OPTIMAL DESIGN OF A PHOTOCATHODE ELECTRON GUN WITH HIGH-BRIGHTNESS AND HIGH-REPETITION RATE BASED ON GENETIC ALGORITHM

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Abstract

A low RF frequency of normal conducting photocathode gun with high-brightness and high-repetition rate is designed as an electron source of the Next Generation Light Source (NGLS). In order to optimize the performance of the gun, a genetic algorithm (GA) of multi-parameter has been used. A genetic algorithm is used because of the inherent complexity of the large number of parameters of the cavity geometry available for optimization. In this paper, we present the status of the optimal simulation using the Python language to write GA program and the code SUPERFISH.

INTRODUCTION

Across the grand challenges in chemistry, physics, materials science and so on, an underlying theme is to understand, predict, and ultimately control the properties of matter. New generation linac-based of the tunable light source over VUV~ soft x-ray is proposed with new capabilities in photon pulse characteristics, which will allow study of phenomena inaccessible to either third-generation synchrotrons or other present-day sources. High repetition rate and high average photon flux are essential to many experimental techniques. To meet these needs, the high quality beam with high bunch repetition rate (~MHz), low emittance and low energy spread is required to radiate the electromagnetic wave in the Free Electron Laser process (FEL) [1-5]. According to the principle of FEL, the electron source is very important for the new light source [6].

The photocathode electron gun is the most potential and competitiveness to generate the excellent quality beam, but not all the type gun is used for the new light source. For example, normal conducting L- and S-band RF guns are limited in the practical repetition rate to the kHz range due to the average power loss in the cavity structure, DC guns are limited in field strength at the cathode due to the heroic effort to prevent insulator breakdown [7-9]. And superconducting RF guns are likely candidates for photo injectors, but are prevented by flux exclusion from placing a solenoid magnetic field to thread flux through the cathode for emittance manipulation techniques [10]. In addition, the cavity's contamination from cathode material is needed to solve. In order to overcome the above disadvantage, the Advanced Photo-injector Experiment (APEX) at the Lawrence Berkeley National Laboratory is proposed that a novel solution, a Very High Frequency gun (VHF) with a re-entrant cavity structure, is to decrease RF power loss in a warm copper cavity, diminish high voltage breakdown issues and generate the MHz-beam [11].

In this paper, we perform an optimal design a VHF gun based on APEX for a high-brightness high-repetition rate (MHz-class) of a VUV ~ soft x-ray light source in Dalian Institute of Chemical Physics (DICP). According to the theoretical analysis, in order to decrease the RF power loss, the optimal method is to improve the shunt impedance of the structure. Because of the structure with more variables, it is difficult to find the optimum parameter. Therefore, we proposes an optimal method based on genetic algorithm to optimize the structure with a nose cone shape.

This paper consists of the following aspects: description of problem, analysis of algorithm, analysis of simulation results and conclusion.

DESCRIPTION OF OPTIMIZATION PROBLEM

By compromising with the photocathode technologies, the accelerating technologies, the cooling technologies, the microwave power technologies, the beam parameters, economic cost and so on, we adopt the VHF gun design with a low frequency of 186 MHz which is the sub-harmonic of the main frequency of the linac. The VHF gun is the re-entrant resonant cavity with a nose cone shape. An half of the structure of the gun is rotationally symmetric about the bottom of horizontal line as shown in Fig. 1.

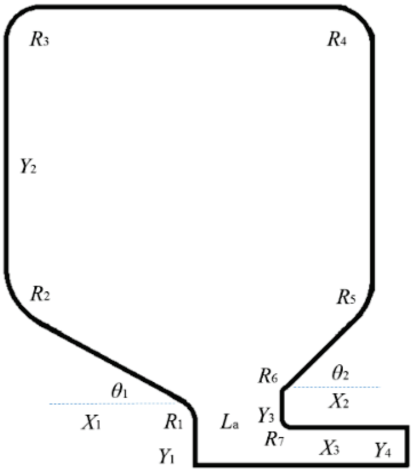

Figure 1: Parameterized dimensions of the VHF gun.

To be specific, the parameters of the nose cone consist of R_1, θ_1, X_1, R_2, R_5, X_2, θ_2, R_6, Y_3, R_7, X_3 and Y_4 at the beam iris in anticlockwise direction; the arc at the wall

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are defined by R_3, R_4; La is fixed values; Y_2 is used to tune the resonator frequencies of the cavity. According to experience and design requirements, the range of each variable can be determined. In the calculation of the tuning, it must guarantee that $Y_2 > 0$. According to the above, the optimal problem can be translated into mathematical description:

$$\begin{aligned} &\max f(x) = f(x_1, x_2, \cdots x_{17}) \\ &x = (x_1, x_2, \cdots x_{17}) \in R \subset U \end{aligned} \tag{1}$$

Where x_i are the decision variables, max $f(x)$ is the objective function, x is constraint condition.

Due to the shunt impedance Z of the structure [12]:

$$Z = \frac{\left[\int_0^L E_z(z)dz\right]^2}{PL} \tag{2}$$

Where P is the total loss of power within the structure, L is the length of the structure, E_z is the amplitude of the electric field intensity on the axis, and the distribution of electric field E which corresponds to the specific boundary conditions can be obtained by solving Maxwell's equations. Thus, it can't directly use the geometric parameters to describe the shunt impedance, nonlinear relation between objective function and constraint, and can't directly use the variable x to establish the analytical expression of the objective function max $f(x)$.

Therefore, in order to establish the relationship between the objective function and variable x, we introduce encapsulation and penalty function to establish the objective function max $f(x)$, as follows:

$$\begin{aligned} &\max f(x) = \begin{cases} Z \\ 0 & Y_2 \le 0 \end{cases} \\ &x = (x_1, x_2, \cdots x_{17}) \in S \subset X \end{aligned} \tag{3}$$

ANALYSIS OF ALGORITHM

The algorithm which consists of genetic manipulation and shunt impedance calculation is used to optimize the structure. Genetic manipulation [13] independently compiled main program to achieve the operation of selection, recombination and mutation operator and shunt impedance calculation complied subroutine to achieve the structure tuning and the objective function calculation. The procedures of optimization with genetic algorithm are as follows.

1) Define the minimum and maximum values and calculate the total bit length which corresponds to resolution within the range to encode each geometry parameter.
2) A set of geometry parameters called individual is converted to an array of bits called chromosome.
3) Initially many chromosomes are randomly generated to form an initial population.
4) Decode chromosome to geometry parameter of the structure.
5) Calculate the field with SUPERFISH [14] code and adjust Y_2 to tune the structure to obtain resonant frequency $f = 186$ MHz. If $Y_2 \leqslant 0$, max $f(x) = 0$, else max $f(x) = Z$.
6) Repeat above procedures from 4) to 5) for all chromosomes.
7) The fitness function is defined with the proportional method and elitist maintaining strategy. Individuals are selected among the existing population according to the fitness function to generate a new generation. And individuals for $Y_2 \leqslant 0$ are replaced with the elitist.
8) Select a pair of parent from the pool selected previously with a new roulette based on the selected individuals.
9) Produce a pair of children from a pair of parent using uniform recombination operator with a constant probability P_c.
10) Repeat above procedures from 8) to 9) until the next generation population reaches the required number.
11) Mutation is operated to the children with a constant probability P_m.
12) Repeat above procedure from 4) to 11), until successive iterations no longer produce better results.

The program flow chart is shown in Fig. 2.

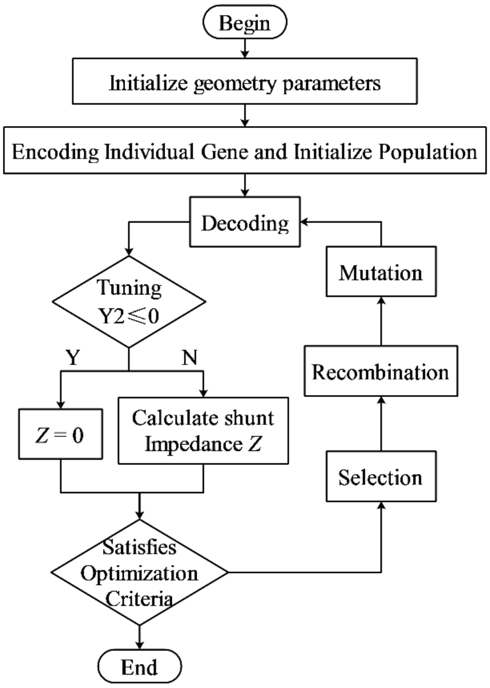

Figure 2: Program flow chart.

ANALYSIS OF SIMULATION RESULTS

According to the above analysis, we develop the optimal program with the Python programming language and the electromagnetic solver SUPERFISH code. The selection of population is performed with the proportional method. In the tuning, if $Y_2 \leqslant 0$, $Z = 0$, otherwise, call the electromagnetic solver code to calculate shunt impedance.

The running parameter of the program is shown in the following Table 1.

The maximum, minimum and average shunt impedance of the population per generation are shown in Fig. 3. The figure shows that the maximum shunt impedance is 231.52 MΩ/m. Because of the stochastic process, the maximum and minimum shunt impedance per generation fluctuate in the evolutionary process. But the average shunt impedance per generation gradually increases and converge after the 80th.

Table 1: The Running Parameter of the Program

Parameter	**Value**
Population size	50
Generation	156
Probability of recombination	0.6
Probability of mutation	0.015

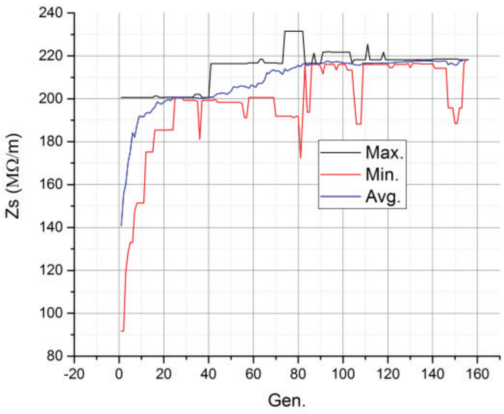

Figure 3: Shunt impedance of the population per generation.

Figure 4 shows that the optimum structure with a nose cone shape was tuned properly which the resonance frequency is equal to 186 MHz. Meanwhile, it gives the electromagnetic field distribution of the structure. Table 2 shows the electrical parameters of the optimal structure.

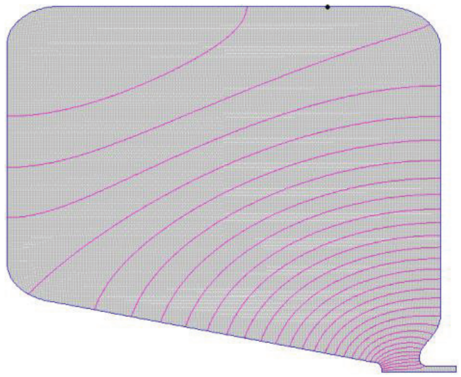

Figure 4: The optimum structure with electromagnetic field distribution.

Table 2: Electrical Parameters of the Optimal Structure

Parameter	**Value**	**Unit**
Frequency f	186	MHz
Quality factor Q	44638.3	
Shunt Impedance Z_s	231.52	MΩ/m
r/Q	245.74	Ω
E_{max}/E_0	5.14	

CONCLUSION

The genetic algorithm is used to optimize the VHF gun with a nose cone shape. In this paper, we realize the algorithm with Python language and the code SUPERFISH. The program is performed to search for the maximum shunt impedance. As a result, the shunt impedance is up to 231.52 MΩ/m. In the future, beam dynamic will perform to study the beam quality.

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