BEAM LOADING COMPENSATION BY RF DETUNING IN A THERMIONIC RF GUN

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Abstract

A new beam energy compensation method was investigated, which can suppress the beam energy drop in a thermionic RF gun caused by the beam current increment due to the back-bombardment effect. The method is to feed a RF power with slightly higher (detuned) frequency than the resonant frequency of the gun. The principle of this method is based on that the increment of the beam conductance could be cancelled out by the increment of beam suceptance when the frequency is detuned. As a result of numerical simulation, the beam energy was kept constant by feeding an RF power with +550 kHz detuning, even though the current density on the cathode surface is increased from 47 to 176 A/cm^2. In experiment, the beam energy was also kept constant by feeding an RF power with +590 kHz detuning for 7.5 μs.

INTRODUCTION

The thermionic RF gun is suitable to realize compact and economical accelerator systems, because it can produce high energy (several MeV) and low emittance (~ 10 π mm-mrad) electron beams without a buncher like a DC gun and an expensive laser like a photocathode RF gun. Applications of the gun, however, are limited to small numbers because of the back-bombardment effect [1]. Since the electric field in an RF gun oscillates in time, electrons which are emitted late in an RF period do not reach the next cavity before the electric field reverses direction. These electrons are accelerated back towards the cathode. If the electron hits the cathode, the kinetic energy of the electron is transferred to the cathode and the cathode temperature rises up. Then the current density on the cathode surface and the beam current are increased. Consequently, if the flat RF pulse is fed to the gun, the beam energy drops during macro-pulse duration. These sequential phenomena are called the back-bombardment effect. To mitigate the effect, two major countermeasures are introduced. One is the application of transverse magnetic field on cathode surface [2] and the other is the RF power ramping [3].

For our purpose to develop compact and economical mid-infrared (λ = 4~13 μm) Free Electron Laser (FEL) for energy science, though the above two methods are introduced, the beam current and macro-pulse duration are not enough. In our case, the beam current and macro-pulse duration are limited by the capability of the RF power ramping induced by voltage ramping of our klystron. To achieve the laser saturation, we need to enlarge the beam current and to lengthen the beam macro-pulse duration. For that purpose, we found and proposed a new method for beam energy compensation by using “RF detuning”. In this paper, the principle of this method is introduced. Results of numerical simulation and experiment are shown and discussed.

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PRINCIPLE OF FREQUENCY DETUNING

Concept

Usually, the beam conductance and suceptance of an RF gun are always positive and negative, respectively. When the current density on the cathode surface is increased, the absolute values of those two are increased. In the presence of beam current, the resonant frequency of the gun slightly shifted to higher frequency because of the negative beam suceptance. When the current density is increased, the shift of the resonance frequency increased as shown in Fig.1.

We found that the phenomena could be used to compensate the beam energy drop induced by the back-bombardment effect. As shown in Fig.1, when the frequency of the input RF power f is adjusted to higher frequency like f_2 or f_3 than the resonant frequency of the gun cavity f_0, the power consumption of the gun P_c is increased, as the current density is increased. Amount of the increment depends on the frequency of input RF power, and the higher frequency makes larger increment. This can be considered as the “self induced RF power ramping” and the beam energy drop should be compensated by this method as same as the usual RF power ramping.

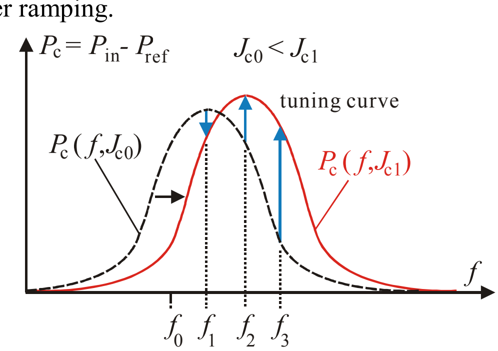

Figure 1: Concept of the frequency detuning (J_c : current density on the cathode surface, f : frequency of input RF, P_{ref} : reflected power, P_{in} : input power, P_c : power consumption in the RF gun). The dashed line and solid line show the tuning curve of the RF gun including the beam loading.

Mathematical Analysis

An RF gun system which consists of a resonant cavity, an electron beam and an RF power source can be expressed as an equivalent circuit shown in Fig.2. The beam admittance $Y_b = G_b + jB_b$ depends on the cavity voltage V_c and the current density J_c on the cathode surface as shown in Fig.3. The absolute value of cavity voltage V_c is expressed as

$$|V_c| = \frac{|I_g|}{\sqrt{(G_c + G_b + G_{ex})^2 + (B_c + B_b)^2}} . \quad (1)$$

The back-bombardment effect is the cavity voltage V_c drop induced by increment of the current density J_c. We differentiate the Eq.1 partially with respect to the current density J_c to understand the effect, then we obtain

$$\frac{\partial |V_c|}{\partial J_c} = \frac{-I_g}{\left\{(G_c + G_b + G_{ex})^2 + (B_c + B_b)^2\right\}^{3/2}} \times \left[(G_c + G_b + G_{ex}) \frac{\partial G_b}{\partial J_c} + (B_c + B_b) \frac{\partial B_b}{\partial J_c} \right], \quad (2)$$

where G_c, G_{ex}, B_c are constant and do not depend on J_c. As shown in Fig.2, the beam conductance G_b and its partial derivative $\partial G_b / \partial J_c$ is always positive, and the beam suceptance B_b and its partial derivative $\partial B_b / \partial J_c$ is always negative. Generally, the RF gun is operated at the resonant frequency with the beam loading. The total suceptance ($B_c + B_b$) is adjusted to zero to obtain the highest beam energy by changing the frequency of an input power. With that condition the second term in [ ] of Eq.2 is zero, and the partial derivative $\partial V_c / \partial J_c$ is negative. This result represents that the energy drop due to the back-bombardment effect.

Considering the second term in [ ] of Eq.2, one can find the probability of mitigation of the energy drop by adjusting the cavity suceptance B_c which is described as

$$B_c = \frac{1}{(R/Q)} \left(\frac{f_{RF}}{f_0} - \frac{f_0}{f_{RF}} \right), \quad (3)$$

where R, Q, f_0 and f_{RF} denotes the shunt impedance, the Q-value, the resonant frequency of the cavity and frequency of the input RF power, respectively. If the RF frequency is adjusted to higher frequency ($B_c + B_b > 0$), the second term of [ ] in Eq.2 is negative and the total value of [ ] should be reduced. If the optimum cavity suceptance B_{co}, which is described as

$$B_{co} = \left\{ -(G_c + G_b + G_{ex}) \frac{\partial G_b}{\partial J_c} \Big/ \frac{\partial B_b}{\partial J_c} \right\} - B_b , \quad (3)$$

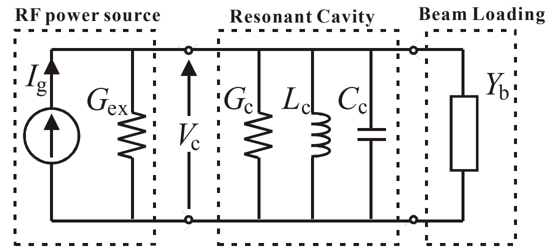

Figure 2: Equivalent circuit of an RF gun system.

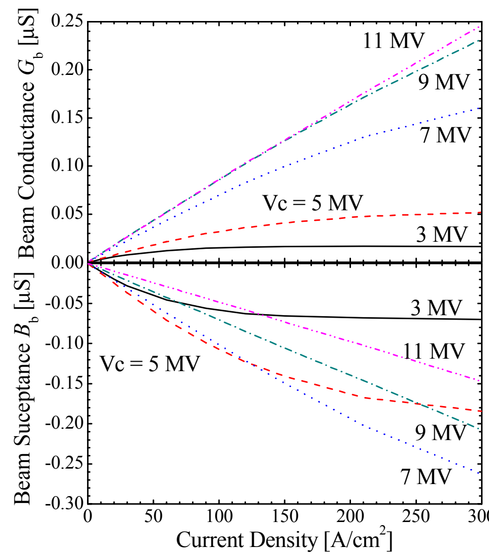

Figure 3: Dependence of the beam admittance on the cavity voltage V_c and the current density J_c.

is selected, the partial derivative $\partial V_c / \partial J_c$ should be zero. With that condition, it is expected that the energy drop induced by the back-bombardment effect at the initial condition become zero. We should notice that the optimum condition $\partial V_c / \partial J_c = 0$ is realized at the initial condition but it no longer satisfied if the beam conductance G_b and suceptance B_b is changed. It is expected that this method has limitation of acceptable increment of the current density J_c.

Advantages and Disadvantages

- Advantages of this method are following items:
  1. Simple
  2. Easy to combine with other methods
- Disadvantages are following items:
  1. Beam energy decrement
  2. Requirement of high frequency stability

By using this method, we can compensate the back-bombardment effect easily without any additional equipment. With RF detuning, however, the initial beam energy is decreased. The sensitivity of the beam energy with respect to the frequency of the input RF power and the resonant frequency of the gun is much higher than the condition without detuning. Therefore high stability both of the frequency of the input RF power and the resonant frequency of the cavity is required.

NUMERICAL SIMULATION

Effect of RF detuning and its limitation were investigated by using the simulation code [3] that was developed in Kyoto University in order to calculate the evolutions of current density on cathode surface and the cavity voltage during macro-pulse duration in a thermionic RF gun. The code simultaneously solves two differential equations. One is the differential equation of the equivalent circuit of the gun and the other is the one dimensional thermal equation of a thermionic cathode, which include heat input from back-streaming electrons. The code succeeded to reproduce the temporal evolution of reflected power and beam energy. The parameters used in this simulation, which are same with usual experimental condition, are shown in Table 1.

Table 1: Parameters of the RF gun

Resonant frequency [MHz]	2855.955
Coupling coefficient β	2.79
Q value	12500
R/Q [Ω]	980
Number of cells	4.5
Accelerating mode	π
Cathode radius [mm]	1
Cathode material	LaB_6
Initial cathode temperature [° C]	1630

Beam Energy Evolution

Figure 4 and 5 shows the temporal evolution of the beam energy and the current density with different detuning amount, respectively. In this simulation, input RF power was 8 MW and the pulse duration was 5 µs. Here the detuning amount $\Delta f = f_{RF} - f_0$ is defined as frequency difference between the resonant frequency f_0 of the gun cavity and the frequency f_{RF} of the input RF power. The beam energy decreased from 8.3 to 5.0 MeV and the beam energy drops during macro-pulse duration were mitigated, as the detuning amount increased. With the 545 kHz detuning, the beam energy from 2 to 5 µs is kept constant. With the 645 kHz detuning, the beam energy is slightly increased during macro-pulse duration

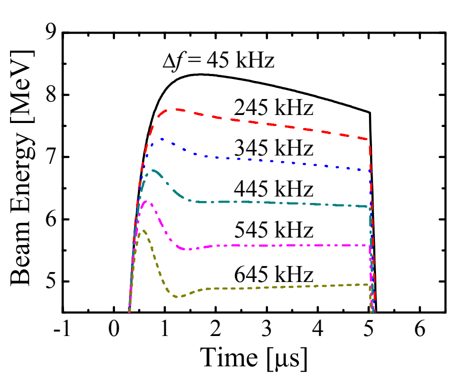

Figure 4: Temporal evolution of beam energy with different detuning amount.

even though the current density is increased as shown in Fig.5.

In Fig.5, the increment of the current density was slightly reduced, as the detuning amount was increased because the heat input from the back-bombardment electrons were decreased when the cavity voltage or beam energy was decreased.

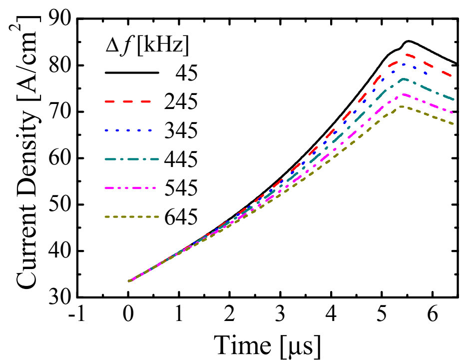

Figure 5: Current density evolution with different detuning condition.

Limitation of Energy Compensation

The limitation of energy compensation of the RF detuning method was examined. In this simulation, RF power was 8 MW, the pulse duration was 14 µs and the detuning amount was 545 kHz.

The result of the beam energy and the current density evolution were shown in Fig.6. Before the current density exceeds 100 A/cm^2, the beam energy fluctuation was less than 20 keV. After the current density got larger than 100 A/cm^2, the beam energy dropped.

Practically, this method will be used with the RF power ramping and small energy drop or increment will be compensated by that method. Considering it, if we accept the 100 keV energy drop, the four times increment of current density will be accepted and it was corresponding to the macro-pulse duration of 9 µs.

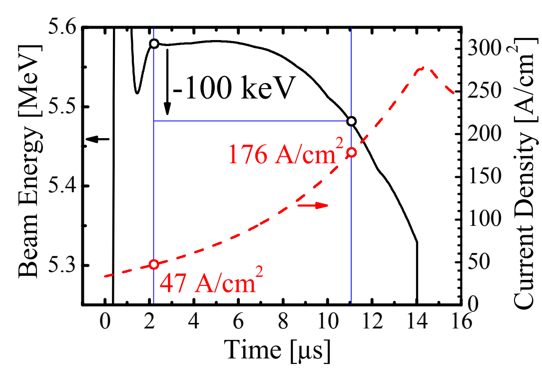

Figure 6: Beam energy and current density evolution as the result of numerical simulation. In this simulation, the RF pulse with 545 kHz higher frequency of the cavity and 14 µs macro-pulse duration was fed to the gun.

EXPERIMENT

The RF detuning was also demonstrated in experiment. Figure 7 shows the geometry of this experiment. The Q3, Q4, Q5 and B2 are turned off, and the B1 and FC are used to measure the temporal evolution of beam energy. The gun parameters are same with Table 1 except for the initial cathode temperature which was around 1650 degree and could not be measured accurately. In this experiment, the detuning amount Δf was adjusted to 590 kHz.

The experimental result is shown in Fig.8. As shown in Fig.8, the amplitude of the input RF power was around 10 MW and its macro-pulse duration was 9 µs. The average current of the output beam was increased from 200 to 650 mA. Even with such a serious condition, the beam energy was kept constant for 7.5 µs as shown in Fig.7 (c).

The detuning amount that made the beam energy constant is slightly different from that in simulation. The difference may be caused by the difference of the input RF power.

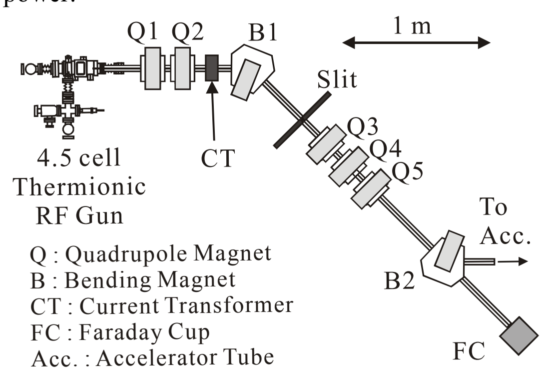

Figure 7: Geometry of experiment.

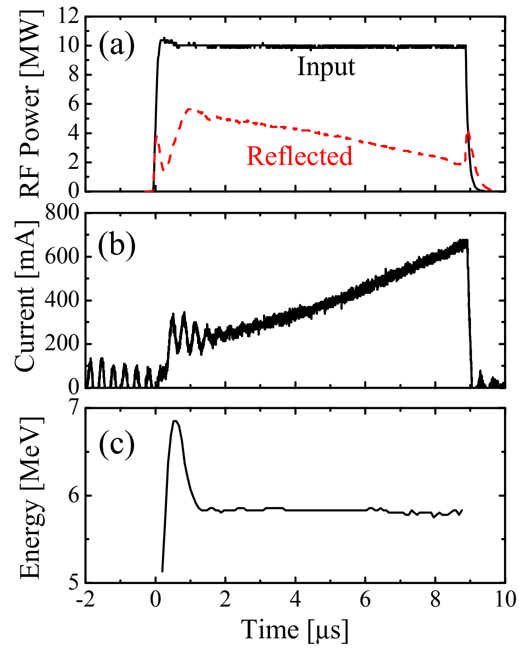

Figure 8: Experimental Result of the large detuning condition (Δf = 590 kHz). (a) Input and reflected RF pulse. (b) Beam current evolution. (c) Beam energy evolution.

CONCLUSION

We proposed a new method named RF detuning to compensate the beam energy drop induced by the back-bombardment effect in a thermionic RF gun. The method is to feed a RF power with slightly higher (detuned) frequency than resonant condition of the gun. From the analysis of the equivalent circuit of the gun and the results of the numerical simulations, we found that the method can ideally compensate the energy drop. The results of the simulations also tell us that the energy drop is compensated with about +550 kHz detuning and current increase by a factor of four is compensated. In experiment, the beam energy was kept constant for 7.5 µs by +590 kHz detuning and the beam current increase by a factor of three was compensated.

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