DESIGN OF AN X-BAND PHOTOCATHODE RF GUN FOR TSINGHUA THOMSON SCATTERING X-RAY SOURCE

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Abstract

Compared with S-band and C-band accelerating structures, X-band structures can run at a higher accelerating gradient and are more compact in size. A new X-band photocathode rf gun operating at 11.424 GHz has been designed at the Accelerator Laboratory of Tsinghua University to obtain higher electron energy in a limited space. The design of the X-band photo-cathode rf gun and the accelerating structures as well as the beam dynamics simulation are presented in this paper, followed by the optimization of the structure based on the differential evolution algorithm (DE). The results show that the design satisfies the working requirements with a small space occupied and a high beam quality.

INTRODUCTION

X-band accelerator structure is attractive by its high accelerating gradient which leads to a miniaturization of device. On the other hand, high gradient also means bunch in small size can be emitted from the cathode to make the thermal emittance small, which is one of the keys to build the compact thomson scattering x-ray source [1].

Many photocathode rf guns operated at high frequence are designed with 1.6 pillbox cells [2]. At the exit iris, there is a transverse rf kick to the beam which is equal to a defocusing lens whose focal length is in proportion to the beam energy while inversely proportional to the accelerating gradient. So it is good to build more cells to increase beam energy to reduce this kick for high gradient rf gun [3]. Thus, a 3.5 cells X-band gun is designed which is operated at 200 MV/m cathode peak field in room temperature.

DESIGN AND OPTIMIZATION

Parameters to be Optimized

There are a few parameters influencing the beam emittance, length of first cell, laser phase to the rf, radius of laser spot, duration of laser pulse, solenoid field strength, length of solenoid, and position of solenoid to the cathode.

Generally, the length of first cell (marked as C) is near a half of full cell length, C ~(0.4,0.6). C is often chosen as 0.6 for S-band gun but a little different for X-band gun. X-band gun with first cell length of 0.4 to 0.5 has a more flat energy curve while gun with first cell of 0.5 to 0.6 has a downward slope which means particles at the end of beam will see lower gradient than that seen by particles in the front, which is bad for bunch compression, as shown in Fig. 1. So there is a rough feeling that short length of first cell is better for X-band gun.

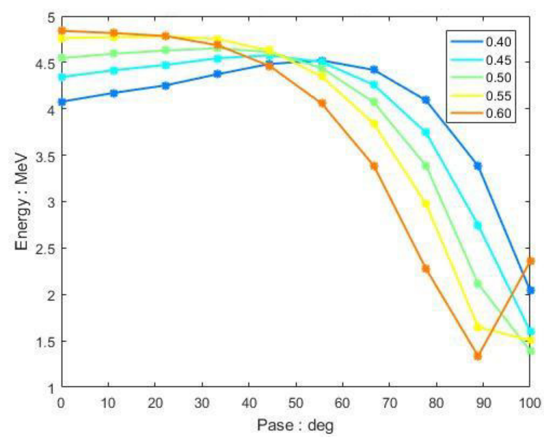

Figure 1: Energy changed with phase for guns with different length of first cell.

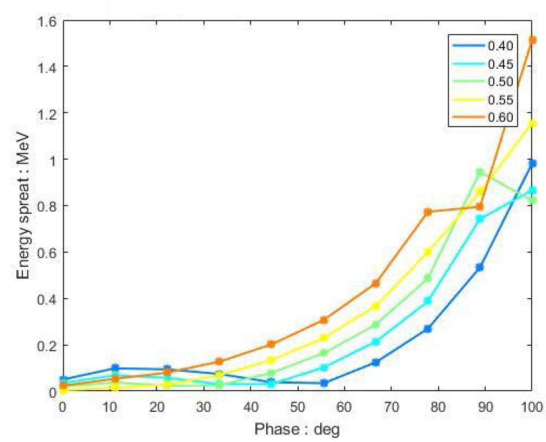

Figure 2: Energy spread with phase for guns with different length of first cell.

The laser phase to the rf (marked as p), the duration of laser (marked as t), and radius of laser spot (marked as r) are related with the charge of beam bunch and

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cathode peak field. Gun operated at phase between 20 degrees and 40 degrees has a smaller energy divergence, as shown in Fig. 2. Thus, for 200 pC and 200 MV/m, p~(20 degrees, 40 degrees), t~(1 pS, 8 pS), r~(0.1 mm, 0.2 mm).

The strength of solenoid field (marked as B), the length of solenoid (marked as L) are related with the momentum of beam bunch, here B~(0.2 T, 0.8 T), L~(5 cm, 15 cm), the position of solenoid (marked as z) is often near the exit of cathode, z~(0.05 m, 0.06 m).

The range of these parameters are listed in Table 1.

Table 1: Range of Design Parameters

Parameter	Lower Limit	Higher Limit
C	0.4	0.6
p	20 degrees	40 degrees
r	0.1 mm	0.2 mm
t	1 pS	8 pS
B	0.2 T	0.8 T
L	5 cm	15 cm
z	0.05 m	0.06 m

Differential Evolution Algorithm

It is hard to describe the influence of these parameters in an analytical formula, which means it is difficult to optimal this gun in general methods such as steepest descent or Newton iterative method, but some artificial intelligence algorithm will have a good performance.

Here the differential evolution algorithm (DE) is chosen to do the optimization, the steps of DE algorithm are described as follow [4]:

- Step1-Initial: Generate random values of parameters belong to the range shown in Table 1 called initial generation I0, each combination in this generation is called the initial individual P0, then initial the differential coefficient F (0<F<1) and the variation coefficient D (0<D<1).
- Step2-Caculate fitness: Simulate the emittance growing with position for each individual by ASTRA, and find the compensation point for each individual, emittance at the compensation point is so called the fitness. The smaller fitness, the better condition.
- Step3-Differential: Do differential for each individual with another random individual, times the result with F and add to the original individual to obtain the differential generation ID.
- Step4-Evalution: Generate a random number K (0<K<1) for every parameter in each individual, if K<D, replace that parameter in the initial individual by the same parameter in the differential individual, else keep this parameter, here a new generation IE is obtained.
- Step5-Chose: Calculate the fitness of each individual in IE and compared with individual in I0. Individual with lower fitness will be chosen into next generation.
- Step6-Iter: Repeat Step3 to Step5 until reach the maximum iteration.

The flow chart of DE algorithm is shown in Fig. 3.

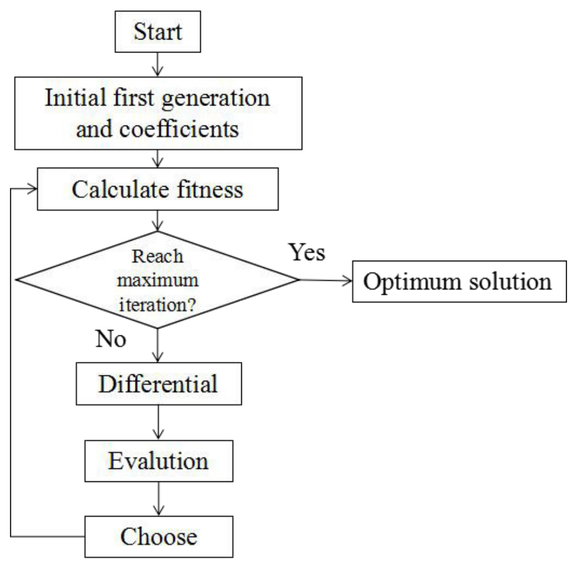

Figure 3: Flow chart of DE algorithm.

Design of Gun

Figure 4 shows the design of a 3.52 cells X-band gun after optimization and the rf parameters of gun are shown in Table 2. The frequency interval of pi-mode with the nearest mode is 33 MHz and the power loss when operated at 200 MV/m is 6.43 MW, which is satisfied with the demand of power source.

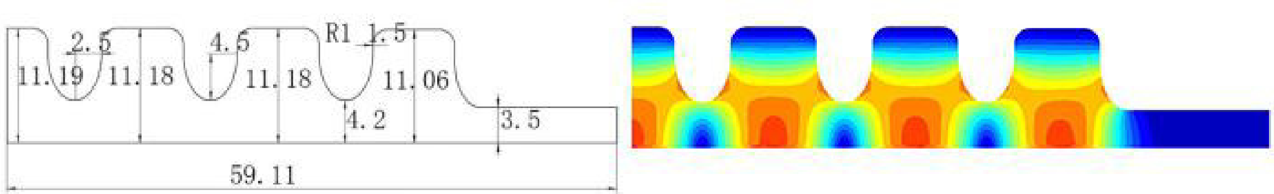

Figure 4: Design of 3.52 cells X-band gun.

Table 2: RF Parameters of Gun

Name	Value	Unit
Quality Factor	7653	1
Frequence	11.424	GHz
Mode Interval	33	MHz
First Cell Length	0.52	Of Full Cell
Cathode Gradient	200	MV/m
Power	6.43	MW
Field Flat Ratio	0.97	1
Ratio of The Maximum Surface Field to The Cathode Field	0.91	1

Beam Dynamics

A Solenoid field shown in Fig. 5 is used to do the compensation of emittance. The length of this solenoid is 5 cm, and the strength of solenoid is 0.39 T. The beam parameters are shown in Table 3.

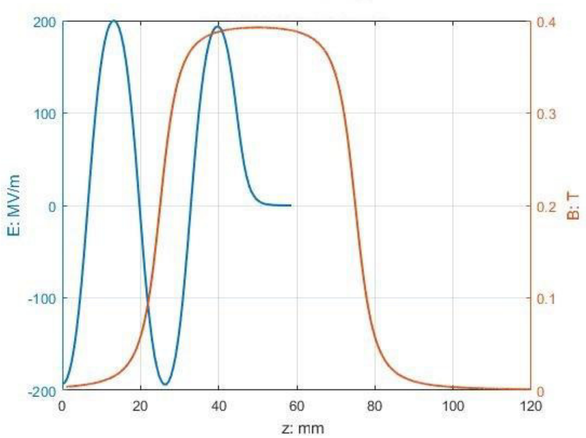

Figure 5: Field of solenoid and gun.

Table 3: Beam Parameters

Name	Value	Unit
Laser Spot Size	0.16	mm
Laser Length	5.6	pS
Laser Phase	26.25	degree
Charge Quantity	200	pC
Final Energy	4.6	MeV
Energy Spread	0.74	%
Compensation Point Position	0.867	m
Compensation Point Size	0.117	mm
Compensation Point Emittance	0.421	μm

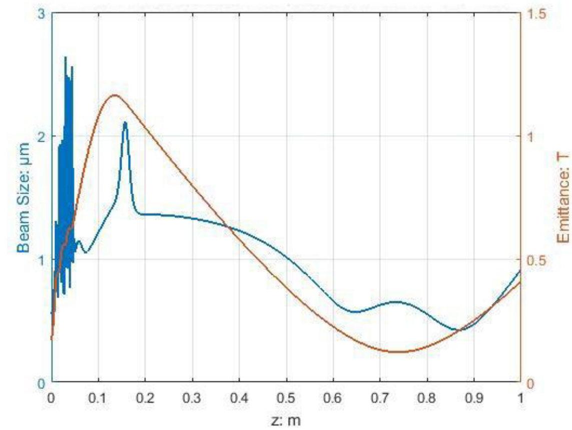

Figure 6: Evolution of emittance and beam size with distance to the cathode.

The evolution of emittance and beam size with distance to the cathode is shown in Fig. 6 which is simulated by ASTRA with 100000 macro particles. It can be seen that there is a compensation point at 0.867 m whose emittance is 0.42 μm and there is a beam wrist at 0.738 m whose beam size is 0.12 mm.

CONCLUSION

DE algorithm is efficient for gun optimization problem and it gives a 3.52 cells X-band structure design for beam parameters shown in Table 3. Multi cells X-band gun is benefited from its high gradient and high output energy, the effect of space charge force can be weakened and could be an important way to obtain high brightness in a compact structure.

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