

Preliminary Title: Plasma Wakefield Acceleration

Veronica K. Berglyd Olsen

Department of Physics

University of Oslo

Norway



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Abstract

Abstract

Acknowledgements

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1.1 Plasma Wakefield Acceleration

Intro to plasma wakefield goes here

1.2 Proton Driven Plasma Wakefield Acceleration

Further details on proton driven plasma wakefield goes here.

1.3 The Self-modulation Instability

Stuff about SMI goes here

1.4 Numerical Simulations of PWFA

Stuff about Osiris and all that jazz.

Reference to PIC appendix.

2 A Wakefield Accelerator Experiment

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2.1 Evolution of the Concept

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Some text.

4.2 Data Acquisition Classes for FESA

Some text.

5 Summary and Conclusion

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Appendices

Appendix A

Particle in Cell (PIC)

Some stuff about PIC codes

Publications

Publication I

Loading of a Plasma-Wakefield Accelerator Section Driven by a Self-Modulated Proton Bunch

Abstract: Abstract

Authors: V. K. Berglyd Olsen, E. Adli (University of Oslo, Oslo, Norway) P. Muggli (Max Planck Institute for Physics, Munich, Germany) J. M. Vieira (Instituto Superior Technico, Lisbon, Portugal)

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Date:

LOADING OF A PLASMA-WAKEFIELD ACCELERATOR SECTION DRIVEN BY A SELF-MODULATED PROTON BUNCH

V. K. Berglyd Olsen*, E. Adli (University of Oslo, Norway)

P. Muggli (Max Planck Institute for Physics, Munich, Germany)

L. D. Amorim, J. M. Vieira (Instituto Superior Technico, Lisbon, Portugal)

Abstract

We investigate beam loading of a plasma wake driven by a self-modulated proton beam using particle-in-cell simulations for phase III of the AWAKE project. We address the case of injection after the proton beam has already experienced self-modulation in a previous plasma. Optimal parameters for the injected electron bunch in terms of initial beam energy and beam charge density are investigated and evaluated in terms of witness bunch energy and energy spread. An approximate modulated proton beam is emulated in order to reduce computation time in these simulations.

INTRODUCTION

The AWAKE experiment [1] is a proof-of-principle demonstration of acceleration of an electron bunch to the TeV energy range in a single plasma section, using a proton bunch driver [2].

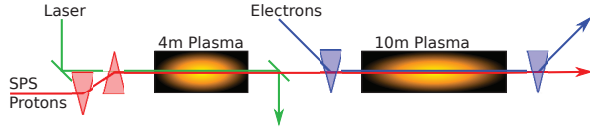


Figure 1: Simplified set-up of AWAKE Phase III. A long proton bunch experiences the SMI in a short plasma cell. The electron bunch is injected before the second plasma cell.

The AWAKE experiment proposes using a proton driver at 400 GeV, delivered by the SPS. The experiment is currently under construction at CERN, scheduled to start in late 2016. The SPS proton bunch is too long to generate a sufficiently strong wakefield [3]. A usable drive bunch needs to be close to the plasma wavelength λ_p in length; however, producing a short enough proton bunch is technically difficult.

The plasma wavelength and frequency are given by

$$\lambda_p = \frac{2\pi c}{\omega_p}, \quad \omega_p = \sqrt{\frac{N_p e^2}{m_e \epsilon_0}}, \quad (1)$$

where N_p is the plasma electron density, e is the elementary charge, m_e is the electron mass and ϵ_0 is the vacuum permittivity.

A proton bunch with $\sigma_{z,0} k_p \gg 1$, where $\sigma_{z,0}$ is the initial length of the bunch, will under certain conditions develop a self-modulation instability (SMI) when it travels through a plasma [4]. The proton bunch will then develop into a train of micro bunches with a period on the order of λ_p .

* v.k.b.olsen@fys.uio.no

In phase I of the AWAKE experiment the SMI of the proton bunch will be studied. In phase II, the proton wake will be studied using a long, externally injected electron bunch that will sample all phases of the wake. In phase III, acceleration of a short bunch in the wake of an already self-modulated proton beam will be studied, as illustrated in Fig. 1. In this paper we study the beam quality of a short electron bunch accelerated by an SMI proton wake in preparation for phase III of AWAKE.

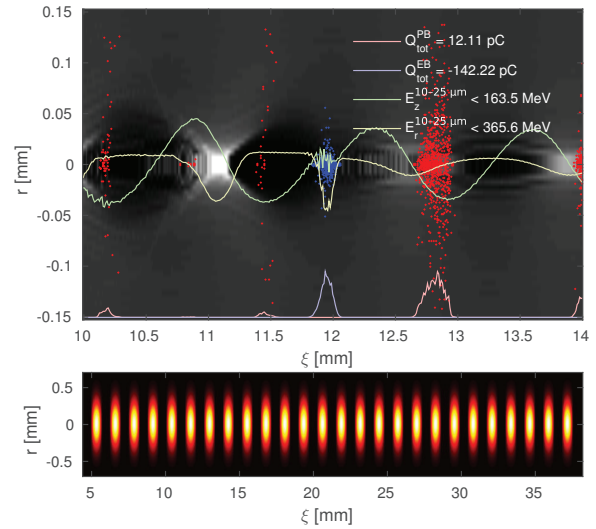


Figure 2: **Top:** An example showing the structure of the plasma electrons (grey) with a projection of the proton beam (red) and the electron bunch (blue) density on the bottom. The E_z (green) and E_r (yellow) fields have been overlaid on the plot. Shown is also a sample of electron (blue) and proton (red) macro particles. **Bottom:** An example of a pre-modulated proton drive beam at $t = 0$ plotted in terms of charge density.

SIMULATION SET-UP

All simulations in this paper have been performed using OSIRIS, a three-dimensional, relativistic, particle-in-cell code for modelling plasma based accelerators [5].

The parameter scans presented have all been run on a small scale test case with a shorter proton drive beam than AWAKE specifications. We simulate here only the second plasma stage in Fig. 1, assuming a pre-modulated proton beam profile with charge density function

$$\rho_{p^+}(\xi) = A \left[\frac{1}{2\sqrt{2}} + \cos(k_p \xi - \mu_1) \right] e^{-r^2/2\sigma_r}, \quad (2)$$

where A is a charge scaling factor, μ_1 is the centre position of the first micro bunch, $k_p = 2\pi\lambda_p^{-1}$ is the wave number, and $\xi = z - ct$ is the coordinates in a frame moving at the speed of light.

The length of the beam is limited by a step function to 33 mm. Negative density values for the density profile is ignored by OSIRIS. This gives a beam of 26 micro bunches of protons, as seen in the bottom plot of Fig. 2. The beam has a total initial charge of 2.6 nC, with an initial peak current per micro bunch of 135 A. For the proton beam $\sigma_r = 200 \mu\text{m} = 1.00 c/\omega_p$ in all simulations, where c/ω_p is the plasma skin depth.

The electron witness bunch is injected between micro bunches 20 and 21 of the drive beam, at $\xi \approx 12 \text{ mm}$, see Fig. 2. The charge density of the electron bunch is given by

$$\rho_e(\xi) = Ae^{-(\xi-\mu)^2/2\sigma_z}e^{-r^2/2\sigma_r}. \quad (3)$$

For the electron bunch $\sigma_r = 105 \mu\text{m} = 0.52 c/\omega_p$, and $\sigma_z = 40 \mu\text{m} = 0.2 c/\omega_p$ in the cases with a short electron bunch. The plasma density at the beginning of the plasma section for all these simulations is $N_p = 7 \times 10^{14} \text{ cm}^{-3}$.

BEAM INJECTION

While the peak-to-peak distance between micro bunches of the self-modulated proton beam corresponds closely to the plasma wavelength λ_p , it is not constant along the length of the beam [6]. A brief study of the SMI of both full scale and small scale proton beams, using Fourier transform and Wavelet analysis, revealed that the fundamental frequency was slightly lower than one k_p .

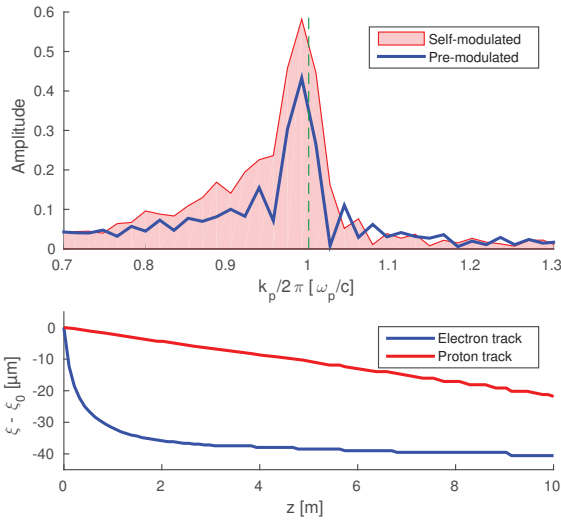


Figure 3: **Top:** The Fourier transform of the proton beam after 10 m of plasma for a self- and pre-modulated beam. The green line indicates $k_p = 2\pi/\lambda_p$. **Bottom:** Typical drift of a proton and electron macro particle through the plasma in respect to c .

To minimise further SMI development with a pre-modulated beam, the micro bunch distance was reduced

to $0.9939 k_p$, which produced a very good fit to the actual SMI for our test case, see Fig. 3.

An electron bunch of low MeV range initial energy will, due to its low gamma factor compared to the 400 GeV proton beam, slip backwards. In order to minimise this effect we set the initial energy of the electron bunch to 30 MeV, a little higher than AWAKE parameters. Typical slip for the beams through 10 m of plasma is illustrated in Fig. 3.

Staying in phase with the drive beam is essential to optimise energy transfer. Establishing an optimal injection point of the electron bunch was achieved by using bunches with length in the order of one λ_p , and tracking a selection of the electrons with optimal energy gain back to $z = 0$.

BEAM LOADING AND ENERGY SPREAD

In a plasma wakefield accelerator, the witness bunch should be accelerated at high efficiency while preserving a low energy spread. Beam loading in the linear regime can be calculated by the linear addition of fields. Only very narrow electron bunches, with $\sigma_r \ll c/\omega_p$, can maintain low energy spread and emittance [7, 8].

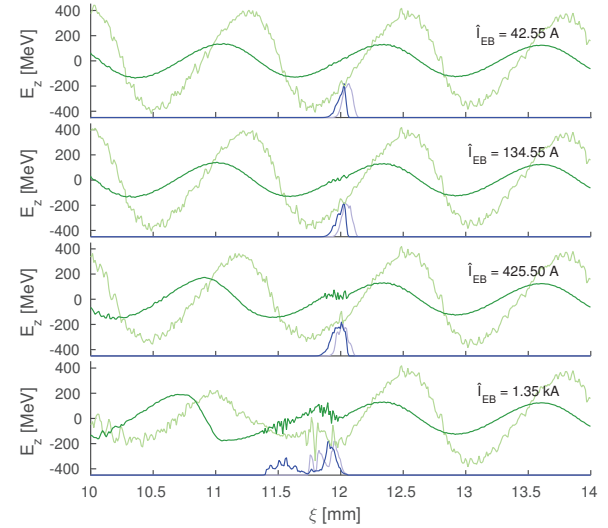


Figure 4: Comparison between the E_z field at 1 m (light green) and 10 m (dark green) of plasma for four different electron bunch currents. The fields are averages over a region $10 - 25 \mu\text{m}$ from the axis. A dimensionless plot of the charge density of the electron bunch is added in blue.

In the non-linear blowout regime, the plasma electrons are blown out by the drive beam, leaving behind a uniform region of plasma ions. The ions pull the electrons back towards the axis, forming a bubble with length on the order of the plasma wavelength [8, 9]. In this regime, the charge and current profile required to optimally load the wake can be estimated analytically. Optimal loading results in a flat E_z field across the bunch with high wake to beam energy transfer efficiency. There is a trade-off between the number of particles that can be accelerated and the accelerating gradient, as discussed in detail by Tzoufras et. al [10].

3: Alternative Particle Sources and Acceleration Techniques

A22 - Plasma Wakefield Acceleration

The beam-plasma interaction studied in this paper has similarities with the above blowout regime, but the train of micro bunches produces a more complex wakefield [4]. We have studied the beam loading through simulations. Based on beam loading in the blowout regime, we use as starting point for the studies a witness bunch with the same peak current as the initial peak current of one proton micro bunch, 135 A. We then performed a scan with logarithmic steps of current from 13.46 A to 13.46 kA. A selection of these are shown in Fig. 4, significant loading of the E_z field does occur when the witness bunch has significantly higher current than the proton beam. An approximate flattening of the field is observed when the witness bunch current is about 3 times higher than the initial micro bunch current, as shown in Fig. 4c. For higher witness bunch currents, we observe that the field from the witness bunch itself starts to dominate the wake it experiences, as expected. The trailing part of the electron bunch is therefore decelerated, as shown for example in Fig. 4d.

We notice that constant loading as the drive and witness bunch propagate in the plasma is not possible, as protons keep being ejected radially throughout the plasma, eating up the micro bunches from the front. This leads to the energy gain levelling off after approximately 4 m of plasma, turning into energy loss as the dephasing between the electron bunch and the E_z fields becomes too large. The phase difference of E_z at 1 m and 10 m is shown in Fig. 4. The mean energy gain (816.2 MeV) and relative energy spread (12%) of the electron bunch, as it travels through the plasma, is visible in blue in Fig. 5, showing a case with peak electron current of 425.5 A. The peak current of a micro bunch after 10 m of plasma, within one skin depth of the axis, is only 45 A.

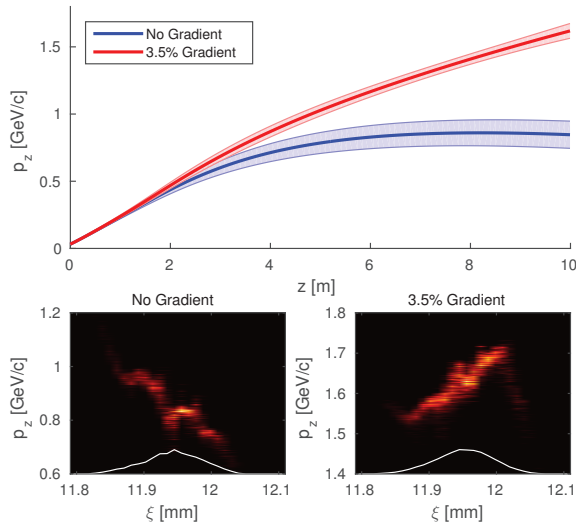


Figure 5: **Top:** Energy gain through 10 m of plasma for a short electron witness bunch with $\sigma_z = 40 \mu\text{m}$ and $\hat{I} = 425.5 \text{ A}$, for the case of no plasma gradient and 3.5% plasma gradient. **Bottom:** $\xi - p_z$ phase plot for both simulations at the end of the plasma.

PLASMA GRADIENT

Due to the backwards drift of the E_z field, the electron bunch falls out of optimal phase after a few metres of plasma. It is possible to stabilise the accelerating bucket by gradually increasing the plasma density. We performed a scan of plasma gradients ranging from 0% to 10% along 10 m of plasma, with a square bunch of length λ_p . We found that a gradient of $0.2 - 0.3 \times 10^{14} \text{ cm}^{-3}$ (3 – 4%) per metre plasma for our initial density of $7 \times 10^{14} \text{ cm}^{-3}$, produced the highest energy gain for the electrons with optimal phase. By tracking some of these electrons back to their injection point, we could move the centre of the short bunch and do a new simulation comparing no gradient to a 3.5% gradient. The best result was for a gradient with a density at 10 m of $7.245 \times 10^{14} \text{ cm}^{-3}$ (3.5%), see Fig. 5 and Table 1.

Table 1: Electron Bunch Energy After 10 m of Plasma

Energy	No Gradient	3.5% Gradient
Mean	846.20 MeV	1618.77 MeV
RMS	101.23 MeV	54.93 MeV
RMS/Mean	11.96 %	3.39 %

CONCLUSION

We have studied beam loading of a SMI proton wake. A scan of electron witness bunch charges over three orders of magnitude revealed that a witness bunch peak current of about a factor 3 higher than the initial peak current of one proton micro bunch was optimal for flattening the wakefield. It is important to note that protons keep getting ejected radially, resulting in a loss of proton charge close to the axis, as the beam travels through the plasma. This decreases the current of a micro bunch by a factor of ~ 3 in the no gradient case.

The electron bunch does not stay in optimal phase for very long as the E_z field starts to drift significantly after 2 – 4 m of plasma. In most simulations the bunch ends up around the zero point of the E_z field, and the energy gradient flattens, and in some cases turns negative. For our optimal case of phase and charge, this effect could to a large degree be counteracted by a 3.5% gradient of the plasma, which forces a positive phase shift of the E_z field, keeping the electron bunch synchronous with the accelerating phase of the wake.

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Publication II

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

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.

Authors: V. K. Berglyd Olsen, E. Adli (University of Oslo, Oslo, Norway) P. Muggli (Max Planck Institute for Physics, Munich, Germany and CERN, Geneva, Switzerland) J. M. Vieira (Instituto Superior Technico, Lisbon, Portugal)

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

V. K. Berglyd Olsen*, E. Adli (University of Oslo, Oslo, Norway)

P. Muggli (Max Planck Institute for Physics, Munich, Germany and CERN, Geneva, Switzerland)

J. M. Vieira (Instituto Superior Technico, Lisbon, Portugal)

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 GeV/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 GeV/c, a bunch length $\sigma_z = 12$ cm, and $\sigma_{x,y} = 200 \mu\text{m}$. [3].

The baseline plasma electron density n_{pe} for AWAKE is $7 \times 10^{14} \text{ cm}^{-3}$. The corresponding plasma wavelength $\lambda_{pe} = 2\pi c/\omega_{pe} = 1.26$ mm, where $c/\omega_{pe} = 200 \mu\text{m}$ is the plasma skin depth, and ω_{pe} is the plasma frequency given as $[n_{pe}e^2/m_e\epsilon_0]^{1/2}$.

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.

* v.k.b.olsen@fys.uio.no

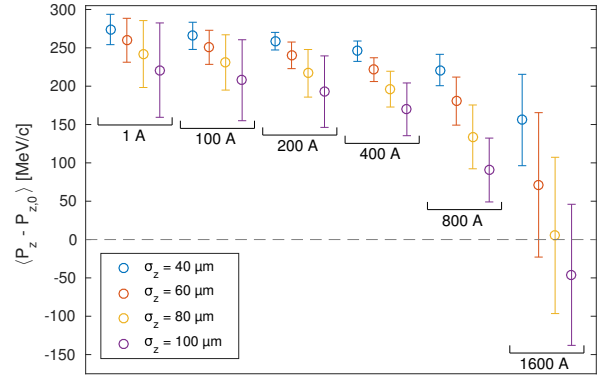


Figure 1: Energy gain and spread for a series of witness beams after ≈ 1.1 m of plasma. The initial momentum of the witness beam is 217.8 MeV/c. Mean momentum and RMS spread is calculated for all macro particles in the PIC simulation.

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].

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, $\sigma_z = 40 \mu\text{m} \ll \lambda_{pe}$, 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].

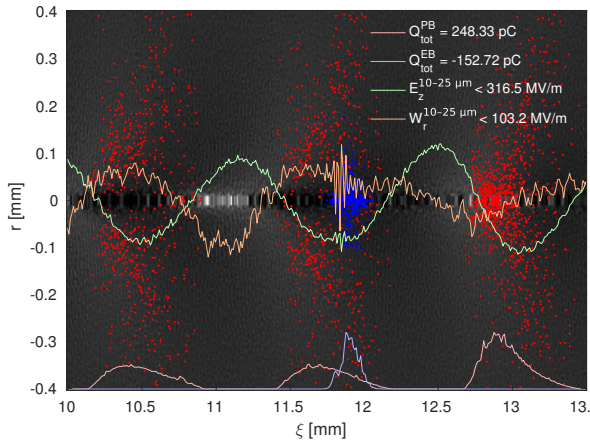


Figure 2: Loading of the field after ≈ 1.1 m of plasma for a 400 A/60 μm electron beam. A sample of electrons (blue) and protons (red) are plotted with their respective projection at the bottom. The total charge within the region of the plot is given as the first two lines of the legend. The longitudinal 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 $\lambda_{pe}/4 \approx 300 \mu\text{m}$ in length, which puts a constraint on the longitudinal size of the witness beam. The transverse size $\sigma_r = 100 \mu\text{m}$, 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.

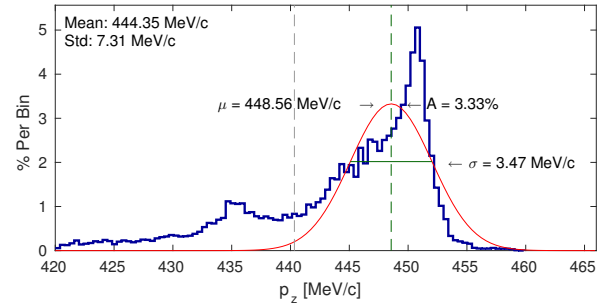


Figure 3: Electron beam momentum spread after ≈ 1.1 m of plasma for the 400 A/60 μm beam. 75 % of the beam charge is accelerated to more than 440 MeV/c, the vertical grey line. The fit is applied to the data above this line, $R^2 = 0.755$.

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 of 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 $\sigma_z = 20 \mu\text{m}$ and keeping the forward half at $\sigma_z = 60 \mu\text{m}$. In simulations this has reduced this loss to 4 – 5 %. However, such shaping of the beam is technically difficult.

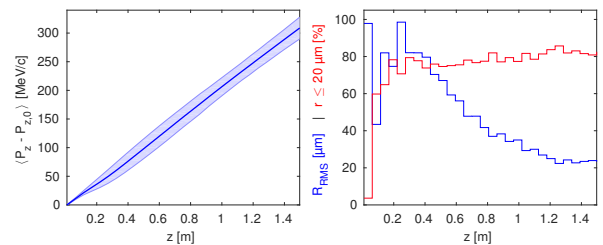


Figure 4: The 400 A/60 μm electron beam as it travels through plasma. The left plot shows the mean energy of the beam with the RMS energy spread as a shaded bar. The right plot shows the RMS radius in blue, and the percentage of macro particles the are within 20 μm of the axis in red.

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 bunch 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.

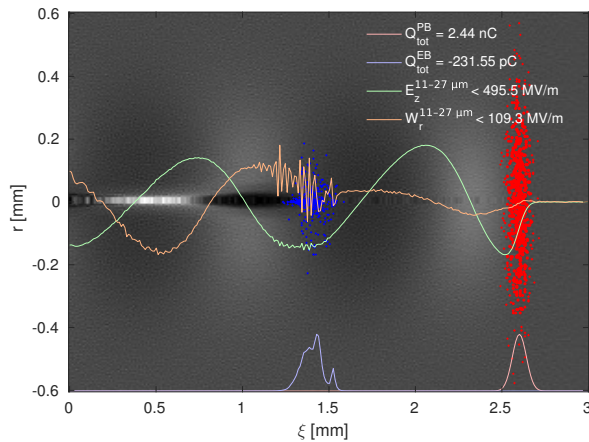


Figure 5: Loading of the field after ≈ 28 cm of plasma for a 500 A/60 μm electron beam. As in Fig. 2 a sample of electrons (blue) and protons (red) are plotted with their respective projections, and the E_z and W_r wakefields are shown.

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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Publication III

Placeholder Title

Abstract: Abstract

Authors: Veronica K. Berglyd Olsen (University of Oslo, Oslo)

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Publication IV

Data Acquisition and Controls Integration of the AWAKE Experiment at CERN

Abstract: The AWAKE experiment has been successfully installed in the CNGS facility at CERN, and is currently in its first stage of operation. The experiment seeks to demonstrate self-modulation of an SPS proton beam in a rubidium plasma, driving a wakefield of several gigavolt per meter. We describe the data acquisition and controls system of the AWAKE experiment, its integration into the CERN controls system and new control developments specifically required for the AWAKE experiment.

Authors: Veronica K. Berglyd Olsen (University of Oslo, Oslo), Edda Gschwendtner (CERN, Geneva), Spencer Jake Gessner (SLAC, Menlo Park, California)

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