SPACE CHARGE EFFECT FOR ROTATION OF LONGITUDINAL PHASE SPACE IN ALPHA MAGNET *

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Abstract

Combined use of thermionic RF gun and alpha ($\alpha-$) magnet seems to be very much effective for production of sub-picosecond bunch length in a compact linac system [1]. In this bunch compression scheme, the α-magnet plays a significant role for controlling particle distribution in the longitudinal phase space. However space charge effects as well as wakefields in the α-magnet have not been well studied. We discuss significant distortion of the particle distribution in both the longitudinal and the transverse phase spaces, which are coupled in α-magnet, by showing numerical simulations employing finite difference time domain (FDTD) method to solve time-dependent Maxwell's equations [2].

INTRODUCTION

Sub-picosecond electron pulse will be valuable in ultra-fast pulse radiolysis experiment for radiation chemistry, and also equally short X-ray pulse can be produced via Compton backscattering. In addition, compression of the electron pulse to a few hundreds femtosecond without emittance deterioration is crucial for SASE-FELs as well. Accordingly various schemes of bunch compression have been studied. Usually magnetic chicane is used as a bunch compressor for energy chirped electron bunches manipulated by RF conditioning, i.e., off-crest acceleration in a linac. However this scheme makes the system larger, and then a compact system with relatively low energy beam requires another compression scheme.

Thermionic cathode for the RF gun is quite attractive for the compact linac system because of stability, multi-bunch operation, and cheaper cost. The beam extracted from the thermionic RF gun is characterized by its energy-temporal correlation. Though considerable amount of the charge is concentrated into the head of the pulse, higher energy electrons exit earlier than lower ones. As for usual thermionic RF guns, the velocity of the beam is still lower than the speed of light, so the beam pulse is simply stretched in travelling drift spaces allocated after the gun. Therefore the α-magnet is employed so as to rotate the longitudinal phase space and then proper particle distribution at the inlet of the linac can be manipulated, which is schematically shown in Ref. [3].

Because the curvature of beam trajectory in α-magnet is very small, effects due to space charge and/or wakefield may be considerably large. Since evaluation of the space charge effects using conventional method (converting the Coulomb interaction between particles into the laboratory frame) is not simply effectual for the non-relativistic particles and bended trajectory, we have to be cautious of using usual simulation codes for the accelerator beams.

To investigate the electromagnetic effect for the beam dynamics, a numerical beam simulation code using the FDTD method in 3-D space has been developed which contains evolution of a field induced by the beam [2]. In this article, we report on the results of a simulation study for the beam dynamics in the α-magnet and discuss characteristics of bunch compression.

A MODEL OF THERMIONIC RF GUN

A high R/Q structure of the cavities shown in Fig. 1 has been chosen for the RF gun, which has been developed at National Synchrotron Radiation Research Centre, Taiwan [4]. The gun consists with 1.5 cells with nose cones and the resonant frequency of both cavities is adjusted to be 2.998 GHz. Assuming to employ a Tungsten-dispenser cathode having a diameter of 6 mm, an emission current of 3 A is used in further simulations.

As shown in Fig. 1, the maximum electric field on the cathode surface and that at the centre of the 2nd cathode are 31 and 74 MV/m, respectively, which allows the gun to produce the beam having the maximum energy around γ = 6. The temporal structure of the extracted beam is shown in Fig. 2. Approximately 32% of electrons emitted

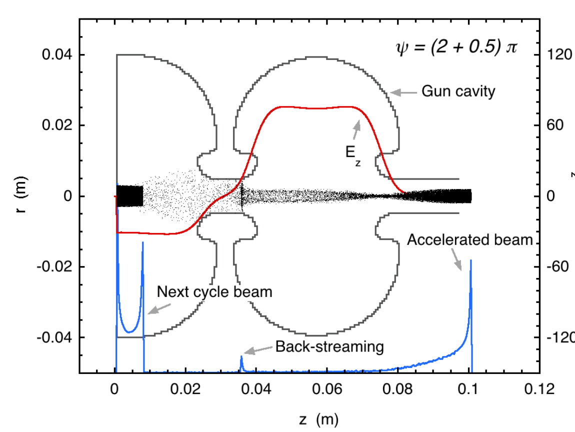

Figure 1: Cavity structure of a model RF gun. The longitudinal electric field is shown by red line. Snap shot of the particles is shown by dots, in which back streaming electrons are contained, and projected particle distribution is also shown (blue line). The beam extracted at the following RF cycle is seen.

*Work supported by Grant-in-Aid for Scientific Research (S), the Ministry of Education, Science, Technology, Sports and Culture, Japan, Contact No. 20226003.
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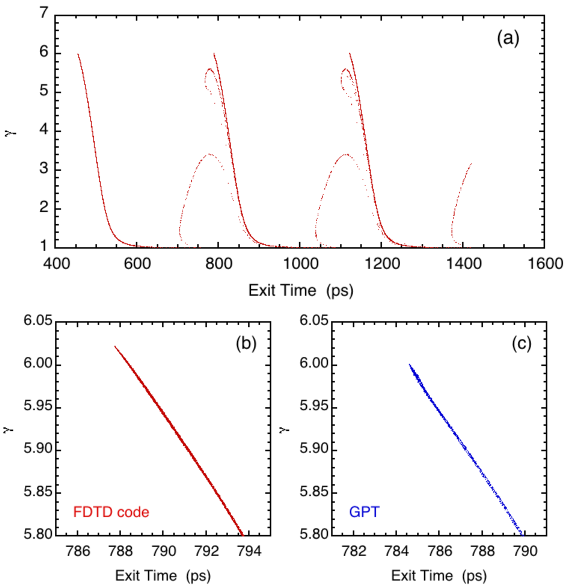

Figure 2: (a)Temporal structure of the extracted beam for three successive RF cycles. Particle distributions around the top energy are shown in lower figures. (b)Resulted from the FDTD code, and (c)that from GPT. Note the input geometry data of the gun are not completely identical.

from the cathode during a half RF cycle are extracted from the gun. A charge of 40 pC is found in an energy region of 2 % from the top energy. Though this amount of charge is not considerably large, the space charge effect can be seen on the particle distribution in the longitudinal phase space. Particularly the effect appeared clearly in the simulation result of GPT.

BEAM SIMULATION IN ALPHA MAGNET

Role of the α-Magnet

For the beam simulation in the alpha magnet, a 10 cm-long drift space is put after the RF gun to connect with an α-magnet because of consideration for an actual injector apparatus. The electron distribution in the phase space is also varied during passing through the drift space, so we have simulated it in advance to prepare a beam data of 6-dimensional phase space for study of the α-magnet. The particle distributions in the horizontal and the longitudinal phase spaces are shown in Fig. 3(a) and (b), respectively. Because of the space charge effect, the normalized transverse emittance grows from 1.7 to 3.1 π mm mrad, which are deduced for the electrons in the energy region of 2 % from the top energy (here we call "40 pC bunch"). However as one can presume from the Fig. 3(a), the slice emittance is not much changed.

What we expect as a role of the α-magnet is not bunch compression itself. The beam velocity is still lower than the speed of light as mentioned previously, the highest

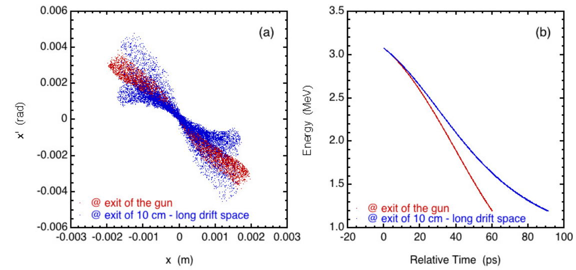

Figure 3: (a)Transverse particle distributions of the head part of the beam containing 40 pC charge and (b) longitudinal ones of almost whole beam. Red and blue dots denote that at the gun exit and the end of the drift space, respectively.

and the lowest ones are $\beta = 0.98611$ and 0.98557 in the 40 pC bunch, respectively. Relative time difference between those particles increases by ~ 200 fs/10 cm. If the distance between the α-magnet and the linac entrance is 1 m, the 40 pC bunch is lengthened to at least 2 ps, when the bunch is compressed to be the minimum at the exit of the α-magnet. Therefore the strength of the magnetic field in the α-magnet has to be optimized by taking the geometry of the injector system into account. In this sense, the α-magnet is so to speak "phase space rotator" rather than a bunch compressor.

Particle Motion in the α-Magnet

Snapshots of the beam motion in the α-magnet are shown in Fig 4. In the simulation, we have assumed a perfect field of a half of the quadrupole. In this case, the horizontal phase space of the exiting beam should be almost same as the mirror symmetric of the entering beam if the beam size is sufficiently small.

In the vertical plane, the filed on the beam trajectory in

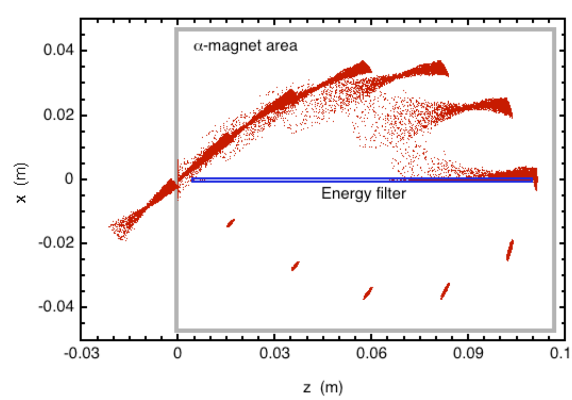

Figure 4: Snapshots of the beam in the α-magnet plotted on the horizontal-longitudinal (x-z) plane. The field gradient is 2.7 T/m. A metal plate in the chamber scrapes the low energy part of the beam, which is working as an energy filter. Here it is put so as to make the 40 pC bunch remains.

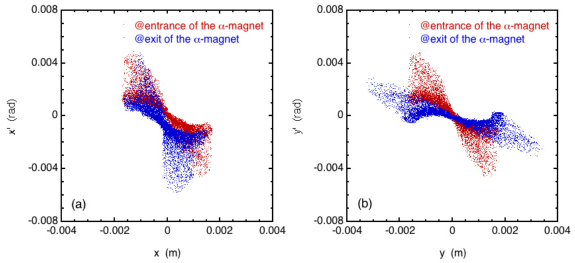

Figure 5: (a)Horizontal phase space distribution of the 40 pC bunch at the entrance and the exit of the α-magnets. (b)Those for the vertical plane.

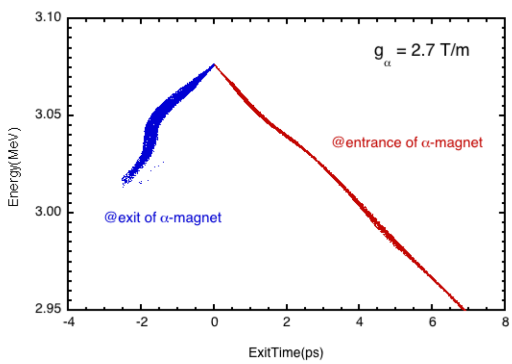

Figure 6: Longitudinal particle distributions of the beam at the entrance and the exit of the α-magnets.

the α-magnet has some defocusing force. The transverse particle distributions at the entrance and the exit of the α-magnet are shown in Fig 5. One can see that the center of gravity of the beam distributions in the horizontal plane is a bit shifted. We have found that this phenomenon resulted from the finite beam current, and is not coming from the numerical error.

Emittance growth was seen in the horizontal plane such as from 3.2 to 3.8 π mm mrad, meanwhile there was no significant difference in the vertical plane. This result of the horizontal emittance growth is smaller than we expected. The particle distributions in the longitudinal phase space are shown in Fig. 6. The phase space is successfully rotated. One notices that the particle distribution got wider after passing through the α-magnet, which is conceivably coursed by the space charge.

In an α-magnet, the space charge effect may be much more complicated because the transverse motion and the longitudinal one are coupled together [5].

SUMMARY

We have investigated the space charge effects for the beam phase spaces in the α-magnet using a 3-dimensional FDTD simulation. Taking the velocity difference of the electrons in a bunch into account, the α-magnet is nothing but a longitudinal phase space rotator. Accordingly the bunch is not much compressed along the beam orbit in the α-magnet, so that the emittance growth is not significant. This conclusion is quite acceptable for the bunch compression scheme employing velocity bunching in the linac structure [4, 6].

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