SIMULATION STUDY OF PROTON-DRIVEN PWFA BASED ON CERN SPS BEAM

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Abstract

We have proposed an experimental study of the proton-driven plasma wakefield acceleration by using proton beam from the CERN SPS. In this paper, the particle-in-cell (PIC) simulation of the SPS beam-driven plasma wakefield acceleration is introduced. By varying the beam parameters and plasma parameters, simulation shows that electric fields in excess of 1 GeV/m can be achieved.

INTRODUCTION

Proton-driven plasma wakefield acceleration (PWFA) has recently been proposed as an approach to bring electron beam in multi TeV energy regime [1]. To demonstrate it, we proposed an experimental study of proton-driven PWFA based on the CERN SPS beam [2]. To keep the cost of the experiment as low as possible, the uncompressed SPS beam will be directly injected to a preformed and uniform plasma. Since the proton bunch length is much larger than the plasma wavelength. We expect a strong beam density modulation will occur due to the transverse wakefield in the plasma. In this paper, we perform the simulation study of a long SPS beam in a plasma and present the simulation results.

SELF-MODULATION OF A LONG BEAM

In plasma wakefield acceleration, an efficient excitation of wakefield requires the bunch length close to the plasma wavelength $\lambda_p = 2\pi c/\omega_p$, where c is the speed of light. $\omega_p = \sqrt{n_p e^2/\varepsilon_0 m}$ is the plasma frequency, where n_p is the plasma density, e, m and ε_0 are the electron charge, electron mass and the permittivity of free space, respectively. However, for the proton-driven plasma wakefield acceleration, the available high energy proton beams from present proton synchrotrons are quite long. For example, the proton bunch length for Tevatron, HERA and LHC are 50 cm, 8.5 cm and 7.55 cm, respectively, which are much longer than the plasma wavelength we are interested in. Such long beam cannot resonantly excite a large amplitude wakefield directly. However, when a beam with bunch length much longer than the plasma wavelength is injected into the plasma, the particles in the bunch head will excite the wakefield. The transverse wakefield will modulate the particle distribution in the bunch tail. This very much resembles the self-modulated laser wakefield acceleration scheme (SM-LWFA) in which a high density plasma can be used for achieving a high amplitude wakefield [3]. The self-modulation of the proton bunch essentially occurs due to the action of the transverse wakefields on the bunch itself. Subject to the density modulation effect, the long proton beam will be split into many slices due to the transverse focusing and defocusing field [4]. After propagating some distances, a full self-modulation will be formed. The beam slices will excite the wakefield coherently and eventually the fields add up to a higher amplitude. PIC simulation shows that working in self-modulation regime, the wakefield amplitude (on-axis electric field) can reach from several hundred MeV/m up to 1 GeV/m by employing the realistic SPS beam.

WAKEFIELD FROM THE SPS BEAM

Two sets of beam parameters can be provided from the SPS. One beam is the standard SPS beam for injection into the LHC, we therefore called it SPS-LHC beam. The other option is the high intensity beam when the SPS operates in a single bunch mode, we named it as SPS intense beam (or abbreviated as SPS-intense). In latter case, the bunch charge is increased by a factor of 2.6 and the bunch length is reduced by 30%. The detailed beam parameters are listed in Table 1. Our simulations are based on these two parameter sets.

Table 1: Parameters for SPS-LHC and SPS-Intense Beam

	SPS-LHC	**SPS-intense**
Beam energy [GeV]	450	450
Bunch population [10^{11}]	1.15	3.0
Beam radius [μm]	200	200
Angular spread [mrad]	0.04	0.02
Normalized emittance [μm]	3.5	2
Bunch length [cm]	12	8.5
Energy spread [%]	0.03	0.04

Generally, the PIC code is employed to simulate the interactions between the beam particles and the plasmas. In our study, we used various PIC and hybrid codes to simulate the behaviour of SPS proton beam in a uniform plasma. The results from various codes have been benchmarked and they in general agree with each other. In this paper, we mainly present 3D simulation results from a quasi-static code QuickPIC [5] and a 2D cylindrical simulation results from OSIRIS [6].

Fig. 1 shows the beam density distribution (which is normalized to the plasma density n_p in right colour bar) at 6 m plasma for a full SPS-LHC beam (uncompressed).

Here ξ ($\xi = ct\text{-}z$) denotes the beam propagation direction (downwards along ξ axis and in units of plasma skin depth) with $\xi = 0$ the middle point of the bunch and X denotes the horizontal direction (in units of plasma skin depth). It is clearly seen that the beam density becomes modulated after 6 m in plasma with plasma density n_p of 10^{14}cm^{-3}. Some particles in the bunch (in focusing phase of the wake) are focused and the beam density becomes denser (~$0.054n_p$), note that the ratio between the initial SPS-LHC beam density and plasma density is $0.015n_p$. Other particles (in the defocusing phase of the wake) are defocused and scattered transversely and therefore the beam density there is thin. Fig.2 gives the beam density distribution after 10 m in plasma. It shows that a density modulation is fully formed (maximum density ~$0.09n_p$). Since it takes some time for start of the self-modulation effect, we found that the protons in the bunch tail gets very good modulation, whilst some fraction of protons in the bunch head are scattered transversely due to less focusing field from the plasma wakefield. Once the self-modulation is nicely set up, the focusing force will act upon the rear part of bunch and keep them focused. These modulated bunch patterns can propagate for a long distance. Fig.3 gives the longitudinal electric field (normalized to the wave-breaking field in the right colour bar) excited by a full SPS-LHC bunch at 10 m plasma. It shows that the field amplitude ~100 MeV/m can be achieved with a plasma density of 10^{14} cm^{-3}.

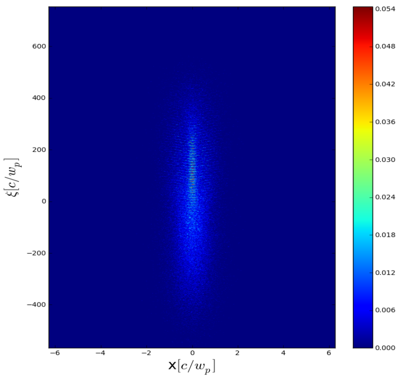

Figure 1: Beam density distribution at 6 m plasma.

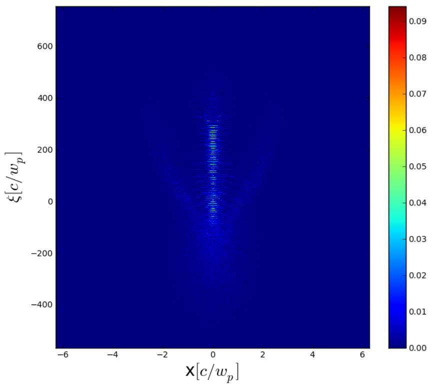

Figure 2: Beam density distribution at 10 m plasma.

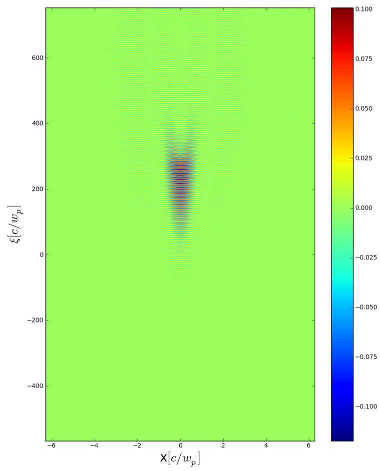

Figure 3: Longitudinal electric field at 10 m plasma.

PARAMETER OPTIMIZATION

Based on the SPS-LHC beam parameter, we found that the maximum electric field amplitude is around 100 MeV/m at plasma density of 10^{14} cm^{-3}. To investigate the possibility of a higher field production, we therefore investigate the impact of the beam properties and plasma density to the wakefield amplitude.

Using the OSIRIS code, we performed 2D cylindrical simulations based on various plasma densities and beam densities. Fig.4 shows one example of the maximum longitudinal electric field as function of the travelled distance for various plasma densities. In order to set up the modulation quickly, we intentionally seed the instability in plasma by a half-cut SPS-LHC beam. In this case, the plasma will see the proton bunch with a very sharp current flank. The instability seeded by this flank modulates the density of proton bunch. To obtain the maximum amplitude of the wakefield envelope at a particular time in the simulation, a 5-point smoothing in the longitudinal direction is applied to the simulation result, this envelope extraction method is simple but more accurate method can also be used. The blue curve in Fig.4 shows that for the half-cut SPS-LHC beam, the maximum wakefield amplitude is ~ 100 MeV/m after 5 m plasma with density of 1×10^{14} cm^{-3}. If the high plasma density of 6×10^{14} cm^{-3} is used, the field amplitude approaches 300 MeV/m after 5 m plasma, as shown in green curve of Fig.4. For even higher plasma density, e.g. 2.4×10^{15} cm^{-3}, the electric field amplitude reaches 1 GeV/m at 5 m plasma (red curve), which is significantly higher than the above two lower plasma density cases. Therefore, high plasma density is very effective to achieve a high wakefield for our experiment. However, hosing instability can be more severe at higher plasma density, so 3D simulations are needed to find out the trade-off between high acceleration wakefield and stability.

On the other hand, for the first experiment, we will work in a single shot beam mode. That is to say, to extract a single proton beam from the SPS and then fire it in a preformed plasma. If the SPS runs in a single bunch mode, there is a little space to upgrade beam properties, e.g. the bunch population or the bunch length. Table 1 also shows a set of intense SPS beam parameters for a single bunch operation case in the SPS. The beam density for SPS-intense is about 3.68 times higher than that of the SPS-LHC beam. Fig.5 compares the maximum longitudinal electric field for these two sets of parameters (here case 3 denotes the nominal SPS-LHC beam) with respect to the travelled distance for various plasma densities. The blue curve here shows that for a half-cut SPS-LHC beam with a plasma density of 1×10^{14} cm^{-3}, the electric field amplitude is around ~100 MeV/m at 10 m plasma. For a half-cut SPS-intense (green curve) beam, the field increases quickly and the field amplitude (~ 300 MeV/m at 10 m plasma) is larger than that of the SPS-LHC beam. With a front-cut SPS-intense beam, that is, to cut the beam at location of ¼ of the beam, then the other ¾ of beam will contribute the wakefield formation. With such a beam, the wakefield excited by the sharp rise of the beam is less stronger compared to a half-cut beam but the modulation instability can grow faster due to longer beam length, however destruction of wakefield from turbulence mixing [7] may be one reason to limit the growth of wakefield at the beam tail hence reducing the advantage of such a beam. The simulation shows that in this case (shown in red curve), the field amplitude is a little bit higher than that for the half-cut SPS-intense beam. If raising the plasma density to 6×10^{14} cm^{-3}, the field amplitude approaches 1 GeV/m after 2 m in plasma for a front-cut SPS-intense beam (cyan curve), which is significantly higher than other low plasma density cases. Further scanning of beam and plasma parameters is still ongoing for achieving a high and stable wakefield.

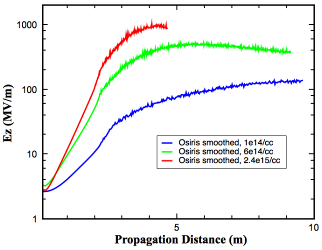

Figure 4: The maximum longitudinal electric fields for SPS-LHC beam *vs.* travelled distance.

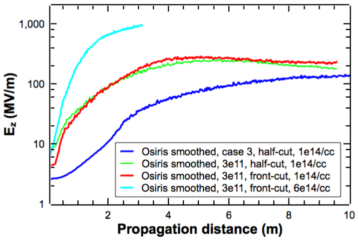

Figure 5: The maximum longitudinal electric fields for SPS-LHC and SPS-intense *vs.* travelled distance.

PLASMA DENSITY STEP

Based upon previous simulations, we found that working in self-modulation regime, the plasma wakefield quickly saturate and even decreases after the field amplitude reaches a maximum value. The beam particles have no time to change their energy considerably. Simulation also shows that almost no particles remain in the near-axis at the stage of field decreasing region. This will greatly limit the maximum energy gain for the witness beam. In order to achieve a higher electric field and a significant energy gain, the control of the self-modulation process via the plasma density step was recently proposed [8]. To clarify the mechanism of the beam destruction, K. Lotov studied the phase of wakefield with respect to the beam density modulation. The results show that at the time of maximum field, the relative positions of the beam and the wave are roughly half of the beam particles are located in the focusing region of wakefield, and another half is already scattered transversely and therefore cannot contribute to the wakefield formation any more. Later, the wave continues moving backward and eventually the defocusing phase of the wave sweeps aside the rest of the beam. To combat this beam destruction, Lotov suggested to control the wave phase by a slightly increase of the plasma density after the beam bunching (start of the modulation). The plasma density increase leads to increase of the plasma frequency and shortening of the wakefield wavelength, and thus a forward shift of the wave with respect to the main part of the beam will compensate the backward shift due to the instability. The simulations from a 2D hybrid code LCODE [9], 3D QuickPIC and 2D OSIRIS already confirmed this mechanism quantitatively. Using a half-cut SPS-LHC beam as driver, the result shows that the beam transformed by the instability in the presence of the plasma density step indeed stably propagates for a long distance with no signs of degradation.

CONCLUSION

A long proton bunch from SPS fired into a uniform plasma will be subject to a density modulation effect due to the transverse wakefield. The self-modulated proton bunches may excite wakefield coherently and the field amplitude adds up to a high amplitude. PIC simulation shows that the field amplitude can reach a few hundred MeV/m to 1 GeV/m depending upon the plasma density. For SPS-intense beam, the wakefield amplitude is higher than that of the SPS-LHC beam at the same plasma density. The plasma density step can be applied to control the phase of wakefield so as to achieve a stable field for accelerating a witness beam to high energy.

REFERENCES

[1] A. Caldwell et al., Nature Physics 5, 363 (2009).
[2] G. Xia et al, these proceedings.
[3] E. Esarey et al., Phys. Rev. Lett. 72, 2887 (1994).
[4] N. Kumar et al., arXiv: 1003.5816 (2010).
[5] C.K. Huang et al., J. Comp. Phys. 217, 658 (2006).
[6] R.A. Fonseca et al., Lecture Notes in Computional Science 2331, 342 (2002).
[7] J. Dawson, Phys. Rev. 113, 383 (1959).
[8] K. Lotov, private communication (2010).
[9] K. Lotov, Phys. Rev. ST Accel. Beams 6, 061301 (2003).