Update of Proton Driven Plasma Wakefield Acceleration

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Abstract. In this paper, the update of proton driven plasma wakefield acceleration (PDPWA) is given. After a brief introduction to the scheme of PDPWA, a future demonstration experiment is discussed. The particle-in-cell simulation results based on the realistic proton beams from the CERN Super Proton Synchrotron (SPS) are presented, followed by a simulation study of proton bunch compression.

Keywords: proton driven plasma wakefield acceleration, particle-in-cell, bunch compression.
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INTRODUCTION

It has been recently proposed to use a high energy proton bunch to drive a plasma wakefield for electron beam acceleration [1]. In this scheme as shown in Fig. 1, a 1 TeV proton beam, with a bunch intensity of 10^{11} and bunch length of 100 microns as drive beam shoots into a preformed plasma confined in a thin tube. Outside the plasma cell, quadrupoles with alternative polarities are placed to focus the proton beam so that it can propagate a sufficiently long distance in the plasma. Particle-in-cell (PIC) simulations have shown that with such a configuration, the proton beam can indeed excite a large amplitude plasma wave [2]. Surfing the appropriate phase of the wave, an externally injected relativistic electron bunch with an initial beam energy of 10 GeV reaches an energy over 600 GeV in a single passage through a 450 meter long plasma, as shown in Fig. 2. The final energy spread of the electron beam is around 1 %. The overall efficiency from the drive proton beam to the witness electron beam is about 10 %. If this scheme can be demonstrated in experiments, this will open a new way to reach the TeV (Teraelectronvolts or 10^{12} eV) energy scale for application on the high energy physics in the future.

Generally speaking, the beam energies stored in the current high energy proton synchrotrons, e.g. Tevatron at FNAL or Large Hadron Collider (LHC) at CERN, are two or three orders of magnitude higher than that of the current highest energy electron beam from SLAC. A new research frontier will be opened if we could find a way to couple the energy of proton beam into the plasma and then to the witness beam. An experimental program is now being planned to extensively study the mechanism of proton driven plasma wakefield acceleration. The idea is to utilize the existing proton beams from the CERN accelerator complex, like the Proton Synchrotron (PS) or the Super Proton Synchrotron (SPS). By sending the beam into a preformed plasma, a large amplitude plasma wakefield is expected to be excited [3].

In this paper, we will present an update of the proton beam driven plasma wakefield acceleration. The drive beam from the CERN SPS will be considered. PIC simulation results based on realistic SPS beam parameters will be given. The experimental setup will be introduced and related issues will be discussed in detail. The proton bunch compression will also be presented.

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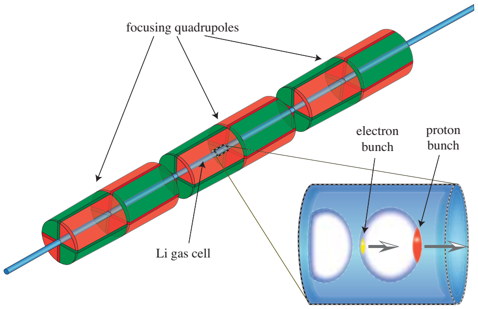

FIGURE 1. Schematics of a proton driven plasma wakefield acceleration.

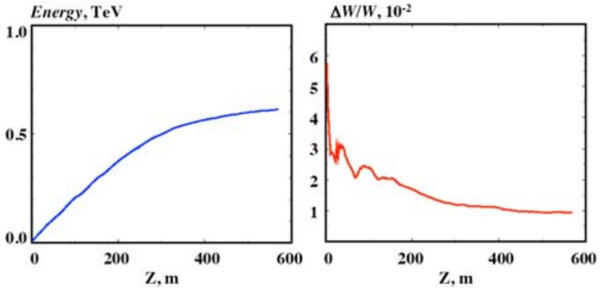

FIGURE 2. The evolution of the electron beam energy and energy spread *vs*. propagation distance.

DRIVE BEAM FOR EXPERIMENT

Considering the high energies stored in current proton synchrotrons, a proposed experiment to demonstrate the principle of proton driven plasma wakefield acceleration is now under discussion as an international collaboration project. The aim is to use the available high energy proton beams, either from the PS or the SPS at CERN as drive beams, shoot them into a plasma and study the interaction between the proton beams and plasma. As the injectors for the LHC, the PS and SPS could provide proton beams with maximum momenta of 26 GeV/c and 450 GeV/c respectively. The bunch intensities vary from 10^9 to $1.6x10^{11}$. If the proton beam is injected into a preformed plasma cell, for example, a uniform Lithium plasma cell as the one used in the former SLAC E-167 experiment [4], the space charge of the proton beam will pull the plasma electrons onto the axis of the beam. Since the mass of the plasma ions is heavier than that of the electrons, the ions are almost immobile. This results in a region near the beam with an excess plasma electrons. As the beam passes by, the space charge of excess electrons pushes them back and therefore excites the plasma wakefield. The associated wakefield amplitude can be deduced via the energy variation of the drive beam or the injected witness beam after exiting the plasma cell.

PIC simulations of interactions between proton beams and plasmas have been done using the beam parameters of the PS and SPS [3,5]. The results show that the high amplitude wakefield can be achieved not only through a short proton driver, but also through micro-bunches produced by the transverse two-stream instability of a long driver. Simulation also indicates that the SPS beam can drive a much higher amplitude plasma wake compared to the field excited by the PS beam. This is largely due to the smaller emittance of the SPS beam. The lower emittance of the SPS beam allows the instability to develop before the beam diverges due to the intrinsic angular spread. In addition, the available tunnel in the current SPS extraction line is around 600 meters long, which far exceeds that of the PS (60 meters maximum). Therefore, it is most likely that the SPS beam will be used in our first demonstration experiment on PDPWA. In December 2009, a kick-off workshop was held at CERN, colleagues from different labs and universities discussed the design of the experimental study of PDPWA [6]. After careful consideration, we set the scientific goal for future experiments, e. g., for the first step, we will demonstrate the capability of proton driven plasma wakefield acceleration, to observe the energy variation of the proton driver and to demonstrate the energy gain of 1 GeV within 5 m of plasma. Based upon the first round of experiment, next step experiment will observe the electron acceleration based on PDPWA scheme. We will concentrate here on the first experimental study of PDPWA. The SPS beam parameters are introduced, followed by a possible beam line layout for the experiment.

The SPS is a part of the injector chain for the LHC. At present, there are two fast extraction lines from the SPS. One is located in the East Area, which can provide the beam for neutrino physics research at Gran Sasso in Italy and the anti-clockwise beam for LHC through the transfer line TI8. The other fast extraction line and transfer line TI2 from the West Area of SPS can send the clockwise LHC-like beam to the LHC ring. The location of the first demonstration experiment on PDPWA is likely to be in the TT61 tunnel in the West Area. The length of tunnel is about 620 meters. The SPS can provide a proton beam with a maximum energy of 450 GeV and an rms bunch length of about 12 cm. The basic beam parameters are listed in Table 1.

Table 1. Basic beam parameters of the SPS.

SPS beam parameters	
Momentum [GeV/c]	450
Protons/bunch [10^{11}]	1.15
rms longitudinal emittance [eVs]	0.05
rms bunch length [cm]	12
Relative rms energy spread [10^{-4}]	2.8
rms transverse normalized emittance [μm]	3.5
beam size [μm]	200
Bunch spacing [ns]	25

To excite a large amplitude plasma wakefield, a short proton driver is required. Linear theory of plasma wakefield acceleration (PWFA) indicates that the amplitude of excited electric field scales inversely proportional to the bunch length squared [7]. However, compression of the SPS bunch length via conventional magnetic compressors from initially 12 cm rms to the scale of hundreds of microns (scale of plasma wavelength) is difficult due to the rigidity of the beam. It requires a lot of RF powers to chirp the beam and large magnets to introduce the dispersive path. To keep the cost of a first experiment as modest as possible, no bunch compression will be implemented. Simulation shows that even without bunch compression, the SPS beam can still excite an interesting plasma wakefield based on the density modulation. This regime resembles the self-modulated laser wakefield acceleration (SM-LWFA) [8], rather than the PWFA. Since the drive beam is much longer than the plasma wakelength, the particles in the driver head will excite wakefield and the particles in the rear of the bunch will feel it and be split into many slices due to the transverse focusing and defocusing field. After propagating over some distance, a full self-modulation will be formed. The beam slices will excite the wakefield coherently and eventually the field adds up to a higher amplitude. PIC simulation shows that the wakefield amplitude (on-axis electric field) can reach several hundred MV/m by employing the real SPS beam. For example, for a plasma density of $10^{15}/\text{cm}^3$, simulations indicate that the amplitude of the wakefield can reach more than 200 MV/m. In addition, if the SPS beam profile can be manipulated, for example, by shortening the bunch length or modulating the beam to a 'hard-cut' beam with a steep leading edge, an even higher field is expected. More recently, the simulation shows that with the plasma density gradient, the beam can propagate stably in the plasma for longer distances and a higher wakefield amplitude will be obtained. More extensive simulations are still in progress to optimize the energy gain achieved in the plasma.

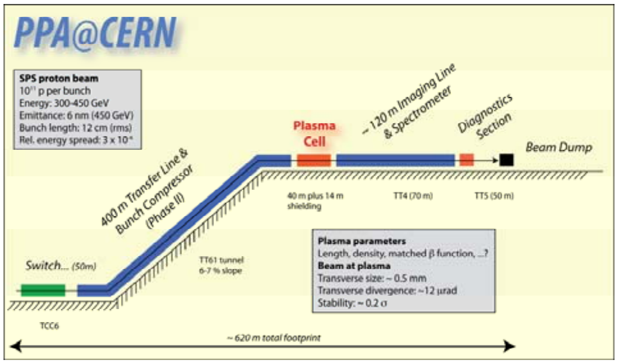

FIGURE 3. A possible beamline layout for PDPWA experiment.

For the first experiment, we will expect to observe the beam density self-modulation effect in the plasma. No bunch compression and electron injection are considered at this stage. A possible beam line layout is shown in Fig. 3. After fine tuning the beam properties such as the beam size, beam angular spread, bunch intensity etc, a matched beam (that is, matched to the betatron oscillation amplitude in the plasma) will be shot into a preformed plasma. Since it takes some time for the full self-modulation in plasma to build up, simulation shows that the length of plasma cell should be of order 5 m. After the plasma cell, a beam line with an energy spectrometer can be used to analyze the proton beam energy variation generated in the plasma. Diagnostic equipment will be employed to characterize the beam properties (beam size, current, emittance, energy etc) with and without the plasma present. The beam dump will eventually absorb the spent beam.

Concerning the plasma source for the experiment, a few prototypes will be tested in the next couple of years. One option is to use the intense lasers to ionize the metal vapors (like Lithium or Cesium). Some fractions of vapors will be ionized as plasma along the lasers' propagation direction. Another option is to utilize the Helicon discharge plasma source which employs the helicon wave induced by radio frequency heating to create a long plasma cell.

SIMULATION RESULTS

Particle-in-cell (PIC) and hybrid codes are used to model the interactions between the plasmas and charged-particle beams. In the PDPWA study, a 2D program LCODE [9] and the 3D code VLPL [10] are initially used to simulate the wakefield excited inside the plasma cell. More recently, another fully electromagnetic 3D code OSIRIS [11] and a 3D quasi-static code QuickPIC [12] are also employed to benchmark the results from various codes mentioned above. To some extent, the results from these codes agree quite well. But still, there is some discrepancy which needs to be analyzed further. Simulation shows with the SPS beam propagating directly (without bunch compression) through the plasma, a strong density modulation occurs, as shown in Fig. 4-7 (from QuickPIC code). In Fig.4, a half-cut SPS beam is used as the drive beam. ξ (ξ=ct-z) denotes the beam propagation direction (downwards along ξ axis), X the horizontal direction and n_b the beam density normalized to the initial background plasma density n_p. It shows clearly that the beam density becomes modulated after 4.8 m in the plasma. Some particles in the bunch are focused and the beam density becomes enhanced. Other particles are defocused and therefore the beam density is locally reduced. Fig.5 gives the on-axis beam density profile (X=0) after 4.8 m propagation in plasma. It looks very similar to the self-modulated laser wakefield acceleration concept. In this regime, a long proton beam with bunch length much larger than the plasma wavelength generates a wake within its body, which modulates the bunch itself, leading to an unstable modulation of the whole bunch along the bunch propagation axis. The self-modulation of the long bunch generates a set of ultra-short bunches as beam particles in other regions are pushed to large transverse amplitude. The length of each bunch is around one half of the plasma wavelength. These bunches excite the plasma wake resonantly and the wakefield is used to accelerate both the protons and possibly also externally injected electrons. Fig.6 shows the longitudinal electric field excited by these modulated proton beams. The amplitude of the field approaches hundred of MeV/m. Fig.7 gives the energy variation for a half-cut SPS beam after 9.6 m propagation in plasma. It shows clearly the full density modulation effect. Some particles lose energy and some of them gain the energy. Fig.8 (a) (from 2D LCODE code) gives the on-axis electric field as a function of traveled distance for the SPS beam (realistic beam without compression) in plasmas of two different densities. It shows that in some circumstances, for example, with the smaller beam size and higher plasma density, the wakefield amplitude can reach values beyond 200 MV/m. Fig.8 (b) and (c) show the beam energy spectra for a low and high plasma density respectively. It can be seen that within tens of meters in plasma, some protons in the bunch lose 1 GeV and some protons gain 1 GeV. More simulation studies are currently ongoing, and optimal parameter regions will be determined for the first demonstration experiment.

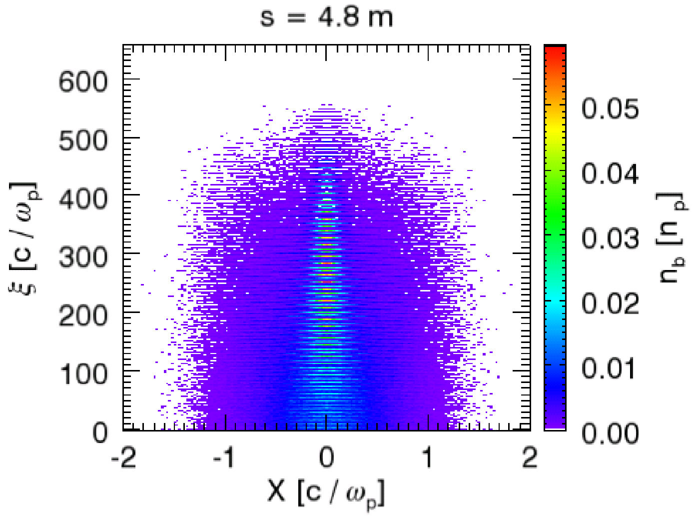

FIGURE 4. Beam density modulation after 4.8 m propagation in plasma.

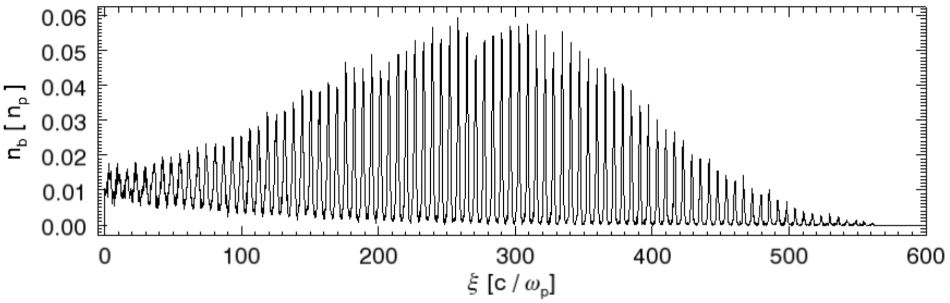

FIGURE 5. On-axis (X = 0) beam density profile after 4.8 m propagation in plasma.

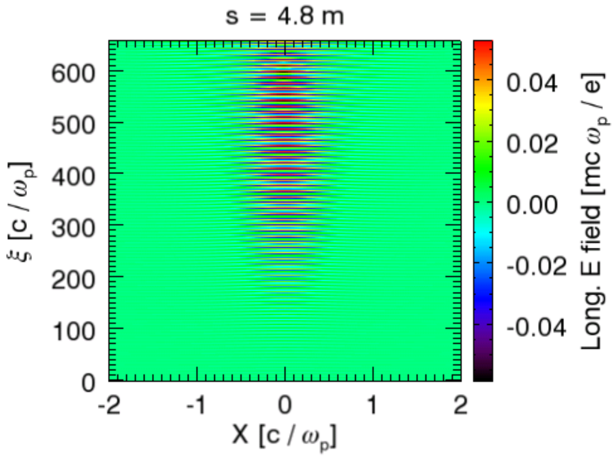

FIGURE 6. Longitudinal electric field (normalized to the wave breaking field) after 4.8 m propagation in plasma.

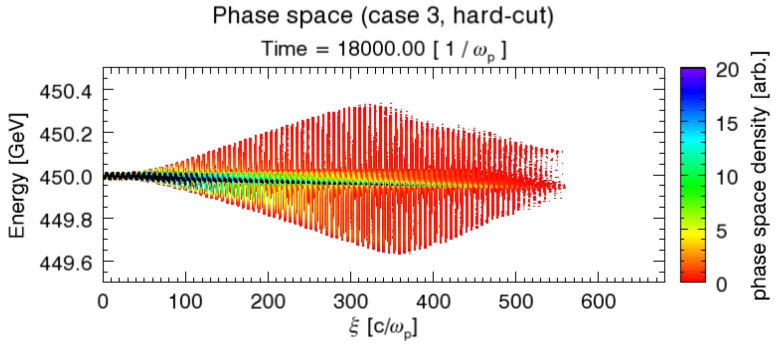

FIGURE 7. Energy variation for a half-cut SPS beam after 9.6 m propagation in plasma.

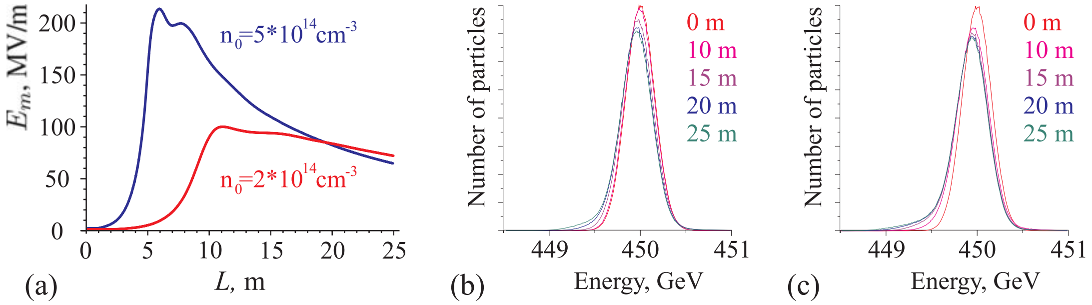

FIGURE 8. (a) Maximum on-axis electric field as a function of travel distance for the SPS beam in a plasma of two different densities: (b) and (c) beam energy spectra for low and high plasma density cases.

PROTON BUNCH COMPRESSION

As mentioned above, the linear theory of PWFA prefers short driver for high amplitude plasma wakefield excitation. For the first demonstration experiment, we will not compress the proton bunch from the SPS. However, for future experiments, bunch compressors that reduce the bunch length to sub-millimeter scale will be considered in order to obtain a more stable and controllable plasma wakefield for electron beam acceleration. As we know, the current SPS can only provide proton bunches with an rms bunch length of 12 cm or higher. We need to explore how to compress the proton bunch within the available space [13]. A test magnetic bunch compressor has been designed for simulation purposes. It includes RF cavities to provide an energy chirp along the bunch, followed by a dispersive beam line for path modulation. The length of the bunch compressor design is around 580 meters. RF sections are assumed to operate at 720 MHz, with a gradient of 25 MV/m. The phase space of the beam before (horizontally flat) and after (sine-like) the bunch compressor is shown in Fig.9 (left). The data analysis shown in Fig.9 (centre) indicates that the bunch length after compression is about 0.004 m (RMS value). In this case, the final energy spread (right) is about 1.9×10^{-2}, and the compressed beam density is around 10 times higher. By using a higher frequency RF for the energy chirp, the length of bunch compressor can be reduced further.

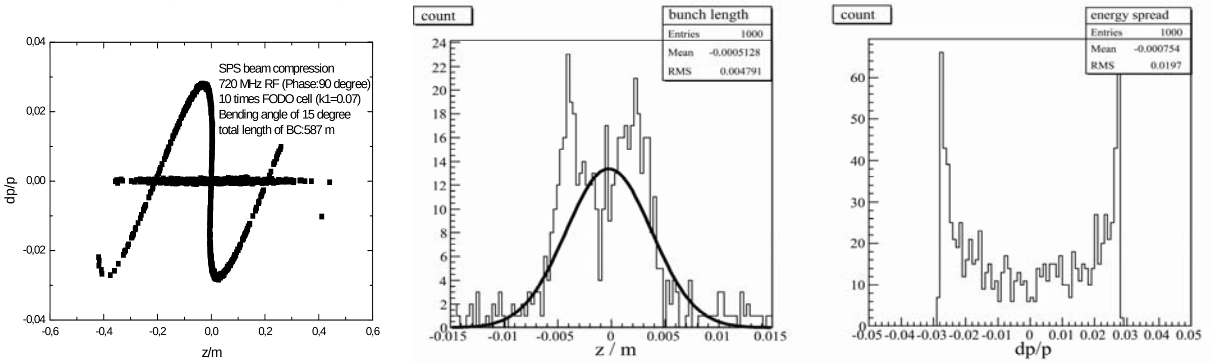

Figure 9. (left) Beam phase space before and after compression; Bunch length (centre) and energy spread (right) after compression.

CONCLUSION

Simulations have shown that a high energy, intense and short proton bunch can excite a large amplitude plasma wakefield and accelerate an electron bunch to the energy frontier in a single pass in a plasma. A demonstration experiment is under discussion at CERN to study the interactions between proton beams and plasmas. For the first experiment, simulation results show that with a long proton beam from CERN SPS as drive beam, a strong self-modulation occurs in the plasma channel. The associated wakefield amplitude is above 100 MV/m. In some optimal conditions, for example focusing the beam radius, increasing the background plasma density to some extent or shortening the bunch length, simulation shows that an even higher plasma wakefield could be excited. For the future experiments, the proton bunch compression will be considered, so as to achieve more stable and higher amplitude plasma wakefield for a witness electron bunch acceleration.

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