Loading of Wakefields in a Plasma Accelerator Section Driven by a Self-Modulated Proton Beam

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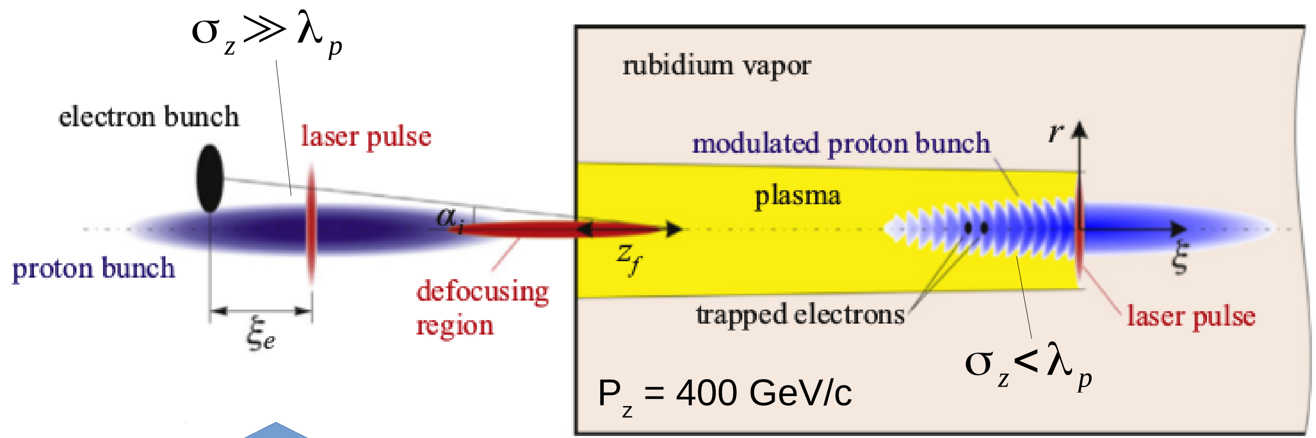
Outline

1) Quick overview of the AWAKE experiment
2) Simulation setup with Osiris
3) Beam loading and phase dependency
4) Beam loading and charge/current dependency

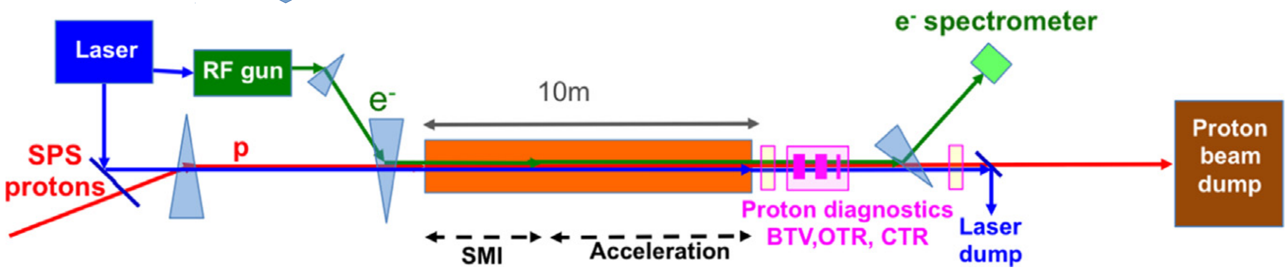
An Overview of the AWAKE Experiment

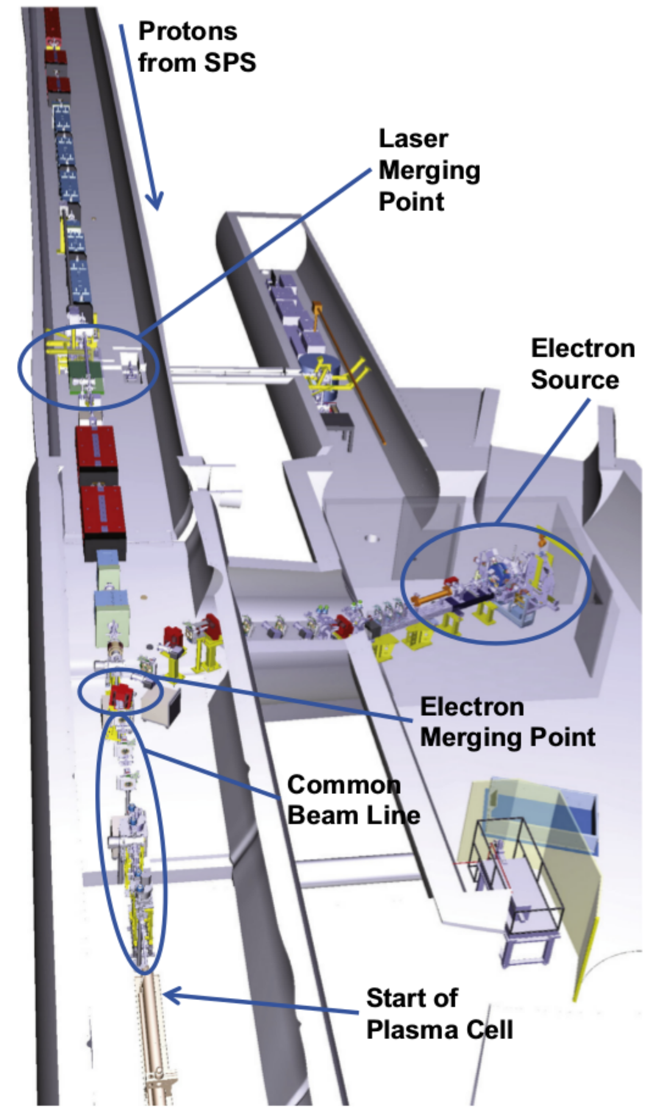


The oblique injection of the electrons into the plasma.

Baseline design.

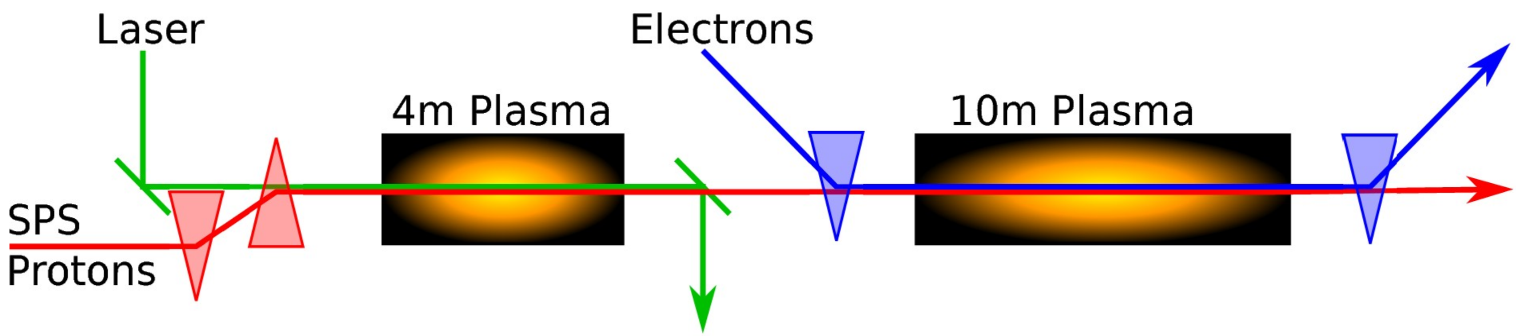
The integration of the AWAKE beam lines (proton, electron and laser) in the AWAKE facility (formerly CNGS).





Gschwendtner, E., et al. Nuclear Instruments and Methods in Physics Research Section A, 2016. doi:10.1016/j.nima.2016.02.026.

Run 2 of the AWAKE Experiment



Proposed setup for AWAKE Run 2.

Two plasma stages

- Stage 1: SMI stage
- Stage 2: Acceleration stage

Typical value expected for the accelerating field in the second plasma stage is between 500 and 800 GV/m.

AWAKE Collaboration, Technical Report, CERN-SPSC-2016-033 (2016).

The Self-Modulation Instability:

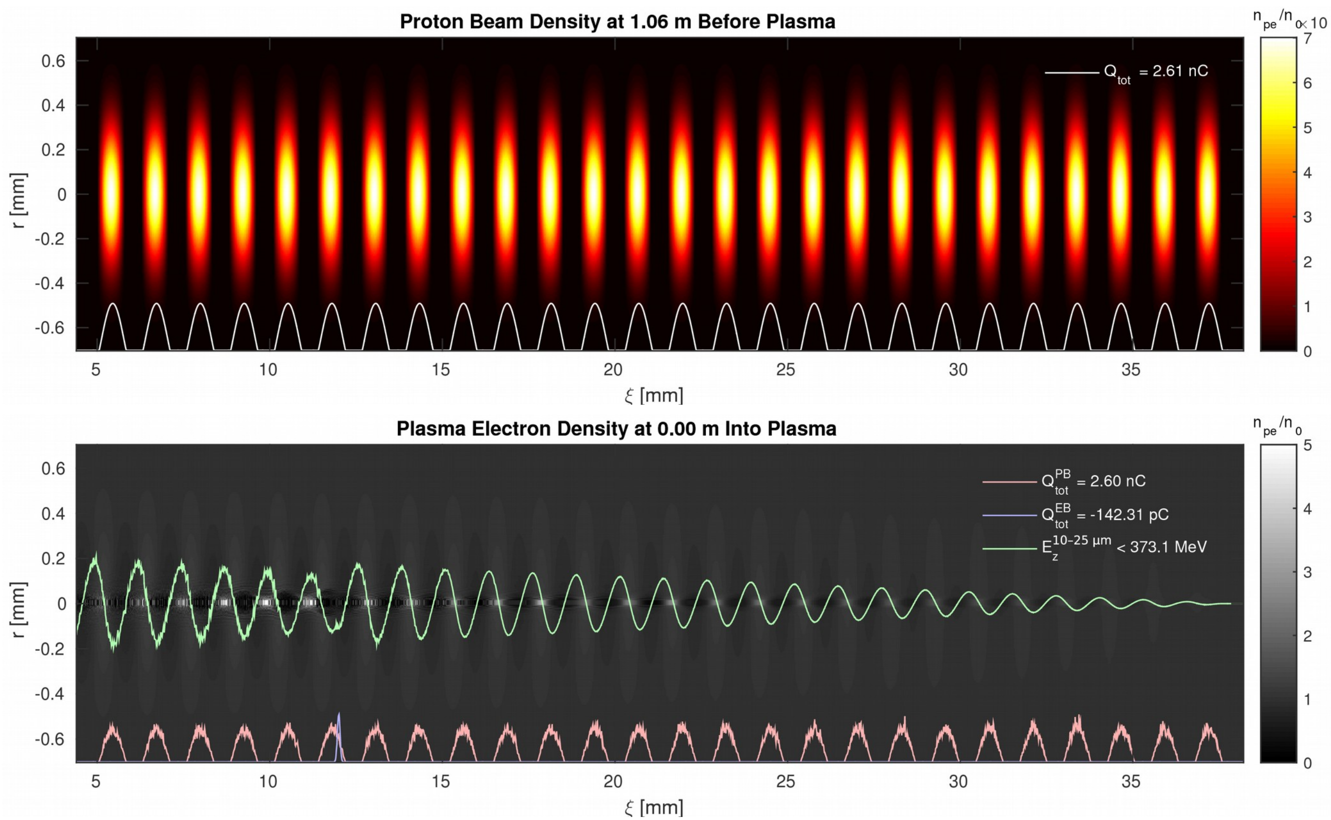
A bunch with $\sigma_z k_{pe} >> 1$ will under certain conditions develop a self-modulation instability (SMI) when it travels through a plasma.

The proton bunch will then develop into a train of micro bunches with a period on the order of λ_p.

$$\lambda_p = \frac{2\pi c}{\omega_p} \qquad \omega_p = \sqrt{\frac{N_p e^2}{m_e \varepsilon_o}}$$

Simulation Setup

- These simulations are set up using a short, pre-modulated proton beam with 26 micro-bunches.
- The electron beam is injected between bunch 20 and 21. Approximately at ξ = 12 mm.



Berglyd Olsen et al. Proceedings of IPAC 2015

Plasma Parameters

ρ_{PE} = 7×10^{14} cm^{-3}
λ_{PE} = 1.26 mm
c/ω_{PE} = 200 µm
L_{PE} = 2 – 10 m

Drive Beam Parameters

Q_{PB} = 2.6 nC
P_z = 400 GeV/c
γ_{PB} = 426
L_{PB} = 26 × λ_{PE} = 32.8 mm
σ_r = 200 µm

Profile function:

$$\rho_s = A\left[\frac{1}{2\sqrt{2}} + \cos(\mu_1 - k_p \xi)\right]\exp\left(-\frac{r^2}{2\sigma_r}\right)$$

Witness Beam Parameters

Q_{EB} = 500 fC – 1 nC
P_z = 217 MeV/c
γ_{EB} = 426
σ_z = 20 – 100 µm
σ_r = 100 µm

Beam Loading and Phase

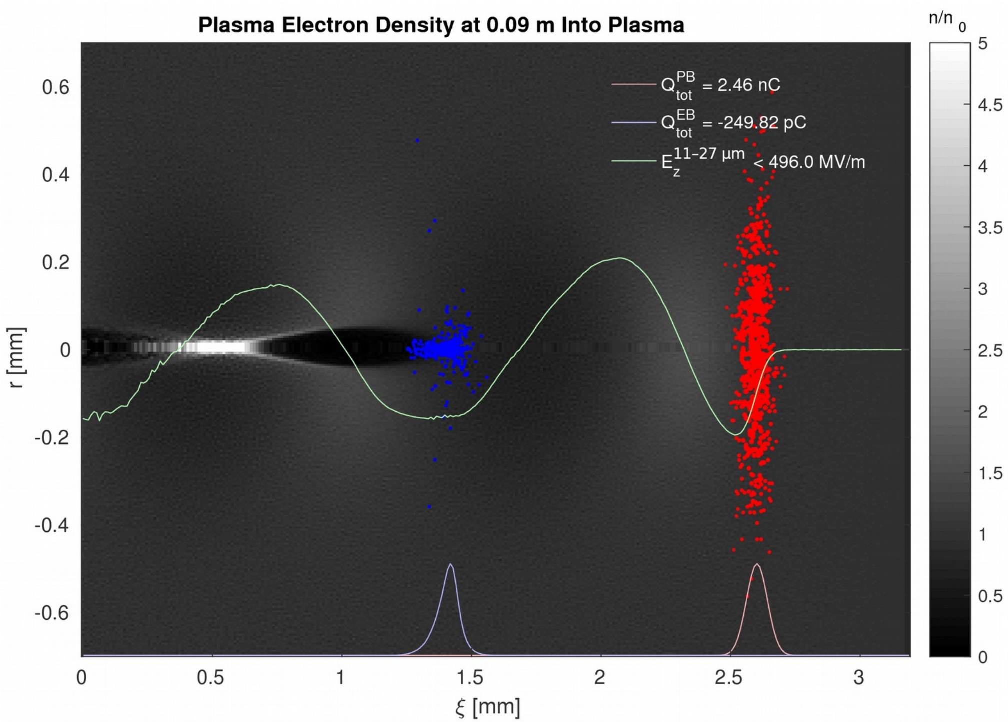
- A large peak current will negatively impact the longitudinal e-field as it will "overload" it.
- A longer beam will carry a larger charge at a lower peak current, but the accelerting flank of the field is on the order of

$$\frac{\lambda_P}{4} \approx 316\,\mu\mathrm{m}$$

which sets a limit on the size of the witness beam as well as room for drift.

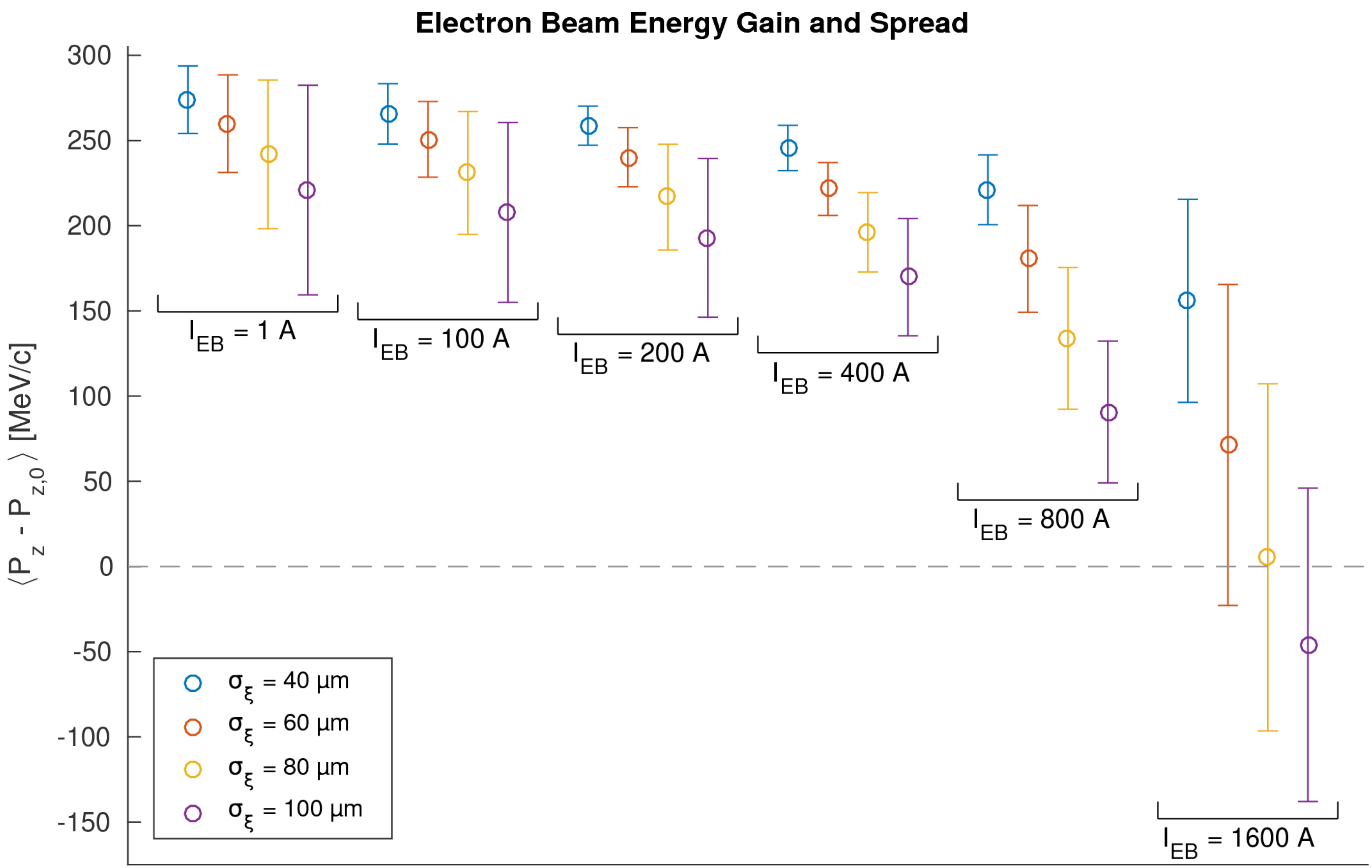
- Low initial energy of the witness beam results in a drift

$$\Delta\xi \approx -\frac{1}{2}\gamma^{-2}\Delta z$$



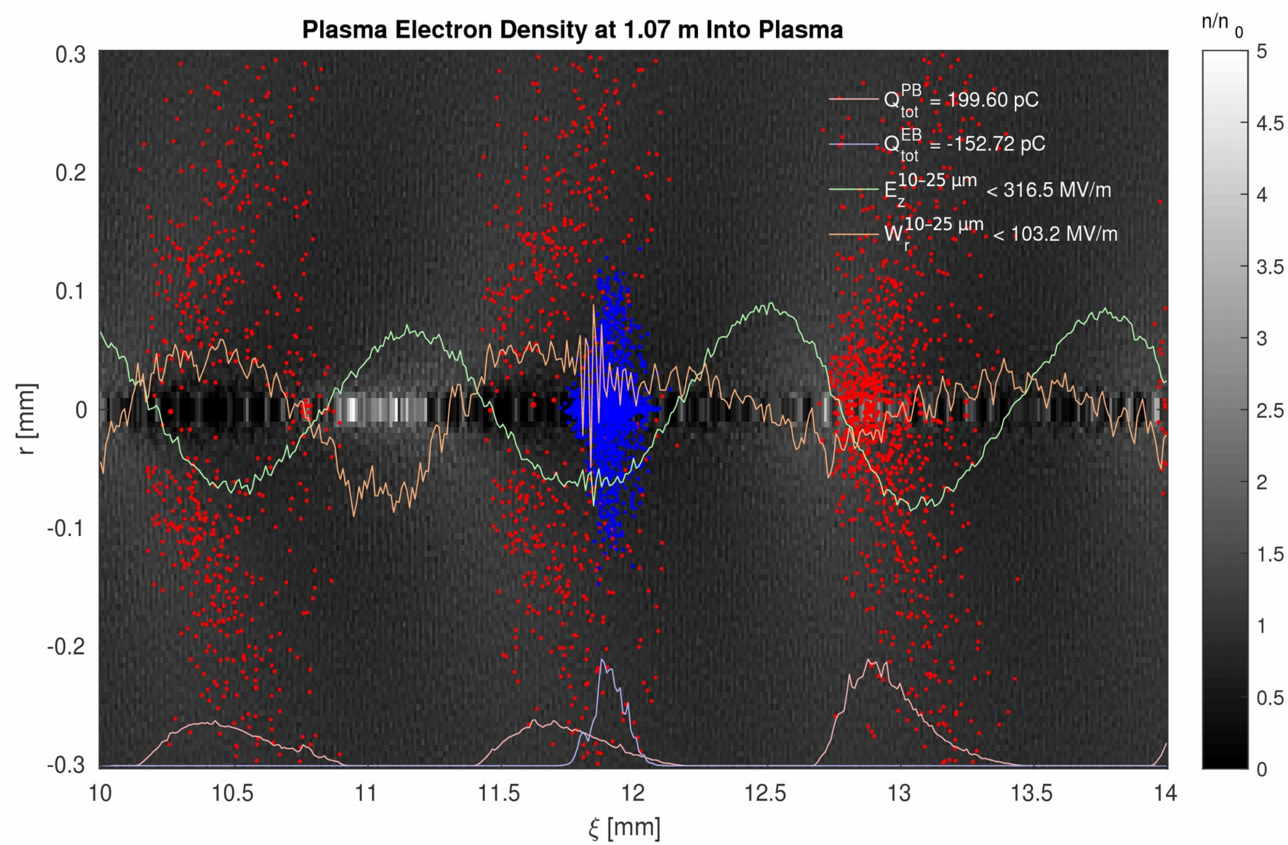
A single, 2.5 nC, proton driver with a 250 pC electron witness beam. The minimum plasma electron density in the bubble created by the driver is ~0.6.

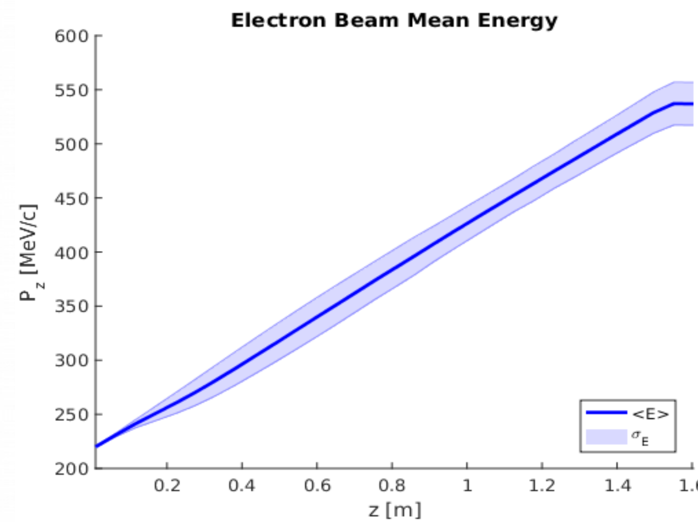
Current and σ_z Scan

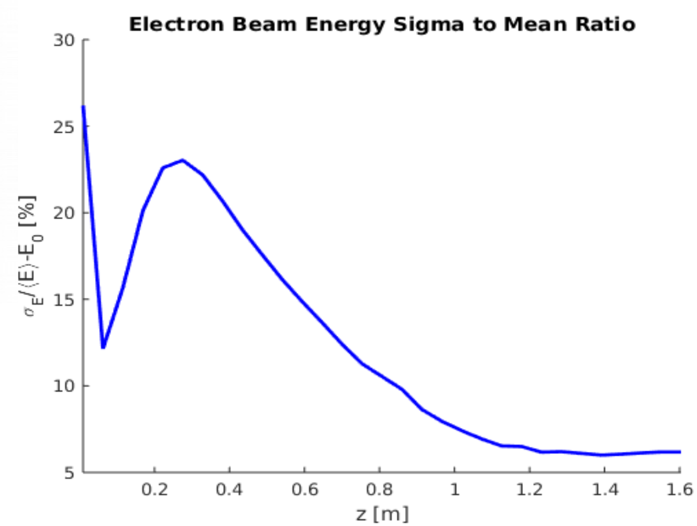


Closer Look: $I_{EB} = 400A$, $\sigma_z = 60\ \mu m$

A good compromise.



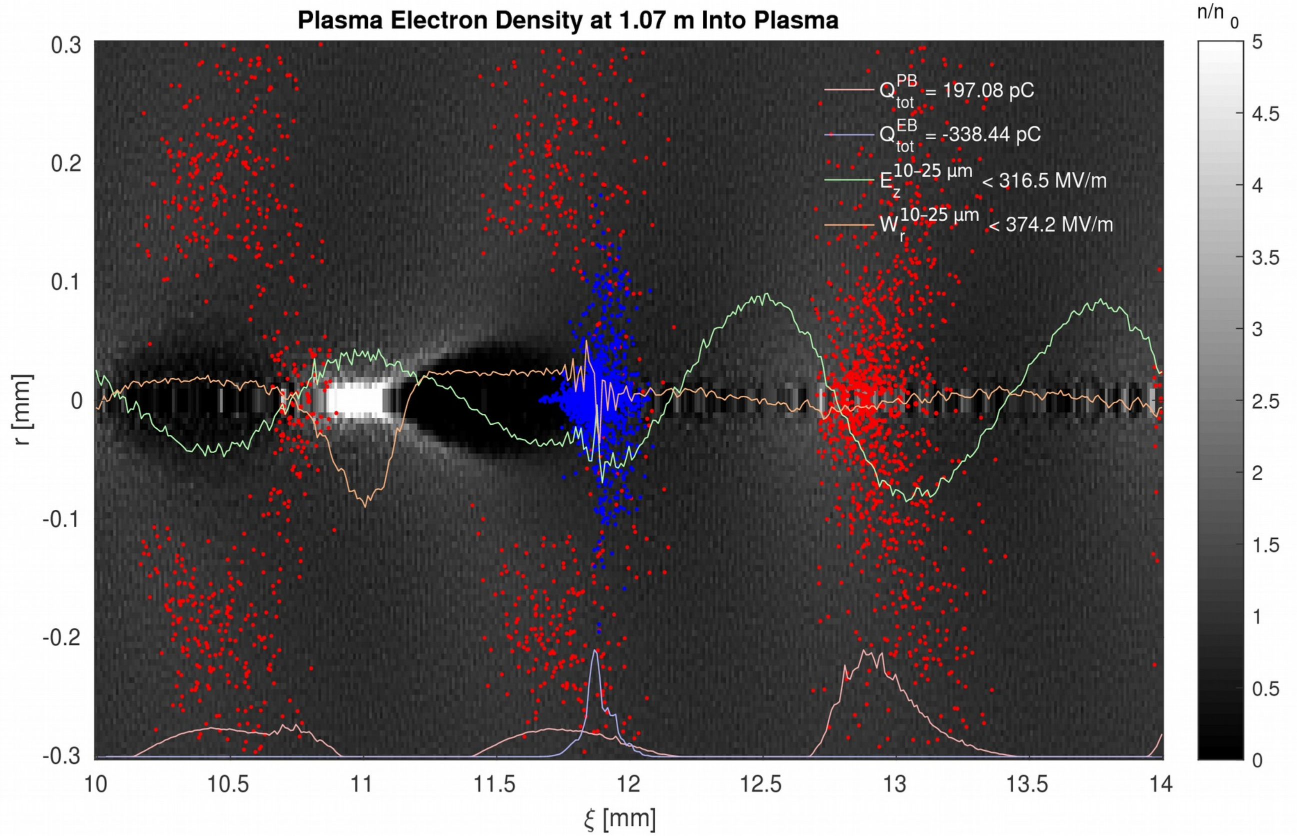


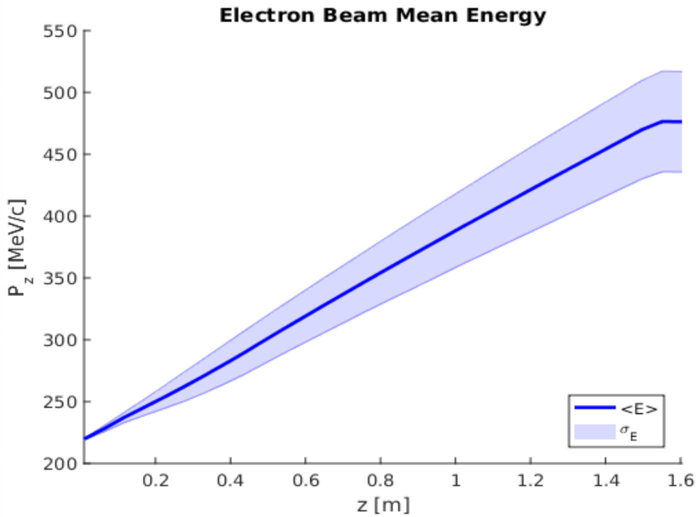


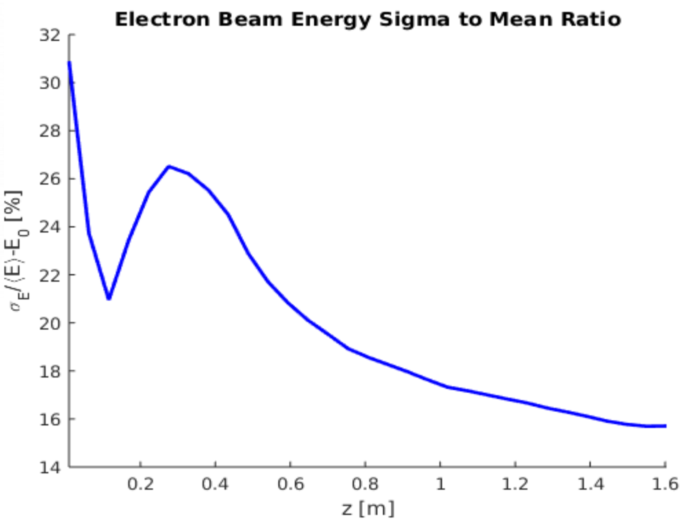
Here we achieved a good balance between energy spread and the amount of charge accelerated. But: initial charge was 201 pC, and has dropped to 153 pC.

Closer Look: I_{EB} = 800A, σ_z = 60 µm

With twice the current, the e_z field is overloaded.

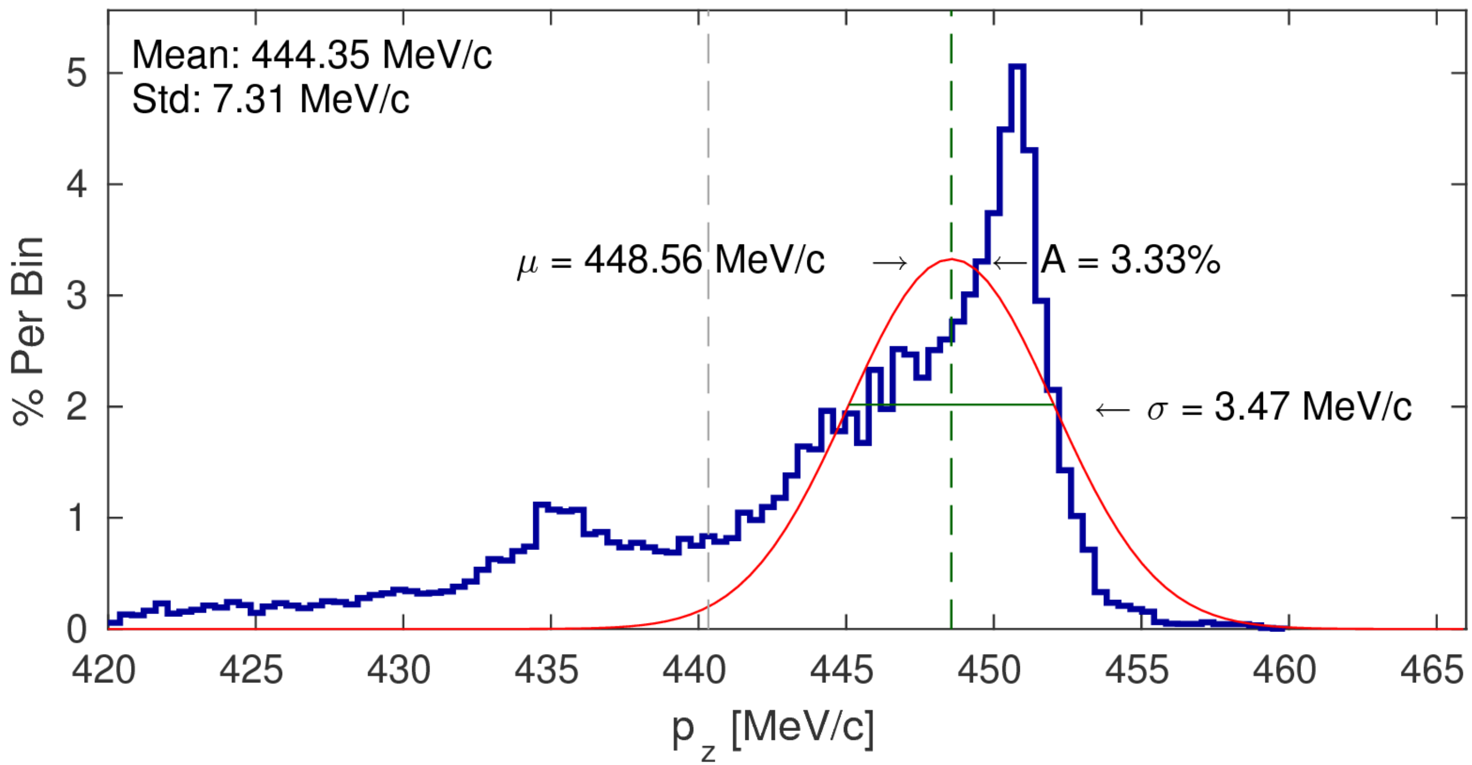






Initial charge was 401 pC in this case. Energy spread is increasing as the beam gains energy.

Energy Spread for I_{EB} = 400A, σ_z = 60 µm



- The tail of the energy spectrum is in the defocusing region and eventually lost.
- The RMS relative energy spread is 3.3%.
- The core of the beam, making up 75% of the charge, has a relative energy spread of 1.5%.

Conclusion

Summary

- We use a small scale simuation with 20 driving micro bunches of protons (a total of 2nC) to emulate self-modulate AWAKE proton bunch.
- For this setup, a σ_z = 60 µm beam at between 200 and 300 pC, positioned about 50 µm from the maximum accelerating field, produces the best results: 3.2% RMS relative energy spread.
- Loss of electrons occurs due to the long Gaussian tail of the bunch. Moving the beam forward solves this, but comes at a cost in both energy gain and energy spread.
- The core of the energy spectrum, containing 75% of the charge, has a Gaussian sigma relative energy spread of 1.5%.

Further Studies

- Understand the evolution of the electron beam at plasma entry (radial shrinking and energy spread growth).
- Further reduce energy spread, and study emittance preservation.

Acknowledgements

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