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# Correlation of Beam Parameters to Decelerating Gradient in the E-167 Plasma Wakefield Acceleration Experiment*

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*Abstract*

Recent experiments at SLAC have shown that high gradient acceleration of electrons is achievable in meter scale plasmas [1,2]. Results from these experiments show that the wakefield is sensitive to parameters in the electron beam which drives it. In the experiment the bunch length and beam waist location were varied systematically at constant charge. Here we investigate the correlation of peak beam current to the decelerating gradient. Limits on the transformer ratio will also be discussed. The results are compared to simulation.

## INTRODUCTION

In the E-167 Experiment, a 42GeV electron beam with $1.8\cdot10^{10}$ electrons and normalized emittances of ~50mm·mrad in x and ~5mm·mrad in y was sent into a neutral lithium vapor column of density $n=2.7\cdot10^{17}/cm^3$ and length 85cm full width at half max (fwhm) confined in a heat pipe oven [3]. The longitudinal bunch length of the beam varied from ~10-40μm, while the beam was focused transversely to a size of ~10μm. At these beam densities, the fields are large enough to ionize the lithium, creating a plasma and driving a wake [4]. With a beam to plasma density ratio greater than 10, this plasma wakefield system is predicted to be outside linear theory [5]. This type of system was simulated using the 2D PIC code OOPIC, commercially available through TECH-X Corporation and UC Berkeley [6].

## EXPERIMENTAL SETUP

### *X-Ray Spectrometer*

The energy spread of the incoming beam was measured by imaging the displacements in an energy dispersive region using incoherent x-ray synchrotron radiation emitted by the beam. The initial energy profile is then matched in the 2D tracking code LiTrack to recover the temporal profile of the beam [1, 7]. Using this, the peak beam current, or $I_{peak}$ of a given event can be determined. Typical initial energy spread of the electron beam is 1.5GeV or 0.5% fwhm.

### *Energy Spectrometer*

Particle energies were measured after exiting the plasma with a magnetic spectrometer and Cerenkov radiation. The electrons were dispersed in energy by a dipole magnet centered 2.18m from the plasma exit with an integrated magnetic field of 12.05kG·m. The dispersed electrons were then passed through an air gap where their Cerenkov radiation was imaged at two locations, 85cm and 1.85cm from the magnet center. The first location, with lower dispersion, allowed measurement of low energy particles, while the second, with higher dispersion, gave better resolution at high energies. Using both screens, it was possible to accurately determine the highest energies reached by the electrons, removing the effect that transverse kicks from the plasma exit would have had on the images [8].

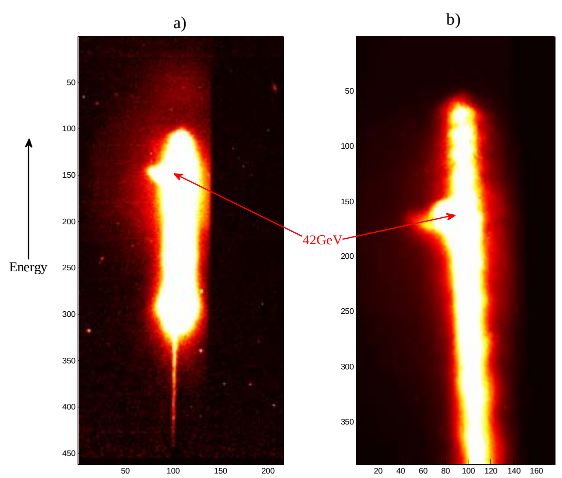


Figure 1: a) Sample low dispersion image. Beam is dispersed in energy on the vertical axis. The entire beam is visible as the bright spot on the image. The final energy spread is significantly larger than the initial. The thin streak of trapped charge can clearly be seen below the beam [9]. b) Sample high dispersion image for the same event. Although the bottom of the beam is no longer visible, there is better resolution at higher energies.

### *Low Energy Measurement*

The lowest electron energy for a given event was used to determine the amplitude of the decelerating wake. As the wake is being driven by the electron beam, the phase velocity of the wake is equal to beam velocity. This means that each particle effectively sees a constant field as it propagates through the plasma. The lowest energy electron in a given event therefore sees the peak decelerating gradient. The field can easily be determined using the change in energy and the plasma length.

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The lowest measured energy was determined by locating the position of the lowest appreciable signal on the low dispersion image, Fig. 1(a). To assure that the entire beam could be seen, only images with features appearing below the beam were chosen. These features were thin streaks in energy that correspond to low energy trapped charge from the plasma [9].

### *High Energy Measurement*

The highest energy electrons were measured using both screens. The same position was identified in the high energy portion of both images in Fig. 1. Then, knowing all the distances between the plasma, the magnet and the screen, the deflection angle, and thus the energy, can be solved for using a system of linear equations. In this way, contributions to the vertical position due to deflections from the plasma exit as opposed to the dipole can be removed [8].

Using this method, the highest energy reached by electrons in a given event can be determined. The accelerating gradient can be calculated as before. However, this value cannot be quoted as the maximum accelerating gradient, as it is only possible to measure the gradient when electrons are present to sample it. The current profile can range from a standard asymmetric Gaussian to one with a long tail. Two events with similar peak currents could have a very different distribution of electrons in the tail to sample the wake and could terminate at different points, shown in Fig. 2.

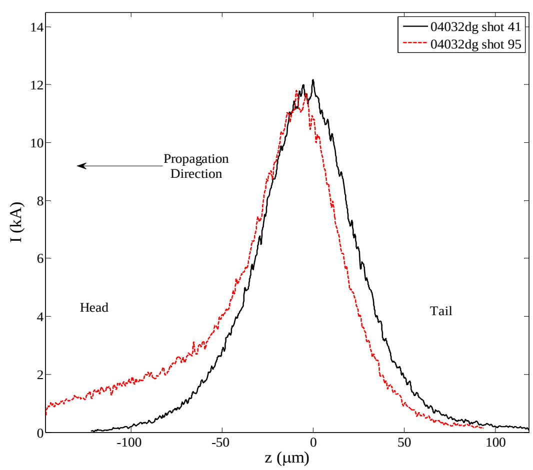


Figure 2: Current profiles for two events with similar Peak Currents. One can be seen to have a significantly larger head, while the core on the other is slightly wider and the tail slightly longer.

### *Limitations*

There are two instrumental limitations to this measurement. The first is caused by the lack of beam focusing elements between the plasma exit and detection planes. This is necessary due to the large energy spread on the beam, but allows the beam to expand as in vacuum. This means that the beam has a finite transverse size on the images, both in x and in y. For low energy particles, even though the dispersion from the magnet dominates, there is still a small effect from the fact that the signal is a convolution of the energy spectrum and transverse size in y. For high energy particles, this lack of focusing necessitates the two screen measurement described above.

The second instrumental limitation is the integrated magnetic field setting of 12.05kG·m. This means that particles with energies less than 10.3 GeV will not appear at the image planes, due to physical apertures in the beam and Cerenkov radiation transport lines. Thus there are some events that must be cut, as it is not clear that the bottom of the beam is actually present. This can be mitigated by using data where the magnet was set at lower field, but that will not be discussed in this paper.

Also, several physics effects have been ignored. First is the effect of the ramp up and ramp down in plasma density at the ends of the oven. These are assumed to be small as the lithium density ramps down Gaussian manner, with an RMS width of 3.97cm, meaning the wake will drop off in a similar fashion. This assumption will have to be checked at a later date. Second is beam head erosion [10].

## EXPERIMENTAL RESULTS

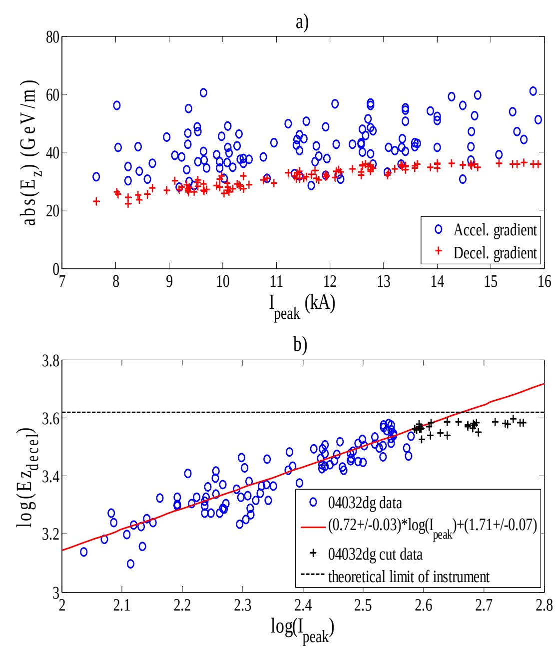


Figure 3: a) Accelerating and decelerating gradient vs. peak current. Events were chosen if both a high and low energy measurement could be made. b) Decelerating gradient vs. peak current, log-log scales. A cut was made perpendicular to fit in order to account for low energy limit on spectrometer

From Fig. 3(a), the measured decelerating gradient ranges from 22 to 36 GeV/m. The measured accelerating gradient varies from 20 to 60 GeV/m with a much larger spread. This is due in part to random error in selecting the same point on both images and in part to differing current profiles, as in Fig. 2. With different events having current profiles which terminate at different longitudinal locations in the wake, it is difficult to understand how to compare accelerating gradients.

The results of this decelerating gradient measurement show a clear correlation with the peak current of the incoming bunch. When the decelerating gradient is plotted versus the peak current on a log-log plot, the data is linearly correlated. The maximum decelerating wake varies as $(I_{peak})^{0.72\pm0.03}$, shown in Fig. 3(b).

## SIMULATION SETUP AND RESULTS

As there is currently no analytic theory to describe these wakes, the experimental results must be compared to simulations, in this case done with the 2D PIC code OOPIC. A 42GeV electron beam with $1.8\cdot10^{10}$ electrons, zero transverse emittance, and zero initial energy spread was injected into a neutral lithium vapor, $n=2.7\cdot10^{17}/cm^3$. The beam ionized the gas to create the plasma and drove the wake. The bunch length was varied from 10 to 50μm and the transverse size set at 2.5 and 10 μm. The beam was allowed to propagate until a stable wake was formed.

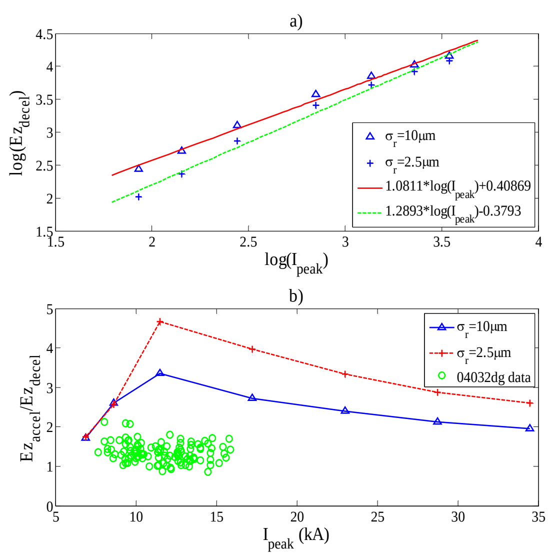


Figure 4: a) Decelerating Gradient vs. Peak Current from simulations. Two different spot sizes are used. The solid line is the fit to $\sigma_r$=10μm and the dashed to $\sigma_r$=2.5μm. b) Ratio of peak accelerating to peak decelerating gradient in simulation vs. peak current. Data are shown as circle points.

The simulations do indeed predict a power law response, but with a scaling of $(I_{peak})^{1\text{-}1.3}$ for the maximum decelerating field amplitude. This is not in agreement with the experimental data. Disagreement between the measurement and simulations could be caused by the non-Gaussian shape of the real distributions, or the asymmetry in x and y of the real beam.

The transformer ratio is more difficult to predict from simulation, due to the resolution difficulties inherent when the plasma electrons rush back on axis and create a high density spike, as well as beam loading [5]. The peak accelerating field was chosen in order to give an upper limit on the transformer ratio. The resulting upper limit is not inconsistent with the measured visible accelerating to decelerating gradient ratio.

## CONCLUSIONS AND FUTURE WORK

The scaling of the decelerating wake with the peak beam current was experimentally measured and shown to be a power law, with:

$$E_{decel,\max} \propto (I_{peak})^{0.72\pm0.03}. \quad (1)$$

The ratio of visible accelerating to decelerating gradient measured was not inconsistent with simulation.

The power law exponent predicted by the simulations was larger than that measured in the experiment. This difference will be examined. Simulations will be done using QuickPIC, a 3D code, to allow for greater access to real beam parameters, specifically real emittance and transverse asymmetry [11]. The effect of the plasma density ramp down and beam head erosion, which have been ignored, will be checked. As well, data taken with lower magnetic field will be used to extend the scaling law over a larger range of peak current.

The final step will be to look at correlations in the accelerating gradient. While these correlations are present in the experimental data, they are more complicated to understand due to variations in the length of the tail on the beam. Further work will be done to draw out the experimental scaling, insuring that the same longitudinal point is being compared in each wake.

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