# PRODUCTION OF ELECTRON BEAM WITH CONSTANT ENERGY BY CONTROLLING INPUT POWER INTO A THERMIONIC RF GUN

N. Okawachi, M. Nakano, H. Zen, T. Kii#, K. Masuda, H. Ohgaki, K. Yoshikawa, T. Yamazaki,
Institute of Advanced Energy, Kyoto University, Uji, Japan

*Abstract*

A thermionic RF gun is compact and economical, but it is difficult to produce electron beam of pulse width longer than a few μsec with constant energy owing to inherent back-bombardment effect. In this work we tried to keep beam energy constant in macro pulse duration by feeding modulated RF power. We also tried to perform transient analysis with equivalent circuit taking into account the back-bombardment effect in macro pulse duration in the cases of the W cathode and the $LaB_6$ cathode. We found that the degradation of the peak energy could be kept below 100 keV in the macro pulse duration of 8.0 μsec and 8.2 μsec, respectively.

## INTRODUCTION

It is necessary for the development of an FEL to improve the source of electron beam, and a thermionic RF gun is suitable for a compact and economical FEL system. However a back-bombardment effect degrades the beam energy during the macro pulse. In a previous work, we reported the preliminary result of improvement of a thermionic RF gun [1]. In this work we tried to reduce beam energy degradation due to the back-bombardment effect by feeding modulated RF power into a thermionic RF gun. In addition, we have performed a self-consistent transient analysis which took into account the back-bombardment effect during macro pulse duration by using an equivalent circuit model and a thermal conduction.

## EXPERIMENTAL SETUP

Fig.1 shows the experimental setup. The cathode is of 6-mm diameter made of porous tungsten impregnated with barium. RF power fed into the RF gun is controlled by remotely adjusting the reactors in the pulse forming network (PFN) with stepping motors. This experiment was performed varying the beam current drawn from the RF gun and input RF power in both the cases a flat input RF and a modulated RF waveform power.

The profiles of the electron beam current were measured with current transformer (CT) and Faraday cup (FC). The energy spectrum of the electron beam was analyzed with a bending magnet, beam slit and CT.

#kii@iae.kyoto-u.ac.jp

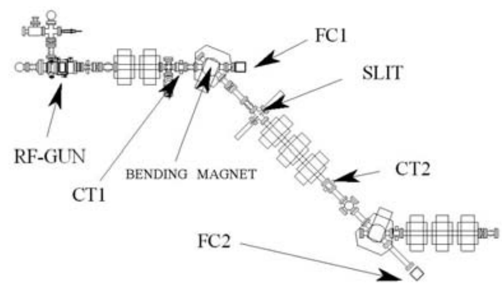


Figure 1: Experimental setup.

## METHOD OF ANALYSIS

Back-bombardment effect depends on both the cavity voltage in the RF gun and the cathode current density. We performed a transient analysis in the RF gun taking into account the time evolution of the beam loading depending on the cavity voltage and the cathode current density by using an equivalent circuit model and a thermal conduction model. The beam loading was calculated from the cavity voltage and the cathode current density which was calculated from the thermal conduction in the cathode taking into account the stopping power of the back streaming electron in the cathode.

### *Analysis of the cathode current density*

The energy distribution of the back-streaming electrons was calculated by using the results of the particle simulation code PARMELA [2]. From this result the heat quantity given to the cathode by the back streaming electron with various energy was calculated. In this calculation we assumed that the cathode consisted of thin 2000 disks.

In order to evaluate the effect of the back streaming electrons on the time evolution of the cathode temperature, we used following quasi empirical formula of the TIO [3]:

$$R = \frac{a_1}{\rho}\left\{\frac{\ln[1+a_2(\gamma-1)]}{a_2} - \frac{a_3(\gamma-1)}{1+a_4(\gamma-1)^{a5}}\right\} \quad (1)$$

$$a_1 = 2.335A/Z^{1.209} \qquad a_2 = 1.78\times10^{-4}Z$$

$$a_3 = 0.9891-(3.01\times10^{-4}Z)$$

$$a_4 = 1.468-(1.180\times10^{-2}Z)$$

$a_5 = 1.232 / Z^{0.109}$ $\gamma = (E + m_0 c^2) / m_0 c^2$

where, $R$ is the stopping range of the electron in m, A is the mass number of the absorber material, Z is the atomic number of it, $E$ is the kinetic energy of electrons in MeV, ρ is the density of the absorber material in kg/m$^3$. Equation (1) is applicable to the 0.3 keV – 30 MeV electrons. With this equation, stopping power d$E_b$/dz was obtained. Here, we used the values of ρ = 19250 kg/m$^3$, A = 183.85, Z = 74 assuming that the cathode material was made of W alone..

The time evolution of the temperature was calculated in each disks of the cathode, and the time evolution of the cathode temperature was calculated by using the equation below,

$$c\rho V \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial z^2} + Q_b(z,t) \qquad (2)$$

where, c is the specific heat, ρ is the density, V is the volume, $T$ is the temperature, λ is the thermal conductivity of the cathode, z is the distance from the cathode surface, $Q_b(z, t)$ is the heat quantity from the back streaming electrons. Here, we used the values of c = 130 J/kg/K, λ = 174 W/m/K.

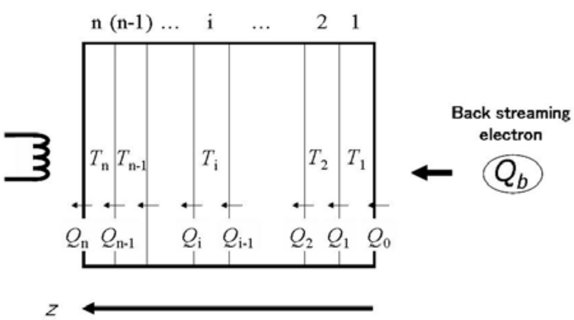


Figure 2: Thermal conduction model.

The cathode current density was obtained from the time evolution of the cathode temperature calculated above. The relationship between the cathode temperature and the cathode current density used in this analysis was obtained by the results of the cathode performance test of Heat Wave Labs, Inc.

### *Analysis of the cavity voltage in the RF gun*

The cavity voltage in the RF gun and the reflecting RF power were calculated with the equivalent circuit model shown in Fig. 3. In this circuit, the RF power source was expressed by a source $i_g$, the RF gun was expressed by LCG resonant circuit, and the beam loading was expressed by an admittance $Y_b$. The conductance and the susceptance of the electron beam were calculated from the cavity voltage and the cathode current density by using the particle simulation code KUBLAI [4]. Thus the beam loading was calculated.

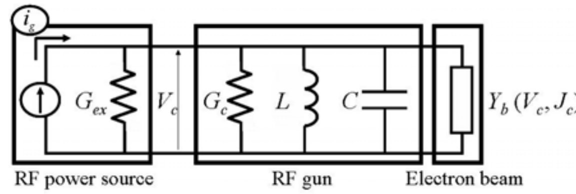


Figure 3: Equivalent circuit model.

## RESULT

### *Experimental result*

We have succeeded to keep the peak energy of the electron beam constant in 4 μsec by feeding a modulated RF power into a RF gun. Fig. 4 shows the flat RF power waveform and the modulated RF power waveform fed into a RF gun. Fig. 5 shows the beam current waveform whose peak energy is 8.6 MeV at CT2. Fig. 6 shows the time evolution of the peak energy in macro pulse duration.

As shown in Fig. 5 feeding modulated RF power into a RF gun was an effective way to extend the macro pulse duration and to increase the beam current. As shown in Fig. 6 the beam energy which had been degraded in the latter part of the macro pulse duration was kept constant by feeding modulated RF power.

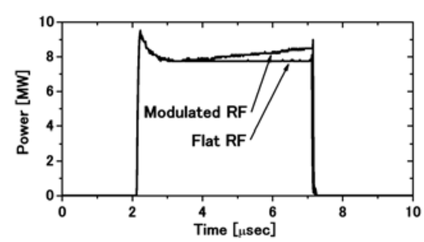


Figure 4: Input RF power waveform.

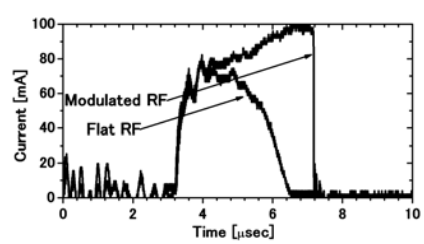


Figure 5: Beam current waveform.

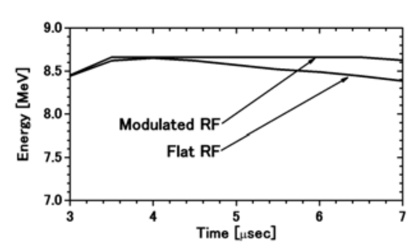


Figure 6: Peak energy @ CT2.

### *Result of calculation*

In order to confirm the validity of calculation model, experimental and calculated reflecting RF power waveforms were compared. Fig.7 shows the measured and reproduced reflecting RF power waveform when a flat RF power was fed. Fig. 8 shows them when a modulated RF power was fed. Experimental and calculation results agree very well.

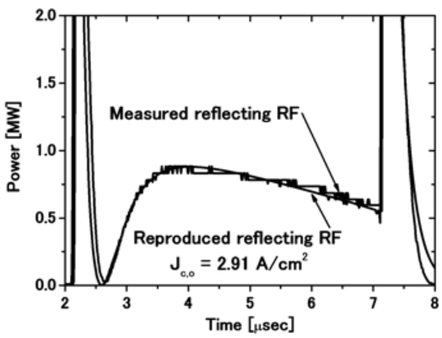


Figure 7: Reflecting RF power waveform.

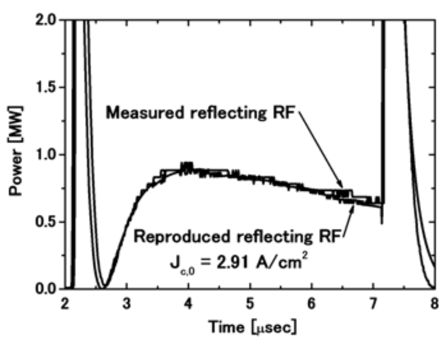


Figure 8: Reflecting RF power waveform.

As shown in Fig. 9, there was a relationship between the cavity voltage ($V_c$) and the peak energy of the electron beam (E), and the peak energy could be kept constant by keeping the cavity voltage constant.

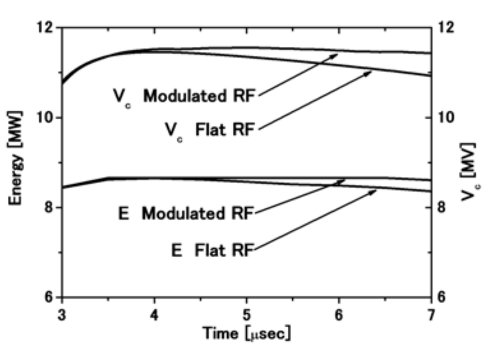


Figure 9: Time evolution of the cavity voltage and the peak energy.

We estimated how long time the peak energy of the electron beam could be kept constant by using our KU-FEL 4.5 cell RF gun. The calculation was performed in both cases of W cathode and $LaB_6$ cathode. We used the value of $\rho$ = 4700 kg/m$^3$, A = 94.75, Z = 40, c = 122 J/kg/K, $\lambda$ = 147 W/m/K and the relationship between the cathode temperature and the cathode current density was obtained by the results of the cathode performance test of KIMBALL PHYSICS INC, in the case of $LaB_6$ cathode.

Fig. 10 shows the time evolution of the cavity voltage of W and $LaB_6$ when a flat RF power was fed, respectively. The degradation of the cavity voltage of $LaB_6$ was a little smaller than that of W.

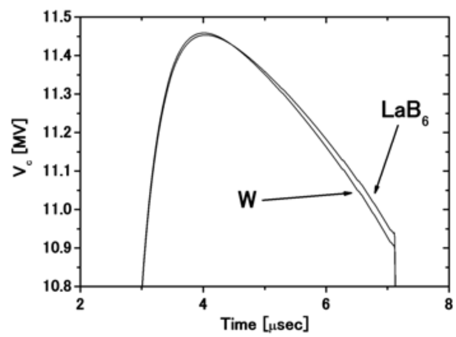


Figure 10: Comparison of W with $LaB_6$.

Fig. 11 and Fig. 12 show the time evolutions of the cavity voltage when an optimized modulated RF power was fed. The input RF power was 8 MW at the beginning of the macro pulse and the controlled range was 1.6 MW and the initial current density was 2.28 A/cm$^2$ in each calculations. We found that the degradation of the peak energy could be kept below 100 keV in the macro pulse duration of 8.0 μsec when the cathode was W, 8.2 μsec when the cathode was $LaB_6$.

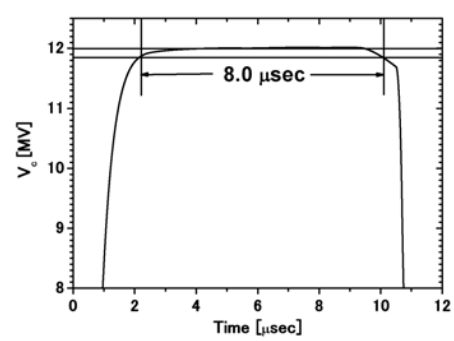


Figure 11: Expected time evolution of the cavity voltage (W).

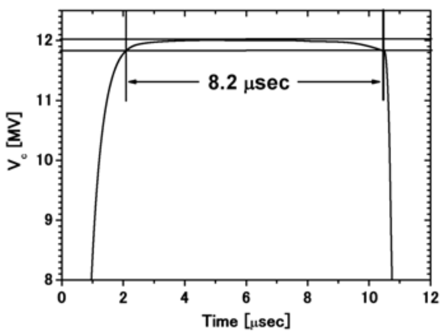


Figure 12: Expected time evolution of the cavity voltage ($LaB_6$).

## SUMMARY

It was confirmed in experiment that feeding modulated RF power into a RF gun was effective on the reduction of the degradation of the beam energy.

By the calculation in this work, the experimental results were reproduced well. Moreover, the degradation of the peak energy of the electron beam could be kept below 100 keV in the macro pulse duration of 8.0 μsec when the cathode was W, 8.2 μsec when the cathode was $LaB_6$.

## REFERENCES

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[4] K. Masuda, Development of numerical simulation code and application to Klystron efficiency enhancement, Ph. D Thesis, Kyoto University, (1998).