NUMERICAL STUDY ON ELECTRON BEAM PROPERTIES IN TRIODE TYPE THERMIONIC RF GUN

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Abstract

The KU-FEL(Kyoto University- Free Electron Laser) facility uses a thermionic 4.5 cell S-band RF gun for electron beam generation. The main disadvantage of using a thermionic RF gun is the back-bombardment effect, which causes energy drop in the macro pulse. A modification of the thermionic RF gun to a triode type RF gun shall reduce the back-bombardment power and enlarge the macro pulse duration.

In this work we report the results of numerical studies of operational parameters depending on electron beam properties for a triode type thermionic RF.

INTRODUCTION

A 4.5 cell thermionic RF gun is used as the injector for oscillator type MIR-FEL facility (KU-FEL: Kyoto University Free Electron Laser) at Institute of Advanced Energy, Kyoto University. As compared with photocathode RF gun a thermionic RF gun has advantage of compact and economic structure, easy operation and high averaged current. The disadvantage however is the occurrence of back-bombardment effect. Thereby some electrons are getting into the decelerating phase of the driving RF wave and are accelerated back into the cathode. The back streaming electrons heat up the cathode additionally and the current rises as the consequence. The ramped current leads to limitation of the macro pulse duration. In order to solve this problem and to obtain electron beam of high brightness with long macro pulse duration, which is essential for oscillator type FEL, we are developing what we call a triode type thermionic RF gun [1]. For it an additional small coaxial cavity (triode cavity, hereafter) which serves as a control grid should be attached to the currently used thermionic RF gun. The triode cavity has a separate from the 4.5 cell gun power supply with amplitude and phase controlled with respect to those driving the gun main cavities. Figure 1 shows schematic drawing for the triode RF gun system, where the triode cavity is integrated into the main thermionic RF gun. The thermionic cathode material is located on the inner rode of the triode cavity. The triode cavity geometry and corresponding cavity voltage and cathode emmition current were designed for reduction of back-bombardment power by more than 80% [2].

The triode cavity was designed and fabricated, such that experimental proof-of-concept is planned for near future [3].

COAXIAL CAVITY DESIGN

Figure 2 shows a cross sectional view and a photograph of the triode cavity. An accessible structure with a demountable aperture as shown in the future has an advantage of being able to align and to measure the cathode position.

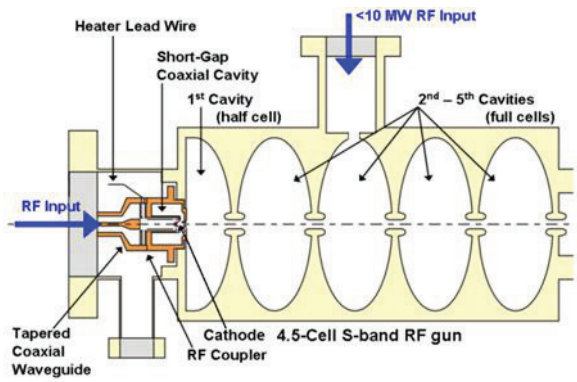

Figure 1: Triode type thermionic RF gun consisting of a small coaxial cavity and the 4.5 cell thermionic RF gun.

The cavity has a stub and spacer tuning system for resonance frequency adjustment. The stub tuning changes the resonance for 15 MHz per each mm stub length. The spacer tuning allows a wider tuning range of resonance by 256 MHz each mm of stub width, while it changes the gap length between the cathode and the aperture as well and might affect the beam focusing as a consequence (see Fig. 3).

The parameters which can be controlled for the operation of the triode cavity are following: The cathode emission J_c by means of the cathode temperature, the triode cathode cavity V_c, and the RF phase difference between triode cavity and main gun cavities φ by means of the input RF amplitude and phase control. Prior to testing the triode system we want to investigate suitable operational conditions which give optimal beam properties like emittance $\varepsilon_{r,n}$ and peak current I_{peak} for minimal power of back streaming electrons P_{back}.

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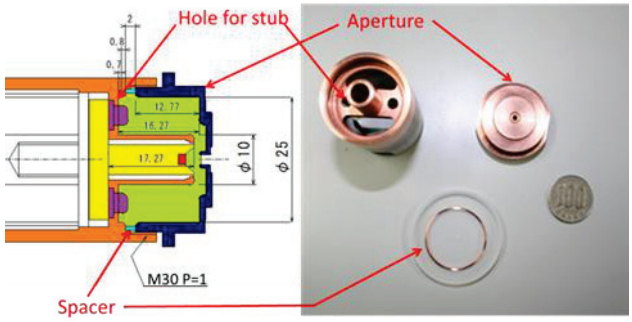

Figure 2: Photo of Triode cavity.

PROCEDURE

For numerical study we have used home developed particle tracking code KUBLAI [4], which includes the beam loading effect in calculation.

Figure 3 shows an eigenmode in the triode cavity used in this simulation. Since cylindrical symmetry is assumed, the effect of misalignment in the transverse position of the cathode was disregarded.

The designed operational parameters for triode type thermionic RF gun, which the design study of the triode cavity geometry was based on, are: V_c = 30 kV, J_c = 80 A/cm^2, gap length L_g = 3.75 mm (see Fig. 3) [5]. The cathode material is tungsten with 1mm diameter.

These conditions might have limitation in experimental feasibility. Especially, the supplied RF power for the triode gun may not be achievable at high values, that is why we study lower cavity voltage (see Table 1). Similarly, lower cathode current densities are studied than the designed value of 80 A/cm^2. Another important operational parameter for the triode RF gun is the gap length L_g, since it might be changed by spacer for reasons of triode cavity resonance adjustment. Thus we investigate the beam performance for 2 different gap lengths L_g.= 3.75, 3.35 mm. These lengths correspond to the tuning range of triode cavity resonance of -100 MHz. This tuning range cannot be covered by stub system (the corresponded simulation has not been published yet).

Further we investigate the correlation between emission current density J_c and the peak current I_{peak} at the exit of triode RF gun. Thereby is important to determine the space charge limit, where the emission current can`t be controlled by cathode temperature.

In Table 1 the parameters used for simulations are summarized. The values for beam charge and emittance at the RF gun exit were obtained from the electron energy distribution of $\triangle E_k/E_k$ = 1%.

For comparison Table 2 shows significant values of calculated beam properties for the 4.5 cell RF gun in conventional structure without the addition of the triode cavity.

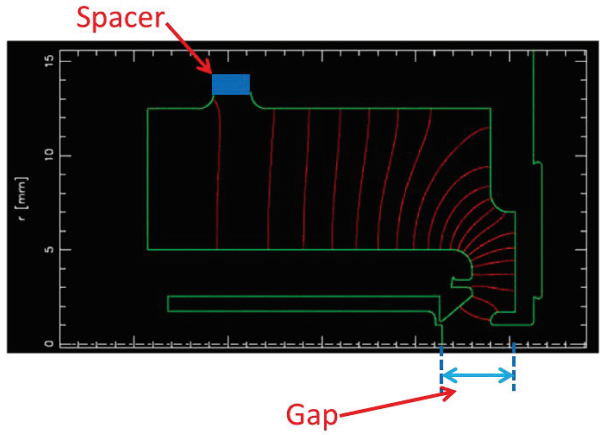

Figure 3: Eigenmode of triode cavity used in simulation.

Table 1: Input Parameters

	Triode	4.5cell
Cavity Voltage V_c	10, 20, 30 kV	11 MV
Gap Length L_g	3.35~3.75 mm	-
Current Density J_c	10~200 A/cm^2	-

Table 2: Calculated Results (Conventional Type)

Total power of back-bombardment electrons P_{back} [kW]	42.9
Peak Current I_{peak} [A]	22
Normalized Transverse Emittance $\varepsilon_{r,n}$ [π mm mrad]	1.23
Bunch Charge Q [pC]	31

Under some conditions, the energy distribution was found to show two peaks. Figure 4 shows energy distribution and the peak current diagram according to the designed operational parameters of the triode RF gun. When such an energy distribution appears, we evaluated the beam parameters of the lower energy peak, because the peak current I_{peak} of the higher energy peak is found not to be high compared with the lower energy peak as shown in the right side graph in Figure 4.

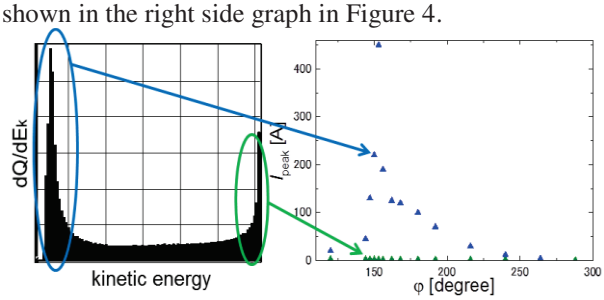

Figure 4: Energy distribution and the results of I_{peak} of triode RF gun (J_c = 80 A/cm^2, V_c = 30 kV, L_g = 3.75 mm).

RESULTS AND DISCUSSIONS

Cavity Voltage

Figure 5 shows dependence of P_{back} in the triode RF gun, normalized by the P_{back} in the conventional RF gun, on phase difference φ and cavity voltage V_c (= 10, 20, 30

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kV). This diagram shows that in order to reduce more than 80% and 90% of P_{back}, φ was needed to be larger than 120 and 150 deg., respectively, for all the three cavity voltages. It can be also seen that there is no significant dependency of φ with lowest P_{back} on V_c.

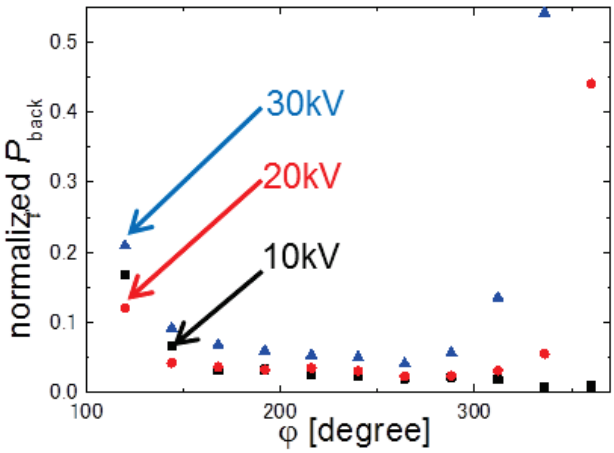

Figure 5: Dependence of P_{back} on φ and V_c (J_c = 80 A/cm^2, L_g = 3.75 mm).

Figure 6 shows the dependence of I_{peak} and bunch charge Q on φ (≥ 120 deg.) and V_c. From this calculation, it was found that acceptably high I_{peak} cannot be obtained for 10 kV. The degradation in I_{peak} is seen more significant than that in Q, and therefore may result from debunching effect because of the low cavity voltage. In constant, a high I_{peak} can be obtained at proper φ for 20, 30 kV. Especially the 30 kV values with φ around 153 deg. show I_{peak} of more than 400 A. Furthermore, we could confirm that φ at the highest Q and I_{peak} increases as V_c becomes lower.

Figure 7 shows the dependence of normalized transverse emittance $\varepsilon_{r,n}$ on φ (≥ 120 deg.) and V_c. The results for 10 kV are not plotted because for 10 kV acceptable I_{peak} cannot be obtained. The $\varepsilon_{r,n}$ for 30 kV is better than that for 20 kV through almost all φ except for around 150 deg. where $\varepsilon_{r,n}$ for 20 kV takes minimum. For 30 kV, $\varepsilon_{r,n}$ at φ of 153 deg. is a bit higher than for 20 kV, but that is within the acceptable range. Further, it can be said that for either 20 kV and 30kV, by selecting the proper φ, very high I_{peak} and comparatively low $\varepsilon_{r,n}$ are obtained as well as a low P_{back}.

Table 3 contains P_{back}, I_{peak}, Q, $\varepsilon_{r,n}$, at the proper φ for 20 kV and 30 kV, respectively. The φ which gives the highest I_{peak} is the desired φ for the triode system, as the result of the most significant dependence of I_{peak} on φ.

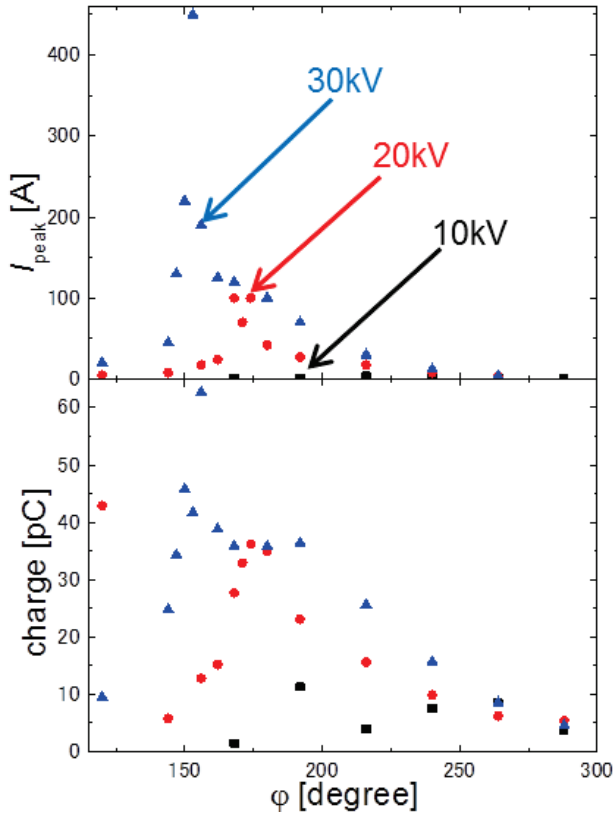

Figure 6: Dependence of I_{peak} and Q on φ and V_c (J_c = 80 A/cm^2, L_g = 3.75 mm).

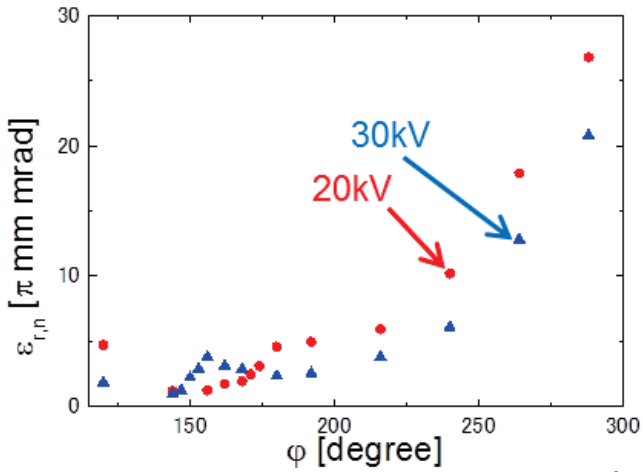

Figure 7: Dependence of $\varepsilon_{r,n}$ on φ and V_c (J_c = 80 A/cm^2, L_g = 3.75 mm).

Table 3: Results for Proper φ (J_c = 80 A/cm^2, L_g = 3.75 mm)

	20 kV	30 kV
φ [degree]	168	153
P_{back} [kW]	1.54	3.51
I_{peak} [A]	100	450
Q [pC]	27.7	41.7
$\varepsilon_{r,n}$ [π mm mrad]	1.92	2.87

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Gap Length

In the same way, we investigated the beam properties for another gap length of L_g = 3.35 mm. Table 4 shows P_{back}, I_{peak}, Q, $\varepsilon_{r,n}$, at the proper φ of 20 kV and 30 kV in L_g = 3.35 mm.

Table 4: Results for Proper φ (J_c = 80 A/cm^2, L_g = 3.35 mm)

	20 kV	30 kV
φ [degree]	156	137
P_{back} [kW]	2.79	4.77
I_{peak} [A]	110	400
Q [pC]	46.6	52.7
$\varepsilon_{r,n}$ [π mm mrad]	3.27	2.69

Compared with Table 3, the proper φ is smaller for both cavity voltages. This is because the gap is shortened, so electrons reach the 1st cavity of 4.5 cell RF gun earlier. It is also found that similar beam properties could be obtained even if the gap length is changed.

Current Density

Figure 8 shows the dependence of I_{peak} on φ in the conditions: J_c = 30, 80 A/cm^2, V_c = 30 kV, L_g = 3.75 mm. It was found that the proper φ for 30 A/cm2 is around 153 deg. just like the proper φ for J_c = 80 A/cm^2.

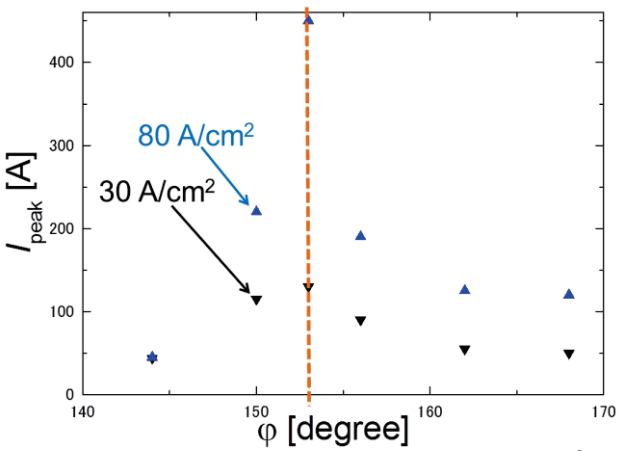

Figure 8: Dependence of I_{peak} on φ (J_c = 30, 80 A/cm^2, V_c = 30 kV, L_g = 3.75 mm).

The dependence of I_{peak} on J_c at φ = 153 deg. is then studied and shown in Figure 9. Beam charge extracted on the cathode over an RF cycle is also shown in the figure as a function of J_c.

The space charge limit is determined from dependency of the extracted charge from the cathode on the J_c. The charge curve saturates around this limit of around 100 A/cm^2. Until that point, cathode temperature is correlated with peak current. The I_{peak} increases almost linearly up to 100 A/cm^2 and decreases abruptly after that. However the I_{peak} curve extends the values of Q curve in the range J_c =60-110 A/cm^2. This behaviour can be explained by the difference in integration process. For calculation of the Q the integration over whole RF period was done, whereas for I_{peak} the integration refers to the accelerating phase, which is a fraction of RF period. The abrupt decrease in I_{peak} at around 100 A/cm^2 may result from debunching and/or defocusing due to enhanced space charge effect.

It is also found that I_{peak} exceeds 100 A that is 5 times higher that the conventional RF gun, even with a moderate J_c of 30 A/cm^2.

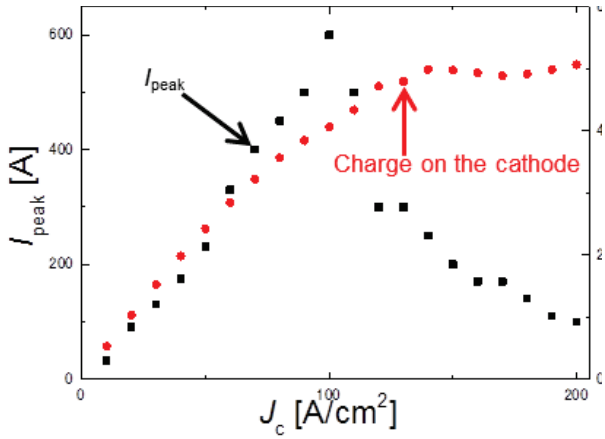

Figure 9: Dependence of I_{peak} and charge on the cathode on J_c (V_c = 30 kV, φ = 153 deg., L_g = 3.75 mm).

CONCLUSIONS

In this work we have numerically investigated beam performance of the triode type thermionic RF gun depending on operation parameters, namely the cavity voltage, gap length and emission current density from the cathode. As a result we found that the reduction of back-bombardment power can be achieved with lower cavity voltage of 20kV without significant loses in beam quality. Whereas for lower cavity voltage of 10 kV the peak current is too low. We expect that for higher cavity voltages the beam properties, especially the peak current, might be further improved. Moreover the change in the gap length of 0.4 mm does not significantly affect the beam properties.

Finally we could confirm that emission current is linearly correlated with peak current until the value of 100 A/cm^2 where space charge limit occurs.

REFERENCES

[1] K. Kanno, et al., "Design of Back-bombardment-less Thermionic RF gun", Japanese Journal of Applied Physics Vol. 41 Suppl. 41-1 (2002) 62-64

[2] K. Masuda, et al., "Development of Thermionic Triode RF Gun", Proceedings of 31st International Free Electron Laser Conference, Liverpool, UK, Aug. 23-28, 2009

[3] K Torgasin, et al., "Cold Test Of The Coaxial Cavity For Thermionic Triode Type RF Gun", Proceedings of IPAC2013, Shanghai, China, May. 12-17, 2013

[4] K Masuda : Ph. D Thesis, Dept. of Engineering, Kyoto Univ(1998)

[5] T. Shiiyama, et al., " A Triode - type Thermionic RF Gun For Drastic Reduction of Back-Streaming Electrons", Proceedings of FEL 2007, Novosibirsk, Russia, Aug. 26-31, 2007

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