NUMERICAL SIMULATION FOR THE BACK-BOMBARDMENT EFFECT ON THERMIONIC CATHODE AT KU-FEL RF GUN

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Abstract

Thermionic RF guns are used as highly brilliant electron source for linac driven oscillator FEL (free electron laser). They can potentially produce an electron beam with high energy, small emittance, moreover economic and compact configuration in comparison with other high brightness electron injectors. 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 macropulse, while longer pulse duration would be desired for the FEL operation. Numerical simulation code has been developed by KU-FEL group to analyse the back-bombardment effect. In this simulation code the beam loading effect in the RF gun and the heating property of cathode were taken in consideration. By using this code we could determine the change of the cathode temperature and the current density. The numerical model for the back-bombardment effect in the thermionic RF gun at KU-FEL and the results are presented.

1. Introduction

A high brightness electron beam with long macro pulse is preferred for high power free-electron lasers (FELs). Thermionic RF guns can produce such high brightness electron beams in an economic and compact configuration using resonance cavities. For these reasons thermionic RF gun has been chosen as electron injector of Kyoto University free electron laser (KU-FEL). KU-FEL thermionic RF gun consists of a 4.5-cell cavity driven by 10-MW RF power, which provides up to 10 MeV electron beam. The most critical issue of the thermionic RF gun is the transient cathode heating problem due to the electron back-bombardment when the gun is used for an FEL driver. 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 macropulse [1, 2]. Back-bombardment effect simply can be explained as because of the cavity field altered in time, electrons that are emitted late in RF period lose the chance to cross the cavity before the accelerating field reverse its direction. A number of these electrons accelerate back towards the cathode. If these electrons hit the cathode its energy will be lost with penetrating cathode through interaction with bound electrons in cathode material. Most of the electron's kinetic energy is converted to thermal energy, and heat up the cathode, then, cathode temperature and beam current increase during the macropulse. As a result, acceleration voltage of RF cavity decreases. Eventually electron beam energy decreases [3, 4]. In this paper, we proposed a developed numerical simulation code to study the transient cathode heating problem due to the back-bombardment effect in thermionic RF gun. And determine the change in the cathode current density caused by back bombardment effect.

2. Analysis Method

The back-bombardment effect depends on the cavity voltage in the RF gun and current density. We divided the analysis to two parts; the first one considered the thermal analysis to the cathode response due to the back-bombardment electrons and the second one considered the analysis of the cavity response due the back-bombardment taking in account the beam loading effect the RF gun. The next subsections introduce precise explanation about the above two pars.

2.1. Analysis of the cathode current density

In order to evaluate the effect of the back-bombardment electrons on the time evolution of the cathode temperature, at first the energy distribution of the back-bombardment electrons was calculated at different current density and cavity voltage by using the particle simulation code PARMELA [5]. Then, the range and the stopping power of the back-bombardment electrons inside the cathode material were determined. From these results the heat quantity given to the cathode by the back-bombardment electrons was accumulated to determine the total power density. Finally, the power density was used to determine the change in the cathode temperature and current density.

For precise evaluation of the deposited power density in the cathode a semi empirical formula of the stopping range [6] was used:

$$R = \frac{a_1}{\rho}\left[\frac{\ln(1 + a_2\tau)}{a_2} - \frac{a_3\tau}{1 + a_4\tau^{a_5}}\right] \tag{1}$$

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where ρ is the material density, τ is the incident kinetic energy in the units of the electron rest energy, and the parameters a_i (i=1,2,…,5) are defined by simple function of atomic number Z, and the atomic weight A. In case of mixture or compound Z and A should be replaced by the effective values of the atomic number Z_{eff} and effective atomic weight A_{eff} [6]. Eq. 1 is applicable to the range of electrons energy between 0.3 keV–30 MeV electrons. It well known that the stopping power of the particles inside material can be determine by using the change of the particles energy relative to the change the stopping range as dE/dR, hence the stopping power can be determined.

The evolution of the change in the cathode temperature was calculated by using thermal diffusion equation as below:

$$\frac{C \rho\, S\, z\, \Delta T}{\Delta t} = Q \qquad (2)$$

where, c is the specific heat, S, z are the cathode area and thickness respectively, ΔT, Δt are the change of the cathode temperature and time duration respectively, Q is the heat quantity from the back-bombardment electrons.

2.2 Analysis of the RF cavity response

The system of thermionic RF gun, which consists of a resonant cavity, an RF power source and electron beam, can be modeled by an equivalent circuit as shown in Fig. 1 [7]. 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 as beam admittance part Y_b, which can be divided into beam conductance G_b and beam 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. The dependences of the beam admittance on J_c and V_c was calculated by using the particle simulation code KUBLAI [8], the results of the simulation shown in Fig. 2. One can see from Fig. 2, that both of the beam conductance and beam susceptance increasing as the current density increase.

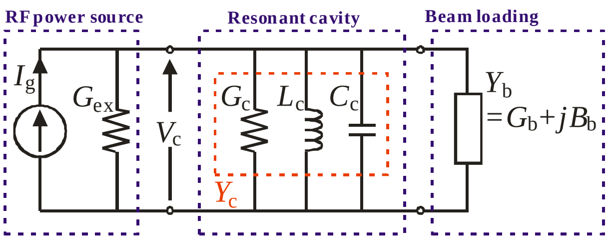

Fig. 1: Equivalent circuit of a thermionic RF gun

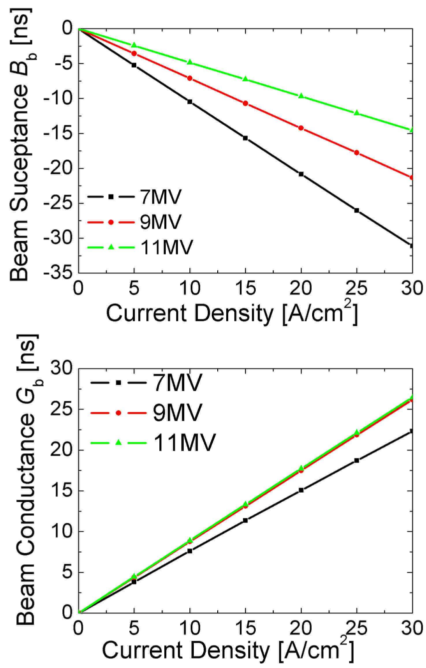

Fig. 2: Beam conductance G_b and susceptance B_b as a function of current density J_c and cavity voltage V_c.

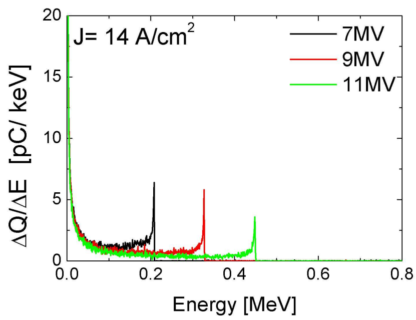

Fig. 3: Energy distribution of back-bombarding electrons simulated by PARMELA code.

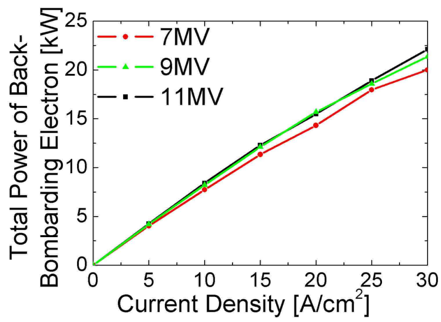

Fig. 4. Dependence of total power of back-bombarding electrons in a RF period as a function of J_c, V_c.

3. Calculation Results

In this calculation we assumed the initial cathode temperature is 1818 K before supplying the RF power to the gun which corresponding to 14 A/cm^2 current density, then we will suppose the increasing of the temperature and current density after supplying the RF power mainly due to the heat deposited by back-bombardment electrons. The relationship between the cathode temperature and the current density was obtained by the results of the cathode performance test of KIMBALL PHYSICS INC. Moreover, the scanned area of the cavity voltage from was is 7-11 MV which corresponding to the electron beam energy from 6.5-9 MeV from PARMELA calculation [9]. Figs. 3

and 4, show the energy distribution and the total power of the back-bombardment electrons at the desired scanning area as a function of the cavity voltage and current density on the cathode surface by using PARMEAL. The typical parameters of the RF gun and the cathode are shown in table 1.

Table 1: Parameters of the RF gun used the numerical simulation code.

Resonant frequency [MHz]	2856
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 [^oC]	1545

The stopping range of the back-bombardment electrons in the cathode was calculated by using Eq. 1, and the results are used to calculate the stopping power and depicted at Fig. 5. Then Eq. 2 was used to calculate the change of the cathode temperature. Finally, the change of the current density was determined by using the cathode performance test depicted in Fig. 6.

The expected change of the cathode temperature due to the heat deposited in the cathode by the back-bombardment electrons was 14 ^oC, finally, the expected change in the cathode current density 3.4 A/cm^2. This result of the cathode temperature change is reasonably with the experimental measurements in KU-FEL. The change in the cathode temperature and the current density are displayed in Fig. 6. As a future work, modification of the simulation code to consider the change of the cathode temperature and beam current during the macropulse.

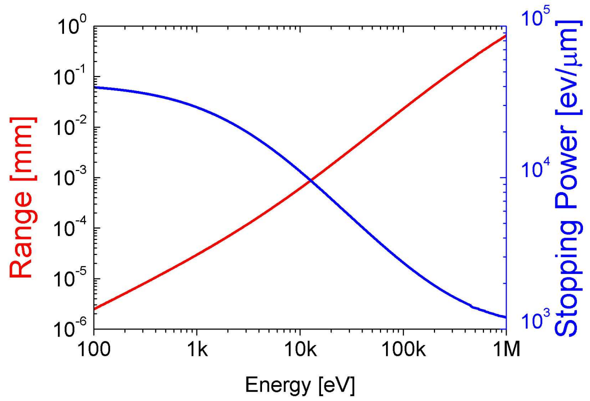

Fig. 5. The range and stopping power in LaB_6 cathode were calculated by using semi empirical TIO Equation.

Moreover demonstration with experimental data is needed to confirm the numerical simulation code.

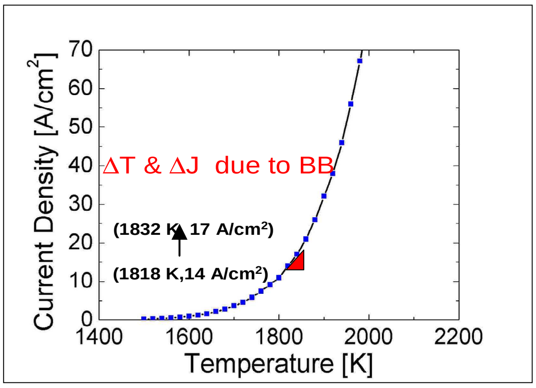

Fig.6. Ideal emission characteristic of single crystal of LaB_6 cathode.

4. Conclusions

We have developed a numerical simulation code for deep understanding of the back-bombardment electrons. The code start with calculated the energy distribution and the total power of the back-bombardment electrons by using PARMELA and KUBALI cods respectively. Then the range and the stopping power were determined by using the semi empirical equation. Then, the change in the cathode temperature is determined by using thermal diffusion equation. Finally, the change in the current density is calculated from the cathode performance test. Modifications with demonstration are required to realize the simulation code.

5. References

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