THREE-DIMENSIONAL TIME-DOMAIN BEAM SIMULATION STUDY FOR A THERMIONIC RF GUN

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Abstract

A thermionic RF gun is going to be employed in a new pre-injector linac for the future synchrotron radiation facility at Tohoku University. A 3-D beam simulation code for the RF gun using a Finite Difference Time Domain (FDTD) method has been developed. As a result of the simulation, an external dipole magnetic field around the cathode is found to be effective to deflect high energy electrons coming back from accelerating cell. However, as increasing the strength of the dipole field, the transmitted beam current decreases and the transverse beam emittance at the gun exit increases, which means careful optimization of the dipole field is required.

INTRODUCTION

Accelerator complex for a future project of synchrotron radiation facility has been under designing at Laboratory of Nuclear Science (LNS), Tohoku University [1]. It will consist of a 1.5 GeV storage ring, a 1.2 GeV booster ring and a 150 MeV pre-injector linac. A newly designed pre-injector linac will provide a 150 MeV electron beam into the 1.2 GeV booster synchrotron which is already operated since 1997. A thermionic RF gun as the electron source is going to be chosen because it seems to have sufficient potential ability for the pre-injector linac.

The thermionic RF gun is attractive because of simple configuration with no high voltage stage, no annoying pre-buncher and buncher section. It is also convenient for the synchrotron to inject the several μs macropulse beam with low repetition. In addition, the beam emittance is possibly very low and the bunch length can be compressed to have a high peak current to drive FEL [2]. However, there are only a few linacs with thermionic RF guns. Back-Bombardment (BB) effect, which is over-heating of the cathode due to the back-streaming electrons, restrains further development as the electron source. In order to reduce the BB effect, most of facilities have been empirically applying dipole magnetic field to deflect the back-streaming electrons aside [3].

At LNS, in order to minimize the BB effect in a design work, a 3-D beam simulation code for the RF gun using Finite Difference Time Domain (FDTD) method to solve the Maxwell's equations has been developed. In the RF gun, especially in a case of the high beam current, electromagnetic fields induced by the electron beam are considered to affect beam characteristics such as beam emittance, energy spread etc. In the FDTD method, because the Maxwell's equations are able to be solved including the term of the current density of the charge, the electromagnetic fields produced by both the external RF power and the electron beam can be anticipated.

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MODELING AN RF GUN

Remarks in FDTD method

A standard method of the finite difference in the time domain as well as in the spatial domain is employed. Maxwell's electromagnetic field equations for time domain are described as,

$$\vec{E}^{n} = \vec{E}\left(t_0 + n\Delta t\right) \tag{1}$$

$$\varepsilon \frac{\vec{E}^{n} - \vec{E}^{n-1}}{\Delta t} = \nabla \times \vec{H}^{n-1/2} - \vec{J}^{n-1/2} \tag{2}$$

$$\mu \frac{\vec{H}^{n+1/2} - \vec{H}^{n-1/2}}{\Delta t} = -\nabla \times \vec{E}^{n} \tag{3}$$

where Δt is a time interval between steps and n is the number of steps. From these equations, the electric field $\vec{E}$ and the magnetic field $\vec{H}$ are solved by the leap-frog algorithm. In the FDTD method, the electron motion and the microwave propagation cannot be separated, so that the space charge effect and the beam loading are able to be taken into account.

For the boundary condition of the gun cavity, perfect electric conductor is applied. At the gun exit, the first order Mur's absorbing boundary condition is employed [4].

The main purpose of the simulation study is to evaluate general properties of the thermionic RF gun. Therefore relatively large time and spatial intervals ($\Delta t = 3$ ps, $\Delta x, \Delta y, \Delta z = 2$ mm) are used to save the CPU time sacrificing accuracy.

RF gun

On-axis coupled 3-cell Cavity Structure (OCS) RF gun [5] is chosen in the simulation study. The cavity geometry has been determined to satisfy following conditions.

- Resonant frequency of accelerating mode (π/2-mode) is close to 2.856 GHz (S-band).
- Frequencies of other modes should be sufficiently distant.
- To reduce the BB power, the electric field of the cathode surface is rather low (max. 20 MV/m).

- The kinetic energy of the extracted beam is approximately 1 MeV, which is also aiming low BB power.

In the beam simulation, an impregnated dispenser cathode is supposed to be used and the constant emission current density over a 6 mm diameter cathode is assumed.

BEAM SIMULATION RESULTS

Characteristics of the extracted beam from the RF gun

In the simulation, the current density is assumed to be 30 mA/cm^2 [6]. Kinetic energy gain of the electrons resulted from the simulation plotted as a function of the initial RF phase is shown in Fig. 1. The positive value of the vertical axis means that the electron transmits from the gun with the kinetic energy. The negative one indicates that the electron goes back to the end wall of the RF gun. The maximum kinetic energy of 1 MeV is much lower than that of usual photocathode injectors. In case of thermionic RF guns, to produce the higher energy beam is considered to be dangerous for the BB effect.

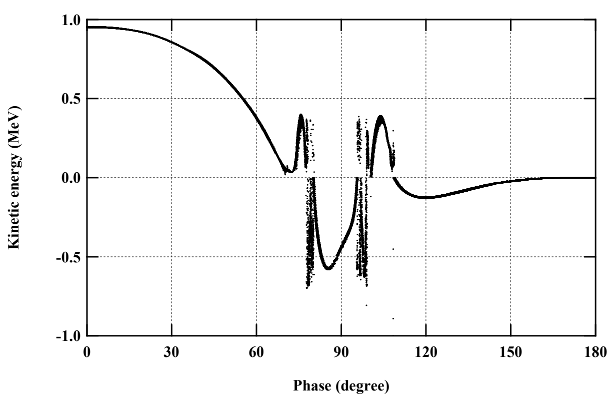

Figure 1: Kinetic energy gain plotted as a function of the initial RF phase of the electron.

As shown in Fig. 1, the back-streaming electrons are produced at the initial RF phase of around 90 deg. and that between 110 and 180 deg. Watching snap-shots of the motion of the macro-particles in the simulation, most of the electrons whose initial RF phase of 90 deg. go back from the third (accelerating) cell. On the other hand, the electrons with initial RF phase between 110 and 180 deg. immediately go back from the first cell.

The particle distribution in the phase space for the energy aperture $\Delta\beta\gamma = 10$ % from the maximum $\beta\gamma$ is shown in Fig. 2. The normalized emittance is 8 π mm mrad. As the horizontal phase space distribution is shown in Fig. 2, the vertical one is the same distribution because of the axisymmetry.

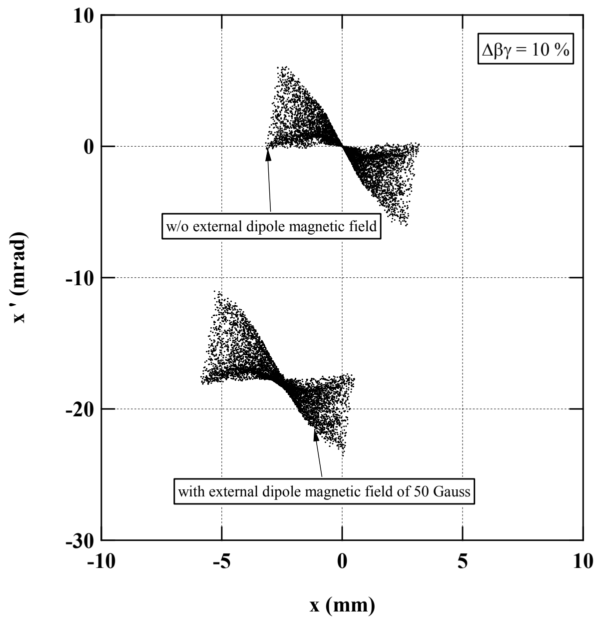

Figure 2: Transverse phase-space distribution at the RF gun exit.

Effect of external dipole magnetic field on back-bombardment

To reduce the BB power by means of the applying external dipole magnetic field is examined. In the simulation, an ideal dipole magnetic field is applied on the first cell and the fringing field is not taken into account. Simulation results of the radial distribution plotted as a function of the kinetic energy of the back-streaming electrons are shown in Fig. 3. Without the external dipole magnetic field, as shown in Fig. 3(a), there are two groups of the back-streaming electrons. One group bombards the cathode with relatively low kinetic energy, which is mostly coming from the initial RF phase of 110 ~ 180 deg. Another one hits onto the cathode with high energy. Although the number of the high energy electrons is very small, the bombarding power to the cathode is much higher than that given by the low energy electrons [6].

Applying the external vertical magnetic field of 50 Gauss, the high energy electrons are removed from the area of the cathode as shown in Fig. 3(b). Applying the dipole magnetic field of 200 Gauss, the high energy electrons are completely removed, as shown in Fig. 3(c). However the low energy electrons still hit the cathode. It is hard to remove those electrons because they travel short path lengths.

The external dipole magnetic field affects not only the back-streaming electrons but also the accelerated electrons in the first cell. As shown in Fig. 2, the transverse phase-space distribution of the RF gun exit is shifted by applying the external dipole magnetic field. The transmitted beam current and transverse emittance plotted by changing the magnetic field is shown in Fig. 4. As increasing the strength of the dipole magnetic field, the extracted beam current is gradually decreased, meanwhile the emittance is not much changed when the dipole field is lower than 150 Gauss.

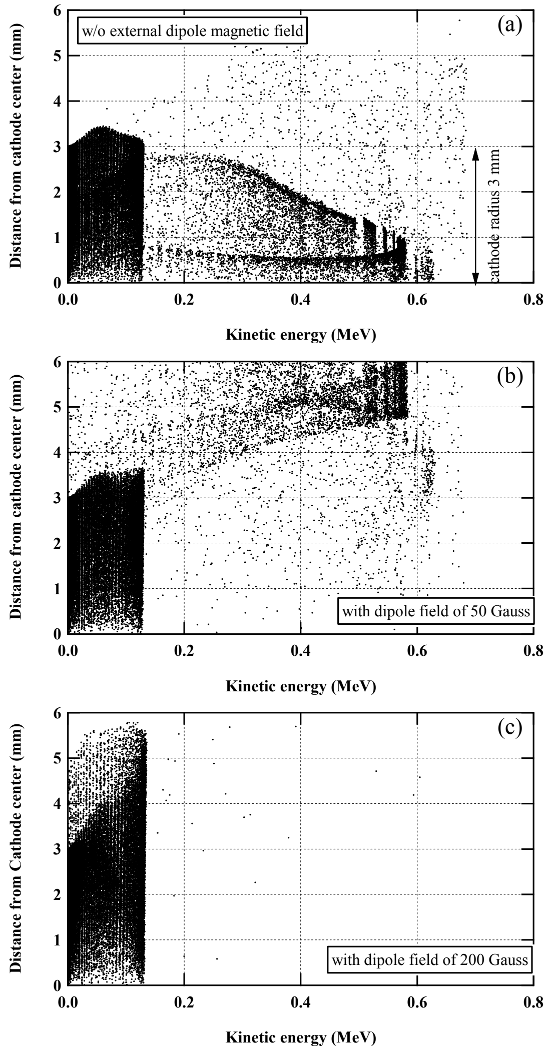

Figure 3: Radial distribution of the back-streaming electrons on the cathode plotted as a function of the kinetic energy.

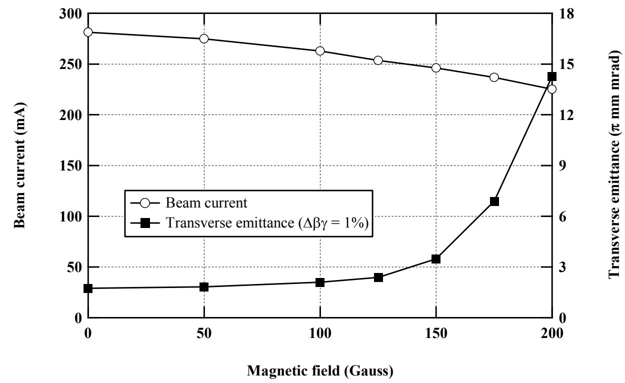

Figure 4: Variations of the transmitted beam current and the transverse emittance by changing the strength of the dipole field.

SUMMARY AND FUTURE PROSPECTS

Using a 3-D FDTD code for solving Maxwell's equations, the behaviour of the electrons in an OCS RF gun is simulated numerically. It is found that the external dipole magnetic field is effective for reduction of the high energy back-streaming electrons. However, it is quite difficult to eliminate the low energy ones which also cause the BB effect. To find out a solution of the BB problem is the most important work for further development of the thermionic RF gun.

On the other hand we are going to manufacture a prototype and install the thermionic RF gun on a test bench, and we hope to obtain the experimental results to compare with the simulation results soon.

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