BEAM POSITION MONITOR FOR MICRO-ACCELERATORS*

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Abstract

Rapid progress in the development of laser technology and in the sophistication of semiconductor manufacturing has enabled the realization of the first dielectric laser-driven particle accelerator (DLA) on a chip [1]. Since the accelerating channel in DLA structures typically have dimensions in the sub-micron range, the ability to precisely control particle position within these structures will be critical for operation. A number of beam deflection and focusing schemes have been devised, but without the ability to measure the position of the particle beam to nanometer accuracy, these schemes will be extremely difficult to implement.

We present a new concept for a beam position monitor with the unique ability to map particle beam position to a measurable wavelength. Coupled with an optical spectrograph, this beam position monitor is capable of sub-nanometer resolution. We describe one possible design of this device, and present the current status of the structure fabrication and experimental demonstration.

INTRODUCTION

Recent success at SLAC and Stanford have demonstrated the proof-of-principle of the dielectric laser-driven accelerator (DLA) [1]. These dielectric accelerator structures are fabricated using commercially developed lithographic fabrication methods and can be mass produced on conventional dielectric wafers. The accelerator structures are powered using commercially available laser systems, rather than specialized klystrons, and can support peak electric fields well beyond those found in traditional accelerator components. Therefore, DLAs have the advantage of requiring a three-order of magnitude smaller footprint, while boasting significantly higher acceleration gradients than those achievable in traditional accelerator structures. With its inherent advantages, DLAs have the potential to revolutionize the concept of particle accelerators, moving the technology from expensive grand-scale machines to low cost printed microstructures. The applications of compact particle accelerators are numerous and extensive, spanning everything from radiation therapy to x-ray microscopy. While the recent proof-of-principle demonstration is a momentous occasion, the road to a complete particle accelerator-on-a-chip is still an arduous journey. A complete particle accelerator will require the staging of hundreds or thousands of individual dielectric accelerator microstructures, as well as beam focusing and beam deflecting elements – with submicron alignment tolerances. And although nanometer-class alignment of structures within a single wafer is inherent through well-established lithography methods, alignment from wafer-to-wafer does not have a corresponding process. For this reason, beam monitoring elements will necessarily be a critical component for DLA devices.

We present experimental demonstration towards a novel beam position monitor (BPM) which has the ability to map beam position to a measurable wavelength [2]. Coupled with a commercial optical spectrograph, this novel BPM device is capable of sub-nanometer resolution. Additionally, this BPM device can be easily fabricated alongside the DLA accelerator structures, using the same mass-producible lithographic processes; thereby ensuring nanometer-class alignment.

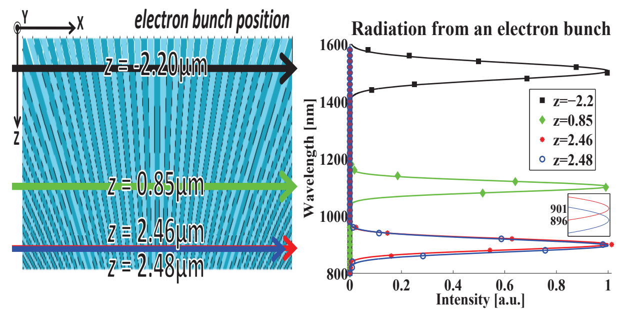

Figure 1: A top-down view of the grating BPM geometry (left), and the predicted normalized radiation spectrum from an electron bunch traversing the grating BPM at four unique positions (right). The markers on the plot represent simulation data, whereas the solid lines depict a Gaussian fit. The inset highlights the distinct radiation spectrum generated by two closely separated bunches.

The geometry of the proposed beam position monitor is shown in Fig. 1. The structure operates on the principles of an inverse-accelerator structure. If a grating accelerator structure can accelerate electrons with a laser pulse, then by reciprocity an electron beam traversing an unpowered grating structure will decelerate (slightly) and radiate. Based on the operating principles of the grating structure as an accelerator, we expect the generated wakefield radiation to be polarized in the direction of beam propagation. Additionally, from the phase-synchronicity condition ($\lambda_{laser} = \lambda_{grating}$), we expect a traversing electron beam to generate wakefield radiation with a center wavelength matching the observed structure periodicity. By varying the periodicity of the grating structure as a function of position, we create a structure which generates position-dependent

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radiation. We can then deduce the position of a traversing electron beam by simply observing the color of the radiation.

We have begun fabrication of a grating beam position monitor with a periodicity varying continuously from 800 nm to 1600 nm. A lithographic mask has be produced, and initial analysis of the exposure of resist on a fused silica wafer look promising, as shown in Fig. 2a. In anticipation of a complete grating BPM structure, we have begun beam-based experiments to demonstrate the proof-of-principle of the BPM device concept. In the following experiments, we verify the operating principles of the grating BPM using a single period grating structure as a stand-in, shown in Fig. 2b. Namely, we verify a polarization dependent radiation, as well as a geometry dependent radiation wavelength.

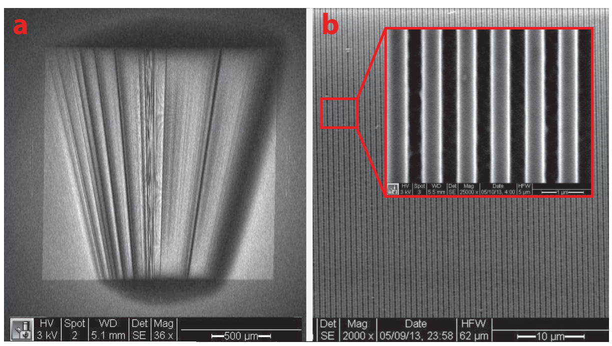

Figure 2: SEM images of (a) the in-progress grating BPM structure and (b) the uniform single period grating accelerator structure.

EXPERIMENT

The experiments were performed at the Next Linear Collider Test Accelerator (NLCTA) at SLAC. The NLCTA beamline is capable of generating a 60 MeV relativistic electron beam, with a bunch length of 130 μm and 5 pC of charge. This electron beam is then focused through a high-field strength permanent magnet quadrupole triplet, which produces a typical beam r.m.s. spot size of 30 x 30 μm^2 at the entrance of our test structure. The test structure itself is mounted on a four-axis stage, allowing for micrometer-precision control of the structure's vertical, horizontal, tip, and rotation with respect to the beam. The structure used in this experiment was the uniform binary dual grating structure optimized for the laser-driven acceleration experiments [1]. In this experiment, a drive laser source was not used to power the structure. Instead, a photomultiplier tube (PMT) was used to monitor the coupling port, along with either a polarizer or a spectrograph to filter the radiation. A simplified schematic is shown in Fig. 3.

In the first experiment, we monitored the strength of the radiation signal filtered by a polarizer. The physics of the grating accelerator predicts a strong wakefield polarization in the direction of the beam trajectory. In our experiment, this will manifest as a cosine-squared pattern in the wakefield intensity versus polarization. We find that our experimental results are in strong agreement with theory, as shown in Fig. 4. This agreement verifies that the nature of the radiation is an inverse-acceleration effect, rather than Cherenkov or optical transition radiation.

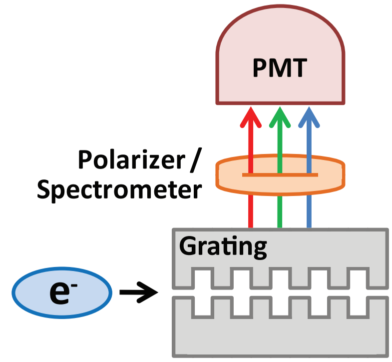

Figure 3: A simplified schematic of the primary components in the wakefield radiation experiment.

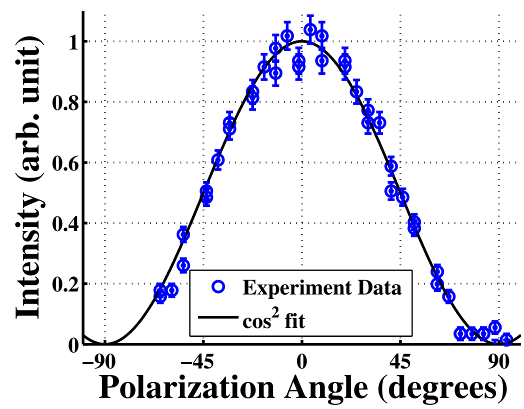

Figure 4: Experimental data (blue markers) showing highly polarized wakefield radiation, which is in strong agreement with theory (black line).

In the second experiment, we monitored the strength of the radiation signal filtered by an optical spectrograph (10 nm slit width). From the electron-laser phase synchronicity condition of the grating accelerator, we expect to observe wakefield radiation with a periodicity matching that of the grating accelerator. A wavelength versus intensity scan of the emitted wakefield radiation reveals a distinct peak in radiation near the design periodicity of the grating structure. We extract the wavelength peak and bandwidth by fitting the recorded wakefield spectrum with an asymmetric Gaussian, as shown in Fig. 5, where we find a center radiation wavelength at 782.5 $\pm$ 9.5 nm. This is in close agreement with the 800 nm design period of the grating structure. The wide bandwidth of the radiation signal is likely due to the 10 nm slit width of the spectrograph.

In the third and final experiment, we varied the rotation of the grating structure relative to the electron beam,

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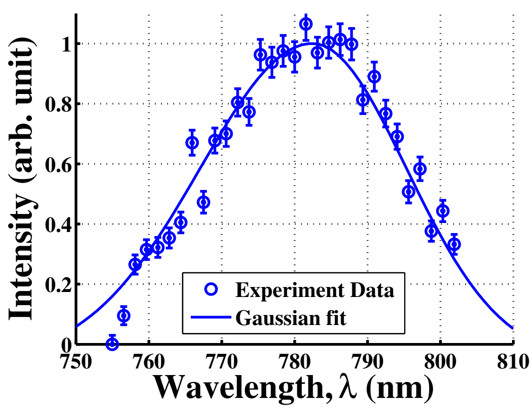

Figure 5: Spectrum of the wakefield radiation as measured by a spectrograph (blue markers). An asymmetric Gaussian fit (blue line) predicts the center wavelength at 782.5 nm with a bandwidth of 9.5 nm.

thereby effectively modifying the grating period observed by the electrons. For a grating structure rotated at an angle ϕ relative to the electron trajectory, the effective grating period λ_e is given by,

$$\lambda_e = \frac{\lambda_0}{\cos\phi} \tag{1}$$

where λ_0 is the nominal grating period. At each grating rotation position, we measured the wakefield spectrum using an optical spectrograph, in the same manner as the previously mentioned experiment. A comparison of the extracted peak wavelength for five unique rotation positions reveals the trend described by Eq. 1. This comparison is shown in Fig. 6.

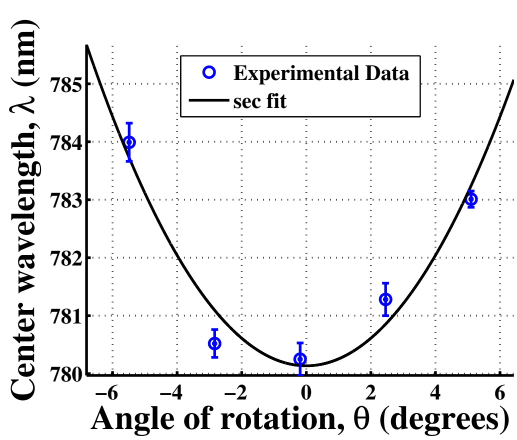

Figure 6: The observed center wavelength (blue markers) at five distinct grating rotation angles. A secant fit to the data (black line) verifies that the radiation wavelength is dependent on the structure geometry.

From these three experiments, we demonstrate the operating principles of the grating beam position monitor. We observed a wakefield radiation signal generated by the inverse-acceleration effect, we measured the spectrum of the wakefield radiation, and we show that the spectrum of the wakefield radiation signal is highly dependent on the geometry of the radiating structure. Future work include the complete fabrication of the continuously variable grating beam position monitor, as well as the beam testing of this device.

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