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DESIGN STUDY OF 3.6-CELL C-BAND PHOTOCATHODE ELECTRON GUN*

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Abstract

A C-band photocathode injector composed of a 3.6-cell C-band photocathode RF gun and two 1.8-meter C-band accelerating structures is proposed. The injector is a low emittance electron source for Free Electron Lasers (FEL) and other compact light sources. The RF structure of the cavities is designed with 2D SUPERFISH simulation. The Beam dynamic study in ASTRA helps rectify the 2D RF simulation. To feed the cavities, a design of extra coaxial coupler with RF gun structure is presented. With compact focusing solenoids, for 0.25nC bunch charge, the final energy can reach 6.9 MeV energy and the 95% emittance can be as low as 0.23 mm mrad (95%). All the details of RF design and beam dynamics studies are presented in this paper.

INTRODUCTION

The requirements of low emittance electron beam for FEL [1, 2], UED and UEM [3, 4] have made the photoinjector a promising source in the past several tens of years. Typical photoinjector in these facilities is based on S-band 1.6-cell gun [5] with gradient around 100MV/m and a section of S-band linac with total length about 10 meters. However, C-band RF technology can achieve higher gradient for photoinjector, thus producing higher quality electron beam with small emittance, as well as more compact scale which is about the half of S-band photoinjector.

A new C-band photoinjector based on 3.6 cells C-band photocathode gun is proposed for lower emittance injector. The gradient of 150MV/m which higher than that of the S-band RF gun is crucial to enhance electron emission on the cathode by overcoming space charge limitation. Therefore, the size of laser spot could be smaller, which results in lower the major characteristic of the beam normalized emittance in a photoinjector -- thermal emittance [6]. Following the C-band RF gun, two accelerating structures as booster can accelerate beam to the energy of 124MeV. The total length of the boosters is less than 5 meters -- only half of the S-band photoinjector.

The C-band RF photoinjector will be developed as the back-up photoinjector for SXFEL facility in the future. This paper describes the conceptual study and design considering beam dynamics and RF design.

2D RF DESIGN FOR BEAM DYNAMICS

The design of the 3.6 cells C-band RF photocathode gun started with 2D SUPERFISH [7] simulation. SUPERFISH not only calculating mode frequency and mode separation of C-band RF gun, but also producing field maps for ASTRA simulation. The gun is operated at π mode with 5712MHz, and the electromagnetic field is presented in Fig. 1. The 3.6-cell gun has four electromagnetic eigenmodes in total, and each with one different frequency. The beam stability could be affected by the mode coupling between π mode and the mode that close to the π mode, like the mode of 5706.4MHz in Fig. 1. In order to reduce the mode coupling, the C-band gun is designed to apply a larger aperture to expand mode separation. However, larger aperture reduces impedance, resulting in a lower power efficiency. The aperture diameter is optimized to 15mm to make compromise between mode separation and impedance. In Fig. 2 frequency separation between π mode (5712MHz) and the close mode (5706.4MHz) is 5.6MHz, which is about 10 times of 550kHz as the FWTH of π modes. This design could reduce the mode coupling to a very low level that the impact on the emittance growth could be neglected.

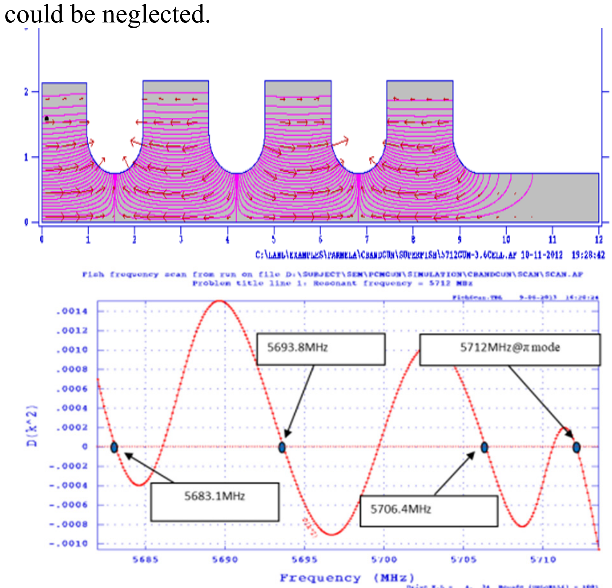

Figure 1: field distribution of π mode (upper) and frequency for four different modes (lower).

BEAM DYNAMICS STUDIES OF C-BAND PHOTOINJECTOR

The layout of C-band photoinjector comprising of the C-band 3.6-cell gun and two C-band accelerating structures is presented in Fig. 2. The optimization will find out optimum parameters including the current and position of solenoid and the gradient of accelerating structure. The injec-

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tor is designed and optimized to achieve minimum emittance at exit. All results of beam dynamic below are calculated by ASTRA [8].

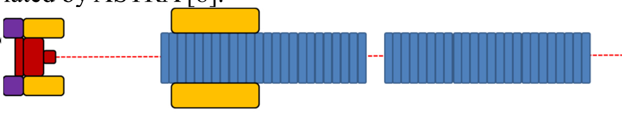

Figure 2: Schematic layout of the C-band photoinjector.

The energy and beam size evolution are presented in Fig.3. The final energy at the exit of second C-band accelerating structure is 124MeV, which's total length is about 4.8m only half length of the S-band injector. The rms beam size at the exit is about 0.1 mm acceptable as well as the emittance for the injection into the main linac. The energy gain is based on the simulation results of 250pC. The energy at exit of the gun is 6.9MeV, and the final energy at the end of the injector is 124MeV. The result of beam size evolution of 250pC is about 0.1mm (rms) at exit of the injector.

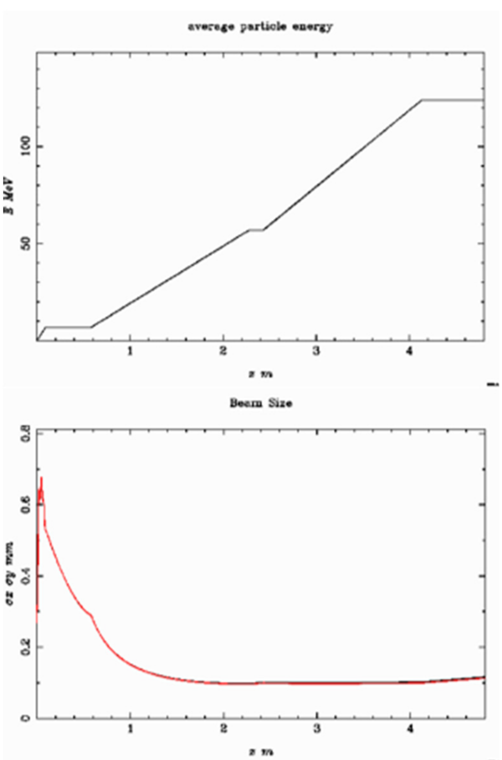

Figure 3: Energy boosting (up) and beam size (down) for 250pC along the photoinjector injector.

The simulation results of transverse phase space, longitudinal phase space, and slice emittance distance based on 250pC at exit of the injector are shown in Fig. 4. The energy spread is about 1.5%, which is comparative to the S-band photoinjector. Energy spread shows nonlinear curve like sine curve from crest acceleration, which must be linearized by higher harmonics before bunch compressing. FEL radiation proceeds and saturates sensitively in the center region of the bunch. The slice emittance is 0.19 mm·mrad, not only lower than the 95% rms projected emittance, but also distributing in the center region of the bunch uniformly.

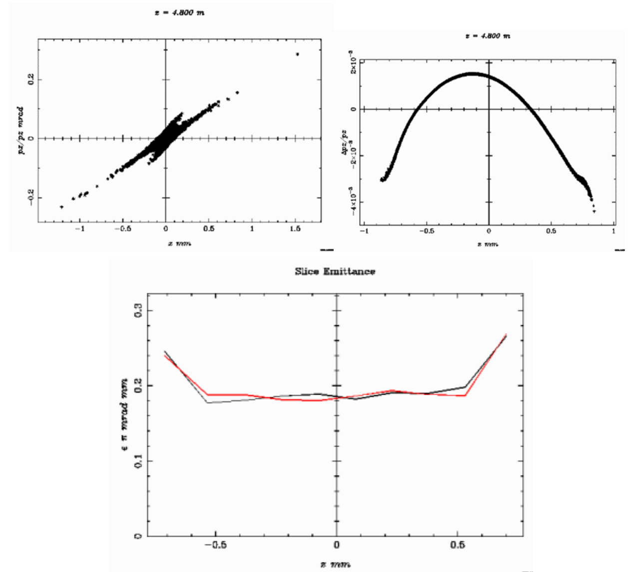

Figure 4: Simulation results of 250pC bunch charge. Transverse phase space (upper left), longitudinal phase space (upper right), slice emittance dist. (lower).

Based on the optimization above, all parameters of the C-band photoinjector could be summarized in Table 1 which is specified for beam charge of 250pC.

Table 1: Parameters of Preliminary Design of C-Band Photocathode Injector on 250pC

Parameters	**Value**
Frequency	5712MHz
Charge	250pC
Bunch duration	5ps
Transverse laser spot size σ	0.3mm
Bunch rise/fall time	250fs
Normalized projected emittance (100%)	0.34 mm·mrad
Normalized projected emittance (95%)	0.23 mm·mrad
Slice emittance (central region)	0.19 mm·mrad
Cathode field	150MV/m
Accelerating gradient	30MV/m (1st), 45MV/m (2nd)
Gun energy	6.9MeV
Final beam energy	124MeV
Total length	About 5 meters

3D RF DESIGN OF C-BAND 3.6-CELL GUN

The C-band 3.6-cell gun is preliminarily designed by SUPERFISH with 2D simulation to get field distribution and mode separation. Before the mechanical design and fabrication, a 3D design including cells and coupler should be proceed to fix real field flatness, coupling coefficient

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and the exact operating frequency. The 3D model is designed and calculated by CST to get exact geometry dimensions of RF gun with coupler. In order to place the solenoid as well as eliminate dipole and quadrupole field a special coaxial coupler is proposed and designed in this model. The 3D model is shown in Fig. 5. The C-band gun is composed of a mode launcher, a coaxial coupler and 3.6 cells. The mode launcher and coaxial coupler which eliminating dipole and quadrupole field is designed with enough length to place the solenoid easily. In Fig. 5 it's indicated that the electromagnetic field in the coupler is very low, which is different from high field in the side-coupling coupler. This type of coupler can reduce pulse heating and breakdown rate effectively, which is much better for high gradient operation.

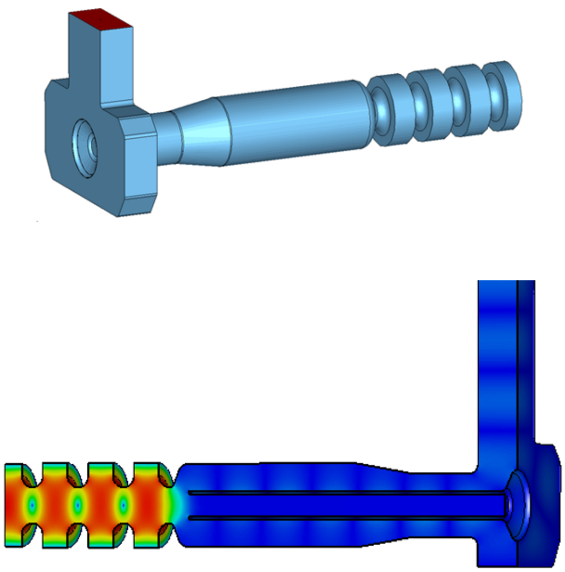

Figure 5: 3D model and field distribution in cells.

In the design and simulation of the structure, the field flatness, the coupling coefficient and the operating frequency reacts differently to different dimensions. The field flatness is mainly a function as relative cell radius; the coupling coefficient is primarily a function of coupler cell radius, coaxial coupler and mode launcher; and the operating frequency is mainly tuned by changing all cell radius. After several iterations of optimization all three design targets are achieved, as shown in Fig. 6. The reflection of π mode (5712MHz) is about -46dB which indicates 1.01 coupling coefficient, and the field flatness is at the ratio of 1.1 between the cathode and the rest of the 3.6-cell cavity.

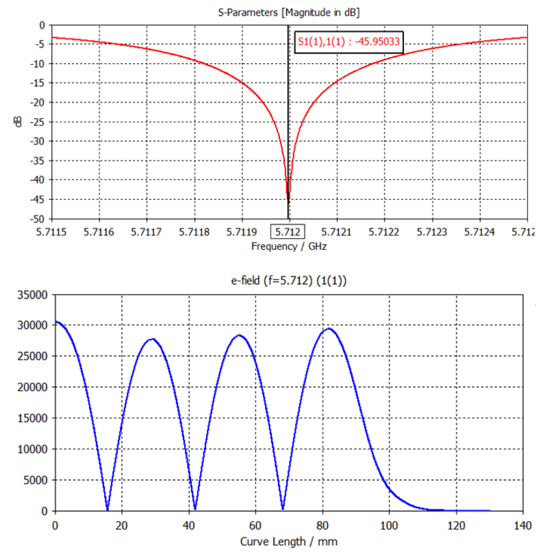

Figure 6: Frequency, coupling coefficient and field flatness.

CONCLUSION

The C-band photoinjector is a competitive and prospective solution to improve FEL performance. Based on a high gradient, it can make the facility more compact, which is promising to build the Compton light source or UED in a small room. The design of the C-band photoinjector is presented in this paper. Simulation of 250pC shows a lower emittance with good beam quality is achieved. The C-band photoinjector is preliminarily studied and designed, and it will be developed continually with mechanical design and fabrication. In the future, a dedicated setup will be built to test the C-band photoinjector in the SXFEL or SDUV-FEL tunnel.

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