OPTIMIZING RF GUN CAVITY GEOMETRY WITHIN AN AUTOMATED INJECTOR DESIGN SYSTEM*

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Abstract

RF guns play an integral role in the success of several light sources around the world, and properly designed and optimized cw superconducting RF (SRF) guns can provide a path to higher average brightness. As the need for these guns grows, it is important to have automated optimization software tools that vary the geometry of the gun cavity as part of the injector design process. This will allow designers to improve existing designs for present installations, extend the utility of these guns to other applications, and develop new designs. An evolutionary algorithm (EA) based system can provide this capability because EAs can search in parallel a large parameter space (often non-linear) and in a relatively short time identify promising regions of the space for more careful consideration. The injector designer can then evaluate more cavity design parameters during the injector optimization process against the beam performance requirements of the injector. This paper describes an extension to the APISA software that allows the cavity geometry to be modified as part of the injector optimization.

INTRODUCTION

The Platform and Programming Language Independent Interface for Search Algorithms (PISA) software package [1] is a modular state machine system for connecting EAs and optimization problems, and Alternative PISA (APISA) [2] is PISA adapted to the study of problems in accelerator physics. Most importantly, by providing an interface to the beam dynamics simulation code A Space Charge Tracking Algorithm (ASTRA) [3], APISA moves the injector design process beyond the interpretation of methodical parameter scans to an automated search of the parameter space guided by the performance requirements of the injector. The first version of APISA assumes that the form of the electromagnetic fields in the injector design is fixed and can vary the amplitudes and phases of accelerating fields in RF elements and field strengths of magnets. It can also vary properties of the initial particle distribution emitted from the gun and the relative spacing between electromagnetic elements. This system is used to optimize or confirm the operational set up of injectors where the accelerating fields of the gun (DC or RF) are fixed or known [1, 4-7].

A logical extension to APISA for RF gun based injector optimizations is to allow the shape of the field to be varied. This can be accomplished in a number of ways. A theoretical approach ignoring boundary conditions can act directly on an analytic assumed shape of the field [8]. This generates obviously nonphysical fields, but it can identify desirable characteristics of the field that may improve injector performance and lead to new candidate cavity designs. Ultimately, even for this theoretical approach, the boundary conditions of a physical structure must be considered in order to arrive at a design that can be built and installed in an injector beam line. This points to the need for another more realistic approach that can use the fields generated by varying aspects of the cavity geometry in the optimization since electromagnetic fields in a resonance structure are purely a function of its physical geometry.

The question then is how to incorporate the field solver and its results into the optimization framework. One way is to use only the results of the field solver in the optimization framework [9]. This entails running the field solver outside of the optimization framework for different variations of the cavity geometry to generate a database of fields, cataloguing the cavity parameters and fields for use in the optimization, and interpolating between fields of known cavity geometries to find fields for intermediate ones. Alternatively, the optimization can generate the fields by internally using a field solver. This paper describes a system based on the latter and the progress toward making the system operational.

OVERALL DESIGN

The basic design of APISA is unchanged in this version. As in the original PISA system, there are two state machines working together in a coordinated fashion to find optimal solutions to the problem. One state machine contains the selection mechanics of the EA. The other state machine maintains the population of candidate parameters, the model of the problem to evaluate, and the corresponding candidate model evaluations. This version optionally finds the field of the RF gun cavity using the field solver Poisson Superfish [10] before simulating the beam dynamics with ASTRA.

All Poisson Superfish related execution, including tuning, is encapsulated in a single program (ps_tuner). This program takes a specialized cavity geometry description, discussed subsequently, that can be modified by APISA as an input. The program produces an on-axis field profile and associated field characteristics for the π mode at the desired frequency if it finds one. If the program does not converge within iteration limits, it produces a zero amplitude field map. The field profile from ps_tuner can be used directly in the ASTRA

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simulation, and the field characteristics can be used as objectives and constraints in the optimization.

GEOMETRY DESCRIPTION

The intent of extending APISA to change the geometry of the RF gun as part of the optimization is to let the beam dynamics performance of the injector influence the shape of the cavity. To facilitate this, a geometry description in terms of identifiable cavity parts such as cavity walls and irises is needed. This allows the designer to single out dimensions or angular inclinations of these elements for the optimization to vary in response to changes in the injector performance. Also, a flexible description that can describe a range of cavity shapes from re-entrant to elliptical with a few parameter changes enables optimizations that directly compare the benefits of these geometries in an injector design.

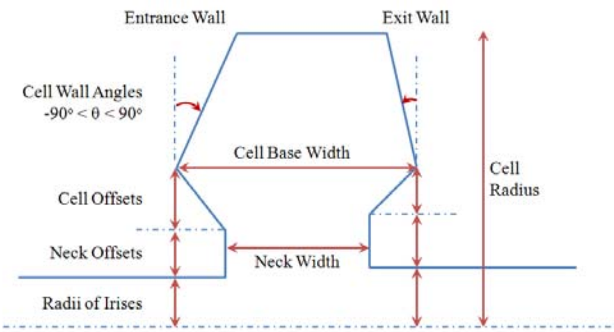

Figure 1: General cavity description parameters.

The description devised for use in this system assumes that multi-cell cavities consist of two main building blocks: beam tubes and cells. A beam tube is a simple entity and can be described with a radius and a length. A cell, in order to support the various possible cell shapes, uses more parameters as shown Figure 1. In this initial version, ps_tuner translates the geometry into a straight line cavity representation, and in the future, curves will be used to create more realistic cavities.

GEOMETRY TUNING

In order for the optimization scheme described in this paper to be useful to the accelerator community, it must create geometries that are reasonable to build and that make efficient use of all of the cells. Efficient use here is characterized by field flatness [11] defined in percent as

$$\text{field flatness} = 100\frac{\left|E_{peak}\right|_{\max} - \left|E_{peak}\right|_{\min}}{\frac{1}{n_{cells}}\sum\left|E_{peak}\right|}$$

where E_{peak} is the peak on-axis electric field in a cell and n_{cells} is the number of cells in the cavity. Under this definition, most designs strive for near zero field flatness to have field amplitude uniformity. If the field flatness of a design is large, the field is unevenly distributed. That translates to some cells in the cavity having little field excitation and therefore very small electric field amplitudes. Because the optimization design relies on the tuning algorithm in ps_tuner to convert its modified geometries to tuned cavities, it is the tuning algorithm that determines the success of this system. This means that the algorithm should produce designs meeting frequency and field flatness goals.

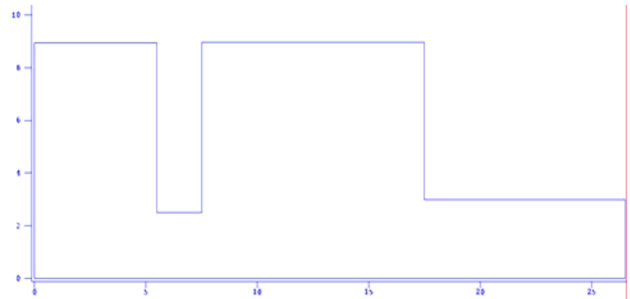

Figure 2: 1300.1 MHz 1.5 cell straight line RF gun cavity (Cell radii 8.936 and 8.971 cm; total length 26.5 cm).

Typically when tuning a multi-cell elliptical cavity design, the end and inner half-cells are tuned individually and then joined together to form the final cavity. In contrast, ps_tuner attempts to tune the entire cavity structure. The algorithm assumes that the relationship between the desired quantity and the tuning parameter is linear. Using cell geometry parameters designated in the geometry description, it changes each parameter in turn to determine slope approximations. Adjusting each parameter sequentially, it iteratively tunes the geometry. Tuning for frequency alone results in cavities with very poor field flatness. This indicates that using frequency as a single objective is not sufficient to produce usable field profiles. An extension to the system to achieve a desired frequency and field flatness makes adjustments alternately for frequency and flatness until the geometry is tuned or iteration limits are reached. This process does not converge in the case where the beam tube radius and adjoining cell iris radii are used to change the field flatness for a 1300 MHz 1.5 cell RF gun cavity similar to Figure 2. To quickly and reliably optimize on more than one objective simultaneously, the tuning algorithm needs to be improved, and cavity parameters that affect field flatness with minimal impact on resonance frequency need to be identified.

FIELD FLATNESS AND RESONANCE

Prior to identifying cavity parameters that affect field flatness, it is important to determine if field flatness is affected by resonance tuning for a 1.5 cell RF gun geometry. Since cavity resonance has mainly a radial dependence, the two cell radii of the cavity in Figure 2 are varied. Figure 3 shows the response of the resonance frequency of the π mode, and each contour is essentially hyperbolic. Figure 4 shows the corresponding field flatness response of the on-axis field profile with the 1298, 1300, and 1302 MHz contours for reference. The field flatness contours are linear and fall into two mirrored groups. As the flatness approaches zero from either side, the spacing between contours decreases indicating a strong sensitivity to either radius as the flatness approaches zero.

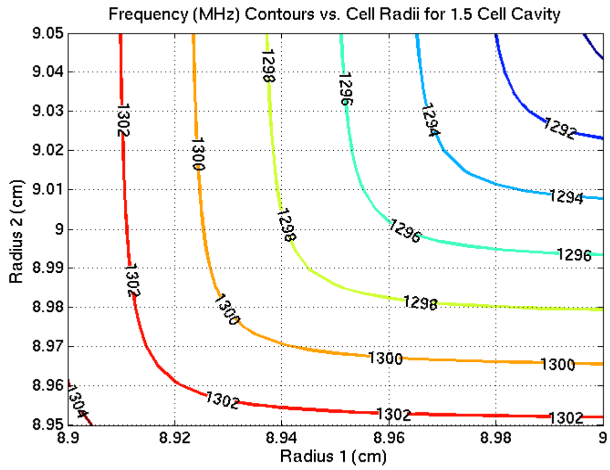

Figure 3: Frequency dependence on cell radii.

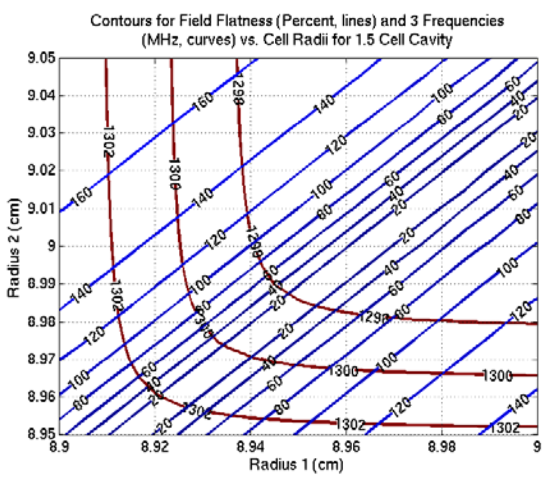

Figure 4: Field flatness dependence on cell radii.

From the field flatness response, it is clear that for the arms of the frequency contours when the response depends mainly on one radius or the other, the field flatness is very poor. Note that for a 1.5 cell cavity, field flatness of 100 % means the peak field in one cell is three times higher than the peak of the other cell. Therefore, in these regions the field distribution is extremely lopsided. There is a small domain of radii that can be used to produce a desired frequency with reasonable field flatness (less than 100 %). For the 1300 MHz case, the radius of the first cell can vary between 8.92 cm and 8.97 cm, and the radius of the second cell is restricted between 8.96 and 8.99 cm. For reference, the cavity in Figure 2 with radii in this region has a field flatness of 0.3 %. The flatness response further indicates that in this small region, except in the case where the two radii are approximately the same (~8.97 cm), the radius of the second cell is larger than the first cell.

This 1.5 cell cavity exercise shows that field flatness has a nonlinear dependence on the cell radii. Also, there is a relatively narrow band of cell radii that produces useful geometries. The next step is to extend the study to include the beam tube radius and length. A similar study for a 3.5 cell geometry will be carried out to see if similar restrictions exist.

CONCLUSION

The framework for an EA based injector design optimization tool that internally computes field profiles exists. Its success depends on finding a quick and reliable algorithm for tuning cavities for resonance and field flatness. Studies are in progress to identify cavity parameters that can achieve each goal without adversely affecting the other.

REFERENCES

[1] S. Bleuler, *et al.*, “PISA - a platform and programming language independent interface for search algorithms,” Evolutionary Multi-Criterion Optimization (EMO 2003), Faro, Portugal, 2003, pp. 494-508 (2003).

[2] 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.

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

[4] F.E. Hannon and C. Hernandez-Garcia, "Simulation and optimisation of a 100 mA DC photoinjector," EPAC’06, Edinburgh, June 2006, THPLS115, pp. 3550-2 (2006).

[5] A. Hofler, *et al.*, “RF gun optimization study,” PAC’07, Albuquerque, N.M., June 2007, TUPMS064, pp. 1326-1328 (2007).

[6] Y.-C. Chao, *et al.*, “TRIUMF-VECC electron linac beam dynamics optimization,” ICAP’09, San Francisco, CA, August 2009, THPSC012, pp. 277-280 (2009).

[7] F.E. Hannon, *et al.*, “Optimizing the CEBAF Injector for Beam Operation with a Higher Voltage Electron Gun,” PAC’11, New York, NY, March 2011, WEP288, to appear (2011).

[8] A.S. Hofler, *et al.*, “Optimizing SRF gun cavity profiles in a genetic algorithm framework,” ICAP’09, San Francisco, CA, August 2009, THPSC020, pp. 296-290 (2009).

[9] I.V. Bazarov, *et al.*, "Geometry optimization of DC and SRF guns to maximize beam brightness", ERL’09, Ithaca, NY, June 2009, PLT20, pp. 1-5 (2009), http://accelconf.web.cern.ch/AccelConf/ERL2009/.

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

[11] S. An and H. Wang, “Tuner Effect on the Field Flatness of SNS Superconducting RF Cavity,” JLAB-TN-03-043 or SNS-NOTE-AP119 (2003).