Bunch length manipulation in a diffraction-limited storage ring *

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Abstract: In an electron storage ring, the bunch length can be increased or decreased by using harmonic cavities. Taking the High Energy Photon Source as an example, we test the bunch length manipulation with harmonic cavities in a diffraction-limited storage ring (DLSR). The most important collective effects in a DLSR, intra-beam scattering and Touschek effects, are evaluated for different bunch-length patterns. Our study shows that it is feasible to produce long and short bunches simultaneously in a DLSR, without causing severe emittance growth and reduction in lifetime.

Key words: high harmonic cavity, diffraction-limited storage ring, intra-beam scattering, Touschek effects

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1 Introduction

Third generation light sources (TGLS) have brought unprecedented X-ray brightness and flux from insertion device photon sources to the synchrotron radiation scientific community. Recently, a new generation of storage ring-based light source, called diffraction-limited storage rings (DLSR), has attracted worldwide interests [1, 2]. In China, DLSR designs for the High Energy Photon Source (HEPS), a kilometer-scale, 5–6 GeV light source have been made and continuously improved [3-6]. By pushing down the emittance to approach the diffraction limit for the range of X-ray wavelengths of interest to the scientific community (e.g., ∼80 pm·rad for λ=1 nm and ∼8 pm·rad for λ=0.1 nm, with λ being the X-ray wavelength), the DLSR is able to push beyond the brightness and coherence reached by TGLSs.

However, associated with the increasing electron density in a DLSR, the strengthened intra-beam scattering (IBS) [7] and Touschek effects [8], if not well controlled, will cause evident emittance growth and reduction of lifetime. Thus, it was proposed [9, 10] to alleviate these effects by enlarging the bunch length to tens of picoseconds in a DLSR with a third-harmonic cavity, while keeping the beam current on the level of a few hundreds of milli-Amperes. It was found that the long bunches also help to keep the heat load due to induced fields at an acceptable level, to avoid excitation of high frequency trapped modes in the chamber structures, and to cope with the coupled-bunch resistive wall instabilities that are enhanced by the compact design of the vacuum chamber in a DLSR.

On the other hand, short pulses (with bunch length of a few picoseconds) have important applications in the study of fast dynamic processes in many disciplines, e.g., time-resolved experiments. Thus, developing the capability of generating short pulses is important for DLSRs. Note that several methods have been proposed to produce short electron bunches in TGLSs, including the laser slicing technique [11], crab cavity approach [12], and low-α method [13], with α being the momentum compaction factor. All these methods, however, have the drawback that the photon flux is relatively low, due to either utilization of only a small fraction of the electrons or strong perturbation of particle motions. To overcome these limitations, an alternating bunch length scheme [14] was proposed for the BESSYII storage ring by using two harmonic cavities, whose frequencies were chosen to be 3 and 3.5 times of that of the main RF cavity. This scheme allows storage of short bunches and long bunches simultaneously in the ring, with a reduction factor of 1/10–1/5 for short bunches and with the length of long bunches the same as the natural bunch length. Unlike in the case of a low-α operation mode, the transverse optics does not need to change and there is little perturbation of beam dynamics. Moreover, with such a scheme, the available beam current (limited by bursting instabilities [15]) can be greatly increased for a higher radiation power from the insertion devices.

In the following, taking one of the DLSR design for HEPS (the second version of lattice design in [6]) as an example, we test the feasibility of bunch length manipulation techniques in a DLSR by means of harmonic cavities. In Section 2, ELEGANT simulations [16] are

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performed for the bunch lengthening with one harmonic cavity and for the alternating bunch length scheme with two harmonic cavities, where we show in the latter case the bunch length of the long bunches can be further increased by tuning the voltage of the harmonic cavity. The IBS and Touschek effects are evaluated for different harmonic cavity parameter settings in Section 3. Concluding remarks are given in Section 4.

2 Bunch length manipulation in a DLSR

Due to the equilibrium between the radiation and the quantum excitation in a storage ring, the natural bunch length $\sigma_{z,0}$ (at zero current limit) and the relative momentum spread of a bunch $\sigma_{\delta,0}$ are related by

$$\sigma_{z,0}=\sqrt{-\frac{\alpha cE/e}{V' f_{\rm rev}}}\sigma_{\delta,0}, \tag{1}$$

where $f_{\rm rev}$ is the revolution frequency, c is the speed of light, E is the beam energy, e is the electronic charge, and V' is the derivative of the RF voltage with z (z is the longitudinal displacement of a particle along the ideal trajectory).

In a storage ring with fixed energy and circumference, $\sigma_{z,0}$ depends mainly on α and V':

$$\sigma_{z,0}\propto\sqrt{-\frac{\alpha}{V'}}, \tag{2}$$

which indicates that the electron bunch can be varied by changing either α or the RF parameters. As mentioned, changing α requires a change of the ring optics, which is not preferred for a DLSR, where the optics are specially designed to minimize the emittance. Thus, in this paper we discuss only the approaches of varying RF parameters.

We first consider the case with only the main RF cavity, whose voltage can be expressed as a function of the time t,

$$V(t)=V_0\sin(\omega_0 t+\varphi_{\rm s}), \tag{3}$$

where V_0 is the RF voltage amplitude, $\omega_0=2\pi f_0$, f_0 is the RF frequency, and $\varphi_{\rm s}$ is the synchronous phase which is usually close to π, $V_0\sin\varphi_{\rm s}=U_0$, and U_0 is the energy loss per turn. Then we have

$$V'=\frac{\partial V}{\partial z}|_{t=2l\pi/\omega_0}=\frac{\partial V}{\partial t}\cdot\frac{\partial t}{\partial z}|_{t=2l\pi/\omega_0}=2\pi f_0 V_0\cos\varphi_{\rm s}/c. \tag{4}$$

Since $\cos\varphi_{\rm s}\sim-1$, therefore V' is mainly determined by the product of the RF frequency and voltage. In many cases, to efficiently vary the bunch length and at the same time to keep the required voltage at a reasonable level, harmonic cavities with higher frequencies are usually adopted.

2.1 Bunch lengthening with one harmonic cavity

For a storage ring with an nth harmonic cavity, the combined function of the voltage from the main and harmonic RF system is given by

$$V(t)=V_0[\sin(\omega_0 t+\varphi_{\rm s})+k\sin(n\omega_0 t+\varphi_{\rm h})], \tag{5}$$

where $k=V_{\rm h}/V_0$, $V_{\rm h}$ and $\varphi_{\rm h}$ are the voltage and the phase of the harmonic cavity, respectively, and $V_0[\sin\varphi_{\rm s}+k\sin(\varphi_{\rm h})]=U_0$.

Taking the derivative of V with z, we obtain

$$V'|_{t=2l\pi/\omega_0}=2\pi[f_0V_0\cos\varphi_{\rm s}+nkf_0V_0\cos\varphi_{\rm h}]/c, \tag{6}$$

where l is any integer.

To maximize the bunch length, one can set the RF parameters in such a way that the absolute value of the second term in Eq. (6) is slightly smaller than the first and the two terms have opposite signs (with $\varphi_{\rm s}$ close to π and $\varphi_{\rm h}$ close to zero). Actually, the optimal bunch lengthening conditions have been obtained [17] under the conditions of V'=0 and V''=0:

$$k=\sqrt{\frac{1}{n^2}-\frac{U_0/V_0}{n^2-1}}, \tag{7}$$

$$\sin\varphi_{\rm s}=\frac{n^2}{n^2-1}\frac{U_0}{V_0}, \tag{8}$$

$$\varphi_{\rm h}=\arctan\left(\frac{1}{n}\tan(\varphi_{\rm s})\right). \tag{9}$$

For the bunch lengthening in HEPS storage ring (see Table 1 for the main parameters) with a third harmonic cavity (n=3), the optimal RF parameters can be obtained, i.e. k=0.327, $\varphi_{\rm h}=-0.0682$, $\varphi_{\rm s}$=2.94. We put these parameters in the lattice model of HEPS, and perform particle tracking with ELEGANT over 200 thousand turns (more than three damping times). The results are shown in Fig. 1. It shows that when turning on the harmonic cavity, the bunch length can be increased from 1.5 mm (the natural bunch length) to about 9 mm.

Table 1. Main parameters for the HEPS storage ring.

parameter	symbol	unit	value
energy	E	GeV	5
circumference	C	m	1364.8
current	I_0	mA	100
bunch number	$n_{\rm b}$		2200
number of particles per bunch	$N_{\rm b}$		1.3×10^9
natural bunch length	$\sigma_{z,0}$	mm	1.5
RF frequency	$f_{\rm rf}$	MHz	499.92
RF voltage	$V_{\rm rf}$	MV	6
harmonic number	h		2276
natural energy spread	$\sigma_{\delta,0}$		7×10^{-4}
momentum compaction	$\alpha_{\rm p}$		4×10^{-5}
emittance of bare lattice	ε_x	pm	51
energy loss per turn	U_0	MeV	1.07

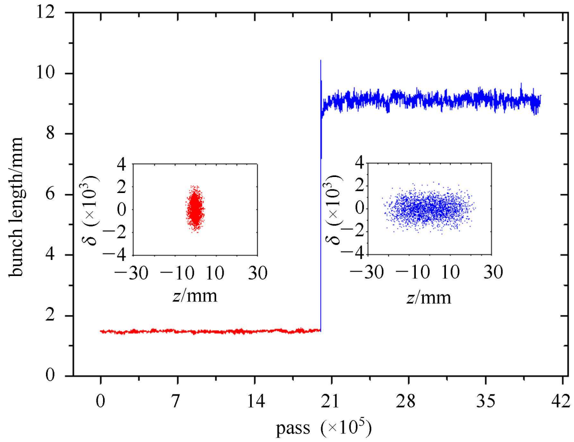

Fig. 1. (color online) ELEGANT simulation results without (red curve) and with (blue curve) harmonic cavity in HEPS storage ring. The final particle distributions in longitudinal phase space are shown in the sub-plots.

In addition, we also perform scanning of the final bunch length with $V_{\rm h}$ and $\varphi_{\rm h}$ over a large range. In each case $\varphi_{\rm s}$ is tuned to ensure that the condition $V_0[\sin\varphi_{\rm s}+k\sin(\varphi_{\rm h})]=U_0$ is satisfied. It is found that the bunch length increases as $V_{\rm h}$ increases towards 2 MV, and beyond this voltage, the bunch will split into two sub-bunches, predicting nonlinear and unstable motion in longitudinal phase space. In addition, as shown in Fig. 2, the bunch length keeps approximately constant with changing $\varphi_{\rm h}$, which is somewhat different from the analytical prediction (i.e., there exists an optimal $\varphi_{\rm h}$ resulting in the largest bunch length). It appears that the bunch length manipulation is not very sensitive to the RF phase variation. Thus, in the following study, we mainly study the dependence of the bunch length on RF voltage.

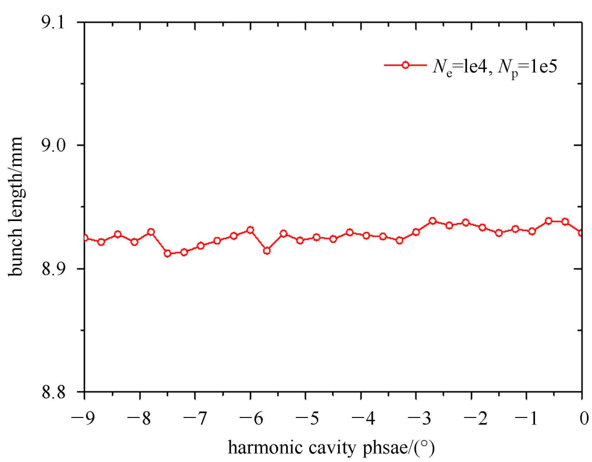

Fig. 2. (color online) Evolution of the bunch length with harmonic cavity phase, obtained with ELEGANT tracking with 10000 micro particles per bunch and over 100 thousand turns.

2.2 Alternating bunch lengths with two harmonic cavities

In the alternating bunch length scheme [14], two harmonic cavities are adopted with a frequency difference of $0.5f_0$. The combined voltage can be represented as

$$\begin{aligned} V(t) &= V_0\sin(\omega_0 t+\varphi_{\rm s})+V_{\rm h1}\sin(n\omega_0 t+\varphi_{\rm h1}) \\ &\quad +V_{\rm h2}\sin[(n+0.5)\omega_0 t+\varphi_{\rm h2}], \end{aligned} \tag{10}$$

where $V_{\rm h1}(V_{\rm h2})$ and $\varphi_{\rm h1}(\varphi_{\rm h2})$ are the voltage and phase of the harmonic cavity, respectively. For simplicity, we choose $\varphi_{\rm h1}=\varphi_{\rm h2}=\pi$.

Taking the derivative of V with z, we obtain different V' for alternating buckets,

$$\begin{aligned} V'|_{t=(2l+1)2\pi/\omega_0} &= 2\pi[f_0V_0\cos\varphi_{\rm s}-nf_0V_{\rm h1} \\ &\quad -(n+0.5)f_0V_{\rm h2}]/c, \\ V'|_{t=4l\pi/\omega_0} &= 2\pi[f_0V_0\cos\varphi_{\rm s}-nf_0V_{\rm h1} \\ &\quad +(n+0.5)f_0V_{\rm h2}]/c. \end{aligned} \tag{11}$$

As a result, the length of the electron bunches in odd buckets will be smaller than in even buckets. For convenience, in the following we use “short bunches” and “long bunches” to represent the bunches in odd and even buckets, respectively.

In Ref. [14], the RF parameters are chosen to such values that $nf_0V_{\rm h1}=(n+0.5)\ f_0V_{\rm h2}$, and the length of the long bunches is the same as the natural bunch length. In our study, it is noted that the length of the long bunches can be further increased, which is preferred in a DLSR, if adjusting the RF parameters to reach the condition below,

$$0<\frac{nV_{\rm h1}-(n+0.5)V_{\rm h2}}{V_0\cos\varphi_{\rm s}}\ll 1. \tag{12}$$

To simplify, we set $k_1 = nV_{\rm h1}/V_0$ and $k_2=(n+0.5)V_{\rm h2}/V_0$, with k_1 and k_2 being the normalized harmonic cavity voltages. Now the above condition becomes

$$0\ll k_2-k_1<1, \tag{13}$$

where the fact that $\varphi_{\rm s}\sim\pi$ is considered.

In ELEGANT simulations, we first use the same RF parameters as those in Ref. [14], i.e., n=3, $k_1=k_2$=12.5, and then slightly increase k_2. The ELEGANT simulation results are shown in Fig. 3. It shows that the bunch length of the long bunches increases as k_2 increases towards 13.5, beyond which the bunch will split into two sub-bunches. At k_2 ∼13.5, a maximum bunch length of about 6 mm can be achieved. The evolution of the bunch length and the final state of the particle distribution in longitudinal phase space are presented in Fig. 4 and Fig. 5, where the results for the case without any harmonic cavity are also shown for comparison.

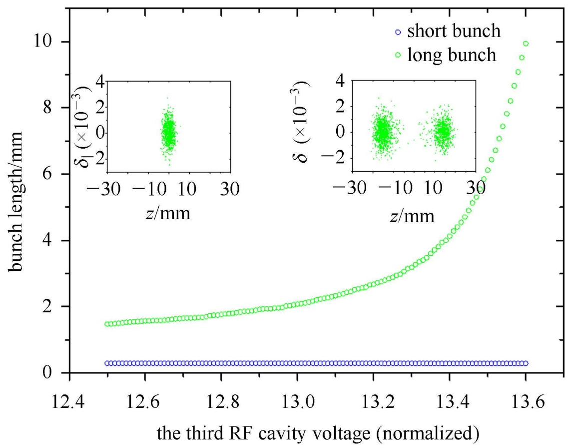

Fig. 3. (color online) Evaluation of the bunch length with normalized voltage of the third harmonic cavity, obtained with ELEGANT.

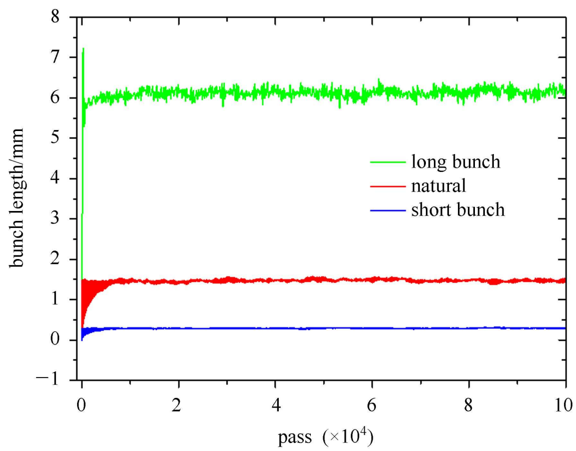

Fig. 4. (color online) ELEGANT tracking results for alternating bunch length scheme in HEPS storage ring. The results for the case without any harmonic cavity are also plotted for comparison.

From Fig. 1 and Fig. 4, it is found that the available maximum bunch length in the alternating bunch length scheme is smaller than that in the case with only one harmonic cavity. Further study reveals that this difference mainly comes from the fact that the RF potential well in the alternating bunch length scheme has a less flat bottom than that with only one harmonic cavity, as shown in Fig. 6.

3 IBS and Touschek effects evaluation

IBS and the Touschek effect are among the most important factors limiting the emittance, lifetime and other beam characteristics in a DLSR. These effects must be controlled to avoid poor performance of the ring. Therefore we evaluate the final horizontal emittance and Touschek lifetime in presence of these effects for different bunch-length patterns, with the results listed in Table 2. In the calculations, the parameters in Table 1 are used, the transverse coupling $\kappa=\varepsilon_y/\varepsilon_x$ is assumed to be 1%, and the momentum aperture ($\delta_{\rm m}$) is tracked with ELEGANT and found to be about 1.5%.

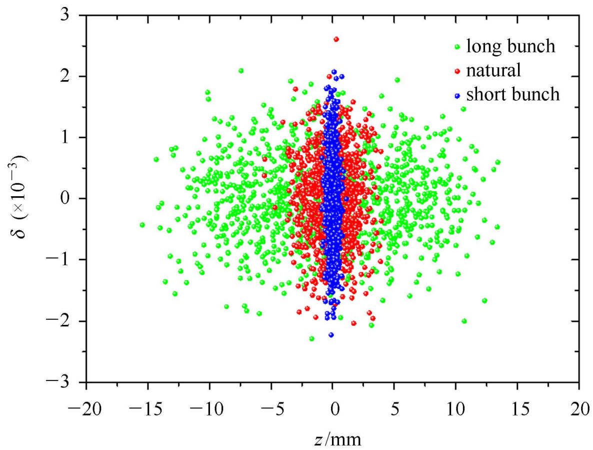

Fig. 5. (color online) ELEGANT tracking results of the particle distributions in longitudinal phase space for alternating bunch length scheme in HEPS storage ring. The results for the case without any harmonic cavity are also plotted for comparison.

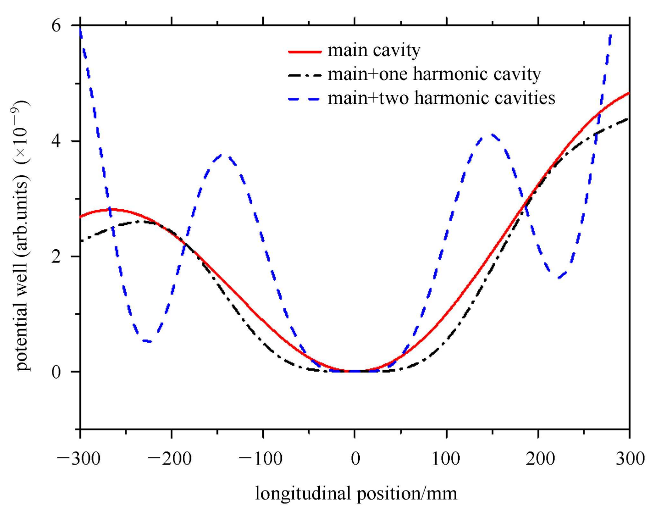

Fig. 6. (color online) RF potential wells for the cases with only the main RF cavity (red curve), with main RF and one harmonic cavity (black curve), and with main RF and two harmonic cavities (blue curve).

For the alternating bunch length scheme, it is assumed each bunch has the same number of electrons. The Touschek lifetimes for the long ($T_{\rm L}$) and short ($T_{\rm S}$) bunches are evaluated separately, by assuming only one kind of the bunches exist in the ring. The global Touschek lifetime T can be estimated by

$$T \approx T_S/f_s, \tag{14}$$

where the assumption $T_s \ll T_L$ is used, and f_s represents the fraction of the number of the short bunches among all the bunches in the ring. For instance, if there are the same number of short and long bunches in the ring, f_s=0.5, $T \approx 2\ T_S$. To increase the global lifetime, one can inject electrons into the buckets corresponding to short bunches. Note that the loss rate of the electrons in a single short bunch does not change. Nevertheless, the quick loss problem for short bunches can be overcome by frequent injecting in a top-up operation mode. In addition, according to the scaling relation of $T \propto \delta_m^5$ [18], one can increase the lifetime by enlarging the momentum acceptance of the ring. A large δ_m of about 3% is achieved in a recent HEPS design (the third version of the lattice design in [6]), which promises a long enough Touschek lifetime (~2 hours) for the short bunches.

Similarly, for the alternating bunch length scheme, the emittance growth for short and long bunches should be evaluated separately. Study shows that by further enlarging bunch length of the long bunches, the emittance growth due to IBS can be decreased from 50% (without any harmonic cavity) to about 20%.

Table 2. Final horizontal emittance and Touschek lifetime for different bunch-length patterns HEPS.

mode	bunch length/mm	Touschek lifetime τ/h	IBS ε_x/pm
nominal	1.5	0.26	75
landau cavities mode	9	1.58	58
alternating bunch length scheme_(BESSYII) long/short bunches	1.5/0.3	0.26/0.06	75/105
alternating bunch length scheme long/short bunches	6/0.3	1.06/0.06	61/105

4 Conclusions

Generally speaking, the performance of a ring-based light source can be efficiently improved by manipulating the bunch length. In this paper, taking the HEPS design as an example, we explore the feasibility of bunch length manipulation in a DLSR. The IBS and Touschek effects for different bunch-length patterns are evaluated and compared. It appears feasible to generate short and long bunches in a DLSR with a high enough beam current (100 mA or higher), while controlling the impact of the IBS and Touschek effects at an acceptable value.

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