BEAM-PLASMA INTERACTION SIMULATIONS FOR THE AWAKE EXPERIMENT AT CERN

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Abstract

The AWAKE experiment at CERN will be the first proof-of-principle demonstration of the proton-driven plasma wakefield acceleration using the 400 GeV proton beam extracted from the SPS accelerator. The plasma wakefield will be driven by a sequence of sub-millimeter long micro-bunches produced as a result of the self-modulation instability (SMI) of the 12 cm long SPS proton bunch in the 10 m long rubidium plasma with a density corresponding to the plasma wavelength of around 1 mm. A 16 MeV electron beam will be injected into the developing SMI and used to probe the plasma wakefields. The proton beam self-modulation in a wide range of plasma densities and gradients have been studied in detail via numerical simulations. A new configuration of the AWAKE experiment with a small plasma density step is proposed.

INTRODUCTION

Presently available proton beams in large accelerators (SPS, LHC) carry enough energy to accelerate large number of electrons to the TeV scale energies in a single stage [1]. The AWAKE experiment [2, 3] is currently under construction at CERN in order to test the concept of electron acceleration in plasma wakefields created by the ultra-relativistic proton beam.

The typical bunch length in a proton synchrotron is measured in tens of centimeters, while the interesting plasma wakefield amplitudes (~1 GV/m) correspond to the plasma wavelength of around 1 mm or less. This would require the 100-1000 times compression of the proton bunch (as suggested in [1]). Since this is technically very challenging, the AWAKE experiment will rely on the resonant excitation of plasma wakefield by a sequence of proton micro-bunches. These micro-bunches will be produced by the transverse two-stream self-modulation instability (SMI) of a long proton bunch in the plasma [4]. Such resonant excitation of plasma wakefield can produce high accelerating electric field even with a long proton bunch.

The AWAKE experiment will be carried out in two phases. The first phase is scheduled to begin in late 2016 with a goal of observing the proton beam self-modulation in the plasma. The second phase will study the low-energy (16 MeV) electron beam injection and acceleration in the plasma wakefield driven by the self-modulated proton beam.

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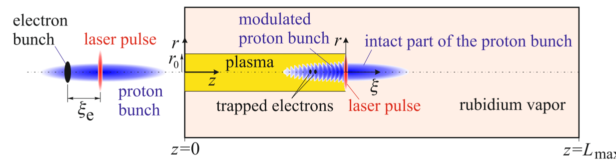

Figure 1: Geometry of the AWAKE experiment (not to scale). The beams are shown before (left) and inside (right) the plasma section. The main simulation parameters are the following: plasma density $n = 7 \cdot 10^{14}$ cm^{-3} (plasma wavelength $\lambda_p = 1.26$ mm), plasma length $L_{\max} = 10$ m, plasma radius $r_0 = 1.4$ mm, number of protons in the bunch $N_b = 3 \cdot 10^{11}$, proton beam momentum $W_b = 400$ GeV/c, length $\sigma_{zb} = 12$ cm, radius $\sigma_{x,y\ \mathrm{beam}} = 0.16$ mm and normalized emittance $\epsilon_{nb} = 2.2$ mm·mrad; electron bunch energy $W_e = 16$ MeV. These parameters are different from the baseline values (given in [5], for example) by the more realistic emmittance of the proton beam — 2.2 mm·mrad [6] instead of 3.6 mm·mrad. The baseline set of parameters used the conservative upper limit for the proton beam emittance instead of the realistic value.

A 10 m long plasma section based on the continuous flow of rubidium vapor at approximately 200 °C will be used in the AWAKE experiment. The selected plasma section design is capable of creating plasma density profiles with a constant gradient along the whole 10 m long section [7–9]. This gradient naturally appears if the temperatures of two rubidium vapor sources at the plasma cell entrance and at the exit are unbalanced. The effects of the plasma density gradient on the acceleration of electrons are described in [10]. The details of electron beam injection and acceleration in the uniform plasma are given in [5, 9].

In this paper we present several simulation results relevant for the first and second phase of the AWAKE experiment which were not covered by previous publications. The simulations are performed using the particle-in-cell version of 2d3v quasi-static code LCODE [11–13] assuming the cylindrical symmetry. The geometry and the main parameters of the simulations are given in Figure 1.

PROTON BEAM SELF-MODULATION AT DIFFERENT PLASMA DENSITIES

The transverse profile of the defocused part of the proton beam after the plasma will be among the first measurements expected at the beginning of the experiment. It is therefore

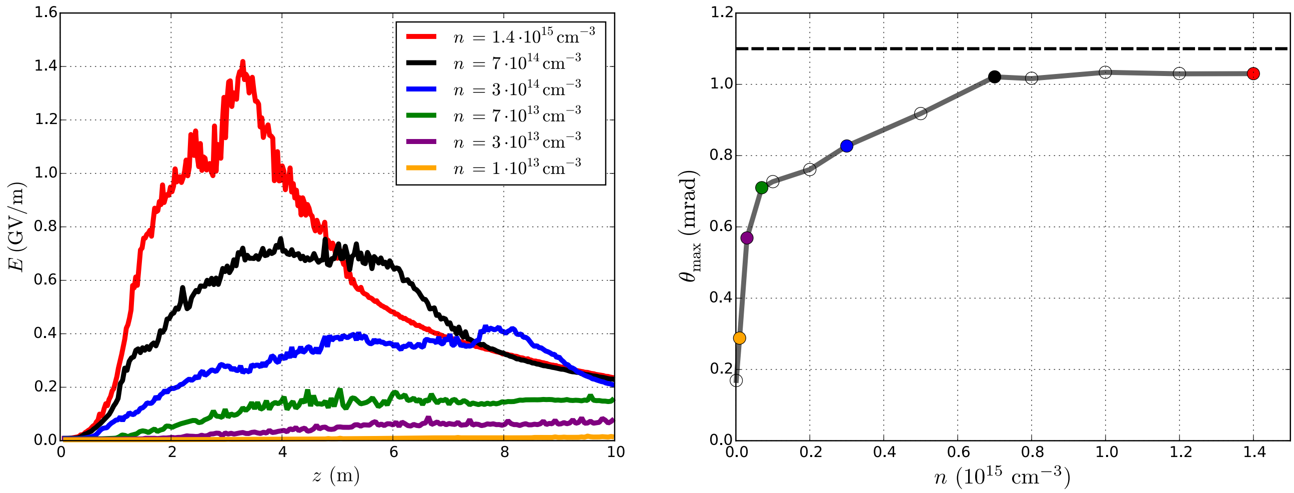

Figure 2: Maximum electric field along the plasma (left) and maximum proton defocusing angle (right) at different plasma densities. The dashed line shows the estimate given by the expression (1).

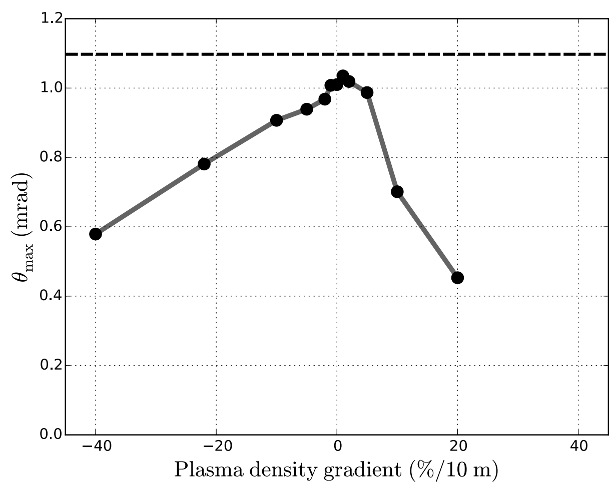

Figure 3: Maximum proton defocusing angle as a function of plasma density gradient. The dashed line shows the estimate given by the expression (1). Plasma density at the beginning of the cell is $7 \cdot 10^{14}$ cm^{-3} in these simulations.

good to understand how the proton beam defocusing in the plasma depends on different parameters of the experiment.

There is a simple estimate for the maximum defocusing angle of protons during the SMI [14]

$$\theta_{\mathrm{max}} \sim \sqrt{\frac{m_e}{\gamma_p m_p}}, \tag{1}$$

where m_e and m_p are the mass of electron and proton, respectively, γ_p is the relativistic factor of the proton beam. This expression agrees well with numerical simulations of saturated SMI. Figure 2 shows the dependence of plasma wakefields and the maximum proton defocusing angle on the plasma density. According to Figure 2 the SMI starts saturating in the 10 m long plasma at the density of approximately 10^{14} cm^{-3}, which should also be visible in the initial experiments – defocused proton beam size grows rapidly with increasing plasma density up to $n \approx 10^{14}$ cm^{-3} and then slowly saturates approaching the limit given by the expression (1).

Figure 3 shows the maximum proton defocusing angle as a function of the plasma density gradient in the 10 m long plasma section. Even steep density gradients up to −40% and +20% in 10 m should still produce a well-detectable self-modulation instability.

According to these simulations the first phase of the AWAKE experiment (the detection of proton beam self-modulation) should not depend on some fine-tuning of the plasma density profile. Proton beam interaction with the plasma in a wide range of densities with a significant density gradient should produce a well-detectable SMI.

However the precise control over the plasma density profile at the 1% level seems to be possible with the current rubidium vapor cell design, and this could be very useful at the later stage of the experiment with electron acceleration, as we explain in the next section.

POSSIBLE EXPERIMENT WITH PLASMA DENSITY STEP

A minor modification of the AWAKE plasma section can produce the plasma profile with a small density step near the beginnig of the section. Such profile has been suggested to stabilize the proton micro-bunches after saturation of the SMI [15,16]. This technique can become critically important for longer accelerating plasma section.

The main idea is to restrict the flow of rubidium vapor in the AWAKE plasma cell using 20 cm long and 1 cm wide aperture reduction as shown in Figure 4. Such an obstacle to the uniform flow will create the required density step of 3% while the density gradient in the main 4 cm wide part of the plasma section will be around 1% over 10 m. More details are given in [8].

Figure 4 shows the possible application of this technique to the high plasma density case (two times higher than the

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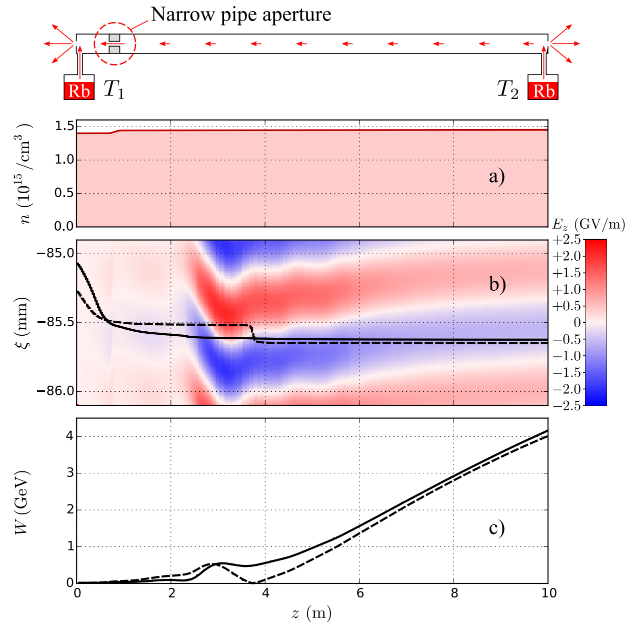

Figure 4: The AWAKE experiment configuration with a small plasma density step optimized to obtain high amplitude of plasma wakefileds and high energy of accelerated electrons. The top schematic picture shows the flow of rubidium vapor in the plasma cell with 20 cm long aperture reduction (from 4 cm to 1 cm). a) The calculated rubidium vapor density profile with 3% step near the beginning of the plasma section. b) Two typical trajectories of accelerated electrons (ξ is the distance to the laser pulse as explained in Figure 1). The color map in the background shows the longitudinal electric field on the axis. c) Evolution of the energy of the selected electrons. The proton beam is assumed to be longitudinally compressed by a factor of two.

baseline value). Also the proton beam is assumed to be longitudinally compressed by a factor of two. The 1.3x proton bunch compression has been already demonstrated [6], and the stronger compression could also be possible with a different bunch rotation scheme [17]. The 2x compression is not necessarily required for this experiment; we just use it here as an example. Such configuration can boost the accelerated electron energies significantly from the typically expected 1-2 GeV in the uniform plasma to 4 GeV in the plasma with the density step. Using even higher plasma density can produce better results.

CONCLUSION

The simulations show that saturation of the proton beam SMI in the 10 m long plasma section corresponds to the saturation of the maximum proton defocusing angle with increasing the plasma density.

A minor modification of the AWAKE plasma section, namely local aperture reduction, can produce the plasma profile with a density step — an interesting possible configuration of the experiment promising higher energy of accelerated electrons compared to the case of the uniform plasma.

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