SIMULATION STUDY OF THE BEAM LOADING EFFECT IN AN RF GUN

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Abstract

A code of time-dependent 3-D Maxwell's equation solver has been developed and applied for a study of beam dynamics in an RF gun. A 1.5-cell BNL type RF gun is chosen for the model field calculation and a beam simulation [1]. Assuming a laser photo-cathode gun, an electromagnetic field induced by the bunched electrons during acceleration in the gun has been extracted from the result of the simulations. Evolution of the beam induced field in the gun, which is equivalent to the space charge force or the beam loading, are presented to discuss general characteristics of the RF gun including thermionic RF guns [2].

INTRODUCTION

Number of simulation code for the laser photo-cathode RF gun have been developed and played important role for production of greatly reduced beam emittance. Transverse growth of beam emittance has been well studied, i.e., linear and nonlinear space charge force and transverse RF field. Results of these investigations have become quite important knowledge for design of optimal RF guns. An ideal method for understanding the RF cavity and the beam dynamics is to solve Maxwell's equations self–consistently in full space. However such calculation would be very complicate and takes a very much long time, so that most of simulator codes reduce the dimension to 2-D and normally separate the RF field calculation from the beam equation of motion.

An FDTD (Finite Deference Time Domain) method, which is widely used for analysis of the electromagnetic wave propagation from antennas, may be potentially employed to the fully self-consistent simulation of the RF gun [3]. At the moment we are trying to adopt the FDTD method for the study of the RF gun. In this article, some simulation results by modelling the 1.5 cell RF gun are presented and discuss feature of the beam loading effect, particularly on the longitudinal beam dynamics.

FDTD SIMULATIONS

Because of acceptable cpu time and memory size, the number of cubic grids has to be reduced, so that the shape of the RF gun is not well reproduced in detail. This is one of the significant disadvantages of the 3-D modelling. The 3-D FDTD method is, therefore, not suitable to design the shape the gun. However we have thought the method is a powerful tool to understand the over all properties of the beam dynamics in the RF gun.

Modelling of the RF Gun

A cross section view of the 1.5 cell gun and the electric field distribution of the longitudinal axis (x = y = 0) is shown in Fig. 1. In order to tune the resonant frequency of π-mode onto the S-band (2856 MHz), the size of one cubic grid ($(\Delta x, \Delta y, \Delta z) = (1.955, 1.955, 2.0)$ mm was determined by frequency analysis. The time step interval has been chosen to be 3 ps. The resonant frequency of the 0-mode was found to be ~ 8 MHz lower than that of π-mode.

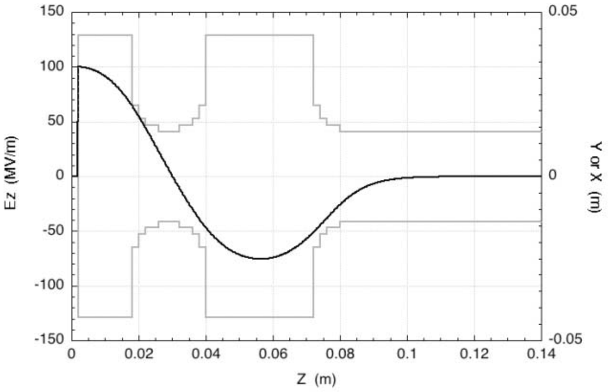

Figure 1: Longitudinal electric field distribution in the RF gun. The maximum field strength on the cathode, E_Z, is adjusted to be 100 MV/m.

The RF field in the gun is established by a point B_X exciter located in the 2nd cavity. An ideal wall-loss of oxygen-free copper and a coupling constant of β = 3 are taken into account in the numerical calculation.

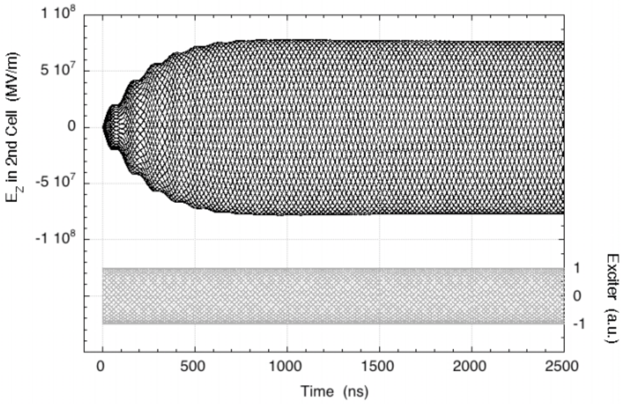

Figure 2: Growth of E_Z in the gun. Excitation of the resonant frequency of 2856 MHz is started at t = 0.

One can see a fluctuation of the RF field strength at the growth time in the Fig. 2. The 0-mode staying nearby is

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also excited because the exciter signal contains wide-band component in the beginning of the excitation.

Initial Phase of Laser and Transverse Emittance

As one knows well, the extracted beam quality from the RF gun strongly depends on the initial laser timing with respect to the RF phase. In Fig. 3, energy gains of single macro-particles (0 charge) at various initial phases are plotted as a function of the time.

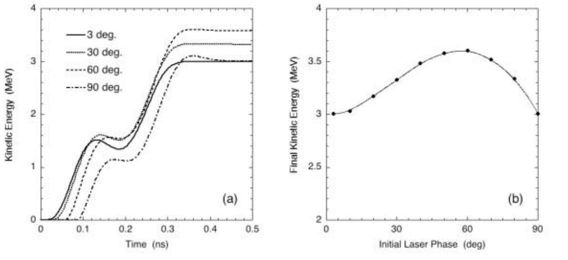

Figure 3: (a) Kinetic energy variations for different initial laser phases plotted as a function of time. (b) Dependence of final kinetic energy on the initial phase.

The maximum energy gain is obtained around 60 degrees as shown in Fig. 3(b). These properties are strongly depending on the longitudinal length of the cavities and the iris. The modelling of the 1.5-cell gun has not been well optimised in this work because such a gun designing is also depending on the RF field distribution and strength.

A laser spot profile of 2 mm-ϕ and the flat distribution of the intensity are assumed. A longitudinally Gaussian distribution of 20 ps-FWHM is employed for incident photoelectron production. Since the thermal emittance of the incident is not significant [4], we have not included it at the moment.

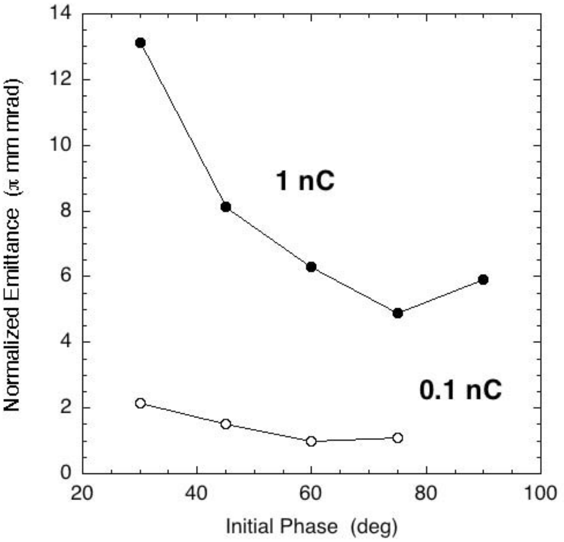

Figure 4: Normalized emittance obtained from the simulation for total bunch charges of 1 nC and 0.1 nC.

The minimum emittance of ~ 5 π mm mrad for the 1nC beam was obtained at the initial phase around 70 deg. On the other hand, a very low emittance of 1 π mm mrad was found to be obtained for the low charge bunch. These results of the simulation are not much different from another simulation result [5].

WAKE-FIELD AND BEAM LOADING

Since the FDTD calculation gives a self-consistent electromagnetic field with proper boundary condition, to extract the wake field induced by the bunched beam is very interesting

Longitudinal Wake

On-axis longitudinal wake field E_Z is shown in Fig. 5. Strength of the wake field is proportional to the beam current in the frequency domain and the impedance spectrum of the gun. Consequently the longitudinal shape of the beam bunch is essential for the wake field. We have, however, not examined yet other shapes of the electron distribution.

From Fig. 5, we can see at the beginning of the acceleration the longitudinal wake on the rear part of the bunch is relatively large. After the bunch passed through the gun, the wake field still remain. This is a quite important fact particularly for thermionic RF guns.

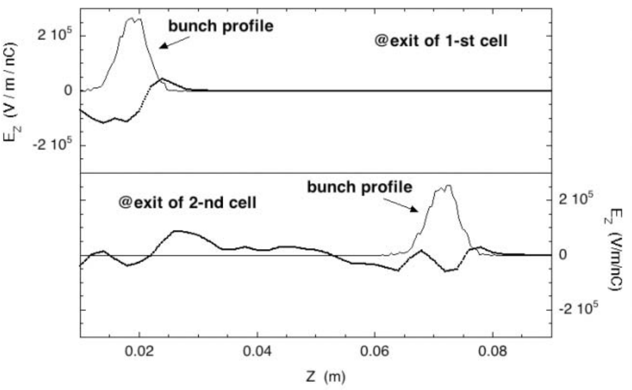

Figure 5: On-axis longitudinal wake field at the exit of each cavity. The strength of the wake field is found to be almost proportional to the bunch charge.

Effect of the on-axis longitudinal wake field is, however, not so significant for the bunch length and the relative energy spread. The simulation result implies there are not big differences between the 1nC charge case and the 0.1 nC one. In Fig. 6, the bunch length and the relative kinetic energy spread at the gun exit for the total bunch charge of 1 nC are shown.

The minimum energy spread is possibly obtained around the same initial laser phase for the minimum emittance as shown in Fig. 4.

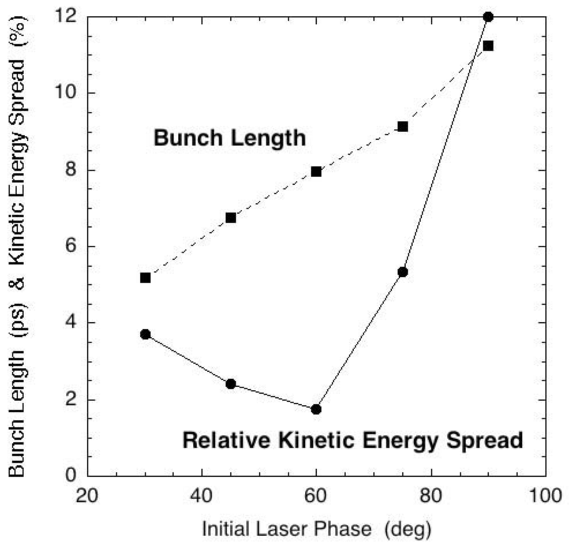

Figure 6: RMS bunch lengths and relative kinetic energy spreads plotted as a function of the initial laser phase. Note, the RMS laser pulse length is 8.49 ps (20 ps-FWHM).

Transverse Wake

The transverse wake field is shown in Fig. 7. Since the transverse electric field does not exist on the axis, so that the wake field shown in Fig. 7 is apparently one of the sources of non-linear space charge force that is not able to be compensated by an external solenoid magnetic field.

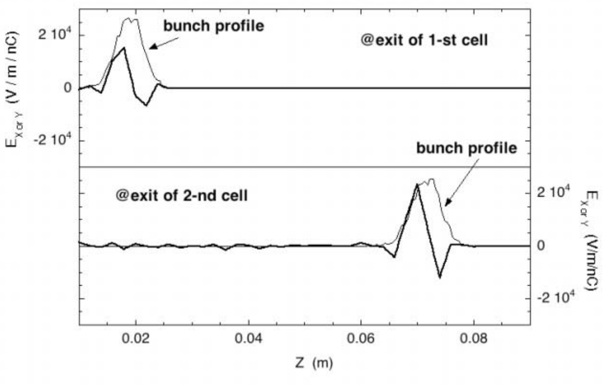

Figure 7: On-axis transverse wake field at the exit of each cavity. Other transverse modes might be not excited by the beam bunch

Effects of transverse non-linear RF fields have been well studied so far [6]. Although the presented results of the simulation using the FDTD method may have poor accuracy because of the large cubic grid, these non-linear properties for the beam dynamics will be very important for further development of the RF gun.

SUMMARY

We have developed a 3-D time dependent Maxwell's equation solver for the study of the beam dynamics in the RF gun. At the moment the accuracy of the calculation is inevitably poor. However our purpose is not a detailed design of the gun. In a future project of synchrotron radiation facility at Tohoku University, we are going to employ a thermionic RF gun to extend performance of a pre-injector linac [7]. However as mentioned previously the study of the beam loading effect is very significant to improve the beam quality from the thermionic RF gun, which may be much more complicate numerical simulation than that of the photo injector.

We are now installing an RF gun for cold tests. Along with experimental work, we will develop further performance of the 3-D simulator code. In the low energy regime, a simulation study for coherent synchrotron radiation in a bunch compressor is of course possible. It is quite interesting to design over-all feature of the injector part for the advanced linac.

In addition, for the circular accelerators, the ring impedance is also able to be estimated by the code, which may be very important work for construction of a new 3-rd generation light source.

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