COHERENT SYNCHROTRON RADIATION SOURCE BASED ON AN ISOCHRONOUS ACCUMULATOR RING WITH FEMTOSECOND ELECTRON BUNCHES*

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Abstract

A compact isochronous accumulator ring has been studied as a source of coherent synchrotron radiation (CSR) at a wavelength region from THz to GHz. Since thermionic RF gun is substantially stable in general, we anticipate a bunch train of very short electron pulses can be provided satisfactorily by means of velocity bunching [1]. Careful numerical simulations show feasibility of the sub-100 fs bunch. The THz-CSR of high average power will be achieved if the short bunches can be circulated in the accumulator ring without bunch lengthening. This paper will describe the optimization of thermionic injector to produce femtosecond bunches in addition to study of lattice designing of complete isochronous optics for the accumulator ring.

INTRODUCTION

The intense coherent THz source is a powerful tool for medical science, biophysics, molecular science and many other fields. An isochronous ring, which can accumulate ultrashort bunches without bunch lengthening is a candidate to produce such high average power radiation. A test accelerator complex towards intense THz source, t-ACTS (test Accelerator as Coherent THz Source), has been proposed at Electron Light Science Centre, Tohoku University. An injector consists of a thermionic RF gun, an alpha magnet and a 3 m traveling-wave accelerating structure. Thermionic cathode RF gun has been chosen because of stability, multi-bunch operation and cheaper cost. Velocity bunching in the linac is employed for bunch compression to provide sub-100 fs micropulses. This compressed beam whose bunch length is much shorter than the THz radiation wavelength has a sufficient large form factor for coherent enhancement of radiation power [2].

In this report, path length deviation comes from the dependence of energy dispersion and betatron motion in an accumulator ring is discussed analytically and numerically. To circulate the beam without bunch lengthening in the ring, reducing of the momentum compaction factor is helpful. Indeed, control of the high order momentum compaction factor must be cautious when the first order of it is set to zero. In addition, the betatron phase advance in the bending magnets also has to be carefully tuned to cancel out the path length deviation due to the betatron motion.

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FEMTOSECOND BEAM FROM THERMIONIC RF GUN INJECTOR

An RF gun consists of two independent cavities, named ITC (Independently-Tunable Cells) RF gun has been developed as the beam source. The linearly energy chirped beam which is suitable for bunch compression can be produced at the gun exit by choosing appropriate relative RF phase and field strengths. The extracted beam from the ITC-RF gun is sent into the alpha magnet for selection and manipulation of particle distribution in the longitudinal phase space. The beam is then injected into the linac after proper transverse focusing performed by quadrupole magnets. To avoid the strong space charge effects in this low energy injector, velocity bunching in the linac plays the decisive role in bunch compression [3]. Figure 1 shows the bunch trajectory through the process of velocity bunching, in which the bunch injected into the linac can be accelerated and compressed simultaneously. From simulations of particle tracking including the space charge effects by GPT code [4], a 20 pC bunch with bunch length of ~ 70 fs, relative energy spread of ~ 0.23 % is attainable after a 3 m linac. The transverse rms beam size is kept less than 2.25 mm through the linac structure, and the normalized emittance of ~ 2.0 mm-mrad at an average energy around 22 MeV can be obtained [5].

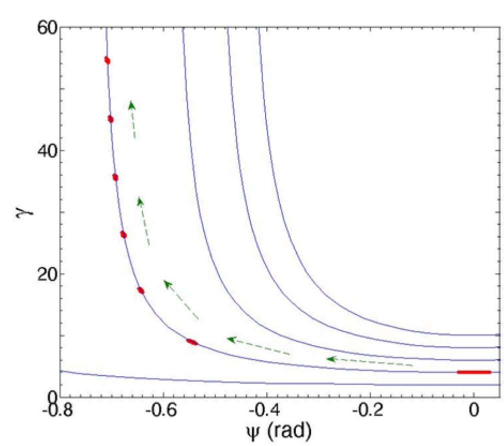

Figure 1: Beam trajectory in equi-potential lines derived from a Hamiltonian of particle motion in the linac. The bunch length is 1 ps at the injection, and then compressed to 72 fs after passing through the 3 m linac in which the field gradient is 15 MV/m.

LATTICE DESIGNING OF ISOCHRONOUS ACCUMULATOR RING

This isochronous ring consists with 4-fold Chasmann-Green lattice. The circumference is 16.795 m that is corresponding to harmonic numbers of 160 and 28 for RF frequencies of 2856 MHz and 499.8 MHz, respectively. An inverted bend is inserted to the center of unit cell where the dispersion function is at the maximum. Therefore, the first order momentum compaction factor can be cancelled out by shorter inverted bend efficiently. By proper manipulation for the dispersion function, the momentum compaction factor can be controlled so as to achieve the isochronous optics. Table 1 is main parameters of the ring, and the lattice functions of the ring are shown in Fig. 2.

Horizontal and vertical chromaticities are corrected to be as 0.02 and 0.09, respectively, by the arrangements of sextupoles located inside the arch. The dynamic apertures for ±1% on- and off- momentum particles after chromaticity correction are shown in Fig. 3. On-axis beam injection employing a fast kicker is considered, so that the dynamic aperture is not apparently small. Since a combined magnet which contains the focusing strength is used as the normal bending magnet, the calculation of chromaticity especially the vertical moment of it needs to be further examined [6].

Table 1: Main parameters of the isochronous ring

Nominal energy	54 MeV
Number of unit cells	4
Superperiodicity	2
Circumference	16.7951 m
Bending radius	0.4 m (normal) - 0.8 m (inverted)
Betatron tune	(4.14, 1.21)
Momentum compaction	0.00000
Natural Chromaticity	(-5.465, -10.012)

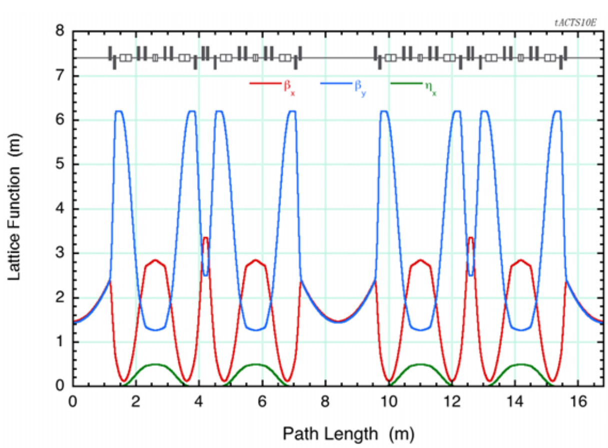

Figure 2: The lattice functions of the ring.

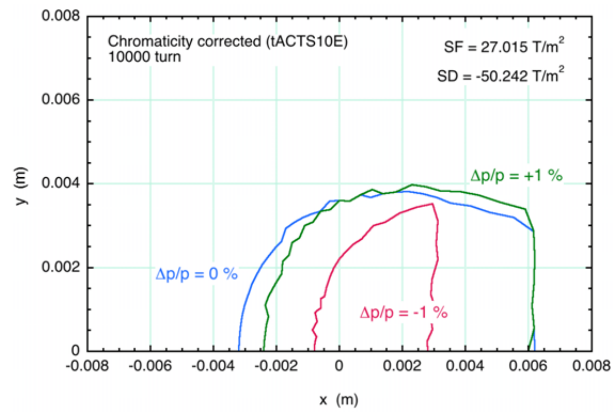

Figure 3: The dynamic aperture at the center of the long straight section after chromaticity correction.

Momentum dependence of path length

The path length deviation through a particle trajectory can be expressed as

$$\Delta L = \int \frac{x}{\rho} ds + O\left(\Delta^2\right), \tag{1}$$

where x is the horizontal displacement in the bending magnet and ρ is the bending radius. The horizontal displacement depends on not only the dispersion function for the off-momentum particles but also the betatron oscillation due to transverse emittance. The horizontal deviation due to the chromatic effect can be expressed as

$$x(s) = \eta_0 \frac{\Delta p}{p} + \eta_1 \left(\frac{\Delta p}{p}\right)^2 + \eta_2 \left(\frac{\Delta p}{p}\right)^3 + O\left(\Delta^4\right), \tag{2}$$

where η_0 is the first order of dispersion function, η_1 and η_2 are the second and the third order of it, respectively.

Figure 4 shows horizontal equilibrium orbits of different momentum particles. From the power series of the horizontal deviation, the non-linear terms of dispersion function can be known. Therefore, the path length difference in a unit cell can be estimated from the momentum compaction factor as

$$\Delta L_{unit-cell} = \left[\alpha_0 \frac{\Delta p}{p} + \alpha_1 \left(\frac{\Delta p}{p}\right)^2 + \alpha_2 \left(\frac{\Delta p}{p}\right)^3\right] \times \frac{C}{4}, \tag{3}$$

where $\alpha_{0,1,2}$ is the momentum compaction factor corresponds to different order respectively. Derived higher order of the momentum compaction factors are $\alpha_1 = -6.40 \times 10^{-3}$ and $\alpha_2 = 2.03$. Assuming the momentum deviation is ± 0.01, the path length deviation after passing through one unit cell is approximately 5.90 μm (19.7 fs) and -11.28 μm (-37.6 fs), respectively. Since the relative energy spread of injection beam after velocity bunching is usually not so small, the correction of the third order of momentum compaction factor by octupoles would be taken into consideration.

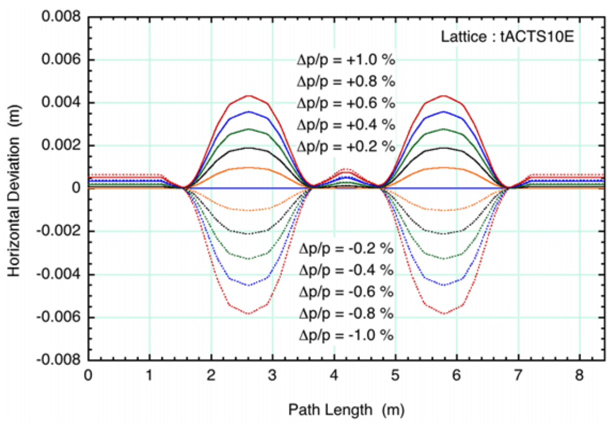

Figure 4: The horizontal deviation of equilibrium orbits in a half ring for different momentum particles.

Betatron amplitude dependence path length

The horizontal displacement comes from the betatron oscillation is expressed as

$$x(s)=\sqrt{\varepsilon\beta(s)}\cos\left[\psi(s)+\phi_0\right], \tag{4}$$

where ε is the beam emittance, ψ is the betatron phase advance and ϕ_0 is the initial phase of the particle. Inserting Eq. (4) into Eq. (1), the deviation of path length comes from the devotions of all the bending magnet can be expressed as

$$\begin{aligned}\Delta L &= \sqrt{\varepsilon}\sum_n\int\frac{\sqrt{\beta(s)}}{\rho}\cos\left(\psi(s)+\phi\right)ds\\ &= \sqrt{\varepsilon}\sum_n\int\frac{\sqrt{\beta(s)}}{\rho_n}\left[\cos\psi\cos\phi-\sin\psi\sin\phi\right]ds,\\ &= \sqrt{\varepsilon}\left(A\cos\phi-B\sin\phi\right),\end{aligned} \tag{5}$$

where

$$\begin{cases} A\equiv\sum_n\int_{\psi_{start}}^{\psi_{end}}\frac{\sqrt{\beta(s)}}{\rho_n}\cos\psi\, ds,\\ B\equiv-\sum_n\int_{\psi_{start}}^{\psi_{end}}\frac{\sqrt{\beta(s)}}{\rho_n}\sin\psi\, ds.\end{cases} \tag{6}$$

Averaging over the initial phase, we can obtain

$$\sqrt{\left\langle\Delta L^2\right\rangle}=\sqrt{\frac{1}{2\pi}\int_0^{2\pi}d\phi\Delta L^2}=\sqrt{\varepsilon}\sqrt{\frac{A^2+B^2}{2}}. \tag{7}$$

From the numerical integration using the lattice function, it is noticeable that the estimated path length deviation after a half turn is less than 0.1 fs for a normalized emittance of 1 mm-mrad beam at 50 MeV. Figure 5 shows the bunch lengthening after a half turn, which is calculated from the simulation of particle tracking and the analytical estimation. In the particle tracking, the Gaussian transverse particle distribution is used. We have supposed that amplitude dependent tune shift is the reason for the discrepancy between these two results.

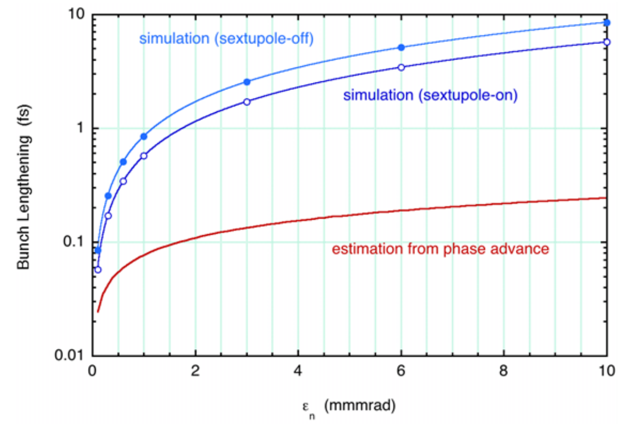

Figure 5: Estimated bunch lengthening from different evaluations plotted as a function of the normalized emittance.

CONCLUSION

An accelerator-based THz radiation source, t-ACTS is developing. By employing velocity bunching, sub-hundred femtosecond beam with a bunch charge of 20 pC can be realized. This study has discussed the analytical estimation of path length difference. The first order momentum compaction factor is mostly set to be zero, and the phase advance of the horizontal beta function is carefully tuned to eliminate the bunch lengthening. However the path length deviation due to both the momentum deviation and the betatron amplitude slightly remains because of the higher order momentum compaction factor and the amplitude dependence of betatron tune. By using the retarded Lienard-Wiechert potential to calculate the synchrotron radiation from a bending magnet at 0.4 T, it shows that the intensity of the coherent part more than ~ 10^6 photons/mrad^2/0.1%-bandwidth at wavelength ~ 300 μm is achievable [7]. This accelerator-based intense coherent THz source will gain interesting attention in numerous applications.

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