A PROPOSAL FOR A 1 GeV PLASMA-WAKEFIELD ACCELERATION EXPERIMENT AT SLAC[1]

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Abstract

A plasma-based wakefield acceleration (PWFA) experiment is proposed that will accelerate parts of an SLC bunch by up to 1 GeV/m over a length of 1 m. A single SLC bunch is used to both induce wakefields in the one meter long plasma and to witness the resulting beam acceleration. The proposed experiment will explore and further develop the techniques that are needed to apply high-gradient plasma wakefield acceleration to large scale accelerators. The one meter length of the experiment is about two orders of magnitude larger than other high gradient PWFA experiments and the 1 GeV/m accelerating gradient is roughly ten times larger than that achieved with conventional metallic structures. Using existing SLAC facilities, the proposed experiment will allow the study of high gradient acceleration at the forefront of advanced accelerator research.

I INTRODUCTION

The energies of most interest for high energy physics today have reached the multi-TeV level. Linear colliders offer the only possibility to access this energy regime with e+e- collisions. Practical limitations on the size and the cost of linear colliders can only be overcome if the acceleration per unit length is significantly increased. By replacing the metallic walls of conventional structures with "plasma-walls" many limitations are avoided and very high gradients can be achieved. A recent laser-driven plasma wakefield acceleration (PWFA) experiment has measured an accelerating gradient of 100 GeV/m[2].

Although plasma-based experiments have shown impressive advances in their accelerating gradients, they are quite short, extending over only a few mm. This proposal aims at demonstrating high gradient acceleration in a 1 m long plasma cell. Plasma modules of this length would be well suited for building a future linear collider. The intended use of the existing SLAC linac for the proposed experiment limits the achievable gradient to about 1 GeV/m. Though not as high as achieved by other plasma-based experiments, this gradient is much larger than in any metallic structure. It would be the first time that plasma-based structures accelerate particles by 1 GeV.

The basic idea for the proposed experiment is to use a single SLC bunch to both excite the plasma wakefield (head of the bunch) and to witness the resulting acceleration (tail of the bunch). For many reasons, the SLC beam is the ideal driver for a plasma acceleration test. It has high energy; it is very stiff and is not subject to distortion or depletion over the length of the experimental section proposed here. In addition, neither the driving particles nor the accelerated particles will significantly phase slip over the length of the experimental section. All of these factors suggest the possibility for a clean test of plasma wakefield acceleration and the opportunity to make detailed comparisons to theoretical models.

The experiments proposed here will assess the viability of wakefield transformers based on beam-driven plasmas. By designing flexibility into the plasma source and/or drive bunch length, we will be able to explore some of the most important phenomena. Specifically, we can measure the transformer ratio (i.e. the decelerating and accelerating fields within the bunch), transverse focusing fields, and the dependence of the gradient on plasma density, bunch length, beam and plasma radius. Furthermore, increasing the plasma density or bunch length will enable a first test for electron hose instability[3]. A secondary benefit of the proposed experiment will be the opportunity to explore the new physics and technology issues associated with particle beam rather than laser drivers.

	PWFA	Standard SLC
Bunch intensity	3.5-4.0 10^{10} electrons	3.5-4.0 10^{10} electrons
Bunch length	0.6 mm	0.6-1.1 mm
Rate into the FFTB	10 Hz	1 - 120 Hz
$\gamma\varepsilon_x$ at LI02	-	30 mm-mrad
$\gamma\varepsilon_y$ at LI02	-	3.5 mm-mrad
Transv. rms jitter at LI30	< 50 μm	50% of spot size
$\gamma\varepsilon_x$ at IP-1	60 mm-mrad	45 mm-mrad
$\gamma\varepsilon_y$ at IP-1	15 mm-mrad	8 mm-mrad
σ_x at IP-1	< 100 μm	23 μm at 1.0 10^{10}
σ_y at IP-1	< 100 μm	37 μm at 1.0 10^{10}

Table 1. Comparison of beam parameters for the PWFA experiment and SLC standard performance at 46.6 GeV.

We propose to place a meter-long plasma of appropriate density in the path of the SLC beam at IP-1 of the FFTB[4, 5]. The beam parameters needed for the proposed experiment are routinely achieved during standard SLC operation (see Table 1). Most important are a beam intensity of between 3.5 to 4×10^{10} electrons and a suitable bunch length (σ_z = 0.6 mm) and shape. Normalized emittances and transverse beam jitter are not critical and can be significantly larger than the standard SLC values at 46.6 GeV.

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In order to minimize the impact and cost of the proposed experiment we plan for parasitic running at 10 Hz during PEPII[6] operation. PEPII will already accelerate the linac beams to 30 GeV for positron production. We avoid additional costs for the maintenance and operation of the RF in the last third of the linac by only requiring 2-3 sectors of acceleration downstream of the positron extraction point. The additional acceleration is needed in order to maintain efficient BNS damping and a small final energy spread. The beam energy in the FFTB will be 30 GeV. Minor modifications in the dumpline transport will allow safe operation of the FFTB with a high current 30 GeV beam.

The development of the different parts of the experiment is well under way. The proposed plasma cell has been built at UCLA and is presently being tested. The beam-induced plasma wakefields have been modeled at USC. The transport of the SLC beam into the FFTB, through the plasma cell and into the beam dump has been modeled carefully at SLAC. Finally, the appropriate beam diagnostic has been specified based on the extensive experience at SLAC and LBNL. We believe that all critical components needed for a successful experiment are in place.

The proposed experiments are envisioned to take place in stages. The first stage will simply place a meter-long plasma of appropriate density in the path of the SLC beam near the end of the FFTB. We expect the head of the bunch to be decelerated by about 0.2 GeV while tail particles are accelerated by up to 1 GeV. The resulting change in energy distribution, will be detected by a time-resolved energy measurement with a streak camera. The wakefield will be diagnosed in detail by subtracting the energy distribution signals with and without the plasma. The second set of experiments proposed here will vary the plasma density, plasma length, and/or beam bunch length to test scaling laws for wake amplitudes and electron hose instability.

We can envision a rich physics program of follow-on experiments not proposed here. Some of these include tests of beam shaping to demonstrate the possibility of high transformer ratios[7], the use of a separate witness beam with a variable delay to fully probe the wakefields[8], the guiding of laser beams with the SLC beam in a plasma over hundreds of Rayleigh lengths[9] and the outcoupling of the plasma wakes as a unique high-power 100 GHz source[10]. We also note that the peak accelerating gradient in the experiment is expected to increase from 1 GeV/m to 2.5 GeV/m if the SLC RMS bunch length can be reduced from 0.6 mm to 0.4 mm. The successful completion of the experiments proposed here will undoubtedly provide a major impetus to advanced accelerator research as well as contribute to fundamental understanding of plasma and beam physics.

In the remainder of this paper we present sample simulations supporting the design of a 1 GeV experiment, and briefly describe the plasma source and beam diagnostic.

II SIMULATIONS

Sample results of a 2-1/2D PIC simulation in cylindrical geometry using the code MAGIC are shown in Figure 1. The parameters correspond to the expected experimental beam and plasma parameters. In Figure 1 the plasma density is 2.1 x 10^{14} cm^{-3} and the beam distribution corresponds to the 36 MV compressor setting of the NRTL bunch compressor (ref.). Figure 1a shows the real space of the plasma electrons in which blowout and crossing of streamlines are clearly visible. Figure 1b is a snapshot of the longitudinal wakefield 6 mm into the plasma. The peak accelerating field is 1 GeV/m.

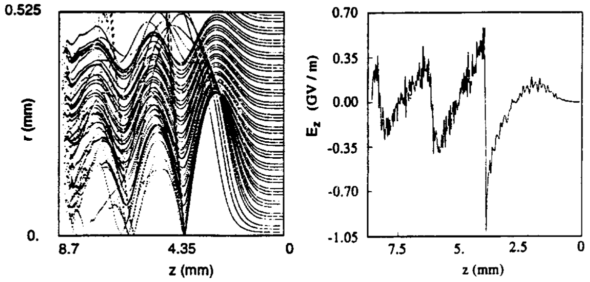

Figure 1. MAGIC PIC simulation of plasma wake for SLC beam (36 MV compressor setting) and plasma density 2.1 x 10^{14} cm^{-3}. (a) Real space r - z of plasma electrons; (b) axial electric field E_z.

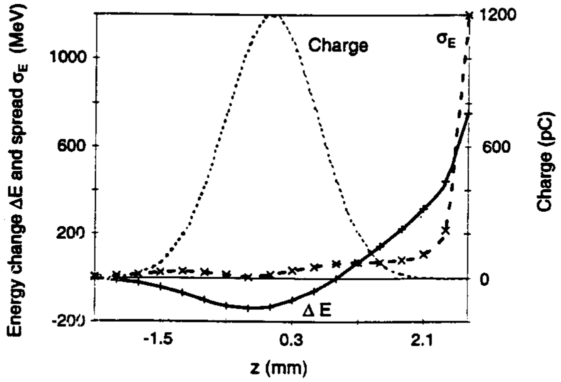

Figure 2. Simulated change of energy (solid line) and absolute energy spread (dashed line) of 1 ps slices along the bunch. This calculation was done for the same parameters as Figure 1 (plasma density of 2.1 x 10^{14} cm^{-3}). The two curves summarize the signature of plasma-wakefield acceleration as expected to be measured with the proposed diagnostic setup. The charge distribution is indicated by the dotted line.

We simulate the experimental observables in Fig. 2. Here we show the beam charge and the simulated beam energy change and beam energy spread in 1 ps intervals as they would be resolved by the streak camera in our transition radiation diagnostic. Even though some particles in the simulation gain over 1 GeV, the 1 ps window captures particles on either side of the acceleration peak. As a result, the energy change of the center of the last ps bin shown is roughly 800 MeV with a spread of 1200 MeV. Note that decelerating and accelerating fields within the bunch are well resolved with 1 ps diagnostic intervals.

As seen in the simulations in Figure 1a, the head of the drive beam rapidly blows out the plasma electrons leaving a positive ion column in the beam path. In this case, the transverse wake on the main body of the beam is particularly simple and takes the value given by a uniform positive cylinder of charge density n_o: $W_r = 2\pi\, n_o e^2 r$. This corresponds to an effective quadrupole focusing strength (in both planes) of

$$W_r / r \ = 960\pi \text{ Tesla/m x } (n_o/10^{14}\,\text{cm}^{-3})$$

The variation in the transverse focusing strength along the bunch in a PIC simulation is shown in Figure 3 (at r = 1σ = 75 μm). From this we see the time-dependent focusing rising at the head then asymptoting to the theoretical valueabove (6400 T/m for this case).

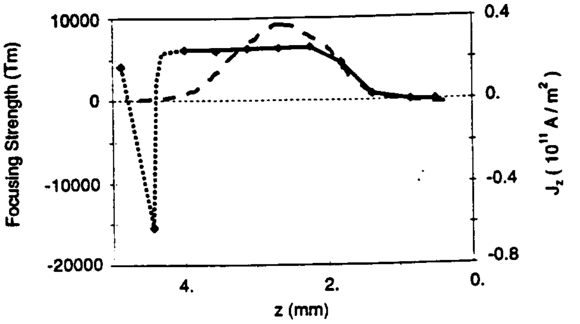

Figure 3. Focusing strength $-(E_r - B_q)/r$ (solid) and axial current J_z (dotted) vs. longitudinal position z for the PIC simulation of Figure 2. Note that there is an important defocusing peak in the far tail of the bunch. Its width is unconstrained within the binning used for this simulation. However, it occurs only after the peak accelerating field. The axial current shows the longitudinal bunch distribution.

The effect of the plasma focusing on the beam optics is shown in Fig. 4. It is seen that the spot sizes with and without the plasma cell are almost identical for certain plasma densities (corresponding to an integer number of betatron oscillations in a one-meter long plasma).

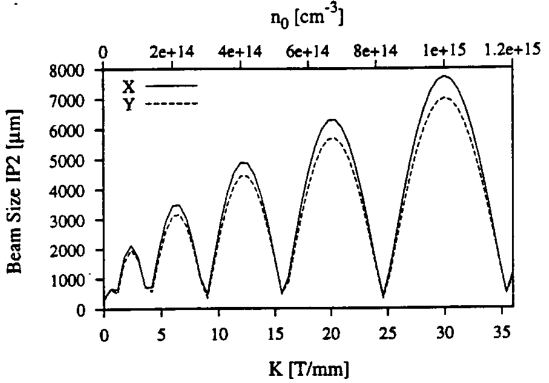

Figure 4. Calculated horizontal and vertical spot sizes at IP-2 *for a 1 ps slice* with 0.3% relative energy spread. The beam size is plotted as a function of plasma density.

III PLASMA SOURCE

The required plasma densities between 2 x 10^{14} and 1 x 10^{15} cm^{-3} can be obtained by photo-ionizing lithium atoms (E_i = 5.9 eV). The vapor pressure required for this range of densities is 10 to 30 mTorr, which can be obtained at temperatures between 550 and 600°C, Such meter long lithium vapors have been produced at these and far higher (Torr-range) pressures in heat pipes for atomic physics and spectroscopy experiments[11].

IV BEAM DIAGNOSTICS

We propose to use time resolved transition radiation to diagnose the beam. The energy of the transition radiation is calculated to be comparable to the synchrotron light intensity that was used for SLC measurements. The intrinsic resolution of the camera for SLC measurements is 0.85 psec, and taking into account chromatic effects the total resolution is σ = 1.0 psec.

The vertical deflection Δy due to an acceleration of 100 MeV is

$$\Delta y = D_y \frac{\Delta E}{E} = 0.33mm$$

which should be easily measurable. The energy change between the decelerated head and the accelerated tail of the bunch is shown in Figure 2 to be about 400 MeV for particles within 2.5 sigma of the longitudinal distribution. The maximum acceleration of 800 MeV for a 1 ps slice will show itself as a large offset (~2.5 mm) and a large vertical beam size (~4mm) due to the large induced energy spread (1.2 GeV).

It will be possible to measure the longitudinal wakefield along the bunch in detail. These measurements will enable direct comparisons to the plasma theory and simulations.

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