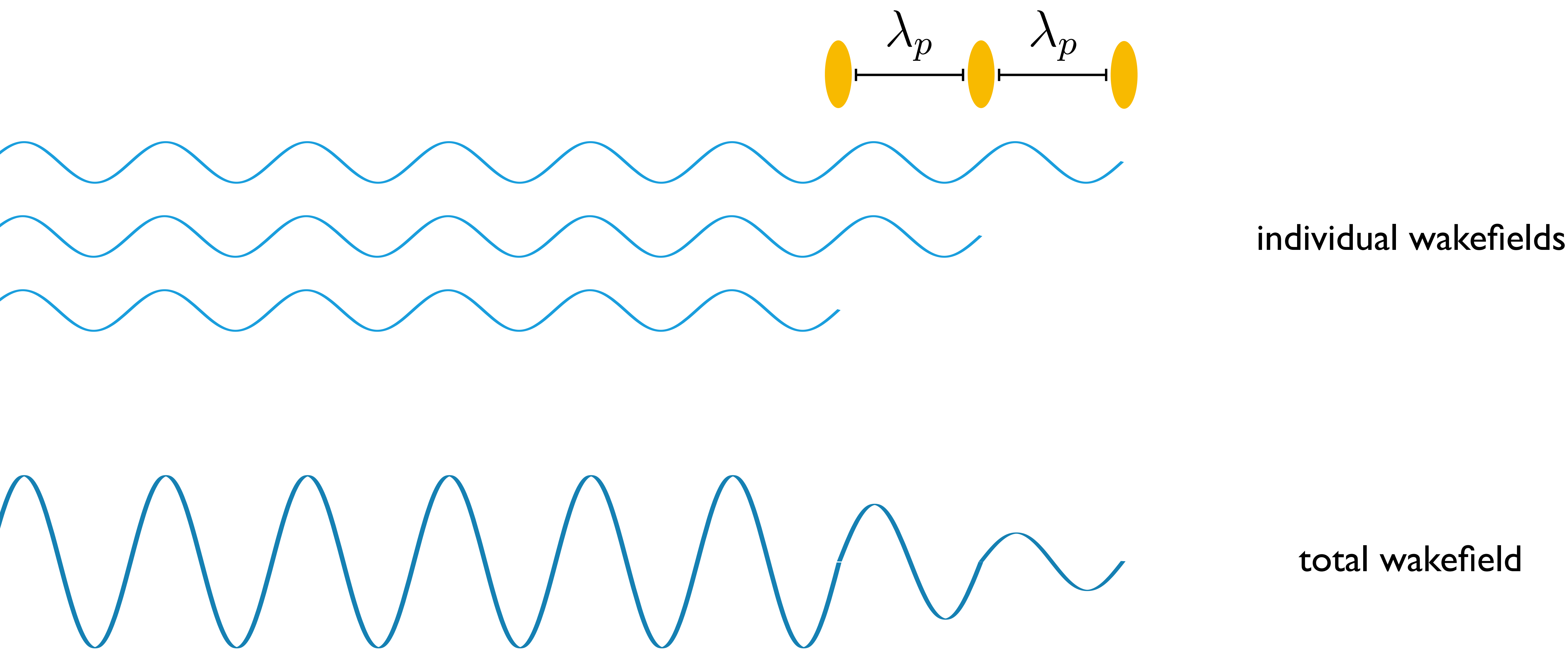


spatial decline

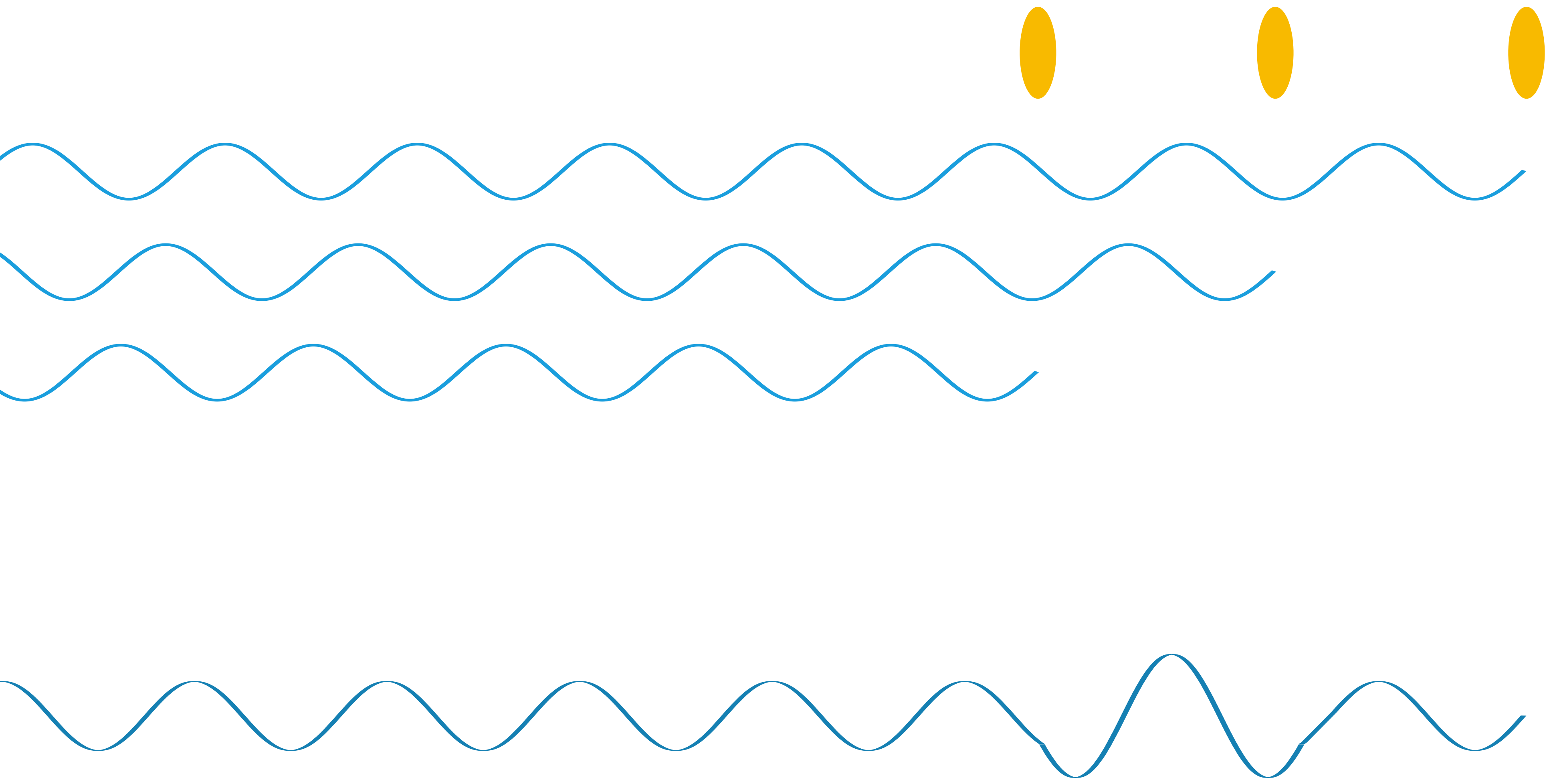
Second question

Why does the wakefield amplitude decrease along the beam and along time (after saturation of the SMI)?

Hypothesis: incoherent interference of wakes



Hypothesis: incoherent interference of wakes



individual wakefields

total wakefield

A tool to study the nonlinear stage

Using linear theory and separating the contributions from each beamlet

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Linear wakefield theory

Axial electric field excited in plasma by an axisymmetric particle beam in cylindrical coordinates:

$$E_z(\xi, r) = 4\pi e k_p^2 \int_{\infty}^{\xi} d\xi' \int_0^{\infty} dr' r' \cos\left[k_p(\xi - \xi')\right] I_0(k_p r_<) K_0(k_p r_>) n_b(\xi', r')$$

A tool to test hypotheses

Using linear theory and separating the contributions from each beamlet

Linear wakefield theory

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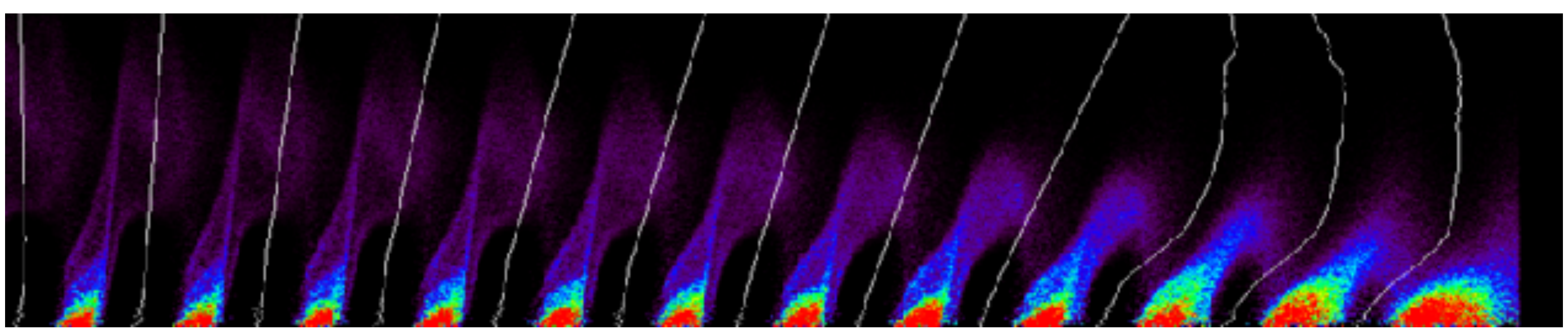
Single beamlet linear wakefield solver

- **input:** charge density data from PIC simulation for the driver beam $\rho(\xi, r)$
- identify and isolate beamlets



} partially parallel

- solve equation for each beamlet and add all the contributions

} parallel

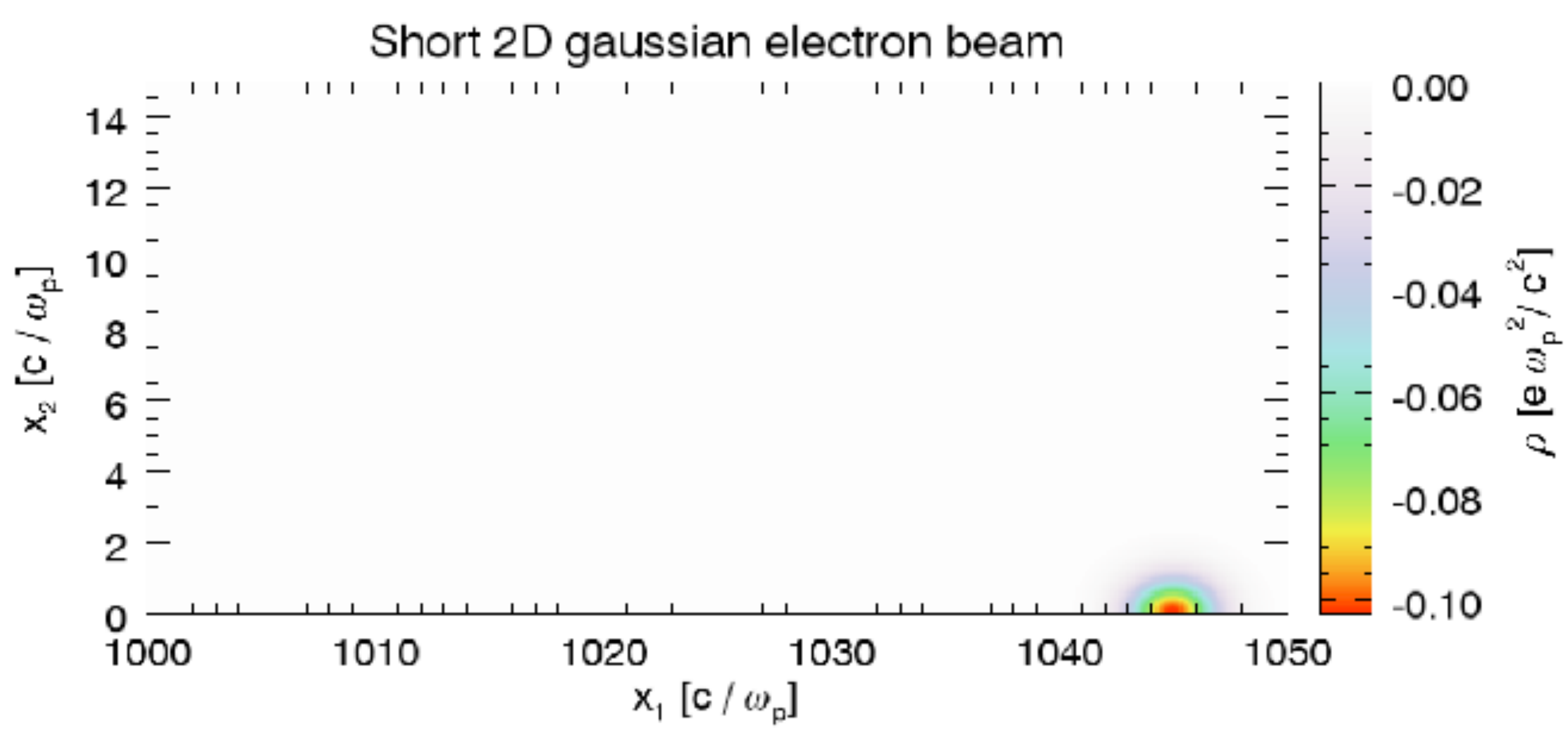
- **output:** axial electric field distribution over simulation window $E_z(\xi, r)$

Benchmarking the program

Subtasks involved

- devising and/or perfecting the algorithms for each step
- implementing in C with parallelization (MPI)
- scalability tests on Accelerates
- benchmark (and finding the last bugs)

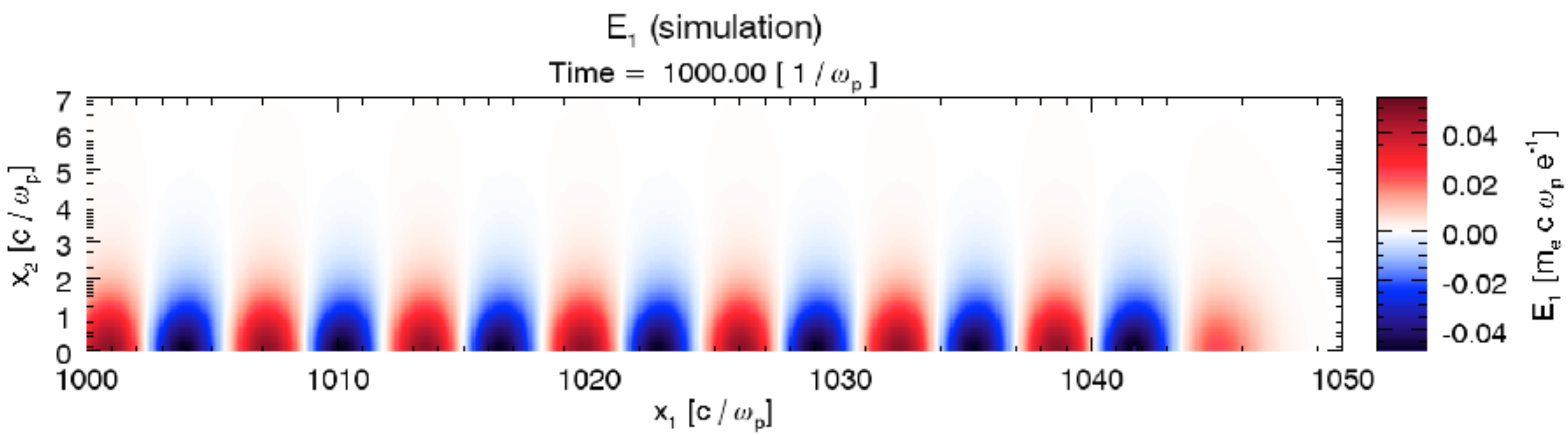
Benchmark



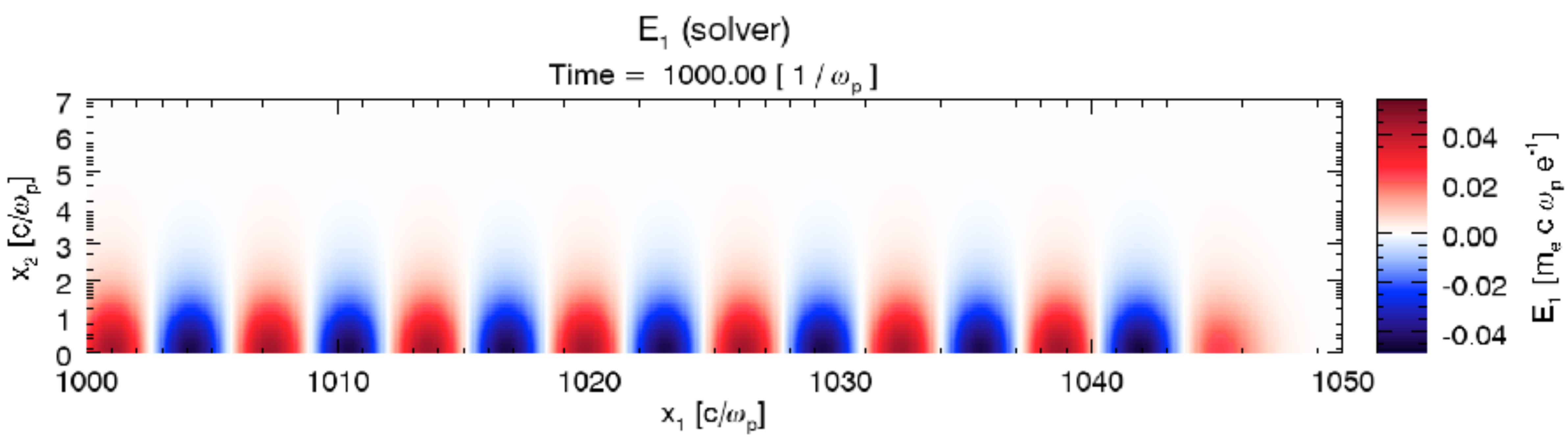
Benchmarking the program

Excellent agreement

Simulation results



Wakefield solver



Applying the program to AWAKE

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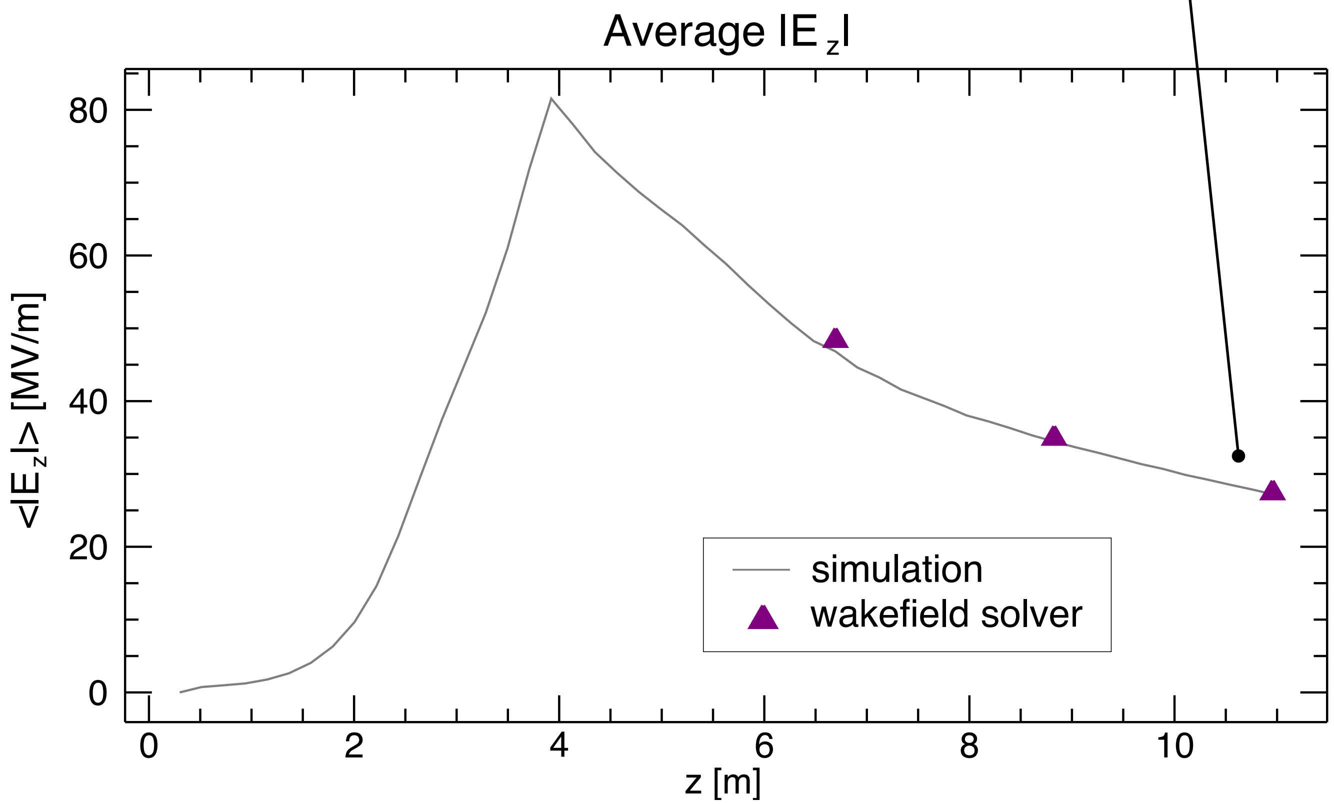
General wakefield

- comparison of the total E_z field at three simulation times
- good agreement both in terms of field amplitude and configuration

better agreement
for later times



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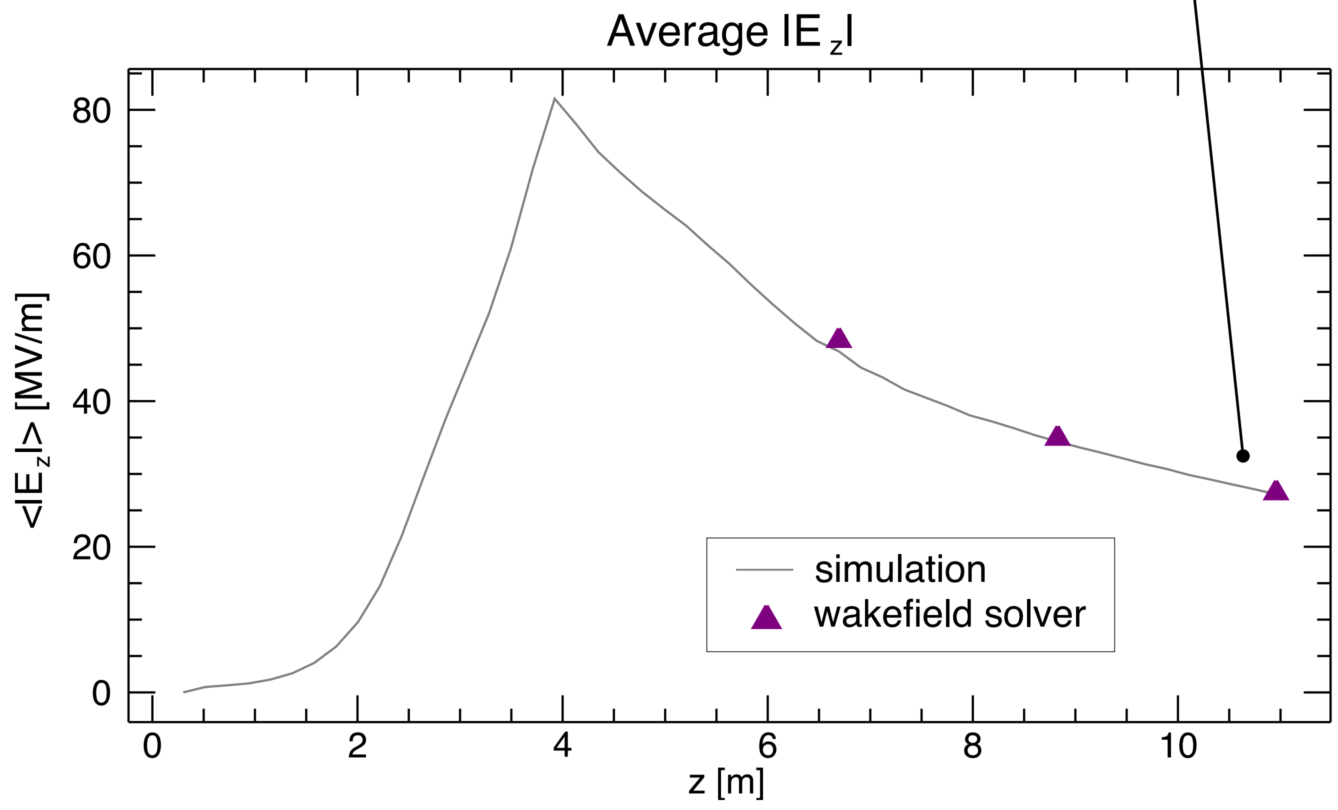


Separate contributions

- wakefield is solved up to a specified beamlet number
- **two outputs:**
  - field due to last beamlet
  - field due to all previous beamlets
- comparison for two simulation times and three beamlet numbers

beamlet nr.	position along simulation window
8	96%
90	60%
170	25%

Incoherence causes the decline along the beam

But the decline along z must have a different dominant cause

beamlet nr. 8
rel. amplitude: 20%

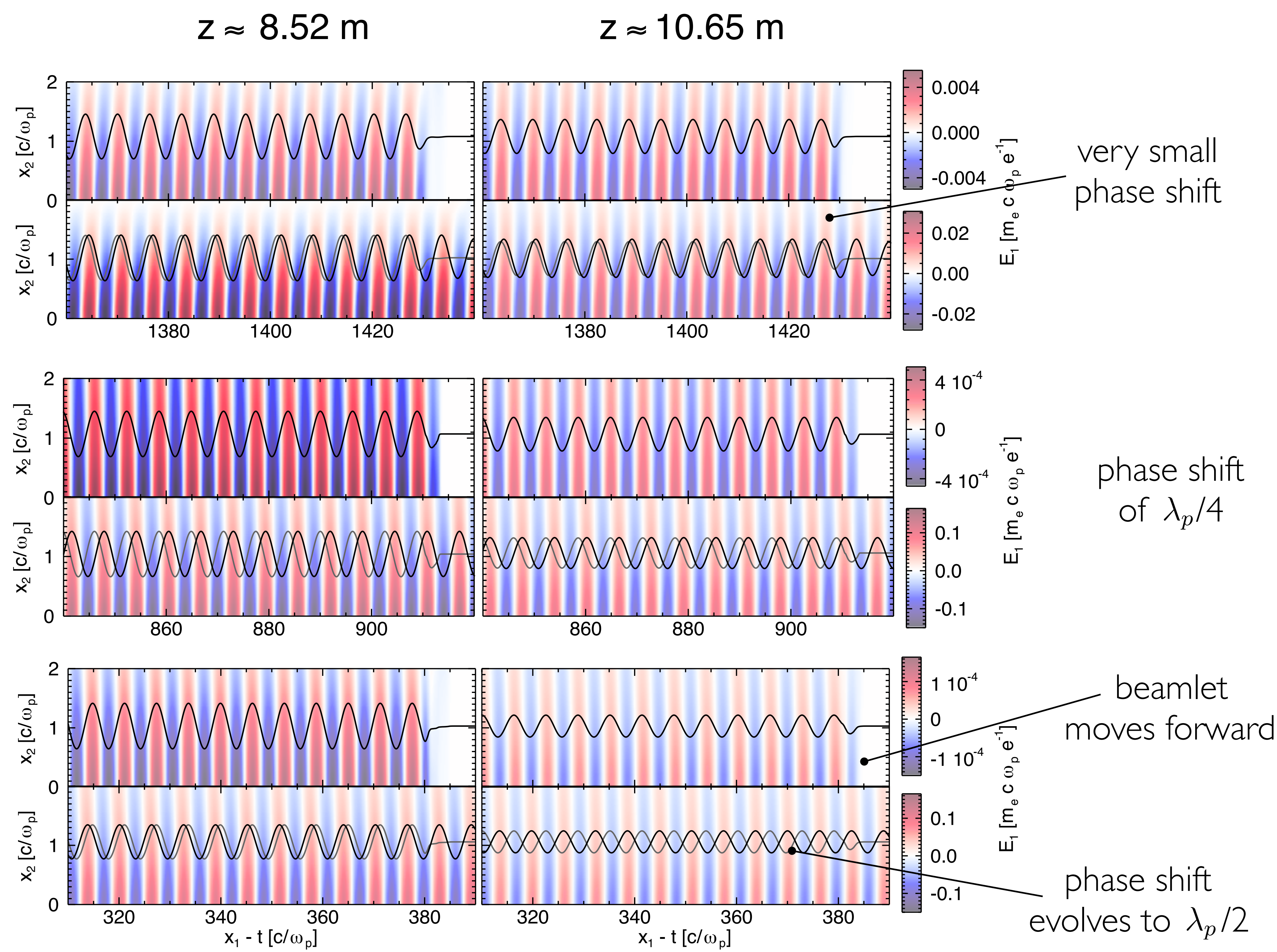
beamlets nr. 1–7

beamlet nr. 90
rel. amplitude: 0.3%

beamlets nr. 1–89

beamlet nr. 170
rel. amplitude: 0.1%

beamlets nr. 1–169



Temporal decline is due to driver charge loss

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Decline along beam (ξ)

- for a fixed time the individual wakes interfere incoherently with one another
- the total amplitude therefore falls in space
- no hidden nonlinear effects (overlap between wakefield solver and PIC simulation)

Temporal decline is due to driver charge loss

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Decline along beam (ξ)

- for a fixed time the individual wakes interfere incoherently with one another
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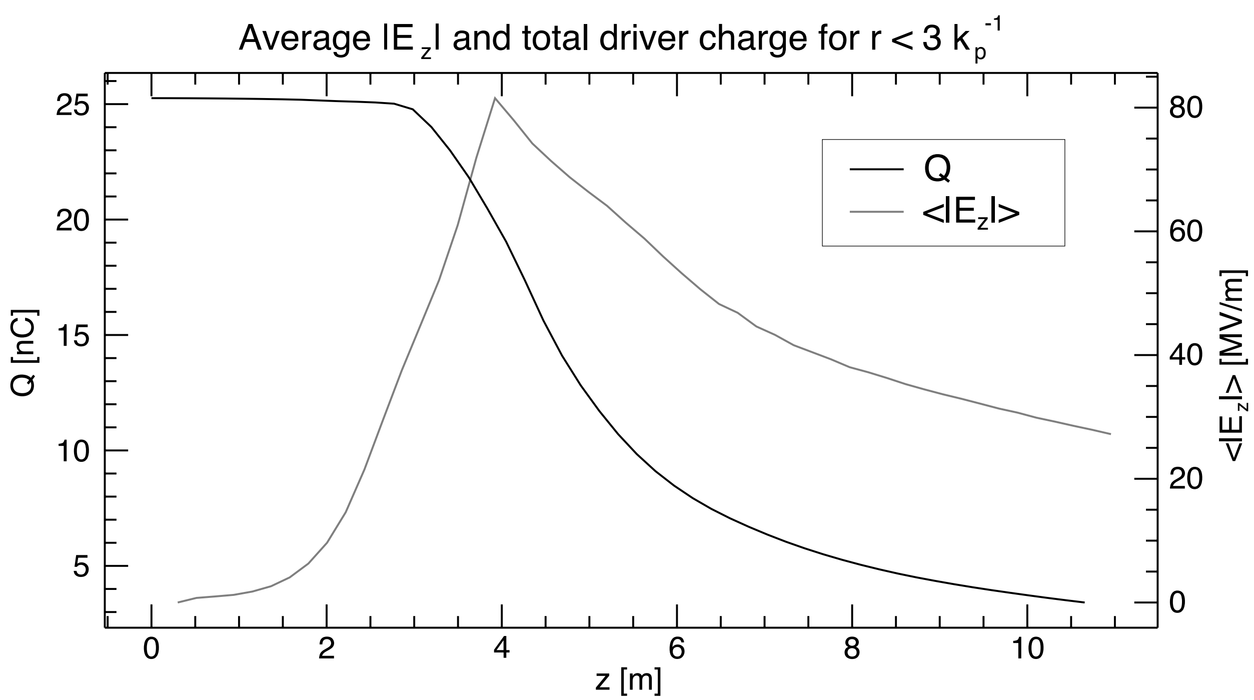
Decline along propagation distance (z)



- identical trends for the wakefield-driving charge and average field after saturation
- loss of driver charge is the overwhelming cause for temporal decline

Contents

Antiprotons as wakefield drivers

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Asymmetry between opposite charges

- most PWFA experiments have used electrons as drivers
- positrons seem to be less efficient as drivers*
- linear wakefield theory is perfectly symmetrical for opposite charges

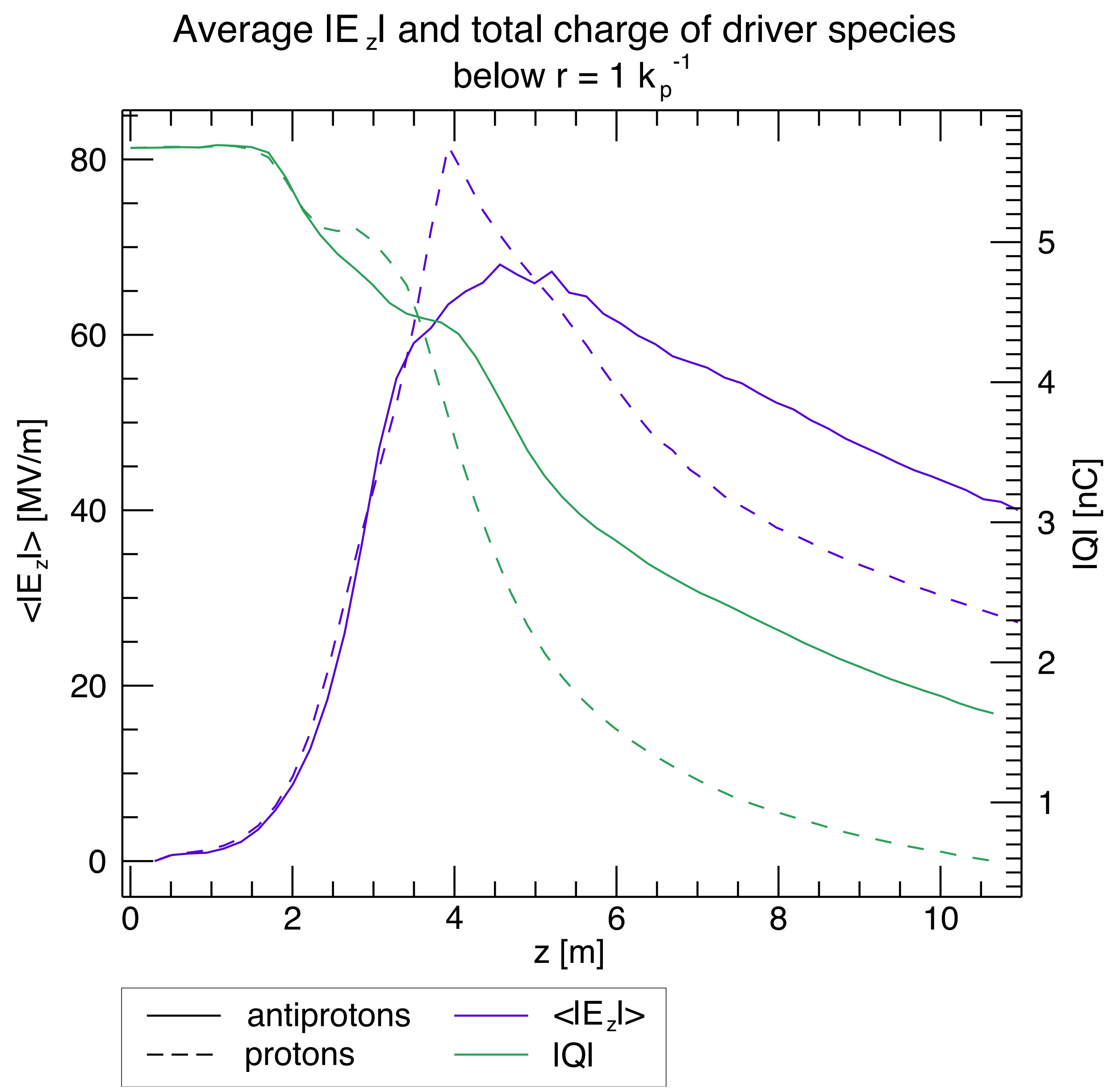
Third question

How would the hypothetical substitution of the driver protons by antiprotons change the AWAKE experiment?

* S. Lee et al. Phys. Rev. E 64 045501 (2001)

An antiproton driver brings several benefits

More driver charge available

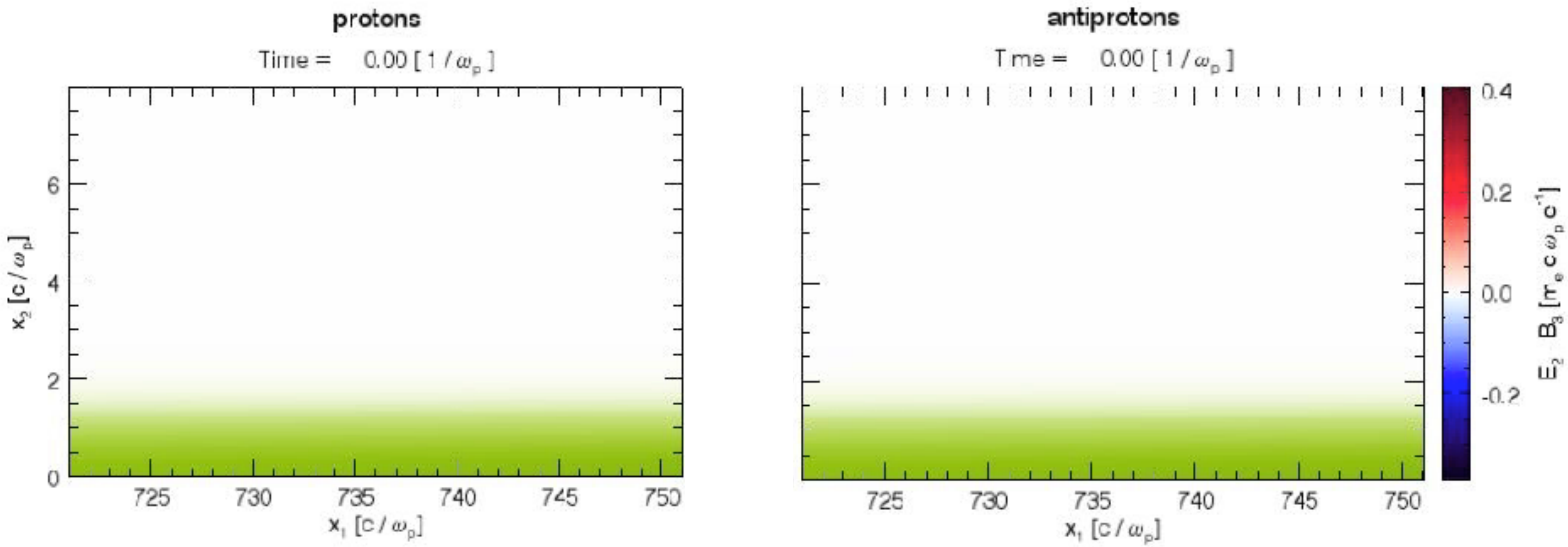


2.8x more driver charge at 10.33 m

1.5x higher average $|E_z|$ at 10.33 m

Field configuration recaptures off-axis charge

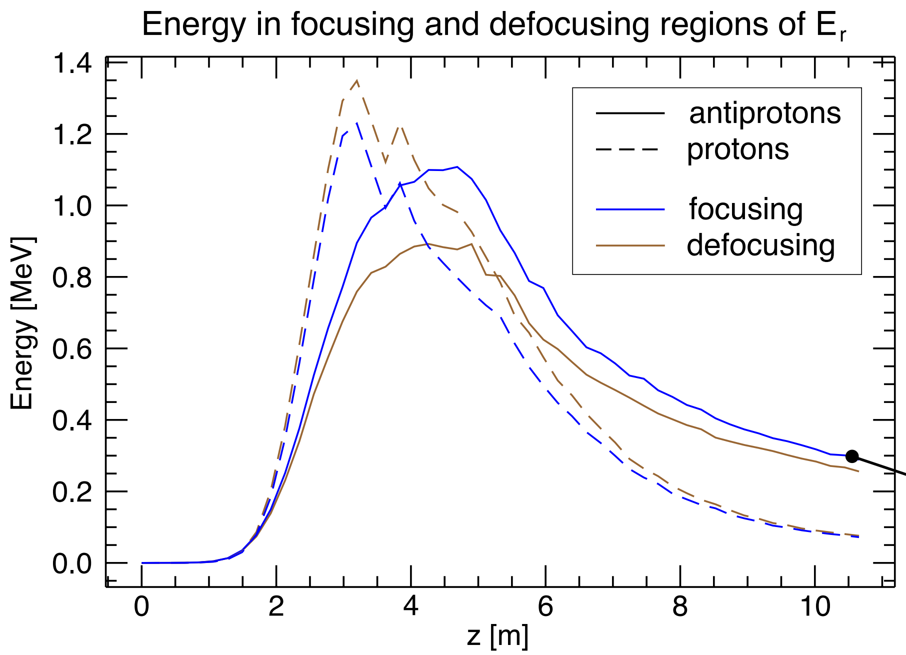
Why is so much antiproton charge retained?



Energy contained in E_r offers important clues

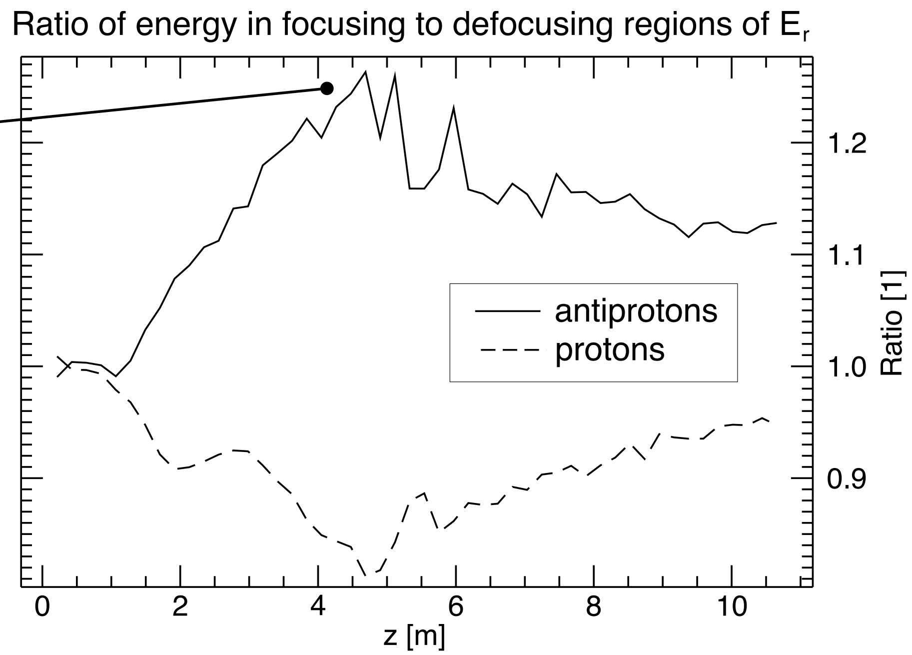
Why is so much antiproton charge retained?

Antiprotons have more energy available for focusing



larger energy imbalance for antiprotons

3.8x more energy in focusing fields



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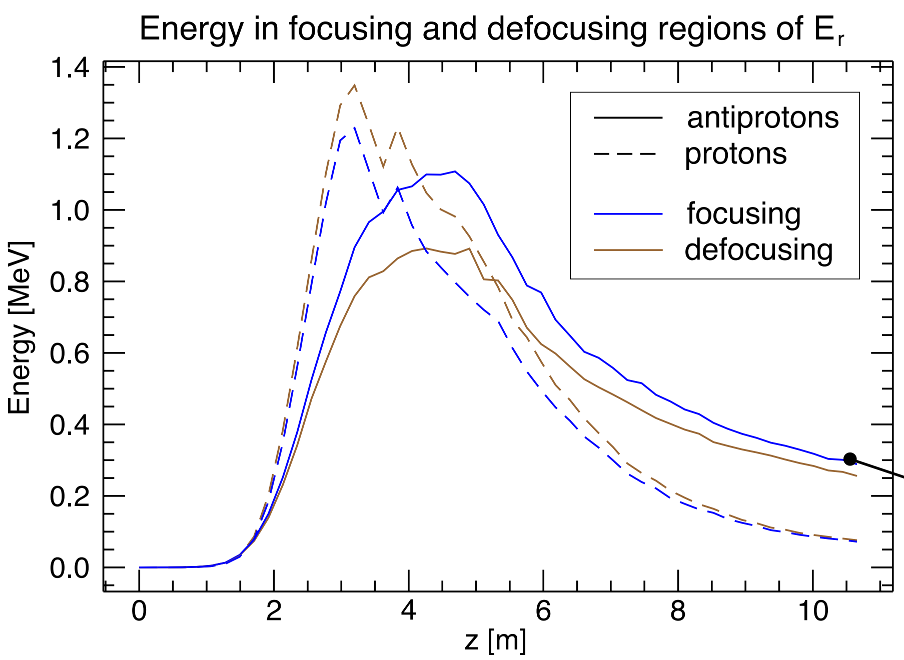
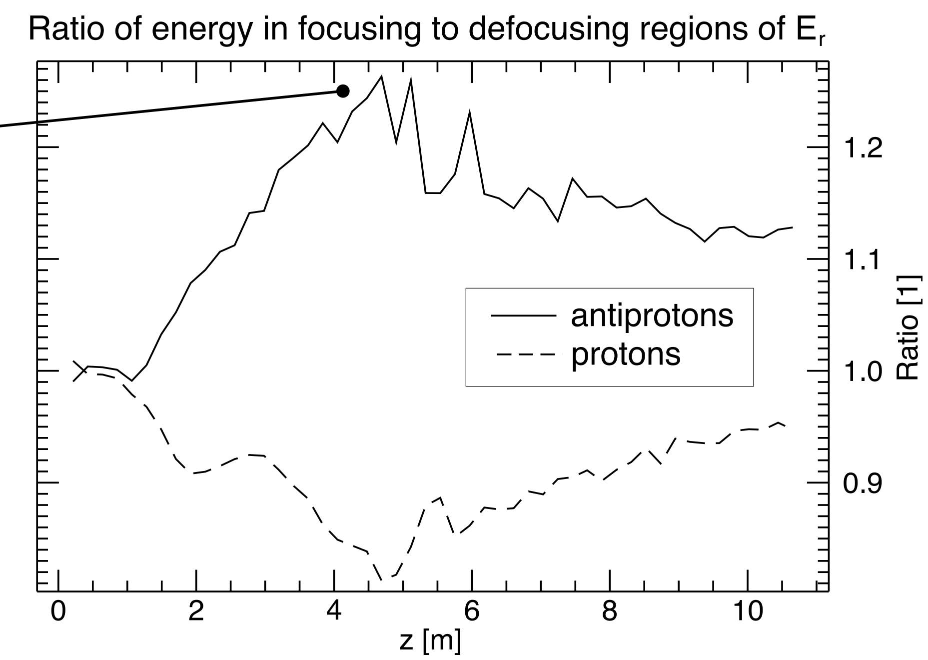




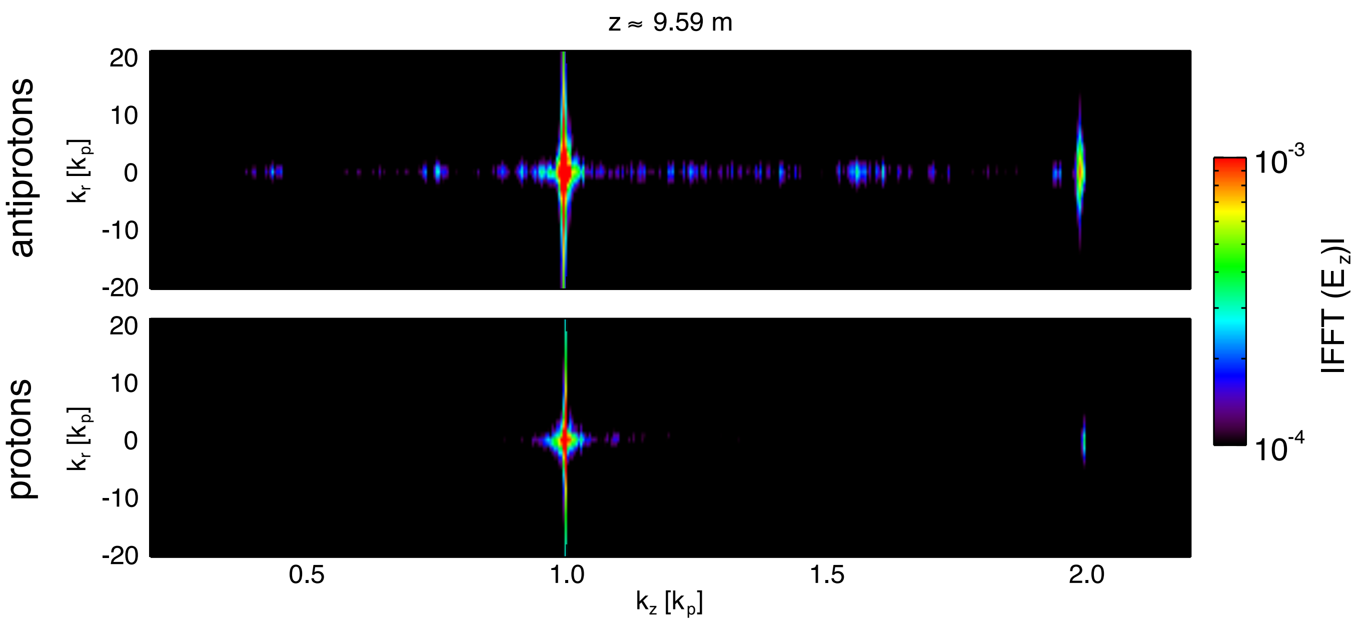
larger energy imbalance for antiprotons

3.8x more energy in focusing fields

The antiproton-driven wakefield is more nonlinear

- 2D Fourier transform of E_z
- purely linear wake:

$$k_z = n\, k_p,\ \ n \in \mathbb{Z}$$



Bunch-plasma energy transfer provides no answer

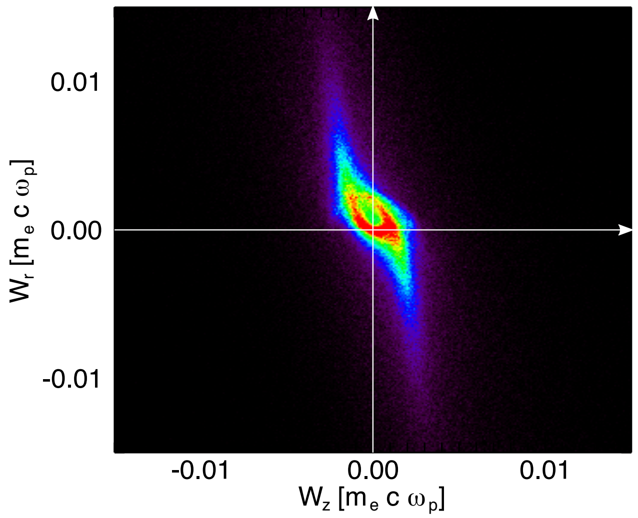
Why is the amplitude of the antiproton wakefield lower than expected?

Charge density in longitudinal and transverse force plane

- normalized, unsigned forces:

  $$W_z = E_z \qquad\qquad W_r = E_r - B_\varphi$$

- each increment of charge is deposited in W_r/W_z plane according to the fields acting on it



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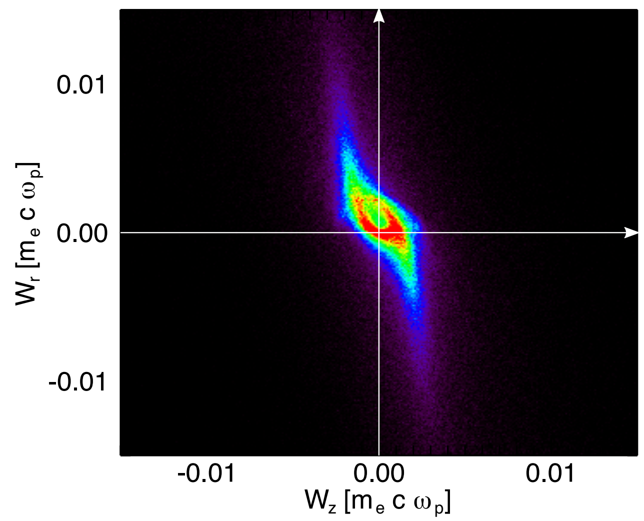
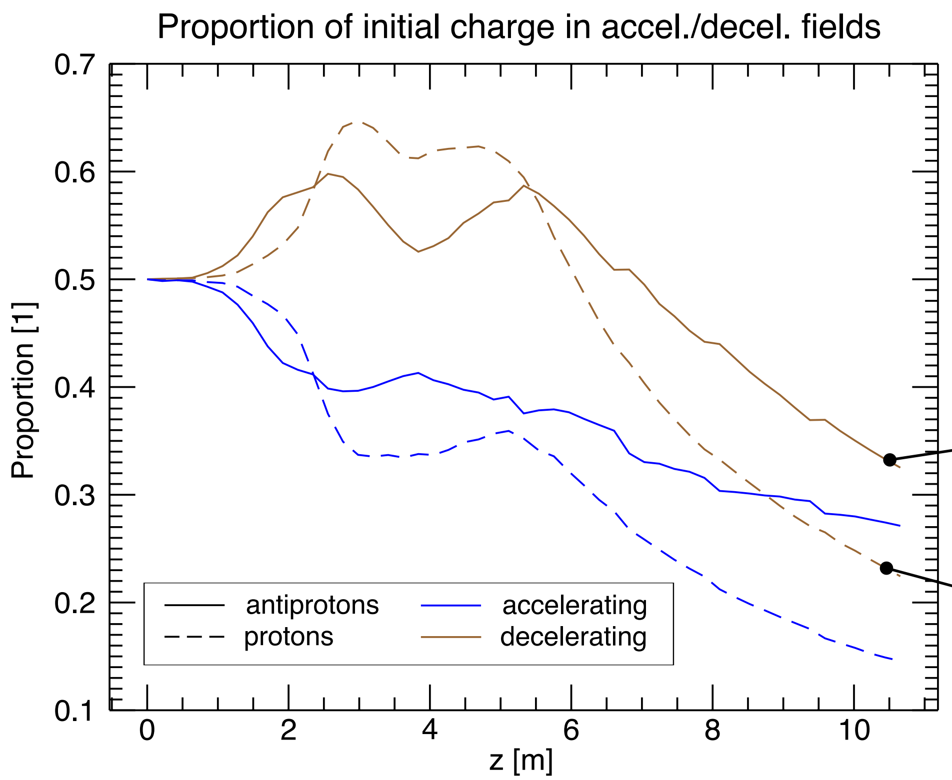


A lower portion of the remaining antiprotons gives up energy



- integrate charge density on W_r/W_z plane for $W_z > 0$ and $W_z < 0$

55% of antiprotons left

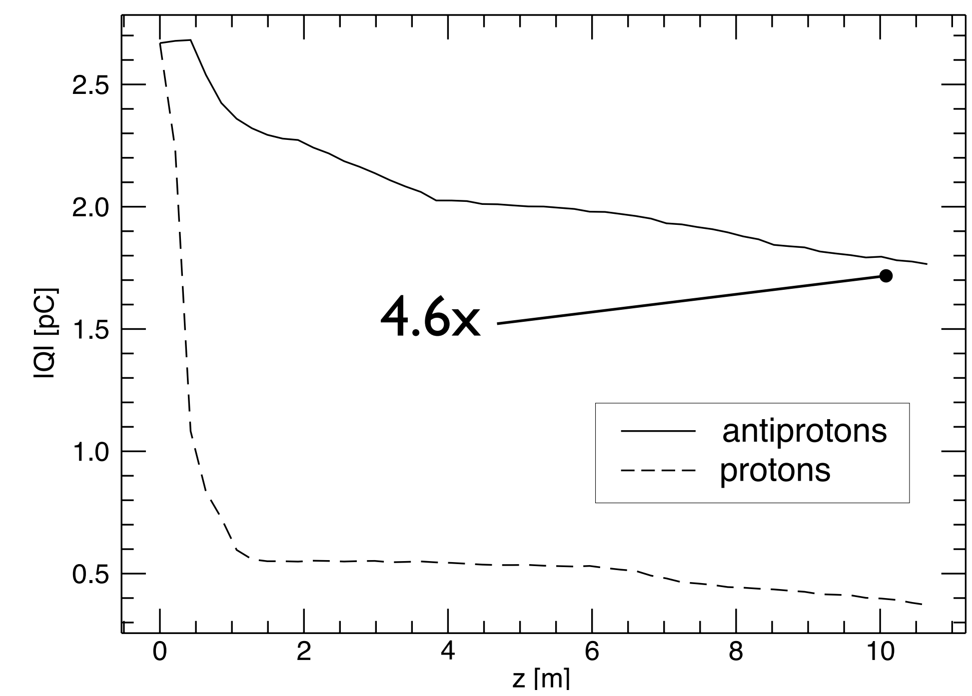
61% of protons left

difference is not large enough to explain the underwhelming amplitude of E_z

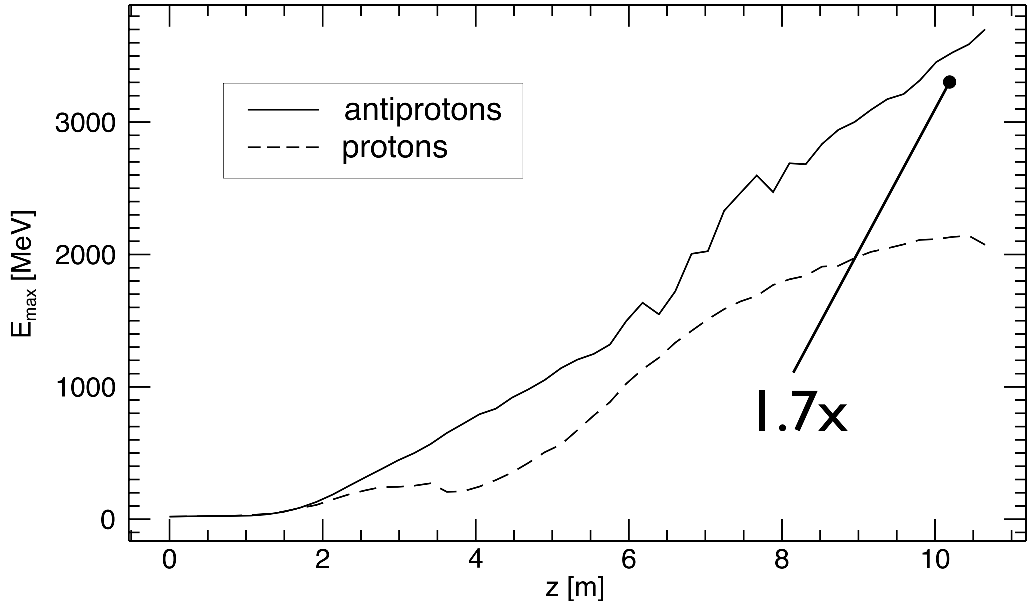
Benefits are also reflected on witness electrons

A witness electron bunch is introduced in the simulation

Witness charge



Max. electron energy



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Conclusions

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Deterministic injection of electrons is possible for AWAKE

The outputs from the experiment are robust against shot-to-shot fluctuations

The temporal decline of the wakefield amplitude is due to charge loss

The spatial decline is due to incoherent interference between individual wake contributions

A parallel program was developed to study the nonlinear phase of the SMI

Antiprotons are more efficient as wakefield drivers

The wakefield driven by antiprotons is more nonlinear than the one driven by protons

More antiproton charge is preserved due to stronger fields