INVESTIGATION OF CSR EFFECT FOR FEMTOSECOND ELECTRON BUNCHES IN AN ISOCHRONOUS ACCUMULATOR RING*

N.Y. Huang#, H. Hama, M. Kawai, S. Kashiwagi, F. Hinode, K. Nanbu, T. Muto, Y. Shibasaki, I. Nagasawa, K. Takahashi, Electron Light Science Centre, Tohoku University, Japan

Abstract

Coherent synchrotron radiation (CSR) from a novel isochronous ring is a candidate for light source that provides THz radiation with high average flux. A compact isochronous accumulator ring (IAR) for the maximum beam energy of 54 MeV has been designed so as to eliminate the 0th order momentum compaction factor, and the 1st order of it is mostly compensated [1]. In addition, the path length deviation due to betatron motion is mostly compensated in a cell. Though there is no RF cavity in IAR, the injected beam may circulate for certain number of turns. Multi experimental stations can be allocated like synchrotron radiation facilities. However, it has been well known that instability due to the CSR wake field is an issue for the beam stability in the ring operated at low alpha mode [2]. Therefore, a study for effects of the CSR wake on the bunch length and shape in IAR has been in progress. It has turned out that the maximum longitudinal field strength created by CSR would be ~ 0.15 MV/m for the case of 100 fs Gaussian bunch, which is considerably an intense field. To protect the bunch shape from the CSR wake, further study is definitely required.

INTRODUCTION

A test accelerator system for high intensity THz radiation source, namely t-ACTS program, has been developed at Tohoku University, Sendai. In addition to the IAR, we have also constructed a long period undulator which will be served as a narrow band THz source. A 50 MeV injector linac consists of a thermionic RF gun equipped with a small size cathode of single crystal LaB_6, an alpha magnet and a 3 m S-band traveling-wave accelerating structure. An RF power from a 50 MW klystron is distributed to two cells of the RF gun and the accelerating structure. Pulse train of very short bunches will be produced by means of velocity bunching [3]. In order to reach sufficient form factor (~ 0.7) for production of CSR in the THz frequency region, the bunch length less than 30 μm (100 fs) is required. Passing through the α-magnet, the longitudinal phase space of the energy-filtered bunch is manipulated. Because of non-relativistic beam energy, the bunch injected onto near zero-cross rf phase of linac slips in the RF field. Therefore, its longitudinal phase space distribution is rotated at the early time in the accelerating structure. Consequently, the bunch length is shortened and accelerated simultaneously. We have anticipated the micropulse train of sub-picosecond bunch length is possibly produced in our injector system.

DETAILED OPTICS OF ISOCHRONOUS ACCUMULATOR RING, IAR

Lattice of IAR

Introducing inverted bends (IBs) in a unit cell, the control of the momentum compaction factor and then the bunch length was successfully achieved on a synchrotron light source, New-SUBARU [4]. Although reducing the momentum compaction factor is possible in a simple double-bend achromat (DBA) lattice. However, the dispersion-free straight section between the cells is violated. Meanwhile by inserting the IB into the center of DBA cell, the dispersion function at the IB is easily controlled independently. Therefore, the momentum compaction factor can be varied without significant change of the lattice property.

The schematic layout of IAR is shown in Fig. 1. The lattice of the IAR is consisted with 2-folded 4 DBA cells, thus the bending angle in one cell is 90°. One ordinary bending magnet deflects the beam by 50° and the IB deflects -10°. Two 2.32 m-long straight sections are used for on-axis beam injection and beam diagnostics or insertion for future progress. There are two families of sextupoles in the cell, which are not only used for the correction of the chromaticity but also the 1st order dispersion. Although the RF cavity will not be used in IAR operated as a THz radiator, however for future feasible application as a storage ring, harmonic numbers are adjusted to be 160 and 28 for the corresponding RF frequencies at 2856 MHz and 500 MHz, respectively (circumference is 16.8 m). The lattice functions are shown in Fig. 2, and some ring parameters are listed in Table 1.

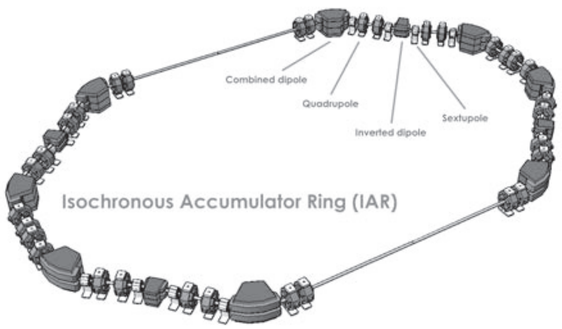

Figure 1: Isochronous accumulator ring (IAR) in the t-ACTS facility.

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#nyhuang@lns.tohoku.ac.jp (on leaving from Institute of Photonics Technologies, National Tsing Hua University, Taiwan)

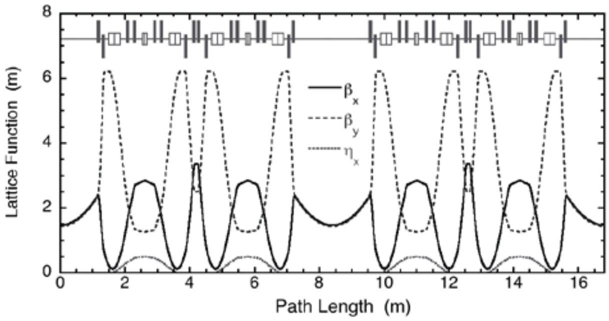

Figure 2: Lattice functions of entire IAR. Magnet configuration is also shown.

Table 1: Parameters of IAR

Nominal beam energy	E	54 MeV
Circumference	C	16.7951 m
Betatron tune	(ν_x, ν_y)	(4.14, 1.21)
Natural chromaticity	$(\xi_x, \xi_y)^{nat}$	(-5.47, -10.0)
Corrected chromaticity	$(\xi_x, \xi_y)^{cor}$	(-0.05, -0.05)
0th momentum compaction	α_0	0.00000155
1st momentum compaction	α_1	-0.00640
2nd momentum compaction	α_2	2.03
Normal bending radius	ρ^n	0.4 m
Normal bending angle	θ^n	50º
Inverted bending radius	ρ^i	-0.8 m
Inverted bending angle	θ^i	10º

Arc Section of IAR

Since the nominal energy of IAR is 54 MeV and the bending radius of the regular bend is 0.4 m, the critical wavelength is ~ 1.4 µm, which is sufficiently short for coherent radiation enhancement at the THz frequency region. When the Gaussian bunch length is 100 fs (30 µm), the form factor of the bunch around 1 THz (300 µm) is ~ 0.7. Expected photon number from the regular bending magnet is ~ 10^{20}/mrad^2/0.1%-b.w./bunch where the bunch charge of 20 pC is assumed [5]. Because of a short pulse train will be produced from the thermionic RF gun, the average THz power may be considerably high. Additionally, the pulse train can circulate in the IAR, the average CSR power will be further enhanced.

In order to keep the bunch length during circulation, the 1st order of momentum compaction factor is corrected by the sextupoles. Nevertheless the tracking simulation has indicated the maximum number of possible turns is ~ 100 since the 2nd order of it is a bit large. To improve this, we already found the octupoles put into the long straight section can eliminate the 2nd order dispersion significantly. We have, therefore, thought the most serious obstacle for multi-turn must be CSR itself, namely the CSR wake.

ESTIMATION OF CSR-WAKE IN BENDING MAGNET

Estimation of 1-D CSR Field

The CSR wake has been well studied for particularly chicanes in XFEL linacs [6, 7]. A simulation code ELEGANT is well known to simulate the particle motion under the 1-D CSR wake [8]. Here we estimate strength of the CSR wake in the regular bending magnet in IAR by using the analytical 1-D equation for arbitrary line-charge distribution [6]. Because the beam energy in IAR is relatively lower and the bending radius is much smaller than those of XFEL linacs, we have been not sure validity of the 1-D line charge model.

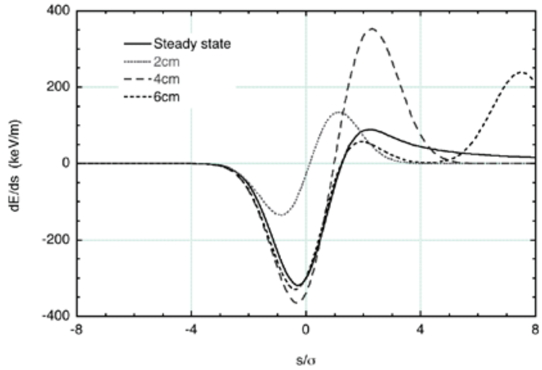

Figure 3: Longitudinal 1-D change rate of the electron energy plotted as a function of relative path length normalized to the bunch length.

According to the Saldin's paper, energy change per unit length for the Gaussian line-charge in a dipole with the bending radius R is expressed as

$$\frac{dE}{ds} = -\frac{2e^2 N}{3^{1/3}\sqrt{2\pi}} \frac{G(\xi,\rho)}{R^{2/3}\sigma^{4/3}} , \tag{1}$$

where σ is the bunch length and N is the number of electrons in a bunch. The function G is

$$G(\xi,\rho) = \rho^{-1/3}\left[e^{-(\xi-\rho)^2/2} - e^{-(\xi-4\rho)^2/2}\right] + \int_{\xi-\rho}^{\xi} \frac{d\xi'}{(\xi-\xi')^{1/3}} \frac{de^{-\xi'^2/2}}{d\xi'}, \tag{2}$$

where $\xi = s/\sigma$, $\rho = R\phi^3/24\sigma$, and ϕ is deflected angle. When ϕ is sufficiently large, G becomes steady state.

In Fig. 3, dE/ds at different path length from the entrance of the regular bend and that at steady state are shown, where the bunch length and the bunch charge are 100 fs and 30 pC, respectively. Note the total path length in the regular bend is 35 cm. For this short bunch length the steady state may be established at early stage. The mean energy loss for the entire bunch is written as

$$\frac{d\langle E\rangle}{ds} = -\frac{e^2 N}{R^{2/3}\sigma^{4/3}} \frac{\Gamma(5/6)}{6^{1/3}\sqrt{\pi}} \sim 187\ keV/m. \tag{3}$$

Accordingly the bunch may lose the energy of 65 keV in one regular bend, which is over 0.1 % of the initial beam energy.

Development of Floating Boundary 2-D FDTD Simulation Code

In order to investigate the CSR effect for not only the longitudinal dynamics but also the transverse one, we have developed a 2-D FDTD (finite difference in time domain) code [9]. To describe the electric field having high frequency component, the mesh size has to be sufficiently small. However, the space involved for simulation is very wide as compared with the mesh size. Alternatively, we have introduced a floating boundary method to reduce the area of calculation for realistic cpu time and memory size. As a test simulation, we have employed following parameters; the beam energy of 54 MeV, the bunch length of 1 mm, the horizontal beam size of 1 mm, the mesh size of 40 μm for both x and z direction, the time interval of 40 μm/c/3, the bunch charge of 1 nC/m and the number of macroparticle is 30,000. Since the bunch form factor of nearly 1 is obtained around at wavelength of 3 mm or longer, this mesh size is enough for describing the CSR wake.

As the initial condition, the bunch is moving along the z-axis wearing a non-radiative Coulomb field, which is given by the Lorentz transformation of static field. The Mur's 1st order absorbing wall is employed for the boundary condition. This initial condition is really important to obtain physical appropriateness of the simulation. After the bunch center is reaching the entrance of the bending magnet, the area to be calculated is shifted toward the z-direction to keep the bunch in the simulation space. At present the mesh shift is conducted in only the z-axis.

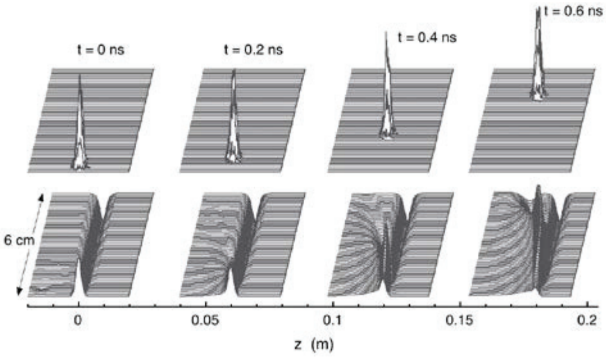

Figure 4: Snapshots of horizontal electric fields and the locations of the electron bunch in the bending magnet calculated by the floating boundary FDTD. The entrance of the magnet is set as $z = 0$. At the beginning only the non-radiative Coulomb field can be seen and then CSR arises.

In Fig. 4, 2-D snapshots of x-component of the electric field and the bunch charge distribution are presented. Derived longitudinal CSR field is shown in Fig. 5. Since the bunch length is rather long, the steady state is not yet established even at path length 24 cm from the entrance. Although overall trend of the CSR wake is quite acceptable, details are much different from the Saldin's formula. At present, we have been checking the accuracy of the FDTD code, and further improvement will be surely required.

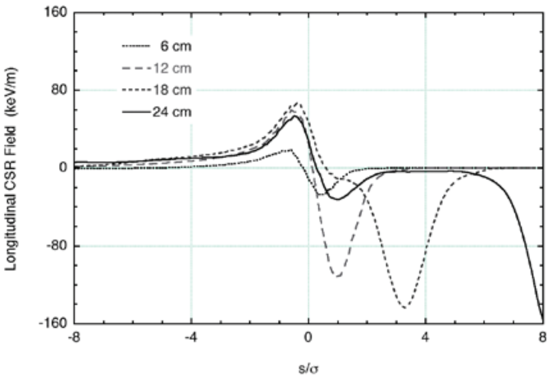

Figure 5: Longitudinal CSR wake field resulted from the floating boundary 2-D FDTD simulation.

SUMMARY AND PROSPECT

A novel accelerator-based light source, t-ACTS, has been developed at Tohoku University. Combined use of a thermionic RF gun injector and velocity bunching technique, short-bunch train will be produced to provide THz radiation with high average power from an isochronous accumulator ring. Although the bunch charge is relatively low (20 ~ 30 pC), the CSR wake is considered to be obstacle for stable circulation in the ring. Using the 1-D CSR formula, the energy loss in a bending magnet is expected to be ~ 0.1% of the initial beam energy which is considerably large. For detailed study of the CSR wake, we have been developing a floating boundary FDTD code.

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