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ELECTRON INJECTION STUDIES FOR THE AWAKE EXPERIMENT AT CERN

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Abstract

The AWAKE experiment recently approved at CERN will use the self-modulation instability (SMI) of long (12 cm), relativistic (400 GeV/c) proton bunches in dense plasmas to drive wakefields with accelerating gradients at the GV/m level. These accelerating gradients will be probed by externally injected electrons. In order to preserve the plasma uniformity required for the SMI the first experiments will use on-axis injection of a low energy 10-20 MeV electron beam collinearly with the proton beam. In this article we describe the physics of electron injection into the proton driven SMI wakefields. Requirements on the injected electron beam are determined and the final accelerated beam parameters are obtained via numerical simulations.

INTRODUCTION

The AWAKE project [1–4] at CERN will be the world's first proof of principle R&D experiment on proton driven plasma wakefield acceleration (PDPWFA) using the 400 GeV/c proton beams extracted from the CERN SPS accelerator. The interest in PDPWFA is motivated by the ability of plasmas to support extremely strong electric fields and by the availability of proton beams carrying tens of kilojoules of energy in a single bunch. The high energy content of proton beams makes it possible to accelerate multi-nanocoulomb electron bunches to sub-teraelectronvolt energies and beyond in a single plasma stage [5], which is the main advantage of PDPWFA over other plasma wakefield acceleration schemes.

The initial proposal [5] of PDPWFA assumed that a sub-millimeter long proton bunch is used as a driver for plasma wakefields. However the presently available high-energy proton bunches (SPS, LHC) have the length of $\sigma_{zb} \approx 12$ cm. Therefore it was proposed that the first experiments on PDPWFA should rely on the resonant excitation of plasma wakefield by a train of micro-bunches produced during the self-modulation instability (SMI) of a long proton beam in the plasma [6].

The AWAKE experiment will be installed at CERN in the deep underground CNGS facility. An LHC-type proton bunch of 400 GeV/c momentum but higher intensity ($3 \cdot 10^{11}$ protons/bunch) is extracted from the SPS and sent towards a 10 m long rubidium vapor cell. A high power (2 TW) laser pulse, co-propagating and co-axial with the proton beam, is used to ionize the (initially neutral) rubidium gas in the plasma cell and also generates a seed of the proton bunch self-modulation. A several millimeter long bunch with $\sim 10^9$ electrons at 10-20 MeV produced by the photo-injector serves as witness beam and is accelerated in the wake of the proton bunches. Several diagnostics tools are installed downstream the plasma cell to measure the proton bunch self-modulation and the accelerated electron bunch properties.

In this article we describe the physics of electron injection into the proton driven wakefields. This process is studied numerically with a fluid [7, 8] and particle-in-cell [8, 9] version of the 2d3v quasi-static code LCODE. The fluid code produces less noisy results and is used for electron injection studies over the first meter of the plasma where the wakefield amplitude is sufficiently low. The particle-in-cell code provides simulation of the full 10 m long plasma accelerator.

ON-AXIS VS SIDE INJECTION

Two configurations of electron injection were considered for this experiment: on-axis injection and side injection. On-axis injection means that the electron bunch is injected into the plasma collinearly and on-axis with the proton bunch as it is shown in Fig. 1. Originally, on-axis injection of electrons into the wakefield of a self-modulating beam turned out to be a nontrivial task. During development of the self-modulation instability, the phase velocity of the wakefield is substantially lower than the light velocity c. It was predicted that the electron energy gain in PDPWFA driven by a self-modulated beam in a uniform plasma will be severely limited by dephasing [10]. However, as it will be shown below the phase velocity of the wakefield at the end of SMI becomes faster than light and then approaches c asymptotically from above. This makes it possible for trapped electrons to move to the accelerating phase of the wakefield and stay there until the end of the plasma section.

Another possible way to high electron energies involves side injection of electrons into the plasma wave at the stage of fully developed self-modulation [1, 11]. Although the side injection is expected to produce narrower energy spectra of accelerated electrons [1], its implementation presents some technical difficulties. The parameter window for good trapping is rather narrow, and the low energy electron beam must be transported through the highly uniform plasma column for several meters and only then injected to a certain region at a certain angle.

Therefore on-axis injection was recently selected as a primary option for the AWAKE experiment. Side injection may be implemented at some later stage.

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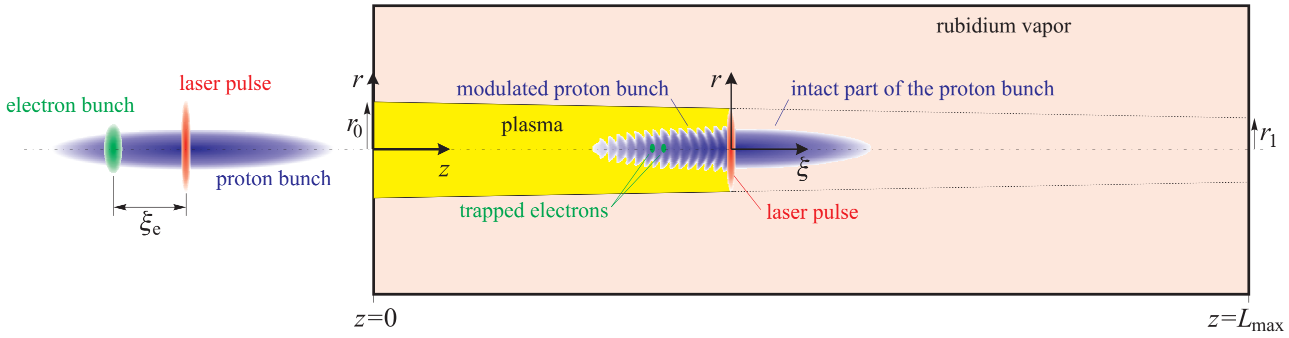


Figure 1: Geometry of the beam injection (not to scale). The beams are shown before (left) and inside (right) the plasma section. Simulation parameters are the following: plasma density $n_0 = 7 \cdot 10^{14}$ (plasma wavelength $\lambda_p = 1.26$ mm), plasma length $L_{\max} = 10$ m, plasma radius $r_0 = 1.5$ mm, $r_1 = 1$ mm, number of protons $N_b = 3 \cdot 10^{11}$, proton beam momentum $W_b = 400$ GeV/c, length $\sigma_{zb} = 12$ cm, radius $\sigma_{x,y\ \mathrm{beam}} = 0.2$ mm and normalized emittance $\epsilon_{nb} = 3.6$ mm·mrad; electron bunch energy $W_e = 16$ MeV, length $\sigma_{ze} = 1.2$ mm, radius $\sigma_{x,y} = 0.25$ mm, normalized emittance $\epsilon_{ne} = 2$ mm·mrad, number of electrons $N_e = 1.25 \cdot 10^9$ and delay $\xi_e = 16.4$ cm.

ON-AXIS INJECTION SIMULATIONS

Figure 1 defines the main parameters of the AWAKE experiment used in our simulations. Three superimposed beams (proton, electron, and laser beam) propagate collinearly through the volume filled with a uniform rubidium vapor. The short laser pulse ionizes the vapor and creates the plasma. The leading half of the proton bunch propagates in the neutral gas and does not contribute to the plasma wakefield. The rear half of the proton beam undergoes self-modulation seeded by the instant onset of the plasma. We use cylindrical coordinates (r, ϕ, z) with the z-axis as the direction of the beam propagation and the co-moving coordinate $\xi = z - ct$ measured from the laser pulse.

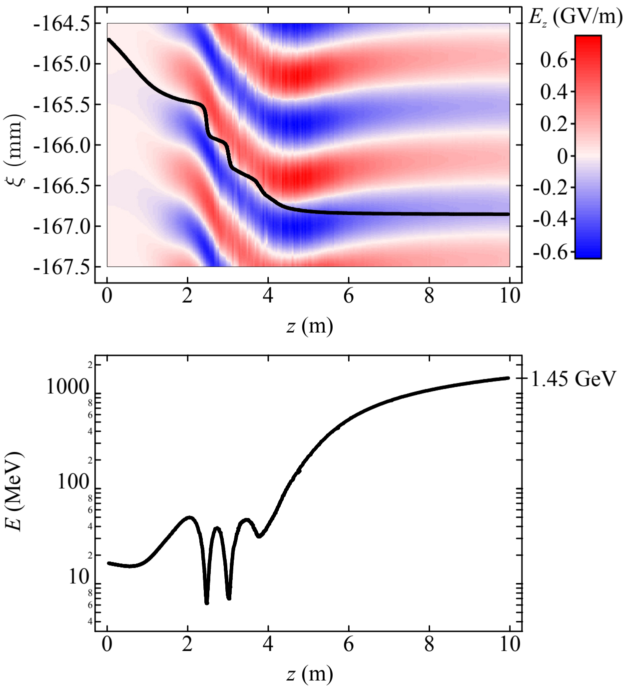


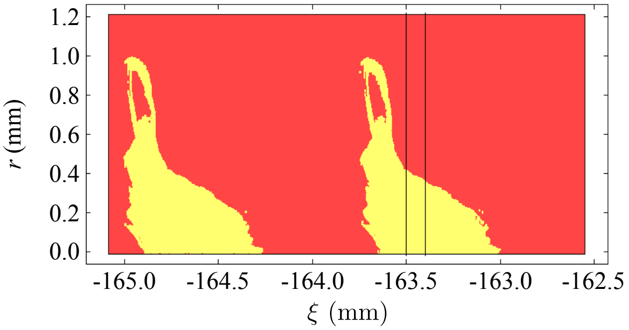
Figure 2: Typical trajectory of accelerated electron. Top plot — trajectory in the (z, ξ) coordinates superimposed on the color map of the longitudinal electric field E_z. Bottom plot — the same trajectory in the (z, E) coordinates, where E is the energy of the electron.

Figure2 shows the typical longitudinal dynamics of accelerated electrons. As soon as the injected electron gains some energy in the accelerating phase of the wake during the development of SMI the electron velocity becomes faster than the phase velocity of the plasma wake. As a result of this acceleration and dephasing the electron enters the decelerating phase of the wake where it looses energy until its velocity becomes slower than the phase velocity of the wake and it enters the accelerating phase again. This process (visible as steps in the electron trajectory at the top picture of Fig. 2) is repeated several times until the SMI is fully developed. Because of superluminal behavior of the phase velocity of the plasma wake after the SMI saturation, the trapped electron which was previously oscillating near the minimum of accelerating/decelerating electric field E_z ends up in the accelerating phase. Therefore the main part of energy gain is obtained by electrons after the saturation of the SMI. The superluminal behavior of plasma wakefield is caused by the combination of two effects: the erosion of proton micro-bunches and the dependence of plasma frequency on the wakefield amplitude. These effects are weak and they require an accumulation over many wakefield periods to become significant. Electron acceleration to high energies in the case of on-axis injection into the SMI is possible only at significant delays $\xi_e \gtrsim 100$ of plasma wavelengths λ_p which is approximately equal to one σ_{zb} for the baseline AWAKE parameters. On the other hand for $\xi_e \gtrsim 200\lambda_p$ the described superluminal shift of the wakefield phase becomes too large so that all initially captured particles are lost because they move into the defocusing phase of the wake.

We note that the separation of injected particles into trapped and untrapped fractions occurs at the very beginning of the plasma cell (over the first meter), before the drive beam has time to self-modulate. In order to define the optimal parameters of the injected electron beam we run acceptance simulations using the fluid version of LCODE. Plasma wakefield acceptance in our case can be defined as the region of initial electron coordinates in $(\xi, r, p_z, p_r, p_\phi)$ where electrons are trapped. The lower limit on p_z is set by the wakefield phase velocity and is around 10 MeV/c. The upper limit of 20 MeV/c for p_z in our case is set by the injector. Fig. 3 shows the longitudinal and transverse acceptance. Instead of p_r we use the angle $r' = dr/dz = p_r/p_z$ which is more convenient in accelerator physics. According to Fig. 3 the injected 16 MeV electron beam should be focused down to 0.5 mm in radius and length (Fig. 3 top), while the angular spread in the beam can be rather large: ± 6 mrad (Fig. 3 bottom). Also it is possible to inject electrons 1-2 mm off-axis with an angle from -1 mrad to -7 mrad.

The first experiments with electron injection assume an electron bunch which spans over several plasma wavelengths. In this case some fraction of the electron beam is inevitably lost due to transverse defocusing wakefields. For the parameters given in Fig. 1 ($\sigma_{ze} = 1.2$ mm) the trapping efficiency is 14%. However for electron beams which are shorter than 0.5 mm the trapping efficiency can go up to 100%.

Energy and angle distributions in the accelerated electron bunch are shown in Fig. 4. A small fraction of the accelerated beam has large positive angles around 5 mrad. These electrons are the ones that reach high energy but are lost from the plasma wakefield because they enter the defocusing phase of the wake near the plasma exit.



-163.5 mm < ξ < -163.4 mm:

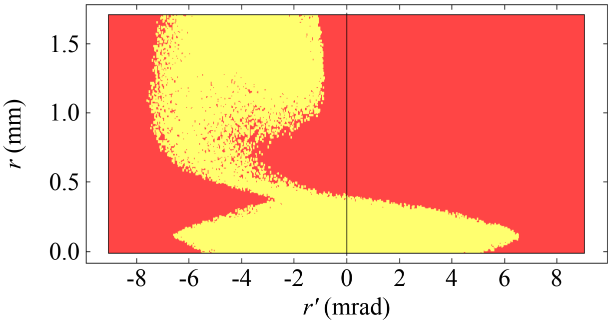


Figure 3: Plasma wave acceptance for on-axis injection of 16 MeV electrons. Yellow dots represent the initial coordinates of the captured particles, and the red dots correspond to the lost particles. The top picture was calculated with all electrons having initial $r' = 0$.

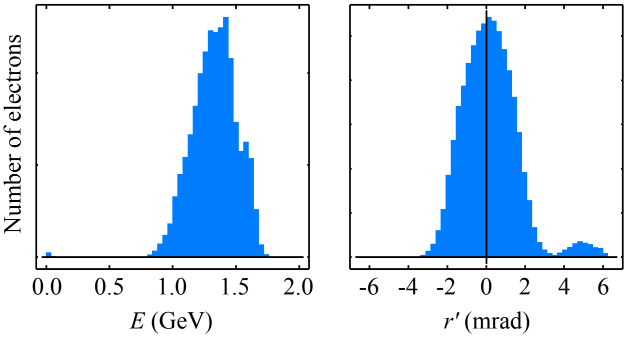


Figure 4: Energy (left) and angle (right) distributions of the accelerated electron beam after 10 m plasma section.

CONCLUSION

Via numerical simulations we have shown that on-axis injection of low-energy (16 MeV) electron beam can be used to probe the wakefields of self-modulating proton bunch in plasma. Due to the superluminal behavior of the phase velocity of the wakefield at the end of self-modulation all trapped electrons move to the accelerating phase of the wakefield and stay there until the end of plasma section. For the baseline parameters of the AWAKE experiment (given in the Fig. 1 caption) the captured $1.7 \cdot 10^8$ electrons (14% of initial bunch with $N_e = 1.2 \cdot 10^9$) are accelerated to 1.3 GeV with an energy spread of ±0.4 GeV. The majority of accelerated electrons have radius $r < 0.1$ mm and angle $|r'| < 2$ mrad.

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