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

Veronica K. Berglyd Olsen* and Erik Adli
University of Oslo, Oslo, Norway

Patric Muggli
Max Planck Institute for Physics, Munich, Germany and
CERN, Geneva, Switzerland
(Dated: July 13, 2017)

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

Beam driven plasma wakefield accelerators have the potential to offer compact linear accelerators with high energy gradients, and has been of interest for several decades [1]. A relativist beam travelling through a plasma will excite a strong longitudinal e-field that can be loaded by a trailing witness beam, which can achieve a high acceleration gradient. Acceleration of an electron beam by an electron drive bunch has been demonstrated experimentally [2–4] in the past. The AWAKE experiment at CERN is a proof of concept proton driven plasma wakefield accelerator [5].

A major challenge with plasma wakefield accelerators is, however, to produce an accelerated beam with a minimal increase in energy spread and emittance. In the well described linear case where the beam density n_b is much smaller than the plasma density n_0 the plasma causes emittance growth in the beam. A finite length beam will also see a varying transverse wakefield causing increasing energy spread [6]. In the non-linear regime, where $n_b > n_0$, the drive beam sees an unvarying transverse field due to a bubble forming in the plasma behind the drive beam. The bubble is formed by the transverse oscillations of the plasma electrons which move near uniformly as a function of distance from the drive beam forming a sheet around an evacuated area. Since the much heavier plasma ions have no significant movement within the relevant time frame, these remaining ion channel creates a focusing force that scales linearly with the radius within this bubble producing a angularly symmetric focusing force [7, 8]. This effect also avoid the issue of increasing energy spread due to transverse beam loading. Increase in energy spread is still dependent on beam loading of the longitudinal e-field, E_z. This effect can be negated by specially shaped beams [6, 9], but this is difficult experimentally and is not a topic explored in this paper.

A. Self-modulation as a Driver

A train of electron drive bunches with a separation λ_{pe} and a length $l_b \ll \lambda_{pe}$, where $\lambda_p = 2\pi c/\omega_{pe}$ and $\omega_{pe} = (n_0 e^2/m_e\epsilon_0)^{1/2}$, will drive an increasingly strong field E_z for each bunch [1]. A tailing witness beam loading the peak accelerating phase of this field will quickly gain energy from the wakefield. Acceleration of an electron witness beam driven by two electron drive beams was demonstrated at Brookhaven National Laboratory [10]. 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.

This de-phasing problem can be minimised by instead using a proton drive bunch [11]. Proton beams, like for instance 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 before injecting the witness beam into one of the buckets in the modulated structure. This self-modulation instability is caused by the transverse fields generated by the beam acting upon the beam itself, causing regions of the beam to rapidly defocus [12]. The modulation frequency is close to that of the plasma, leaving a train of proton bunches along the beam axis.

B. The AWAKE Experiment

The AWAKE experiment, currently in its first stages of operation at CERN, uses the SPS beam as its driver. The first run of the experiment is set up with a 10 m rubidium plasma cell, with a nominal plasma density of $7\times10^{14}\,\mathrm{cm}^{-3}$ [13]. The corresponding plasma wavelength is 1.26 mm. The plasma density is matched to the SPS proton beam such that $k_{pe}\sigma_r = 1$ where $k_{pe} = \lambda_{pe}/2\pi$ is the plasma wave number. The aim of the first run is to demonstrate self-modulation of the proton beam, and in 2018 to sample the wake field with a long electron bunch.

* v.k.b.olsen@cern.ch

The study presented here is for run two, which aims to demonstrate acceleration of a short electron bunch producing at high energy and low emittance and low energy spread.

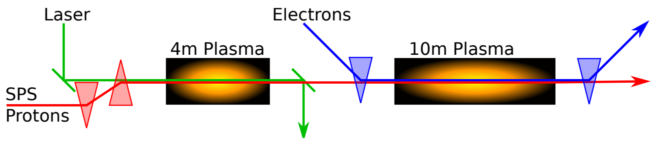

FIG. 1. A simplified illustration of the experimental setup for AWAKE Run 2. The SPS proton beam undergoes self-modulation in the first 4 m plasma cell. The electron witness beam is injected in one of the buckets, and undergoes acceleration in the second plasma cell [14, 15].

The preliminary design of the second run proposes to use two plasma sections, illustrated in figure 1. The first section of 4 m is the self-modulation 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 [15].

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.

Our first approach was to use a pre-modulated, short proton beam with similar structure to the one produced by the self-modulation of the SPS beam in AWAKE. These studies were done using the full PIC code Osiris [16] using 2D cylindrical-symmetric simulations. The proton beam was pre-modulated by a clipped cosine function to the longitudinal density profile, with a period matching λ_{pe}. Its transverse profile was kept as a Gaussian with $\sigma_r = k_{pe} = 200\,\mu$m. The length of the simulation beam was limited to $26 \cdot \lambda_{pe}$, and the electron beam injected after the 20th micro-bunch [14]. We performed several parameter scans with this setup, testing for the the maximum beam charge that could be accelerated with a high energy gain and low energy spread [15, 17].

In order to evaluate the quality of the beam, we also needed to study emittance evolution. However, full PIC codes like Osiris are vulnerable to numerical growth of emittance caused by the "numerical Cherenkov effect" [18]. This is a know issue with the Yee EMF solver, which causes the phase velocity of electromagnetic fields to be lower than c while the beam moves very close to c. The effect can be mitigated somewhat by replacing the Yee solver with a solver designed by Lehe [19]. These simulations showed that this numerical effect is still prominent in the high density regions of the electron beam, making it difficult to distinguish the physics from the numerical error.

Quasi-static PIC codes do not suffer this problem, so in order to study the emittance evolution of the beam we instead turned to the recently released open source version QuickPIC developed by UCLA. QuickPIC a fully relativistic 3D PIC code [20, 21].

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 [13]. 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 phase 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 [22]. 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 also increased its mass.

The baseline AWAKE drive beam current is insufficient to reach the non-linear regime and 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 as the peak density of the drive beam is $0.83 \cdot n_0$. The single bunch setup uses the baseline proton energy $W_{pb} = 400\,\mathrm{GeV}$, and retains the transverse size $\sigma_r = k_{pe}$. The length of the bunch $\sigma_z = 40\,\mu$m.

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 was done to eliminate the problem of initial de-phasing of the witness beam. AWAKE baseline energy for the long witness beam for Run 1 is $W_{eb} = 10-20\,\mathrm{MeV}$ [13]. 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 de-phasing as the drift $\Delta\xi \propto \gamma^{-2}$ [14]. 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 $\sigma_r = 100\,\mu$m caused the beam radius to undergo rapid transverse evolution as the beam enters the plasma, reducing its σ_r from $100\,\mu$m to $< 10\,\mu$m [17]. This is due to a mismatch between beam emittance and the plasma density. This 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 $6\,\mu$m, corresponding to σ_r ranging from $5.25\,\mu$m to $9.09\,\mu$m.

III. BEAM LOADING

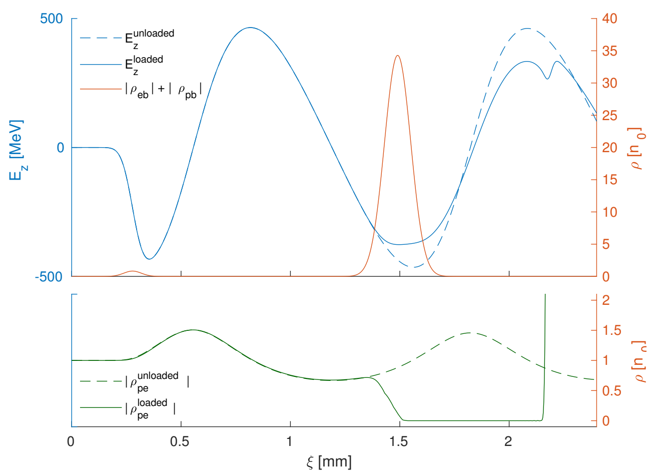

FIG. 2. Comparison between the unloaded longitudinal e-field (no witness beam) and the loaded e-field along the axis. The magnitude of the beam density along the axis is shown for reference. The beams travel towards the left. $\xi = z - tc$ is the position in the simulation box. The beam density is in units of initial plasma density $n_0 = 7 \times 10^{-14}\,\mathrm{cm}^{-3}$. 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.

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 field generated by the proton drive bunch is seen as the dotted lint in figure 2. With a proton beam density $n_{pb} \simeq n_0$, we are in the quasi-linear regime but near non-linear [23]. There is some depletion of plasma electrons, but not enough to form a bubble. The dotted green line in the lower part of figure 2 shows that the on-axis plasma density has a depletion of 67%.

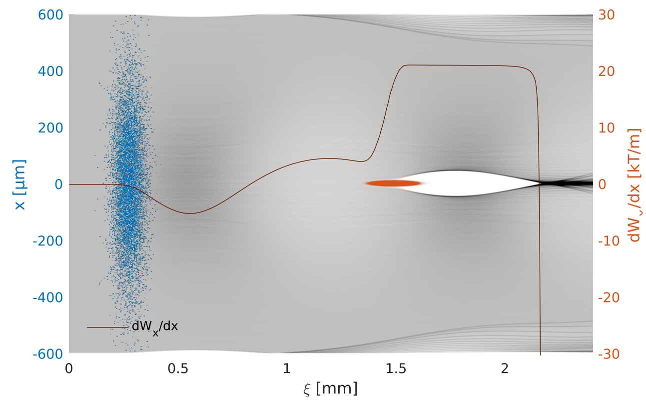

FIG. 3. The plasma density in grey with the proton beam (blue) and the electron beam (red) superimposed. The line plot indicates the transverse wakefield gradient dW_x/dx where $W_x = E_x - v_b B_y$, evaluated along the beam axis.

IV. PARAMETER OPTIMISATION

V. DISCUSSION

VI. CONCLUSION

[1] P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas, Physical Review Letters **54**, 693 (1985).

[2] J. B. Rosenzweig, D. B. Cline, B. Cole, H. Figueroa, W. Gai, R. Konecny, J. Norem, P. Schoessow, and J. Simpson, Physical Review Letters **61**, 98 (1988).

[3] I. Blumenfeld, C. E. Clayton, F.-J. Decker, M. J. Hogan, C. Huang, R. Ischebeck, R. Iverson, C. Joshi, T. Katsouleas, N. Kirby, W. Lu, K. A. Marsh, W. B. Mori, P. Muggli, E. Oz, R. H. Siemann, D. Walz, and M. Zhou, Nature **445**, 741 (2007).

[4] E. Kallos, T. Katsouleas, W. D. Kimura, K. Kusche, P. Muggli, I. Pavlishin, I. Pogorelsky, D. Stolyarov, and V. Yakimenko, Physical Review Letters **100**, 074802 (2008).

[5] AWAKE Collaboration, R. Assmann, R. Bingham, T. Bohl, C. Bracco, B. Buttenschn, A. Butterworth,

A. Caldwell, S. Chattopadhyay, S. Cipiccia, E. Feldbaumer, R. A. Fonseca, B. Goddard, M. Gross, O. Grulke, E. Gschwendtner, J. Holloway, C. Huang, D. Jaroszynski, S. Jolly, P. Kempkes, N. Lopes, K. Lotov, J. Machacek, S. R. Mandry, J. W. McKenzie, M. Meddahi, B. L. Militsyn, N. Moschuering, P. Muggli, Z. Najmudin, T. C. Q. Noakes, P. A. Norreys, E. z, A. Pardons, A. Petrenko, A. Pukhov, K. Rieger, O. Reimann, H. Ruhl, E. Shaposhnikova, L. O. Silva, A. Sosedkin, R. Tarkeshian, R. M. G. N. Trines, T. Tckmantel, J. Vieira, H. Vincke, M. Wing, and G. Xia, Plasma Physics and Controlled Fusion **56**, 084013 (2014).

[6] T. Katsouleas, S. Wilks, P. Chen, J. M. Dawson, and J. J. Su, Particle Accelerators **22**, 81 (1987).

[7] W. Lu, C. Huang, M. Zhou, W. B. Mori, and T. Katsouleas, Physical Review Letters **96**, 165002 (2006).

[8] W. Lu, C. Huang, M. Zhou, M. Tzoufras, F. S. Tsung, W. B. Mori, and T. Katsouleas, Physics of Plasmas (1994-present) **13**, 056709 (2006).

[9] M. Tzoufras, W. Lu, F. S. Tsung, C. Huang, W. B. Mori, T. Katsouleas, J. Vieira, R. A. Fonseca, and L. O. Silva, Physics of Plasmas **16**, 056705 (2009).

[10] P. Muggli, B. Allen, Y. Fang, V. Yakimenko, M. Fedurin, K. Kusche, M. Babzien, C. Swinson, and R. Malone, in *Proceedings of PAC2011* (New York, NY, USA, 2011) pp. 712–714.

[11] A. Caldwell, K. Lotov, A. Pukhov, and F. Simon, Nature Physics **5**, 363 (2009).

[12] N. Kumar, A. Pukhov, and K. Lotov, Physical Review Letters **104**, 255003 (2010).

[13] E. Gschwendtner, E. Adli, L. Amorim, R. Apsimon, R. Assmann, A. M. Bachmann, F. Batsch, J. Bauche, V. K. Berglyd Olsen, M. Bernardini, R. Bingham, B. Biskup, T. Bohl, C. Bracco, P. N. Burrows, G. Burt, B. Buttenschn, A. Butterworth, A. Caldwell, M. Cascella, E. Chevallay, S. Cipiccia, H. Damerau, L. Deacon, P. Dirksen, S. Doebert, U. Dorda, J. Farmer, V. Fedosseev, E. Feldbaumer, R. Fiorito, R. Fonseca, F. Friebel, A. A. Gorn, O. Grulke, J. Hansen, C. Hessler, W. Hofle, J. Holloway, M. Hther, D. Jaroszynski, L. Jensen, S. Jolly, A. Joulaei, M. Kasim, F. Keeble, Y. Li, S. Liu, N. Lopes, K. V. Lotov, S. Mandry, R. Martorelli, M. Martyanov, S. Mazzoni, O. Mete, V. A. Minakov, J. Mitchell, J. Moody, P. Muggli, Z. Najmudin, P. Norreys, E. z, A. Pardons, K. Pepitone, A. Petrenko, G. Plyushchev, A. Pukhov, K. Rieger, H. Ruhl, F. Salveter, N. Savard, J. Schmidt, A. Seryi, E. Shaposhnikova, Z. M. Sheng, P. Sherwood, L. Silva, L. Soby, A. P. Sosedkin, R. I. Spitsyn, R. Trines, P. V. Tuev, M. Turner, V. Verzilov, J. Vieira, H. Vincke, Y. Wei, C. P. Welsch, M. Wing, G. Xia, and H. Zhang, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment EAAC 2015, **829**, 76 (2016).

[14] V. K. Berglyd Olsen, E. Adli, P. Muggli, L. D. Amorim, and J. Vieira, in *Proceedings of IPAC 2015* (Richmond, VA, USA, 2015) pp. 2551–2554.

[15] E. Adli and AWAKE Collaboration, in *Proceedings of IPAC 2016*, International Particle Accelerator Conference (JACoW, Busan, Korea, 2016) pp. 2557–2560.

[16] R. A. Fonseca, L. O. Silva, F. S. Tsung, V. K. Decyk, W. Lu, C. Ren, W. B. Mori, S. Deng, S. Lee, T. Katsouleas, and J. C. Adam, in *Computational Science ICCS 2002*, Lecture Notes in Computer Science No. 2331, edited by P. M. A. Sloot, A. G. Hoekstra, C. J. K. Tan, and J. J. Dongarra (Springer Berlin Heidelberg, 2002) pp. 342–351.

[17] V. K. Berglyd Olsen, E. Adli, P. Muggli, and J. Vieira, in *Proceedings of NAPAC 2016* (Chicago, IL, USA, 2016).

[18] B. B. Godfrey, Journal of Computational Physics **15**, 504 (1974).

[19] R. Lehe, A. Lifschitz, C. Thaury, V. Malka, and X. Davoine, Physical Review Special Topics - Accelerators and Beams **16**, 021301 (2013).

[20] C. Huang, V. K. Decyk, C. Ren, M. Zhou, W. Lu, W. B. Mori, J. H. Cooley, T. M. Antonsen, and T. Katsouleas, Journal of Computational Physics **217**, 658 (2006).

[21] W. An, V. K. Decyk, W. B. Mori, and T. M. Antonsen, Journal of Computational Physics **250**, 165 (2013).

[22] AWAKE Collaboration and A. Caldwell, *AWAKE Status Report, 2016*, Tech. Rep. CERN-SPSC-2016-033 (CERN, Geneva, 2016) sPSC-SR-194.

[23] J. B. Rosenzweig, G. Andonian, M. Ferrario, P. Muggli, O. Williams, V. Yakimenko, and K. Xuan, AIP Conference Proceedings **1299**, 500 (2010).