PRELIMINARY STUDY OF PROTON DRIVEN PLASMA WAKEFIELD ACCELERATION

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Abstract

The idea of proton bunch driven plasma wakefield acceleration was recently proposed. The motivation is to use an existing high energy proton beam to drive a large amplitude electric field, and then accelerate a trailing electron bunch to energies beyond 500 GeV. Simulation results of the plasma wakefield production and acceleration process using a hybrid PIC code are given in this paper. In order to get a high accelerating field, the proton bunches have to be extremely small. A preliminary investigation on the production of short proton bunches is also presented.

INTRODUCTION

High energy particle accelerators are the fundamental tools used to discover new elementary particles and new phenomena. However, the costs of these accelerators at the energy frontier have already reached a level that led to slow down in the constructions of such high energy accelerators in recent decades. The cost of the recently completed Large Hadron Collider (LHC) at CERN and the proposed International Linear Collider (ILC) makes this trend clear.

The accelerating gradient is one of the crucial parameters affecting the design, construction and cost of the next generation linear accelerator - the ILC. For a specified final energy, the gradient sets the length of the accelerator. The acceleration gradient in conventional accelerators is limited to 20~100 MeV/m due to material breakdown. Plasmas, because they are already in an ionized state, can sustain very large electric fields that are several orders of magnitude higher than those in conventional accelerating structures. Therefore, plasma wakefield acceleration holds the promise to reduce the size of accelerators significantly and therefore lower the price tag of the future high energy linear colliders.

From the famous 1979 paper of Tajima and Dawson to nowadays [1], the field of novel accelerator concepts has achieved many successes. Wakefields in plasmas can be driven by either an intense laser beam (LWFA) or by a short electron beam (PWFA). In the LWFA it is the radiation pressure of the laser pulse, whereas in the PWFA case it is the space charge force of the electron beam that expels the plasma electrons. Given the large

mass of plasma ions, they are nearly immobile. The plasma electrons are predominantly blown out radially but they are attracted back toward the back of the laser beam or electron beam, due to the space charge attractive force of the plasma ions, where they overshoot the beam axis and set up a wakefield oscillation. So far, both laser driven and electron beam driven plasma wakefields have demonstrated controllable acceleration gradients of the order of 50 GeV/m [2,3].

PROTON DRIVEN PLASMA WAKEFIELD

Generally speaking, the plasma accelerator is an energy transformer. The plasma itself cannot produce net energy to accelerate particles. However it is a good medium to transfer the energy from a driver to a witness bunch. For longitudinally symmetric bunches, the transformer ratio (ratio of electric field seen by the witness particles to that seen by the drive particles) is limited to 2 [4]. That is to say, when the drive and witness beam start with the same energy, the drive beam could lose all of its energy, and in return the witness beam could triple its energy.

It is not possible to get very high electron or positron energies from circular machines due to the significant synchrotron radiation losses at high energy. The highest energy achieved so far in a conventional linear collider was the 50 GeV electrons and positrons generated at SLAC. If one could triple the beam energy, the maximum output beam energy would reach 150 GeV. This energy is still below the energy frontier that the high energy physics community is interested in. On the other hand, circular accelerators can bring massive particles such as protons, antiprotons and ions up to multi-TeV energies since their energy loss via synchrotron radiation is small (the energy loss due to synchrotron radiation inversely scales as the fourth order of the particle mass). For example, the Tevatron in FNAL can produce nearly 1 TeV proton beam, and the LHC at CERN will produce a proton beam of 7 TeV. Therefore, our idea is to extract the energy from these existing proton beams through a plasma wakefield and use it to accelerate electron beams to high energies [5]. Assuming that the energy loss of the drive beam is equal to the energy gain of the witness beam, it is expected that a 1 TeV or greater electron or positron beam can be generated. The simulations results in the following section support this novel idea, to a certain extent.

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SIMULATION RESULTS

The scheme of proton-driven plasma wakefield acceleration is given in Fig. 1. A high density proton bunch propagates through the plasma and excites the plasma electrons into motion. A plasma of the required density can be produced either by tunnel ionization of a neutral gas with a high intensity laser pulse or by field-ionization from the intense high energy beam.

The acceleration over hundreds of meters of plasma has been simulated using a quasi-static hybrid code LCODE [6]. The beam parameters in the simulation are listed in Table 1. A proton bunch with a beam energy of 1 TeV, a bunch length of 100 µm and a bunch intensity of 1e11 is used to drive a plasma wave. The injected 10 GeV electron bunch feels this wave and gains energy. Fig.1 describes the plasma channel arrangement, in which a thin tube containing Lithium gas is surrounded by quadrupole magnets with alternating polarity. The blow-up shows the bubble created by the proton bunch. The electron bunch undergoing acceleration is located at the back of the bubble. Fig. 2 shows the plasma wave generated by the proton driver. The rightmost region of high electron density in frames of b) and d) results from plasma electrons being 'sucked-in' by the proton bunch. The electrons then continue to move across the beam axis and create a depletion region in analogy to the blowout region seen in the case of the electron driver. The witness electron bunch is placed on the left edge of the first bubble, where the longitudinal fields are strongest. It can be seen that the maximum accelerating field is about 3 GeV/m as shown in Fig. 2.e). The electric field and electron density from a loaded plasma wave are shown in Fig. 2 c)-d). The maximum accelerating field is about 1.7 GeV/m and is nearly constant over the witness bunch. Fig. 3 a)-d) shows snapshots of the particle phase space (energy versus distance from the front of the proton bunch) at several locations along the plasma channel. Further down the channel, it is seen that the tail of the proton bunch loses significant amounts of energy, while the electron bunch picks up energy. Fig.3 e)-h) shows the energy spectra of the driver and of the witness bunch at different locations along the plasma channel.

The mean energy and energy spread of the electron bunch as a function of the distance along the channel are shown in Fig.4. It shows that the electron bunch reaches a mean energy of 0.62 TeV per electron after 450 m of acceleration. The final energy spread of electrons is about 1% at the highest energy. The overall energy conversion efficiency from driver to the witness beam is nearly 10 %.
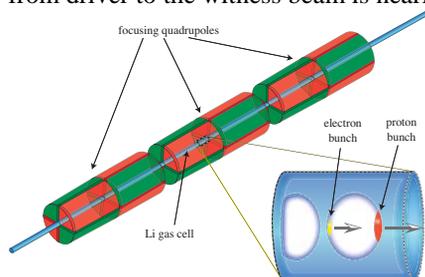
Figure 1: Schematics of plasma wakefield accelerating structure.

Table 1: Parameters in the Simulation

	Symbol	Value
Drive Beam		
Protons in drive bunch[10^{11}]	N_p	1
Proton energy [TeV]	E_p	1
Initial proton momentum spread	σ_p/p	0.1
Initial longitudinal spread [µm]	σ_z	100
Initial angular spread [mrad]	σ_θ	0.03
Initial bunch transverse size [mm]	$\sigma_{X,Y}$	0.4
Witness Beam		
Electrons in witness bunch[10^{10}]	N_e	1.5
Energy of electrons [GeV]	E_e	10
Plasma Parameters		
Free electron density [cm^{-3}]	n_p	6×10^{14}
Plasma wavelength [mm]	λ_p	1.35
External Field		
Magnetic field gradient [T/m]		1000
Magnetic length [m]		0.7
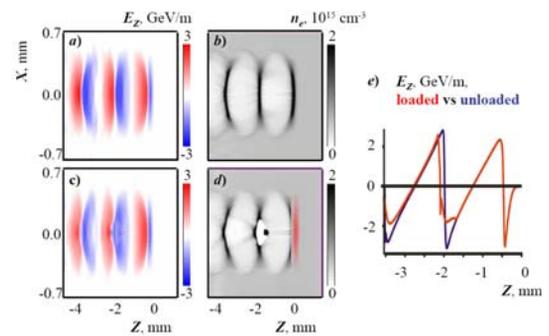
Figure 2: Plasma wakefield driven by a proton bunch.
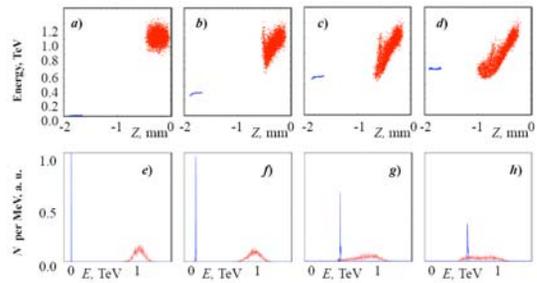
Figure 3: Snapshot of the longitudinal phase space of the driver and the witness beam.
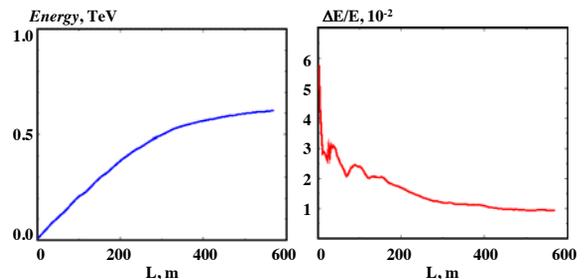
Figure 4: Mean energy and energy spread of the witness beam as a function of the acceleration distance.

SHORT PROTON BUNCH PRODUCTION

The simulation results indicate that a proton bunch can be used to accelerate an electron bunch to high energies. Now one hurdle needs to be overcome is the generation of short proton bunches. The definition of a short bunch here is a bunch length of 100 μm. However, the current circular proton accelerators use bunches which are typically several tens of centimeters in length. For example the bunch length in the Tevatron is 50 cm and the designed bunch length in the LHC is 7.55 cm. The reason the proton bunches are long is that collider designers strive for a higher luminosity which scales as the beam charge. One limiting factor is a limit on beam current which scales as the charge divided by the bunch length. Magnetic bunch compression (BC) is an effective way to get a short bunch. We investigate this scheme in detail.

A magnetic compressor includes an RF system introducing an energy chirp (energy modulation) within a bunch followed by a dispersive path for path modulation. Given the limitations on the current RF technology, it assumes that the LHC ring can compress the proton bunch by a factor a 7.55 and then this 1 cm proton bunch gets further compressed through the BC we designed. The parameters of the beam and the BC are listed in Table 2.

Table 2: Parameters of the Beam and the BC	
	Value
Bunch charge	10^{11}
Proton energy [TeV]	1
Initial energy spread [%]	0.01
Initial bunch length [cm]	1.0
Final bunch length [μm]	165
RF frequency [MHz]	704.4
Average gradient of RF [MV/m]	25
Required RF voltage [MV]	65,000
RF phase [degree]	-102
Compression ratio	~60
Momentum compaction (MC) [m]	-1.0
Second order of MC [m]	1.5
Bending angle of dipole [rad.]	0.05
Length of dipole [m]	14.3
Drift space between dipoles [m]	190.6
Total BC length [m]	4131
Final beam energy [GeV]	986.5
Final energy spread [%]	0.93

MAD is used to simulate the beam dynamics in the BC [7]. An initial bunch with a Gaussian distribution is injected into the system. 1000 particles are tracked in the simulation. The final phase space of the beam is recorded. Fig.5 a) shows the initial beam phase space in the longitudinal direction. Fig.5 b) gives the beam phase space after the BC. It can be easily seen that the bunch gets compressed and its relative energy spread increases correspondingly. Fig.6 compares the phase space of the initial beam and the final beam. It shows that the final beam becomes upright after the BC. Further analysis of the final beam is shown in Fig. 7. The left one is the bunch length and the right one is the energy spread. A Gaussian fit gives a one sigma bunch length of 165 μm and the relative energy spread of 9.26e-3. If the proton

bunch gets further accelerated after the BC, its length can be reduced further. Attempts are still ongoing to further reduce the bunch length based on this scheme.
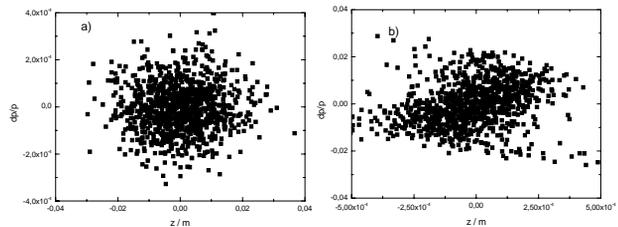
Figure 5: Beam phase space before BC and after BC.
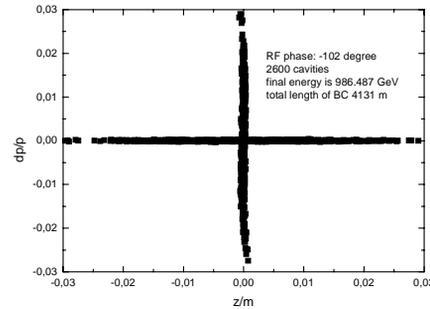
Figure 6: Beam rotation after BC.
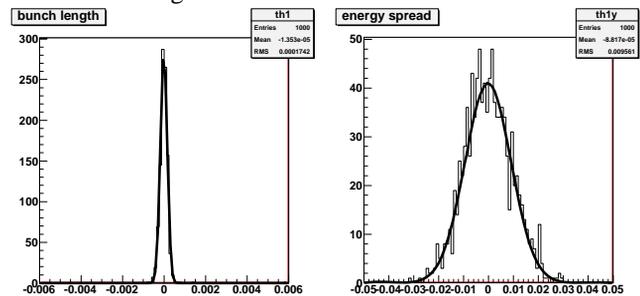
Figure 7: (left) bunch length after the magnetic chicane; (right) energy spread after the bunch compressor.

SUMMARY

A short, intense high energy proton bunch can be used to drive a plasma wakefield. An electron bunch injected in the right phase can be accelerated to high energies using this wake. The simulation results discussed here confirm this idea. In order to get a short proton bunch, a magnetic compressor was investigated and the simulation results show that short bunches can be achieved with magnetic bunch compression. The short proton bunch can be used to drive the plasma wakefield and therefore be used to accelerate electrons to the energy frontiers in one stage.

REFERENCES

[1] T. Tajima, J. Dawson, Phys. Rev. Lett. **43**, 267 (1979).

[2] W. P. Leemans, et al., Nature Physics **2**, 696 (2006).

[3] I. Blumenfeld, et al., Nature, **445**,741 (2007).

[4] R. Ruth, et al., Part. Accel. **17**, 171 (1985).

[5] A. Caldwell, K. Lotov, A. Pukhov and F. Simon, Nature Physics, DOI:10.1038/NPHYS1248(2009).

[6] K. V. Lotov, PRST-AB **6**, 061301 (2003).

[7] H. Grote, et al., CERN/SL/90-13 (AP).