

# STUDY ON THE BACK-BOMBARDMENT EFFECT IN THE ITC-RF GUN FOR t-ACTS PROJECT AT TOHOKU UNIVERSITY

Xiangkun Li<sup>\*A)</sup>, Shigeru Kashiwagi<sup>A)</sup>, Masayuki Kawai<sup>A)</sup>, Fujio Hinode<sup>A)</sup>, Kenich Nanbu<sup>A)</sup>, Toshiya Muto<sup>A)</sup>, Fusashi Miyahara<sup>B)</sup>, Yu Tanaka<sup>A)</sup>, Hiroyuki Hama<sup>A)</sup>,

<sup>A)</sup>Electron Light Science Center, Tohoku University

1-2-1 Mikamine, Taihaku-ku, Sendai, Miyagi, 982-0826, Japan

<sup>B)</sup>KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801 Japan

## 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. Both experiments and simulations of particle tracing by GPT have shown that the back-bombardment(B.B.) effect on the LaB<sub>6</sub> cathode's surface is serious and should be controlled carefully. To evaluate the temperature increase due to B.B. 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 B.B. inside the cathode is calculated by EGS5 or Geant4 by use of the information of back-streaming electrons derived from GPT simulation. The results of simulation on time dependent evolutions of temperature and emission current density of the cathode caused by B.B. were compared with experimental data.

## INTRODUCTION

A terahertz source project, t-ACTS(test-Accelerator as Coherent Terahertz Source), is currently under construction in Tohoku University [1]. To provide sub-picosecond electron pulses a specially designed thermionic RF gun (shown in Fig. 1) is employed for bunch compression in an ensuing  $\alpha$ -magnet, followed by velocity bunching in the main accelerating structures [2]. Although the ITC-RF gun can be optimized to generate an appropriate energy-chirp [2] for the  $\alpha$ -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 electrons 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

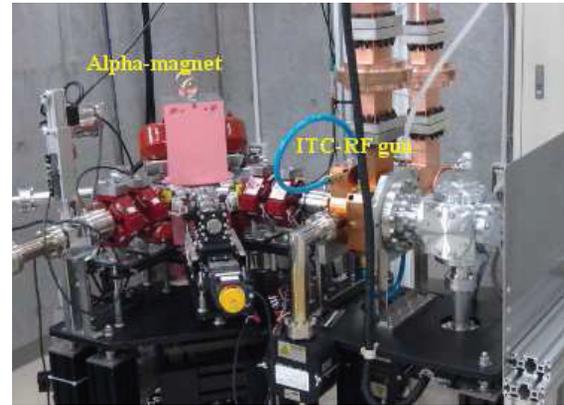


Figure 1: The ITC-RF gun and  $\alpha$ -magnet

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,

$$J = AT^2 e^{\frac{-W}{kT}} \quad (1)$$

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 LaB<sub>6</sub> crystal with an emitting diameter of 1.75 mm and a thickness of 1.25 mm is used. The Richardson's constant and work function for it are 29 A/cm<sup>2</sup>/T<sup>2</sup> and 2.69 eV, respectively.

Back-bombardment will damage the cathode, reducing both its performance and life time. Further more, an increasing emission current density will lead 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-

\* xkli@ins.tohoku.ac.jp

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.

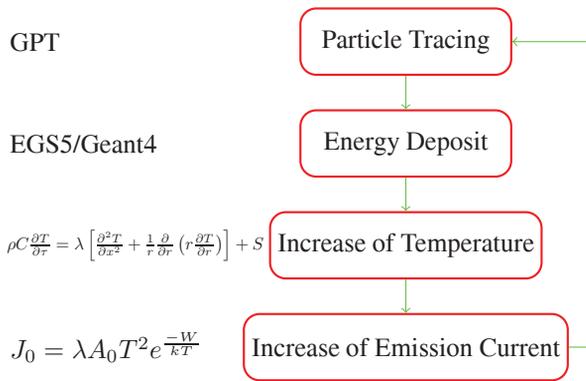


Figure 2: The procedure of evaluating the effect of B.B.

### Characteristics of the Back-streaming Electrons

At present a LaB<sub>6</sub> single crystal is used as the cathode in the ITC-RF gun for its high emission current density (50 A/cm<sup>2</sup> is preferred for the operation of the ITC-gun). 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. Fortunately, the B.B. power increases much slower than that of emission current density because of the existence of space charge.

**Energy spectrum of B.B.** It was found that there are two major groups of B.B. (Fig. 3) in the ITC-RF gun: the

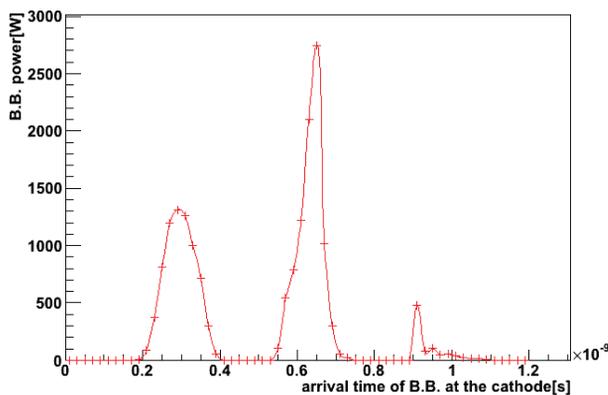


Figure 3: The back-streaming electrons can be divided into groups according to their arrival time at the cathode.

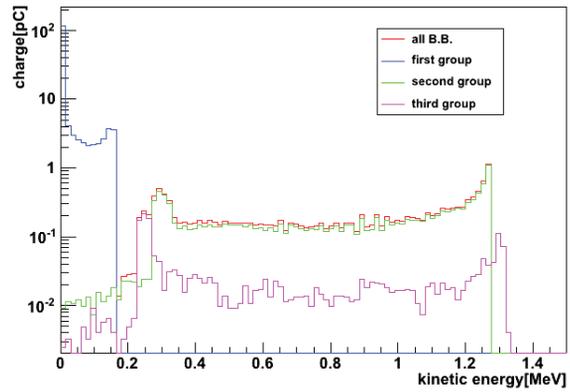


Figure 4: Energy spectrum of the back-streaming electrons

first group with lower energies (<200 keV) coming from the first cell and reaching the cathode earlier and the second group with higher energies(200 keV - 1.3 MeV) coming from the second cell and reaching the cathode later. The energy spectrum is shown in Fig. 4. Although the total energies in the first two groups are close, deposited energies inside the cathode from these groups differ a lot(Fig. 5) because electrons with higher energies are much more likely to penetrate the cathode and lose a little amount of their energies in the cathode while the low energy group lose most of their energy near the surface of the cathode. It means the first group need to be controlled to reduce the effect of B.B. on the cathode.

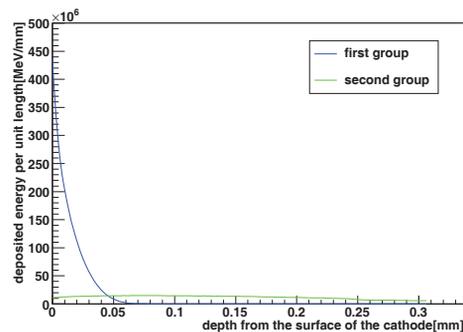


Figure 5: Energy deposit of different groups of B.B. along the axis of the cathode which has a thickness of 1.25mm.

### 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 additional heating energies on the cathode. The 2D equation [7] is

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

where  $T$  is absolute temperature and  $t$  is time,  $\rho$ ,  $C$  and  $\lambda$  are density, specific heat and thermal conductivity of LaB<sub>6</sub>,

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. 6b. Fig. 6a gives the detailed structure of the cathode but for both simplicity and convenience only the LaB<sub>6</sub> crystal is considered in the 2D model. Note that in Fig. 6b the thermal radiation consists of two parts, one from the surface and bottom of LaB<sub>6</sub> with an emissivity of  $\epsilon_1$ , the other from its side where tantalum contributes to the thermal radiation with an emissivity of  $\epsilon_2$ . Equation (2) is solved by finite difference method [7].

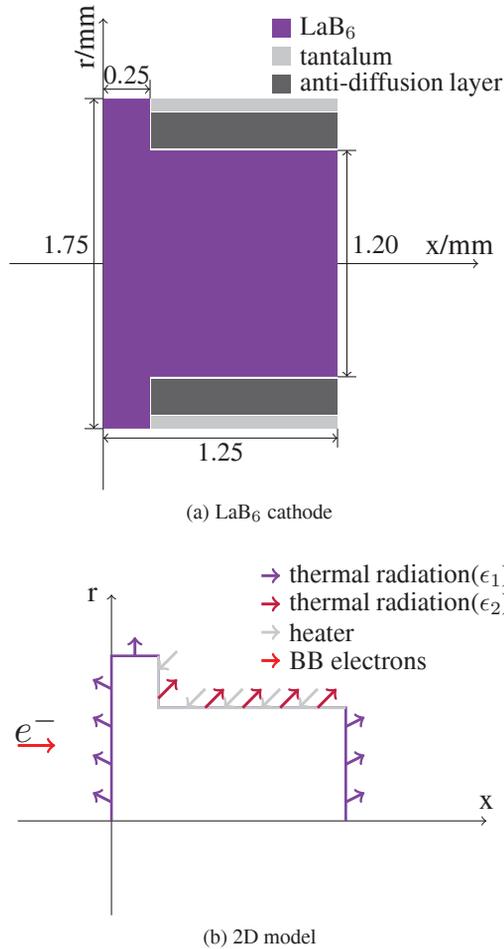


Figure 6: Schematic of the cathode and its 2D model.

**Test of the 2D model.** Another DC gun developed in Tohoku University [8] 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, 8 A) 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. 7.

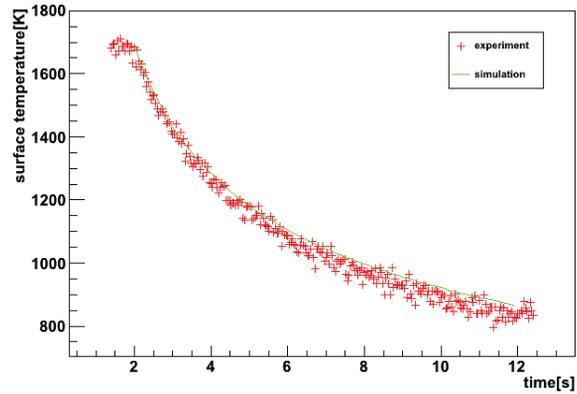


Figure 7: Temperature evolution of the cathode's surface. The heating current is 8A before being cut off.

### 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 not been measured yet and there is some ambiguity for the phase difference 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 25 MeV/m and 70 MeV/m theoretically. The scanning results were compared with that of GPT simulation to determine the phase difference and here the case of  $\pi - 60^\circ$  is used to implement the procedure in Fig. 2.

The beam current around  $\pi - 60^\circ$  is shown in Fig. 8. The initial and final current density were estimated as 42.38 A/cm<sup>2</sup> and 53.15 A/cm<sup>2</sup>. After doing the procedure in Fig. 2, the current density increased to 56.01 A/cm<sup>2</sup>, that is slightly higher than the experiment as one can see in Fig. 9.

### SUMMARY

The disagreement in Fig. 9 may be resulted by many reasons. When calculating B.B. information by GPT, we supposed that the electrical fields were unchanged. But actually, it needs time for the RF power to feed into the gun and this process lasts almost 0.5  $\mu$ s, comparable with the period of the macro pulse (2  $\mu$ s). The simulation shows that a smaller electrical field in the first cell will lead to a reduced effect of B.B. because the energy of back-streaming electrons becomes smaller. In the future, we will take into account the feeding of RF power into the gun as a way to overcome the disagreement in Fig. 9. In addition, we will check if some parameters such as Richardson's constant

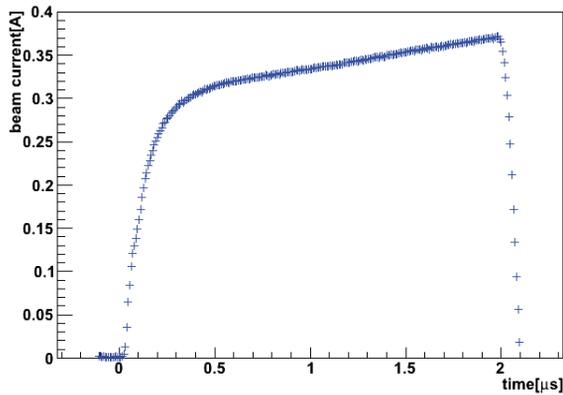


Figure 8: Measured beam current. The electric fields are 25 MV/m and 70 MV/m, respectively, and phase difference is  $\pi - 60^\circ$ .

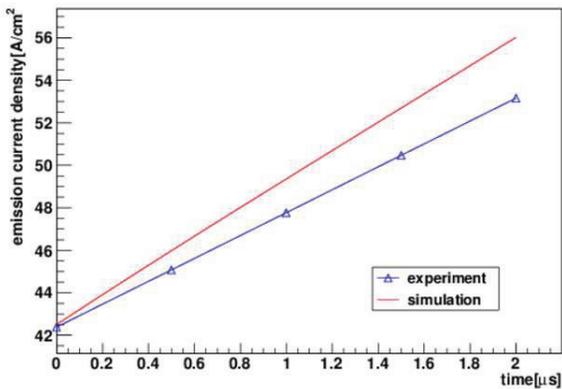


Figure 9: Comparison of experiment and simulation.

and work function we used in the simulation are sensitive to the result. After getting a better description of B.B. effect on the cathode, we will study how to reduce B.B. to an acceptable level.

## REFERENCES

- [1] H. Hama et al., *New J. Phys.* 8 (2006) 292.
- [2] F. Miyahara, Production of Femtosecond Electron Pulse Using Alpha Magnet Together with Off-crest Acceleration for Generation of Coherent THz Radiation, *Proceedings of IPAC'10*, 2010.
- [3] M. Borland, A High-brightness Thermionic Microwave Electron Gun, PhD Thesis, Stanford University, April 1991.
- [4] General Particle Tracer, <http://www.pulsar.nl/gpt>.
- [5] Electron Gamma Shower, <http://rcwww.kek.jp/research/egs/egs5.html>.
- [6] Geant4, <http://geant4.cern.ch/>.
- [7] 陶文铨, 数值传热学, 第2版, 西安交通大学出版社, 2001. W. Tao, *Numerical Heat Transfer*, 2<sup>nd</sup> edition, Xi'an Jiaotong University Press, 2001.
- [8] K. Kasamsook, K. Nanbu, M. Kawai, K. Akiyama, F. Hinode, T. Muto, T. Tanaka, M. Yasuda, H. Hama, A compact low emittance dc gun employing single crystal cathode of LaB6, *Proc. 28th International Free Electron Laser Conference*, Berlin (2006) 680.