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MODELING OF DIAMOND FIELD EMITTER ARRAYS FOR SHAPED ELECTRON BEAM PRODUCTION

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Abstract

We present simulations of shaped electron beam production from diamond field emitter array (DFEA) cathodes [1, 2]. DFEAs are arrays of diamond pyramids with bases of the order of 10 microns that produce high current densities. These arrays can be fabricated in arbitrary shapes such as a triangle or a double triangle, so that they produce an inherently shaped beam. These transversely shaped beams can be put through an emittance exchanger (EEX) [3-7] to produce a longitudinally shaped electron beam distribution for use with high-transformer ratio wakefield accelerators. Simulations are conducted with MICHELLE. We design cathodes and focusing systems that preserve the beam's shape while transporting it to the emittance exchanger.

WHY SHAPED BEAMS

Dielectric wakefield accelerators (DWA) are an emerging alternative accelerator schematic to reduce the footprint of traditional accelerators. DWAs are capable of achieving acceleration gradient on the order of 1 GV/m with 100 MV/m demonstrated [8, 9]. This high gradient performance depends on a high transformer ratio (TR), the ratio of the peak accelerating gradient to the peak decelerating gradient experienced by the drive bunch. To achieve a high TR, we must shape the electron beam.

Recently a double triangle longitudinal bunch beam shape was proposed that makes it possible to achieve high transformer ratios [4, 5]. The double triangle beam shape makes it possible to achieve high TRs with nearly uniform drive bunch deceleration.

There are two fundamental approaches to achieving a longitudinally shaped beam: direct and exchange based. In the first approach, the longitudinally shaped electron bunch is produced directly at the cathode by varying the parameters of the electron gun that determine the current. However, existing pulsed power systems do not allow for time scales on the order of ps, which are essential for accelerator applications such as DWAs.

In an exchange-based approach, the required beam features are introduced in a transverse plane of the electron beam, and then the beam's transverse phase space coordinates (x, x') are exchanged with the longitudinal phase space coordinates (z, δ) through electron beam manipulations, leading to a longitudinally shaped electron beam. The electron beam manipulations are conducted by means of an EEX that consists of two identical doglegs and a transverse deflecting cavity in between, as seen in Fig. 1.

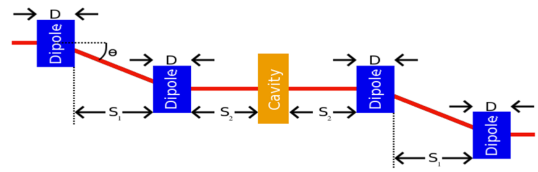

Figure 1: Typical EEX schematic.

Presently, the shaped beam can be made in transverse phase space with a mask and then be transformed to longitudinal phase space with an emittance exchange (EEX). This experiment was recently performed at Argonne Wakefield Accelerator [6, 7], the disadvantageous for this method include a loss of up to 80% of the electron beam, hazardous x-ray production, and beam jitter. We propose using DFEAs for creating the shaped beams without need of a mask, eliminating the issues of lost beam current, inconsistent shape due to jitter, and hazardous x-rays.

MODELING OF THE DFE SINGLE TIPS

Single tip simulations were performed using MICHELLE [9, 10]. The simulations present numerous challenges due to unknowns about the tip geometry, the impact of tip size variation on the surface E-field, and the small feature size. In addition, experiments show that tip emission is statistical in nature, generally following a log-normal distribution [11]. MICHELLE has the option to overwrite the field-enhancement factor (FEF) to achieve current emission on the order achieved in the experiments, this allows us to account for the sharpness of the emitter tips without impractically large meshes. The first single tip simulations were performed with a very high resolution mesh encompassing the pyramid shape of the emitters and a rounded emission tip. The artificial FEF was then adjusted to approximately match the measured beam current from experiments. These simulations show good correlation with available experimental data using an applied field of 11.63 MV/m, we get a current of 14.05 uA in the simulation and 15.27 uA in the experiment. This uses an artificial FEF of 2.0 to account for the lack of sharpness in the simulated tip geometry. Mesh of the single tip simulation and beamlet profile can be seen in Fig. 2. In addition, a line-charge model for field emission has been developed in MICHELLE that allows one to mesh flat emission surfaces and use a virtual tip for field emission [12], these simulations were also performed and show a better correlation with beamlet size and spread than their tip-resolved counterpart simulations.

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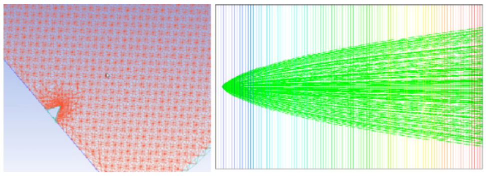

Figure 2: Single tip simulation mesh detail (left) and beamlet profile (right).

MODELING OF THE DFE ARRAYS

Three dimensional simulations were performed in MICHELLE 3D. To simplify the geometry for 3D simulations, we use 'minion' shape emitters to manage the mesh size while still providing height off the substrate which creates a more correct surface E-field distribution. The minion emitters and the electron beam simulation can be seen in Fig. 3. An artificial FEF was still needed to account for the lack of sharpness in the simulations, this was chosen as 3.6 to better match the current emission from the arrays in experiments (in our experiments, current per tip does not scale with the Fowler-Nordheim curve because of the log-normal statistical emission factor). A robust simulation was performed with the minion shaped emitters approximating DFE pyramids with a base of 25u and a periodicity of 25 um. This array produced a beam of 3.55 mA, 6 mm mrad emittance, with 86 DFEs, and an energy of 10 kV. This beam was exported to be used in transport and electron gun simulations. There is no magnetic field on the cathode.

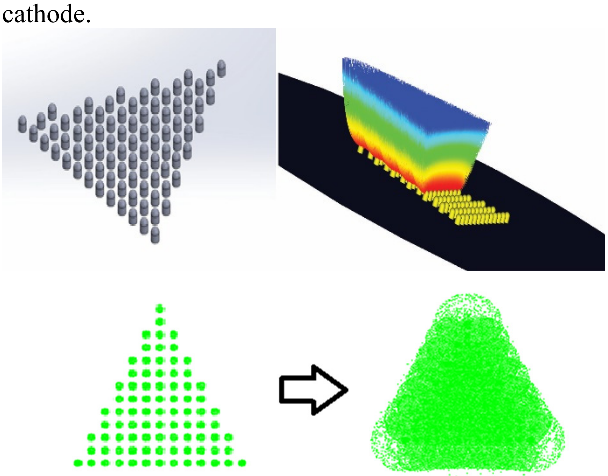

Figure 3: Top: minion emitters and beam, bottom: evolution of beam shape.

DESIGN OF ELECTRON GUN

A pierce-type multi-anode electron gun was designed to deliver the e-beam to the emittance exchanger. It is a multi-anode type gun using high gradients and accelerating the beam to 24 kV over 6mm. The first anode is at 8 kV, the second at 16 kV, and the third at 24 kV, each 1mm thick and with 1 mm spacing between. This gun was designed to work with the beam from a single DFE, it was then simulated with an equivalent current to the DFEA, it is these simulations that are presented here. Gun design modifications for transport of the shaped beam are ongoing and are not presented here. The electron gun schematic is presented in Fig. 4.

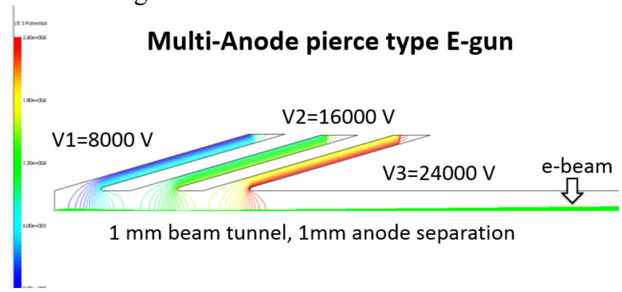

Figure 4: Electron gun simulation from MICHELLE, using equivalent beam parameters with a round beam.

Final beam parameters for the output beam in the e-gun are: 24 kV, 2.8 mA, 8 mm mrad emittance, and a size approximately 0.44 mm at a distance 37 mm from the cathode face. Efforts are being made to reduce beam crossover at the waist which is causing a spike in the transverse emittance, see Fig. 5.

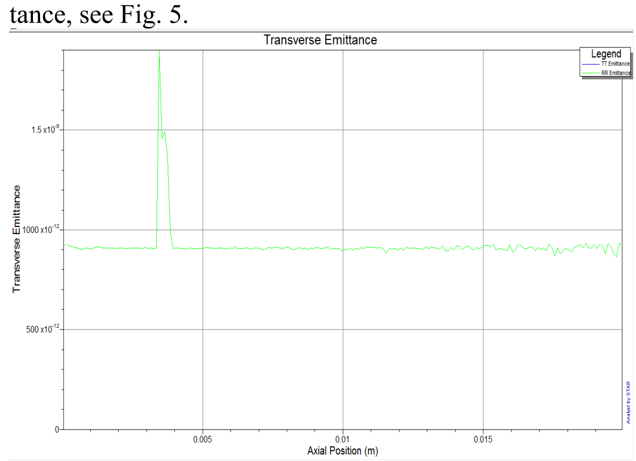

Figure 5: Transverse emittance spike corresponding to beam crossover.

FUTURE WORK

Three dimensional simulations are ongoing right now to examine the shaped beam transport through the electron gun.

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