EVALUATION OF THE BACK-BOMBARDMENT EFFECT IN THE ITC-RF GUN FOR T-ACTS PROJECT AT TOHOKU UNIVERSITY

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Abstract

An ITC (independently tunable cells) RF gun is currently used to produce sub-picosecond electron pulses as part of the injector for coherent terahertz radiation at Tohoku University. Experiments and simulations of particle tracing by GPT show that the back-bombardment effect on the LaB6 cathode's surface is serious and should be controlled carefully. To evaluate the temperature increase due to back-bombardment a 2D model is created for heat transfer inside the cathode. In the 2D model, the back-streaming electrons are treated as external heat source as well as the cathode heater that heats the cathode from its side along with thermal radiation from its surface. The energy deposit of back-bombardment inside the cathode is calculated by EGS5 or Geant4 by use of the information of back-streaming electrons derived from GPT simulation. In addition, we will also compare the simulating results with experimental data on the increase of emission current density of cathode due to back-bombardment.

INTRODUCTION

A terahertz source project, t-ACTS(test-Accelerator for Coherent Terahertz Source), is currently under construction in Tohoku University [1]. To provide sub-picosecond electron pulses a specially designed thermionic RF gun (see Fig. 1) is employed for bunch compression in an ensuing α-magnet, followed by velocity bunching in the main accelerating structures [2]. Although the ITC-RF gun can be optimized to generate a good energy chirp [2] for the α-magnet by tuning the amplitudes of electrical fields in both cells and their difference of phase, it lacks the ability to reduce back-bombardment(B.B.) which is common in thermionic RF guns [3].

Back-bombardment originates from the continuous emission of current and time-dependent field strength in thermionic RF guns. Electrons can be pulled out of the cathode as long as the electrical field on its surface is negative but they will go through different field strengths depending on the RF phase. Those electrons emitted later during the negative half circle begin to lose their energies when the RF field turns positive and finally move backward to the cathode, contributing to back-bombardment. As a result, the cathode will be overheated to a higher temperature and the emission current density rises following Richardson's equation,

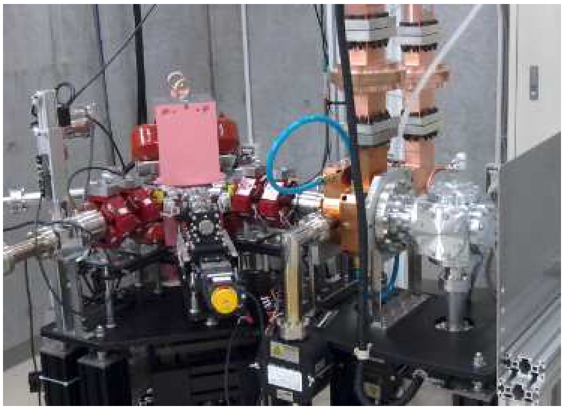

Figure 1: The ITC-RF gun and α-magnet

$$J = AT^2 e^{\frac{-W}{kT}} \tag{1}$$

where A and W are Richardson's constant and work function of the cathode material, respectively, T is the temperature of the cathode and k is Boltzmann's constant. In our gun, a cylindrical $\mathrm{LaB_6}$ cristal with an emitting diameter of 1.75mm and a thickness of 1.25mm is used. The Richardson's constant and work function for it are 29A/cm^2/T^2 and 2.69eV, respectively.

Back-bombardment will damage the cathode, reducing both its performance and life time. Further more, an increasing emission current density will leads to an increasing beam current which is unfavorable for the ensuing stages of t-ACTS. As a first step to study how to reduce back-bombardment in our gun, the way to evaluate the effect of B.B. on the cathode and thus to the emission current density is introduced here.

EVALUATION OF B.B. EFFECT ON THE CATHODE

First, the information of the back-streaming part of the electron beam is obtained by GPT [4] simulation, from which we know when and where the cathode is hit. Follow-

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ing is energy deposit of those electrons inside the cathode, accomplished by EGS5 [5] or Geant4 [6].After this, a 2D equation for heat transfer is solved numerically to get the temperature increase of the cathode, using the energy deposit as heat source for it. Finally, we estimate the increase of emission current density of the cathode theoretically by Richardson's equation as mentioned above. The whole procedure is shown in Fig. 2.

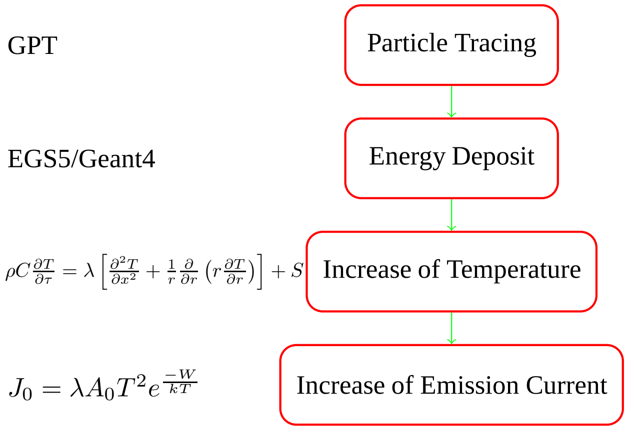


Figure 2: The procedure of evaluating the effect of B.B.

Characteristics of the back-streaming electrons

At present a LaB_6 crystal emitter is used as the cathode in the ITC-RF gun for its high emission current density (say, 50A/cm^2). The small size and high emission current make it better to meet the requirements of t-ACTS, although higher emission current density might also cause higher B.B. power at the cathode. However, our simulation shows the B.B. power increases much slower than that of emission current density because of the existence of space charge.

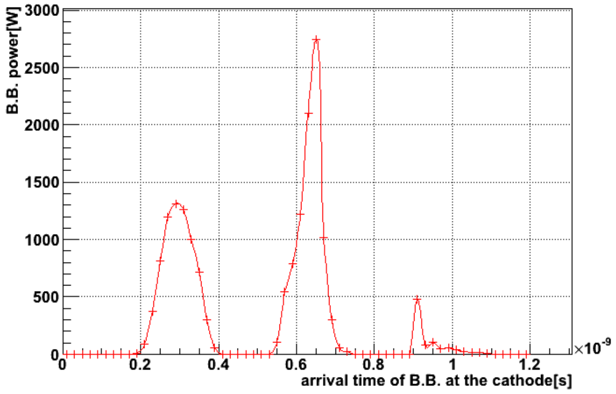


Figure 3: The back-streaming electrons can be divided into groups according to their arrival time at the cathode.

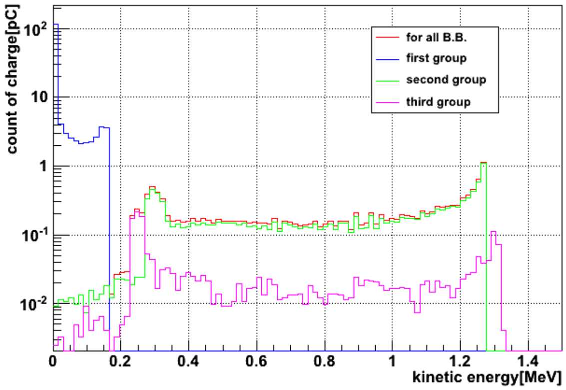


Figure 4: Energy spectrum of the back-streaming electrons

Energy spectrum of B.B. It has been found that there are two major groups of B.B. (see Fig. 3) in the ITC-RF gun: the first group with lower energies (0-200keV) coming from the first cell and reaching the cathode earlier and the second group with higher energies(200keV-1.3MeV) coming from the second cell and reaching the cathode later, see Fig. 4. Although the total energies in the first two groups in Fig. 3 are close, deposited energies from these groups inside the cathode differ a lot because electrons with higher energies are much more likely penetrate the cathode and lost only a little part of their energies.

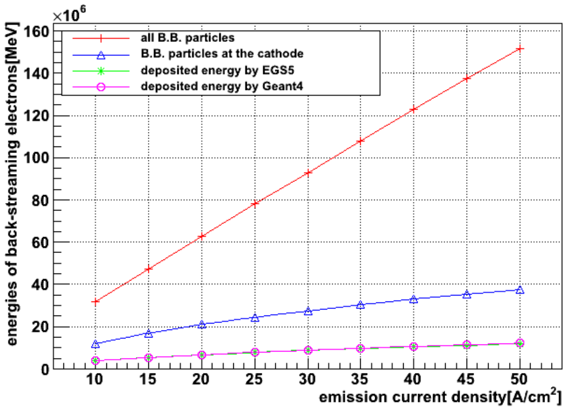
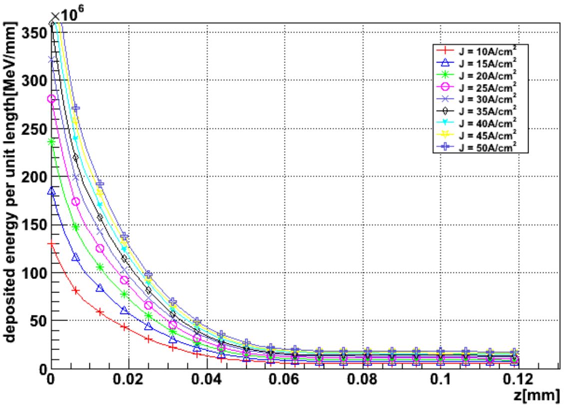
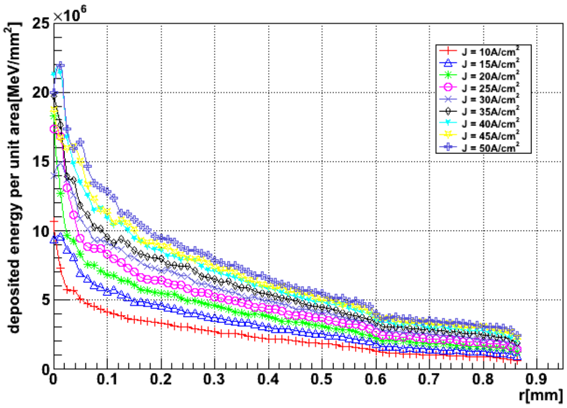


Figure 5: The dependency of B.B. and energy deposit on emission current density.

B.B. with emission current density. The ITC-RF gun is operated under an RF period of 2.856GHz and a macro-pulse of 2-3μs and our interest is to know how the emission current increases during the macro-pulse due to B.B. The best way to implement the procedure in Fig. 2 is like this: 1) updating the information of B.B. at a given emission current density, J_0 2) calculating the effect of this part of B.B. for some time, ΔT, and 3) get a new emission current density ,J and do 1) again. Here the key is for how long should we update the information of B.B. Previous experiences tell



(a) Longitudinal



(b) Radial

Figure 6: Distribution of energy deposit.

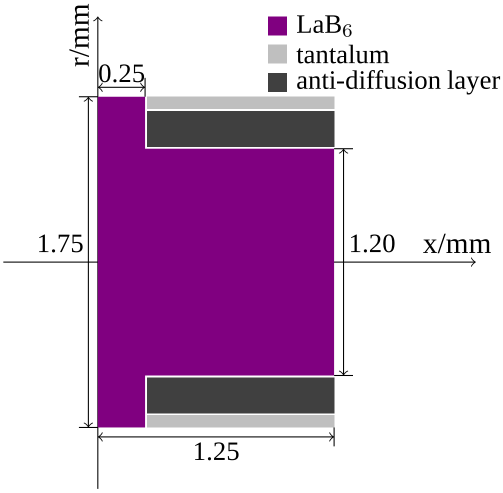
us the GPT simulation would take almost one hour to calculate an RF circle so ΔT should never be small. Fig. 5) is the relationship of B.B. with J. It shows that the total B.B. energy is proportional with J but the part at the cathode increases much slower. After taking into account energy deposit inside the cathode, the effect of increase of current density is furthermore reduced. Fig. 6 is the detailed spatial distribution of deposited energies; the smooth increase of energy deposit with current density makes it reasonable to use interpolation to estimate the spatial distribution if we have known some other distributions under other current densities in advance.

2D model for heat transfer in the cathode

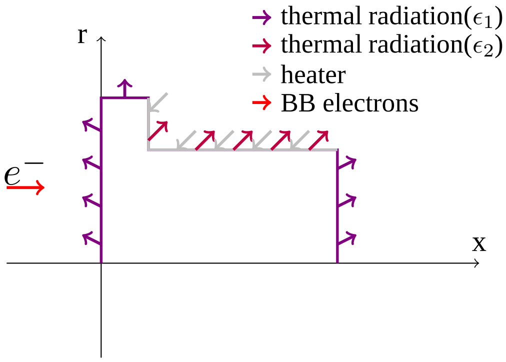
After knowing the distribution of energy deposit from the back-streaming electrons, the 2D equation for heat transfer is solved to calculate the effect of those extra energies on the cathode. The 2D equation [7] is

$$\rho C \frac{\partial T}{\partial \tau} = \lambda \left[\frac{\partial^2 T}{\partial x^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r} \right) \right] + S \qquad (2)$$

where T is absolute temperature and t is time, ρ, C and λ are density, specific heat and thermal conductivity of LaB$_6$, respectively, S is heat source. In our case, S includes the heat from the cathode heater, the thermal radiation of the cathode and the heat from back-streaming electrons, see Fig. 7b. Fig. 7a gives the detailed structure of the cathode but for both simplicity and convenience only the LaB$_6$ crystal is considered in the 2D model. Note that in Fig. 7b the thermal radiation consists of two parts, one from the surface and bottom of LaB$_6$ with an emissivity of ε_1, the other from its side where tantalum contributes to the thermal radiation with an emissivity of ε_2. Equation (2) is solved by finite difference method [7].



(a) LaB$_6$ cathode



(b) 2D model

Figure 7: Drawing of the cathode and its 2D model.

Test of the 2D model. Another DC gun in Tohoku University is employed to test the 2D model. The DC gun uses the same type of cathode as that in the ITC-gun. First, the cathode in the DC gun was heated under a constant current (say, 8A) to an equilibrium state. Then, the heating current was cut off and the temperature was measured by a thermometer. This process was simulated by the 2D model and the result agreed well with experiment, see Fig.6.

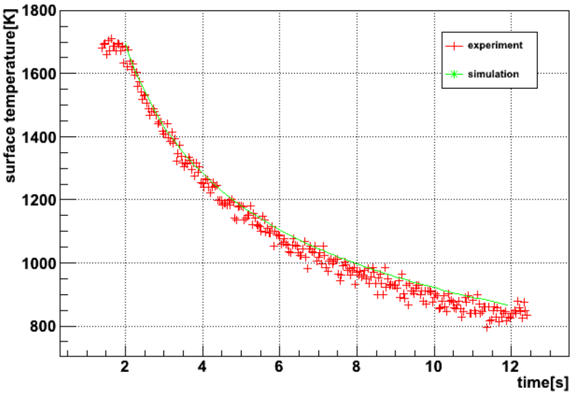


Figure 8: Temperature evolution of the cathode's surface. The heating current is 8A before being cut off.

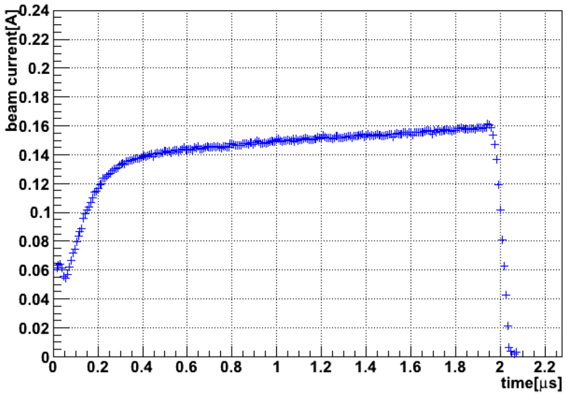


Figure 9: Measured beam current.

COMPARISON OF EXPERIMENT AND SIMULATION ON THE ITC-GUN CATHODE

The ITC gun, as its name implies, has two independently tunable cells and thus three adjustable parameters. They are the amplitudes of electrical fields in the cells and the phase difference between them. However, the amplitudes have never been measured and the phase difference is also unknown at present. In previous experiments, the phase difference was scanned to measure the beam current at the gun exit, with amplitudes of electrical fields estimated as 25MeV/m and 70MeV/m theoretically. The scanning results were compared with that of GPT simulation to determine the phase difference and finally we chose 30° to implement the procedure in Fig. 2.

The beam current around 30° is shown in Fig. 9. The initial and final current density were estimated as 27A/cm^2 and 31A/cm^2, also from comparison of experiment and simulation. After doing the procedure in Fig.1, the current density increased from 27A/cm^2 to 33A/cm^2, 50% higher than the experiment, see Fig. 10.

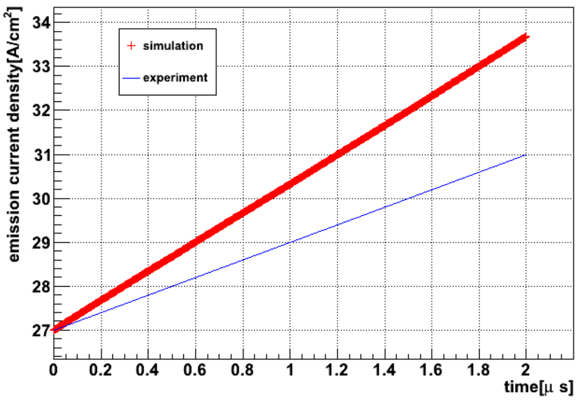


Figure 10: Comparison of experiment and simulation.

SUMMARY

The disagreement in Fig. 10 might be resulted by many reasons. On one hand, the amplitudes of electrical fields and phase difference which are sensitive to B.B., especially the amplitude in the first cell, are to be confirmed in the future. On the other hand, values of Richardson's constant and work function for LaB_6 in equation (1) is also cited from literatures and those values may differ with that of our cathode. Anyway, these problems should be solved as soon as possible to give a better description of B.B. effect on the cathode. And after that, we will study how to reduce B.B. to an acceptable level.

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