# TWO-SCREEN METHOD FOR DETERMINING ELECTRON BEAM ENERGY AND DEFLECTION FROM LASER WAKEFIELD ACCELERATION*

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*Abstract*

Laser Wakefield Acceleration (LWFA) experiments have been performed at the Jupiter Laser Facility, Lawrence Livermore National Laboratory. In order to unambiguously determine the output electron beam energy and deflection angle at the plasma exit, we have implemented a two-screen electron spectrometer. This system is comprised of a dipole magnet followed by two image plates. By measuring the electron beam position on each plate, both the energy and deflection angle at the plasma exit are determined through the relativistic equations of motion.

## INTRODUCTION

Laser wakefield accelerators employ high intensity ($\geq 10^{18}$ W/cm$^2$) laser pulses to produce high energy, low divergence electron beams [1]. Typical electron energy measurement schemes consist of placing a dipole magnet after the plasma, followed by an image plate or phosphor screen [2]. By assuming that the electrons exit the plasma parallel to the laser axis, the vertical position of the electron beam on the image plate determines its energy by setting the beam Larmour radius in the dipole magnet.

However, we find that small-angle deflections of the electron beam from the laser axis at the plasma exit can become convolved with the cyclotron motion in the magnet, leading to large errors in the calculated electron energy. Placing an aperture between the plasma and the spectrometer limits the maximum deflection angle for electrons reaching the image plate, but we will show that even a 2 degree deflection can result in a factor of a few error in the energy measurement.

This ambiguity between energy and deflection is removed when a second image plate is added after the magnet [3]. By measuring the deviation of the electron beam from the laser axis at two positions the electron trajectory at the magnet exit is uniquely determined. This results in a unique solution to the relativistic equations of motion for the electron beam energy and deflection angle at the plasma exit.

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## EXPERIMENT SETUP

Laser Wakefield Acceleration experiments have been performed using the Callisto laser at the Jupiter Laser Facility, Lawrence Livermore National Laboratory. Callisto is a Ti:Sapphire laser, which has recently been upgraded to deliver 60 $\pm 5$ fs pulses of 800 nm light at energies above 10 J. The 200 TW pulses are focused on the leading edge of a gas jet by an f/8 off-axis parabola to a vacuum spot size of 18 microns FWHM. The gas jet supplies He gas at neutral densities of 1x10$^{18}$-1x10$^{19}$ cm$^{-3}$. Nozzle diameters of 5 mm and 8 mm are used, and the profiles are well characterized using interferometry [1].

Measurements of the resulting electron beam are performed with a dipole magnet and two image plates, as shown in Figure 1. The dipole magnet is comprised of two permanent magnetic plates, each measuring 20 cm long by 8 cm high. The field between the plates is determined by their separation distance; B=0.46 T for a plate separation of 3.5 cm. The magnet entrance is located 62.5 cm from the gas jet. In order to resolve the electron energies, two Fuji BAS-MS image plates are placed after the exit of the magnet at distances of 144.6 cm and 203.8 cm from the jet. They are read with a Fujifilm FLA-7000 scanner providing 200 micron spatial resolution. There is a minimum 20 minute delay between image plate exposure and scanning to minimize error introduced by fading effects in the plates [4]. The location of incident electrons is measured on each plate, and solving the relativistic equations of motion then determines the electron energy and the beam deflection from the laser axis at the plasma exit.

## ANALYSIS

In order to uniquely solve for the electron beam energy and initial deflection angle consider the relativistic Lorentz equation

$$\gamma m \frac{d\mathbf{v}}{dt} = q\mathbf{v} \times \mathbf{B} \qquad (1)$$

where $\gamma$ is the electron beam energy normalized to 511 keV, m (q) is the electron rest mass (charge), and B is the field

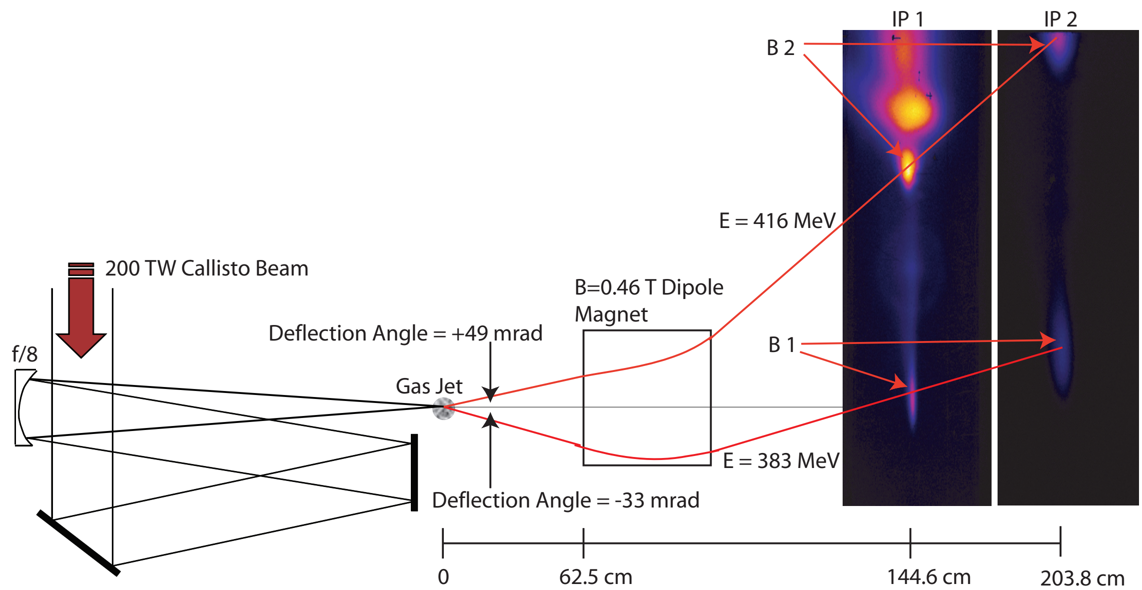


Figure 1: The 200 TW Callisto laser is focused by an f/8 off-axis parabola to a vacuum spot size of 18 microns (FWHM) at the leading edge of a gas jet. The jet delivers He gas at neutral densities of 1x10$^{18}$-1x10$^{19}$ cm$^{-3}$. A dipole magnet is placed after the jet, followed by two image plates. The displayed trajectories through the magnet correspond to the features labeled B1 and B2 on the image plates.

strength of the dipole magnet. While the electrons traverse the magnetic field they undergo Larmour motion at the relativistic gyrofrequency, $\omega_c = qB/\gamma m$, which is determined by the beam energy for a given field strength. Allowing for an initial deflection angle $\theta$ of the electron beam from the laser axis and solving Equation 1 for the electron orbit due to the field yields the vertical position ($y_{exit}$) of the electrons at the magnet exit

$$y_{exit} = z_0 tan\theta + \frac{v}{\omega_c}(cos\theta - cos\phi) \quad (2)$$

where $z_0$ is the distance from the gas jet to the magnet entrance and $\phi$ is the electron beam angle relative to the laser axis at the magnet exit.

Since the vertical displacement of the electron beam is known in two positions after the magnet we obtain a second relation for $y_{exit}$

$$y_{exit} = y_1 - d_1 tan\phi \quad (3)$$

where L is the length of the magnet, $d_1$ is the distance from the magnet exit to the front image plate, $y_1$ is the height of the electron beam on the front image plate, and tan$\phi$ is the slope of the electron beam trajectory as determined from both image plates. The system of equations is closed by relating the beam energy to the deflection angle by L=$r_L$(sin$\phi$-sin$\theta$), with the Larmour radius $r_L$=v/$\omega_c$.

## RESULTS

Electron beam energy and deflection angle are determined by measuring the position of the electrons on two image plates. Figure 1 shows the result of a 145 TW laser pulse incident on a plasma with an electron density of 3.2x10$^{18}$ cm$^{-3}$. In this particular example there is more than one bunch of accelerated electrons visible on the image plates. For the bunch labeled B1 on each image plate, the deviation from the laser axis is 3 mm for the first plate and 26 mm for the second plate.

If the electron beam is assumed to have no deflection angle at the plasma exit, using only the first image plate position to solve the equations of motion in the magnet results in an energy measurement of 5 GeV. Using only the second image plate with the same assumption gives an electron beam energy of 1.4 GeV. However, since the beam height is known in two locations the trajectory of the beam back to the exit plane of the magnet is determined. It is now not possible to solve the equation of motion without allowing for an initial deflection angle at the plasma exit. For the data in Figure 1, the electrons exit the plasma with an angle of -33$\pm$1.5 mrad; this corresponds to a beam energy of only 383$\pm$20 MeV.

The same analysis can be applied to the each successive electron beam. For the bunch labeled B2, the beam height is 11.7 (18.55) cm on the first (second) plate, which independently corresponds to 165 (195) MeV assuming no deflection. Solving using both measurements yields an energy of 416$\pm$30 MeV with a deflection angle of +49$\pm$3 mrad. This indicates that not only is it necessary to allow for initial deflections, but that each electron beam trajectory must be solved for its own deflection.

Figure 2 shows the results of all of our recorded electron beams. Each beam has been analyzed first using both im-

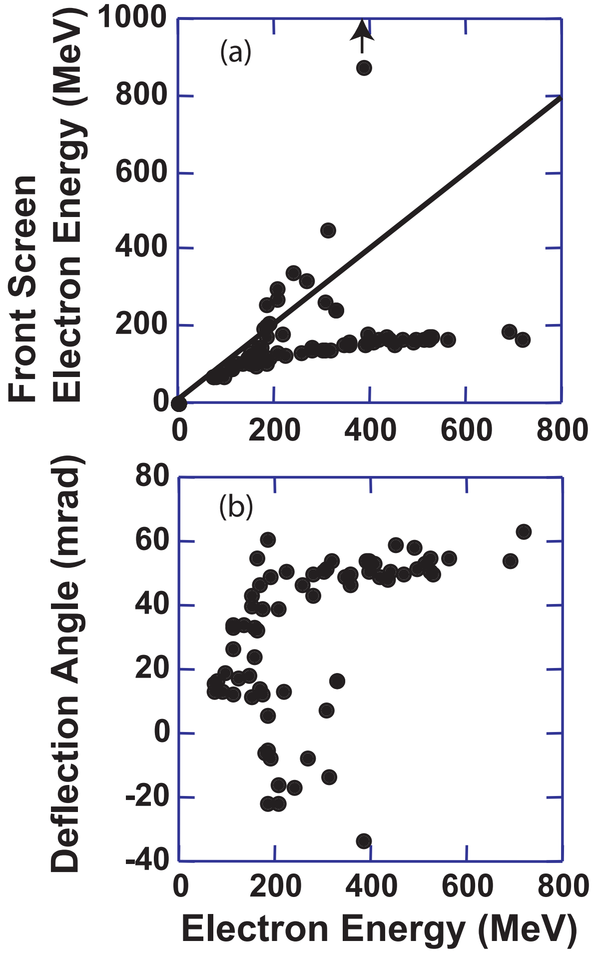


Figure 2: a) The energy of each of our electron beams is measured first using both image plates and then again with just the front image plate. The solid line divides electron beams with positive (below the line) and negative (above the line) deflection angles. b) The deflection angles for all electron beams are shown; there is no apparent correlation to beam energy.

age plates, and then again with only the front plate. The solid line in Figure 2a corresponds to equal energy measurements for both methods. Electron beams above this line underwent a downward deflection at the plasma exit, while beams below the line had a positive deflection angle. Every beam suffered from some initial deflection, as shown in Figure 2b.

For the lowest energy electron beams the energy measured with the two-screen system closely follows the solid line of Figure 2a. This is to be expected, since lower energy beams are deflected more by the dipole magnet. As the electron beam energy increases, the magnet deflection decreases, and the effect of the initial deflection becomes more pronounced. This necessitates a two-screen electron spectrometer system in order to resolve GeV-scale electron beams.

## CONCLUSION

This laser wakefield acceleration study implemented a novel technique for measuring output electron beam energies. By using two image plates after a dipole magnet we have shown that electron beams produced by LWFA can have significant deflections from the laser axis upon exiting the plasma. The result of these deflections is up to an order of magnitude error in the electron energy measurement. Furthermore, multiple electron beams with different deflection angles can be produced by a single laser pulse. Only by measuring the position of each electron beam in two locations can the energy be uniquely determined.

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