RF DESIGN AND HIGH POWER TESTS OF A NEW TSINGHUA PHOTOCATHODE RF GUN*

H. J. Qian, Y. C. Du, L. X. Yan, C. Li, J. F. Hua, W. H. Huang, C. X. Tang#,
Department of Engineering Physics, Tsinghua University, Beijing 100084, China

Abstract

A new photocathode RF gun has been designed and fabricated to meet beam brightness requirements (0.5-1 nC, 1-2 mm mrad) of Tsinghua Thomson scattering project (TTX) and Shanghai soft X-ray free electron laser test facillity (SXFEL). Compared with classical BNL type gun, the new Tsinghua gun features improved cathode sealing structure, 0-mode and multipole field suppression, and higher quality factor. Single RF feed is kept in the new gun for simplicity, and beam dynamics due to single RF feed are investigated theoretically, which predict negligible emittance growth. After high power conditioning, the new gun operates stably with a peak acceleration gradient of ~120 MV/m. Measurements of dark current, Quantum Efficiency (QE), and transverse emittance are presented and discussed in this paper.

INTRODUCTION

Tsinghua University has been developing BNL type photocathode RF gun since 2001, and three generations of RF guns have been fabricated to support Thomson scattering X-ray source project (TTX) and MeV ultrafast electron diffraction (UED) in Tsinghua University, free electron laser projects in Shanghai and so on [1-3]. With progress of TTX and Shanghai soft X-ray free electron laser project (SXFEL), higher beam brightness are required from the RF gun, such as a normalized transverse emittance of 1.5-3 mm mrad for a beam charge of 0.5-1 nC. Besides, MeV UED requires lower dark current for sharper diffraction pattern imaging. RF guns of the first two generations have relatively low acceleration gradient (~75 MV/m) and high dark current (~100 pC/pulse), which are imposing limitations on the above projects, so a third generation RF gun has been developed since 2011 to address the above issues.

Based on the BNL type gun, a lot of RF guns have been developed around the world, which successfully improved gun gradient, RF field properties, gun rep rate and generated lower emittance electron beams. Many modifications in these guns, such as the LCLS gun, UCLA gun, Eindhoven gun, KEK gun, and PAL gun, have been adopted in the third generation Tsinghua photocathode RF gun [4-7].

The new gun has been fabricated, cold tested, and high power conditioned in Tsinghua Univeristy. In the rest of this paper, features of the third generation Tsinghua photocathode RF gun are briefly described [8]; then, impact of single RF feed on beam dynamics is analyzed; finally, the high power conditioning results and emittance measurements are presented.

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#tang.xuh@mail.thu.edu.cn

FEATURES OF THE NEW TSINGHUA PHOTOCATHODE RF GUN

The main goal of the new gun is to increase the gun gradient from ~75 MV/m to ~100 MV/m, and the gradients of the previous Tsinghua guns are limited by RF breakdowns, as shown in Fig. 1. The cathode plate sealing structure was improved in many guns, such as knife edge sealing, brazing and Matsumoto gasket, which eliminate gaps exist in Helicoflex seal and successfully increased the gun gradient above 100 MV/m. Matsumoto gasket is adopted in the new Tsinghua gun due to its simplicity and frequency tuning function. Besides structure optimization, the new gun will operate with a shorter RF pulse width (< 2 μs), which is also expected to bring down the RF breakdown rate.

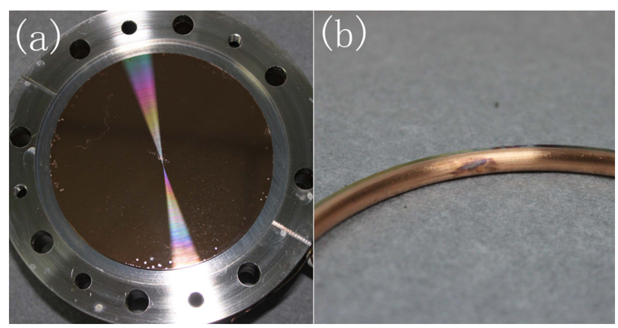

Figure 1: RF breakdown spots in the 2nd generation Tsinghua gun, (a) edge of the cathode plate, (b) Helicoflex seal.

Besides gun gradient, the RF field properties also affect the beam emittance, such as nonaxisymmetry of the acceleration mode and excitation of the non-resonant mode. Nonaxisymmetry of acceleration field (π-mode) contains multipole harmonics, and excitation of non-resonant mode (0-mode) increases beam energy spread, both of which result in beam emittance degrade. The π-mode field symmetry of the BNL gun is further improved by dual RF feed and racetrack full cell shape in LCLS gun and coaxial coupler in Eindhoven gun, both of which require major change of the original structure of BNL gun. For simplicity, single RF feed is reserved in the new gun instead of the dual RF feed. Dipole field component is reduced by asymmetric vacuum port design, while quadruple component is reduced by 4-port design [8]. Compared with the BNL gun, dipole and quadruple are decreased by 10^{-2} and 10^{-3} respectively. Phase asymmetry induced multipoles due to single RF feed are analyzed in the following section, and its impact on beam dynamics is

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negligible in our new gun. Besides, 0-mode excitation is reduced by 80% after increasing the mode separation from 3.3 MHz to 15.3 MHz, same as that of LCLS gun.

By eliminating the gaps of the Helicoflex seal in half cell and changing the gun profile, the unloaded quality factor (Q_0) increases from ~10000 to ~14000, which reduces the heat load by ~20%. Besides, by operating the RF gun with a shorter RF pulse, for example, 1.5 µs instead of 3 µs, the heat load reduces by another ~50%.

Similar to LCLS gun, the profile of the disk iris is modified from circular to elliptical, and the major axis of the ellipse is further extended by 50% than the LCLS gun. Compared with the BNL gun, the max surface electric field on the iris is reduced from 8% higher than the cathode field to 12% lower, which is expected to help lower the dark current. Besides, the copper cathode plate center was hand polished by polycrystalline diamond after off-center diamond turning. The final rms roughness was measured to be 18.8 nm, and the surface fluctuation is within ±50 nm.

The new Tsinghua gun is shown in Fig. 2, and cold testing results are summarized in Table 1.

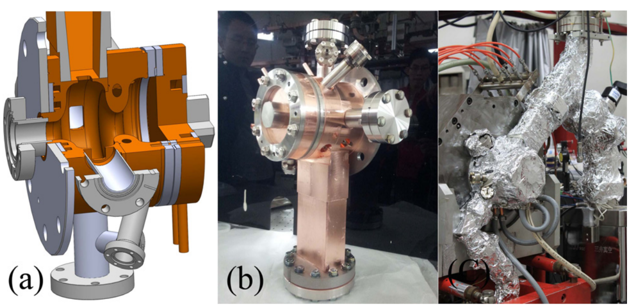

Figure 2: Image of the new Tsinghua RF gun, (a) cutaway view, (b) assembled, (c) installed on TTX beamline.

Table 1: Cold Testing Results of the 2nd and 3rd Generation Tsinghua Photocathode RF Gun

	2nd	3rd
f_π [MHz]	2856	2856
f_π-f_0 [MHz]	3.3	15.3
Q_0	10000	14400
β	1.1	1.3
R_{shunt} [MΩ]	2.7	3.5

ANALYSIS OF MULTIPOLES INDUCED BY PHASE ASYMMETRY

Due to RF loss on cavity walls, there will be travelling wave component in the standing wave RF gun, so single RF feed will cause phase asymmetry along the power flow direction, as shown in Fig. 3, which will manifest itself as multipoles. Following the notation of Ref [9], the axial electric field in full cell can be expressed as follows:

$$E_z = e^{i(\omega t+\varphi_0+k_y y)}\sum_{n=0}^{\infty} E_n \cos(kz) J_n(k_{n,c} r)\cos[n(\theta-\theta_0)] \quad (1)$$

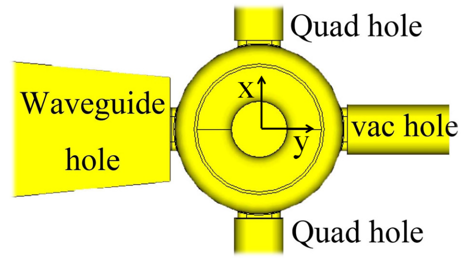

Figure 3: Layout of the 4-port in fullcell.

where k_y is the wave number of the travelling wave component along the waveguide direction and quantifies the phase asymmetry. Since $k_y y << 1$ near axis, Eq. (1) can be divided into two parts:

$$E_z^{amp} = e^{i(\omega t+\varphi_0)}\sum_{n=0}^{\infty} E_n \cos(kz) J_n(k_{n,c} r)\cos[n(\theta-\theta_0)] \quad (2)$$

$$E_z^{pha} = ik_y y E_z^{amp} \approx ik_y y e^{i(\omega t+\varphi_0)} E_0 \cos(kz) \quad (3)$$

where Eq. (2) and Eq. (3) represent multipole series caused by amplitude asymmetry and phase asymmetry respectively. The amplitude asymmetry has been elaborated in Ref [9], and is not detailed here. The phase asymmetry term is 90 degree off the amplitude term, and is approximated as a dipole. The imparted transverse kick and emittance growth is derived as:

$$p_{n,\perp}^{pha} = -\frac{1}{2}\alpha k_y \lambda \cos\varphi_0 \hat{y} \quad (4)$$

$$\varepsilon_{n,y}^{pha} = \frac{1}{2}\alpha k_y \lambda \sigma_y \sigma_\varphi \sin\varphi_0 \quad (5)$$

where $\alpha = eE_0/2mc^2k$ is the normalized gun gradient, λ is the wavelength, φ_0 is the gun phase, σ_y and σ_φ are the average rms beam size and bunch length (in radian) in full cell. φ_0 is defined in such way that it equals zero when the acceleration is maximized, so the phase induced dipole kick the beam hard but the emittance growth is negligible.

k_y for our new gun is simulated by CST Microwave studio to be 0.013 rad/m. Considering a beam with 1 mm rms beam size and 3 ps rms bunch length, the emittance growth in a gun of 120 MV/m is evaluated to be 0.01 mm mrad when φ_0 is off the maximum acceleration phase by 10 degree, and normalized transverse momentum increase is 1.3 mrad, which can be compensated by dipole

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correctors at gun exit. From the above analysis, it is shown single RF feed is acceptable in our design.

HIGH POWER TESTING RESULTS

After baking at 350˚C for 36 hours in a vacuum furnace, the RF gun was immediately installed on the TTX beamline, and then the RF gun was baked online for another 24 hours. The high power conditioning started with a pulse width of 0.25 μs at 10 Hz, and the pulse width increases with a step size of 0.2-0.3 μs during conditioning. Within the first 10 hours, ~11 MW RF power was fed into the gun with a pulse width of 1μs, and the pulse width was increased to 1.5 μs at the end of the next 10 hours. Finally, the pulse width was set at 1.7 μs, and ~11 MW power was fed into the gun, corresponding to a gradient of 120 MV/m, which is verified by electron energy measurement. The new gun was also tested at 40 Hz with a gradient of 100 MV/m, and it works fine as well.

Dark current of the new gun, measured by an integrated current transformer (ICT), is lower than the LCLS gun (Fig. 4 (a)) [10], and field enhancement factor stabilized around 60 (Fig. 4 (b)) after high power conditioning. The copper cathode QE is measured to be 1.4×10^{-5} at the beginning of conditioning, and gradually increased to 4×10^{-5} after conditioning.

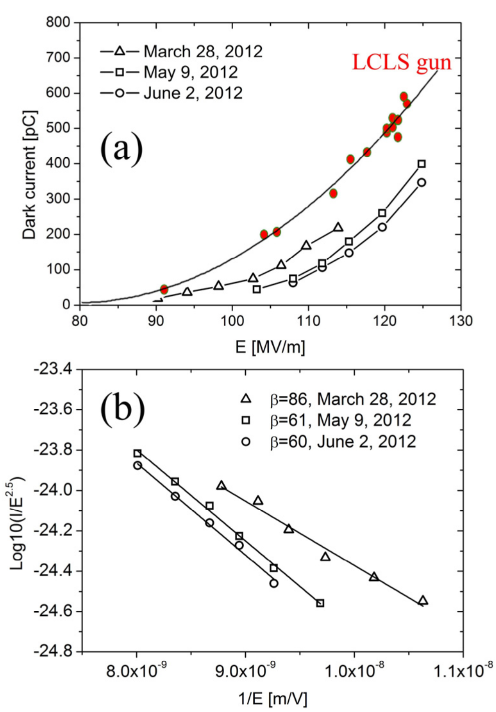

Figure 4: Dark current measurement, (a) dark current vs gradient, (b) F-N plot.

After exiting the gun, the photoelectron beam is accelerated by one SLAC type travelling wave tube, and the transverse emittance is measured by quadruple scan with a beam charge of 250 pC at 55 MeV. The transverse UV laser profile is truncated from a Gaussian profile, and the longitudinal shaping is done by pulse stacking, both of which are not fully optimized yet. The rms and p-p fluctuation of the transverse profile are 50% and 240% respectively, as shown in Fig. 5. Considering the actual laser profile, an ideal pulse stacking, whose pulse width and rising time are 10 ps and 3.6 ps respectively, and a thermal emittance of 0.5 mm mrad, GPT predicts an emittance of 1.2 mm mrad. The actual measurements show the normalized horizontal and vertical emittances are 1.80±0.04 mm mrad and 1.09±0.04 mm mrad respectively (Fig. 6). Further optimizations of the laser quality and beam emittance are still in process.

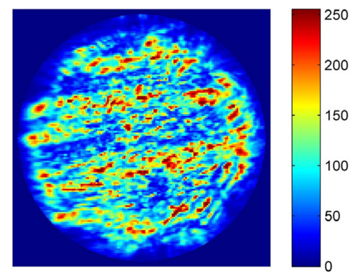

Figure 5: Transverse profile of the UV laser, D=2 mm.

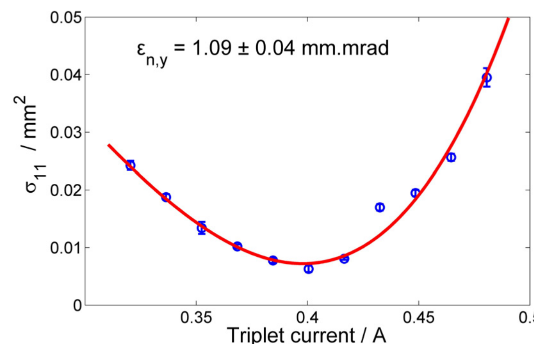

Figure 6: Vertical emittance of a 250 pC beam.

SUMMARY

A new S-band photocathode RF gun, modified from the BNL design, was fabricated and high power tested at Tsinghua University. The new gun operates at 120 MV/m stably with a reduced dark current of 200 pC per pulse, and the copper cathode QE reaches 4×10^{-5}. The optimization of both laser and electron beam are still in process, and the best emittance measured for a 250 pC beam is 1.09±0.04 mm mrad until now.

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