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DIELECTRIC WAKEFIELD ACCELERATION WITH A LASER INJECTED WITNESS BEAM

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Abstract

The plasma photocathode concept, whereby a two-species gas mixture is used to generate a beam-driven accelerating wakefield and a laser-ionized generation of a witness beam, was recently experimentally demonstrated. In a variation of this concept, a beam-driven dielectric wakefield accelerator is employed, filled with a neutral gas for laser-ionization and creation of a witness beam. The dielectric wakefields, in the terahertz regime, provide comparatively modest timing requirements for the injection phase of the witness beam. In this paper, we provide an update on the progress of the experimental realization of the hybrid dielectric wakefield accelerator with laser injected witness beam at the Argonne Wakefield Accelerator (AWA), including engineering considerations for gas delivery, and preliminary simulations.

INTRODUCTION

In advanced acceleration schemes, there is a consistent effort to achieve higher quality beams. Methods to improve beam brightness include the direct generation of the witness beam within the plasma wakefield bubble by the ionization of a secondary gas at an appropriate phase [1]. In the approach presented here, a gas filled dielectric wakefield accelerator (DWA) with laser injected witness beam (i.e. plasma photocathode) is examined in an experimental context. The hybrid concept aims to generate a high-brightness beam, which can serve as a source for next-generation light sources, and improvements in scientific tools such as ultrafast electron diffraction sources.

The conceptual scheme consists of a drive beam propagating axially through the center of a dielectric capillary filled with a gas. The beam generates a wakefield due to the retarding nature of the dielectric medium. An incoming, co-propagating laser is focused near the maximum of the wakefield behind the drive beam, which locally ionizes the gas. The locally released electrons are then trapped and accelerated by the wakefield. The experiment to demonstrate the proof-of-concept is currently being hosted at the Argonne Wakefield Accelerator (AWA) [2] facility at Argonne National Laboratory, where the initial preparatory runs have already taken place.

SIMULATION RESULTS

The dielectric wakefield accelerator is a cylindrical structure of silicon dioxide ($\epsilon = 3.85$) coated with a thin layer of copper (~ 10 µm). The inner diameter of the cylinder is 500 µm and the thickness of the dielectric is 500 µm. The fundamental frequency for the structure is 103 GHz. The AWA beams for this experiment contain 5 nC charge per bunch with a bunch duration of 3 ps, and an rms bunch radius of 40 µm at the interaction point. The structure is filled with xenon gas for ionization.

GPT simulations [3] are used to study the bunch dynamics at the AWA facility. The simulation results include space charge effects necessary to account for the beam charge at the facility. For this experiment, a 4-bunch drive train is produced, by a multi-pulse laser on the cathode surface, which is transported through the linac to the interaction region. Including effects of apertures, simulations show that over 80% transmission is achievable at the interaction chamber, yielding approximately 5 nC per bunch.

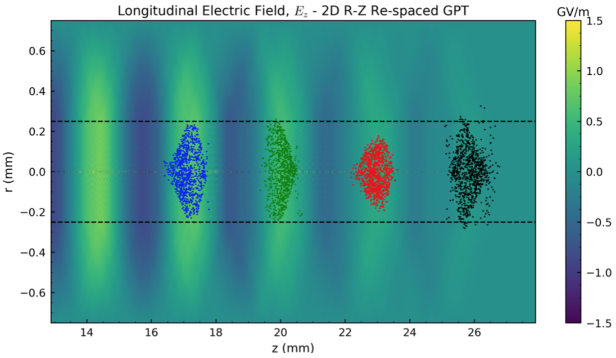

Figure 1: Model of 4-bunch drive train exciting ~GV/m scale wakefields.

WARP simulations [4] are used to study the wakefield effects in the dielectric. For the multi-bunch drive train, with the spacing of the bunches set to resonantly excite the fundamental wavelength, the longitudinal wakefield available for acceleration reaches approximately 750 MV/m (See Fig. 1). This figure includes transverse effects which lead to degradation of the final bunches in the train.

The accelerating wakefield in the dielectric structure does not ionize the xenon gas. When the high intensity laser pulse is introduced electrons are liberated to form the witness beam. The parameters of the witness beam from this plasma photocathode [5] depend on the laser intensity and pulse duration. The main dependencies of the witness beam charge are plotted in Fig. 2. For the available UV laser pulse energy at the AWA (50 µJ and 300 fs pulse duration), a 25 pC witness beam is expected.

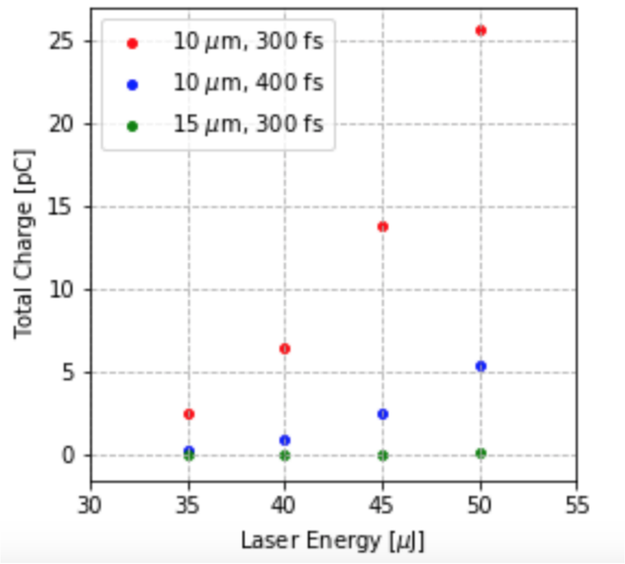

Figure 2: Witness beam bunch charge as a function of laser energy for different spot sizes at focus.

ENGINEERING CONSIDERATIONS

The copper coating was applied by an initial sputtering deposition technique, followed by an electroplating process. Cutting down the capillaries to length (2 cm or 5 cm for the AWA experiments), was performed on a precision diamond saw typically used for silicon wafers (Fig. 3).

The dielectric structure, once coated with copper, also requires an inlet to allow for the delivery of Xe gas. Since the structure integrity had to be maintained, a precision laser milling method was used to drill a ~400 µm hole in the structure. The custom ablation technique is well calibrated and highly precise, and more appropriate for the dimensions and delicacy of the dielectric structure than standard machining or microfabrication techniques [6]. Although it should be noted that, once coated with copper, the dielectric wakefield structure is fairly robust.

The first measurement at AWA was a study on the potential escape of Xe gas and its effects on quantum efficiency of the beamline cathode. While the differential pumping system was already tested, and allowed for windowless operation, the effects of Xe impingement on the cathode were uncertain. In a controlled test setup, a controlled leak of Xe was introduced while the quantum efficiency was monitored. No observable change was recorded during this test. Based on these results, the gas delivery system was set up at the interaction chamber. The gas delivery tube is made of ceramic with a conical tip just long enough to cover the thickness of the silicon dioxide dielectric through the hole. Both the gas delivery tube and the inlet aperture on the copper cladding of the dielectric structure are pictured in Fig. 4.

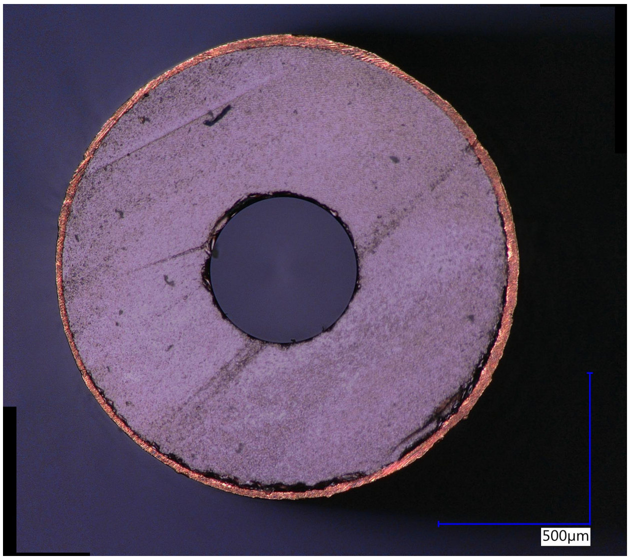

Figure 3: Head-on optical microscope image of copper clad dielectric structure. The dielectric material is silicon dioxide with inner diameter of 500 µm and thickness of 500 µm.

The extra attention to gas delivery, as opposed to filling the entire chamber with xenon, was needed to minimize gas load on the turbomolecular pumps so that the chamber maintains appropriate vacuum levels during operation. The incorporation of a rapid-action valve allows for gas pulses of 40–400 µs duration at repetition rates matching the beam repetition rate. The gas puffer, with the differential pumping setup, allows for windowless operation, which is a necessity such that the drive beam emittance is not affected by scattering through a window or foil prior to introduction into the dielectric structure.

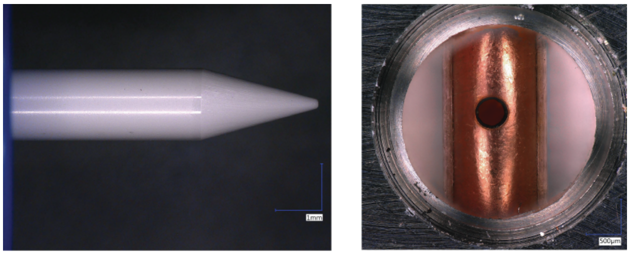

Figure 4: Left: Conical, ceramic, gas delivery tube, where the conical end has a length of 300 µm. Right: Close-up photograph of laser drilled inlet in the copper-clad capillary.

The entire assembly is set into an aluminum mount that is attached to a 5-axis manipulation arm for alignment in all relevant degrees of freedom. Visual inspection of the tube is possible from the window ports on the central chamber. An off-axis paraboloid mirror is used to inject the high intensity laser. The mirror is co-aligned with the structure and incorporates a hole on-axis to allow the drive beam to pass through. The mirror is placed just upstream of the structure such that the focus of the laser is within the dielectric. Synchronization of the laser pulse with the drive beam is accomplished using a delay stage, where the laser delay can be varied to sample different phases of the wakefield to scan for optimal trapping and acceleration of the witness pulse.

FIRST EXPERIMENTAL RUN

During the first experimental run, a number of concerns were addressed in a practical environment, as the experiment requires many seemingly disparate components to operate at the same time. The main goal was the preparation of the 4-bunch drive train. The effort was two fold: to generate the appropriate bunch length and charge and to achieve the target bunch-to-bunch spacing of 2.9 mm. The bunch generation and spacing were achieved and transported to the interaction region, and subsequently to the diagnostic line. The temporal profile of the bunches is presented in Fig. 5, which shows four bunches at the desired spacing of 2.9 mm. The spacing between bunches is established from the laser pulse train on the cathode, where each laser pulse is controlled by a delay stage. When the pulses are sent through the dielectric structure, the last two bunches are degraded in terms of overall charge. This is attributed to the transverse wakefields excited through the structure. The effect is more severe than predicted by simulation and effectively reduces the overall longitudinal wakefield strength to less than 500 MV/m. While different methods to mitigate the effects of transverse wakefields are planned for future studies, further experimental work in alignment should lead to improved transmission of the entire bunch train.

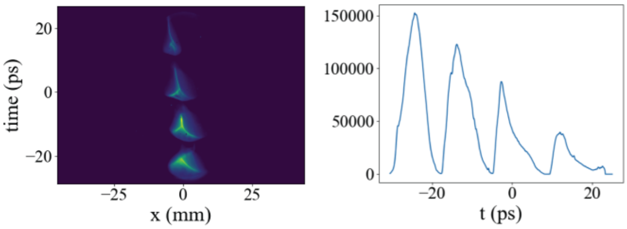

Figure 5: Left: Streak camera image of 4-bunch train with 2.9 mm spacing. Right: Histogram (vertical axis shows intensity count on detector) of the 4-bunch train showing the degradation of the final bunch.

Also, during the initial preparatory runs, the gas delivery system was tested. It was observed that the pulsed gas puffer operated in the nominal fashion, while the neighboring vacuum in the beamline remained unperturbed. This step was necessary to allow windowless operation so that the beam emittance would not be spoiled when entering the structure. An additional test of the injection laser delivery was also conducted at the same time, and the focal spot of the laser was transported into the dielectric structure from the off-axis paraboloid mirror. In addition, both coarse and fine timing of the laser pulse were demonstrated during the run.

SUMMARY

The dielectric wakefield acceleration experiment with a plasma photocathode generated witness beam has been designed and implemented at the AWA facility. The initial runs showed that the engineering challenges were successfully addressed and that the gas delivery system implementation was adequate for future ionization experiments, and also compatible in the differential pumping configuration for windowless operation. In addition, the experiment focused on preparing the drive beam, in a 4-bunch modality with appropriate bunch-to-bunch spacing for resonant wakefield excitation as determined by streak camera measurements. A consequence of the experimental runs was the discovery that the transverse wake effects, in practice, were more pronounced than in initial simulations, leading to degradation of the final bunch in the train.

The follow on experiments include opportunities for testing the complete scheme, with plasma photocathode beam generation and acceleration in the DWA. The diagnostics line is well equipped for characterization of the low energy witness beam, with the ability to measure the complete longitudinal phase space and transverse profile screens for emittance measurements. Upcoming experiments will also used advanced dielectric structures [7, 8], that are specially tailored to mitigate effects of transverse wakefields with appropriately shaped drive beams.

ACKNOWLEDGEMENTS

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