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DESIGN AND MODELING OF DIELECTRIC A WAKEFIELD ACCELERATOR WITH PLASMA IONIZED WITNESS BUNCH

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Abstract

A planned experiment at the Argonne Wakefield Accelerator (AWA) facility will demonstrate the plasma photocathode concept, wherein precise laser-based ionization of neutral gas within the wakefield driven by a relativistic particle beam generates a high brightness witness beam, which is accelerated in the wakefield. Replacing the plasma wakefield acceleration component with a dielectric wakefield acceleration scheme can simplify experimental realization by relaxing requirements on synchronization and alignment at the expense of accelerating gradient. However, this places rigorous constraints on drive beam dynamics, specifically charge, size, and relative separation. This paper presents progress on the design of such a hybrid scheme, including improved simulations accounting for anticipated beam properties and revised structure characteristics.

INTRODUCTION

Many applications can benefit from compact sources of ultrahigh brightness MeV-scale electron beams. The plasma photocathode technique, as demonstrated by the so-called "Trojan-Horse" scheme, leverages the low emittance of an RF photocathode with the accelerating and focusing properties of a plasma accelerator [1]. However, such a scheme requires sophistication, leveraging a two-component gas to act as the witness beam source and plasma waveguide, and necessitating fs-scale synchronization between an ionization pulse and the accelerating bucket, which is of the orders of hundreds of microns [2]. The use of dielectric structures to provide the accelerating response eliminates the need for multiple gas species, easing restrictions on chamber design and target optimization. Furthermore, the ten-fold larger wavelengths accessible by dielectrics significantly reduce spatiotemporal demands on the beam-laser synchronization and diagnostics. Figure 1 depicts the basic concept [3].

To realize this scheme with a dielectric accelerator, a series of experiments are underway at the Argonne Wakefield Accelerator (AWA) facility. The AWA operates an L-band photoinjector capable of producing up to 100 nC electron bunches with short duration, and possesses appropriate short-pulse lasers for ionizing the witness beam. The proposed experiment will generate a four bunch train to propagate through a dielectric lined cylinder. The four bunches are spaced at the fundamental wavelength of the structure to resonantly excite a trailing wake, and the bunch charge is high enough to drive a wake sufficient to capture an ionized electron beam from rest. More details regarding prior efforts can be found in [3].

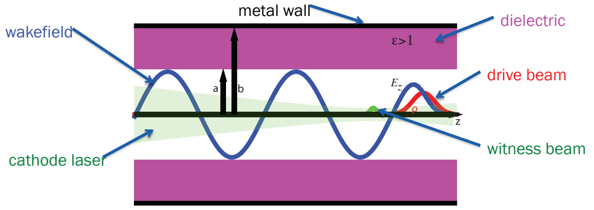

Figure 1: Illustration of the dielectric plasma photocathode scheme, wherein a laser-ionized witness bunch is accelerated in the trailing wake of a beam traversing a dielectric-lined structure, from [3].

WITNESS BEAM IONIZATION

Injection of a high quality witness beam is achieved by ionizing a narrow region of plasma synchronous with the beam-driven wake. Subsequent acceleration of the witness beam is sensitive to the location and timing of the ionization relative to the wake, as well as the space charge forces of the ionized electrons, which are emitted at near rest. The AWA features a 266 μm frequency-tripled Ti:Sapphire laser to provide ionization. We considered a range of energies (50-300 μJ) with a full-width half maximum of 300 fs to achieve sufficient peak intensities to ionize the gas.

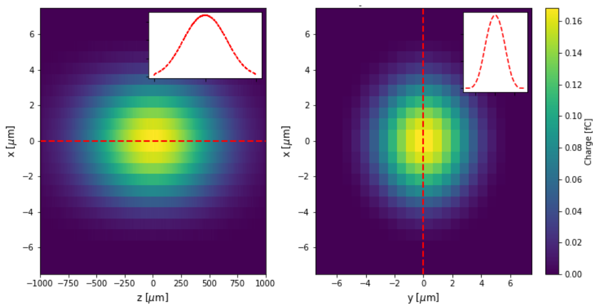

Figure 2: Example longitudinal and transverse profiles of electrons ionized from a 50 uJ pulse focused to a 2mm spot.

With these parameters, ADK ionization is the primary mechanism by which ionization occurs. Because the laser pulse and wavelength are so short compared to the ionization region, particle-in-cell modeling of the process requires extremely high resolution to avoid numerical aberrations, and is impractical for scans of different parameters. Our approach reduces the laser representation to an analytical form for a Gaussian pulse, while the background gas is represented as a reservoir from which electrons and ions may be released. While the resulting laser propagation is no longer self-consistent with changing plasma properties, the background density is low enough to prevent significant

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ionization-induced defocusing. For a given laser and gas configuration, we compute the ionization on a per-step basis, writing to file both the time-signature of the electron production and the cumulate ionized distribution. The time-signature can be used to reconstruct the ionization process for loading electrons into witness beam simulations, as described later. Figure 2 depicts an example ionization profile.

BUNCH TRAIN SPACING CONSIDERATIONS

Coordinating a four bunch train to resonantly excite the wake while maximizing bunch transmission within a narrow structure introduces many practical challenges. While the structure is designed for 100 GHz operation (3 mm spacing), the AWA photo injector may produce beams with varying inter-bunch spacings, either with systematic or stochastic offsets from the design spacing. We considered the influence of these spacings on the resulting wake structure, frequency, and accelerating region amplitude. Figure 3 shows the simulated longitudinal wakefields generated by bunch trains with two different spacings; for 3mm bunch spacings the fundamental mode is resonantly excited, while spacing the bunches by a larger distance (3.34 mm) introduces higher order mode content that modifies the trailing wake and reduces its accelerating capacity.

A TAPERED STRUCTURE CANDIDATE

To improve capture efficacy, we consider tapering of the outer radius of the structure to gradually increase the wavelength of the excited mode. By maintaining the same inner radius, the reduction in wakefield amplitude is minimized. Figure 4 depicts CST mockup of such a structure, for which the outer radius is increases from 675 micron to 800 micron along the length of the structure. For this structure, the inner radius is also reduced to 200 microns to increase the peak field while maintaining a wavelength > 3 mm throughout the structure. Figure 4 shows the on-axis accelerating fields.

The use of such a structure can help improve energy transfer into the accelerating mode of the structure while also modifying the phase velocity of the wake to relax capture requirements. Figure 5 depicts the accelerating region of the wake for the tapered structure alongside the excited modes of the 3mm structure for different bunch spacings described above. Figure 6 shows an FFT of the excited fields, confirming that proper spacing reduces HOM content, as does the use of a tapered structure.

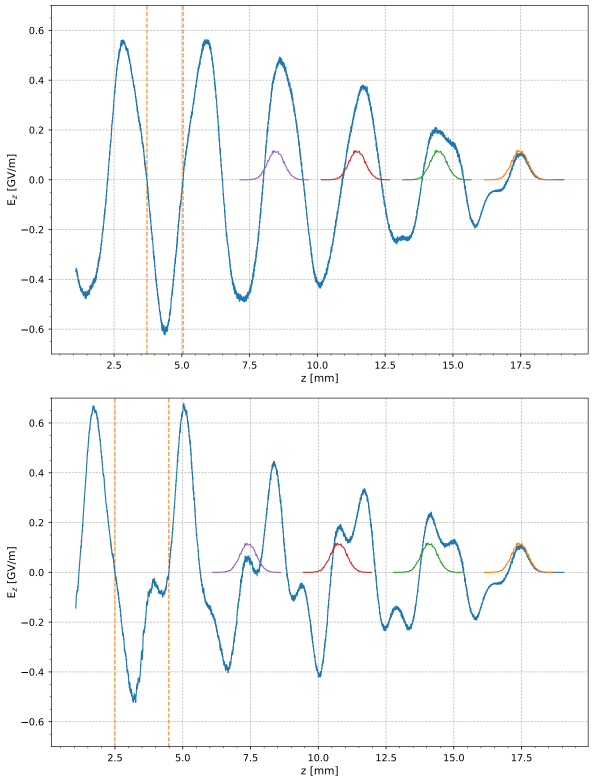

Figure 3: At top, the excited longitudinal wake for a 3mm spaced bunch configuration showing constructive wake addition. Below, the excited longitudinal wake for a mismatched drive bunch with spacing 3.34 mm excites HOM contributions that can narrow the accelerating regions and reduce peak fields. Dashed lines show the accelerating bucket region considered for injection.

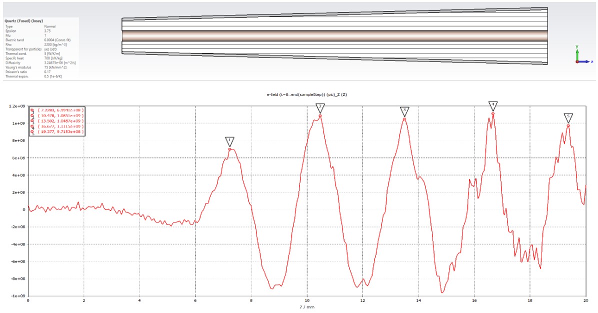

Figure 4: Above, a cutout of the CST cylinder. Below, a central profile of the longitudinal fields generated by a CST simulation, after the center of the bunch train has traversed the entire structure.

WITNESS BEAM PROJECTSION

We model the evolution of an estimated witness beam in Warp, using spatiotemporal profiles from the ionization studies to load the witness beam at the wake crossing point with a time signature consistent with the co-propagating ionization laser. We then track the beam evolution in response to externally loaded longitudinal wake fields computed from Warp simulations of the drive beam. The simulations provide initial estimates of the capture efficacy and resultant phase space profiles anticipated after 2 cm of transport within the structure. We note that the best results are obtained from the narrow, tapered structure, while the mixed spacing drive bunch configuration with reduced transmission captures significantly less charge. More studies are needed to maximize drive bunch transmission through a realistic structure.

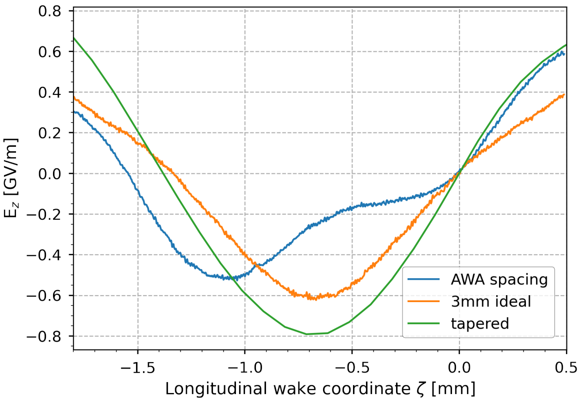

Figure 5: Excited accelerating wakes for different structures and spacings.

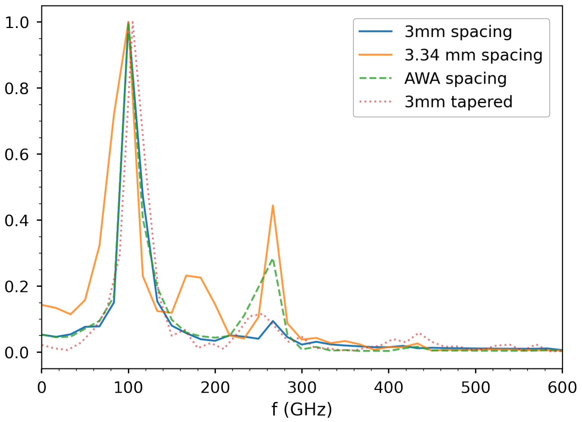

Figure 6: An FFT of the wakefields produced by varying drive beam spacings and geometries illustrate the influence on frequency content of the excited modes as spacings move away from the resonance condition.

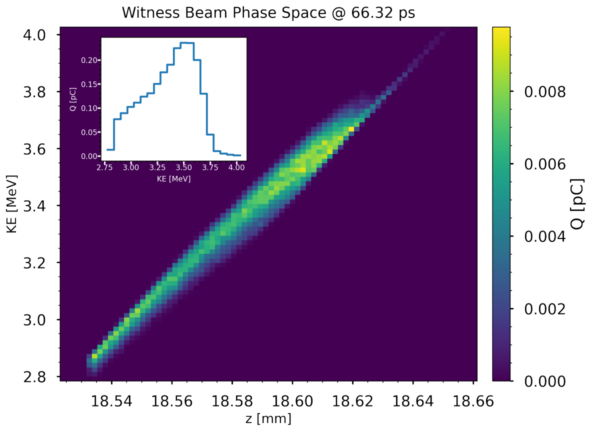

Figure 7: Simulated witness beam longitudinal phase space when accelerated by a 16 nC train with 3 mm bunch spacing.

CONCLUSION

We are exploring a hybrid plasma photocathode dielectric wakefield acceleration scheme, wherein a laser-ionized witness beam is accelerated by a beam-driven dielectric wakefield accelerator. We have identified a realistic structure and drive bunch train to achieve sufficient gradients for capture and acceleration, along with ionization laser and gas parameters for producing the witness bunch. Proof of principle experiments are underway at the AWA. Ongoing simulation studies are exploring sensitivities to drive beam spacing, while novel tapered structures remain in consideration for increasing witness beam energy and quality.

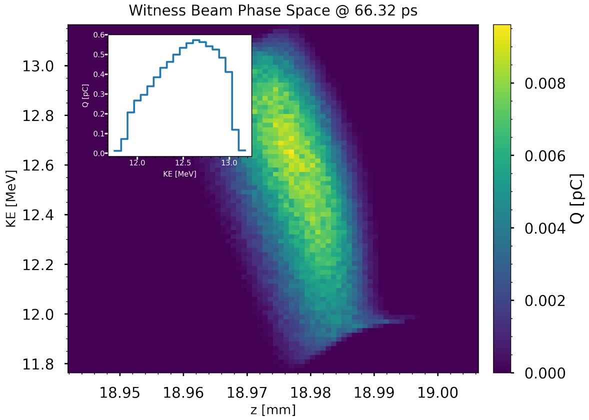

Figure 8: Simulated witness beam longitudinal phase space when accelerated by a 16 nC train through a tapered structure with 200 micron inner radius

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