CONSIDERATIONS ON DEVELOPING A DEDICATED TERAHERTZ LIGHT SOURCE BASED ON THE HLS-II STORAGE RING.*

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Abstract

There is an increasing interest in generating terahertz radiation for different kinds of researches. A high-power terahertz light source can be realized through coherent synchrotron radiation from a storage ring. The radiation power of coherent synchrotron radiation is proportional to the square of the number of electrons in a bunch. To generate coherent synchrotron radiation, the electron bunch length should be shorter than its radiation wavelength. This paper presents our preliminary study on developing a terahertz light source based on Hefei Light Source. We will introduce the status of Hefei Light Source (HLS) and discusses the approach to change it to a dedicated terahertz light source using coherent synchrotron radiation. Several schemes are proposed to shorten the electron bunch length in the storage ring, including using a low-α_c lattice, adopting a magnetic chicane and upgrading the RF system with much higher frequency. The related beam instabilities are also analyzed to predict the beam current threshold.

INTRODUCTION

Hefei Light Source (HLS-II) is a low energy, second-generation synchrotron light source with an 800 MeV storage ring which has a circumference of about 66 meters. It was first commissioned in 1989 and opened to users in 1991. In the following years, Hefei Light Source successfully undergone two major upgrade projects started in 1998 and 2010, respectively. This light source has provided synchrotron radiation from infrared to soft x-ray for more than two decades. In the recent years, the construction of a new light source called Hefei Advanced Light Source, which is a diffraction-limited light source with a beam energy of 2.0 GeV, has been put on agenda. Therefor it is the time to plan the future for the old light source. Since terahertz light sources have been more and more popular in many research areas especially in life sciences, it is a good idea to transform Hefei light source into a dedicated THz light source. In this paper, we present the physics design of this THz light source including the machine parameters, the light source performance, and the discussion on the beam current limit due to beam instabilities [1].

INCOHERENT AND COHERENT SYNCHROTRON RADIATION

Incoherent synchrotron radiation (ISR) is generated by individual electrons that randomly emit photons while coherent synchrotron radiation (CSR) is produced when a group of electrons coherently emit photons in phase. Compared with the incoherent synchrotron radiation, the coherent radiation power is greatly enhanced, shown in Fig. 1. Generating coherent synchrotron radiation requires that the electron bunch length should be shorter than the radiation wavelength. When passing through bending dipoles, these electrons will emit synchrotron radiation coherently, making the radiation power proportional to the square of the number of electrons. Therefore CSR can be used to generate high power terahertz (THz) radiation.
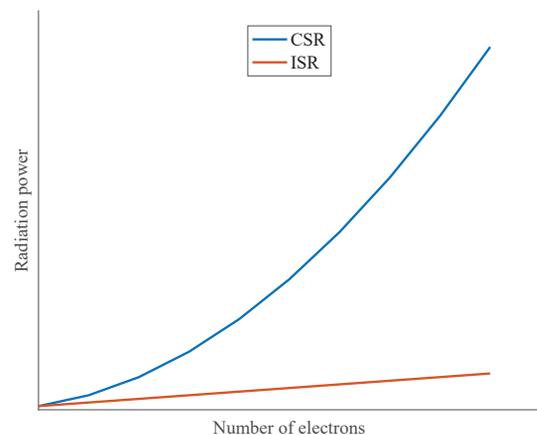
Figure 1: Comparison of radiation power from CSR and ISR as a function of electron number.

SHORTENING BUNCH LENGTH IN A STORAGE RING

Short bunch length is a key factor for generating CSR. The bunch length in a storage ring is expressed by [2]

$$\sigma_0 = \frac{c\sigma_e}{f_{rev}} \sqrt{\frac{|\alpha_c| E_0}{2\pi h e V_{RF} \cos \phi_s}}, \qquad (1)$$

where σ_e is the energy spread of the electron beam, f_{rev} is the revolution frequency, α_c is the momentum compaction factor, h is the harmonic number and V_{RF} is the RF voltage. Several measures can be adopted to shorten the bunch length, such as increasing the RF voltage and frequency, lowering

momentum compaction factor (α_c) and using a magnetic chicane in a straight section.

Low-α_c Lattice for the HLS-II Storage Ring

A low momentum compaction factor (α_c) operation mode can be applied to the HLS-II storage ring in order to obtain a shorter bunch length. The first order momentum compaction factor is given by

$$\alpha_c = \frac{1}{C} \oint \frac{\eta}{\rho} ds, \tag{2}$$

where η is the dispersion function and ρ is the bending radius. The low-α_c lattice can be realized by lowering the dispersion functions in the bending magnets.

The low-α_c lattice for HLS-II storage ring can be modified from the original DBA lattice structure. To save construction cost, we only change the magnet strength using the same magnets and remain their locations. The lattice design is carried out using the ELEGANT programme [3]. The DBA structure of the HLS-II storage ring is formed by 2 bending magnets, and 8 quadrupoles which can be used for lattice matching. To lower the dispersion function in the bending magnets, the strengths of 4 quadrupoles are adjusted and the strengths of the other 4 quadrupoles are adjusted accordingly to preserve the symmetry of the lattice.

Two different lattices are obtained with low α_c for the HLS-II storage ring. The beta functions β_x, β_y and dispersion functions η_x for these two different low-α_c modes in one superperiod are plotted in Fig. 2. Through optimization, the α_c is adjusted to 3.6×10^{-6} and 4.81×10^{-5} respectively, which is much lower than the present one (0.02). The low-α_c mode is realized by lowering the dispersion functions at the bending magnets. As a consequence, the beta functions of low-α_c lattices become larger compared with the normal lattice. The ring chromaticity can be corrected using the existing sextupoles. The dynamic aperture (DA) needs to be further optimized in order to make the injection easier.

Magnetic Chicane

A magnetic chicane can be inserted to a straight section of the storage ring to compress the bunched beam longitudinally. Usually a chicane is composed of a set of 4 bending magnets, which is illustrated in Fig. 3. The difference in the path lengths of the electrons in a bunch caused by their energy deviation can be approximated as

$$\Delta S = R_{56}\delta, \tag{3}$$

where R_{56} describes the momentum compaction, give by

$$R_{56} = \frac{dz}{d\delta} = \int \frac{\eta}{\rho} ds. \tag{4}$$

To compress the bunch, the path length difference of the electrons with an energy spread in a bunch should be shortened. This means that R_{56} should take a negative value, i.e., a larger δ leads to a smaller ΔS. In a chicane, the bending angle θ for a particle with an energy deviation δ is $\theta = \theta_0/(1+\delta)$, where
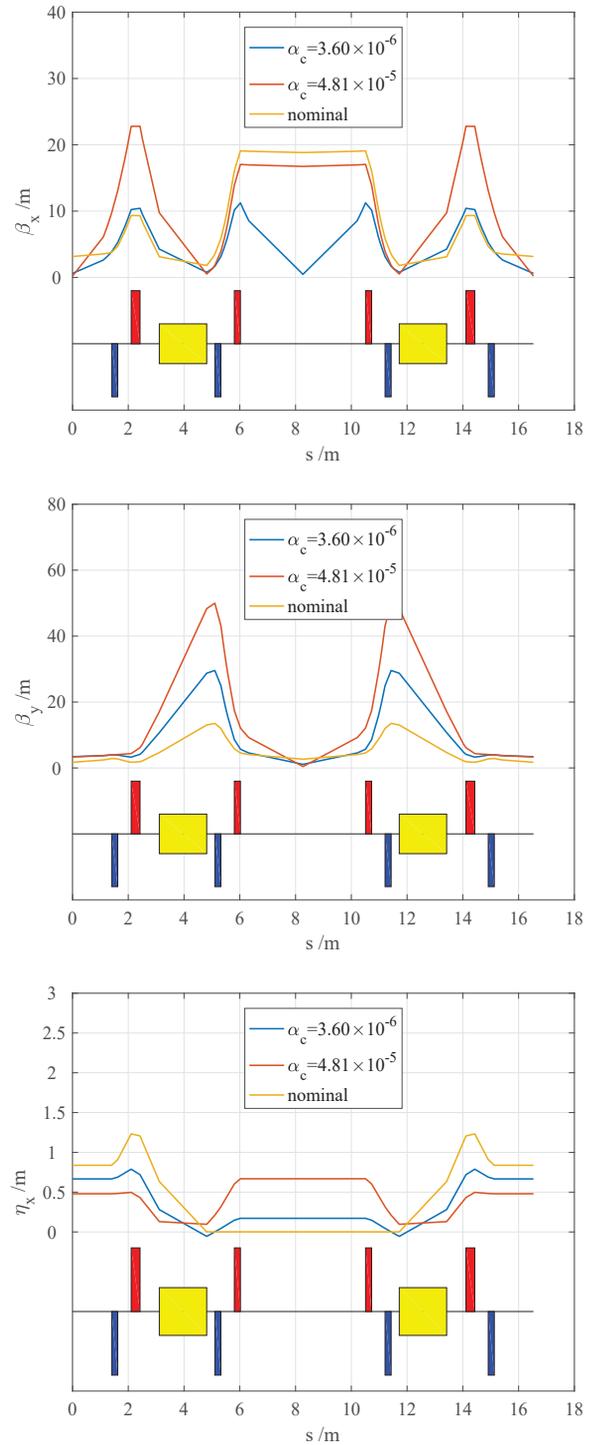
Figure 2: Low-α_c lattices for the HLS-II storage ring.

θ_0 is the bending angle for an on-momentum particle [4] (see Fig. 3). The path length through a chicane is approximately

$$s = 2a[\cos(\frac{\theta_0}{1+\delta})]^{-1} + b \approx 2a + a(\frac{\theta_0}{1+\delta})^2 + b. \tag{5}$$

Then R_{56} can be approximately expressed as

$$R_{56} = \frac{ds}{d\delta}|_{\delta=0} = -2a\theta_0^2, \tag{6}$$
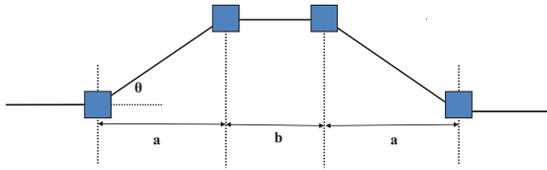
Figure 3: A magnetic chicane for bunch compression.

which shows that a minus R_{56} can be achieved by the chicane structure. Therefore another method to shorten the bunch length for the HLS-II storage ring can be realized using a magnetic chicane in its straight section.

BEAM COLLECTIVE INSTABILITIES

The coherent synchrotron radiation based on short bunches could lead to large wake fields, resulting in strong beam instabilities. The longitudinal wake function can be expressed as

$$W_{\parallel} = \frac{Q}{\epsilon_0 (2\pi)^{3/2} (3\sigma_z^4 \rho^2)^{1/3}}, \quad (7)$$

where σ_z represents the bunch length. We can see that the wake function is inversely proportional to the bunch length. The CSR induced beam instabilities could severely degrade the light source performance, e.g., by limiting the beam current.

The microwave instability is a very common longitudinal collective instability. The beam current threshold for the microwave instability can be estimated as

$$I_{th} < \frac{1.5(\omega_0 \sigma_\tau)^3 V_{rf} h \cos \phi_s}{\sqrt{2\pi} R_{eff}/n_r}, \quad (8)$$

which shows that a shorter bunch length σ_τ can leads to a lower current.

CSR can also drive the microbunching instability in the electron bunch, resulting in periodic bursts of the terahertz synchrotron radiation. The beam current threshold for the microbuching instability is estimated as [5]

$$I_b = \frac{\pi^{1/6} I_A \alpha_c \gamma \sigma_\delta^2 \sigma_\tau}{\sqrt{2} \rho^{1/3} \lambda^{2/3}} \quad (9)$$

A rough estimation of the CSR related beam instabilities shows that the beam current threshold for the HLS-II storage ring with THz mode is about 5 mA.

MAIN PARAMETERS

Based on the above analysis, we obtain a preliminary design of a terahertz light source using coherent synchrotron radiation at Hefei Light Source. The main parameters of the storage ring can be found in Table. 1. In order to shorten the bunch length, a major upgrade needs to be carried out on the RF system, including raising the RF voltage and the RF frequency (also the harmonic number). Compared with the present light source, the beam current gets much lower because of the severe beam instabilities. The performance

of the CSR light source is shown in Fig. 4. With coherent synchrotron radiation, the radiation power is much higher than the incoherent synchrotron in the THz region.

Table 1: Main Parameters of the Nominal Storage Ring and the one as a THz Light Source

Parameters	nomial HLS	THz HLS
Circumference (m)	66.13	66.13
Beam current (mA)	300	2
RF frequency (MHz)	204	2856
Harmonic number	45	630
RF voltage (kV)	200	500
Bunch length (mm)	3	0.1
α_c	2×10^{-2}	10^{-5}
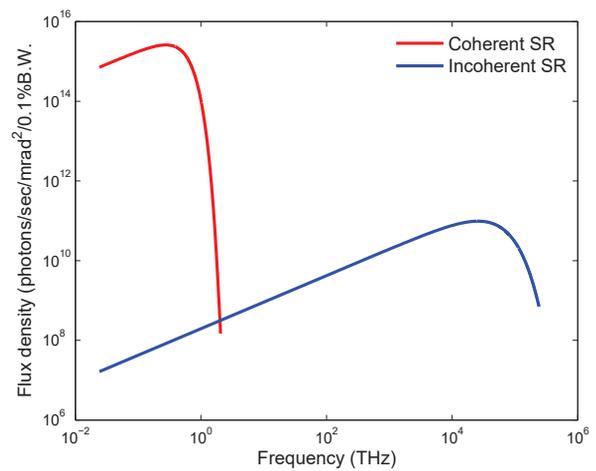
Figure 4: Light source performance.

SUMMARY

The preliminary design of a dedicated, high-performance THz synchrotron light source based on the HLS-II storage ring is presented. Several approaches are taken to shorten the bunch length, including adopting low-α_c operation mode, changing the RF system with higher frequency, etc. The current threshold due to CSR related instabilities is also estimated.

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