EXPERIMENTAL SEARCH FOR ACCELERATION IN THE MICRO-ACCELERATOR PLATFORM*

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Abstract

An ongoing experimental program to observe acceleration in the Micro-Accelerator Platform (MAP) is described. The MAP is a slab-symmetric dielectric laser accelerator that, when side-illuminated by an optical laser, accelerates electrons via a standing wave resonance. This structure is undergoing testing in the beamline at the Next Linear Collider Test Accelerator at SLAC. A 60 MeV electron beam is injected into the MAP structure when it is illuminated by a laser; the resulting electron energy spectrum is observed using a high-resolution magnetic spectrometer. We present details of the experimental arrangement and discuss predicted acceleration signatures, along with supporting simulation results.

THE MICRO-ACCELERATOR PLATFORM

The Micro-Accelerator Platform (MAP) is a dielectric laser accelerator that builds on existing laser technology and solid-state device fabrication techniques to accelerate electrons with an energy gradient approaching 1 GeV/m [1]. In what follows, ongoing experimental efforts to show evidence of acceleration in the MAP and the simulation work that motivated these efforts will be described.

Structurally, the MAP consists of two slab-shaped Distributed Bragg Reflectors (DBRs) surrounding a rectangular vacuum cavity through which electrons propagate. Energy is coupled into this vacuum cavity when a laser pulse is incident upon and diffracted through periodic coupling slots and matching layers that lie upon the outside face of one of the DBR slabs. These coupling slots have a periodicity that matches the wavelength of the incident Ti:Sapphire laser (800 nm), and in turn enforces the same periodicity for the standing-wave accelerating mode excited in the vacuum cavity. A cross-section that illustrates both the structure of the MAP and the longitudinal component of the electric field of the resonant accelerating mode is shown in Fig. 1 below.

The slab upon which the laser is incident (on top, in Fig. 1) is fabricated by sputtering the coupling layers onto a fused silica substrate, and then evaporatively depositing the DBR on top of these coupling layers. The other slab contains only a DBR, which is deposited directly onto a fused silica substrate. Spacers are then deposited on the DBR-only slab and the two slabs are glued or bonded together, forming a vacuum gap between the slabs that is 800 nm tall and approximately 250 μm wide [2].

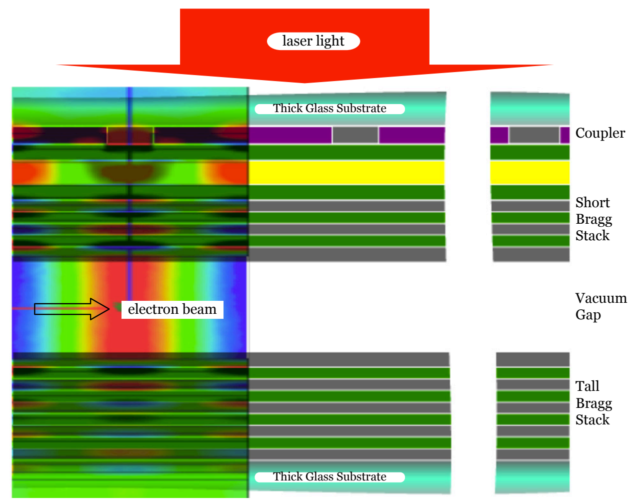

Figure 1: A cross-section of the MAP showing 3 structural periods. An infrared laser pulse is incident upon the structure from above; axial fields of the resulting accelerating mode are shown overlaid on the first structure period (red corresponds to positive values, blue negative). Electrons are accelerated synchronously along the π-mode standing wave resonance.

Electrons entering the vacuum gap encounter a standing wave resonance with a periodicity equal to the incident laser wavelength. Since relativistic electrons travel ~800 nm during one optical cycle of the incident laser, those electrons that enter the accelerating gap at an optimal phase will only see accelerating fields. Peak structure fields are expected to approach 1 GV/m before the dielectric materials break down; in this standing-wave structure, half of the laser energy is coupled to the synchronous forward wave, and therefore we expect that those electrons injected at maximally accelerating fields will see an energy gain of up to 500 keV. In these experiments, however, the electron bunch length is much longer than the structure period, resulting in beam injection over all possible phases of the structure field; thus, portions of the injected bunch are maximally decelerated, while other portions see no energy modulation at all.

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EXPERIMENTAL FACILITIES AND DESIGN

This experimental program makes use of the laser and electron-beam capabilities of the Next Linear Collider Test Accelerator (NLCTA) facility [3] at the SLAC National Accelerator Laboratory. At the NLCTA, 60-MeV bunches of approximately 10 pC each are produced from a photocathode rf gun followed by an X-band linac. A chicane and collimator arrangement is used to reduce the beam energy spread. In the experimental hall, the beam passes through 6 final focusing quads and then through a triplet of permanent magnetic quadrupoles (PMQs). A diagram of the final section of the experimental set up is given in Fig. 2. The MAP is placed at the final focus.

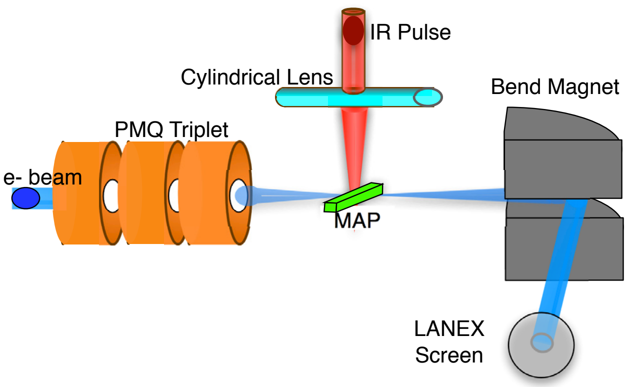

Figure 2: A diagram of the final section of the NLCTA beamline, including the interaction with the MAP. The electron beam is focused to a small spot at the MAP's location, where an IR laser pulse excites the accelerating mode. Downstream of the MAP, the right angle bending magnet is an energy spectrometer.

The MAP is placed on a micro-structure holder that is situated on a 4-axis piezo actuator stage. Within the holder is a cerium-doped YAG screen used to measure the transverse spot size of the electron bunch. Insertable YAG screens placed between the focusing quadrupoles and the PMQ triplet are used to image the beam as the fields of upstream quadrupoles are varied, yielding an emittance measurement that tends to be approximately 20 μm-rad in both transverse dimensions.

To power the MAP, a separate Ti:Sapphire laser system generates an infrared laser pulse ($\lambda = 800$ nm); the pulse length and energy are variable, but usual operating values are 1 ps and 1 mJ respectively. The IR pulse is transported into the experimental hall and is directed downward onto the MAP from above.

To ensure temporal overlap between the IR pulse and the electron beam, a portion of the IR pulse is directed towards a fast photodiode downstream of the accelerating structure. The optical transition radiation signal generated by the electron bunch is also steered towards this fast photodiode and then overlapped with the IR signal to ensure timing overlap within the resolution of the diode, 50 ps. Since this precision is still not nearly sufficient to guarantee temporal overlap, a voice coil in the laser path randomly varies the delay line length over a range of 50 ps during the experiment. Thus, the electron beam and IR beam will overlap temporally on a subset of the shots. (This method was developed at SLAC for the E-163 experiment.) Spatial overlap between electrons and laser photons is ensured by aligning the locations of the OTR signal from the electron beam to the IR spot on the structure.

Achieving acceleration in the MAP also requires that the IR beam be incident perpendicularly to the structure. This ensures that the phase front of the incident IR encounters the coupling slots at the longitudinal front of the structure at the same time as when it encounters the coupling slots at the back of the structure, thus maintaining a consistent phase along the structure axis. To ensure perpendicular incidence of the IR beam on the top surface of the MAP, a camera and set of mirrors, lenses and a partial pick-off mirror are set up above the sample to observe both the incident and reflected IR spots and a screen. When these spots overlap on the screen, perpendicularity is achieved to within 0.01 degrees.

To monitor the beam after it has traversed the IR-illuminated MAP, a 90-degree spectrometer bending magnet is situated downstream of the structure that sends the beam to a point-to-point Lanex screen imaged by an intensified camera (PI-MAX3). Since the bend radius of an electron traveling through the spectrometer magnet is dependent on its energy (momentum), the horizontal position of the beam-image on the screen is linearly correlated with energy, and a full energy spectrum can be obtained.

DIAGNOSING ENERGY MODULATION IN THE ELECTRON BEAM

Since the electron beam is tens of μm in diameter and the acceleration cavity in the MAP is less than 1 μm in its short dimension, most of the electron beam travels through the dielectric films and substrate instead of traveling through the vacuum cavity. Those electrons that travel through material lose energy due to scattering losses and thus form a large, lower-energy peak on the downstream screen. We used the Geant4-based code G4Beamline [4] to model this scattering effect, and the resulting energy distribution of one such simulation is shown in Fig. 3 (left), next to experimental results (right) that are in general agreement with simulation.

As explained previously, the beam overfills the accelerating phase and will have both accelerated and decelerated portions. The acceleration process was modeled using the particle-in-cell code VORPAL [5] to simulate an electron bunch traversing the MAP cavity as a standing wave resonance mode is excited by a side-coupled gaussian laser pulse. The resulting "double-horned" energy spectrum is shown in Fig. 4.

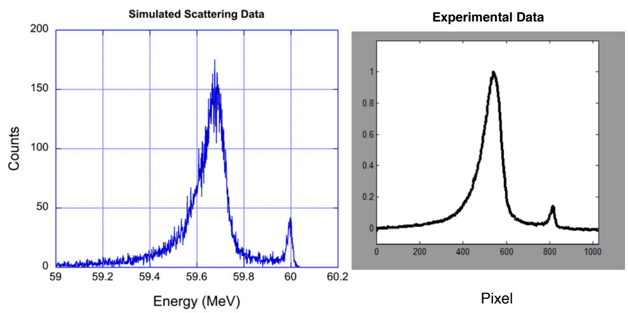

Figure 3: Energy profiles (simulated on the left, experimental on the right) of an electron beam after it has traversed the MAP in the absence of laser fields. The large, lower energy peak corresponds to electrons that have lost energy by scattering with the dielectric materials. The smaller, higher energy peak corresponds to electrons that have passed through the vacuum channel.

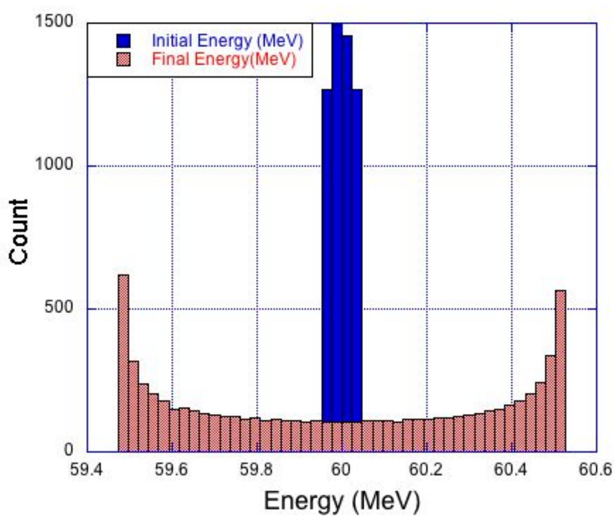

Figure 4: Simulated energy histogram of electron beam after it has passed through the MAP with (red) and without (blue) the accelerating mode excited. Energy modulation due to the accelerating mode results in a broader, double-peaked distribution. Bins are 20 keV wide.

When the accelerating mode is excited, only the beam portion within the vacuum channel will experience an energy modulation; therefore, only the small transmitted vacuum peak (to the right in Fig. 3) will be modified. Nevertheless, the expected acceleration signature has been shown in simulation to be well within the resolution of the experimental diagnostics. As previously explained, the laser timing is randomly varied within a 50-ps interval, using a voice coil stage and delay line, in order to obtain temporal overlap for a portion of the laser shots. For a given delay line setting, we alternate shots with laser on and laser off, enabling us to verify that any modulation in the electron spectrum is due to acceleration rather than systematic effects. A sample pair of laser on and off spectra is given in Fig. 5.

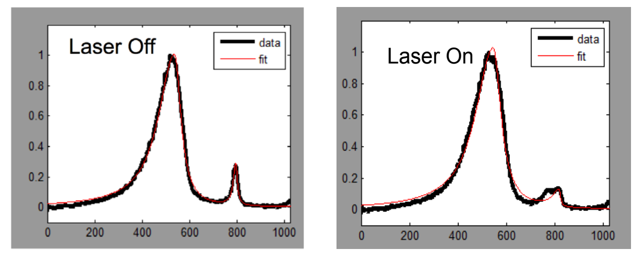

Figure 5: Preliminary experimental results showing the characteristic double-horned distribution when the laser is on, but not when it is off, a possible sign of acceleration.

CONCLUSION

While Fig. 5 (and similar experimental spectra found to date) suggests that acceleration may have been observed in the MAP, verified acceleration results have not yet been obtained. Post-processing analysis is required to demonstrate correlation between the voice coil stage position and the total energy gain obtained from the spectrum; since the accelerating mode remains excited for only a few ps, a cross-correlation can show the range of delays for which acceleration is observed. The effects of laser polarization, fluence, and pulse length on the strength of acceleration also need to be examined in more detail. These efforts, as well as further details of the post-processing analysis, are described elsewhere [6].

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