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FIRST OBSERVATION OF LASER-DRIVEN ACCELERATION OF RELATIVISTIC ELECTRONS IN A SEMI-INFINITE VACUUM SPACE*

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Abstract

We have observed acceleration of relativistic electrons in vacuum driven by a linearly polarized visible laser beam incident on a thin gold-coated reflective boundary. The observed energy modulation effect follows all the characteristics expected for linear acceleration caused by a longitudinal electric field. As predicted by the Lawson-Woodward theorem the laser driven modulation only appears in the presence of the boundary. It shows a linear dependence with the strength of the electric field of the laser beam and also it is critically dependent on the laser polarization. Finally, it appears to follow the expected angular dependence of the inverse transition radiation process.

INTRODUCTION

The development and implementation of new accelerator technologies has allowed particle accelerators to experience near-exponential growth in the available particle energy [1]. The advent of relatively inexpensive and reliable high peak power lasers in the past has become a motivation to explore laser-driven particle acceleration as a potential future particle acceleration scheme. Our effort has been focused on linear particle acceleration of relativistic electrons that relies on the longitudinal electric field of the laser, as was first proposed by Pantell and Piestrup [2].

In a similar fashion to RF technology, this laser acceleration method employs a structure that guides and controls the phase of the electric field along the electron beam trajectory. Compared to RF accelerators the wavelength of the accelerating field is reduced by almost 5 orders of magnitude to the visible or near infrared, which is readily available from efficient and inexpensive tabletop lasers and allows the use of dielectric materials instead of metal for the accelerator structure.

Dielectric materials are known to be capable of sustaining fluences of 2 J/cm^2 from ultra-short laser pulses [3] and can hence survive peak electric fields of 10 GV/m for 100 fsec near-infrared laser pulses. Conceptual laser-driven particle acceleration structures made from dielectric materials have shown promise to achieve sustainable gradients of 1 GeV/m [4], which has motivated us to launch a proof-of-principle experiment that demonstrates the acceleration of electrons from a single interaction with a linearly polarized laser beam in vacuum [5]. We refer to this experiment as the Laser Electron Accelerator Project (LEAP).

DISCUSSION

The Single Laser Beam Approach

Our initial experimental approach involved the use of crossed laser beams in a dielectric based accelerator cell in a fashion similar to that proposed by Sprangle and Esarey [5]. However we abandoned the crossed laser beam configuration and opted to employ a single laser beam oriented at a shallow angle to the electron beam and terminated by a very thin disposable boundary that reflects the laser beam but is no significant barrier for the traversing electron beam. This approach allowed us to overcome a variety of previously encountered experimental limitations such as laser damage threshold of the accelerator cell, tight alignment tolerances, electron beam transmission problems through the accelerator cell apertures and optical phase uncertainties between the crossed laser beams.

Figure 1 illustrates the laser and electron beam configuration used in the experiment. The laser beam intersects the electron beam at an angle α and shown in the figure there is an electric field component from the laser beam that is parallel to the electron beam trajectory. This electric field component is responsible for the particle acceleration and it depends on the laser crossing angle α and on the laser beam polarization. The boundary reflects the laser beam and limits the interaction with the electrons to a semi-finite distance.

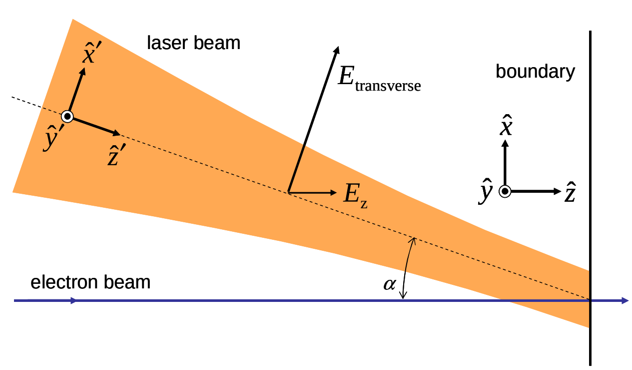

Figure 1: Schematic diagram of the laser beam and the electron beam incident on a thin boundary.

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The Experiment

The LEAP experiment was carried out at the SCA-FEL facility at Stanford University. The primary choice for carrying out our experiment at this facility is the low energy spread of the 30 MeV electron beam from the superconducting accelerator. Table 1 summarizes the important laser and the electron beam parameters.

Table 1: The laser and electron beam parameters

Laser beam parameters	
Wavelength λ	800 nm
Waist FWHM spot size	110 µm
FWHM pulse duration	2-4 psec
Crossing angle α	3-20 mrad
Laser pulse energy	½ mJ/pulse
Electron beam parameters	
Beam energy	30 MeV
Initial energy spread	~30 keV
FWHM spot size	50 µm
FWHM pulse duration	1-2 psec
Initial energy spread	25-30 keV
Approximate bunch charge	1 pC/bunch

The key components of the LEAP experiment consisted of a vacuum interaction chamber containing the accelerator cell and spatial and temporal beam overlap diagnostics [6] followed by a high resolution energy spectrometer. We developed a number of laser and electron diagnostics located in the vicinity of the accelerator cell. We employed long distance microscopes to verify spatial alignment of the laser and the electron beam and a streak camera to determine the relative timing between the laser and the electron beam to within 100 ps. In our latest accelerator run we incorporated an upstream IFEL as additional timing monitor that allowed us to reduce the timing uncertainty by an order of magnitude. The IFEL was setup in a way that would not interfere with the laser acceleration experiment and would allow for a set of separate IFEL experiments [7,8].

The boundary consisted of an 8 µm thick, 230 m long kapton tape with a 1 µm thick reflective gold coating that was moved to a new surface for each laser shot. The "disposable" boundary approach circumvented the damage threshold limitation encountered in previous dielectric permanent accelerator cell approaches [9,10] and allowed us to operate the laser at full power and to maximize the signal to noise in the experiment. The laser pulse energy available at the tape boundary was ½ mJ per pulse. Furthermore, employing an 8 µm thick boundary allowed us to run the electron beam through the tape and avoid tight electron beam alignment requirements through few-micron wide slits and heavy beam loss. These modifications allowed us speed up the alignment and to apply larger laser powers, enabling us to observe laser driven particle acceleration.

Observed Results

A high resolution energy spectrometer located downstream of the interaction region was used to record the energy spectrum of the electron bunches and to look for energy modulation caused by the interaction with the laser. Typical energy spectra are displayed in Figure 2a. The blue traces correspond to the natural energy spread of the electron beam when the laser was not applied and the red traces correspond to the increased energy width of the electron beam when the laser was present. The energy broadening occurred over a ~5 psec laser timing window that was found by scanning the laser pulse timing over a ~30 psec range. Figure 2b illustrates one such typical laser time scan.

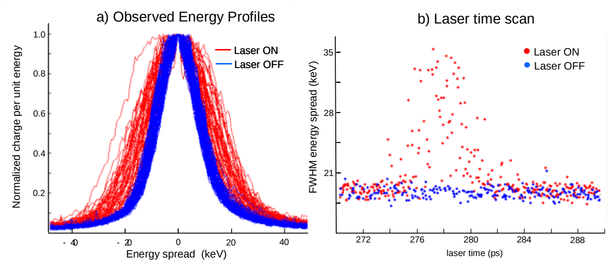

Figure 2: a) observed energy spectrum b) typical laser time scan.

The experimental parameters such as laser power or laser polarization were kept fixed during the laser time scan. Thus, each laser time scan allowed us to find the maximum energy modulation as a function of the given fixed experimental parameter. To study the effect of an individual parameter such as the laser electric field dependence a series of scans with varying laser powers were carried out. To verify the Lawson-Woodward Theorem two successive laser time scans, one with the boundary in place and the following with the tape moved out were taken. Figure 3 shows the experimental confirmation of the Lawson-Woodward Theorem.

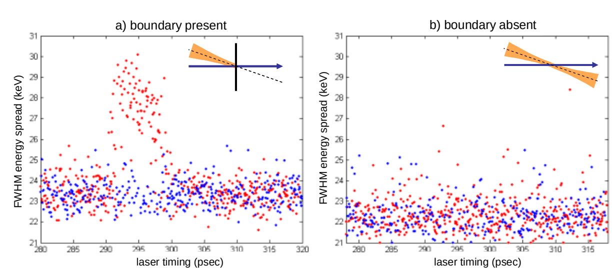

Figure 3: a) boundary present. b) boundary absent.

Figure 3a corresponds to the situation when the boundary is present and shows a clear laser-driven energy modulation whereas Figure 3b, when the boundary is removed, displays no such laser induced energy modulation. Due to shot-to-shot noise, we compute an average energy modulation consisting of

50 events closest to the optimum laser timing. Figure 4 displays the average energy modulation strength as a function of the laser electric field strength with the corresponding fitted line to the data.

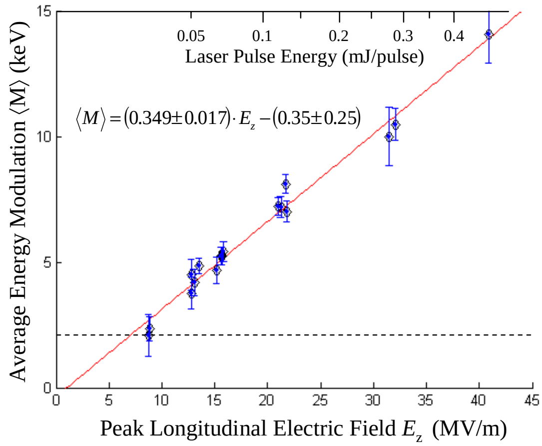

Figure 4: Dependence of the average energy modulation $\langle M \rangle$ on the laser peak electric field.

The dependence on the laser polarization angle was measured by recording the average energy modulation at different laser polarization angle values. The recorded data is shown in Figure 5 and shows good agreement with expected cosine-type dependence of the energy modulation on the laser polarization angle.

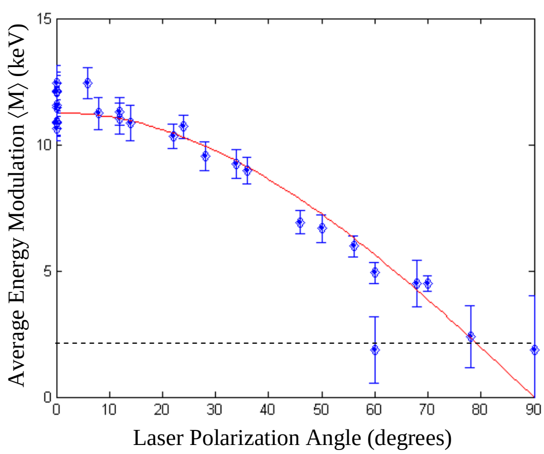

Figure 5: Dependence of the average energy modulation $\langle M \rangle$ on the laser polarization angle.

CONCLUSIONS

We have succeeded in observing laser driven acceleration of relativistic electrons in a semi-infinite vacuum. The observed energy modulation was verified to scale linearly with the longitudinal component of the electric field of the laser and to follow a cosine dependence on the polarization. Furthermore, in accordance to the Lawson-Woodward Theorem it was observed to require a boundary to limit the spatial interaction of the incident laser beam with the electron beam.

The physics confirmation from a single laser-electron beam interaction will lead to staged and extended accelerator cell experiments in the near future and eventually to experimental testing of proposed extended laser accelerator structures.

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