OPTIMIZING SRF GUN CAVITY PROFILES IN A GENETIC ALGORITHM FRAMEWORK*

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Abstract

Automation of DC photoinjector designs using a genetic algorithm (GA) based optimization is an accepted practice in accelerator physics. Allowing the gun cavity field profile shape to be varied can extend the utility of this optimization methodology to superconducting and normal conducting radio frequency (SRF/RF) gun based injectors. Finding optimal field and cavity geometry configurations can provide guidance for cavity design choices and verify existing designs. We have considered two approaches for varying the electric field profile. The first is to determine the optimal field profile shape that should be used independent of the cavity geometry, and the other is to vary the geometry of the gun cavity structure to produce an optimal field profile. The first method can provide a theoretical optimal and can illuminate where possible gains can be made in field shaping. The second method can produce more realistically achievable designs that can be compared to existing designs. In this paper, we discuss the design and implementation for these two methods for generating field profiles for SRF/RF guns in a GA based injector optimization scheme and provide preliminary results.

OPTIMIZATION SYSTEM OVERVIEW

Alternative Platform and Programming Language Independent Interface for Search Algorithms (APISA) [1] builds on the Platform and Programming Language Independent Interface for Search Algorithms (PISA) [2] system. PISA provides a modular way to combine GAs and problems. It uses two communicating state machines to separate the GA implementation from the problem model evaluation. It is easy to apply different GAs to a given problem because the state machine structures are well defined and the files used to communicate between the two state machines are standardized. Changing the GA only requires running the optimization scheme with a different GA state machine; the problem model is unchanged. APISA takes advantage of this compartmentalization and provides problem model evaluations customized for accelerator physics. APISA uses A Space Charge Tracking Algorithm (ASTRA) [3] or General Particle Tracer (GPT) [4] to simulate particle dynamics making it a suitable tool for injector design optimization. The version of APISA described in this paper relies on ASTRA for the beam dynamics simulations.

FIELD MORPHING

The original version of APISA assumes that the field descriptions provided for the magnets and rf accelerating components are fixed and that the optimization can vary the amplitude and/or phase of these elements. This version of APISA, which is geared toward designing SRF/RF gun based injectors, allows the functional form of the on-axis field description of the gun to be varied.

Under the assumption that the desired field pattern resembles a π mode, the software uses a sine wave as the fundamental form for the field description. A truncated Fourier series,

$$f(z) = 1 + \sum_{n=1}^{15} a_n \cos\left(2\pi n \frac{z}{L_{\text{cavity}}}\right) + \sum_{n=1}^{15} b_n \sin\left(2\pi n \frac{z}{L_{\text{cavity}}}\right)$$

where L_{cavity} is the length of the cavity, is then applied to the fundamental form to produce the field description used in the beam dynamics simulation. Each coefficient of the series can be designated as a variable controlled by the optimization scheme or fixed to a specified value. The default value for all coefficients is zero. Other variables that can be fixed or varied are the frequency of the underlying sine function and the number of cells the underlying sine function should represent. The fractional part of the number of cells is interpreted as a gun cell, that incorporates the beam emitting cathode and generally precedes the full cells. The number of cells and the sine frequency are used to calculate L_{cavity} and the free space wavelength of the cavity.

The system computes characteristics of the generated field profile and the morphing function, $f(z)$, and these characteristics can be used as constraints or objectives in the optimization. For example, to preserve the nodes that occur between cells in a π mode, the minimum of $f(z)$ must be positive; otherwise, additional unwanted zero crossings are introduced in the generated field profile. Because $f(z)$ can change the frequency of the generated field, the system determines the resonance frequency from a Fourier transform of the field profile. The frequency can be used as a constraint and an objective to guide and restrict the frequencies of the fields produced.

Preliminary results for a PITZ-like 1.5 cell RF gun operating at 40 MV/m followed by an emittance compensation solenoid [5] indicate that the field amplitude in the half cell should be much larger than in the full cell. These results are obtained using 128 nodes of a Jefferson Lab cluster computer. Each case represents

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14 generations with 128 individuals in each generation. The optimization attempts to minimize the beam size and emittance for a 1.65 nC 24 ps FWHM plateau electron bunch 1.618 m downstream of the cathode [6] for a fixed RF phase and solenoid setting. The variables in the optimization are the coefficients of $f(z)$ subject to the constraints that the beam size, emittance, and the minimum of $f(z)$ are all positive. Two cases are shown in Figures 1 and 2 where the half cell amplitude is more than twice the full cell amplitude.

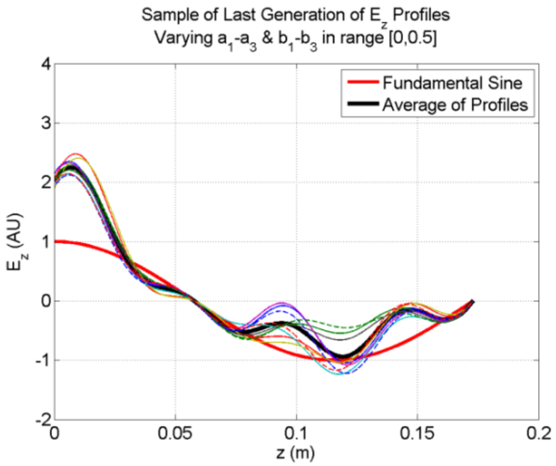

Figure 1: Varying the first three Fourier coefficients.

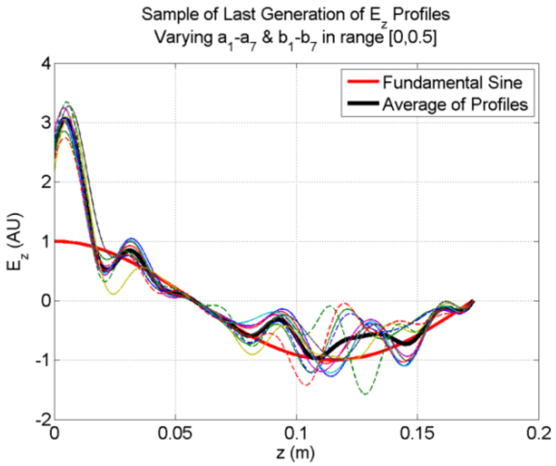

Figure 2: Varying the first seven Fourier coefficients.

In Figure 1, the optimization is changing six coefficients, a_1 through a_3 and b_1 through b_3 of $f(z)$, while in Figure 2 the optimization is varying fourteen coefficients, the first seven for each a_n and b_n. In Figure 2, with more and higher frequencies available to include in the field profile, the optimization pushes the peak field closer to the cathode. Both cases strongly indicate that high electric fields on the cathode yield better gun performance. These cases, also, have significant particle loss which requires further study.

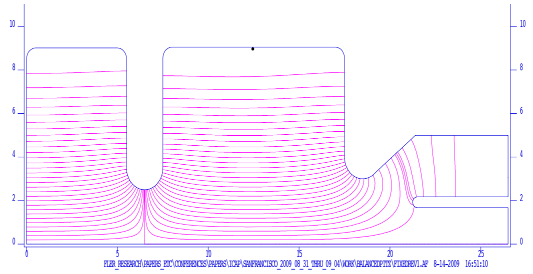

Figure 3: Standard balanced field PITZ geometry.

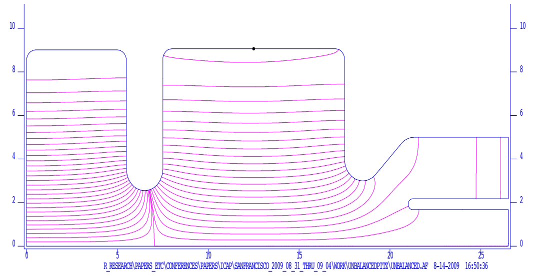

Figure 4: Unbalanced field geometry.

Table 1: Changes relative to the balanced geometry

Element	Dimension	Change
Half Cell	radius	-37.4 µm
Iris	radius	+0.5 mm
Full Cell	radius	+162.6 µm

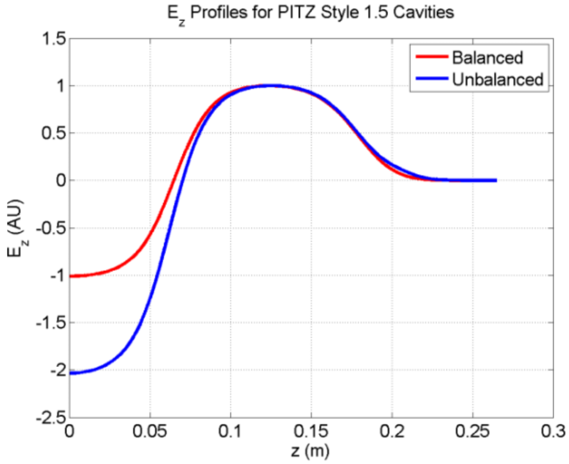

Figure 5: Normalized E_z profiles for the two geometries.

To test the validity of this conclusion in a realistic cavity design, two variations of the PITZ 1.5 cell cavity have been modelled. The first yields the standard well balanced field profile design in Figure 3. Figure 4 shows the second case where the geometry is modified slightly to create a field with the amplitude in the half cell being roughly twice the full cell amplitude. Table 1 summarizes the relative changes in the physical dimensions for the unbalanced geometry relative to the balanced case. The on-axis field profiles for both geometries are shown in Figure 5.

As in the optimization, the main solenoid strength and RF injection phase are fixed in the ASTRA simulations. In addition, simulations using ASTRA's autophase feature to find the phase for maximum energy gain are provided for comparison. For the balanced field cases, the peak electric field is 40 MV/m whereas it is 80 MV/m in the unbalanced case. Figures 6 and 7 show the transverse normalized emittance and beam size, respectively, for all cases.

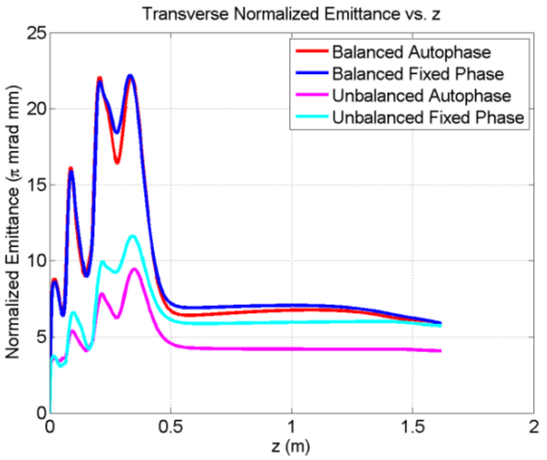

Figure 6: Transverse emittance along beam line.

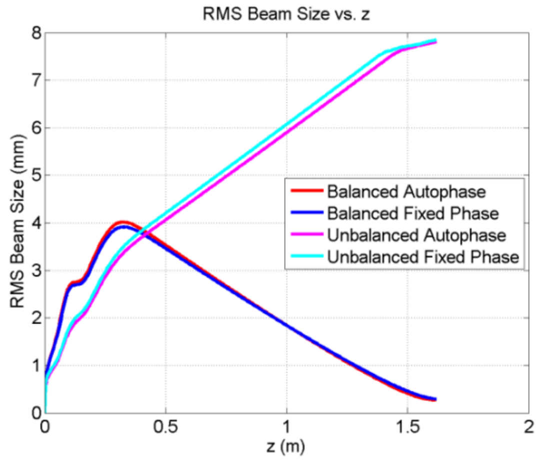

Figure 7: RMS beam size along beam line.

While the final emittance for the fixed phase unbalanced field case is comparable to both balanced field results, the unbalanced results show a general improvement in emittance due to the increased RF focusing from the higher gradient in the half cell. The charge transmission is significantly better in the unbalanced case where particles are lost on apertures. In contrast, the balanced case particle loss is due to backward travelling particles. The difference in beam size is due to changes in RF focusing and can be managed by increasing the solenoid strength.

CAVITY GEOMETRY MORPHING

Cavity geometry determines the field characteristics, so it is necessary to consider a system that varies the cavity geometry. Including the geometry configuration in the optimization allows for studying the impact of changes in the cavity geometry on the beam dynamics of an injector design. It is also a step forward in automating the injector design and optimization process since the cavity shape can be developed and tested concurrently with the other injector elements.

Including cavity geometry in the optimization framework requires incorporating into APISA a field solver to compute the field from the specified geometry. A goal of this effort is to use free software packages as much as possible. Poisson Superfish [7] is a generally accepted tool for computing the field information for cylindrically symmetric cavities and will be the field solver used in this system. Using Wine (Wine Is Not an Emulator) [8] with Xvfb, the X Window's virtual frame buffer [9], to capture the graphics output, Poisson Superfish can run on a monitorless Linux machine in a cluster computer.

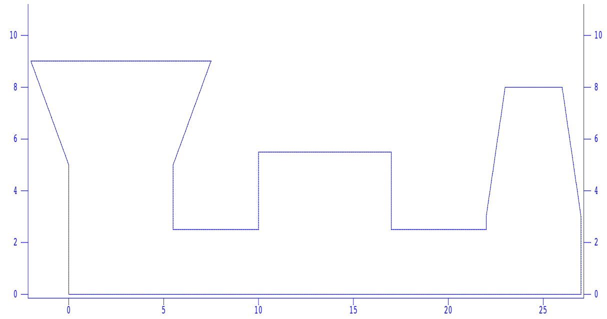

Figure 8: Straight line approximations for re-entrant (left), pillbox (center) and elliptical (right) cavities.

Poisson Superfish relies on a drive point that is treated as a source of a fictitious magnetic current to compute the cavity fields [7]. The drive point must be placed in an area of the cavity geometry that has a sufficiently high magnetic field. Changing the drive point location can significantly affect the cavity mode that is excited in the structure. Also, the search frequency can impact the field mode Poisson Superfish finds. To isolate these issues from the optimization, the Poisson Superfish processing, which will consider the results of several drive point locations and search frequency choices, will be encapsulated in a separate program that feeds back to the optimization scheme the generated field profile for the most π–like mode and characteristics of the field and cavity properties that can be used as constraints or objectives. The Poisson Superfish processing will not include tuning the cavity geometry as that can change parameters that are under the control of the optimization and therefore mislead the optimization.

The geometry file generation will be broken into two phases. The first will use straight line cavity geometries shown in Figure 8 that can be easily morphed from a pillbox cavity to approximations for elliptical and re-entrant cavities by changing the tilt of the cavity end caps. The second phase will generate more realistic cavities using smooth elliptical curves to describe the geometry.

CONCLUSION

Two methods for bringing cavity field characterization into an automated injector optimization framework have been presented. The first method assumes a general underlying form of the optimal cavity field profile that the optimization can transform by varying the coefficients of a truncated Fourier series used to morph the fundamental form. Applying this approach to a PITZ style 1.5 cell RF gun based injector leads to the conclusion that higher accelerating field in the cathode region of the gun improves gun performance. An unbalanced field profile, with the field stronger in the half cell, is preferred. Because the field morphing method does not consider the boundary conditions of the cavity, a second approach that works with cavity geometries is needed to develop more realistic optimized injector designs. The design for a scheme that morphs the cavity geometry has been described. The two methods balance each other because the first concentrates on what the injector designer wants from an optimal field profile to achieve the desired injector beam characteristics and the second considers the optimal performance that can be realized subject to the physics of the cavity.

REFERENCES

[1] I. V. Bazarov and C. K. Sinclair, “Multivariate optimization of a high brightness dc gun photoinjector,” Phys. Rev. Special Topics - Accelerators and Beams 8 (2005), 034202.

[2] S. Bleuler, M. Laumanns, L. Thiele, and E. Zitzler, “PISA - a platform and programming language independent interface for search algorithms,” Evolutionary Multi-Criterion Optimization (EMO 2003), Faro, Portugal, 2003, pp. 494-508 (2003).

[3] K. Floettmann, “ASTRA: A Space Charge Tracking Algorithm,” http://www.desy.de/~mpyflo.

[4] General Particle Tracer, http://www.pulsar.nl/gpt.

[5] K. Abrahamyan, *et al.*, “Characterization of the electron source at the photo injector test facility at DESY Zeuthen,” Nuclear Instruments and Methods in Physics Research A 528 (2004), pp. 360-365.

[6] A. Hofler, P. Evtushenko, and M. Krasilnikov, “RF gun optimization study,” PAC’07, Albuquerque, N.M., June 2007, TUPMS064 pp. 1326-1328 (2007); http://www.JACoW.org.

[7] J. Billen and L. Young, “Poisson Superfish,” LA-UR-96-1834, Revised January 13, 2006.

[8] Wine HQ, http://www.winehq.org/.

[9] Xvfb, http://ftp.x.org/pub/X11R7.0/doc/html/Xvfb.1.html.