ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB158

ELECTRON WITNESS CONSTRAINTS FOR AWAKE

J. P. Farmer[1]*, P. Muggli, Max Planck Institute for Physics, Munich, Germany
L. Liang, University of Manchester, UK
M. Weidl, Max Planck Institute for Plasma Physics, Garching, Germany
E. Gschwendtner, CERN, Meyrin, Switzerland
[1]also at CERN, Meyrin, Switzerland

Abstract

The AWAKE project at CERN successfully demonstrated the use of a proton driver to accelerate an electron witness in plasma [1]. One of the key goals for AWAKE Run 2 is to better control this acceleration, separating the proton-beam-modulation and electron-acceleration stages in order to achieve high energy electrons with high beam quality. Controlled acceleration additionally requires careful tuning of the witness bunch parameters at the injection point. In this work, we use particle-in-cell simulations to study the tolerances for this matching, and discuss techniques to loosen these constraints.

INTRODUCTION

Proton beams stand out as drivers for plasma wakefield acceleration, as their high energy makes them the only driver capable of accelerating a witness bunch to the energy frontier without the need for staging or a high transformer ratio. However, currently available beams have a long bunch length of ~10 cm - too long to effectively drive a high (>100 MV/m) amplitude wakefield. The AWAKE project at CERN is a proof-of-principle experiment to show that such beams can indeed be used to accelerate a witness bunch to high energy.

AWAKE Run 1 demonstrated that the self-modulation instability in plasma may be harnessed to convert the long proton bunch into a series of microbunches [2], which act to drive the wakefield more effectively [3], allowing an externally-injected witness bunch to be accelerated to GeV energies [1]. The experiment also showed that the phase of this modulation, and so the accelerating field, may be controlled via seeding [4].

The goal of AWAKE Run 2 is to build on these successes by working to better control the acceleration process. This will involve the use of two plasma sources in order to separate the self modulation of the driver from the acceleration of the witness [5], as well as the careful tuning of the witness bunch to the excited wakefield. This work makes use of simulations to investigate the physical processes governing the latter. It is shown that higher emittance at the injection point leads to a larger emittance growth during the acceleration process. This may be compensated by using a higher-charge witness beam - however, this in turn has consequences for the energy spread.

* j.farmer@cern.ch

SIMULATION CONFIGURATION

In order to greatly reduce the computation overhead of this study, a "toy model" for the acceleration scheme is used, with a short, non-evolving drive bunch exciting a quasilinear plasma wake, as shown in Fig. 1. Although the full modulated proton beam is not modelled, the results should still be applicable - the separation of the self-modulation stage in AWAKE Run 2c [6] means that the driver should not evolve significantly during the acceleration process. Although the witness bunch here trails the driver, rather than sitting amongst the train of microbunches, the density of each microbunch is much less than the background plasma density, and so the contribution of a single bunch overlapping with the witness is expected to be small. The use of such a model also makes the results more broadly applicable – the wake is only weakly dependent on the type of driver, and so the conclusions drawn here are also relevant to quasilinear wakes driven by an electron beam or laser pulse.

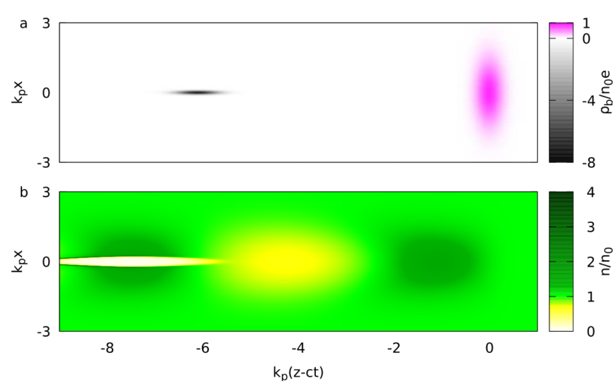

Figure 1: The toy model consists of a) a short, positively charged driver (violet), trailed by the witness electron bunch (black). The two are coupled by b) the plasma response, with the driver exciting a quasilinear wake. If the witness is sufficiently dense, it will drive a blowout.

The driver parameters follow those used by Olsen *et al.* in their study of emittance growth [7], with a positively charged, non-evolving driver with a Lorentz factor $\gamma = 426$ and a radius of $\sigma_x = \sigma_y = 200\,\mu\text{m}$, chosen to match the CERN SPS beam used in AWAKE. The driver bunch length is 40 µm with a charge of 2.34 nC, resulting in a wakefield amplitude of ~500 MV/m in a plasma density $7\times10^{14}\,\text{cm}^{-3}$.

The electron witness parameters are varied in the study, but in all cases presented here the witness length is $\sigma_z = 60\,\mu\text{m}$ and the initial energy is 150 MeV (the change

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in energy with respect to [7] representing the evolution of the witness beamline design [8]).

The simulations themselves were carried out with the two-dimensional quasistatic particle-in-cell code LCODE [9, 10]. Comparisons made against the fully 3D quasistatic code qv3d [11], built on the framework of the VLPL platform [12] show excellent agreement. A resolution of $\Delta_z = \Delta_r = 0.02/k_p$ was used, where $k_p = \omega_p/c$ is the plasma wavenumber, with 10 plasma particles per cell and a simulation window of radius $3.84/k_p$. The witness was modelled with 100,000 equally weighted macroparticles using a timestep of $2/\omega_p$, sufficient to resolve the betatron oscillations of the bunch.

EMITTANCE STUDY

For a sufficiently high charge, the witness will drive a plasma blowout - a cavitated "bubble" region free from plasma electrons, as seen in Fig. 1. The focussing force inside this region then depends only on the background ionic charge, which does not evolve on the timescale of the witness duration. For an initially homogeneous plasma, this focussing field is linear, and so it is possible to match the radius of a Gaussian witness bunch such that it does not undergo transverse oscillations as it propagates. For a witness with normalised emittance $\epsilon^* = \epsilon_x^* = \epsilon_y^*$ and Lorentz factor γ, this matched size can be calculated as:

$$\sigma_{matched} = \left(\frac{2\epsilon^{*2}}{\gamma k_p^2}\right)^{1/4}. \quad (1)$$

Scattering of the witness bunch prior to injection, for example when propagating through the window to plasma source, may lead to an increase in the witness emittance at the injection point. Figure 2a) shows emittance evolution for a 100 pC witness bunch during the first metre of acceleration, for different initial emittances. In each case, the initial radius is matched according to Eq. (1), corresponding to 5.76 µm for $\epsilon_0^* = 2$ µm. In each case the emittance initially grows over the first ~10 cm, before stabilising. The subsequent decrease in emittance seen for the $\epsilon_0^* = 8$ and 16 µm cases is likely due to incomplete witness capture, with a charge loss of 0.8 and 10.8%, respectively, effectively cooling the beam. Following the period of rapid evolution after injection, the emittance stays essentially constant over the remainder of the 10 m acceleration length, over which the particle energy increases to ~4 GeV. The ratio of the final emittance after 10 m to the initial value is shown in Fig. 2b). It can be seen that higher emittance at injection not only leads to a larger emittance growth, but that the relative growth also increases.

To understand this behaviour, we consider the transverse wakefields acting on the witness, shown in Fig. 3 for an initial charge of 100 pC and an initial emittance $\epsilon_0^* = 8$ µm. In order for the witness to be captured, it should be positioned such that its head lies in the focussing region of the driver-excited wakefield. Moving backwards from the witness head, its charge density increases, growing to far exceed that of the driver, resulting in a transverse field dominated by the

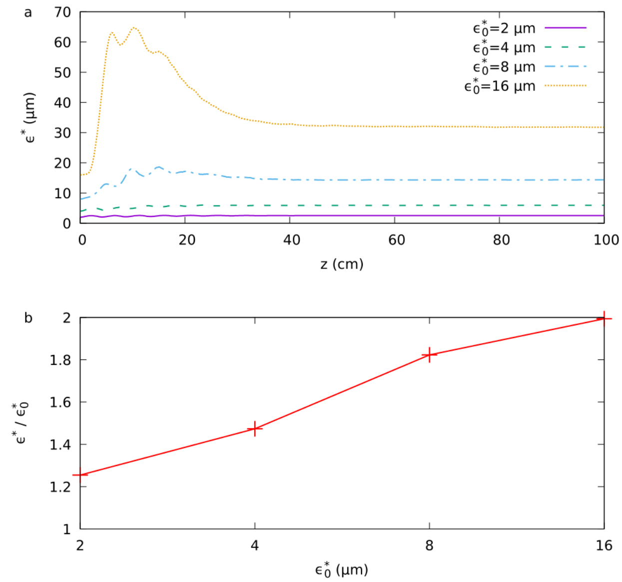

Figure 2: Influence of initial emittance on emittance growth. a) Witness emittance over the first metre of acceleration for different initial emittances. b) Witness emittance after 10 m acceleration, relative to the initial emittance.

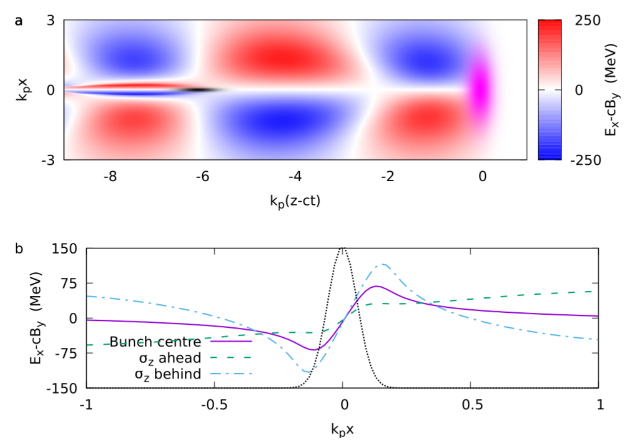

Figure 3: Transverse wakefields $E_y - cB_z$ at the beginning of the simulation. a) 2D-slice of the transverse field, with the driver and witness overlaid (colours as in Fig. 1a)). b) Lineouts of the transverse field taken at the centre of the bunch and at +/- $\sigma_z = 60$ µm. Witness transverse profile is overlaid for comparison (black dotted line).

plasma response to the witness, ultimately leading to the formation of the blowout.

For a higher initial emittance, the matched radius is larger, and so for a fixed charge, the witness charge density will be lower and the blowout will take longer to form. This is illustrated in Fig. 3b), which shows lineouts of the transverse field taken at the centre of the witness bunch, and $+/-\sigma_z$. In the blowout, the focussing field saturates to some constant value. The difference in the focussing fields acting on the bunch in Fig. 3 show that the bubble has not fully formed by the centre of the witness bunch. The initial bunch radius will therefore not be correctly matched to the focussing fields,

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and the witness envelope will oscillate transversely, leading to the fields themselves to oscillate.

Although the blowout is not complete, the focussing fields acting on the witness are close to linear, and so it can be expected that the slice emittance, i.e. that of a narrow range $z - ct$, will be preserved. However, the variation in this focussing along the bunch will lead to dephasing between the envelope oscillations at different positions along the bunch, resulting in an increase in the projected (full beam) emittance.

The emittance growth can therefore be remedied by addressing the mismatch between the witness and the focussing fields, removing the witness oscillations and the associated dephasing. One solution would be to attempt to match to the nonlinear focussing fields in the incomplete blowout. This is challenging, as the focussing fields, and so the matching condition, vary along the bunch length. Furthermore, if the normalised emittance is conserved, the witness radius will decrease as it gains energy, again resulting in a change in the focussing fields. Alternatively, one may attempt to ensure that the blowout forms soon after the witness head. This can be achieved by maintaining a low emittance at the injection point, or by increasing the witness charge.

As increasing the witness charge modifies the plasma response, it will also impact on the accelerating field experienced by the witness. This is an important consideration when attempting to control the energy spread of the accelerated bunch. Figure 4 shows that this beamloading increases with increasing charge, reducing the accelerating field. In each case, the witness delay relative to the driver is chosen to minimize the relative RMS energy spread after 10 m acceleration. For a higher witness charge, the optimal delay becomes smaller. Beamloading limits the maximum charge that can be accelerated for a given wakefield amplitude - if the charge is too high, parts of the witness bunch will begin to lose energy instead of being accelerated.

The evolution of different witness charges is shown in Fig. 5. As expected, a higher charge acts to reduce the emittance growth by causing the blowout to form more rapidly. However, this also impacts on the energy spread - the relative energy spread for the 400 pC witness is almost twice that of the 200 pC beam. However, it should be noted that this is caused, not by an increase in the absolute spread, but by a decrease in the mean energy after acceleration, falling from 3.3 to 2.0 GeV.

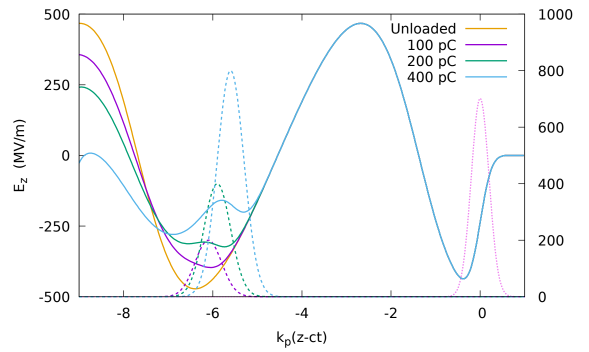

Figure 4: Accelerating field E_z (solid lines) and witness current (dashed lines) taken at the start of the simulation for witness charges of 100, 200 and 400 pC, as well as for the unloaded wakefield. The drive bunch is centred at z-ct = 0 and is is illustrated by the violet dotted line (not to scale, peak current 17.5 kA). For each witness charge, the position is chosen to minimize the relative RMS energy spread after 10 m.

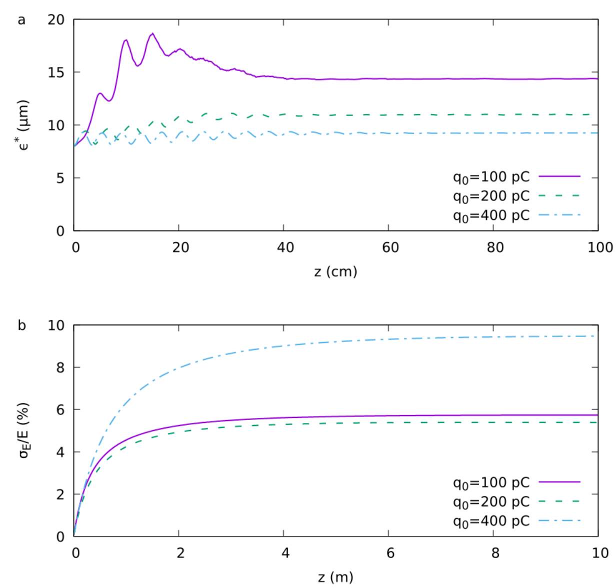

Figure 5: Influence of initial charge on acceleration quality for an initial emittance of 8 μm. a) Witness emittance over the first metre of acceleration for different initial charge, and b) Relative witness energy spread over the full 10 m acceleration.

CONCLUSIONS

AWAKE Run 2 aims to build on the successes of Run 1 by tailoring the witness bunch to the proton-driven wakefield, limiting both the emittance growth and increase in energy spread during acceleration. We here show that the witness emittance at the injection point is an important consideration for this goal. A higher initial emittance may lead to an incomplete plasma blowout, leading to further emittance growth. This may be compensated by increasing the witness charge, but this in turn can increase the relative energy spread.

ACKNOWLEDGEMENTS

The simulation studies in this work were carried out using the CERN batch service.

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