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ENERGY MEASUREMENT IN A PLASMA WAKEFIELD ACCELERATOR*

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Abstract

In the E-167 plasma wakefield acceleration experiment, electrons with an initial energy of $42\,\mathrm{GeV}$ are accelerated in a meter-scale lithium plasma. Particles are leaving plasma with a large energy spread. To determine the spectrum of the accelerated particles, a two-plane spectrometer has been set up.

INTRODUCTION

In the E-167 plasma wakefield acceleration (PWFA) experiment at SLAC, a $42\,\mathrm{GeV}$ electron beam was sent into an $85\,\mathrm{cm}$ long lithium vapor with a density of $2.7 \cdot 10^{23}\,\mathrm{m}^{-3}$. The Coulomb field of this beam ionizes the lithium and drives the newly created electrons away from the beam axis, creating a plasma wake. The present experiment operates in the so-called blowout regime, where plasma electrons are expelled completely from a bubble surrounding the beam. The longitudinal electric fields of the wake decelerate electrons in the front of the bubble and accelerate electrons in the back. In an actual plasma accelerator, one would position two bunches, a drive bunch in the front of the bubble, and a witness bunch in the back. Such a configuration could not be produced in the SLAC Linac. In its place, a single bunch with a $50\,\mathrm{fs}$ long core that sits on a much longer pedestal is sent into the plasma. As a result, the electrons acquire a continuous energy spectrum that maps the accelerating fields onto the longitudinal axis.

Previous experiments [1] used an imaging electron spectrometer, covering an energy range limited by the transport optics to the detection plane. For the present experiment, a very broad energy spread was expected, and several devices have been set up to determine the electron energy spectrum. In this article, we describe a two-plane spectrometer, which has been used to show the energy doubling of $42\,\mathrm{GeV}$ electrons [2]. It is possible to use only the first plane of this spectrometer to detect those electrons that lose energy by generating the wake, down to a final energy of $10.3\,\mathrm{GeV}$ [3]. This instrument is complemented by spectrometers for the ranges from $0 - 200\,\mathrm{MeV}$ and $60\,\mathrm{MeV} - 10\,\mathrm{GeV}$ [4].

ENERGY SPECTROMETER

The particles exiting the plasma are deflected by a dipole magnet with an integrated magnetic flux density of $\int B\mathrm{d}L = 1.2\,\mathrm{Tm}$, whose center is located at a position $L_0 = 218\,\mathrm{cm}$ after the plasma exit. The magnet disperses the electrons vertically according to their momentum p. The dispersion can be closely approximated by a single deflection in the center of the magnet, $\theta_1 = e \int B\mathrm{d}L/p = 8.6\,\mathrm{mrad}$. The integrated magnetic flux density has been determined in situ by measuring the dispersion of the beam in the absence of the plasma. Directly after the magnet, the beam exits the vacuum chamber through a stainless steel window.The experimental setup is shown in Figure 1.

The plasma is able to impose significant transverse forces on the electrons. While being transmitted through the ion column of the plasma wake, focusing forces keep the electrons close to the axis. All particles leave the plasma from a spot smaller than $10\,\mu\mathrm{m}$, which can be considered point-like. Transverse forces on the beam at the exit of the plasma can result in a deflection of the particles. It is therefore important to differentiate between a vertical

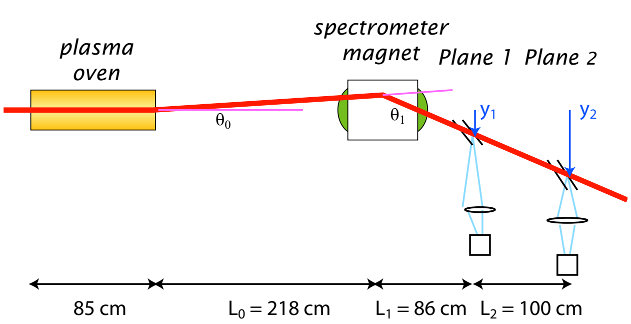

Figure 1: Experimental setup for the energy measurement. Measuring the vertical displacement in two planes allows to distinguish between a transverse deflection at the plasma exit and an energy change of the particles.

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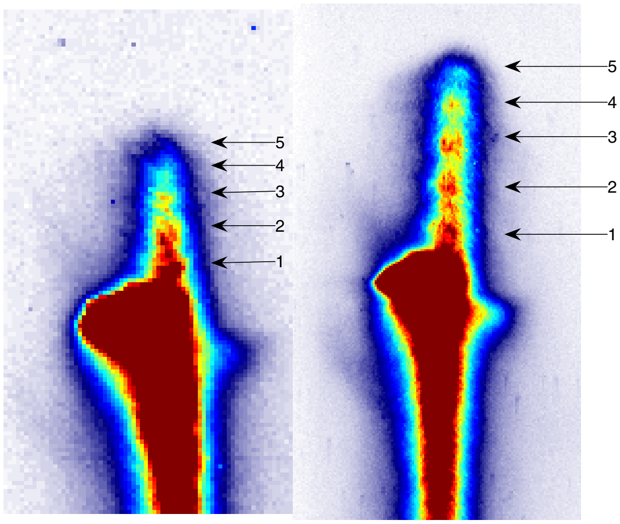

Figure 2: Dispersed images recorded by the cameras in Plane 1 and 2. In the present example, the beam size is not exactly matched to the plasma density [5]. Therefore, the beam envelope oscillates along the plasma. This oscillation is energy-dependent, and therefore pinches the beam at regular intervals. Waists, indicated by the arrows, occur at 45, 51, 56, 61 and 70 GeV.

angle θ_0 at the plasma exit and the deflection θ_1 in the spectrometer magnet.

The transverse particle distribution is therefore simultaneously measured in two planes, $L_1 = 86\,\mathrm{cm}$ and $L_1 + L_2 = 186\,\mathrm{cm}$ downstream of the magnet center. A system of equations relates the position y_1, y_2 of a particle in these planes to the defection at the plasma exit and in the magnet:

$$\theta_0 = \frac{L_1 y_1 - L_1 y_2 + L_2 y_1}{L_0 L_2}$$

$$\theta_1 = \frac{-L_0 y_1 + L_0 y_2 - L_1 y_1 + L_1 y_2 + L_2 y_1}{L_0 L_2}$$

At each of the measurement planes, an air gap is defined by two silicon wafers, spaced by 15 mm and oriented at an angle of $45°$ to the beam. Cherenkov light generated in the air is reflected by the second wafer and imaged onto cooled charge-coupled devices (CCD). The electrons pass through the wafers almost unperturbed, and images in both planes are recorded on a shot-to-shot basis.

The optical setup in the two planes is somewhat different. The downstream plane, which can achieve a higher resolution because the ratio of dispersion to beam size is more favorable, uses a thinned back-illuminated CCD, which achieves a high signal-to-noise ratio by using large pixels ($25\,\mu\mathrm{m} \times 25\,\mu\mathrm{m}$) and a 16-bit ADC. The upstream plane is equipped with a camera that is somewhat more cost-effective, combining a front-illuminated CCD with $9\,\mu\mathrm{m}$ pixel size with a 12-bit ADC. To protect the cameras from radiation damage, they are shielded by a 10–20 cm thick lead wall, and the light is deflected by mirrors such that no direct path exists for X-rays from the beam line to the camera. The optical distance from the silicon wafers to the cameras is 2.5 m.

Cherenkov light is emitted in a cone around the particles, peaking at an angle of $\theta_C = \arccos\left(1/(\beta n)\right) = 24\,\mathrm{mrad}$, where $\beta = v/c$ is the speed of the particles and n is the index of refraction of air. The lens needs to cover a portion of the Cherenkov radiation that is independent of its origin, i.e. the particle energy. For the downstream camera, this is achieved by using an imaging system whose first lens has a diameter of $150\,\mathrm{mm}$, which covers the entire Cherenkov ring[1]. For the upstream camera, the smaller sensor size requires a shorter focal length of the imaging system[2]. Its first lens has a diameter of $107\,\mathrm{mm}$, barely larger than the diameter of the Cherenkov ring at this location. Positioning this ring onto the edge of the lens would have required very tight alignment tolerances, and Cherenkov light emitted by particles with a different energy and a different dispersion would miss the lens. The two rings were therefore aligned such that the center of the Cherenkov ring is located at the horizontal edge of the camera lens. This way, when the ring moves up or down for different particle energies, the amount of light captured by the lens varies by less than one percent for energies between 30 and $100\,\mathrm{GeV}$. Figure 2 shows images recorded simultaneously by the two cameras.

STATISTICAL ANALYSIS OF THE E-167 EXPERIMENT

The two-plane spectrometer was used for the E-167 experiment at SLAC. Incoming electrons with an energy of $42\,\mathrm{GeV}$ ionize lithium vapor in a heat-pipe oven and generate a plasma wake. The plasma density is $2.7 \cdot 10^{23}/\mathrm{m}^3$, and oven lengths up to $113\,\mathrm{cm}$ have been used. The data presented here was acquired with a plasma length of $85\,\mathrm{cm}$, which resulted in the highest energy gain. The incoming electron bunches were compressed longitudinally to a nominal bunch length of $50\,\mathrm{fs}$ and focused to a diameter of $10\,\mu\mathrm{m}$ in the plasma.

After all parameters had been optimized for maximum acceleration, images and relevant beam parameters were recorded for 800 consecutive events, with three short breaks to save data to disk. For each event, the highest energy electrons were determined in both planes; the detection threshold is approximately $3 \cdot 10^6$ electrons per GeV. The energy is shown in Figure 3.In some events, the energy of incoming electrons was doubled in the plasma [2], which implies an accelerating field of $52\,\mathrm{GV/m}$. Fluctuations in the energy gain have been correlated to deviations in the incoming electron beam parameters. In particular, the peak current plays a critical role in generating the wake [1]. Another important parameter is the charge density in the accelerating part of the wake. These variations nonwithstanding, more than 30% of the events showed an energy gain greater

[1] Nikkor 600 mm f/4D ED-IF AF-S II
[2] Nikkor 300 mm f/2.8 ED-IF AF-S VR

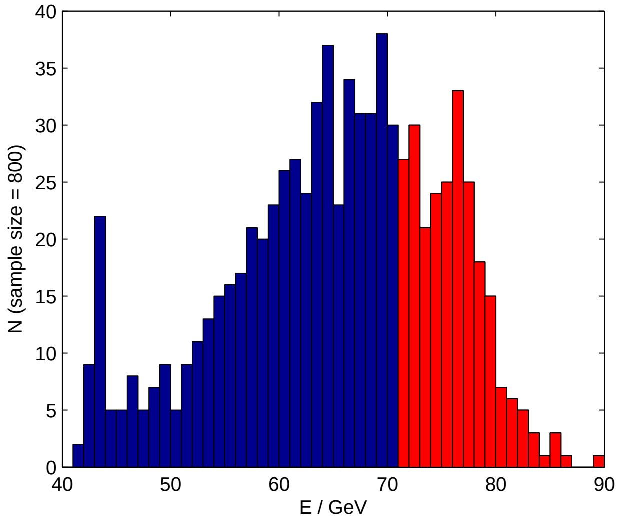

Figure 3: In 800 consecutive events, more than 30% showed an energy gain greater than $30\,\mathrm{GeV}$. The plasma density was $2.7 \cdot 10^{23}/\mathrm{m}^3$, the plasma length $85\,\mathrm{cm}$.

than $30\,\mathrm{GeV}$. This corresponds to accelerating fields in excess of $35\,\mathrm{GV/m}$.

The distribution of the exit angle at the plasma θ_1 is shown in Figure 4. A Gaussian fit to the vertical distribution results in a vertical standard deviation of $186\mu\mathrm{rad}$. If the two-screen method were not used, this exit angle would be the dominant contribution to the uncertainty of the energy measurement. For the event shown in [2], the total uncertainty in the peak energy would be $(+17/-14)\,\mathrm{GeV}$. This uncertainty is even larger for runs where larger exit angles were measured, to the point of rendering a single-plane spectrometer useless. By using the information from both planes, the confidence interval for the present data could be reduced to $\pm 7\,\mathrm{GeV}$. The horizontal standard deviation of $209\,\mu\mathrm{rad}$ is somewhat larger. This is possibly due to the larger horizontal emittance of the incoming beam.

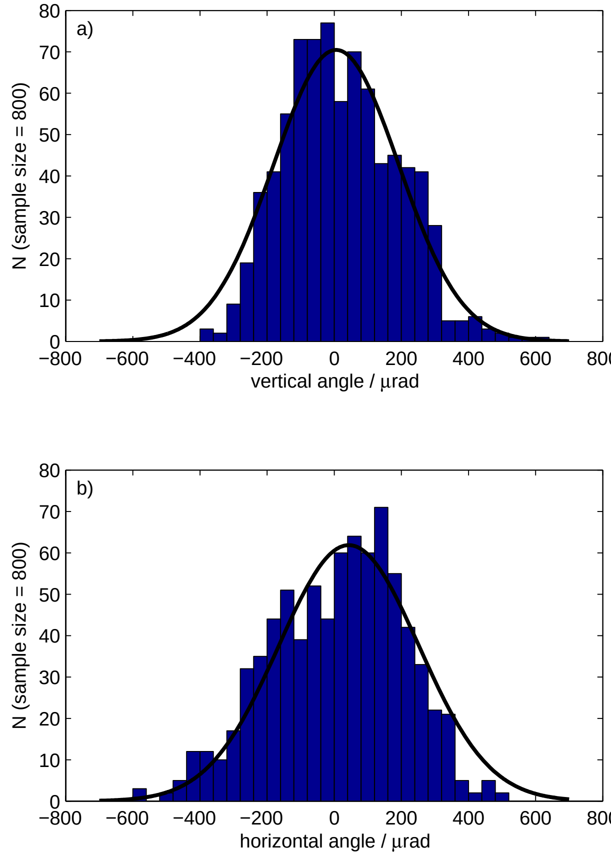

Figure 4: Exit angle (θ_1) distribution: a) vertical, b) horizontal. The line shows a Gaussian fit with standard deviation $186\,\mu\mathrm{rad}$ (vertical) and $209\,\mu\mathrm{rad}$ (horizontal).

CONCLUSION

A two-screen spectrometer provides a convenient way to determine the spectrum of the high-energy electrons coming from a plasma wakefield accelerator. It avoids ambiguities due to unknown angle at the plasma exit. In the E-167 experiment at SLAC, it has been used to show the energy doubling of $42\,\mathrm{GeV}$ electrons with an uncertainty of $\pm 7\,\mathrm{GeV}$.

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