LOADING OF WAKEFIELDS IN A PLASMA ACCELERATOR SECTION DRIVEN BY A SELF-MODULATED PROTON BEAM

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Abstract

Using parameters from the AWAKE project and particle-in-cell simulations we investigate beam loading of a plasma wake driven by a self-modulated proton beam. Addressing the case of injection of an electron witness bunch after the drive beam has already experienced self-modulation in a previous plasma, we optimise witness bunch parameters of size, charge and injection phase to maximise energy gain and minimise relative energy spread and emittance of the accelerated bunch.

INTRODUCTION

The AWAKE experiment at CERN proposes to use a proton beam to drive a plasma wakefield accelerator with a gradient on the order of 1 $^{\mathrm{GeV}}/_{\mathrm{m}}$ to accelerate an electron witness beam [1, 2].

In this paper we present two simulation configurations with a modified proton drive beam based on the baseline parameters for the AWAKE experiment. The drive beam is delivered from the SPS accelerator at CERN at an energy of 400 $^{\mathrm{GeV}}/_{\mathrm{c}}$, a bunch length $\sigma_z = 12$ cm, and $\sigma_{x,y} = 200\,\mu$m. [3].

The baseline plasma electron density n_{pe} for AWAKE is $7 \times 10^{14}\,\mathrm{cm}^{-3}$. The corresponding plasma wavelength $\lambda_{pe} = 2\pi c/\omega_{pe} = 1.26$ mm, where $c/\omega_{pe} = 200\,\mu$m is the plasma skin depth, and ω_{pe} is the plasma frequency given as $[n_{pe}e^2/m_e\varepsilon_0]^{1/2}$.

In order to generate a suitable wakefield, the drive beam must be shorter than λ_{pe}. This is not achievable for the SPS proton beam. In order to use such a beam to drive a wakefield we exploit the self-modulation instability (SMI) that can occurs when the beam travels through a plasma and $\sigma_z \gg \lambda_{pe}$. The SMI modulates the beam at a period of $\approx \lambda_{pe}$ [4], allowing us to inject the witness beam in an optimal bucket between two such proton micro bunches.

BEAM LOADING

A particle beam at high energy travelling through a plasma will excite a plasma wave in its wake, and the plasma can sustain a very high accelerating gradient [5]. It is possible to accelerate a secondary beam by extracting energy from this wakefield, thus transferring energy from a drive beam to a trailing witness beam. Such an accelerator design was first proposed by Chen in 1985 [6]. However, there are some challenges in this transfer of energy from drive to witness beam.

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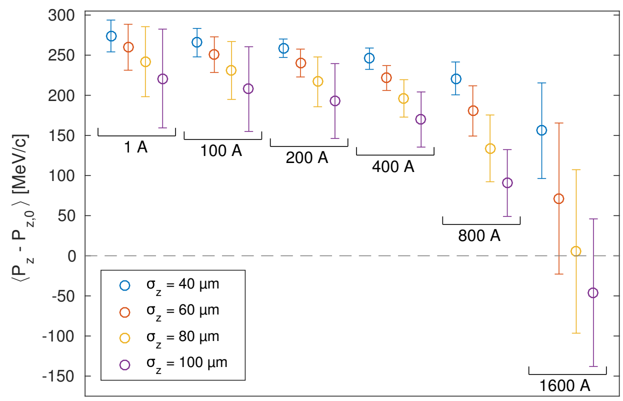

Figure 1: Energy gain and spread for a series of witness beams after ≈ 1.1 m of plasma. The initial momentum of the witness beam is 217.8 $^{\mathrm{MeV}}/_{\mathrm{c}}$. Mean momentum and RMS spread is calculated for all macro particles in the PIC simulation.

One such challenge stems from the witness beam generating its own field, modifying the E_z-field behind it such that the particles in the tail will be accelerated less than those in the front. This causes an increase in energy spread in the beam [7]. This effect can in theory be corrected for by shaping the witness beam. An optimally shaped and positioned beam, such as a triangular beam, can flatten the wakefield such that change in energy spread is effectively zero [8]. However, this requires beam shapes that are difficult to produce experimentally.

BEAM LOADING OF SMI WAKEFIELDS

For AWAKE, most of the SMI evolves during the first stage of $z < 4$ m [2]. This evolution results in a phase change of the wakefields that causes the optimal point for acceleration to drift backwards relative to the witness beam [9, 10].

In our current study we have restricted ourselves to Gaussian witness beams, and seek to demonstrate through simulations how small energy spread can still be achieved by optimally loading the field. The first set of simulations presented uses a subset of 26 micro bunches resulting from the self-modulation that occurs in the previous plasma stage. The pre-modulated beam does undergo further evolution as the envelope function does not fully match the SMI beam, but we only look at the first ≤ 3 m of this stage, before the phase change starts to dominate [11]. All simulations have been done using OSIRIS 3.0 [12].

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A second set of proposed simulations for the second plasma stage will use a single drive beam scaled to produce an accelerating field of 500 MV/m, but with its transverse evolution inhibited in order to study the loading of the field produced by the witness beam alone. The drive beam is short, $\sigma_z = 40\,\mu$m $\ll \lambda_{pe}$, which is well below the SMI limit.

MULTI DRIVE BUNCH SIMULATIONS

In the multiple drive bunch simulations we assume self-modulation has occurred in a previous stage, and approximate the resulting proton beam in the second stage where acceleration of the witness beam occurs. In this first series of studies we have used a short series of 26 proton bunches with a clipped cosine envelope. This setup is about 10 times shorter than full scale AWAKE simulations, allowing us to run more detailed parameter scans. The setup is described in more detail in our IPAC'15 proceedings, where we looked at beam loading as well as the evolution of the proton beam in a 10 m plasma section [11].

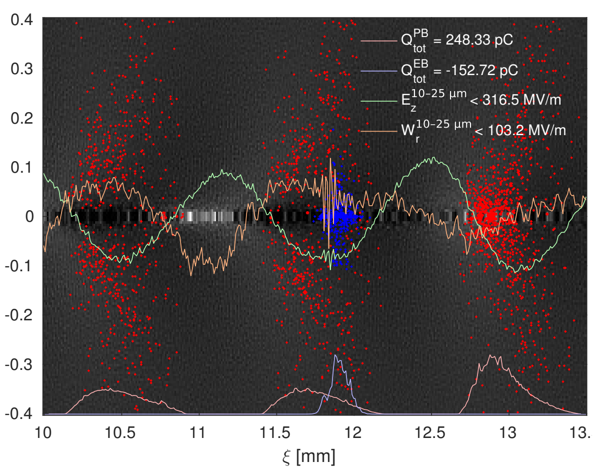

Figure 2: Loading of the field after ≈ 1.1 m of plasma for a 400 A/60 μm electron beam. A sample of electrons (blue) and protons (red) are plotted with their respective projection at the bottom. The total charge within the region of the plot is given as the first two lines of the legend. The longitudinal e-field E_z is shown in green. The transverse wakefield $W_r = E_r - v_z B_\theta$ is shown in orange, where $v_z = c$ is the moving frame of the simulation. The fields are averages over 15 μm near the axis.

The quality and energy of the accelerated witness beam depends on both its position in relation to the field as well as how uniform the field is in the region where the beam is located. We have matched the initial γ of both witness and drive beam in order to avoid initial slipping of the witness beam with relation to the wakefield. The accelerating phase of the field is in the order of $\lambda_{pe}/4 \approx 300\,\mu$m in length, which puts a constraint on the longitudinal size of the witness beam. The transverse size $\sigma_r = 100\,\mu$m, however we observe in simulations that the beam shrinks by a factor of 4 – 6 as it enters the plasma section. This again results in a sharp increase in charge density. A scan of different beam sizes and initial beam current and their corresponding energy gain and spread is shown in Fig. 1.

The best result in terms of total energy spread is for the 40 μm beam of an initial current of 200 A, and for the 60 μm beam of an initial current of 400 A. The former beam carries 67 pC and the latter beam 200 pC. As we want to load the field as close to its maximum as possible, this comes at a cost as the tail of the beam will extend beyond the optimal point into the defocusing region of the wakefields. Fig. 2 shows a snapshot of the 60 μm/400 A simulation from Fig. 1. The longitudinal field is nearly flat as a result of the loading.

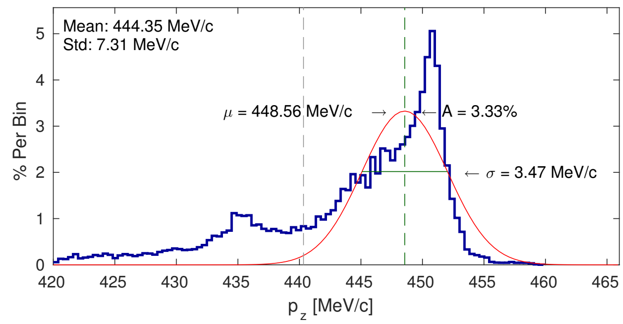

Figure 3: Electron beam momentum spread after ≈ 1.1 m of plasma for the 400 A/60 μm beam. 75 % of the beam charge is accelerated to more than 440 MeV/c, the vertical grey line. The fit is applied to the data above this line, $R^2 = 0.755$.

A closer look at the energy spread in Fig. 3 reveals that ≈ 75 % of the beam is accelerated in this region, with a long tail in energy. This case is not only optimal in terms of beam loading, but also in energy spread of the bulk of the beam of 150 pC. For that part of the beam in front o f the grey line we get a relative energy spread $\sigma_{P_z}/[P_z - P_{z,0}] = 1.5\,\%$. The tail of the beam in terms of energy is lagging behind as it is experiencing defocusing and being pushed outwards and eventually lost from the plasma channel. This loss of beam in the tail can be counteracted by shaping the beam, and making the backwards half $\sigma_z = 20\,\mu$m and keeping the forward half at $\sigma_z = 60\,\mu$m. In simulations this has reduced this loss to 4 – 5 %. However, such shaping of the beam is technically difficult.

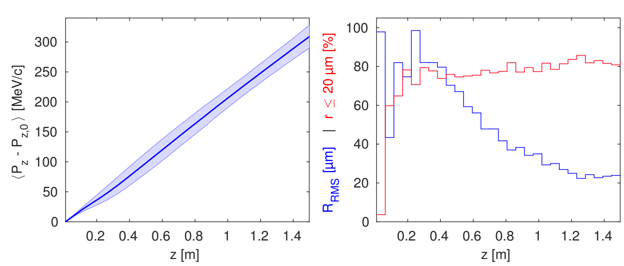

Figure 4: The 400 A/60 μm electron beam as it travels through plasma. The left plot shows the mean energy of the beam with the RMS energy spread as a shaded bar. The right plot shows the RMS radius in blue, and the percentage of macro particles the are within 20 μm of the axis in red.

The relative energy spread of 1.5 % is still undesired. The witness beam in these simulations is initiated with no energy spread in the longitudinal direction. Fig. 4 shows that for our best case the energy spread we see mainly develops in the first 20 cm of plasma. As the right plot illustrates, the transverse RMS size of the beam shrinks by a factor of 5 over the first metres of plasma, but already after a few centimetres about 80 % of the charge is found near the axis. It is this more compact beam that optimally loads the field, and for the first 20 cm the field is under-loaded, probably causing the increase in energy spread. This, however, needs to be studied further.

SINGLE DRIVE BUNCH SIMULATIONS

In order to study the loading of the accelerating e-field in more detail, a second set of simulations have been set up where we have a single proton drive brunch driving a wakefield on the order of 500 MV/m, which is the magnitude of the field we expect to see in the second plasma stage of AWAKE Run 2, based on simulations [13, 14].

This series of simulations is set up in such a way that the accelerating field is as static as possible in order to eliminate other factors than the beam loading by the witness bunch. To achieve this, the proton bunch is prevented from evolving transversely by setting the proton mass to a much higher value than its real value. The gamma of the drive and witness bunches are again matched to prevent dephasing.

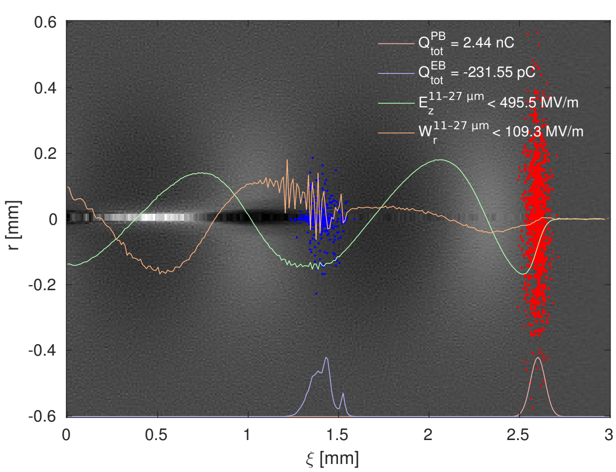

Figure 5: Loading of the field after ≈ 28 cm of plasma for a 500 A/60 μm electron beam. As in Fig. 2 a sample of electrons (blue) and protons (red) are plotted with their respective projections, and the E_z and W_r wakefields are shown.

This provides a much cleaner environment to study the effects of beam loading from the electron beam alone without any evolution caused by the proton beam. Fig. 5 shows an example of this setup. It reproduces the transverse wakefields we saw in our 26 bunch simulations. We also see a shrinking of the witness beam in the first few centimetres, which, together with emittance evolution, is the focus of this next stage of on-going simulation studies.

CONCLUSION AND CONTINUATION

There are a number of challenges with accelerating an electron beam by a self-modulated proton beam in plasma. Not only does the continued evolution of the proton beam affect the wakefield and thus the acceleration of the witness beam, but the evolution of the witness beam itself affects the wakefields, causing among other things, energy spread. However, by tuning the charge density of the beam, this loading of the field can be used to prevent continuing growth in energy spread provided the phase of the wakefield does not evolve too much.

This is an on-going study, and we are currently looking into the cause of the growth of energy spread. It is worth noting that we have so far run these simulations with an unmatched witness beam. We do see emittance growth in this same region where energy spread increases, but further studies are needed to properly understand the numerical contribution to both these effects.

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