Energy Measurements of Trapped Electrons from a Plasma Wakefield Accelerator

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Abstract. Recent electron beam driven plasma wakefield accelerator experiments carried out at SLAC indicate trapping of plasma electrons. More charge came out of than went into the plasma. Most of this extra charge had energies at or below the 10 MeV level. In addition, there were trapped electron streaks that extended from a few GeV to tens of GeV, and there were mono-energetic trapped electron bunches with tens of GeV in energy.

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INTRODUCTION

Figure 1 illustrates a plasma wakefield accelerator (PWFA). A neutral lithium vapor with a density of $2.7 \cdot 10^{23}$ m^{-3} was confined by a helium buffer gas in a heat-pipe oven [1]. An ultra-relativistic electron drive beam with $1.8 \cdot 10^{10}$ electrons, focused to a transverse spot size of 10 µm, and compressed longitudinally to a minimum of about 12 µm was sent through the neutral lithium vapor [2]. The electrons in the front of the bunch both field ionized the lithium vapor and drove out the plasma electrons [3]. The lithium ions then pull the plasma electrons back to the beam axis. This interaction set up longitudinal electric fields, which accelerated electrons in the back of the bunch [4]. When PWFA experiments started to produce longitudinal fields that were tens of GV/m, the drive beam's wakefield began to trap plasma electrons. The trapping of plasma electrons was apparent from the comparison of charge measuring toroids upstream and downstream of the plasma oven. There was as much as four times more charge coming out of than went into the plasma. Simulations indicate that helium electrons are trapped in the transition region between the helium buffer gas and the lithium vapor. Helium has a higher ionization potential than lithium so it is ionized at a different position in the wake, which allows the helium electrons to satisfy the condition for trapping [5].

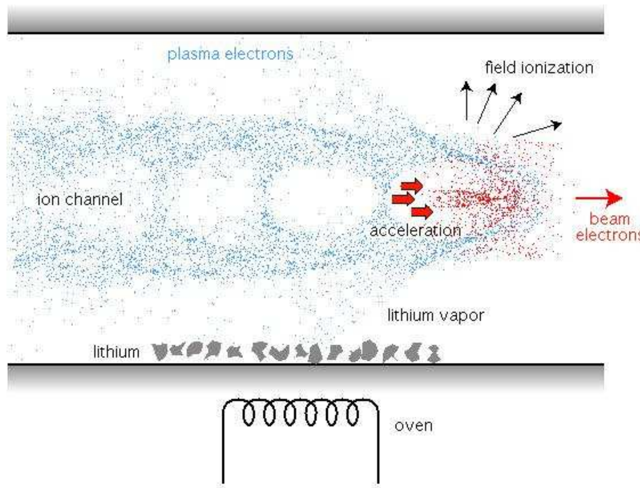

FIGURE 1. An illustration of a plasma wakefield accelerator.

It is important to understand what limitations electron trapping has on plasma wakefield acceleration; however, the trapped electrons have properties that make them interesting all on their own. There are indications that the trapped electrons had sub-micron features in a system with length scales of tens of microns or more. In addition, the trapped electrons had energies up to tens of GeV.

EXPERIMENTAL SETUP

Figure 2 shows pictures of our experimental setup. Compressed electron bunches were sent through the lithium heat-pipe oven. The beam charge was measured with toroids both upstream and downstream of the heat-pipe oven. Downstream of beam-plasma interaction there were three different energy spectrometers: a low energy spectrometer (10 - 200 MeV), a Cherenkov cell spectrometer (60 MeV – 10 GeV), and a high energy spectrometer (>2 GeV). Two of the spectrometers were based on deflections created in a small dipole, $\int B\cdot dl = 0.033$ Tm, and the other spectrometer was based on deflections created in a large dipole, $\int B\cdot dl = 1.2$ Tm.

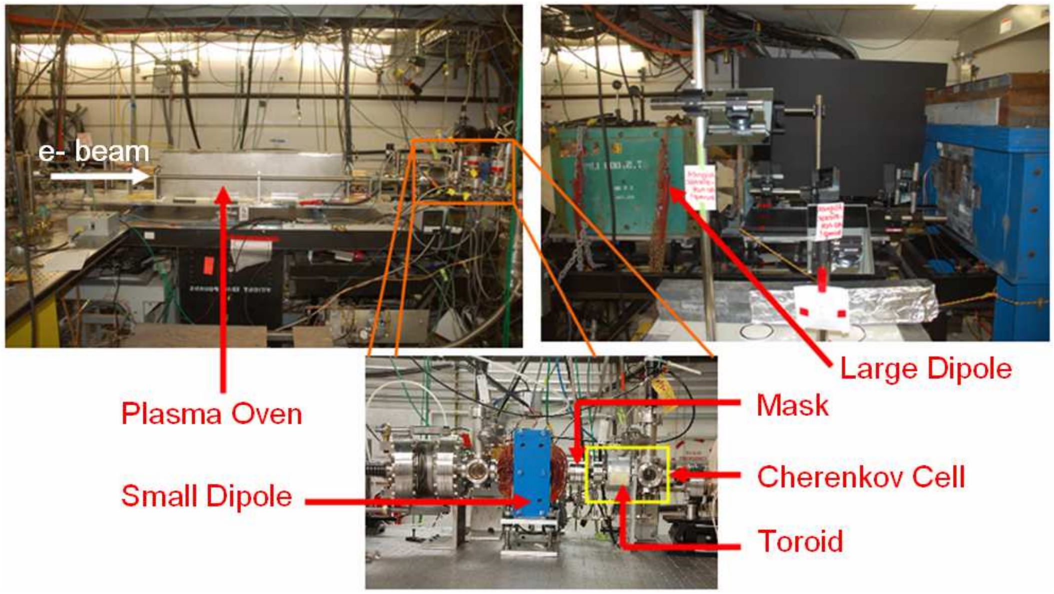

FIGURE 2. The experimental setup.

Low Energy Spectrometer

Figure 3 illustrates the low energy spectrometer, which had an energy range from 10 to 200 MeV. A small dipole, a mask, and a toroid were placed downstream of the plasma oven. The dispersion of the dipole magnet allowed the mask to collect electrons with momentum below a cutoff. By changing the magnetic field, the momentum cutoff was changed. By recording the amount of charge through the toroid versus the magnetic field, the amount of charge at low energies was measured.

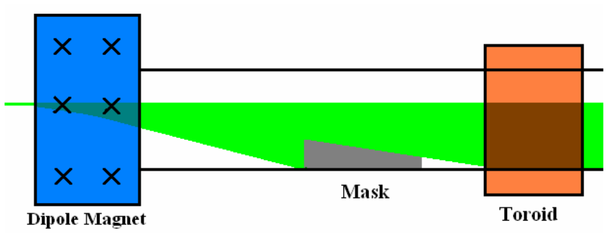

FIGURE 3. An illustration of the low energy spectrometer.

Figure 4 shows how the amount of extra charge pulled from the plasma varied with the momentum cutoff. The lithium vapor length was 30.5 cm. The drive beam had $1.8{\cdot}10^{10}$ electrons with an initial energy of 28.5 GeV. The extra charge had as much as $7{\cdot}10^{10}$ electrons; however, only had these high values for low momentum cutoff. The variation in the charge values at a fixed cutoff indicates the shot to shot variations of the experiment. These measurements show that most of the extra charge pulled from the plasma is at or below the 10 MeV level.

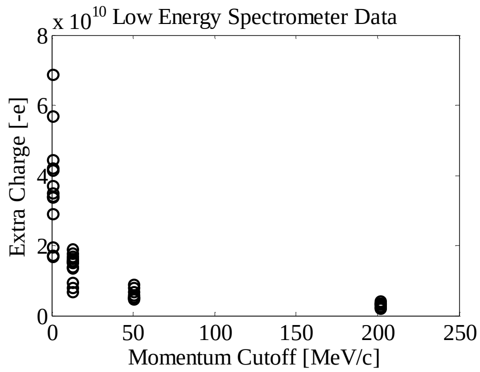

FIGURE 4. Typical low energy spectrometer data. This shows that most of the extra charge pulled from the plasma has energy at or below 10 MeV.

Cherenkov Cell Spectrometer

Figure 5a illustrates our Cherenkov cell spectrometer, which had an energy range from 60 MeV to 10 GeV. A gas cell was placed downstream of a small dipole. The cell was 20 cm long and filled with 1 atm. of helium corresponding to a Cherenkov angle of 8 mrad. A titanium foil was inserted inside the cell to reflect Cherenkov light off of the beam axis. The far-field of this light was imaged with an optical camera. Since, for a fixed momentum, the Cherenkov light was emitted with a delta function in angle, the electrons showed up as rings. The dispersion from the magnet made different energy electrons show up as rings with different displacements.

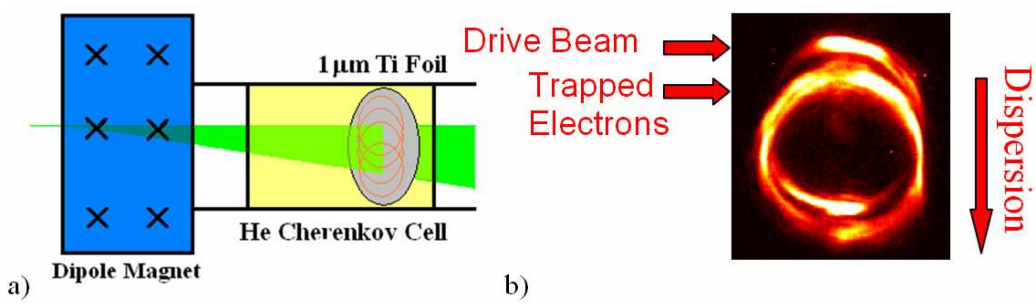

FIGURE 5. a) An illustration of the Cherenkov cell spectrometer. b) An example of dispersed Cherenkov rings (saturated color map).

This spectrometer was used for 13, 22.5, and 30.5 cm lithium vapor lengths. The drive beam's initial energy was 28.5 GeV. For about 50% of the shots in a data set there appeared two distinct rings. One ring was from the drive beam, and the second ring was from trapped electrons. Figure 5b shows an example of the dispersed rings with a saturated color map. The lack of azimuthal symmetry of the Cherenkov rings indicates a lack of azimuthal symmetry in the beams that produced the Cherenkov light. The energy of the second ring scaled linearly with plasma length. The mean of the second ring energy was 7.6 GeV for the 30.5 cm plasma. The energy scaling of the trapped electrons with plasma length is consistent with the hypothesis that some of these trapped electrons are picked up by ionization of the helium buffer gas at the entrance to the plasma.

The ring intensities were at least three orders of magnitude brighter than rings from incoherent emission. This meant the distribution of both the drive beam and the trapped electrons had a significant Fourier component at the optical wavelength along the direction of Cherenkov emission. Put in simpler terms, the drive beam and trapped electrons had sub-micron features. The characteristic length scales of the system are the drive beam dimensions and the plasma wavelength. The drive beam was focused to a transverse spot size of 10 µm and compressed longitudinally to a minimum of about 12 µm at the entrance of the plasma [2]. The plasma wavelength was on the order of 64 µm. Thus, the beam-plasma interaction produced sub-micron features in a system initially characterized by tens of microns.

High Energy Spectrometer

Figure 6 illustrates the high energy spectrometer, which had an energy range greater than 2 GeV. A large dipole and an air gap were placed downstream of the plasma. The displacement of the electrons was measured by imaging the Cherenkov light they produced in the air gap. This was part of the PWFA experiment's energy gain spectrometer [6]. The lithium vapor length was 85 cm, and the initial energy of the drive beam was 42 GeV. In addition to the typical signatures of energy gain and loss on the drive beam, there were narrow streaks and small bunches. These streaks and bunches had smaller transverse sizes than the drive beam, so they were not considered to be part of the drive beam. They were believed to be trapped electrons.

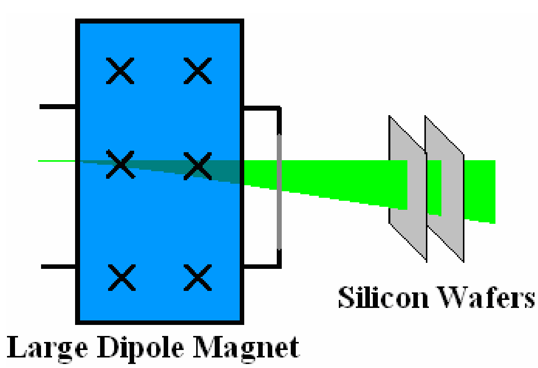

FIGURE 6. An illustration of the high energy spectrometer

In addition the smaller transverse sizes, there is other evidence that shows the streaks and bunches were trapped electrons. The system started with 42 GeV drive beam electrons and 0 GeV plasma electrons. The streaks and bunches showed up with energies up to 30 GeV, so they were either accelerated from 0 GeV or decelerated from 42 GeV. By noticing how the energy of these streaks changed with the amplitude of the accelerating field, their origin can be deduced.

Upstream of the plasma, coherent transition radiation (CTR) was collected from the drive beam [2]. This was used to monitor the amplitude of the accelerating field in the following way. Both CTR signal and accelerating field amplitude are inversely related to the drive beam bunch length, which was varied. Higher CTR signal, to first order, corresponded to stronger electric fields. If the streaks and bunches were originally part of the 42 GeV drive beam, then as the CTR signal increased their energy would move farther away from 42 GeV to lower energies; however, the energy of the streaks and bunches increased with higher CTR signal. This showed that they were not originally part of the drive beam but came from the plasma.

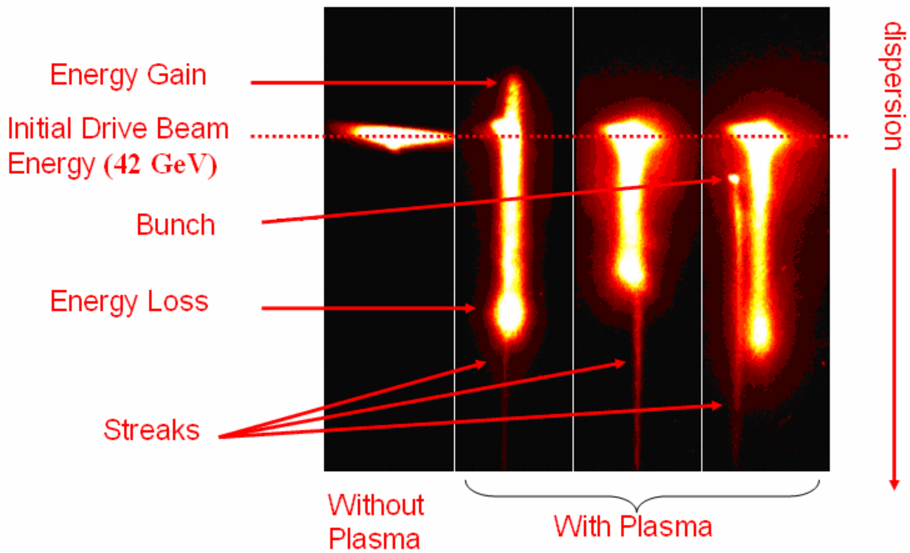

FIGURE 7. Example of the streaks and bunches that appeared on the high energy spectrometer (saturated color map).

Figure 7 shows some examples of the streaks and bunches with a saturated color map. By changing the magnetic field of the large dipole, the energy range of the spectrometer was changed. The streaks extend from tens of GeV to below 2 GeV, which was the lowest energy measurable. The electron densities of these streaks were from around 10^7 per GeV up to almost 10^9 per GeV. At the top of these streaks, frequently a mono-energetic bunch appeared. These bunches appear with around $3{\cdot}10^8$ electrons, energy spreads better than a few percent, and tens of GeV in energy.

CONCLUSION

More charge came out of than went into the PWFA. Most of the extra charge had energies at or below the 10 MeV level. In addition, there were trapped electron streaks that extended from a few GeV to tens of GeV, and there were mono-energetic trapped electrons that appeared with tens of GeV in energy.

One future trapped electron experiment will be to change the buffer gas from helium to neon. Since neon has a different ionization potential, the neon will be field ionized at a different position in the wake than the helium. The neon electrons would then be trapped a different positions in the wake than the helium electrons or may not even be trapped. This is a way to confirm the belief that the trapped electrons come from ionization of the buffer gas.

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