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A HIGH-CURRENT LOW-ENERGY STORAGE RING FOR PHOTON-HUNGRY APPLICATIONS

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Abstract

Many applications of synchrotron light sources, such as imaging, lithography and angle-resolved photoemission spectroscopy, can benefit from high photon flux, which, unlike the brightness, is almost independent of electron beam transverse emittance. To realize high photon flux, it is desirable to increase the stored current or number of periods of insertion devices. To this end, a low-energy (500 MeV) and high-current (1000 mA) storage ring with long straight sections is under design at Chongqing University in China. This paper presents the physical design, highlighting both the feasibility and challenges.

INTRODUCTION

Brightness and flux are two key parameters of a storage ring light source. The former can be improved by reducing transverse electron beam emittance due to their inverse-like relation, while the latter linearly relies on beam current and periods of insertion device (ID). For the time being, typical current stored in a ring is about 300-500 mA, as shown in Fig. 1 [1, 2]. In the Laboratory for Ultrafast Transient Facility (LUTF) at Chongqing University, a 500 MeV and 1000 mA ring is now under design and construction as the phase-I project for a high-photon-flux 3 GeV light source.

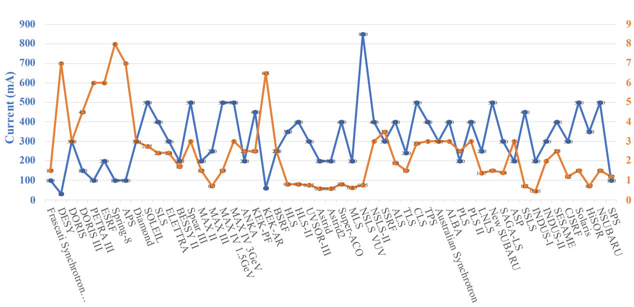

Figure 1: Operation current and energy of typical rings.

For the phase-I 500 MeV ring, various aspects have been considered up to now, including linear and nonlinear dynamics, errors, Touschek lifetime and instabilities like Coherent Synchrotron Radiation (CSR) instability, longitudinal microwave instability (LMWI), transverse mode coupling instability (TMCI), resistive wall instability (RWI) and coupled bunch instability (CBI). Through a bunch-by-bunch feedback (BBFB) system and the controlling of cavity higher order modes (HOMs), a current of 1000 mA is expexted, and a photon flux of 1.4×10^{16} photons/s/0.1%bw can be provided in ultraviolet and extreme ultraviolet range with an out-vacuum undulator.

LATTICE AND DYNAMICS

For the sake of high current, LUTF 500 MeV ring does not follow the path of a diffraction-limited storage rings. Instead, a 4BA lattice and moderate emittance are chosen. The main parameters are presented in Tab. 1. During the design, to get a large dynamic aperture (DA) and momentum aperture, the horizontal (x) and vertical (y) betatron phase advances between the upstream and downstream focusing sextupoles inside a supercell (see Fig. 2) are set around π, and the horizontal phase advance of the entire supercell is fixed around 3π. Besides, all quadrupoles are set intentionally as weak as possible to allow for a larger physical aperture. In the current lattice, all quadrupoles have a strength below 10 T/m, and the maximum sextupole strength to correct chromaticity to unity is 130 T/m^2.

Table 1: Parameters of LUTF 500 MeV ring

Parameters	Characters	Value
Energy (MeV)	E_0	500
Ring circumference (m)	C	76.78
Momentum comp. factor	α_c	8.143×10^{-3}
Natural emittance (nm)	ϵ_{x0}	8.59
Energy loss per turn (keV)	U_0	4.34
Main RF peak voltage (kV)	V_0	600
Main RF frequrncy (MHz)	f_{RF}	499.784
3rd HC voltage (kV)	V_h	200
Energy spread (RMS)	σ_δ	3.80×10^{-4}
Beam length wo/w HC (mm)	σ_{z0}/σ_z	2.7/12.2
Betatron Tunes	ν_x/ν_y	6.199/3.357
Natural damping time(ms)	$\tau_x/\tau_y/\tau_s$	59/59/29.5

Owing to good nonlinear performance, DA in x/y plane reaches 44 mm/16 mm when half width of physical aperture is 80 mm/40 mm respectively, as shown in Fig. 3. For electrons with energy deviations ranging from $-4\% \sim 4\%$, DA changes little, and chromatic tune shift is well controlled when ξ_x and ξ_y is corrected to unity. In general, the trans-

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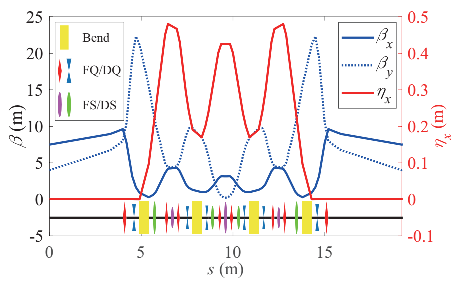

Figure 2: LUTF ring lattice and optics.

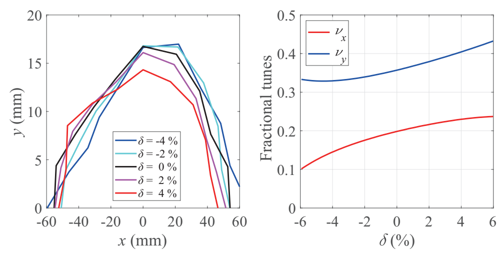

Figure 3: Dynamic aperture and chromatic tune shift ($\xi_x = \xi_y = 1$).

verse momentum acceptance is better than the longitudinal one decided by RF when cavity voltage is below 650 kV.

Longitudinally, an active room-temperature 3rd harmonic cavity (HC) is used to stretch the beam, increase Touschek lifetime and mitigate instabilities. Compared with the passive case, an active HC can work at a damping state like the main cavity (MC). Considering an appropriate surface power density and just one cavity for MC/HC, the voltages are chosen to be 600 kV and 200 kV respectively. And the beam length can be stretched to 12.2 mm, a factor of 5.

The help of HC improves Touschek lifetime to 2.3 h. Furthermore, top-up injection is adopted to keep the stability of synchrotron radiation furthermore. To reduce perturbations to the circulating beam, nonlinear kicker (NLK) scheme is used, and its layout is given in Fig. 4. With a pulse of 0.5 µs, and peak field of 200 Gs, for an injection beam with emittance of 50 nm, the expected injection efficiency can be 100%. For the time being, the NLK is under design, and strip TiN coating with thickness of 3 µm is planed on ceramic chamber to mitigate impedance and eddy-current-induced beam oscillation [3].

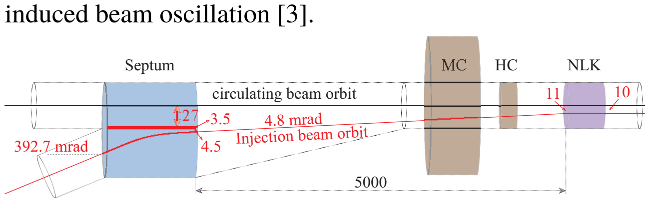

Figure 4: Injection Layout.

Moreover, analyses to dipole fringe effect, orbit correction and misalignment errors have also been carried out. As a result, just a small tuning of all quadrupoles' strength within ±5% is enough for the recovery of working point. As for orbit correction, 6 BPMs and 9 correctors each supercell behave well in orbit distortion diminution. And the tolerance on horizontal/vertical/longitudinal position errors are 100 µm/100 µm/200 µm, roll angle misalignments should be better than 200 µrad.

INSTABILITY ANALYSIS

Instabilities induced by beam collective effects are dominant limitation of average current in storage rings, especially for the case of low energy like LUTF 500 MeV ring. For a purpose of potential higher current, the vacuum pipe is designed to octagon with copper (the left of Fig. 5). The flanges, bellows, valves are all shielded type. And all transitions are also required to have a taper smaller than 0.2 for small geometrical impedance. In the current design, the preliminary obtained total longitudinal geometrical impedance is given in the right of Fig. 5. The effective impedance $\left|\frac{Z}{n}\right|_{\text{eff}} = 0.28\ \Omega$. For the total resistive wall (RW) impedance, two kinds of pipes are assumed: two elliptical pipes, representing two IDs and each with a (semi-major axis, semi-minor axis, length) of (30, 5.5, 6000) mm and the other octagonal parts. Based on impedance, the threshold current of various instabilities can be estimated. Here, we start from CSR instability first.

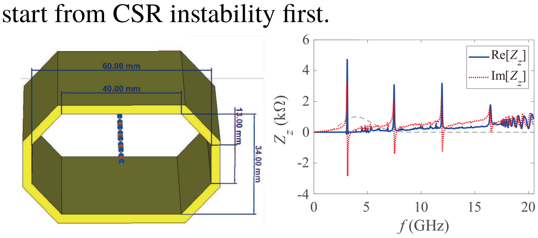

Figure 5: LUTF 500 MeV ring vacuum pipe and preliminary total longitudinal geometrical impedance.

CSR effect can cause additional energy loss and distort beam longitudinal phase space, leading to CSR microwave instability. For the case of free space [4], shielded coasting beam [5] and shielded bunched beam [6], CSR thresholds are

$$I_{\text{th}} = \begin{cases} 0.482\dfrac{I_A|\eta|\gamma_s\sigma_\delta^2\sigma_{z0}^{1/3}}{\rho_s^{1/3}} & \text{Free-space;} \\ \dfrac{I_A|\eta|\gamma_s\sigma_\delta^2\sigma_{z0}^{1/3}}{\rho_s^{1/3}}\dfrac{\Pi^{2/3}}{\sqrt{2\pi}} & \text{Coasting;} \\ \dfrac{I_A|\eta|\gamma_s\sigma_\delta^2\sigma_{z0}^{1/3}}{\rho_s^{1/3}}(0.5+0.12\Pi) & \text{Bunched;} \end{cases} \quad (1)$$

Here, $\Pi = 2\sigma_{z0}/\lambda_0$ is shielding factor, $I_A \approx 17$ kA is the Alfen current. When $\Pi < (\pi/2)^{3/4}$, shielded bunched beam model will give a larger value than shielded coasting beam one. While if $\Pi < 1.33$, coasting-beam model has a threshold smaller than the free space, which is impossible and needs to be more involved. For LUTF ring, $\Pi = 1.22$, both coasting-beam and free-space model indicate a threshold ~ 1.1 mA/bunch, though slightly varies, consistent with ELEGANT [7] simulation result.

However, Eq. (1) should be suspected when a HC joins in, especially in the idea stretching situation. Because it is obtained based on the standard longitudinal synchrotron oscillation function and the relation $\sigma_{z0} = \frac{\sigma_\delta|\eta|C}{2\pi\nu_s}$, both of which break down when HC appears. In this case, simulations are effective and straightforward. As a result, when

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beam current exceeds 22.5 mA/bunch, there will be particle lost under LUTF ring parameter.

Unlike CSR, LMWI is another kind of instability that relays on RW and geometrical impedance. According to the Keil-Schnell-Boussard criterion [8], the threshold current of LMWI can be expressed by

$$I_{\text{th}} = \frac{(2\pi)^{3/2}\alpha_c E_{0[\text{eV}]}\sigma_\delta^2\sigma_{z0}}{C\left|\frac{Z}{n}\right|_{\text{eff}}}. \tag{2}$$

For LUTF ring, this formula predicts a LMWI threshold current for RW and geometrical impedance of 34.85 mA and 1.03 mA per bunch. For the HC case, simulation shows again that 10 mA/bunch is well below LMWI threshold for geometrical impedance.

TMCI, or strong head-tail instability, describes the coupling of azimuthal modes when electron beam circulates in the ring and does betatron oscillation transversely. Based on azimuthal-mode decomposition, Ref. [9] presents a detailed theory of both with/without HC cases. For RW impedance of a round pipe with radius b and length L, if only MC works, the resulted threshold reads

$$I_{\text{th},0} \approx \hat{I}_{0c}\frac{2\pi I_A\gamma_s\omega_y\omega_s}{c^2}\frac{b^3}{L}\sqrt{\frac{Z_0\sigma_c\sigma_{z0}}{2}}. \tag{3}$$

Here, $\hat{I}_{0c} = 0.197$ is a numerical value for the merging of two modes. Z_0 and σ_c are the free space impedance and RW conductivity, R_s is the transverse shunt impedance, ω_y represents the transverse betatron oscillation frequency. In the HC case, the corresponding threshold becomes to

$$I_{\text{th}} = 0.31\left(\tau_y\omega_s\right)^{-1/6}\left(\frac{\sigma_{z0}}{\sigma_z}\right)^{1/3}\frac{I_{\text{th},0}}{\hat{I}_{0c}}, \tag{4}$$

Usually, Eq. (4) gives a smaller value than Eq. (3) for the fact that electron longitudinal oscillation frequency, which is beneficial to TMCI, can be much slower in the HC case. For example, in LUTF ring, RW impedance induced TMCI threshold is 242 mA without HC, while only 42 mA when 3rd HC is applied.

Compared with single bunch instabilities mentioned above, mutibunch ones are usually more serious. For instance, the RWI under the case of uniformly distributed N_b bunches in the ring can be described by [10]

$$\Delta\Omega^{(\mu)} = -\mathrm{i}\frac{4\pi\varepsilon_0 N_b N_e r_e c}{2\gamma_s T_0^2\omega_y}\sum_{p=-\infty}^{\infty} Z_\perp(\omega_{\mu,p}), \tag{5}$$

with $\omega_{\mu,p} = \omega_y + (pN_b + \mu)\omega_0$, and the mode number $\mu = 0, 1, ..., N_b - 1$. Under the work of RW impedance, and when two IDs are considered, the RWI growth rate can be $2452\,\text{s}^{-1}$@1 A. This mean a total threshold current of 6.9 mA under natural damping for LUTF ring.

Besides, higher order mode (HOM) from RF cavities and other narrow-band impedances can cause another kind of mutibunch instability, coupled bunch instability (CBI). The threshold current of longitudinal and transverse dipole CBIs driven by monopole and dipole HOMs is habitually estimated by [11]

$$I_{\text{th,total}} = \begin{cases} \frac{\omega_s}{\eta\tau_d\omega}\frac{4\pi E_0}{e\omega_0 Z(\omega)F^2(\omega)} & \text{Longitudinal;} \\ \frac{1}{\tau_d\beta}\frac{4\pi E_0}{e\omega_0 Z_\perp(\omega)} & \text{Transverse;} \end{cases} \tag{6}$$

where $F(\omega) = \exp\left(\frac{-1}{2\omega^2\sigma_t^2}\right)$ is bunch form factor at ω. In the single RF case, Landau damping is usually weak compared with natural damping, and longitudinal CBI will be serious. To handle this, also increase the Touschek lifetime, a harmonic cavity, no matter passive or active, is commonly used. By stretching the beam and increasing synchrotron tune spread, Landau damping can be greatly improved. Generally, Landau damping rate has the form of

$$|\Delta\Omega|_{\text{th,Landau}} = 0.78\frac{\eta^2\sigma_\delta^2}{\omega_R}\left|\frac{3c}{\omega_R^3} - \left(\frac{3b}{\omega_R^2}\right)^2\right|, \tag{7}$$

where b and c are the 2nd and 3rd derivative of synchrotron effective potential defined in Ref. [12]. In LUTF ring, when the beam is stretched to 12.2 mm by HC, Landau damping rate can be as large as $1.35 \times 10^4\,\text{s}^{-1}$, the threshold HOM impedance can be greatly improved, as the left picture of Fig. 6 shows, leaving only 3 frequencies exceed the threshold. (a) and (b) are fundamental frequency of MC and HC. They represent actually the Robinson instability. By a −40 kHz and −13 kHz detuning respectively, they both can be safe for beam. As for (c), exact calculation shows that it only contributes a growth rate of $1037\,\text{s}^{-1}$, well below Landau damping.

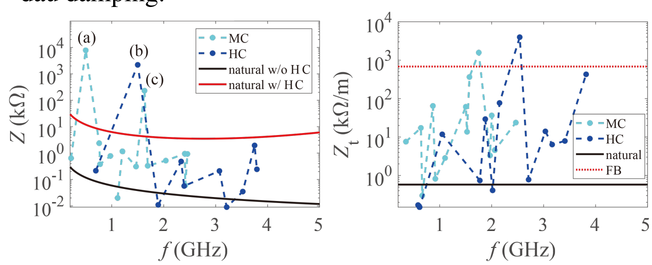

Figure 6: Threshold and designed cavity HOM impedance of LUTF ring.

The transverse CBI is more intractable. An active BBFB system is planed to overcome it, and also the RWI. With an extra damping of 0.05 ms provided, the HOM impedance threshold increases to the red line in the right picture of Fig. 6. Through this approach, there still exist two dangerous points, 1.75 GHz from MC and 2.54 GHz from HC. Higher-order-mode dampers, higher-order-mode frequency shifters and tuning of cavity temperatures are under consideration for these two points. Once done, a current of 1 A or more can be expected.

CONCLUSION

A high-current and low-energy storage ring is being designed and constructed in LUTF of Chongqing University. Analyses show that by the utilization a 3rd HC and BBFB system, together with the control of cavity HOMs, A Touschek lifetime at 2.3 h and current at 1 A can be reachable.

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