Emittance preservation of an electron bunch in a loaded quasi-linear plasma wakefield

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We investigate beam loading and emittance preservation for a high-charge electron beam being accelerated in quasi-linear plasma wakefield driven by a short proton beam. The structure of the wakefield is similar to that of a long, modulated proton beam. By selecting transverse and longitudinal electron beam parameters in order to appropriately load the wake, we show that the bulk of the electron beam can be accelerated without significant emittance growth.

I. INTRODUCTION

The preliminary design of AWAKE Run 2 proposes to use two plasma sections. The first section of 4m is the SMI stage. The electron beam will be injected into the modulated proton beam before stage two, where acceleration will occur. As the e_z field will decrease due to the gap between the two cells, it is desirable to keep this as short as possible [1].

A. Self-modulation as a Driver

A train of electron drive bunches with a separation λ_p and a length $l_b \ll \lambda_p$, where $\lambda_p = 2\pi c/\omega_p$ and $\omega_p = (n_0 e^2/m_e \epsilon_0)^{1/2}$, will drive an increasingly strong field E_z for each bunch [2]. A tailing witness beam loading the peak accelerating phase of this field will quickly gain energy from the wakefield. However, electron drive bunches will quickly lose energy to the plasma, and the accelerating witness beam will eventually catch up with the drive beam and the acceleration stop.

The de-phasing problem can be minimised by instead using a proton drive bunch [3]. Proton beams, like the LHC and SPS beams at CERN, are ideal candidates for such an accelerator; however, they are orders of magnitude longer than the plasma wavelengths needed for such applications. This issue is resolved by letting the proton beam undergo self-modulation, an instability caused by the transverse fields generated by the beam acts upon itself causing regions of the beam to rapidly defocus [4]. The modulation frequency is close to that of the plasma, leaving a train of proton bunches along the beam axis.

The AWAKE experiment currently in its first stages of operation at CERN, uses the SPS beam as its driver. The experiment is set up with a 10 m rubidium plasma cell, with a nominal plasma density of $7 \times 10^{14}\,\mathrm{cm}^{-3}$.

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II. METHOD

The main focus of this study has been on the beam loading of the electron beam. In order to eliminate other factors that may affect this, we have tried several approaches to create a stable drive beam structure based on previous SMI studies [citations].

Our first approach was to use a premodulated, short proton beam with the same structure as a section of the full AWAKE proton drive beam. These studies were done using the full PIC code Osiris [5] using 2D cylindrical-symetric simulations. The proton beam was pre-modulated by a clipped cosine function to the longitudinal density profile, with a period matching the wavelength, λ_p, of the plasma. The length was limited to $26 \cdot \lambda_p$, and the electron beam injected after the 20th micro-bunch [6]. We performed several parameter scans with this setup, testing for optimal charge as well as beam length [1, 7].

[Add something about the optimal results]

In order to evaluate the quality of the beam, we also needed to study its emittance. Full PIC codes like Osiris are vulnerable to numerical growth of emittance caused by the "numerical Cherenkov effect" [8]. This is a know issue with the Yee EMF solver, which causes the phase velocity of electromagnetic fields to be lowet than c, while the beam moves very close to c. The effect can be mitigated somewhat by a the Lehe solver [9], but the effect is still prominent in the the high density regions of the electron beam.

In order to study the emittance evolution of the beam we used QuickPIC, a fully relativistic 3D PIC code [10, 11].

A. Drive Beam Parameters

In these simulations we use a single proton drive bunch that sets up a wakefield comparable to that which we expect to see from the self-modulated SPS beam in AWAKE. The baseline AWAKE drive beam contains 3×10^{11} protons [12]. Only half of these are driving the wakefield, presuming the self-modulation is seeded in the middle of the unmodulated bunch. In addition. a significant portion of the protons are lost during self-modulation. The needed gap between the two plasma cells also contributes to a decreased density of protons near the axis, and some of the field is drained by other protons seeing an accelerating face within the drive beam. In total, the expected peak E_z field of $2\,\mathrm{GV/m}$ in the first plasma cell drops to $500-600\,\mathrm{MV/m}$ in the second cell [13]. A single proton beam of 1.46×10^{10}, or $2.34\,\mathrm{nC}$ and $7\,\mathrm{kA}$, is needed to drive an E_z field of a comparable magnitude.

The single bunch approach was chosen to reduce simulation time for the 3D simulations, and to create a stable environment for the witness beam. We are not considering the evolution of the proton beam in this test setup, so to prevent the proton beam from evolving radially, we increased its mass.

The basline AWAKE drive beam current is insufficient to produce a plasma bubble. The plasma electrons are depleted to around 65% of nominal plasma density at the injection point of the electron beam. This condition is replicated in out single bunch case. The single bunch setup also uses the baseline proton energy $W_{pb}=400\,\mathrm{GeV}$.

B. Witness Beam Parameters

The witness beam in our simulation differs from AWAKE baseline parameters on several key points. Initial beam energy is set such that $\gamma_{eb}=\gamma_{pb}=426.3$. This is to eliminate the problem of initial de-phasing of the witness beam. AWAKE baseline witness beam energy for Run 1 is $W_{eb}=10-20\,\mathrm{MeV}$ [12]. Beam loading of a short witness beam is sensitive to initial position. AWAKE Run 2 will likely require a higher initial energy, but a $W_{eb}=30--50\,\mathrm{MeV}$ is sufficient to minimise dephasing [6]. For this case we have eliminated it entirely in order to reduce the number of variables in our parameter scans.

Earlier simulations with witness beam $\sigma_r = 100\,\mu\mathrm{m}$ causes the beam radius to rapidly shrink as the beam enters the plasma [7]. This is due to a mismatch between beam emittance and the plasma density. The relation is given by

$$\beta=\frac{\sigma_r^2}{\epsilon_g}=\frac{\lambda_p}{2\pi}\sqrt{2\gamma_{rel}}, \tag{1}$$

where λ_p is the plasma wavelength. In these simulations we have used matched beams for emittances between 2 and 6 μm.

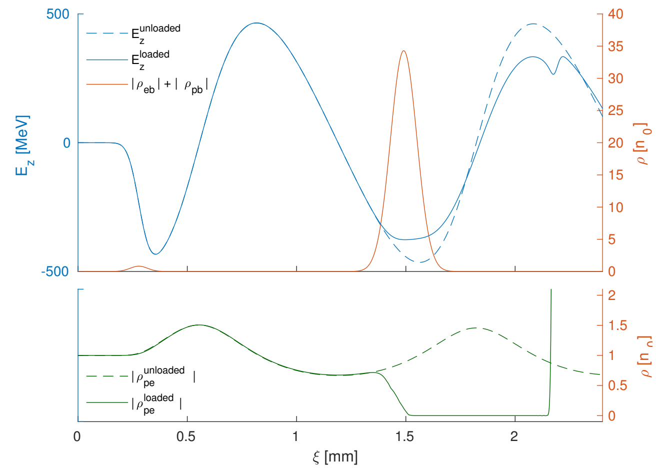

FIG. 1. Comparison between the unloaded longitudinal e-field (no witness beam) and the loaded e-field along the axis. The magnitude of the beam density along the axis is shown for reference. The beams travel towards the left. $\xi=z-tc$ is the position in the simulation box. The beam density is in units of initial plasma density $n_0 = 7\times10^{-14}\,\mathrm{cm}^{-3}$. The bottom plot shows the plasma density for the loaded and unloaded case. The plasma depletion region behind the proton bunch has a minimum of 67.4% of n_0.

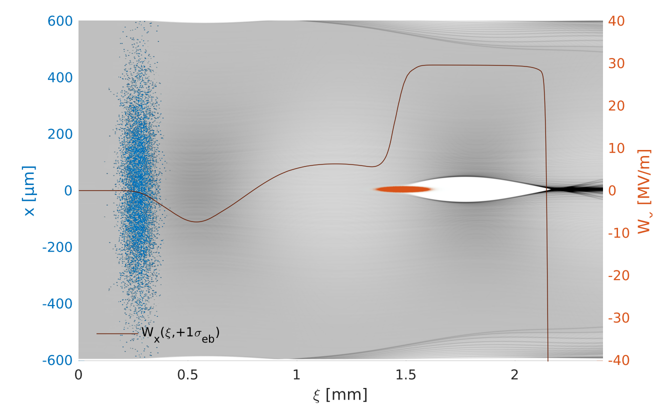

FIG. 2. The plasma density in grey with the proton beam (blue) and the electron beam (red) superimposed. The line plot indicates the transverse wakefield $W_x(\xi,x)=E_\xi(z,x)-B_y(\xi,x)$ evaluated at $+1\sigma_{eb}$ from the axis.

III. BEAM LOADING

The single drive beam setup is designed to behave similarly to the self-modulated case. However, since the drive beam is prevented from significant transverse evolution, we are presented with an idealised case where the electron witness beam sees consistent fields. The

IV. PARAMETER OPTIMISATION

V. DISCUSSION

VI. CONCLUSION

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