A TRIODE-TYPE THERMIONIC RF GUN FOR DRASTIC REDUCTION OF BACK-STREAMING ELECTRONS

T. Shiiyama, K. Masuda, H. Zen, S. Sasaki, T. Kii, H. Ohgaki,
Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan
K. Kanno, E. Tanabe, AET, INC., 2-7-6 Kurigi, Asaoku, Kawasaki, 215-0033, Japan

Abstract

We have proposed a triode-type thermionic RF gun with an additional small cavity replacing the conventional cathode, which provides the beam extraction phase independent of the main accelerating phase to suppress the back-bombardment effect drastically. In order to compensate the predicted degradation in transverse emittance, a design refinement was carried out by the use of numerical simulations in this study. The results showed that the back-bombardment power can be reduced by more than 80% and the peak current of the output electron beam will be enhanced greatly without emittance degradation. Also the cavity parameters, namely the quality factor and the coupling coefficient of the additional cavity with the RF feed coaxial cable were designed to ensure both the induction of the required cavity voltage and a wide frequency acceptance. The prototype design of the triode-type thermionic RF gun was completed and ready for experiments.

INTRODUCTION

We have used a 4.5-cell thermionic RF gun for the injector of MIR-FEL facility (KU-FEL: Kyoto University Free Electron Laser) at Institute of Advanced Energy, Kyoto University. As is well know thermionic RF guns suffer from the back-bombardment of electrons onto thermionic cathodes, which eventually leads to an output beam energy drop and limitation of the macro pulse duration [1, 2]. This effect is seen significant especially in the 4.5-cell RF gun in the KU-FEL because of its high coupling coefficient β and large number of cells. Some countermeasures were applied so far, such as the use of transverse magnetic fields [3] and the temporal control of the RF input for compensating time-varying beam-loading [4] with limited successes. A longer macro-pulse duration by a new technique against the back-bombardment effect is thus essential for the first FEL lasing.

For this purpose, we have proposed a triode-type thermionic RF gun [5, 6]. An additional small cavity with a thermionic cathode replaces the conventional cathode in the RF gun as schematically shown in Fig.1. An RF field induced at the short gap of the additional small cavity, and both the amplitude and the phase are controlled independently of the main accelerating cavities to minimize the back-bombardment of electrons onto the cathode.

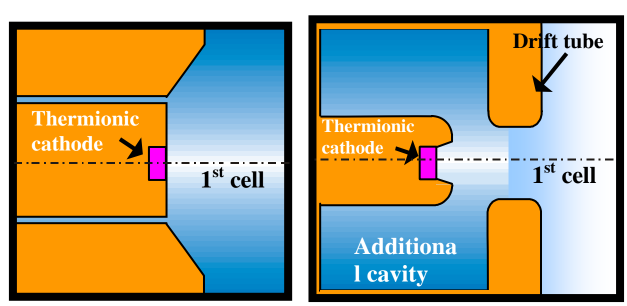
Numerical studies so far have shown that the RF triode concept could reduce the back-bombardment power drastically (80% or higher) while it tends to induce inherent defocusing force at the same time, eventually resulting in an expense of the transverse emittance increase [7].

In this paper, design refinement of a triode-type thermionic cathode was carried out in order to suppress the transverse emittance increase. A wehnelt structure schematically shown in Fig.1 (b) was studied by PIC simulations to compensate the defocusing effect induced by the RF triode.

Also discussed in this paper is the selection of cavity parameters, namely the coupling coefficient β to the additional RF power feed, and the quality factor *Q*.

A potential feature of the RF triode concept is that the requirement of the RF power into the additional cavity is moderate, thus the cost for the RF system modification is low. For the first experiments we have installed a directional coupler to split the RF power from the existing klystron to feed < 40kW to the additional cavity.

To ensure a sufficient cavity voltage with the limited RF power and also expected resonant frequency shifts due to the beam loading effect and/or the cavity temperature change, the tuning curves were calculated by the use of an equivalent circuit model with the beam loading effect taken into account.



(a) Conventional type (b) Triode type

Figure 1: Schematics of RF cavity structures in the vicinity of the thermionic cathode in (a) a conventional, and (b) a triode-type RF gun.

DESIGN REFINEMENT OF THE ELECTRODE IN A TRIODE-TYPE RF GUN

Numerical Method

Design refinement of a triode-type thermionic cathode was carried out by using a cylindrically 2-dimensional group of codes (KUCODE) [8], which calculates electron dynamics in the RF gun, as follows.

Electric field patterns of cylindrically symmetric standing waves in the 4.5 cells and in the additional small cavity for an RF triode are calculated by a 2-dimensional eigenmode solver (KUEMS). The electric fields are then given with cavity voltages and relative phases as the input parameters, and electron dynamics are calculated by the PIC simulation code (KUBLAI). In this study for simplicity, the back-bombardment effect on the temporal beam-loading variation was neglected, i.e. both the cavity voltages and the cathode current density were assumed to be constant. The KUBLAI code takes into account the space-charge effects by simultaneously solving Maxwell's equations and Lorentz equation.

We used these codes to calculate the beam quality by changing the cathode shape and the relative phase between the main accelerating fields and the additional small cavity fields. From results of simulations, we have evaluated the beam emittance (transverse and longitudinal) and the peak current of the output beam at the exit of 4.5-cell RF gun, as well as the back-bombardment power onto the thermionic cathode.

Design refinement of the cathode by PIC simulations

In this study, the cathode mount position was fixed at -6mm with respect to the cathode position in the original conventional RF gun, according to the numerical results so far from the viewpoints of reducing the back-bombardment power and minimizing the transverse emittance degradation [7]. To further reducing the transverse emittance by compensating the defocusing force induced by the triode system, we adopted a wehnelt structure. Figure 2 shows the electrode geometry and the design parameters in this study, namely the cathode depth *d* and the wehnelt angle θ.

For every set of *d* and θ, the optimum RF phase of the additional cavity with respect to the main accelerating cavity of RF gun was searched for the maximum output beam brightness at the exit of RF gun. The other operational parameters were fixed, such as the extraction current density on cathode surface of 80A/cm^2, the cavity voltage in the additional small cavity of 30kV, and the total cavity voltage in the 4.5 main accelerating cavities of 10MV.

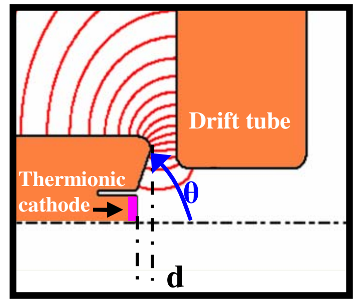


Figure 2: Close-up of a triode-type thermionic cathode with wehnelt structure

As the result, the beam brightness shows maximum at *d* = 1.6 mm and θ = 40 deg. Figure 3 shows the dependence of the output beam properties on θ for a fixed *d* = 1.6mm. Only the results with over 80 % reduction of the back-bombardment power are plotted in the figure.

As seen in Figure 3 we can prevent the transverse emittance from increasing, and improve the brightness by 15 times at the wehnelt angle θ of 40 degrees.

Finally, with the optimal *d* and θ, a minor design modification was then made in practical viewpoints of minimal edge fields and a deep cutoff between the additional cavity and the main cavities, and so on. Table 1 shows the expected electron beam properties by the final design of the refined triode-type thermionic cathode. In comparison with the conventional RF gun, the refined triode-type thermionic RF gun is expected to improve the peak current by 10 times and to reduce the back-bombardment power by ~90 % without degradations of the transverse emittance. The charge in a micro bunch was 77pC.

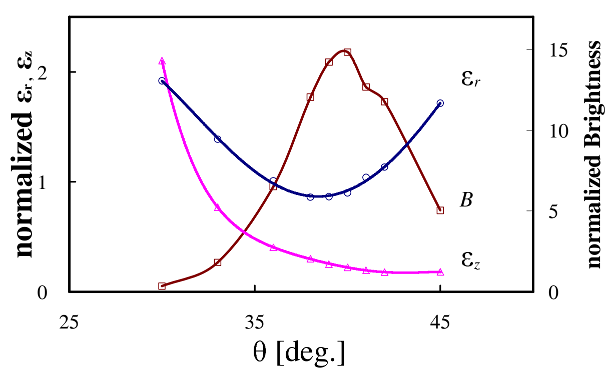


Figure 3: Beam properties by the triode-type cathode at the 4.5-cell RF gun exit as functions of the wehnelt angle θ showing the transverse and longitudinal rms emittances ε_r, ε_z, and the brightness *B* normalized by those by the conventional RF gun.

Table 1: Comparisons of the back-bombardment power and the output beam properties between the conventional and the refined triode-type thermionic RF gun at the 4.5 cell gun exit.

	Conventional	Triode
P_{back} [kW]	36	3.6
I_{peak} [A]	17	114
ε_r [πmm mrad]	2.5	2.0
ε_z [psec MeV]	0.046	0.012
B [A/(πmm mrad)^2 keV]	0.27	1.6

DESIGN OF CAVITY PARAMETERS

In the additional small cavity for the triode system neither a temperature control nor a frequency tuner is to be installed for simplicity and low cost. Instead, we rather set the coupling coefficient β of the additional cavity with the RF feed coaxial cable at over coupling in order to grade the tuning curve and to ensure a wide frequency acceptance. For this purpose, we will also consider a low unloaded quality factor Q_0 of the additional small cavity. At the same time we have to choose β and Q_0 so that a sufficient RF fields should be induced with the limited RF feed power supplied of < 40 kW$_{peak}$.

Equivalent circuit model

Frequency tuning curves were calculated by using the equivalent circuit model in Figure 4. The RF power source is represented by a current source I_g, the RF resonant cavity by a resonant circuit with G_c representing the cavity loss, and the beam loading by an admittance Y_b. The external load G_{ex} can be expressed by the coupling coefficient β as $G_{ex} = \beta G_c$.

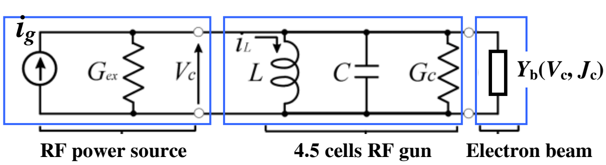


Figure 4: Equivalent circuit model of triode system

In this equivalent circuit shown in Figure 4, the cavity voltage V_c is expressed as formula (1), and I_g is given by the RF input as formula (2).

$$V_c = \frac{I_g}{(G_c + G_b + G_{ex}) + j(B_c + B_b)} \tag{1}$$

$$I_g = \sqrt{8 G_{ex} P_{in}} \tag{2}$$

The RF power P_c consumed by G_c and Y_b i.e. the cavity wall loss and the beam the acceleration, is expressed as follows.

$$P_c = \mathrm{Re}\left[\frac{1}{2}(V_c^* I_g - G_{ex} V_c^* V_c)\right] \tag{3}$$

The reflected RF power P_{ref} is equal to the power subtracted the power consumption P_c from the RF input power P_{in} as formula (4). We thus can calculate the RF power reflection ratio by formula (5).

$$P_{ref} = P_{in} - P_c \tag{4}$$

$$\frac{P_{ref}}{P_{in}} = 1 - \frac{P_c}{P_{in}} = 1 - \frac{4(G_c + G_b)G_{ex}}{(G_c + G_b + G_{ex})^2 + (B_c + B_b)^2} \tag{5}$$

In the formula (5), the beam admittance G_b and B_b are determined by the PIC simulations as functions of the cavity voltage V_c and the cathode surface current density. The cavity admittance G_c and B_c are given by the drive frequency and the cavity parameters, namely the resonant frequency (2856MHz), the shunt impedance (R/Q = 63Ω), and the unloaded quality factor Q_0.

Selection of the coupling coefficient and the quality factor

We used the equivalent circuit model in Fig.4 for calculation of the required RF feed power fed into the additional cavity. From formula (1) and (2), we obtained Fig.5 showing the required RF feed power as a function of the coupling coefficient β for a cathode surface current density of 80 A/cm^2, and a cavity voltage of 30 kV. The unloaded quality factor Q_0 = 4000 was assumed according to the eigenmode calculation for an oxygen-free copper wall.

At a coupling coefficient β of 9.6 the required RF feed power P_{in} is minimum of ~17 kW, which is below the 40 kW limitation of the experimental RF feed system. Taking this margin, we then design a lower Q_0 and/or a higher β for a wide frequency acceptance.

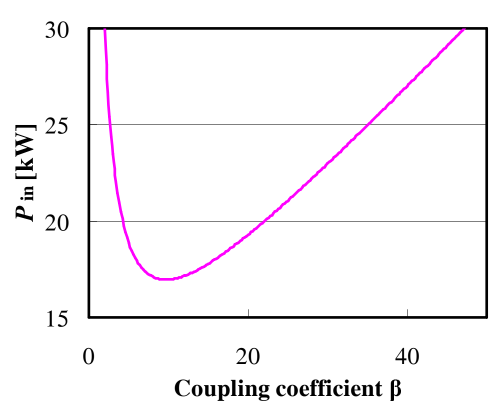


Figure 5: RF input requirement as function of the coupling coefficient β for a cavity voltage of 30kV.

Firstly, we drew tuning curves for various coupling coefficients for $Q_0 = 4000$ and $P_{in} = 40$ kW, and thus obtained the Figure 6 showing the frequency acceptance for $V_c > 30$ kV as a function of β. In Figure 5 and Figure 6, we can see more than 20MHz of frequency acceptance can be ensured by β = 20, and the required RF feed power at resonant frequency is ~20 kW still below the RF feed limitation of 40 kW.

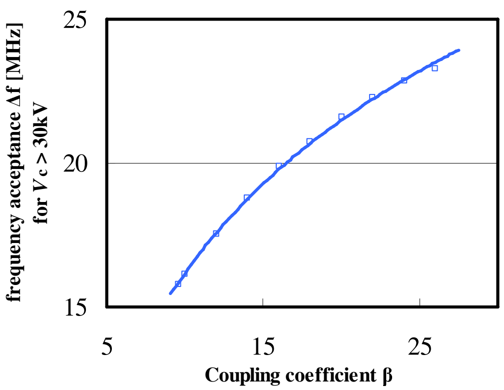


Figure 6: Frequency acceptance Δf for V_c > 30kV, as a function of the coupling coefficient β (P_{in} = 40 kW, Q_0 = 4000)

The red lines in Figure 7 show the calculated tuning curves of the designed additional small cavity (β = 20 and Q_0 = 4000 for oxygen-free copper cavity) with P_{in} = 40 kW. Note that the calculations take the electron beam admittance Y_b into consideration. In Figure 7, the solid lines represent the cavity voltage V_c, the dashed lines the RF power reflection ratio P_{ref}/P_{in}. The black lines in Figure 7 shows those for β = 9.6 and Q_0 = 4000 for comparison.

Secondly we consider a lower Q_0 of ~1000 for a stainless steel (SUS) cavity. The SUS cavity can lower the coupling coefficient β in the same frequency acceptance, so the coupler design is easier than over coupling. The blue lines in Figure 7 show curves for β = 9.6 and Q_0 = 1000. It is found that the SUS cavity can realize the more gentle tuning curves by the lower Q_0. However the frequency acceptance for V_c > 30 kV is found not to be wider, and furthermore the maximum available cavity voltage V_c at resonance is lower.

Thus the additional small cavity for the triode system is to be made of an oxygen-free copper with an over coupling of ~20 with the coaxial RF feed cable.

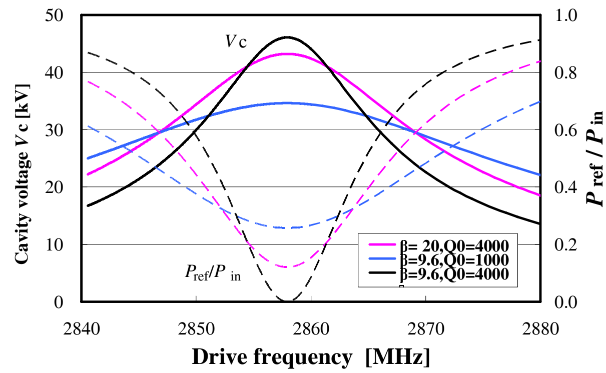


Figure 7: Tuning curves of the additional small cavity, taking the electron beam admittance Y_b into consideration.

SUMMARY

In this study, we evaluated the reduction of the back-bombardment and the output beam properties in a triode-type thermionic RF gun with PIC simulations. With an RF power of ~20 kW fed to the additional small cavity for the triode system, the back-bombardment power is expected to reduce to 3.6 kW from 36 kW in conventional RF gun. Furthermore, the output beam properties at the 4.5-cell RF gun exit, such as the beam emittance and the peak current, are improved as the result of the triode geometry refinement. Especially a great improvement of the peak current is expected because the bunch length of electron beams is to be shortened by using the RF triode system.

We also designed the coupling coefficient β, the shunt impedance *R/Q,* and the quality factor Q_0 to ensure a wide frequency acceptance. Now we are then designing the coupler geometry realize the designed coupling coefficient. We are planning to install a triode-type thermionic cathode based on the designed geometry and parameters for the first experiment this year.

REFERENCES

[1] T. Kii, et al., Nuclear Instruments and Methods in Physics Research A 475 (2001) 588.

[2] K. Masuda, et al., Nuclear Instruments and Methods in Physics Research A 483 (2002) 315.

[3] T. Kii, et al., Proc. 9th Intnl. Conf. Synchrotron Radiation Instrumentation, 2006

[4] T. Kii, et al., Proc of FEl2005 (2006) 584.

[5] E. Tanabe et al., Proc of 27th Linear Accelerator Meeting in Japan, 2002, pp.57 (in Japanese).

[6] K. Kusukame, et al., Proc of the 30th Linear Accelerator Meeting in Japan, 2005

[7] K. Masuda, et al., Proc of FEL2006

[8] K. Masuda, a dissertation of Ph, D. Kyoto University, 1998