THE POSSIBILITY OF CONVERSION OF HEFEI LIGHT SOURCE STORAGE RING INTO A DEDICATED THZ RADIATION SOURCE *

Wang Lin, Xu Hong-liang, Zhang Shan-cai, Feng Guang-yao, Wu Cong-feng, Li Wei-min, Liu Zu-ping, National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei, Anhui, 230029

Abstract

A short electron bunch can be obtained in the storage ring with low momentum compaction factor, which also is named quasi-isochronous ring. When bunch length is shorter than concerned radiation wavelength, the radiation will be enhanced significantly, which usually lies in the THz range. Idea of ring-type THz radiation source was put forward several years ago [1]. In this paper, the focusing parameter with low momentum compaction of HLS storage ring was calculated and possible achieved bunch length in low intensity regime was discussed. Then, limitation of some collective effects on ring performance was estimated roughly by existing theory. Considering above factors, the possibilities of converting current HLS storage ring to a dedicated coherent THz ring-type THz source was evaluated. .

INTRODUCTION

In the future plan of NSRL of USTC, a new VUV and soft X-ray synchrotron radiation light source, whose name is HALS (Hefei Advanced Light Source) and brilliance exceeds that of HLS (Hefei Light Source) much, would be designed and constructed [2]. Then, current SR research activities of NSRL with VUV and soft X-ray would be carried out at HALS. There are two ways for HLS storage ring. Except for retirement we can convert it into a dedicated coherent THz radiation source. With the development of SR research activities with THz radiation, there is a potential requirement for dedicated THz radiation source with high power. At present, quasi-isochronous operation mode was developed at some light source for production of powerful coherent THz radiation [3]. Due to inconsistent requirement of other SR users, proposal of dedicated coherent THz radiation source was brought forward also. For example, the CIRCE light source scheme of Berkeley National Laboratory, where the booster of Advanced Light Source will be converted into dedicated THz source [1]. The key of ring-type THz radiation source is achievement of short bunch length with low momentum compaction. In the following sections, some issues of converting HLS storage ring into a THz source would be discussed.

HLS STATUS

The HLS is a dedicated second generation light source, whose circumference is about 66 m and is composed of four TBA cell. There are four long straight sections with length 3m, among them one is used for RF system, one is used for injection system and others used for undulators. Its basic parameters were listed in the table 1. There is a stringent limitation of upgrading, that settlement of storage ring is a concrete torus，thus the positions of dipole magnets can not move much. The figure 2 gives the radiation power of HLS in the FIR and THz range.

Table 1: Main parameters of HLS

Energy	800MeV	Circumference	66.13m
Structures	4×TBA	emittance	165nm·rad
RF frequency	204MHz	Momentum compaction	0.048
RF Voltage	150kV	Natural bunch length	27mm
Beam intensity	4.136×10^{11}	Radius of bending	2.2221m

LATTICE WITH LOW MOMENTUM COMPACTION FACTOR

Usually, the bunch length is proportional to square root of linear slippage factor,

$$\sigma_z = \frac{c}{\omega_0}\sqrt{\frac{-2\pi\eta_0 E_0}{hV_{rf}\cos(\phi_s)}}\sigma_\delta \quad (1),$$

where c is light speed, ω_0 is revolution frequency, η_0 is linear slippage factor and can be expressed as $\eta_0 = \alpha_0 - 1/\gamma^2$, α_0 is linear momentum compaction factor, E_0 is energy, h is harmonic number, V_{rf} is cavity voltage, ϕ_s is synchronous phase, σ_δ is equilibrium momentum spread. According to (1), there are several methods to reduce bunch length, such as lowering beam energy, which limited by collective effects, increasing RF frequency, which limited by physical aperture, and decreasing slippage factor. For ultra relativistic beam, the key issue to shorten bunch length is to lower momentum compaction. Momentum compaction factors reflect the variation of path length with momentum deviation, $C(\delta)=C_0\left(1+\alpha_0\delta+\alpha_1\delta^2+\alpha_2\delta^3+\ldots\right)$. Knowing various order momentum compaction and linear optics, the slippage phase factor can be determined [4]. The linear compaction factor is determined by dispersion function and can be expressed as

$$\alpha_0 = \frac{1}{C}\oint\frac{\eta_x(s)}{\rho(s)}ds \quad (2),$$

* Work supported by National Natural Science Foundation of China ((10675117 and 10575096))
#wanglin@ustc.edu.cn

where $\eta_x(s)$ is horizontal dispersion function, $\rho(s)$ is curvature radius. To reduce linear momentum compaction there are some methods. The idea of introducing negative dispersion into straight sections was adopted in our lattice design. Focusing parameters of HLS storage ring with low momentum compaction factor were calculated. Results showed that the linear momentum compaction can be varied smoothly from normal value to little negative value. The figure 1 displayed the β and dispersion function of one cell when α is 1e-4. The table 2 lists main parameters of the low momentum compaction mode.

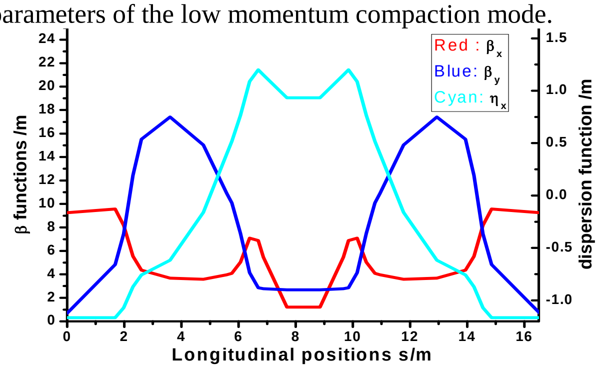

Figure: 1 β and dispersion function of low α-mode.

Except for reduce linear momentum compaction, controlling of second order momentum compaction is necessary for shortening bunch length and improving beam performance. This is achieved by adjusting sextupole strength. There are two families of sextupoles used for natural chromaticity compensation in HLS storage ring. For controlling of second order momentum compaction, additional sextupole family should be introduced. According to effects of sextupole on chromaticities and second order momentum compaction, following equations would solved for sextupole strength,

$$\begin{cases} \frac{1}{4\pi}\oint \beta_x(s)\lambda(s)\eta_x(s)ds = \Delta\xi_x \\ -\frac{1}{4\pi}\oint \beta_y(s)\lambda(s)\eta_x(s)ds = \Delta\xi_y \\ \oint \lambda(s)\eta_x^3(s)ds = \Delta\alpha_2 \end{cases} \quad (3),$$

where $\Delta\xi_{x,y}$ and $\Delta\alpha_2$ is horizontal, vertical chromaticities and second order momentum compaction needed to be corrected.

The requirement of transverse beam emittance is not very stringent and the dynamic aperture is enough large with normal chromaticity compensation scheme.

LONGITUDINAL DYNAMICS

Ignoring radiation effects, synchrotron Hamiltonian including higher order terms is:

$$H(\delta,\phi) = \frac{1}{2}h\omega_0\eta_0\delta^2 + \frac{1}{3}h\omega_0\eta_1\delta^3 + \frac{1}{4}h\omega_0\eta_2\delta^4 \quad (4),$$
$$+\frac{\omega_0 eV_{rf}}{2\pi\beta^2 E_0}\left(\cos(\phi) - \cos(\phi_s) + (\phi-\phi_s)\sin(\phi_s)\right)$$

where $\eta_{0,1,2}$ is linear, second and third order slippage phase factor. The first term is dominated for normal RF bucket, the second term is important to low α case, and the third term is ignored usually. The rms momentum variation or energy spread of bunch is determined by equilibrium between synchrotron radiation damping and quantum excitation and can be evaluated using synchrotron radiation integral theory [5]. Usually, the energy spread is small and the Hamiltonian can be Taylor expanded around the stable fixed point $(\phi=\phi_s, \delta=0)$. For normal case, the rms phase width of bunch can be derived and converted to bunch length showed in (1). With the decreasing of η_0 or η_0/η_1, the RF bucket was distorted. When η_0/η_1 approaches the merging point [4], the RF bucket becomes α-like and bucket area should be shrunk. When energy spread is small, the bunch length can be calculated according to (1). In the limiting case of $\eta_0 = 0$ and $\eta_2 \approx 0$, the beam is unstable in synchrotron motion. So there is necessary to control η_1 through adjusting second order momentum compaction. In the limiting case of $\eta_0 = 0$ and $\eta_1 = 0$, the bunch length is:

$$\sigma_z = \frac{c}{\omega_0}\sqrt{\frac{-\pi\eta_2 E_0}{hV_{rf}\cos(\phi_s)}}\sigma_\delta^2 \quad (5).$$

Since the energy spread is small, the bunch length maybe very small in the η_2 -dominated RF bucket.

COLLECTIVE EFFECTS

Various collective effects would influence beam stability, among them the more detrimental effects are longitudinal which alter energy spread and length. The first is micro-bunching instability, which caused by coherent synchrotron radiation and produce irregular coherent synchrotron radiation [6, 7]. According to existing theory, the threshold is expressed as

$$N \le A\frac{f_{rf}V_{rf}\sigma^{7/3}}{\rho^{1/3}}F \quad (6),$$

where $A = 1.67[MKS]$ units, σ is the natural bunch length, F is a numerical factor and about 5. Other instability concerned is microwave instability, which results in energy spread increasing and bunch lengthening. We make rough estimation of microwave instability threshold by assumption of ring impedance 10 Ohms [8].

$$I_p \le \frac{2\pi|\eta_0|\beta^2 E_0}{e}\left|\frac{Z_{//}}{n}\right|^{-1}\sigma_\delta^2 \quad (7),$$

where $I_p = eN/\sqrt{2\pi\sigma_\tau}$ is peak intensity, $\left|Z_{//}/n\right|$ is reduced impedance [9]. Avoiding the bunch lengthening and CSR burst, relatively low operation beam intensity is preferred. Finally, to extract THz radiation successfully, the shielding effect of vacuum chamber is important. The allowed THz radiation can be calculated according to [10]

$$\sigma_s < \lambda/2 < h/\pi\sqrt{h/\pi\rho} \quad (8),$$

where σ_s is bunch length, λ is allowable coherent radiation wavelength, h is height of vacuum chamber, ρ is curvature radius. For HLS storage ring, the h is 40mm, and $\lambda_{\max}$ is 61mm. If chamber is renewed and h is 50mm, $\lambda_{\max}$ is 85mm. When $\alpha_0 = 2.5e-4$, the bunch length and intensity threshold were calculated and listed in table 2. If RF system were upgraded, the achievable bunch length and intensity were calculated again. If the energy is 600MeV, bunch length is 0.26mm. According to rough estimation, the impedance of HLS storage ring is large and should be optimized in the low α upgrading.

We assume following conditions: $\alpha_0 = 0.00025$, $f_{rf} = 1.3GHz$, $V_{rf} = 1MV$, $|Z_{//}/n| = 1\Omega$, $E_0 = 800MeV$, and the achievable bunch length is 0.30mm (1ps), electron number per bunch is 3.6×10^6.

Table 2: Main parameters of low α mode

emittance	460nm·rad	Tunes	3.38/2.72
Energy spread	0.00043	Momentum compaction	1e-3~ 1e-5
RF voltage	250kV	RF frequency	204MHz
	1000kV		1300MHz
Natural bunch length	1.5mm	Reduced impedance	10Ω
	0.30mm		
$N_{th,mw}$	1.8×10^6	$N_{th,mb}$	8×10^7
	3.6×10^5		4.8×10^7

RADIATION SPECTRUM

If the bunch length is shorter than radiation wavelength, the synchrotron radiation should be enhanced considerably. The radiation spectrum is

$$\frac{dP(\omega)}{d\omega} = \frac{dp(\omega)}{d\omega}\left(N + N(N-1)g(\omega)\right) \quad (9),$$

where $dp(\omega)/d\omega$ is incoherent radiation power spectrum of incoherent radiation, N is electron number per bunch, the $g(\omega)$ is form factor associated with distribution function, for Gaussian distribution, $g(\omega) = \exp\left(-\omega^2\sigma_s^2 / 2c^2\right)$. Assuming Gaussian distribution, the calculated radiation power spectrum is showed in figure 2. As expectation, the radiation power at long radiation wavelength is higher than that of incoherent radiation of HLS by several orders and maybe become a new tool to investigate THz radiation application.

DISCUSSION AND CONCLUSION

According to lattice calculation with low momentum compaction factor and estimation of the coherent THz synchrotron radiation, upgrading of current HLS storage ring to a dedicated ring-type THz source is possible with a few updating of some components, including replacement of one quadrupole family with quadrupole-sextupole combined function magnets to control second order momentum compaction, renew of vacuum chamber to extend CSR range and optimize ring impedance for avoiding detrimental collective effects, replacing RF system by new one with higher frequency and higher voltage. With the help of higher-order harmonic RF cavity working at shortening bunch length condition, the achievable coherent synchrotron radiation maybe extend to higher frequency.

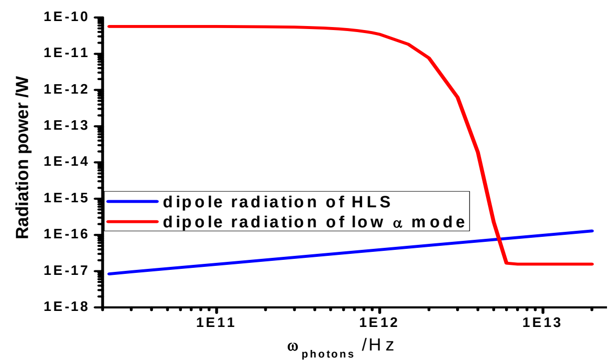

Figure 2: Radiation power spectrums at THz range.

REFERENCES

[1] W.Barry, A.Biocca, J.M.Byrd, et al, “A dedicated infrared synchrotron radiation source at the ALS”, Proceedings of PAC2001, USA, p2623.

[2] W-M.Li, L.Wang, G-Y.Feng, et al, “The concept of Hefei Advanced Light Source (HALS)”, these proceedings.

[3] M.Abo-Bakr, J.Feikes, K.Holldack, et al, “Steady-state far-infrared coherent synchrotron radiation detected at BESSY II”, PRL, June, 2002, 254801.

[4] K.Y.Ng, “Physics of intensity dependent beam instabilities”, Fermilab-FN-0713, USA, 2002.

[5] M.Sands, “The physics of electron storage rings introduction”, SLAC-121 UC-28, USA, 1970.

[6] F.Wang, D.Cheever, W.Franklin, et al., “Terahertz coherent synchrotron radiation in the MIT-BATES south hall ring”, Proceedings of PAC2005, USA..

[7] J.M.Byrd, W.P.Leemans, A.Loftsdottir, et al., “Observation of broadband self-amplified spontaneous coherent terahertz synchrotron radiation in a storage ring”, Physical Review Letters, Nov.2002, 224801.

[8] B.G.Sun, L.K.Chen, J.H.Wang, et al., “Bunch length measurement and its lengthening in HLS”, Proceedings of PAC1999, USA, p2184.

[9] K.Y.Ng, “Microwave instability in α-like quasi-isochronous buckets”, Fermilab-Conf-96/378, USA, 1996.

[10] B.W.Zotter, S.A.Kheifets, “Impedances and wakes in high-energy particle accelerators”, World Scientific, 1997..