ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPWA053

FIRST ACCELERATION IN A RESONANT OPTICAL-SCALE LASER-POWERED STRUCTURE

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Abstract

The Micro-Accelerator Platform (MAP), an optical-scale dielectric laser accelerator (DLA) based on a planar resonant structure that was developed at UCLA, has been tested experimentally. Successful acceleration was observed after a series of experimental runs at SLAC's NLCTA facility, in which the input laser power was well below the predicted breakdown limit. Though acceleration gradients were modest (<50 MeV/m), these are the first proof-of-principle results for a resonant DLA structure. We present more detailed results and some implications for future work.

INTRODUCTION

Dielectric Laser Accelerators (DLAs) have the potential to operate with high (~GV/m) acceleration gradients, and represent a path toward extremely compact colliders and industrial accelerator technology [1]. DLA devices are optical-scale microstructures that can be fabricated on wafers via methods developed for the microchip industry, and powered using fiber lasers, which afford very high repetition rates in compact packages. These devices are naturally suited to a novel length and time scale, producing sub-fs, sub-μm and sub-pC bunches at MHz repetition rates.

Experimentally, advanced accelerators are at the proof-of-principle stage [2], with performance metrics including total energy gain, maximum acceleration gradient, and peak field strength. We report here on a series of experimental tests of the Micro-Accelerator Platform (MAP), a resonant DLA based on a slab-symmetric structure. As a resonant (rather than near-field) device, the MAP is distinct from other DLAs [1].

STRUCTURE AND FABRICATION

Theoretical analysis and many fabrication details of the MAP have been described in previous work [3,4]. In brief, the MAP is a slab-symmetric (planar) resonant structure constructed from a pair of partial Bragg reflectors (DBRs), which surround an accelerating gap. Laser power is coupled into the structure through a transmissive diffraction grating placed atop one of the surfaces, which serves to enforce a synchronous accelerating mode within the gap.

Potential dielectric materials used for fabrication are limited to a small class of oxides having high breakdown thresholds, high transparency, and good uniformity. The MAP is constructed on a fused silica substrate, with the DBRs made from alternating layers of hafnia and zirconia for maximum contrast. The MAP structures as built measured 1.0 ± 0.1 mm in length and 1.00 ± 0.01 mm in thickness, with a transverse area of 3.3 mm, comprising 1250 optical periods.

An error tolerance budget was established via simulation, tracking mode quality and resonant frequency shift. The main tolerance constraint is not the mode quality itself, but the need to maintain the resonant frequency within 25 THz. The most restrictive tolerances, on the boundary layers in the Bragg reflectors, are on the order of ±1 nm; and are at state-of-the-art, for many processes.

In practice, dozens to hundreds of half-structures were fabricated at once, diced, then bonded in pairs. Each structure was checked for quality both visually and optically. We note that bonding the structure halves, and determining the exact gap height, are significant technological challenges.

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THE EXPERIMENT

Acceleration tests of the MAP structures were carried out using the E-163 beamline at the SLAC National Accelerator Laboratory's NLCTA facility. The E-163 beamline, with an energy of 60 MeV, is well instrumented for installing and measuring laser-driven accelerators. An rf photoinjector produces electron bunches at a 10 Hz repetition rate, which are pre-accelerated in an X-band linac before interacting with the DLA. The energy spread of each electron bunch is 10 keV, but the shot-to-shot jitter can approach 70 keV when system conditions are poor (Table 1). For acceleration tests, the MAP structure is installed on a positioning stage at the final beam focus, and its upper surface is illuminated by an 800-nm Ti:Sapphire laser, with the laser pulse length matched to the fill time of the MAP accelerator (5 ps). The laser spot is highly asymmetric in order to match the dimensions of the acceleration channel.

Table 1: Un-collimated Experimental Parameters

Parameter	Value
Beam energy	60 MeV
Energy jitter	±50–70 keV
Energy spread (FWHM)	10 keV
Charge per bunch	10 pC
Electron bunch length (FWHM)	1 ps
Beam spot size (FWHM) at IP	
Vertical	(25 ± 10) µm
Horizontal	(50 ± 25) µm
Beam emittance (norm. rms)	2-10 µm
Laser pulse length	5 ps
Laser spot Trans. (x),Axial (z)	50 µm, 1 mm

The beam spot size is far larger than the aperture of the MAP structure (400 nm vertically x 3 mm horizontally). The majority of the electrons will travel through the dielectric material rather than the vacuum gap, thereby losing energy via scattering at a rate of several hundred keV/mm. Only those electrons transmitted through the vacuum gap will emerge unchanged (with no laser present) or experience acceleration (in the presence of laser fields). The measured energy spectrum thus shows two peaks: the larger one, at lower energy, is the scattered beam, with a small peak at 60 MeV containing the transmitted beam. As the electron bunch length is far longer than a structure period, electrons experience all possible acceleration phases, and the signature of acceleration is thus a broadening of the 60-MeV peak, with enhancement at the high- and low-energy extremes, forming a "double-horned" spectrum [5].

Synchronization of electron and laser pulse at the picosecond level was established via a temporal cross-correlation method, in which the relative timing of the laser and electron beams was sampled over a 50-ps window with 0.25-ps resolution. A full description of structure alignment, data collection, and analysis techniques has been presented previously [5].

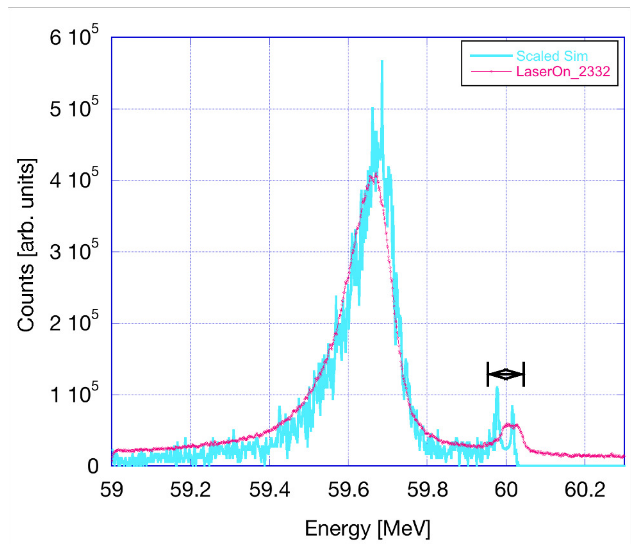

Figure 1: Raw single-shot spectrometer data (red) and simulated spectrum (blue), showing evidence of acceleration in the increased width of the smaller peak.

A total of eight experimental runs using the E-163 facility were performed over 18 months, in which both experimental techniques and structure design were continuously improved. In our final run, successful acceleration was observed and measured. Figure 1 shows a raw spectrogram in which beam energy change is observed. The data is well fit by numerical simulation that models both the intra-dielectric scattering and the laser acceleration within the vacuum channel.

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RESULTS

Figure 2 presents complete time-correlation data from the successful run. A clear signature of acceleration (in which the transmitted electron energy is modulated at the 3σ level compared to the baseline fluctuations) is visible for a laser-electron delay interval of 6–7 ps. The timing overlap is a highly sensitive parameter, requiring ±3 ps of accuracy for acceleration to be observed; this value is comparable to the structure fill time, as expected. Fluctuations in the background are due primarily to variation in the energy and phase of the electron beam earlier in the beamline, which is visible as jitter in the pointing, energy, and energy spread of the beam incident on the MAP structure. Despite filtering to remove the most evident of these poor shots (based on variation in the height and energy of the unaccelerated particles in the scattered peak), it is likely that some percentage of the remaining shots did not meet the conditions needed for successful injection.

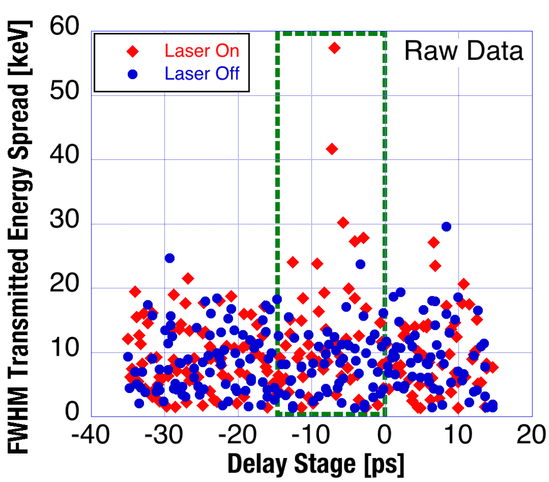

Figure 2: Time correlation data, showing energy spread of the transmitted electron population versus relative laser-electron timing. Energy modulation is observed near –7 ps for laser-on shots (red) but not laser-off (blue).

It is difficult to draw rigorous conclusions about the acceleration gradient from the sparse dataset, but a lower bound of 28 MeV/m can be inferred from the increase in width of the transmitted peak, assuming that the full 1 mm of structure is supporting fields. This data was obtained with a relatively low laser fluence of 0.027 J/cm^2 (estimated damage threshold: 0.2 J/cm^2); however, predicted gradients were considerably higher, at 62 MV/m.. In addition to the sparse sampling, the difference between the predicted and measured values is likely also due to possible structure deformation during insertion, variation in thin-film quality, and degradation of the structure during the experiment. Post-inspection showed occlusion of the gap by peeling or buckling of adjacent dielectric layers, and partial laser damage to the structure. This would result both in a decreased interaction length, as some portion of the structure periods are no longer resonant, and in degradation of the field enhancement.

CONCLUSION

We have shown that resonant standing-wave optical-scale structures can be built and operated. This work evidences control of beam, alignment and tolerances at or near the level required for optical scale structures, and that cumulative errors in fabrication and alignment can be controlled to the level required for signal measurement.

ACKNOWLEDGMENT

Work at UCLA was supported in part by the U.S. DTRA, under Grant HDTRA1-09-1-0043. SLAC/Stanford work was supported by the U.S. Dept. of Energy under Grants DE-AC02-76SF00515, DE-FG06-97ER41276 and by the DARPA under Grant N66001-11-1-4199.

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