Field Optimization of a McMillan Shaped Electron Gun

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Abstract

This paper describes the results of a field optimization based design of an electron lens for use as a non-linear optic in the IOTA ring.

1 Introduction

Electron lenses have a broad use in particle accelerators as collimators and as focusing elements [ref]. Many of the designs are based on shapes that are fairly easy to construct for example a uniform field profile or an annular electron beam [ref]. Recently there have been some developments that require the use of more exotic electron current profiles such as a Gaussian [ref] or McMillan profile. Because electron lenses usually operate in the space-charge limited regime inside a large uniform magnetic field, shaping the field on the cathode should result directly in shaping of the output current distribution. This can be accomplished by adjustment of the voltage on a control electrode and by shaping of cathode profile itself. This has been successfully implemented for a Gaussian electron beam [ref] and modern manufacturing techniques allow for an almost arbitrary shape of cathode to be manufactured [ref]. However there does not yet exist a general formula or tool to produce an electron beam with arbitrary shape as may be required by future machines. Additionally there does not exist a gun design that produces a McMillan shaped electron beam which is one of the candidate non-linear optics for the Integrable Optics Test Accelerator (IOTA). In order to address the need for both a general design tool for electron lenses and the need for a McMillan shaped electron beam we have developed a tool for electron gun optimization using the McMIllan gun as the test case.

In this paper we will explore the gun optimization process using field optimization by adjusting the cathode shape using the McMillan design as a test bed for this process. We begin with an overview of our initial geometry and a discussion of the parameters to be varied in the optimization. We will then discuss the electrostatic simulations and how we address issues relating to mesh resolution. This is followed by an analysis of our field optimization with results from two different simulation tools. Finally we present the results of beam simulations using the results of the field optimization to show how well this technique will produce the desired current distribution.

2 Geometry

There are two candidate geometries studied in this paper, the first has a very simple control electrode and anode who's position and height are allowed to vary in the optimization while the second has a slightly more complex geometry. The simpler geometry is shown in Figure 1 and the more complex geometry in Figure 2. In both cases the geometries are broken down into four parts: the emitter (magenta), the cathode stalk (green), the control electrode (red), and the anode (blue). The parameters shown in figure's 1 and 2 represent the free parameters for the optimization. In addition the emitter tip is also optimized. In both cases the emitter tip is constructed by shaping the cathode to match the McMillan profile. The emitter tip is constrained by the desired cathode radius and the location of the cathode in the geometry. The profile of the emitter tip is defined using Equation 1.

$$x(y) = x_{\text{scale}} \frac{a^4}{(y^2 + a^2)^2} \tag{1}$$

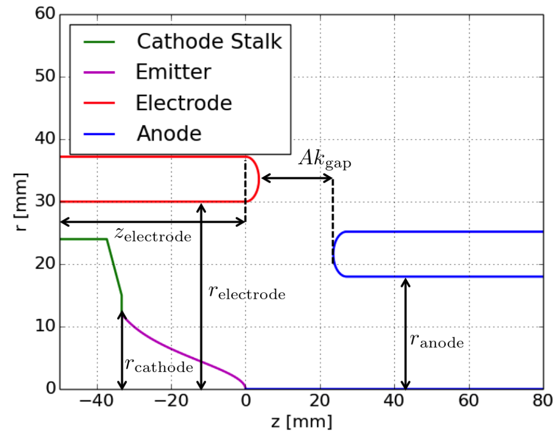

Figure 1: Overview of the gun geometry showing the McMilan option for the emitter tip.

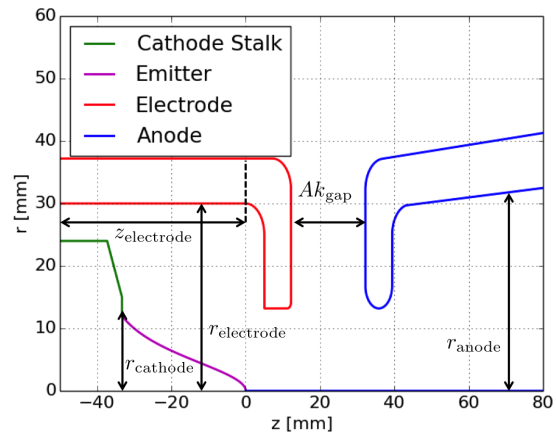

Figure 2: Overview of the gun geometry showing the McMilan option for the emitter tip.

Here a is a free parameter for the optimization that determines the rate of curvature of the tip, x_{scale} is a free parameter that defines the depth of the emitter tip, and y are equally spaced points between 0 and 12 mm. The control electrode is an axially symmetric component used to provide additional shaping of the field on the cathode. The geometry of the electrode is constructed using a number of curves and straight segments, these curves are required to be tangent to the straight segments. During the optimization the control electrode shape is fixed, however the position both transversely and longitudinally can be varied. Additionally the voltage on the electrode can also be varied. The anode is similarly defined, in the optimization the anode voltage, the gap between the control electrode and the anode, as well as the radial anode position can be varied. The use of an emitter tip separately from the other geometry components allows the simulation to be easily modified for different cathode geometries.

3 Electrostatic simulations in SPIFFE

The electrostatic simulations are performed using SPIFFE [ref]. SPIFFE is a 2.5-D particle-in-cell electromagnetic field solver with the ability to solve Poisson's equation in order to perform electrostatic calculations. Because we are only optimizing an electrostatic problem without beam we only use the Poisson solver within SPIFFE for these simulations. SPIFFE is an attractive tool for these simulations because it is free, has a fairly straightforward interface, and can easily be hooked into python optimization algorithms through the use of a wrapper developed for this purpose [ref]. SPIFFE is also compatible with the SDDSToolkit [ref] which can also be used for scripting of optimizations. One downside to SPIFFE is the use of a 2-D uniform mesh. For a cathode with a fairly irregular profile, improper mesh intervals can lead to errors in the optimization that are nonphysical. For this geometry in particular, the longitudinal mesh is particularly important due to large variation in the cathode tip as a function of longitudinal position. To understand this effect we computed the field along the cathode surface for different longitudinal and transverse mesh intervals. Figure 3 shows the field on the cathode as a function of radial position for several different longitudinal mesh intervals.

Here we see that the field on axis is particularly sensitive to the longitudinal mesh while the field away from the axis is less sensitive. For the optimization it is important to understand the tradeoff between accuracy and speed for each simulation. A reasonable tradeoff is to have a fine longitudinal mesh with a fairly coarse transverse mesh. In addition in the optimization we ignore the first field bin as this is assumed to be nonphysical.

4 Cathode field optimization

Using the geometry definitions in Section II and the optimization framework in Section III we can now optimize the gun geometry to create a cathode field profile that will match the desired current distribution. The cathode voltage was set to 10 kV for all simulations and the anode voltage was set to zero.

4.1 SPIFFE

We conducted field optimizations using SPIFFE integrated with the python using two different optimization algorithms, simplex and LBFGS. This particular use of Simplex did not allow for constraints however LBFGS did allow for constraints on the optimization.

Simplex
LBFGS
Congaguate Gradient

4.2 Field simulations in WARP

5 Beam simulations

6 Conclusions

7 References