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MITIGATION OF NONLINEAR PHASE SPACE IN A SPACE-CHARGE-LIMITED INJECTOR DIODE

W. D. Stem*, Y.-J. Chen, J. Ellsworth
Lawrence Livermore National Laboratory, Livermore, CA, USA

Abstract

The performance of an accelerator is limited by the quality of the beam produced at the injector. For a Pierce-type diode structure, the cathode-shroud interface and the anode pipe entrance are sources for undesired, irreversible phase space nonlinearities that lead to emittance growth. In this contribution, we present ways to mitigate these nonlinearities by adjusting the cathode-shroud interface to meet the beam edge boundary conditions and by adjusting the solenoidal focusing magnet in the diode region such that the nonlinear focusing magnetic fringe fields compensate the nonlinear defocusing electrical fields of the anode pipe entrance.

INTRODUCTION

In a flash radiography linear induction accelerator (LIA), the spot size on target and therefore the radiographic image quality is limited by the emittance. The beam emittance is largely determined by the performance of the injector, since the high intensity beam is subject to larger space charge effects at lower energies, and thus is more difficult to control.

This contribution studies a 2 MV, 2 kA space-charge-limited injector diode with thermionic electron emission as a reference case. Pierce showed [1] that for such cases a shroud with angle of 67.5° with respect to the normal will allow the cathode to birth a beam with laminar flow in which particles are emitted perpendicularly from the cathode surface. Above the thermal threshold, the emitted current depends solely on the field stress, for which the required anode-cathode (AK) gap is approximately determined by the Child-Langmuir law (e.g. [2]) for planar diodes.

When designing an injector diode, these models are a good starting point, but they do not capture some of the more subtle physics. The limitation arises at the beam edge, where nonlinear electric fields cause the particle trajectories to cross. Once particles at a given radius have different velocities, the phase space is no longer single-valued. This leads to emittance growth and beam degradation that is nearly impossible to correct with external fields downstream, and this is what we refer to in this paper as the "phase space nonlinearity". Figure 2 shows how quickly the phase space degradation is exacerbated due to this nonlinearity. This contribution identifies two sources of nonlinear electric fields and offers simple, effective methods to mitigate the harmful effects using simulation results from the 2D particle tracking code Trak [3] and particle-in-cell (PIC) slice code Amber [4]. Due to the injection energy, the relativistic correction is included.

* stem1@llnl.gov

The first source of nonlinear fields is the interface between the cathode and the shroud, which can be mitigated by leaving a simple gap at thermal equilibrium. The second source is caused by the spherical aberration of the anode pipe aperture or anode hole. One way this can be mitigated is by positioning a focusing solenoid such that the spherical aberration of the fringe fields helps to cancel the spherical aberration from the anode hole. Trade-offs for the DARHT-II injector diode design were studied in [5, 6]. A method to compensate for the anode hole with a spherical cathode on small length scales was studied in [7]. Mitigating the spherical aberration of the anode hole with a solenoid magnet was first demonstrated through simulations in [8].

CATHODE/SHROUD INTERFACE

To achieve uniform, laminar flow of electrons off of the cathode surface, the following boundary conditions must be satisfied [1, 9]:

$$\left.\frac{\partial V}{\partial r}\right|_{r=R} = 0, \tag{1}$$

$$V \sim z^{4/3}, \tag{2}$$

for axisymmetric coordinate system (z, r), beam radius R, and space-charge-modified electrostatic potential V. With a traditional Pierce-type shroud structure, condition 1 is not automatically satisfied. The problem is caused by the corner of the cathode-shroud interface. At thermal equilibrium, the electrostatic model assumes that the cathode and shroud are in contact. The equipotential voltage lines follow the contour of the shroud, but the voltage lines are smooth by definition. At the edge of the cathode, the voltage lines do not intersect the beam perpendicularly and instead cause the particles there to over-focus.

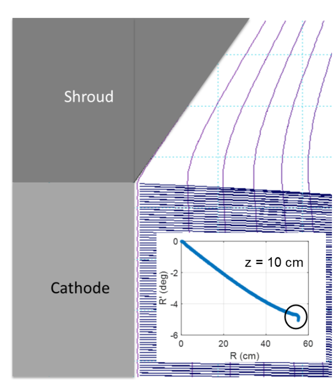

Figure 1: The phase space nonlinearity at the beam edge exists in the absence of an anode hole or magnetic fields, indicating that the cathode/shroud interface is a source.

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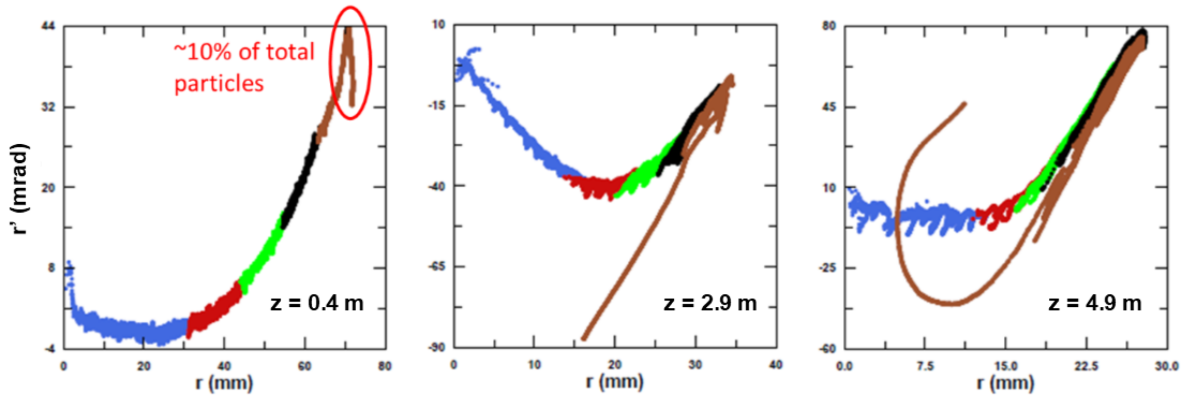

Figure 2: The nonlinearity, representing 10% of the beam, greatly degrades the beam quality as the beam propagates through the injector. Simulation was performed in Amber. Cathode surface is at $z = 0$.

The injector diode region is usually treated holistically, and because of this it is difficult to determine the cause of any given phase space nonlinearity. To determine this interface was a cause for the over-focusing at the edge, we simulated the beam accelerated into a wall in the absence of an anode hole or magnetic fields. Figure 1 shows that a beam edge nonlinearity clearly remains.

Many solutions to mitigate this field nonlinearity were considered, including a flat annulus design such as studied in [10], an etched curve in the shroud to accommodate the electric field, and a protruded cathode. However, due to ease of implementation and tolerable edge emission, we decided to go with a simple gap. Figure 3 shows that with a properly chosen gap width, the phase space straightens out and the nonlinearity is removed. The gap size limit is determined by the edge emission tolerance, however the edge-emitted particles do not carry a large current.

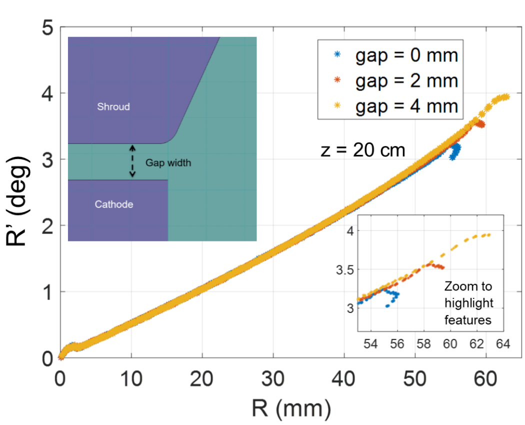

Figure 3: As the gap between the cathode and shroud is opened up, the phase space straightens up at the beam edge. The simulation was performed in Trak with edge emission neglected.

ANODE HOLE SPHERICAL ABERRATION

The aperture at the entrance to the anode pipe can be treated as a lens [9, 11] that has a spherical aberration. Because of this aberration, especially near the beam edge, particle trajectories cross and generate phase space nonlinearities. One option would be to open up the pipe radius, but there is a limit due to the vacuum vessel size and field stress requirements. Another option would be to use a gridded pipe, but such grids cannot withstand large beam power. A triode geometry can also be used to straighten out the equipotential lines at the anode hole, but this is not only difficult to design, but it does not allow for flexible AK gap variations if a variable current is desired. A spherical cathode can also be used to cancel the spherical aberration in the anode hole, but these are difficult to manufacture and again leaves no flexibility for AK gap variations. We instead follow the work performed by Hughes et al. [8] to use a solenoid magnet to correct for the degradation caused by the anode hole.

Solenoid magnets have a spherical aberration that can be approximated by [12]

$$C_{s,n} = \frac{(n+1)}{12}\frac{1}{a^2}, \tag{3}$$

for magnet order n and half-width half-max a. As a magnet radius decreases, its spherical aberration increases. Figure 4 depicts a possible design whereby a magnet can be moved inward to increase its spherical aberration. Moving a magnet inward also increases its on-axis magnetic field B_z, so fewer turns are required to produce the same magnetic field, allowing for a magnet to be manufactured with a smaller profile, which will have an even larger spherical aberration for the same interior radius (IR). A large spherical aberration is necessary to mitigate the large spherical aberration of the anode hole.

Figure 5 shows that as the spherical aberration of the magnet is increased, the emittance is reduced while maintaining

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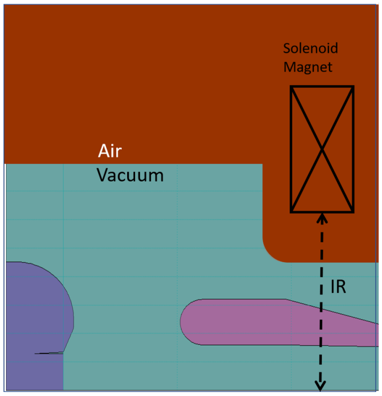

Figure 4: Scale drawing of the injector diode region showing how the radius of the solenoid focusing magnet can be adjusted.

the same beam radius and distribution. Normalized current I/I_0 is plotted as function of radius to show the that the distribution remains constant. The normalized Lee-Cooper emittance ϵ_n [13] is plotted as a function of radius to show the contribution to emittance as a function of radius. Particles near the core were removed due to numerical errors in the code. These particles constitute $< 3\%$ of the total beam current. It is seen that there is a 15.4% reduction in emittance with a 24.9% reduction of magnet radius, and a 41.3% reduction of emittance with a 49.8% reduction in magnet radius. These values were calculated at 0.9 m from the cathode surface.

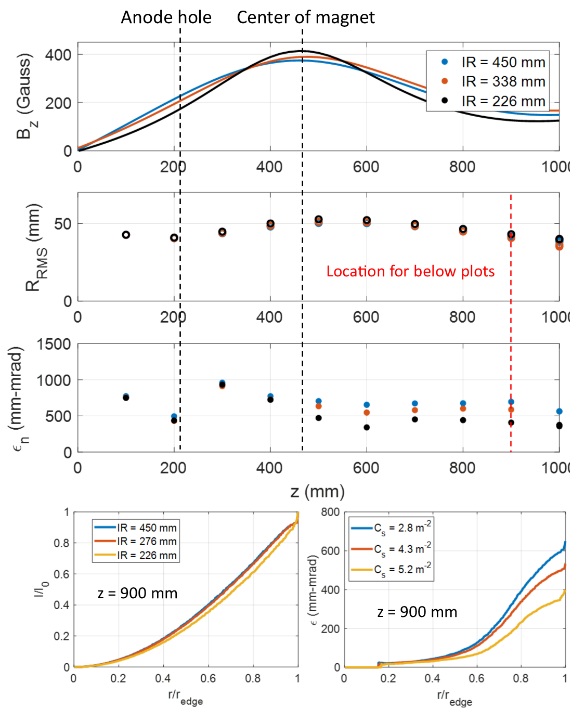

Figure 5: Reducing the magnet radius improves the emittance while maintaining the same beam radius and distribution. This is because the spherical aberration of the magnet fringe fields compensate for the spherical aberration of the anode hole. A magnet with a smaller radius has a larger spherical aberration. The dashed lines indicate where the anode hole and magnet center are located.

CONCLUSIONS

In the context of a 2 MV, 2 kA space-charge-limited injector diode, mitigation strategies are presented for sources of nonlinear, not single-valued phase space that leads to beam degradation and consequently poorer radiographic image quality. For the cathode-shroud interface, a simple gap maintained after thermal equilibrium can effectively straighten out the phase space hooking. For the anode hole, a strategic solenoid placement can mitigate the spherical aberration of the unwanted lens. These strategies were selected due to their effectiveness and ease of implementation.

A reactive mitigating option would be to collimate the beam to remove the nonlinearity in the phase space before it degrades the beam quality. However, the particles at the edge are over-focused and very quickly travel to the core of the beam, so the collimation must be early. The problem with early collimation is the generation of secondary ions emitted off of the collimator that will poison the cathode. Therefore, it is much better to find a proactive solution to the phase space nonlinearity rather than rely on a method in which beam current is reduced by 10% that also carries the risk of damaging the cathode.

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