SPACE CHARGE EFFECT FOR SHORT ELECTRON BUNCHES IN AN ALPHA MAGNET*

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Abstract

Sub-picosecond electron pulse with relativistic energy may perform a source of coherent synchrotron radiation in terahertz (THz) frequency region [1]. In addition, such short pulse will be used directly in pulse radiolysis experiment for radiation chemistry, and also equally short X-ray pulse can be produced via Compton backscattering. On the other hand, compression of the electron bunch to a few hundreds femtosecond is crucial for SASE-FEL, accordingly various schemes of bunch compression have been studied [2]. Usually magnetic chicane is used as a bunch compressor for energy chirped electron bunches manipulated by RF beam-conditioning, i.e., off-crest acceleration in accelerator structures. However this scheme makes the system large, and then relatively low energy and compact system require another compression scheme. Combined use of RF gun and α-magnet seems to be very much effective for production of sub-picosecond bunch length in a compact injector system [3]. Nevertheless space charge effects including wakefield in α-magnet have not been well studied. In this paper we discuss emittance growth in both the longitudinal and the transverse phase spaces (actually those are coupled in α-magnet) by showing numerical simulations employing finite difference time domain (FDTD) method for a Maxwell's equation solver [4].

INTRODUCTION

Accelerator based light source for THz frequency region will be a powerful tool in various scientific fields. Particularly beam pulses shorter than the wavelength seems to bring unique applications. Short THz pulses of coherent synchrotron radiation (CSR) from sub-picosecond electron bunches is linearly polarized and "half-cycle" pulse. In chemical photo-reactions, the electronic state of molecules is pulled or pushed toward one direction by such a short pulse in a reaction time. If the electric field of the THz pulse is sufficiently strong, abnormal ionization process is conducted, and then novel reactions are possibly executed to create new functional molecular. As an intense narrowband source, pre-bunched THz free electron laser is another interest in making use of the sub-picosecond pulse. From theoretical study so far, the pre-bunched THz FEL is considered to have higher gain than that of conventional FELs with same amount of FEL parameter, and there is a possibility to produce very short FEL pulses [5].

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A compact THz light source based on sub-picosecond electron pulses has been developed at Laboratory of Nuclear Science, Tohoku University, Japan, to supply THz lights for both fundamental and applied sciences. Even if we employ CSR and/or FEL, the light source may be characterized mainly by ability of the electron pulse. In particular how much shorter the bunch length can be achieved is crucial for performance limit of light source. Because the curvature of beam trajectory in α-magnet is very small radius, effects due to space charge or wakefield may be considerably large.

To evaluate effect for the beam dynamics, a numerical beam simulation code using FDTD method in 3-D space has been developed which contains evolution of electromagnetic wave induced by the beam. The code can be basically applied for simulation for RF guns. Although a couple of simulation codes have been widely used for strategic design of accelerators, it seems that validity for the space charge effects has not well established yet. In this note, we report on the results of a simulation study for the beam dynamics in α-magnet and discuss characteristics of bunch compression.

ITC-RF GUN

Electron distribution in the longitudinal phase space of the beam extracted from a thermionic RF gun is generally well suited for bunch compression. Independently tunable cells RF gun (ITC-RF gun) is specially dedicated to create optimized longitudinal phase space for bunch compression [6].

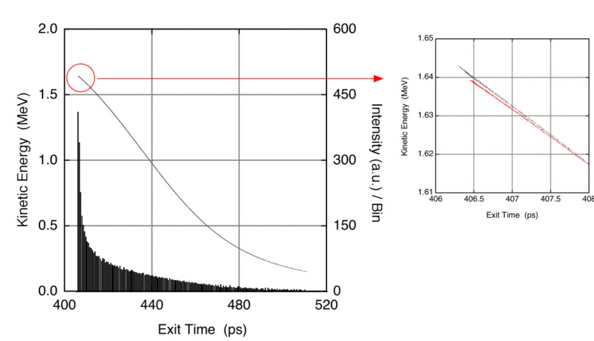

Figure 1: Longitudinal phase space distribution of the beam produced by the ITC-RF gun. Emission current of the cathode is 50 A/cm^2. Maximum electric fields are 25 MV/m and 70 MV/ m for the 1-st cell and the 2-nd cell, respectively. An RF phase between the cells is π + 24 deg. (right) Expanded head of the beam. Red dots indicate the case of no space charge effect (zero-current case).

The ITC-RF gun is consisted with two independent power-feeding cavities, so that the longitudinal phase space can be manipulated by choosing appropriate power ratio and phase. Single crystal LaB_6 cathode is employed to minimize the transverse emittance, whose diameter is 1.9 mm. Figure 1 shows an electron distribution in the longitudinal phase space simulated by a code employing 3-D FDTD method. Gathering the electrons having kinetic energy larger than 98 % of the top energy, normalized transverse emittance is deduced to be ~ 0.75 π mm mrad and a total charge is ~ 25 pC.

SPACE CHARGE EFFECT IN A DRIFT SPACE

As a first step to understand how the space charge effects work on electron motion at a relatively lower energy region around 2 MeV, evolution of the 6-dimensional phase space of the beam in a drift space was simulated by the computer code employing 3-D FDTD method. The length of the drift space has been chosen to be 0.1 m. Even such a short distance, emittance growths in both transverse and longitudinal directions is considerably induced by the space charge as shown in followings.

Table 1: Initial beam parameters for the simulation in a drift space

Top beam energy	2.15 MeV (total energy)
Energy width	2 % from the top energy (flat distribution)
Rms bunch length	100 fs (Gaussian)
Norm. rms emittance	1 π mm mrad (Gaussian)
Twiss parameters	β = 1 m, α = 0
Bunch charge	0, 20, 100 pC
*Chamber dimension	0.10 × 0.02 × 0.02 (m)

*Perfect conducting material.

Transverse Motion

Transverse phase spaces after passing through the drift space are shown in Fig. 2. Because of the short drift space, the phase space distribution at 0 pC is not much different from the initial one.

Kick due to the space charge is clearly seen, and there should be nonlinear force, which causes the emittance growth. At a higher charge case such as 100 pC, the normalized emittance reaches 10 π mm mrad. Though the emittance growth is, of course, depending on the transverse beam size, bunch compression at the lower energy seems to be pretty dangerous.

Longitudinal Motion

Since the electron velocities at such a lower energy do not reach the one of the light, the drift space stretches the bunch. A transport line from the bunch compressor to an accelerating structure should be designed carefully for minimization of this de-bunching effect.

As one can seen in a phase space at the higher current, the pull and push space charge effect is not completely symmetric because of interaction with a wakefield. In addition, the average energy is a bit lower than the initial one (- 0.025 MeV for the 100 pC case). The most serious matter should be addressed for generating femtosecond high energy electron pulses is that once the bunch is compressed to very short in the lower energy range, the beam acceleration has to be performed immediately to preserve the bunch length.

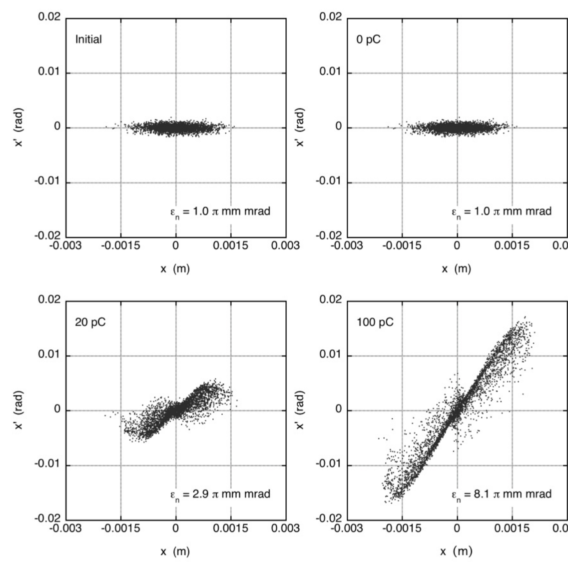

Figure 2: Horizontal phase spaces after passing through the 0.1 m long drift space for various bunch charges. There is no obvious difference in vertical phase spaces.

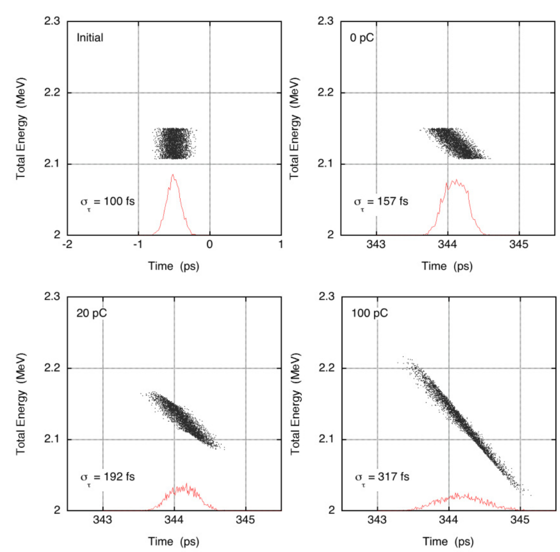

Figure 3: Same as Fig. 2 but for the longitudinal phase space.

SPACE CHARGE EFFECT IN AN α-MAGNET

From the simulation study of the extreme short bunch in a drift space presented in the previous section, the space charge effects act significantly on the beam dynamics when the beam energy is lower. In an α-magnet the effects may be more complicate because the transverse motion and the longitudinal one are coupled together [7]. It must be worthy investigation if the space charge effects are evaluated systematically. It is not sure whether the space charge in the 3-dimensional space can be treated properly (for example PARMERA can treat it only in the cylindrical polar coordinates). Since the FDTD method based on the time dependent Maxwell's equations can calculate evolution of the electromagnetic field self-consistently with a certain boundary condition, there is no contradiction logically. However computing error coming from lattice (or grid) size cannot be ignored, so that we should examine the simulation results carefully.

As shown in Fig. 1, a liner correlation can be seen in the longitudinal phase space for the beam extracted from the thermionic RF gun. In order to simplify the model for the simulation, here we have chosen uniform distributions in both axes. The initial bunch length of 5 ps covers an energy width of 2 % from the top energy.

Table 2: Initial beam parameters for the simulation in an α-magnet

Top beam energy	2.15 MeV (total energy)
Energy width	2 % from the top energy
Bunch length	5 ps
Norm. rms emittance	1 π mm mrad (Gaussian)
Twiss parameters at the entrance of α-magnet	β = 1 m α = 0
Bunch charge	0, 20, 100 pC
*Chamber dimension	$0.07 \times 0.05 \times 0.02^{t}$ (m)

*Perfect conducting material.

We have chosen the field strength of the α-magnet so as to which the bunch is compressed to the maximum at the exit of the α-magnet including no space charge effects (zero bunch charge), and that is 6.27 T/m. Figure 4 shows the initial electron distribution and a beam trajectory in the α-magnet. One can see the electron density is rapidly increasing after passing the middle of the route. Because the beam trajectory is not straight line, the space charge effects may not work as the previous case of the drift space. It apparently seems to be interaction with coherent synchrotron radiation rather than the space charge effects.

Transverse Motion

Horizontal (deflecting plane) and vertical phase space distributions at the exit of α-magnet are shown in Fig. 5 and Fig. 6, respectively. There are significant differences between the horizontal and the vertical ones.

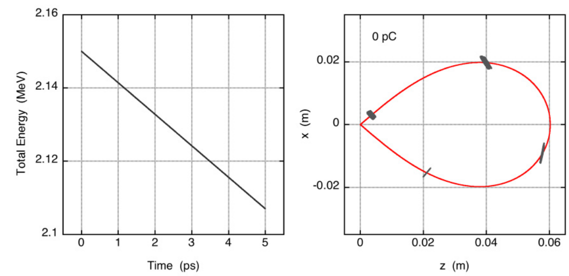

Figure 4: (left)Initial longitudinal phase space for the simulation. Uniform particle distribution is employed. (right)Trajectory of a particle located on the middle of both the time and the energy (red line). Evolution of two-dimensional beam profile in the α-magnet is shown by black dots.

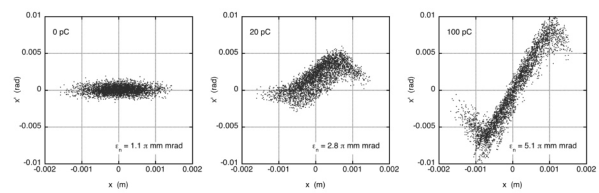

Figure 5:Horizontal phase spaces at the exit of the α-magnet for various beam charges. At the moment it is not clear why the center of gravity of horizontal momenta is not zero at the bunch charge of 20 pC.

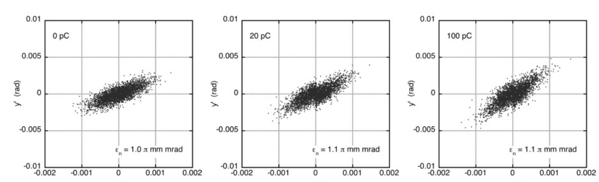

Figure 6: Vertical phase spaces at the exit of the α-magnet for various beam charges.

The horizontal phase space is disordered, which is nearly same as that of the drift space. On the other hand, the vertical phase space is not so much distorted. Though there is small kick in the vertical direction, no obvious emittance growth can be seen.

Longitudinal Motion

The space charge effects for the longitudinal phase space are shown in Fig. 7. For the bunch charge of 0 pC, a deduced rms bunch length is 5.5 fs, which is coming from higher order dispersions in the α-magnet and a coupled term with the transverse motion. Regardless of the finite bunch length, the bunch is ideally well compressed.

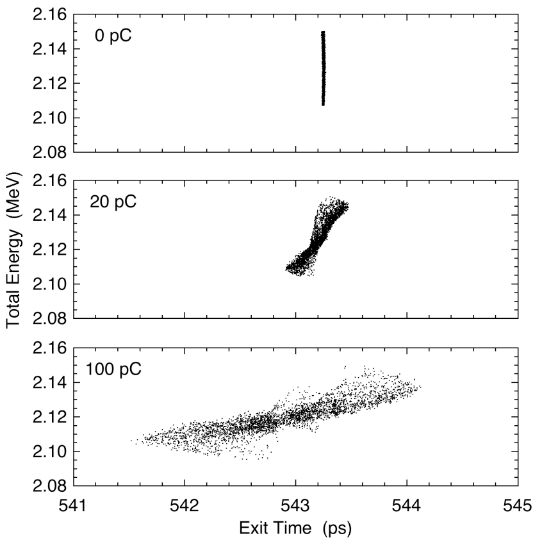

Figure 7: Longitudinal phase spaces at the exit of the α-magnet for various bunch charges.

Bunch lengthening due to space charge seems to be much different from the case of the drift space. As shown in Fig. 3, "push and pull" effect is quite acceptable as an effect of space charge. However a noteworthy trend can be seen in Fig. 7 is that the lower energy part exits from the α-magnet earlier and the higher energy one takes longer time to pass through. This is a distinctive effect of space charge in bended trajectory.

Corrected Bunch Compression

By increasing the field gradient of the α-magnet, optimum bunch compression can be obtained. Figure 8 shows the longitudinal phase spaces at the shortest bunch length. Field gradients for the bunch charges of 20 pC and 100 pC are 7.40 and 11.3 T/m, respectively. Though the bunches were successfully compressed, normalized horizontal emittances increased to 3.5 and 13.9 π mm mrad, respectively.

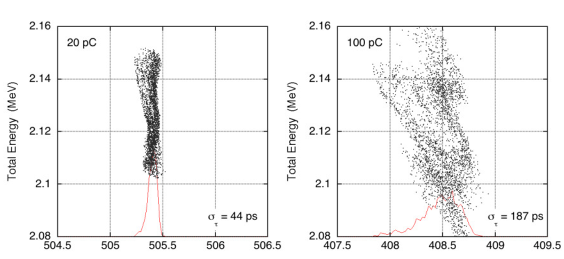

Figure 8: Corrected longitudinal phase spaces for bunch charges of 20 pC (left) and 100 pC (right).

SUMMARY

The space charge effects for the electron phase spaces in the α-magnet are investigated by using the 3-D FDTD simulation. Emittance growth in both the horizontal and the longitudinal space is considerably large even low bunch charge such as 20 pC. The space charge effects for the longitudinal phase space are significantly different from that in the drift space.

In the beginning of the project a compact triple-bend achromat system was considered as a bunch compressor containing nonlinear magnets such as sextupoles to compensate higher order dispersion functions [8]. That was finally concluded to be very dangerous for the space charge effects due to longer straight sections, so that we have switched to the α-magnets. However the space charge effects in the α-magnet are still obstacle to compression of the low energy beam. In order to achieve a very short electron pulse, further investigation on the space charge effects is required.

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