TECHNIQUE FOR DETERMINING THE MAXIMUM ENERGY OF A DISPERSED ELECTRON BEAM FROM LASER WAKEFIELD ACCELERATORS*

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Abstract

We present a new curve-fitting method based on asymptotically fitting transverse size contributions to the measured electron spectrum that is capable of determining the maximum energy of a dispersed electron beam from a laser wakefield accelerator regardless of its transverse size. This method is applied to experimental spectra obtained in the characterization of a new injector stage to show that Direct Laser Acceleration may be an additional acceleration mechanism in laser wakefield accelerators where the laser pulse is long enough to overlap the trapped electrons.

INTRODUCTION

The energy of electron beams from an accelerator is typically measured by magnetically dispersing the electron beam onto a detector. Because the magnetic dispersion is highly nonlinear, the lower-energy charge generally experiences higher deflection and is well dispersed on the detector, whereas the higher-energy charge is deflected less and therefore is less dispersed. This small spatial separation leads to reduced resolution at higher energies and makes it challenging to accurately determine the maximum energy of an electron beam in the 10s to 100s of MeV energy range using a non-imaging but dispersive magnet. The issue of determining the maximum energy of an electron beam is further complicated when that beam has a large transverse size at the detection plane. In such a case, it is difficult to determine whether the signal at high energies on the detector is actually high-energy electrons or if it is an artifact of the transverse size of the beam. This proceedings describes a curve-fitting method to determine the maximum energy of an electron beam regardless of its transverse size.

EXPERIMENT

This curve-fitting method was developed to accurately characterize a newly-designed laser wakefield acceleration (LWFA) injector, which could produce ~100 MeV electron bunches in gas cells with lengths of 400 µm to 1100 µm [1, 2]. The Ti:Sapphire laser used to do this characterization had a pulse width of 45 fs FWHM and an a_0 of ~2. During the characterization, the injector was tested over a range of plasma densities from 8.1 x 10^{18} cm^{-3} to 2.5 x 10^{19} cm^{-3}. For these laser and plasma parameters, the LWFA is not operating in the ideal

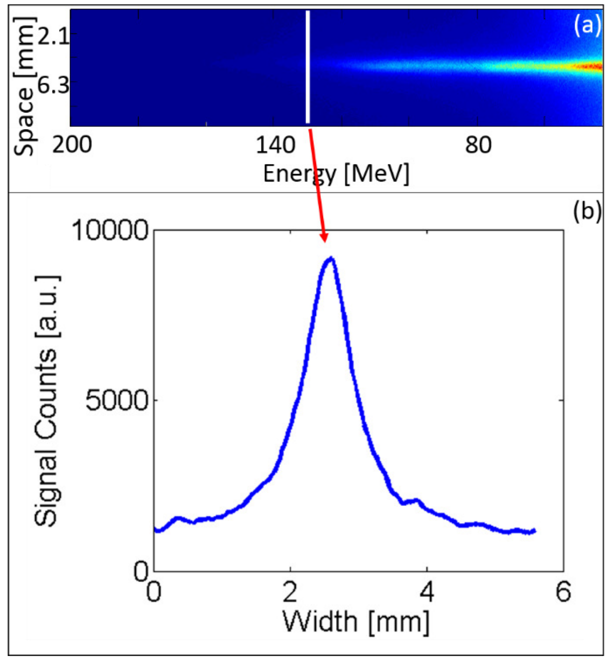

Figure 1: (a) Linearized electron spectrum showing the location of the transverse lineout taken at 130 MeV. (b) Typical raw transverse lineout of the electron spectrum taken at 130 MeV before being rotated and linearized.

blowout regime [3]. Therefore, self-trapping of electrons in the wake will not occur without significant laser pulse evolution. To eliminate the need for laser pulse evolution and thus devote the length of the injector to acceleration, the ionization injection technique [4] was employed. As a result, the spectrum of the accelerated electrons was typically continuous with an exponentially decreasing tail as shown in Figure 1(a). To demonstrate that the injection stage was capable of producing ~100 MeV electrons as designed, it was critical to accurately measure the maximum energies of these electron beams even though they have exponentially decreasing tails. The method described here was found to converge on many real data sets and enabled us to determine the maximum energy of an electron beam regardless of its transverse size, its energy spread, or its exponentially decreasing tail.

DETAILS OF THE METHOD

The method separates out the transverse size contribution by comparing the signal in the dispersed plane to the signal in the transverse (undispersed) plane. In the dispersion plane, the lineout of the electron spectrum has the combined effects of energy dispersion and transverse size. The transverse lineout, however, only

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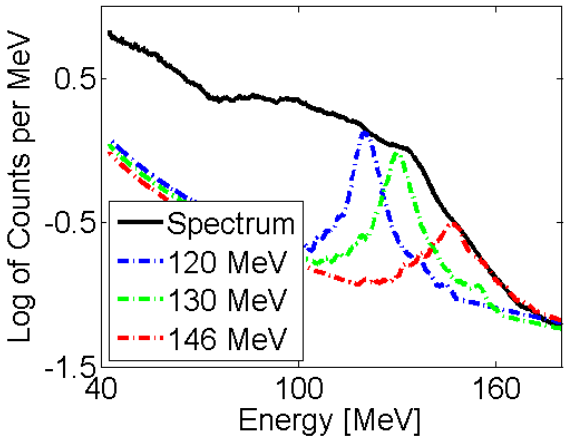

Figure 2: Process of comparing the rotated and linearized transverse lineouts (dashed lines) against the central lineout of the electron spectrum (solid black line). The converted transverse lineout at 146 MeV (red dashed curve) is asymptotic with the central lineout; therefore the maximum electron energy is 146 MeV.

shows the effects of the transverse size. Therefore, by comparing the transverse and longitudinal lineouts of the electron spectrum at a particular energy, it is possible to determine if the signal at that point is due to electrons of that energy or if the signal is from the transverse size contribution of lower-energy electrons.

To compare the transverse lineout of the signal at a particular energy to the actual spectrum, the transverse size contribution of the transverse lineout must first be converted into a dispersed signal. This process is best illustrated on an actual electron spectrum. The raw electron spectrum is first linearized as shown in Figure 1(a) to correct for the energy dispersion of the spectrometer. Based on the energy scale of this linearized spectrum (Figure 1(a)), the maximum electron energy appears to be between 110 MeV and 160 MeV. Therefore, transverse lineouts of the raw spectrum are taken for a series of energies between 110 MeV and 160 MeV. A typical transverse lineout is shown in Figure 1(b).

Each transverse lineout contains the transverse size contribution from the electrons at the energy where it was taken. Assuming that the transverse size effects are radially symmetric, this transverse lineout also includes the contributions of any lower-energy electrons whose transverse sizes are large enough to overlap the chosen energy. The selected transverse lineouts are rotated 90^0 to orient them in the dispersion plane. They are then linearized using the same process used to linearize the dispersed spectrum. Again, because the transverse lineout has no dispersion effects and therefore only accounts for the transverse size contribution, by rotating it into the dispersion plane and linearizing it, the transverse size contribution is converted into a linearized signal in the dispersion plane. This converted transverse lineout thus only shows the portion of the total signal at a given energy that is due to the transverse size. Each converted transverse lineout can then be compared to the central lineout of the actual dispersed signal as shown in Figure 2. In this figure, the solid black curve is the central lineout of the dispersed electron spectrum, and the blue, green, and red dashed curves are the converted transverse lineouts from 120 MeV, 130 MeV, and 146 MeV, respectively. If the tail of the longitudinal lineout has a greater magnitude than the tail of the converted transverse lineout, then the longitudinal signal cannot be caused by the transverse size of the energy of interest alone. There must be a contribution from higher-energy electrons. However, if the tail of the converted transverse lineout at a given energy has a higher signal, then the longitudinal signal at that energy can be attributed to the transverse size contributions of electrons at energies less than the energy being compared. Therefore, the comparison must be repeated with the transverse lineout at the next lowest energy.

To illustrate this comparison, in Figure 2, the tail of the blue curve (the transverse lineout at 120 MeV) is below the dispersed signal. Therefore, 120 MeV is not the maximum measured electron energy; there must be a contribution to the measured electron spectrum from higher-energy electrons. The tail of the red curve falls on the dispersed lineout. Therefore, the tail of the actual dispersed signal can be attributed to the transverse size contribution of the 146 MeV electrons. Therefore, 146 MeV is the maximum energy of this electron spectrum. Note that this method does not account for errors in the measurement of the maximum electron energy due to the electron bunch leaving the plasma at an angle relative to the laser axis. However, if this method is used with a two-screen spectrometer [5, 6], both the transverse size and the exit angle of the electron bunch can be taken into account when calculating the maximum electron energy.

EXPERIMENTAL FINDINGS

Using the curve-fitting method just described, the maximum energy of the electron beams produced in the characterization of the injector cell [1, 2] were determined. Figure 3 shows typical electron spectra obtained at low ($<1\times10^{19}$ cm^{-3}) and high ($>2\times10^{19}$ cm^{-3}) plasma densities.

The performance of LWFAs operating in the blowout regime ($a_0>2$) is commonly benchmarked against the scaling equation for the dephasing-length-limited energy gain [3]:

$$\Delta E \cong \frac{2}{3} mc^2 \frac{\omega_0^2}{\omega_p^2} a_0 \qquad (1)$$

where ω_0 is the frequency of the drive laser and ω_p is the plasma frequency. Equation 1 predicts a maximum energy gain of 126 MeV for the typical low-density shot (Figure 3(a)) and of 48 MeV for the typical high-density shot (Figure 3(b)). Though the parameters of the UCLA injector characterization are not rigorously in the blowout

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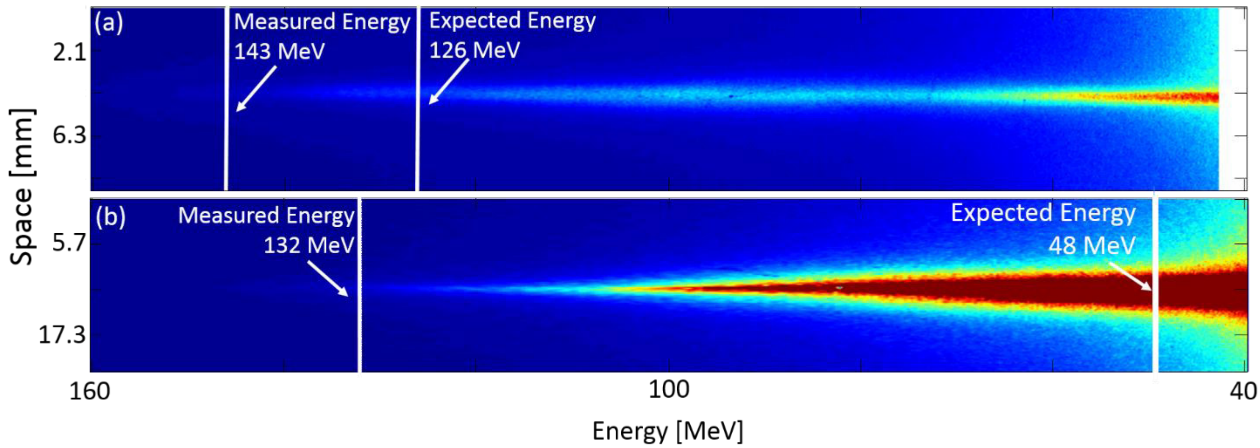

Figure 3: (a) Typical low-density electron spectrum. The cell length l_{cell} was 1100 μm, the plasma density n was 9.1 x 10^{18} cm^{-3}, and a_0 was 2.00. (b) Typical high-density spectrum. l_{cell} was 430 μm, n was 2.2 x 10^{19} cm^{-3}, and a_0 was 1.86.

regime, the measured energy for the low-density spectra agree relatively well with the energies predicted by Equation 1. However, for the typical high-density spectrum shown in Figure 3(b), there is a 175% difference between the maximum measured energy (132 MeV) and the energy predicted by Equation 1 (48 MeV).

DIRECT LASER ACCELERATION

Through a detailed study and a series of OSIRIS [7] particle-in-cell simulations (future publication), it was determined that the source of the additional energy gain produced in high plasma densities is Direct Laser Acceleration (DLA). In LWFAs, the electrons that are trapped in the wake therefore undergo betatron oscillations in response to the field of the ion column formed behind the drive laser. In the UCLA work, the laser had a fixed pulse length of 45 fs and an approximately constant a_0 of 2. Because the length of the bubble formed in LWFAs decreases for increasing plasma densities [3], when the injector was operating at low densities, only the tail of the 45-fs pulse overlapped the electrons trapped in the back of the first bubble, but when the injector ran at high densities, the bubble length was short enough that the higher-intensity portions of the 45-fs pulse overlapped the electrons trapped at the back of the bubble. When the pulse overlaps the trapped electrons that are oscillating in the ion column, the transverse field of the laser will increase the transverse momentum of the electrons that are at the correct phase. This increased transverse momentum can then be transformed into longitudinal momentum through the **v** x **B** force due to the magnetic field of the laser. This process of enhancing the transverse momentum of an electron and then converting that increase to longitudinal momentum is known as DLA [8]. DLA can lead to increased energy gain in LWFAs operating in a regime where the pulse overlaps the electrons trapped in the first bucket and is the source of the additional energy gain seen at UCLA when the injector was operating at high densities.

CONCLUSION

This proceedings details a newly-developed curve-fitting method for determining the maximum energy gain of a dispersed electron beam regardless of its transverse size. This method was applied to experimental work at UCLA to find that DLA is an additional acceleration mechanism at work in LWFAs where the laser pulse overlaps the trapped electrons.

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