DESIGN AND COLD TESTS OF A PROTOTYPE PHOTOCATHODE RF GUN FOR SHANGHAI SXFEL FACILITY*

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Abstract

A soft X-ray (~9 nm) FEL (SXFEL) facility is going to be constructed in Shanghai, China, which requires high charge (>500 pC) electron beam with low transverse emittance (<1.5 mm.mrad) at photoinjector exit. One of the keys to achieve a low emittance with high charge is high gradient on the photocathode, so an S-band photocathode RF gun modified from BNL type gun is designed, which aims running 100 MV/m peak gradient at 10 Hz. By changing the cathode seal technique, removing the insertion RF tuner, and reducing the peak surface field, RF breakdown possibility is reduced. Besides, RF pulse width is also considered to be reduced to lower the RF breakdown possibility. Since zero mode and multipole field degrades the beam emittance, they are also suppressed in the new gun design. Design details and cold testing results are presented in this paper.

INTRODUCTION

The Shanghai Soft X-ray FEL (SXFEL) is a test facility for exploring novel FEL principles (HGHG/EEHG) and key technologies in the X-ray regime [1], which is expected to radiate at wavelength of 9 nm with full coherence. The SXFEL project demands a high brightness electron beam, which will be generated by photoinjector built by Tsinghua Univeristy [2], and the beam requirements at photoinjector exit is shown in Table 1.

Table 1: Electron Beam Baseline of SXFEL at Photoinjector Exit

Item	Value	Unit
Chage	500	pC
Energy	~130	MeV
Bunch length (FWHM)	~10	ps
Normalized transverse emittance (RMS)	1.5	mm.mrad
e^- beam to RF jitter (RMS)	0.25	ps
Repetition rate	1~10	Hz

Simulations show one of the challenges of achieving such a high brightness electron beam is RF gun gradient. Currently, most of the BNL type RF guns fabricated at Tsinghua University are limited to ~75 MV/m due to RF breakdown issues. Fig. 1 shows optimized photoinjector transverse emittance evolution with two RF gun gradients by PARMELA simulations. Obviously, RF gun with 75 MV/m generates an electron beam which just meets the baseline of SXFEL without considering other nonideal situations, like UV nonuniformity, multipole field and so on, so improving RF gun gradient is the first priority in the new RF gun design.

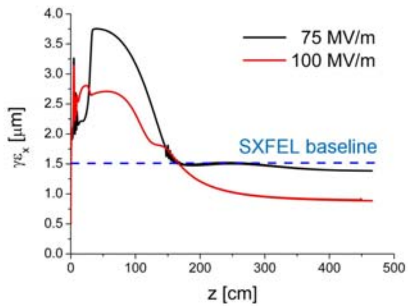

Figure 1: Photoinjector emittance optimizations with two RF gun gradients.

In the following, RF gun fabrication activities at Tsinghua University are briefly introduced, then features of the new gun are described, and finally the cold testing results are presented.

FEATURES OF THE NEW PHOTOCATHODE RF GUN

Tsinghua University has been developing photocathode RF guns for almost 10 years, during which we devoted efforts to test fabrication technique, optimize washing method and built RF measurement platforms. The first BNL type S-band RF gun was tested in 2005 at Tsinghua University [3], and generates huge amount of darkcurent (~6 nC, 3.5 μs) due to brazing alloy of Ag/Cu. Its gradient was limited to 75 MV/m due to frequent RF breakdowns. After two years of operation, the RF gun was taken apart from the beamline, and inner surface damage at cathode seal gaps and iris surfaces were clearly observed (Fig. 2). Both the two locations have electric fields higher than that at cathode centre, and are susceptible to RF breakdowns.

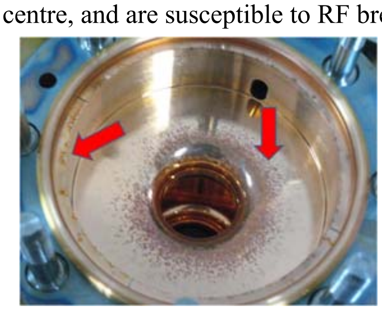

Figure 2: inner surface damage of the first photocathode RF gun after operating two years at Tsinghua University.

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During collaboration with Brookhaven National Lab in 2006, Ag/Cu brazing alloy was changed for the Au/Cu alloy, and dark current decreased by a factor of 100 (~50 pC, 2μs), but peak gradient is still limited to 100 MV/m.

During the last five years, BNL type photocathode RF gun has seen a great leap at LCLS and many other institutes [4], peak gradient has gone to ~120 MV/m and repetition rate has increased to 100 Hz [5]. With so many improvements to the RF gun technique in rescent years, a new gun design started in 2010 at Tsinghua University to meet the SXFEL requirements.

Gun Profile

The gun profile was modified as described in Fig. 3. Based on the experience of LCLS, the disk iris was modified from circular to elliptical to reduce surface electric field, and further extending the major axis of the elliptical shape decreases the peak surface electric field from 98% (LCLS case) of the cathode peak field to 88%. Besides, the coupling between full cell and half cell was enhanced by increasing the hole size, and the mode separation was modified to be 15.28 MHz, which will depress the zero mode excitation at PI mode frequency. To increase the quality factor of the gun cavity, the corner of the gun was curved to reduce the lossy area, thus cavity Q_0 will be increased by 10%. The SUPERFISH simulation results compared with other gun profiles are shown in Table 2.

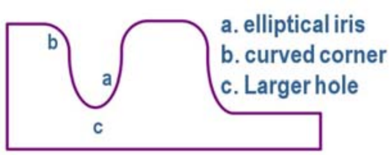

Figure 3: New gun profile modifications.

Table 2: Superfish Simulation of Different Gun Profiles

Item	BNL	LCLS	THU
f_π-f_0 [MHz]	3.3	15	15.28
Q_0	11800	14300	15400
R_{shunt} [MΩ/m]	36.2	41	44.2
E_{surf}/E_{cath}	111%	98%	88%

Cathode Seal and RF Tuner

In the original BNL type gun, the cathode plate was vacuum and RF sealed to half cell end by a HELICOFLEX seal, as shown in Fig. 4. HELICOFLEX seal works as both cathode seal and half cell RF tuner (by changing the pressure), but leaves an extended gap area which not only degrades Q_0 of the cavity but is also susceptible to RF breakdown because the gap area has both intense electric and magnetic field. In the new design, a MATSUMOTO gasket is used [6], which is a unisex pair with a 90-deg sharp edge forming a continuous smooth connection providing almost zero impedance as seen from the bunched beam and RF power. The new gasket eliminates the cathode gap as much as possible, and reduces the RF breakdown possibility there. By changing thickness of and pressure on the gasket, half cell frequency can be easily tuned.

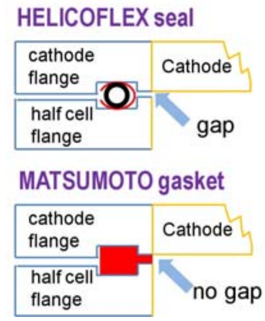

Figure 4: Schematic drawing of cathode seal technique.

Besides, the inserted RF tuners in the full cell are also removed for a pair of symmetric deformation tuners to reduce the RF breakdown possibility induced by inserted tuner rods.

Multipole Field Reduction

In the photocathode RF gun, there exist many ports at the inside cavity wall, such as oblique laser incident ports and RF coupling port between waveguide and cavity, which breaks the axisymmetry of the gun. RF coupling port is the largest port which creates field asymmetry in the coupler cell, and excites multipole fields.

Among the multipole field, dipole field not only kicks the beam from the beam axis, but also contributes greatly to the RF emittance increase. In the original BNL design, a vacuum port 180 deg opposite the RF coupling hole was added to compensate the dipole field. Even if the vacuum port has the same dimension as the RF coupling port, the geometry nonsymmetry remains due to the difference of vacuum pipe and waveguide system behind the symmetric holes. Besides, single side RF coupling creates RF phase nonsymmetry, so a residual dipole field remains. LCLS RF gun adopts the dual RF coupling scheme to eliminate the dipole field. In our new gun, we adopt the nonsymmetric vacuum port design to eliminate the dipole field [7], by carefully tuning the vacuum port length with MAFIA code, and the dipole field was reduced by two orders of magnitudes with single RF coupling (Fig. 5).

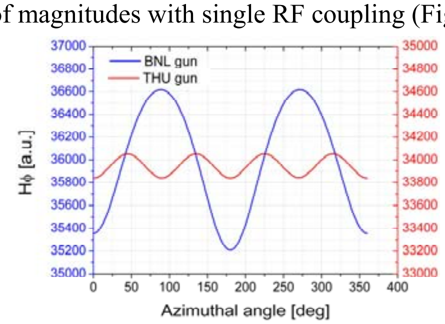

Figure 5: Azimuthal magnetic field distribution in full cell at radius of 10 mm (by MAFIA simulation).

Since the full cell in the BNL design is divided by the two ports into two periods, not only a residual dipole field remains but also a strong quadruple field is excited (Fig. 5). LCLS gun used the racetrack full cell shape to damp the quadruple field [4], while LLNL and PAL gun used the 4-port design to reduce the quadruple field [8, 9]. The 4-port scheme is simple for fabrication, but may cause more pulse heating problems at the additional holes. Our gun is expected to work at a low repetition rate and considered to do RF pulse shaping [4], so the simple 4-port scheme is used to reduce the quadruple by four orders of magnitudes (Fig. 5).

COLD TESTING RESULTS

The gun machining completed in early July, 2011, brazing and cold testing finished in late August, 2011, and high power conditioning was expected to start in October.

Cold testing was done by measuring S11 and field distribution. By detuning the half cell with a blind plate, the frequency and Qe of the full cell was tuned to the design value. With a small coupling between full cell and half cell, the frequency sum of the two cells equals that of the two modes. By measuring the mode and full cell frequencies, the half cell frequency was decided and tuned to the desired value. At last, fine tuning to achieve field balance between two cells was done by doing field distribution measurements. The final S11 curve and π-mode field distribution are shown in Fig. 6.

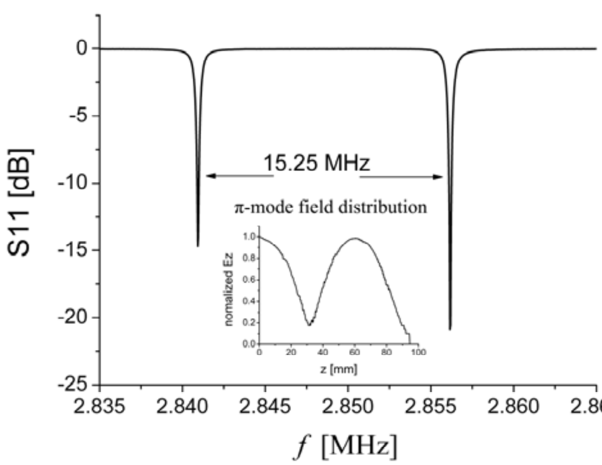

Figure 6: Mode separation and field distribution measurements.

The final π-mode frequency is 2856.16 MHz at room temperature (25℃) in air, thus 43℃ and vacuum will make its frequency at 2856 MHz. Q_0 factor of π-mode is 13000, which is about 90% of the 3D simulation value, and RF power coupling factor β is 1.1, thus 7.1 MW RF power will make a gradient of 100 MV/m in the gun. Figure 7 shows the status of the gun after completing cold testing.

Figure 7: New photocathode RF gun after completing cold testing.

SUMMARY

A new S-band photocathode RF gun was designed, machined and cold tested at Tsinghua University for the SXFEL project. The gun was modified from the BNL type gun, and improvements include reducing RF breakdown possibility by using new cathode seal, new RF tuner and lower surface peak field design; zero mode suppression by increasing mode separation to 15.3 MHz; decreasing mutipole field and so on. The focus of this gun is to achieve a gradient of 100 MV/m, so RF pulse shaping is also considered to reduce the RF breakdown issue. Cold testing shows good results, and high power RF conditioning is about to start next month.

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