A Meter-Scale Plasma Wakefield Accelerator

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Abstract. Plasma wakefield accelerators (PWFA) have recently shown substantial progress, attaining accelerating fields of more than 30 GV/m. The goal of the present experiment is to show that such accelerating fields can be sustained over the scale of a meter, resulting in a total energy gain comparable to the entire SLAC linear accelerator. We also seek to determine which factors limit the length of the interaction and determine the maximum achievable energy.

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INTRODUCTION

Particle accelerators at the energy frontier, such as the Large Hadron Collider (LHC) and the planned International Linear Collider (ILC) will extend the energy frontier of particle physics into the TeV range. Considering the investments into these colliders and the time scales to their completion, it is important to explore alternative ways to accelerate particles. Plasma wakefield accelerators are particularly attractive because they support accelerating fields of 30 GV/m [1]. It is important to show that these fields can be sustained over a substantial length to achieve a significant energy gain.

The experiments are performed in the Final Focus Test Beam (FFTB) at Stanford Linear Accelerator Center (SLAC). The experimental setup has been upgraded from the one described in [1]: to accommodate the large energy spread expected after the plasma, three spectrometers with overlapping energy ranges have been installed. Figure 1 shows the layout of the beamline.

INCOMING ELECTRON BEAM

The linear accelerator provides an electron pulse with a charge of 2.9 nC and a particle energy of 42.2 GeV, which is compressed longitudinally to a minimum length of 12 μm and can reach a peak current of 20 kA. The compression process is sensitive to the phasing of the accelerating structures along the whole accelerator. This leads to some pulse-to-pulse fluctuations in the longitudinal bunch profile. It is important to measure these fluctuations because the field ionization, the formation of the plasma wake and the

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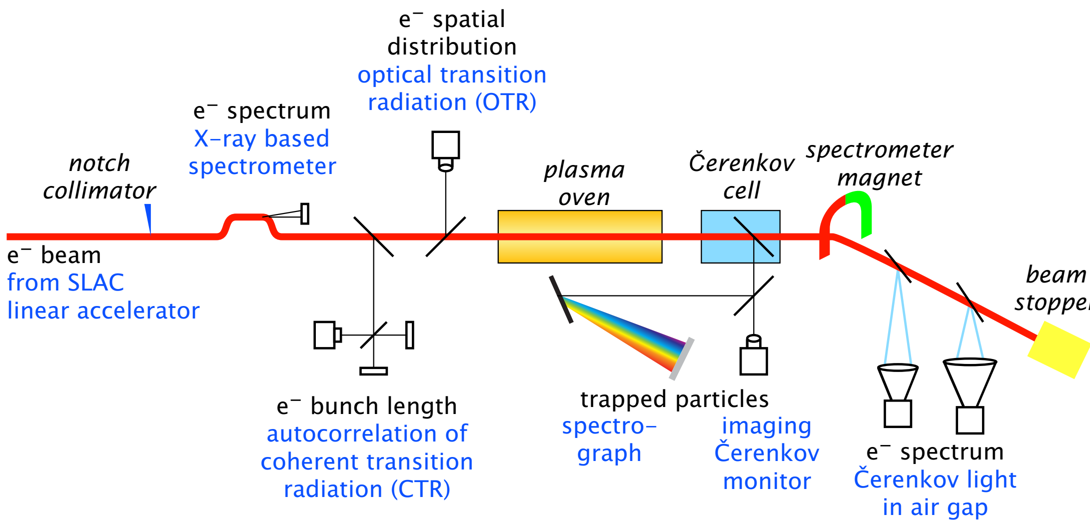

FIGURE 1. Experimental setup in the FFTB.

acceleration of particles in the tail of the bunch depend strongly on this profile. However, the profile of electron bunches of this length is extremely difficult to measure. Therefore, an indirect method is chosen, relying on a simulation of the (ζ, E) phase space (where ζ is the longitudinal coordinate in the bunch frame and E is the particle energy). The energy spectrum is measured in a horizontally dispersive region in the beginning of the FFTB beamline. A magnetic chicane creates a small vertical bump in the trajectory. The electrons then emit synchrotron radiation, which is detected by a Ce:YAG crystal that is imaged onto a CCD [2].

Simulations of the phase space evolution in the linear accelerator are performed using the code LiTrack [3]. We give the simulation input parameters (such as bunch charge or phase of the accelerating cavities) the freedom to vary within the uncertainty margin of the measured values. By adjusting these parameters such and optimizing the agreement between the simulated energy spectrum and the spectrum measured in the chicane, we can infer the full phase space from the simulations, and therefore the longitudinal bunch profile [1].

In addition to the measurement of the incoming energy spectrum, the total energy of coherent transition radiation (CTR) at a thin titanium foil intercepting the beam provides an estimate of the peak current [4]. Autocorrelation of this radiation confirms the bunch length that are deduced from the energy spectrum [5].

The transverse profile of the bunches is measured with optical transition radiation. The bunches are focused with quadrupole magnets to a spot with 10 μm radius at the plasma entrance.

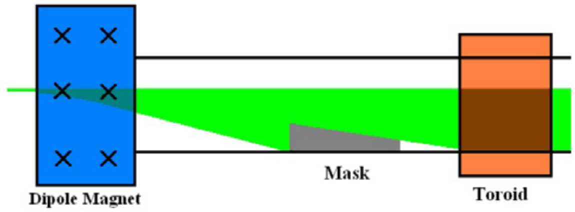

FIGURE 2. Low-energy spectrometer

PLASMA SOURCE

The plasma source is a heat-pipe oven, where a column of lithium vapor with a density of $2.7 \cdot 10^{23} \mathrm{m}^{-3}$ is confined by a helium buffer gas [6]. The incoming electron beam field-ionizes the lithium atoms and creates a uniform plasma channel. The length of the lithium vapor column can be varied by changing the number of heaters. Data has been recorded with a length of 85 cm and 113 cm FWHM. The plasma oven rests on a pneumatically actuated table and can be inserted and removed quickly.

ENERGY SPECTROMETERS

Three energy spectrometers are set up to characterize the particles exiting the plasma. The first one, shown in Figure 2, consists of a small dipole magnet, a mask and an integrating current monitor (toroid). By varying the magnetic field, cutoff energies between 10 and 200 MeV can be chosen. This is used to study trapped particles [7, 8].

The second energy spectrometer is used to detect particles between 60 MeV and 10 GeV. It consists of a dipole magnet with an integrated magnetic flux density of up to OIOIOI, followed by a helium-filled cell in which Čerenkov radiation is emitted. It has been observed that the emission of visible Čerenkov light is increased by four orders of magnitude when the plasma is inserted. This is attributed to a beam density variation on a femtosecond time scale, which would result in a coherent emission of optical Čerenkov radiation.

The energy distribution of particles with more than 6 GeV is measured using the third spectrometer, which consists of a dipole magnet that disperses the particles vertically (see Figure 3). Images of the dispersed bunches are recorded on a pulse-to-pulse basis. The dispersion can be closely approximated by a deflection in the center of the magnet:

$$\theta_1 = \frac{cq}{E} \int B \mathrm{d}L \tag{1}$$

where q is the charge and E is the energy of the particles. Due to the focusing force of the ion column, all particles in a bunch leave the plasma from a spot smaller than 10μm, which can be considered point-like for the present analysis. However, their exit angle can reach a value of several 100μrad, and a vertical exit angle could be mistaken for an energy change.

To differentiate between an exit angle at the plasma exit and a deflection by the magnet, the particle distribution is measured in two planes, 86 cm and 186 cm downstream

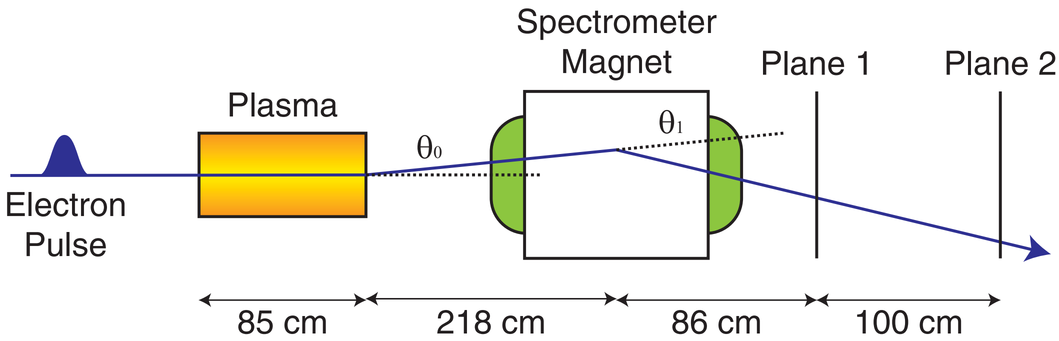

FIGURE 3. Two-plane spectrometer. To distinguish between a vertical deflection at the plasma exit and a deflection in the spectrometer magnet, the transverse distribution is measured in two planes.

of the center of the dipole. At each of these planes, the transverse profile is measured by imaging Čerenkov radiation emitted as the electrons pass through a 15 mm air gap established by two silicon wafers, positioned at an angle of 45° to the beam. Due to the emission angle of 24 mrad of Čerenkov radiation in air at a pressure of 100 kPa and the large transverse size of the bunch in the air gap, the radiation is emitted incoherently, and the light intensity is proportional to the number of particles. The second wafer acts as a mirror and deflects the Čerenkov light into a lens that images the origin of the light onto a cooled charge-coupled detector (CCD). The electrons pass the silicon wafers almost unperturbed.

For a given feature in the transverse distribution that can be observed in both planes, a system of equations can be set up that relates the offsets in the two planes to the angle at the plasma exit θ_0 and the deflection angle in the magnet θ_1:

$$y_1 = (L_0 + L_1)\theta_0 + L_1\theta_1 \tag{2}$$

$$y_2 = (L_0 + L_1 + L_2)\theta_0 + (L_1 + L_2)\theta_1 \tag{3}$$

This system of equations is solved for θ_0 and θ_1, the latter resulting with Eq. (1) in the energy of the particles in this feature.

The deflections were measured with respect to two reference points, given by a beam with the initial energy of 42.2 GeV and by an undeflected beam, determined with the plasma out and the magnet turned off. This determines a self-consistent integrated magnetic flux density $\int B\mathrm{d}L = 1.2\mathrm{Tm}$.

DATA ANALYSIS

A first analysis of the data shows that the plasma wake can be sustained up to a length of 85 cm. The detailed analysis is underway, and the results will be published shortly [9]. Furthermore, it has been found that plasma electrons are trapped by the plasma wake in the transition region between the helium buffer gas and the lithium vapor [7, 8].

REFERENCES

1. M.J. Hogan et al., "Multi-GeV energy gain in a plasma-wakefield accelerator," *Phys. Rev. Lett.* **95**, 054802 (2005). http://dx.doi.org/10.1103/PhysRevLett.95.054802
2. K.L.F Bane et al., "Measurements of longitudinal phase space in the SLC Linac," Technical report, Stanford Linear Accelerator Center Report No. SLAC-PUB-5255, 1990.
3. P. Emma and K. Bane, "LiTrack: A fast longitudinal phase space tracking code with graphical user interface," Proceedings of the 2005 Particle Accelerator Conference, 2005.
4. C. Barnes, *Longitudinal Phase Space Measurements and Application to Beam-Plasma Physics*, PhD thesis, Stanford University, 2005.
5. I. Blumenfeld, "Electron bunch length measurements in the e-167 plasma wakefield experiment," in *Proceedings of the Advanced Accelerator Concepts Workshop 2006*, 2006.
6. P. Muggli et al., "Photo-ionized lithium source for plasma accelerator applications," *IEEE Transactions on Plasma Science* **27**, 791 (1999).
7. N. Kirby, "Energy measurements of trapped electrons from a plasma wakefield accelerator," in *Proceedings of the Advanced Accelerator Concepts Workshop 2006*, 2006.
8. E. Oz et al., "Ionization induced electron trapping in ultra-relativistic plasma wakes," submitted for publication, 2006.
9. I. Blumenfeld et al., "Energy doubling of 42 GeV electrons in a meter scale plasma wakefield accelerator," submitted for publication, 2006.