CAVITY DETUNING METHOD TO COMPENSATE BEAM ENERGY DECREMENT IN THERMIONIC RF GUN DUE TO BACK-BOMBARDMENT EFFECT*

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Abstract

Thermionic RF guns are strongly suffered from back-bombardment effect, which causes rapid increase of beam current and rapid decrease of beam energy during a macro-pulse. A new method to compensate the energy decrease has been proposed. The method is quite simple and just requires detuning of the resonant frequency of the RF cavity from the frequency of fed RF power. The method enables us to keep the electron beam energy generated by a thermionic RF gun, in spite of heavy back-bombardment effect. A mathematical analysis clearly shows the principle of the method. As results of proof of principle experiments, we succeeded in keeping the beam energy for 8 µs, even with rapid beam current increase from 250 to 650 mA. The beam current increase due to the back-bombardment effect also induces bunch phase shift, which cannot be compensated by the detuning method. The phase shift measurement and compensation were also reported in this paper.

INTRODUCTION

Thermionic RF guns [1] are compact, economical and high brightness electron sources. However, when the guns are used for a driver linac of oscillator-type Free Electron Lasers (FELs), which requires moderate bunch charge (several tens pico-coulomb) and long macro-pulse duration (several micro-seconds), the guns have been suffered from strong back-bombardment effect [2]. The effect induces beam current increment in a macro-pulse. And consequently the current increment leads to decrement of beam energy during a macro-pulse and significant beam loss. Some methods to mitigate the back-bombardment effect [2, 3] have been invented. However, in our case they did not work effectively. In this paper, we propose a new method called as cavity detuning to compensate the energy decrease caused by the back-bombardment effect. The principle of the method and proof of principle experiments are reported. Moreover, phase shift of generated electron bunch which can not be compensated by the detuning method is discussed.

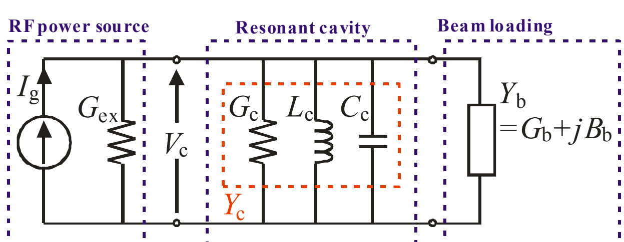

Figure 1: Equivalent circuit of a thermionic RF gun.

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PRINCIPLE OF BEAM ENERGY COMPENSATION BY CAVITY DETUNING

The system of thermionic RF gun, which consists of a resonant cavity, an RF power source and electron beam, can be modelled by an equivalent circuit shown in Fig. 1 [4]. The beam loading is modelled as beam admittance Y_b, which can be divided into beam conductance G_b and susceptance B_b, in the circuit. The G_b and B_b depend on the current density on the thermionic cathode surface J_c and the acceleration voltage of the cavity V_c whose dependences are shown in Fig. 2.

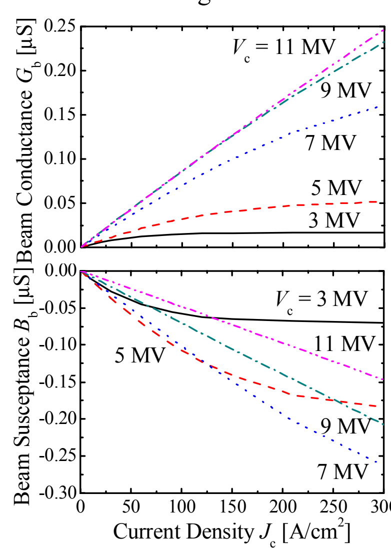

Figure 2: Beam conductance G_b and susceptance B_b as a function of current density J_c and cavity voltage V_c.

From the equivalent circuit, the partial derivative of the amplitude of cavity voltage V_c by current density J_c is described as

$$\frac{\partial|V_c|}{\partial J_c} = \frac{-|I_g|}{\left[(G_c+G_b+G_{ex})^2+(B_c+B_b)^2\right]^{3/2}} \times\left[(G_c+G_b+G_{ex})\frac{\partial G_b}{\partial J_c}+(B_c+B_b)\frac{\partial B_b}{\partial J_c}\right], \quad (1)$$

where the generator current I_g, cavity conductance G_c, external conductance G_{ex} and cavity susceptance B_c are independent of the current density J_c. The susceptance B_c is described as

$$B_c = \frac{1}{(R/Q)}\left(\frac{f_{RF}}{f_0} - \frac{f_0}{f_{RF}}\right), \quad (2)$$

where f_{RF} and f_0 are frequency of fed RF power and resonant frequency of the gun cavity, respectively.

As one can obviously see in the Fig. 2, the partial derivative $\partial G_b/\partial J_c$ and $\partial B_b/\partial J_c$ are always positive and negative, respectively. When the cavity is adjusted at resonant condition including the beam loading effect ($(B_c+B_b) = 0$), increase of J_c always leads to reduction of cavity voltage, i.e. decrement of beam energy.

However, when the cavity is detuned to be $(B_c + B_b) > 0$, the term of $(B_c+B_b)\partial B_b/\partial J_c$, has opposite effect of the $\partial G_b/\partial J_c$ term. And the condition $\partial|V_c|/\partial J_c = 0$ can be achieved by adjusting the cavity susceptance to

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

Then the beam current increase does not change the amplitude of cavity voltage, i.e. the beam energy. From Eq. 2, the optimum detuning frequency of the cavity can easily be calculated as

$$\Delta f_{opt} \approx -\frac{(R/Q)}{2} B_{co} f_{RF} \quad (4)$$

Above analytical results shows that the beam energy decrease due to the back-bombardment effect can be compensated by detuning the resonant cavity of thermionic RF guns.

Concerning to the phase of the cavity voltage, which determines the riding phase of generated electron bunch, the phase angle is described as

$$\angle\theta_{V_c} = \angle\theta_{I_g} - \tan^{-1}\frac{B_c + B_b}{G_c + G_b + G_{ex}}. \quad (5)$$

The back-bombardment effect (change of G_b and B_b) leads to undesired phase shift of the cavity voltage, i.e. electron bunch phase, and it cannot be compensated by the detuning method.

EXPERIMENTS

To demonstrate the cavity detuning method, beam energy evolution of the generated electron beam has been measured with the resonant and optimum detuning condition. For the experiment, we used the thermionic RF gun that used for drive a mid-IR free electron laser, KU-FEL [5]. The typical parameters of the gun are shown in Table 1. During experiments, instead of changing the resonant frequency of the RF cavity, the frequency of fed RF power was changed to introduce the cavity detuning.

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 [^{o}C]	1630

Energy Evolution Measurement

The geometry of energy evolution measurement is shown in Fig. 3. The beam current evolutions were measured by a current transformer at the gun exit. The beam energy evolutions were measured by using an energy analyser which consists of a bending magnet, an energy slit and a Faraday cup. Results with resonant condition and optimum detuning condition (Δf = -590 kHz) are shown in Fig. 4.

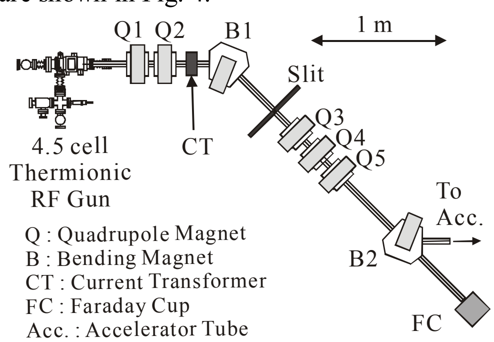

Figure 3: Geometry of energy evolution experiment.

As one can obviously see in Fig. 4, the beam energy rapidly decreased after 2 µs under the resonant condition due to increase of beam current. Contrary, with the optimum detuning condition, the beam energy was kept constant after 2 µs in Fig. 5 (b), even with rapid increase of beam current shown in Fig. 5 (a). We have succeeded in keeping the beam energy for around 8 µs with optimum detuning condition.

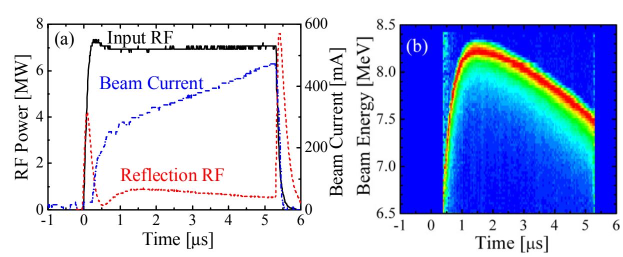

Figure 4: Temporal evolution of input RF, reflected RF, beam current (a) and beam energy (b) under the resonant condition of the thermionic RF gun. In (b), the colour indicates the normalized charge amount at each time-slice.

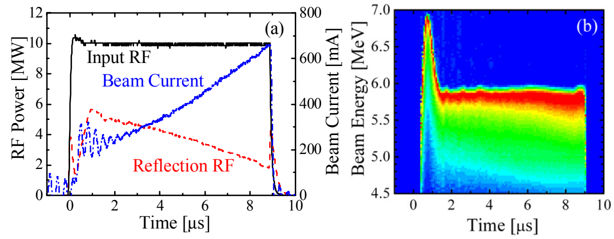

Figure 5: Temporal evolution of input RF, reflected RF, beam current (a) and beam energy (b) under the optimum detuning condition (Δf = -590 kHz) of the thermionic RF gun. In (b), the colour indicates the normalized charge amount at each time-slice.

Phase Shift Measurement and Compensation

The beam induced phase shift has been measured by using a button-type-electrode Beam Position Monitor (BPM). Figure 6 shows the schematic diagram of the measurement system. The BPM electrodes were used as pick-up electrodes of bunch signal and the phase of bunch signal was compared with the reference RF phase by a phase detector (Model: PDU-NK02N-01, NIHON KOSHUHA Co., Ltd.).

Figure 7 shows the results of phase shift measurement. The beam current increased from 300 to 550 mA during the macro-pulse (Fig. 7 (a)) and then the bunch phase shift of around 10 degree was observed.

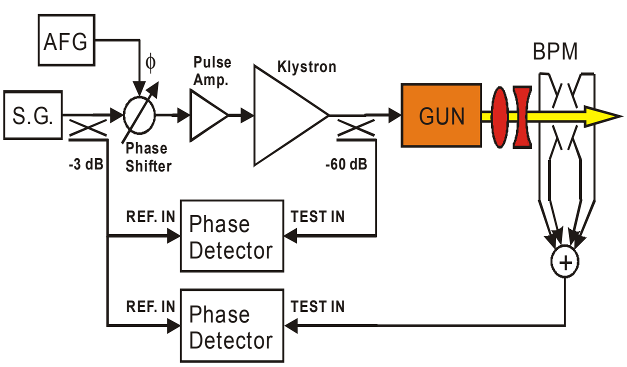

Figure 6: Schematic diagram of system for bunch phase shift measurement. S.G. and AFG mean signal generator and arbitrary function generator, respectively.

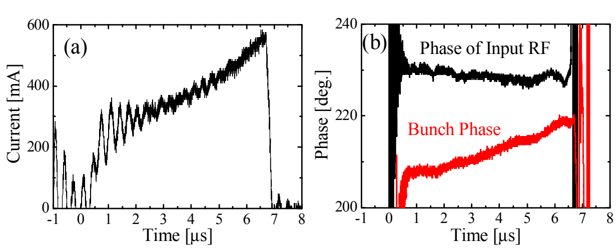

Figure 7: Result of phase shift measurement. (a) Temporal evolution of beam current. (b) Temporal evolution of input RF phase and bunch phase.

The phase shift of electron bunch was compensated by pre-setting phase pattern of input RF power as shown in Fig. 8. The pre-setting phase pattern was introduced by the voltage controlled phase shifter and arbitrary function generator shown in Fig. 6. We have succeeded in keeping the bunch phase constant during a macro-pulse.

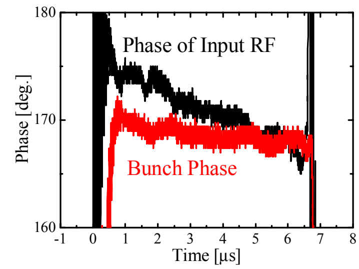

Figure 8: Result of bunch phase shift compensation.

CONCLUSION

A compensation method of beam energy decrease caused by back-bombardment effect in thermionic RF guns has been proposed. The mathematical analysis clearly shows the principle of compensation method. Temporal evolutions of the beam energy with and without detuning were measured to prove the principle of detuning method. As the results of experiment, we succeeded in keeping the beam energy for 8 μs, even with rapid current increase from 250 to 650 mA. The bunch phase shift induced by increase of beam current was also measured. Measured results show that the beam current increase from 300 to 550 mA induces bunch phase shift of around 10 degree. We succeeded in compensating the bunch phase shift by pre-setting pattern of the RF phase fed to the gun cavity.

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