ELECTRON BEAM ENERGY COMPENSATION BY CONTROLLING RF PULSE SHAPE

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Abstract

A thermionic RF gun is a compact and economical electron beam system that is easy to operate. However, the electron back-bombardment of the cathode results in deterioration of beam quality and seriously limits the pulse duration. In this work, we investigate the use of time varying RF power into a thermionic RF gun in order to reduce the beam energy degradation by the back-bombardment effect during a macropulse. We have successfully increased the pulse duration from 3 μs to 4 μs and the total charge from 98 nC to 206 nC by monotonically increasing the RF power from 5 MW to 6 MW during the macro pulse. In addition, we calculated the RF power deposition using an equivalent circuit model. The beam loading was evaluated using one dimensional thermal conduction model. Good agreements with the experimental results were obtained for the beam energy and the RF power deposition during the macropulse.

INTRODUCTION

High brightness electron beam is crucial to develop an FEL, and a thermionic RF gun is suitable for a compact FEL system. However, there is a serious problem of the back-bombardment effect. Due to the operating principle of an RF gun, some electrons emitted from the cathode at non identical phase return to the cathode, raise temperature and degrade the beam energy during the macropulse. With this effect, macro pulse duration is limited. In order to reduce beam energy degradation by the back-bombardment effect, we tried to compensate the beam energy with modulated RF power. In addition, to understand the cathode heating phenomena and the effect of the time varying beam loading to the electron beam properties, we have analyzed temporal profile of the electron beam energy using an equivalent circuit analysis and an one dimensional heat conduction model.

EXPERIMENTAL SETUP

Figure 1 shows the experimental setup.

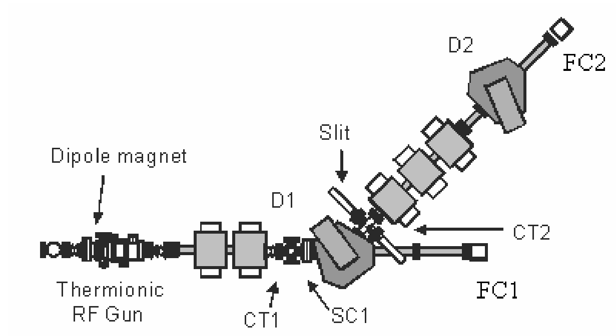

Figure 1: Experimental setup.

A dispenser cathode is of 2 mm diameter and is made of porous tungsten impregnated with barium. The initial cathode surface temperature was kept at around 1020 ºC. RF power fed to the RF gun is controlled by remotely adjusting the reactors in the pulse forming network (PFN) with stepping motors. By using this system, we can modulate RF amplitude up to about 20 % [1].

The temporal profiles of the electron beam current and energy were measured with a bending magnet (D1), beam slit, current transformer (CT2) and Faraday cup (FC2).

ANALYSIS

In this chapter, the way of calculating transient evolution of the beam energy is mentioned. This calculation is made of two parts. The one is calculating the time evolution of the electric field in the RF gun using equivalent circuit model and solve the circuit equation. The other is to figure out the time evolution of the cathode temperature, because temperature evolution is required to evaluate the beam loading in the first part, and it is estimated by use of an one dimensional heat conduction model.

Electric field in the RF gun

The electric field in the RF gun is calculated with the equivalent circuit model shown in Figure 2. In this circuit, the RF power source is expressed as a source i_g, the RF gun is expressed as LCG resonant circuit, and the beam loading is expressed as a current sink i_b.

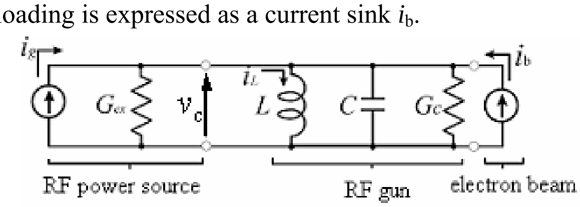

Figure 2: Equivalent circuit model.

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To evaluate the transient evolution of the beam energy, equivalent circuit voltage v_c was calculated using i_g, derived from the measured RF temporal profile, the resonant parameter L, C and R determined by experiment and eigenmodel analysis and time varying beamloading i_b. The beam loading i_b was calculated as a function of the electron beam trajectories in the RF gun, cavity voltage v_c and the cathode surface temperature [2, 3].

Time evolution of cathode surface temperature

As mentioned previous section, time evolution of cathode surface temperature needs to be calculated. In order to evaluate the time evolution of the temperature, we have introduced one dimensional heat conduction model as shown in Figure 3 [4].

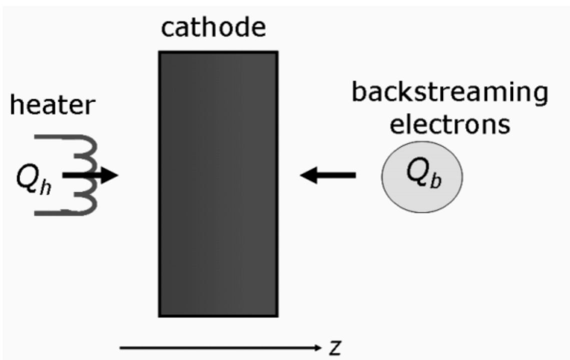

Figure 3: One dimensional heat conduction model.

In this model, following assumptions are adopted. Radiation cooling occurs only from the cathode surface. Heating power is supplied from the heater and the backstreaming electrons. All the kinetic energy of back-streaming electrons is converted into heat. Thermal transfer occurs only in the longitudinal direction.

Thermal conduction in the cathode is calculated using the equation below.

$$c\rho V \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial z^2} + Q_b(z,t) \qquad (1)$$

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 from the backstreaming electrons. The energy distribution of the back-streaming electrons is calculated with PARMELA [5]. In this study, two improvements were carried out to solve this equation. One is to evaluate the power density more precisely using following quasi empirical formula of the stopping range [6].

$$R = \frac{a_1}{\rho}\left\{\frac{\ln\left[1 + a_2(\gamma-1)\right]}{a_2} - \frac{a_3(\gamma-1)}{1 + a_4(\gamma-1)^{a5}}\right\} \qquad (2)$$

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

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

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

$$a_5 = 1.232/Z^{0.109} \qquad \gamma = (E + m_0c^2)/m_0c^2$$

where, R is the stopping range of the electron in m, A is it's mass number, Z is it's atomic number, E is the kinetic energy of electrons in MeV, ρ is the density of the absorber material in kg/m^3. Equation (2) is applied for the 0.3 keV – 30 MeV electrons. In this study, ρ value was used 15400 as the density of the cathode. With this equation, stopping power dE_b/dz is obtained.

The other improvement is to treat the time evolution of the current density recursively as follow.

1) The current density was determined from the surface temperature.
2) The energy distribution of the back-streaming electrons was calculated using the results of the particle simulation code PARMELA [5].
3) The time evolution of the temperature is solved.

RESULTS

Experimental results

Figure 4 and Figure 5 show the temporal profiles of the RF input and the electron beam energy when constant and time varying RF was fed into the RF gun respectively.

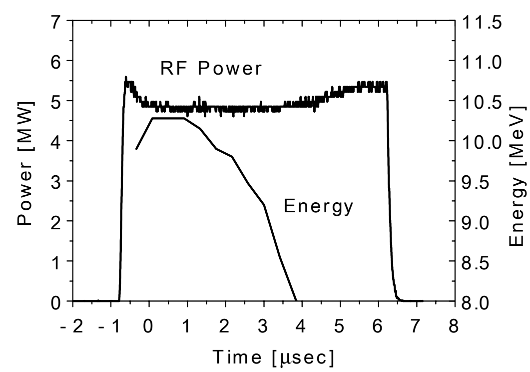

Figure 4: Beam energy and RF power fed into the gun (constant RF).

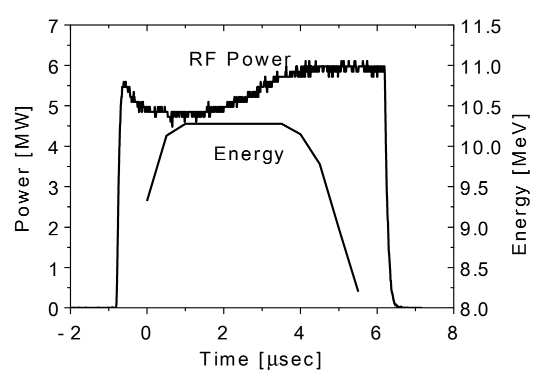

Figure 5: Beam energy and RF power fed into the gun (modulated RF).

The temporal profiles of the electron beam current after the bending magnet were also measured with CT2 for each RF input. The results are shown in Figure 6.

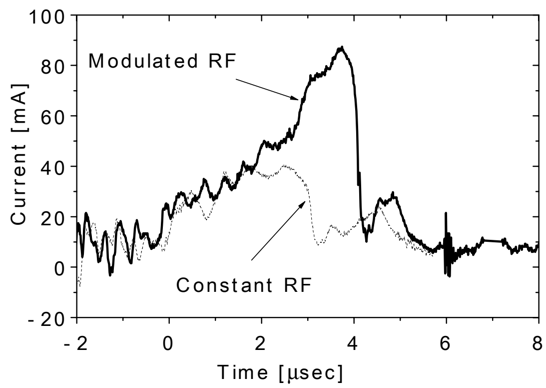

Figure 6: Temporal profiles of the electron beam

When constant RF power was fed to the RF gun as shown in Figure 4, beam energy decreases around 1µs. Thus, pulse duration after the bending magnet (D1) is limited to about 3.0 µsec as shown in Figure 6. To compensate the energy decrease, RF amplitude was modulated to rise around 1.5µs where beam energy decreases when constant RF pulse was fed as shown in Figure 5. As a result, beam energy was successfully kept constant up to around 3.5µs. However the RF amplitude saturates around 4µs because of the PFN performance limit.

The pulse duration was also improved up to 4µs and peak current increased as shown in Figure 6. The total charge in a macropulse increased about twice, from 98 nC to 206 nC.

From these experimental results, feeding modulated RF pulse into the gun is an effective way to compensate the beam energy degradation caused by back-bombardment effect.

Calculation results

In order to confirm the calculation model, and understand the effect of the time varying beam loading to the electron beam properties, experimental and calculation results of the beam energy are compared.

Time evolution of the cathode temperature and current density were calculated using one dimension thermal conduction model and particle simulation. These results are seen in Figure 7 and Figure 8.

With these results, the RF power deposition was calculated using an equivalent circuit model. Beam energy was also evaluated with the model. These results are shown in Figure 9 with the experimental results. As seen in this figure, experimental and calculation results agree very well. Thus the equivalent circuit analysis and the one dimensional heat conduction model are concluded to be reasonable ones.

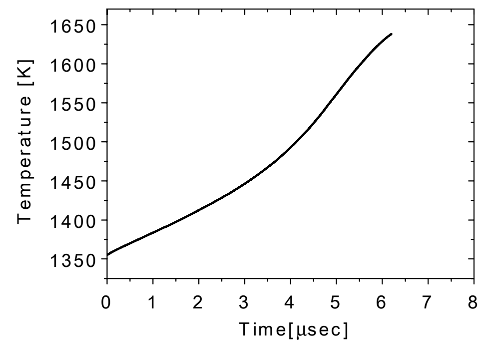

Figure 7: Time evolution of the cathode temperature

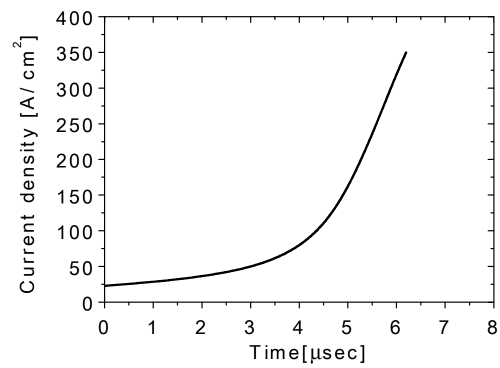

Figure 8: Time evolution of the cathode current density

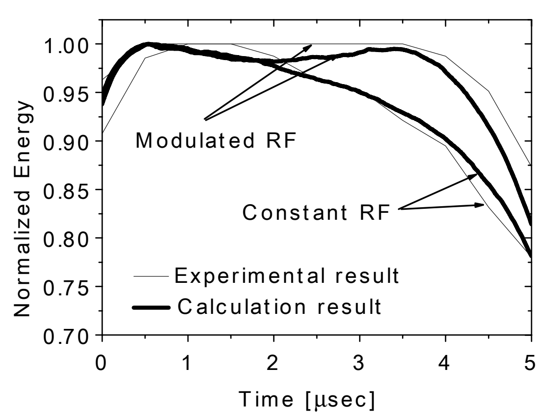

Figure 9: Experimental and calculation results of beam energy

SUMMARY

In this study, the RF power fed into the thermionic RF gun was controlled to compensate the drop in beam energy by the increase of beam loading from the back-bombardment effect. With this technique, the pulse length and the beam current were increased and the beam energy was kept constant for up to 4μs. The results show that controlling the input RF power is an effective way to lengthen the pulse duration of the macropulse. The transient RF power deposition in the RF gun was also calculated with an equivalent circuit model. Good agreements with the experimental results were obtained for the beam energy and the RF power deposition during the macropulse.

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