A PROPOSED EXPERIMENTAL TEST OF PROTON-DRIVEN PLASMA WAKEFIELD ACCELERATION BASED ON CERN SPS*

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Abstract

Proton-bunch driven plasma wakefield acceleration (PDPWA) has been proposed as an approach to accelerate electron beam to TeV energy regime in a single plasma section. An experimental test has recently proposed to demonstrate the capability of PDPWA by using proton beams from the CERN SPS. The layout of the experiment is introduced. Particle-in-cell simulation results based on the realistic beam parameters are presented.

INTRODUCTION

Plasma accelerators have made significant progress over the past decade. By employing an ultra-short, ultra-intense laser beam as a driver, the Laser Wakefield Acceleration (LWFA) has successfully demonstrated 1GeV electron beam acceleration in a 3.3 cm long plasma channel [1]. With the progress of laser technology and laser guiding techniques in plasma, it is foreseen to reach a few tens of GeV electron acceleration for high energy physics application. Meanwhile the electron-beam driven Plasma Wakefield Acceleration (PWFA) experiment, conducted at the Final Focus Test Beam (FFTB) at SLAC, has demonstrated the energy doubling of some fraction of the electrons of the SLC beam [2], which corresponds the wakefield amplitude in excess of 50 GeV/m, more than two orders of magnitude higher than the current radio-frequency technology. The next generation experiment foreseen at FACET will accelerate a separate witness electron bunch to high energy with narrow energy spread and preserved emittance [3]. However, to reach the Terascale energy regime, both the LWFA and PWFA have some technical challenges, for instance, synchronising and aligning of many accelerating modules may become difficult.

More recently, Caldwell et al. proposed a new scheme so-called 'proton-driven plasma wakefield acceleration' [4]. The underlying physics is similar to the other positively-charged particle beam driven plasma wakefield acceleration, e.g. using positron beam. However, the advantage of using the proton beam is that there are a few TeV proton synchrotron facilities around the world, e.g., Tevatron, HERA and the LHC. The energy stored in a typical TeV scale proton bunch is two or three orders magnitude higher than that of the highest energy electron beam from the SLC. The idea behind this PDPWA scheme is to transfer the energy from high energy protons to the plasma and then to the electrons. In this scenario, a proton beam is sent into a preformed plasma, the space charge of the bunch pulls the ambient plasma electrons in the vicinity of the beam. Because of the heavy mass of the plasma ions, they remain immobile and act to the electrons via Coulomb force. The plasma electrons oscillate and the wakefield is therefore formed. Particle-in-Cell (PIC) simulations show that a 1 TeV proton bunch with bunch population of 10^{11} and a length of 100 μm injected in a pre-ionized uniform plasma with density of 6×10^{14} cm^{-3} excites a wakefield amplitude of ~ 2 GeV/m. A 10 GeV electron bunch witnesses this accelerating field and reaches a final energy greater than 600 GeV in a single 450 m long plasma section [4]. This will potentially open a new research frontier to accelerate electron beam to TeV energy regime in a single accelerating stage. This exciting result has aroused great interests in the community. A wide collaboration has been formed to investigate the underlying physics and the key issues in realizing an experimental test of the proton-driven plasma wakefield acceleration.

SPS BEAM FOR EXPERIMENT

To demonstrate the capability of proton-driven plasma wakefield acceleration, we proposed an experimental test of this scheme based on the CERN Super Proton Synchrotron (SPS) accelerator [5]. They could provide the proton beam for our experiment. Currently there is a 600 m spare tunnel in the West Area of SPS. As injector

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for the LHC, the SPS can provide very intense and high energy proton beams for the LHC and other experiments. The maximum beam energy from SPS is 450 GeV, with a bunch population of 1.15×10^{11} and an rms bunch length of 12 cm. The transverse normalized emittance is around 3.5 mm·mrad and the energy spread is 3×10^{-4}. The SPS-LHC beam parameters are listed in Table 1.

Based on the linear theory of PWFA, a short drive beam with a bunch length a fraction of the plasma wavelength is needed to resonantly excite a large amplitude wakefield. However, compression of SPS beam from initially 12 cm to few hundreds microns (the same scale as the plasma wavelength at a density around 10^{15} cm^{-3}) seems difficult due to high beam energy [5]. The rigid beam requires large amounts of RF power to chirp the beam and large dipole magnets to provide a dispersive path. In order to keep the cost of the first experiment as modest as possible the beam will not be compressed in the first step, but the long beam will be directly sent into the plasma and we will study the interactions between the proton beams and the plasmas. Since the proton bunch is much longer compared to the plasma wavelength, a strong self-modulation will occur within the body of beam due to the transverse instability. Subject to this modulation effect, the long proton bunch splits into many ultra short beam slices, with periodicity of a plasma wavelength [6]. These beam slices will then excite the wakefield coherently and as a result, a large amplitude wakefield builds up. This very closely resembles the concept of the self-modulated laser wakefield acceleration (SM-LWFA), in which the laser wavelength is longer than the plasma wavelength [7].

In the first experiment, we anticipate demonstrating a 1 GeV energy gain for the SPS beam within 5 m plasma. Based upon the success of first round of experiments, we will further study acceleration of an electron bunch to 100 GeV in a 100 m plasma. The schematic of the beam line layout is shown in Fig.1. After being switched into the proposed experimental tunnel, the beam will follow a 400 m transfer line (in the future experiment this tunnel may also be used for beam manipulation, e.g. bunch length and density shaping) and reach the ground surface area. The beam properties like the beam size, beam angular spread, etc, will also be adjusted to well match with plasma parameters. We assume a 5-10 metre long homogenous plasma is produced by either a laser ionized metal vapor [8] or by a helicon plasma source. To witness the wakefield, we will inject an electron beam (in the future, we may also employ a compact laser plasma injector to produce high quality electrons), with an energy of tens of MeV (relativistic regime) before the plasma cell. Electrons injected at a right phase will sample the wakefield and reach the high energy while others will be decelerated. Exiting the plasma cell an energy spectrometer will be used to analyze the electron beam energy variation due to the plasma. The diagnostic equipment will be employed to characterize the beam properties (beam size, current, emittance, self modulation effect, electron/proton energy variation, etc.) with and without the plasma present. The spent proton beam will eventually be absorbed in the beam dump area.

SIMULATIONS BASED ON SPS BEAM

The parameters of nominal SPS beam (standard SPS-LHC beam for injection into LHC) and an optimum SPS beam (or SPS-Opt. beam for a single bunch operation in SPS) are listed in Table 1. The beam density for an optimum SPS is 2.5 times higher than that of the SPS-LHC beam. It is expected that the optimum SPS beam can therefore excite a larger electric field in the plasma. All the simulations are based on these two sets of SPS beam parameters. Various PIC and hybrid codes have been used to simulate the interactions between the SPS beams and the plasmas. Most results have been compared and benchmarked and found to be in good agreement with each other. Fig. 2 shows (from QuickPIC code [9]) the full SPS-LHC beam density distribution (normalized to the plasma density in the right color bar) after 10 m plasma with a density of 10^{14} cm^{-3}. Here ξ ($\xi = ct-z$) denotes the beam propagation direction (downwards along ξ axis) with $\xi = 0$ in the middle of the bunch and X denotes the horizontal direction. It is clearly seen that the beam density becomes fully modulated after 10 m plasma. Some particles in the bunch (in the focusing phase of the wake) are focused and the beam density becomes denser. Other particles (in the defocusing phase of the wake) are defocused and scattered transversely leading to the lower beam density regions. Fig.3 shows the longitudinal electric field (normalized to the wavebreaking field in the right colour bar) excited by a full SPS-LHC beam at 10 m plasma. It also shows that the field amplitude ~100 MeV/m can be achieved at plasma density of 10^{14} cm^{-3}.

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

	SPS-LHC	**SPS-Opt.**
Beam energy [GeV]	450	450
Bunch population [10^{11}]	1.15	3.0
Beam radius [μm]	200	200
Angular spread [mrad]	0.04	0.04
Normalized emittance [μm]	3.5	3.5
Bunch length [cm]	12	12.4
Energy spread [%]	0.03	0.03

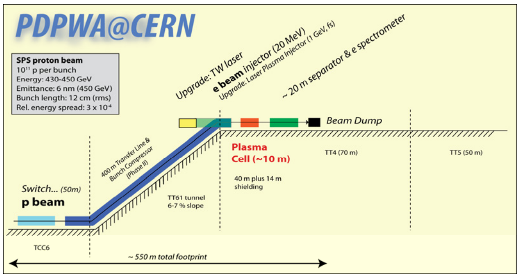

Figure 1: Beam-line layout for PDPWA experiment.

More recently, we performed 2D cylindrically symmetric OSIRIS simulations [10] and compared the half-cut SPS-LHC beam and a half-cut SPS-Opt. beam (the purpose of using a half-cut beam is to introduce the seeding instability as early as possible) driven plasma wakefield amplitude with respect to the propagation distance. Fig. 4 shows that with the plasma density of 7×10^{14} cm^{-3}, the maximum longitudinal electric field driven by SPS-LHC beam is beyond 500 MeV/m after 6 m in plasma. For SPS optimum beam, the wakefield amplitude is over 1.5 GeV/m after 5 m in the plasma.

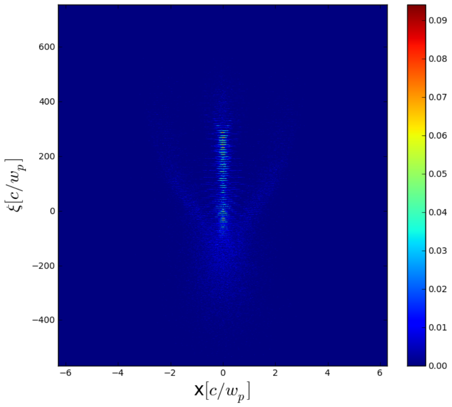

Figure 2: Beam density distribution at 10 m plasma.

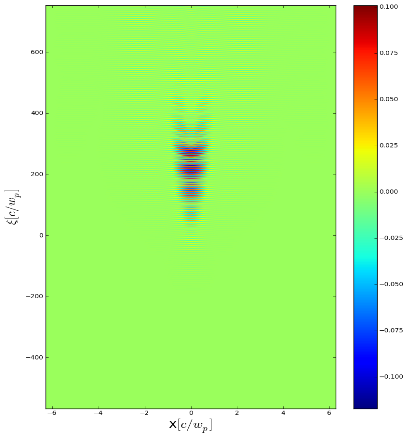

Figure 3: Longitudinal electric field at 10 m plasma.

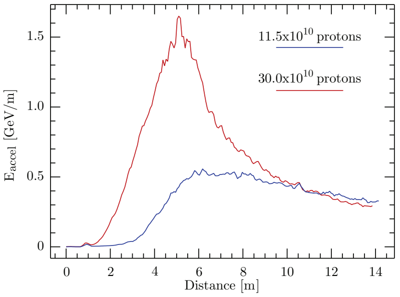

Figure 4: The maximum longitudinal electric fields for SPS-LHC beam and SPS-Opt. beam *vs*. travelled distance.

ELECTRON INJECTION

Based on previous study, the energy change of the SPS proton beam in a 10 m plasma (with plasma density of 10^{14} cm^{-3}) is around 1-2 GeV, which is not significant compared to the initial beam energy and therefore is difficult to be observed in the experiment. We therefore plan to inject an external electron beam for diagnostic of the wakefield (as shown in Fig. 1). We have performed a 2D cylindrically symmetric simulation using OSIRIS to check the electron acceleration in the wakefield driven by the self-modulated proton bunch. The result is shown in Fig.5. The injected electron beam energy is 10 MeV which is in the relativistic regime. They co-propagate with the proton beam and trace the phase of wakefield and gain energy from the wakefield. The simulation shows that after 10 meter long plasma (with plasma density of 7×10^{14} cm^{-3}), the electron gains energy greater than 0.5 GeV (blue curve) if the nominal SPS-LHC beam is used. For the SPS optimum parameters, the maximum energy of electron beam is beyond 2.0 GeV in a 10 m plasma (red curve). We expect that more energy gain can be achieved by optimizing the electron beam and plasma parameters (beam energy, beam charge, emittance, and plasma density, etc.) and by controlling of the phase of the wakefield.

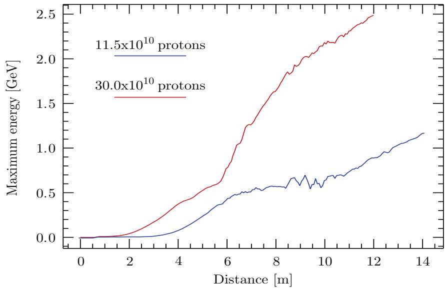

Figure 5: Maximum energy of the externally injected electrons as function of travelled distance.

CONCLUSION

We introduce a proposed experimental study of proton-driven plasma wakefield acceleration. By using the SPS beam as the driver, PIC simulation shows that we could achieve the accelerating gradient of several hundreds MeV/m. By using a higher plasma density, 1 GeV/m electric field can be achieved. For the SPS optimum beam, the wakefield is even higher. An externally injected relativistic electron beam can surf the wakefield and gain energy around 1~2 GeV in a 10 m long plasma cell for the SPS beam driven plasma wakefield acceleration.

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