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STATUS ON A LASER INJECTION IN BEAM DRIVEN DIELECTRIC WAKEFIELD ACCELERATOR EXPERIMENT

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Abstract

The generation of high-brightness beams with ultra-low emittance using the plasma photocathode technique has gained significant traction in recent years. The practical execution of a combined plasma wakefield acceleration section and a laser injected typically requires a dual gas medium for precision ionization of low and high ionization thresholds. The concept can be partially simplified in experiment by replacing the plasma wakefield acceleration component with a dielectric wakefield acceleration scheme, sacrificing field gradient but maintaining low emittance beam generation. In this paper, we describe the progress on the design of a hybrid scheme, using laser injection in a gas medium within a dielectric wakefield accelerator structure. The proof-of-concept experiment is planned to take place at the Argonne Wakefield Accelerator.

INTRODUCTION

Beam brightness is a key parameter in practical particle accelerator applications, such as ultra-fast electron microscopy [1] and diffraction with temporal resolution on the sub-picosecond scales. Adapting advanced accelerator methods to these needs is critical for achieving high brightness beams beyond traditional means. A relevant example is the plasma photocathode and blow-out acceleration technique, so called Trojan Horse, where the plasma can sustain accelerating gradients approaching 100 GV/m [2]. In this technique, the solid cathode is replaced with a gas that is ionized by an intense laser pulse which is precision timed to the accelerating phase of the wakefield behind the driving electron beam. The Trojan Horse method produces low emittance beams but is quite challenging experimentally [3], due to the short plasma wavelength (~100 µm), strict timing demands (~10 fs between drive beam and injection laser), and non-linear effects of the field on the witness beam properties leading to consequences such as large energy spread.

The experimental complexities of the Trojan Horse technique can be reduced for lower-charge applications with simple replacement of component systems. In this method which we call the Capillary Trojan Horse (CTH), we replace the plasma wakefield accelerator with a dielectric accelerator [4], while maintaining the plasma photocathode technique. An illustration of the concept is shown in Figure 1. A drive bunch (or bunch train) travels through a dielectric lined waveguide exciting a wakefield. Following the drive beam, a laser ionizes a diffuse gas that is inside the tube, generating electrons that are essentially at rest. For the appropriate phase, these electrons are captured by the wakefield from the drive beam and accelerated to the desired energy.

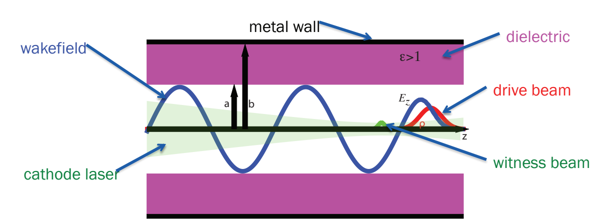

Figure 1: Sketch of dielectric lined waveguide with inner/outer radii a/b, and injection laser profile in green shadow, drive beam profile in red, and wakefield in blue. The acceleration channel is filled with diffuse gas. Laser ionization occurs at optimal position for trapping and acceleration.

A dielectric lined structure filled with a single gas species, operating at ~mm wavelengths leads to reduced timing tolerances. High gradients (>500 MV/m) are achievable [5] and will reduce the emittance degrading effects of space charge, while single mode excitation will improve the final energy spread of the electron beam.

In this paper we describe an experimental program to demonstrate key facets of this concept. An important point is that the longitudinal trapping condition, establishing required properties of the electron beam driving the wakefield, necessitates high charge (several nC), or bunch train, operation. The Argonne Wakefield Accelerator facility (AWA) at Argonne National Laboratory provides unique beam properties that are appropriate for demonstration of the proposed hybrid scheme. The AWA operates an L-band photo-injector capable of producing 100 nC electron bunches of 10s of picoseconds duration. In addition, AWA runs state-of-the-art lasers with ample UV power for ionizing the background gas required to make the high brightness witness electron beam.

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Finally, the AWA has a long history of dielectric wakefield acceleration experiments [6], recent success in plasma wakefield acceleration studies [7], and single-shot longitudinal phase space diagnostic capabilities [8].

SIMULATIONS

For the CTH experimental program, the AWA provides electron beams of 60 MeV, in a 4-bunch modality. The bunch train spacing allows for selective single-mode operation by coherent excitation of specific modes [9]. For the CTH experiment, the dielectric lined waveguide is composed of SiO_2 ($\epsilon = 3.8$), of inner/outer radii of 250 / 750 µm, with a metal cladding, and a corresponding fundamental wavelength of 2.9 mm. The simulation of the process includes modeling and optimization of the driver multi-bunch evolution and subsequent modeling of the wakefield and injection laser for the witness beam dynamics. The code, General Particle Tracer (GPT) [10], is used extensively for modeling the AWA beamline which must account for space charge and coherent synchrotron radiation effects. The drive bunch train is optimized to include four bunches, with equidistant spacing at the fundamental wavelength, for optimal wakefield generation and maximal transmission. Operation with four bunches, as opposed to a singular high charge bunch, allows for lower current in each bunch to mitigate the emittance growth due to space charge and transport through the sub-mm aperture of the dielectric structure. In the GPT models, the 4 bunch, 5 nC per bunch, distribution consists of 10k macro particles and is focused near the central axis of the dielectric structure.

The simulation for the wakefield dynamics is setup in 2D Cartesian geometry, using the Warp code [11], which reduces on-axis noise (compared to the r-z cylindrical geometry). The initial structure tested for simplicity is a planar structure with inner and outer half-gap of 250 µm and 750 µm respectively. Although the field is lower for the planar structure, the relatively fast turn-around time on the calculations allows for setup optimization during the initial studies. The simulation consists of a 40 ps (1.2 cm) duration of propagation. The initial results of the Warp simulations are shown in Figure 2. The locations of the individual drive bunches are represented by vertical dashed lines. It is evident that the bunches cooperatively contribute to the growth of the wakefield up to ~2 GV/m. While such fields are attractive, there is strong incentive to remain below GV/m acceleration gradients due to adverse effects on dielectric conductivity at high fields. Yet, the achievable gradients enable flexibility in the design of the CTH scheme with AWA drive beam parameters.

The first attempts of studying injection, showed that a > 10 fC witness beam is generated, however the initial emittance of ~nm grows about a factor of three, attributable to the transverse wakefield generation of the leading high-charge drive beam. While appreciable, the emittance growth is still within acceptable values for specific applications. The injection process will continue to be modeled using Warp-X, which permits use of advanced algorithms, including boosted frame and mesh refinement, to resolve fine features in the witness beam phase space, which is orders of magnitude shorter than the acceleration length of the experiment.

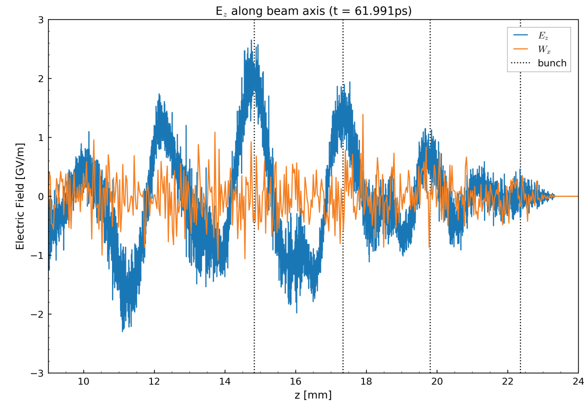

Figure 2: Wakefield simulations using WARP for the 4-bunch train. The centroid locations of the indiviudal bunches are marked by vertical dotted lines, the longitudinal field is given in blue, and the transverse fields in orange.

EXPERIMENTAL LAYOUT AND CONSIDERATIONS

Due to the relatively short spacing of the bunches in the train, both the transmission and the average energy difference between bunches are critical considerations for the application of the CTH concept. Enhancement is achievable via the separate control of the individual laser parameters for each individual bunch and the adjustment on gradient and phase of gun and linac sections at the AWA. The results will provide an initial point for machine development and beam commissioning for the bunch train.

Additionally, a Beryllium window may be required to separate the plasma gas (Xenon) from the drive beam photocathode (Cs_2Te). Tests are underway to determine if the Be window is necessary, due to degradation of quantum efficiency of the Cs_2Te cathode after exposure to Xenon gas. Molecular flow calculations show that differential pumping schemes, coupled with fast valve puffers, may provide the necessary evacuation of gas for adequate vacuum levels.

The proposed experiment layout is sketched in Figure 3. In the layout, the bunch train is collimated through the dielectric structure using a focusing quadrupole triplet. The injection laser is transported and focused using an off-axis parabolic mirror. The mirror has a focal length of 6-inches, and a 5 mm hole on center, which allows for the unperturbed traversal of the electron beams to the diagnostic line. The diagnostic line consists of an integrating transformer for charge measurements, a transverse deflecting cavity for temporal measurements, and a dipole spectrometer for energy characterization. When coupled together, the deflector and spectrometer provide the entire beam longitudinal phase space in a single shot. The spectrometer is tunable to provide adequate resolution since the witness beam is much lower charge and at different energy than the drive bunches.

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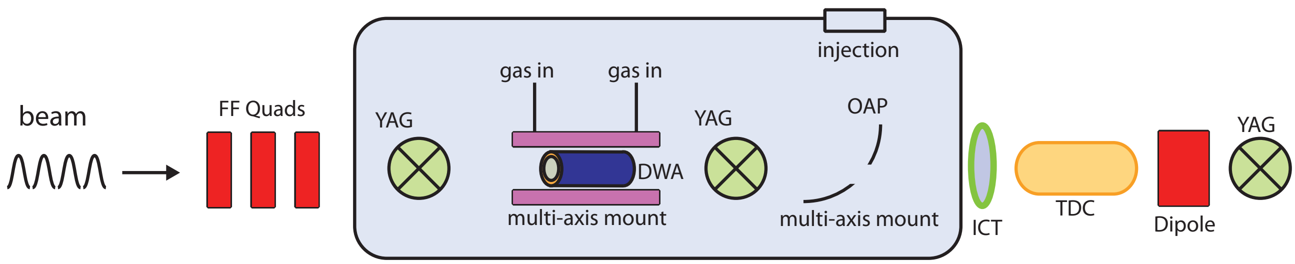

Figure 3: Sketch of the experimental layout. The bunch train is focused through the dielectric capillary using a matching quadrupole triplet. YAG scintillator screens as used for alignment of the beam trajectory to the laser spot. The dielectric structure is mounted on a 5-axis positioner for precision alignment with gas inlets. An off-axis parabolic mirror, with a centered hole, is used to focus the injection laser. Downstream diagnostics include charge and full longitudinal phase space.

The challenges of engineering the hybrid dielectric/gas accelerating structure include tight tolerances for alignment of the <10 cm long structure with 5-axis precision control, and the added complexity of introducing the gas within the capillary at a reasonable flow rate. A candidate rendering for an experimental chamber is shown in Figure 4. The main features of the interaction region chamber include maintaining adequate ultra-high vacuum levels in the neighboring transport, while providing flexibility for remote control precision movement and alignment of the dielectric structure. Simultaneously, the laser injection system includes a collimating optic to attain the appropriate intensity to ionize the Xenon gas. The chamber provides numerous ports for optical and electronic feedthroughs.

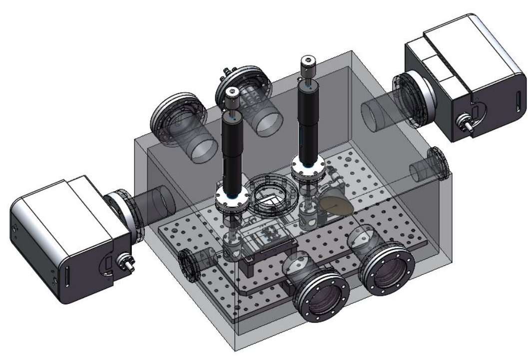

Figure 4: Rendering of experimental chamber and subcomponents, including beam diagnostics, laser injection feedthrough, and pumping ports.

In conclusion, the CTH experiment to demonstrate a hybrid plasma photocathode concept within a dielectric wakefield acceleration channel is designed for deployment at the AWA facility. Integral questions on windowless plasma operation with a CsTe cathode will determine the drive beam quality available for high gradient operation. Continued studies with 3D PIC software will guide the experimental progress and analysis of the witness beam properties. The results of the CTH tests are valuable for advanced acceleration concepts and may provide a reasonable compromise in complexity for low-charge, low-field applications.

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REFERENCES

[1] R. K. Li and P. Musumeci, "Single-Shot MeV Transmission Electron Microscopy with Picosecond Temporal Resolution", *Phys. Rev. Applied*, vol. 2, p. 024003, 2014.

[2] B. Hidding *et al.*, "First Measurements of Trojan Horse Injection in a Plasma Wakefield Accelerator", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 1252–1257.

[3] B. Hidding *et al.*, "Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout", *Phys. Rev. Lett.*, vol. 108, p. 035001, 2012.

[4] G. Andonian *et al.*, "Dielectric Wakefield Acceleration of a Relativistic Electron Beam in a Slab-Symmetric Dielectric Lined Waveguide", *Phys. Rev. Lett.*, vol. 108, p. 244801, 2012.

[5] B. O'Shea *et al.*, "Observation of acceleration and deceleration in gigaelectron-volt-per-metre gradient dielectric wakefield accelerators", *Nat. Comm*, vol.. 7, pp. 1–7, 2016.

[6] W. Gai *et al.*, "Experimental Demonstration of Wake-field Effects in Dielectric Structures", *Phys. Rev. Lett.*, vol. 61, pp. 2756-–2758, 1988.

[7] R. Roussel *et al*, "Transformer Ratio Measurements from Ramped Beams in the Plasma Blowout Regime Using Emittance Exchange", presented at the 10th International Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May. 2019, paper THPGW088, this conference.

[8] Q. Gao *et al.*, "Single-shot Wakefield Measurement System", *Phys. Rev. Accel. Beams*, vol. 21, p. 062801, 2018.

[9] G. Andonian *et al.*, "Resonant excitation of coherent Cerenkov radiation in dielectric lined waveguides", *Appl. Phys. Lett.*, vol. 98, p. 202901, 2011.

[10] S. B. van der Geer *et al.*, "3D space-charge model for GPT simulations of high brightness electron bunches", *Institute of Physics Conference Series*, vol. 175, p.101, 2005.

[11] J. L. Vay, "A domain decomposition method for pseudo-spectral electromagnetic simulations of plasmas", *J. Comput. Phys.*, vol. 243, p. 260, 2013.