Editors' Suggestion

Obtaining picosecond x-ray pulses from fourth generation synchrotron light sources

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Fourth generation storage ring light sources enabled by multibend achromat lattices and high-gradient magnets can reach unprecedented photon brightness. In this study, we show that, through the two-frequency crab cavity scheme, such machines also offer a unique opportunity to produce intense short x-ray pulses that are ideal for time-resolved user experiments. The short pulses and the high brightness photon beams are simultaneously available at all beamlines in a fully compatible operation mode. Owing to the small momentum compaction factor characteristic in fourth generation storage rings, the vertical emittance contribution due to coupling between the longitudinal and transverse planes by the crab cavities is small, which allows choosing a lower fractional vertical tune and in turn enables reaching the desired beam bunch tilting with a weaker deflecting voltage. However, bunch lengthening by the harmonic cavity is found to drastically increase the vertical emittance, which poses a serious hurdle to the scheme. We propose to use a half-integer harmonic cavity to simultaneously produce bunch lengthening and shortening in the bunch train to facilitate the compatible operation of the normal and short-pulse beams. A concrete case study based on the Advanced Photon Source Upgrade lattice is provided to demonstrate the system configuration and beam performance.

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I. INTRODUCTION

Storage ring based light sources are the workhorses for cutting-edge scientific research that uses high brightness x rays. Several tens of synchrotron light source facilities operate worldwide, each typically serving a few tens of experimental stations. The need for further x-ray brightness improvement has driven the development of multibend achromat (MBA) based, ultralow emittance storage rings, either as upgrades of existing facilities or as green field new projects [1–4]. These newer storage rings may be referred to as fourth generation synchrotron light sources. Besides brightness, most users traditionally care about only the integrated photon rate on the sample and are not sensitive to the time structure of the x-ray beams. However, there are also users who study dynamic processes in physics, chemistry, and biology using short x-ray pulses ranging from a few tens to a few hundreds of picoseconds. In recent years, a demand is growing from this user community to develop new capabilities on synchrotron light source facilities for expanding this range down to 1 ps.

Since the majority of the synchrotron light source users need high brightness or high flux photon beams and are insensitive to the beam time structure, it is crucial that the short pulse capabilities be compatible with the usual mode of operation. The variable pulse length storage ring (VSR) scheme is such a scheme designed to provide short pulses by using strong rf focusing of two frequencies to create two types of rf buckets [5]. The idea has been adopted in the two-frequency crab cavities (2FCC) scheme [6,7] where tilting of electron bunches is used to obtain short pulses analogous to [8]. The 2FCC scheme appears to be a promising candidate that could achieve short pulse performance in a cost-effective manner and in an operation mode compatible with simultaneous delivery of the usual high flux, high brightness x-ray beams. A previous study has investigated the performance and challenges of the 2FCC scheme for a third generation light source in detail [7]. A follow-up study [9] has demonstrated the increased value of the 2FCC for the fourth generation light sources confirmed later in [10]. As the fourth generation synchrotron light sources differ from their third generation counterparts in various aspects of beam distribution and machine lattice properties, the short pulse performance and operation

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considerations of the 2FCC scheme may also differ. A close examination may help understand the complications and provide guidance in future design studies.

In this study, we investigate the advantages and disadvantages of the 2FCC scheme on the fourth generation synchrotron light sources by applying it to the lattice of Advanced Photon Source Upgrade (APS-U), an upgrade project currently undergoing at the Argonne National Laboratory [3]. Several important aspects are discussed and illustrated with calculations or simulations. For example, the ultralow momentum compaction factor of the newer rings is found to enable choosing a lower vertical fractional tune, which reduces the required deflecting voltages of the crab cavities. The bunch lengthening harmonic cavity is found to cause a significant increase of the vertical emittance and thus severely impact the short pulse performance. An innovative approach of using a half harmonic (with frequency at a half harmonic of the fundamental rf system, such as $4.5f_{\mathrm{rf}}$, where f_{rf} is the fundamental rf frequency) cavity to simultaneously provide lengthening and shortening, respectively, for beam in different buckets is proposed to address the difficulty.

This paper is organized as follows: In Sec. II, we discuss the general considerations related to applying the 2FCC scheme to fourth generation synchrotron light sources. In Sec. III, application to the APS-U is presented, including the system layout and the choice of parameters, short pulse performance, and injection and beam lifetime simulations. The conclusion is given in Sec. IV.

II. 2FCC FOR FOURTH GENERATION RINGS

The 2FCC scheme employs crab cavities of two different frequencies, $f_1 = nf_{\mathrm{rf}}$ and $f_2 = (n+\frac{1}{2})f_{\mathrm{rf}}$. The crab cavities are placed in the same straight section and are symmetrically arranged. The beam bunches center at the zero-crossing of the crab cavity waveforms. By properly choosing the deflecting voltages for the two frequencies, the deflecting slopes of the crab cavities will cancel for half of the buckets and add up for the other half. For the buckets where the effects of the two frequencies add up, the z-dependent vertical kick by the crab cavities causes linear coupling between the longitudinal and vertical planes, which results in a tilted equilibrium beam distribution across the two planes. The photon beam radiated from the tilted electron beam will also be tilted, making it possible to select a slice of short pulse with vertical slits [6].

As the general principles of the 2FCC scheme have been previously discussed, in this report, we focus on issues or considerations specific to its application to fourth generation storage ring based light sources. One issue is the choice of betatron tune and its impact on the required deflecting voltage. Another issue is the impact of bunch lengthening harmonic cavity on the vertical emittance. We propose to use half harmonic cavity to simultaneously lengthen and shorten selected bunches as a solution to the latter issue.

A. Choice of betatron tune and deflecting voltage

The y-z coupling parameter that represents the slope of the vertical kick with respect to the z coordinate is defined as

$$\chi = \frac{e(k_1V_1 + k_2V_2)}{E_0}, \tag{1}$$

where $k_{1,2} = \frac{2\pi f_{1,2}}{c}$, c is the speed of light in vacuum, $V_{1,2}$ are the deflecting voltages of the two frequencies, respectively, e is the electron charge, and E_0 is beam energy. The tilting slopes of $\frac{dy}{dz}$ and $\frac{dy'}{dz}$ at the source points of beamlines are proportional to the coupling parameter and can be calculated, with additional parameters such as the betatron tune, beta functions at the crab cavity and the source points, and the betatron phase advances from the location of the crab cavities to the source points [6,11]. The pulse duration achievable with the scheme depends on the tilting slopes, the electron beam emittance, and the beamline optics between the photon source point and the pulse selection slit. As was shown in Ref. [7], the minimum pulse duration with the simple drift optics is given by

$$\sigma_{z,\min} = \frac{2\sin\pi\nu_y}{\chi\sqrt{1+\beta_y^2/L^2}}\sqrt{\frac{\epsilon_y}{\beta_2} + \frac{\beta_y}{\beta_2}\sigma_\theta^2}, \tag{2}$$

while the same performance metric for the imaging optics is

$$\sigma_{z,\min} = \frac{2\sin\pi\nu_y}{\chi}\sqrt{\frac{\epsilon_y}{\beta_2} + \frac{\sigma_r^2}{\beta_2\beta_y}}, \tag{3}$$

where ν_y is the vertical betatron tune, β_y is the vertical beta function at the source point, β_2 is the vertical beta function at the crab cavity, ϵ_y is the electron beam emittance, L is the drift distance between the source point and the slit, and σ_r and σ_θ are the size and divergence of the emitted photon beam by a single electron at the source point, respectively, with $\sigma_r\sigma_\theta = \lambda/4\pi$ and photon beam wavelength λ.

From Eqs. (2) and (3), it can be seen that a large coupling parameter χ and a small fractional tune are preferred for producing shorter pulses, for given beam emittance and photon beam parameters. However, it has been found that the tilted beam distribution in bending magnets contributes to an increase of the vertical beam emittance which depends on both the χ and ν_y parameters [11],

$$\Delta\epsilon_y = C_q\gamma^2\frac{\chi^2C^2\alpha_c^2\beta_2}{12J_y\rho}\frac{2+\cos 2\pi\nu_y}{(\cos 2\pi\nu_s - \cos 2\pi\nu_y)^2}, \tag{4}$$

where $C_q = 3.83\times10^{-13}$ m, γ the Lorentz factor, J_y the vertical damping partition number, ρ the bending radius, C the ring circumference, α_c the momentum compaction factor, and ν_s the synchrotron tune. It is worth noting that the $\frac{1}{\rho}$ dependence in Eq. (4) is by assuming the isomagnetic condition, which is often not satisfied in fourth generation storage rings as they typically adopt longitudinal gradient dipoles. To keep the vertical emittance low, for 2FCC applications in third generation light sources, it is preferred to have a higher fractional tune (toward the half integer). For example, for the SPEAR3 2FCC case [7], the betatron tune of $\nu_y = 6.32$ is chosen; and, for the deflecting voltage of $V_1 = 1$ MV, the corresponding vertical emittance increase is 80 pm, which is the dominant contribution of vertical emittance and is thus a limiting factor to the short pulse performance.

To maintain the same tilting slope as the betatron tune is increased, the coupling parameter χ is required to increase, which in turn requires a higher deflecting voltage by the crab cavity. Given the limited space available for the crab cavities, the requirement for a high deflecting voltage poses serious engineering challenges in cavity design. Furthermore, with a higher deflecting voltage, the disturbances to the electron beam by the crab cavities, such as the kicks on the injected beam and the Touschek scattering, also increase. Fortunately, for fourth generation storage ring light sources, the vertical emittance increase due to the crab cavity tends to be significantly smaller than third generation light sources. The main reason is that the momentum compaction factor for a fourth generation storage ring is typically much smaller than its third generation counterparts. For example, for APS-U, the combined factor $C\alpha_c = 0.0446$ m, while for SPEAR3, the corresponding value is $C\alpha_c = 0.380$ m. APS-U, as a large ring, has a significantly larger average bending radius ($\rho = 65.3$ m) than that of SPEAR3 ($\rho = 8.1$ m), which also helps decrease the vertical emittance. The small contribution to vertical emittance by the crab cavities in fourth generation storage rings allows a lower fractional betatron tune to be chosen and thus the deflecting voltage can be lowered accordingly. This is a tremendous advantage for applying the 2FCC scheme to the new generation of rings. As we will show later, a deflecting voltage of $V_1 = 0.5$ MV would be adequate to produce short pulses on the ~2 ps scale (FWHM) for APS-U, a storage ring with a high beam energy (6 GeV).

B. Emittance growth with bunch lengthening harmonic cavities

Owing to the low emittance and low momentum compaction, beam bunches in fourth generation storage rings are of considerably smaller dimensions in the horizontal and longitudinal directions than beams in third generation light sources. The resulting high beam density causes high Touschek beam loss and intrabeam scattering (IBS)-induced emittance growth. To alleviate such issues, a harmonic cavity is usually introduced to the new generation of low emittance rings to lengthen the bunches. For example, APS-U will lengthen the bunch by a factor of about 3–4 with a harmonic cavity, the frequency of which is 4 times the fundamental rf frequency [12].

If beam motion in the ring is linear and the crab cavity is a linear device, i.e., it acts on the beam with only a kick that depends on beam coordinates up to the linear order, the increase of vertical emittance due to the crab cavity should have only a weak dependence on bunch lengthening (through $\cos 2\pi\nu_s$ in Eq. (4), which is nearly equal to unity). However, as revealed in Ref. [13], with nonlinear coupling through the vertical chromaticity, the vertical emittance contribution by the crab cavity has a strong nonlinear dependence on the chromaticity as well as the bunch length.

In particle tracking simulation, we observed a substantial increase of vertical emittance for the 2FCC scheme for APS-U when the harmonic cavity is used to lengthen the bunch. In the simulation, the two crab cavity frequencies are 8 and 8.5 times the fundamental rf frequency, respectively, and the corresponding deflecting voltages are in the ratio of $V_2/V_1 = 0.967$. The bunch lengthening harmonic rf cavity (hereafter referred to as RFH) is a fourth harmonic of the fundamental rf and its voltage is set to $V_h = 0.866$ MV, as needed to cancel the linear focusing slope by the fundamental rf cavities (with a total rf voltage of 4.5 MV and one-turn radiation energy loss of

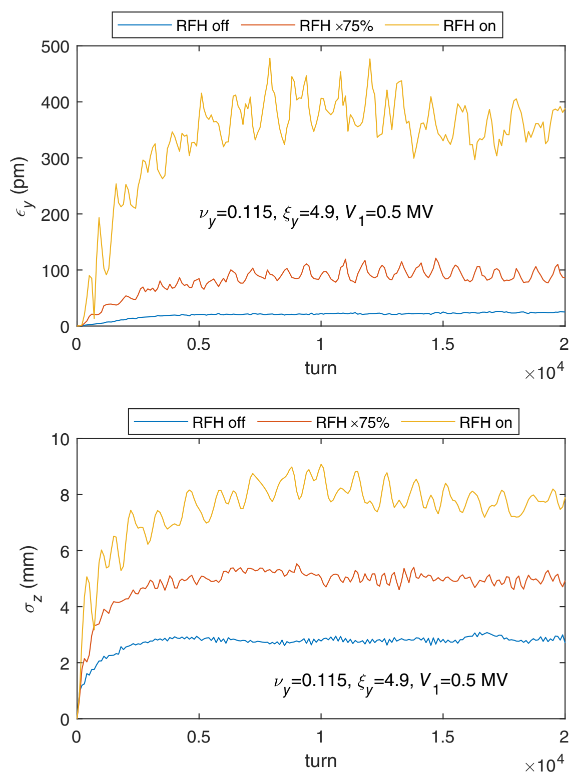

FIG. 1. Evolution of vertical eigenemittance (top) and rms bunch length (bottom) in tracking simulation with radiation damping and quantum excitation and with harmonic cavities on or off. About 1000 particles are tracked with zero initial emittance. The betatron tunes are $\nu_y = 36.115$ and $\nu_x = 95.10$, the vertical chromaticity is $\xi_y = 4.9$, and the crab cavity deflecting voltages are $V_1 = 0.5$ MV and $V_2 = 0.483$ MV.

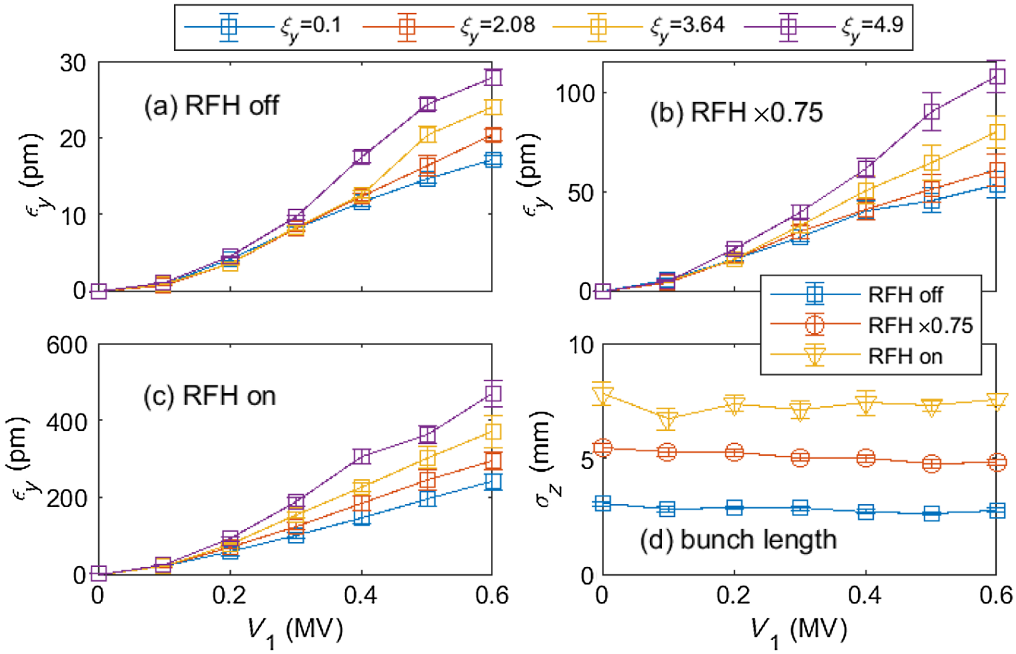

FIG. 2. Vertical eigenemittance (a–c) and rms bunch length (d) for the APS-U lattice with 2FCC obtained by particle tracking simulation as functions of the deflecting voltage V_1 (for $f_1 = 8f_{\mathrm{rf}}$) and a corresponding value for V_2 (for $f_2 = 8.5f_{\mathrm{rf}}$). Emittance for three settings of the bunch lengthening cavity: (a) RFH turned off; (b) RFH at 75% strength; (c) RFH fully turned on, with the vertical chromaticity varied on four levels, are shown. The bottom right plot (d) shows the bunch length for the three settings, with chromaticity $\xi_y = 0.1$.

$U_0 = 2.87$ MeV). In the simulation, 1000 particles are launched with initially all zero coordinates and tracked in the six-dimensional phase space using the tracking code Accelerator Toolbox (AT) [14]. Quantum excitation and radiation damping are implemented in the dipole pass method. Figure 1 shows the evolution of the vertical emittance and rms bunch length for 20,000 turns for three settings of the RFH, with it turned off, at 75% strength, or fully turned on. The deflecting voltage is $V_1 = 0.5$ MV and accordingly for V_2. The vertical chromaticity is $\xi_y = 4.9$. The emittance and bunch length reach an equilibrium, as the damping time corresponds to 4180 and 5570 turns in the vertical and longitudinal directions, respectively. The rms bunch length is $\sigma_z = 2.87 \pm 0.11$ mm (RFH off), $\sigma_z = 4.95 \pm 0.15$ mm (RFH at 75% strength), and $\sigma_z = 7.72 \pm 0.31$ mm (RFH on), respectively, where the error bars are estimated with the standard deviations of 50 observations uniformly distributed in the last 5000 turns. The corresponding vertical emittance is 24 ± 1 pm (RFH off), 90 ± 10 pm (RFH at 75% strength), and 356 ± 28 pm (RFH on), respectively. The vertical emittance is substantially higher for longer bunch lengths.

Simulation shows that the vertical emittance increase depends on the vertical chromaticity. Figure 2 shows the vertical emittance and the bunch length of the equilibrium distribution as functions of deflecting voltages for the same three settings of the RFH and four levels of vertical chromaticity. The equilibrium bunch length has a weak dependence on the deflecting voltage, due to longitudinal focusing by the crab cavities, and no appreciable dependence on the chromaticity. The emittance increase has a clear dependence on the vertical chromaticity. However, even for a near-zero vertical chromaticity, there is a significant difference in the resulting emittance between the three levels of bunch lengths, which indicates a different mechanism is also contributing to the emittance increase.

This additional emittance increase could come from the curvature of the crab cavity waveform. To test this hypothesis, we change the crab cavity frequencies to $f_1 = 4f_{\mathrm{rf}}$ and $f_2 = 4.5f_{\mathrm{rf}}$, double the deflecting voltage V_1 and set V_2 accordingly. The resulting coupling coefficient is the same as the configuration with $f_1 = 8f_{\mathrm{rf}}$ discussed earlier. Figure 3 shows the vertical emittance as a function of the deflecting voltage V_1 (for the first frequency, $f_1 = 8f_{\mathrm{rf}}$), for the cases with RFH on or off. For the cases with RFH off, as the bunch is short, the curvature of the crab cavity waveform does not make much a difference and thus the vertical emittances are the same for the two frequencies. However, for the cases with RFH on, where the rms bunch length is about 8 mm without accounting for collective effects, the waveform curvature has a significant impact on the beam, resulting in an increase to the vertical emittance, and the increase is much bigger for the $f_1 = 8f_{\mathrm{rf}}$ case than the $f_1 = 4f_{\mathrm{rf}}$ case.

The large increase in the vertical emittance due to bunch lengthening by the RFH will greatly affect the short pulse

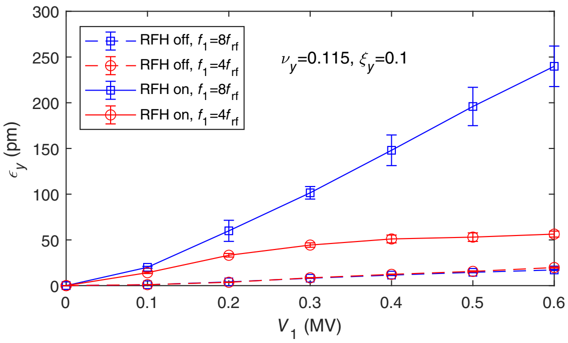

FIG. 3. Vertical emittance with crab cavity frequency $f_1 = 8f_{\mathrm{rf}}$ is compared to a case with lower frequency, $f_1 = 4f_{\mathrm{rf}}$, with the RFH on or off. The horizontal axis is deflecting voltage V_1 for the $f_1 = 8f_{\mathrm{rf}}$ case, while V_1 for $f_1 = 4f_{\mathrm{rf}}$ case is twice the corresponding value. Vertical chromaticity is $\xi_y = 0.1$ for all cases.

performance. In addition, the lengthened bunch causes a decrease in the charge density, which in turn will decrease the short pulse flux for a given selected pulse duration. The equilibrium bunch distribution in y-z and y'-z planes are shown in Fig. 4 for the cases with RFH on or off. With RFH on, the bunch length is long relative to the crab cavity wavelength such that the curvature of the deflecting voltage is clearly visible.

As discussed above, the bunch lengthening harmonic cavity common in future fourth generation synchrotron light sources poses a serious issue for the application of the 2FCC scheme to these machines. In the next subsection, we propose an innovative solution to the issue.

C. Simultaneous bunch lengthening and shortening with half harmonic cavities

Following the same principle of using a half harmonic crab cavity frequency to selectively tilt the beam bunches as in the 2FCC scheme, we propose to use a half harmonic cavity to lengthen only the regular, nontilted beams.

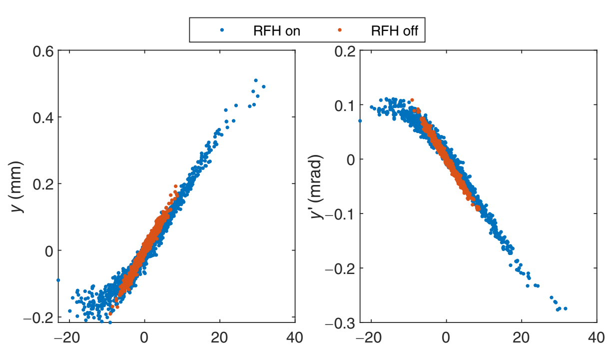

FIG. 4. The y-z (left) and y'-z (right) distributions observed at one straight section, vertical chromaticity $\xi_y = 4.9$, with crab cavities on ($V_1 = 0.5$ MV) and RFH on or off.

Unlike the BESSY-VSR scheme [5], where a harmonic cavity and a half harmonic cavity are both required in order to cancel focusing slopes of each other, here we do not need to use the harmonic cavity as we do not need to substantially increase the focusing slope. The half harmonic cavity produces the defocusing slope that cancels the focusing slope of the fundamental rf system and achieves bunch lengthening for the nontilted beam as desired in the usual case where a harmonic bunch lengthening cavity is used. At the same time, it applies a focusing slope of equal strength that will double the focusing at the tilted bunches, which would shorten the bunch length by a factor of $\sqrt{2}$. Without adding an additional rf system, this method will achieve simultaneous bunch lengthening for the regular beam and shortening for the tilted beam. It not only meets the usual requirements for the regular beam but also helps improve the short pulse performance.

It is worth pointing out that the half harmonic cavity would greatly improve the resolution of time resolved user experiments even without adopting the 2FCC scheme.

III. APPLICATION TO APS-U

APS-U is a fourth generation storage ring being built to replace the Advanced Photon Source. With an electron beam energy of 6 GeV and a circumference of 1104 m, the hybrid seven-bend achromat lattice reaches a natural emittance of 41 pm [15]. Bunch lengthening harmonic cavity is planned. In fact, a fourth harmonic cavity has been built and tested for that purpose [12]. However, for the purpose of illustration of APS-U capacity for the generation of picosecond long x-ray pulses, we will assume it to be a half harmonic cavity.

A. The 2FCC system layout

The fundamental rf frequency for APS-U is $f_{\mathrm{rf}} = 352.06$ MHz. The two crab cavity frequencies assumed in the study are $f_1 = 8f_{\mathrm{rf}} = 2.816$ GHz and $f_2 = 8.5f_{\mathrm{rf}} = 2.993$ GHz, respectively. The f_1 frequency is the same as what was adopted for the APS-SPX project [16]. To cancel the linear y'-z slopes of the two frequencies, the deflecting voltages would be related by $\frac{V_2}{V_1} = \frac{f_1}{f_2}$. However, as suggested in Ref. [6], a slight overcompensation works better for the entire bunch. For this reason, we choose $V_2 = 0.967V_1$. Two crab cavities for each frequency are assumed. If the total deflecting voltage for the first frequency is $V_1 = 0.5$ MV, the deflecting voltage for one cavity would be 0.25 and 0.242 MV for f_1 and f_2, respectively. According to previous cavity design studies [17–19], such parameters are readily achievable and there would be plenty of space for a 5-m straight section in the APS-U to host these cavities.

As discussed in Ref. [7], the crab cavities of the two frequencies should be symmetrically placed, e.g., in the $[f_1, f_2, f_2, f_1]$ configuration, such that not only the y'-z

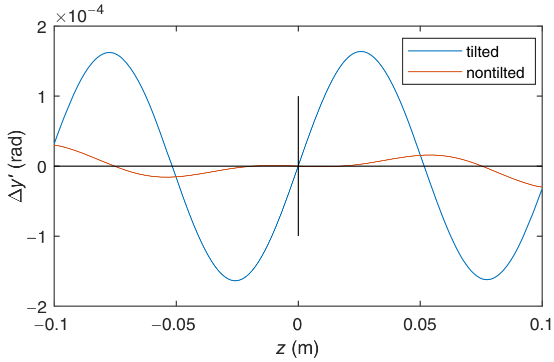

FIG. 5. The vertical kick, $\Delta y'$, received by particles with different longitudinal coordinates as they travel one pass through the crab cavity straight section, for both the titled and nontilted buckets. The nontilted bucket is shifted by one bucket separation to overlap with the tilted bucket. The deflecting voltages are $V_1 = 0.5$ MV and $V_2 = 0.483$ MV.

slope is canceled but also leaving no y-z deflection on the beam. In Fig. 5, the $\Delta y'$-z relation for particles travel one pass through the crab cavity straight section is plotted for both the titled and the nontilted (shifted by one bucket) buckets.

The total rf voltage for the fundamental rf system is assumed to be $V_{\mathrm{rf}} = 4.5$ MV, which is to provide beam energy replenishment of $U_0 = 2.87$ MeV per turn and to provide longitudinal focusing. The frequency of the half harmonic cavity is chosen to be $f_{\mathrm{rfh}} = 4.5 f_{\mathrm{rf}} = 1.584$ GHz. The voltage is set to $V_{\mathrm{rfh}} = 0.770$ MV. The momentum kick vs longitudinal coordinate by the fundamental and the fractional harmonic rf systems for the tilted and nontilted (shifted by one bucket) buckets are shown in Fig. 6.

The nominal betatron tunes for the APS-U lattices are $\nu_x = 95.1$ and $\nu_y = 36.1$ [15]. At this vertical tune, there is a considerable increase in vertical emittance due to crab cavities. However, the small fractional vertical tune also helps create a large tilt with modest deflecting voltages. Overall, we found the nominal working point for APS-U is a good choice for the 2FCC scheme.

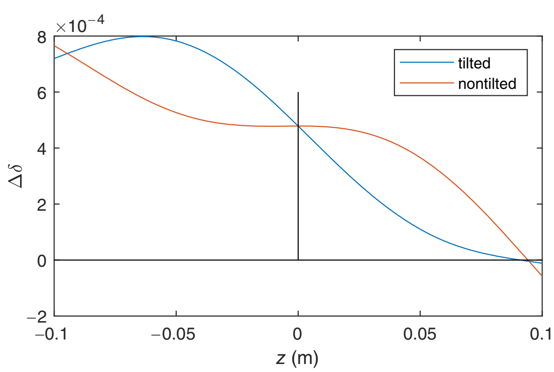

FIG. 6. The momentum kick, $\Delta\delta$, as a function of the longitudinal coordinate for particles in the tilted and nontilted buckets. The nontilted bucket is shifted by one bucket separation.

The equilibrium distribution of the beam can be obtained by six-dimensional particle tracking. To simulate the more realistic scenario, random linear coupling error sources are introduced by adding skew quadrupole components to the sextupole magnets in the lattice model. The linear coupling is needed to generate a sufficiently large vertical emittance for the regular, nontilted beam to maintain a long Touschek lifetime and to keep intrabeam scattering effects low. The fractional tunes are moved slightly apart to generate the desired emittance ratio. For example, for the error seed used in tracking simulation, the betatron tunes are set to $\nu_x = 95.1$ and $\nu_y = 36.115$ to obtain a $\sim 20\%$ emittance ratio. The tracking results show that, with crab cavities off, the long bunch has a bunch length of $\sigma_z = 7.5 \pm 0.5$ mm and the short bunch has $\sigma_z = 2.13 \pm 0.06$ mm, respectively, and the vertical emittance is $\epsilon_y = 9.5 \pm 0.7$ pm.

Figure 7 shows the equilibrium distribution in the y-z plane for the nominal setting (with crab cavities at $V_1 = 0.5$ MV and $V_2 = 0.483$ MV) for the short, tilted bunch and the elongated, nontilted bunch. The bunch lengths are $\sigma_z = 1.93 \pm 0.09$ mm (tilted) and $\sigma_z = 7.1 \pm 0.8$ mm (nontilted). The vertical eigenemittances are $\epsilon_y = 22.8 \pm 1.7$ pm (tilted) and $\epsilon_y = 10.0 \pm 0.5$ mm (nontilted).

B. Short pulse performance

Knowing the equilibrium beam parameters and the photon parameters, the minimum pulse duration can be calculated with Eqs. (2) and (3). Assuming a photon energy of 50 keV and undulator length of 4.5 m, we have photon parameters of $\sigma_r = 1.19$ μm and $\sigma_\theta = 1.66$ μrad. With $V_1 = 0.5$ MV and V_2 specified accordingly, the crab cavity coupling coefficient is $\chi = 0.01\,\mathrm{m}^{-1}$. The vertical beta function at the straight sections are $\beta_y = \beta_2 = 2.4$ m. It is assumed that the first slit is at $L = 10$ m downstream of the photon source point. Using the vertical emittance of 22.8 pm, we found that the minimum pulse duration with drift optics is $\sigma_{t,\min} = 0.80$ ps, or $t_{\mathrm{FWHM,min}} = 1.89$ ps, and

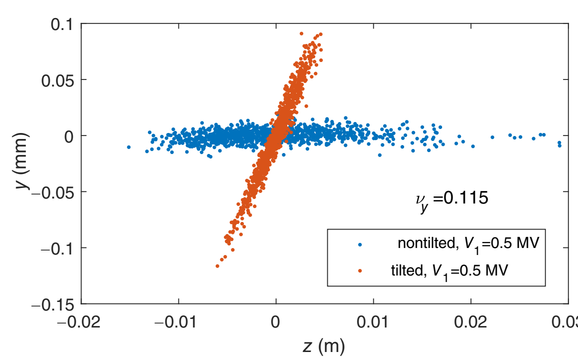

FIG. 7. The equilibrium y-z distribution at one straight section for APS-U 2FCC for the short, tilted beam and the elongated, nontilted beam. The deflecting voltages are set with $V_1 = 0.5$ MV, the vertical tune is $\nu_y = 36.115$ and the vertical chromaticity is $\xi_y = 4.9$.

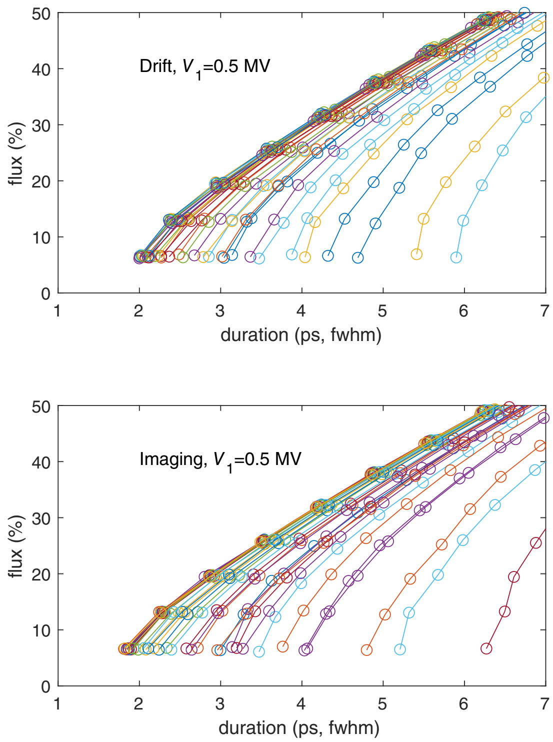

FIG. 8. The fractional flux as a function of pulse duration for APS-U for the drift optics (top) and imaging optics (bottom), with $V_1 = 0.5$ MV and accordingly for V_2 and $\nu_y = 36.115$. Each curve represents a beamline.

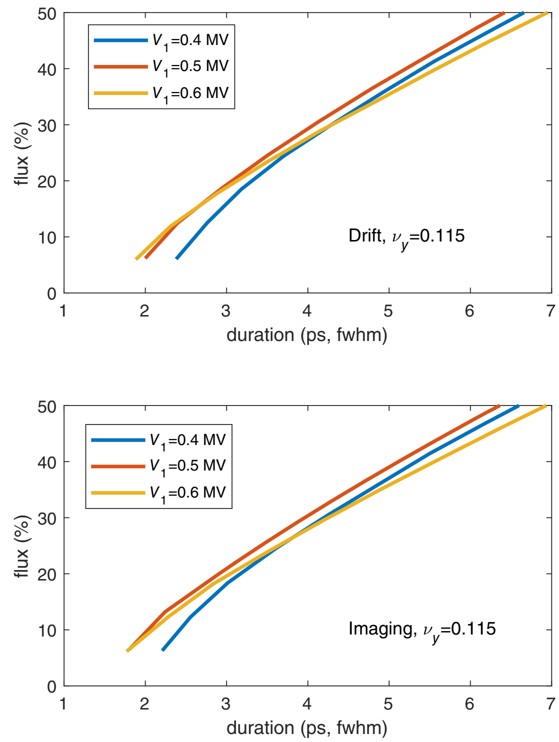

FIG. 9. The fractional flux as a function of pulse duration for the best performing beamline in APS-U for the drift optics (top) and imaging optics (bottom), with $V_1 = 0.4$, 0.5, and 0.6 MV and accordingly for V_2, and $\nu_y = 36.115$.

the minimum pulse duration with imaging optics is $\sigma_{t,\mathrm{min}} = 0.74$ ps, or $t_{\mathrm{FWHM,min}} = 1.73$ ps.

Following the practice in Ref. [7], we generate the photon beam distribution at the source point and transport it to the slit, where the short pulse selection is done and the fractional flux as a function of pulse duration can be obtained. The result is different for different beamlines as the tilting in y-z and y'-z varies with location. Figure 8 shows the results for both the drift optics and imaging optics for the 40 beamline locations. For a 6.5% flux, the pulse duration (FWHM) is down to 2.0 ps for the drift optics and 1.8 ps for imaging optics. The minimum pulse duration obtained with simulation is in good agreement with the theoretical formulas. For both drift and imaging optics, 50% of the flux can be collected for a pulse duration below 7 ps (FWHM). If a beamline is not suitable for drift optics, it would be usually suitable for imaging optics, as the y-z and y'-z slopes alternate with betatron phase advance.

Changing the deflecting voltage would impact the short pulse performance. However, as it affects both the tilting slopes and the vertical emittance, it is not immediately clear if increasing the deflecting voltage will always help. Figure 9 shows the flux vs duration curves for the best performing beamlines for the APS-U case with three levels of deflecting voltage, $V_1 = 0.4$, 0.5, and 0.6 MV, for both drift and imaging optics. It can be seen that a higher deflecting voltage decreases the minimum achievable pulse duration, as shown in the comparison of the $V_1 = 0.4$ and 0.6 curves. However, as the duration of the admitted pulse increases, the flux for the higher deflecting voltage case decreases. The $V_1 = 0.5$ MV case appears to be an optimal choice for the given 2FCC parameter set. The optimal deflecting voltage would depend on linear coupling errors, the betatron tune of the lattice, and the photon properties (energy and divergence).

We also investigated the short pulse performance for dipole magnet beamlines, using radiation from the dipole magnet at the center of the cell, which has a bending field of 0.61 T and a corresponding critical photon energy of 14.6 keV. Because the vertical divergence of the dipole magnet radiation is on the order of $\frac{1}{\gamma}$ (with a weak dependence on wavelengths near the critical photon energy), which dominates the y'-z distribution of the photon beam at the source point, the drift optics cannot be used. However, the single photon size has little effect on the y-z distribution of the photon, and consequently, the imaging optics can be used to produce short pulses for the dipole magnet beamlines. Simulation shows that the short pulse performance of dipole magnet beamlines is similar to the insertion device beamlines as shown in Fig. 9, for photon energy from 1 to 50 keV, with the minimum pulse duration at about 1.8 ps (FWHM).

The short pulse performance can be improved if the linear coupling in the lattice is reduced. This could be achieved by moving the betatron tunes further apart or better correcting the linear coupling errors. It will decrease the beam lifetime of the regular beam as the vertical beam size will decrease. However, there may be some room to make adjustment in this regard.

C. Injection and beam lifetime

For APS-U, the on-axis swap-out injection scheme will be adopted [20]. The beam injected into the storage ring comes from the booster synchrotron. The rms bunch length of the injected beam is approximately 74 ps. Hence the full injected beam will cover a large portion of a period of the deflecting waveform of the crab cavities. Some particles will see substantial kicks on each turn after injection. The crab cavities have the potential to negatively impact the injection efficiency. Given that synchrotron motion is slow and thus particles stay at the same longitudinal position for many turns, the particle motion over a fraction of the synchrotron period can be seen as oscillation about a deflected orbit. Based on such a picture and the vertical acceptance, an estimate of the maximum kick can be obtained [7]. Assuming the vertical limiting aperture is 2 mm at the ID straight section, where $\beta_y = 2.4$ m, and $\nu_y = 36.115$, we estimate the maximum kick by the crab cavities is 0.30 mrad, which corresponds to $V_1 = 0.9$ MV for the 6-GeV beam.

Tracking simulation can be performed to study the injection beam loss directly, which has the benefit of being able to account for the dynamic effects of beam motion. In the simulation, we track 2400 particles in six-dimensional phase space. The horizontal and vertical emittance of the injected beam is assumed to be $\epsilon_x = 90$ nm and $\epsilon_y = 3$ nm, respectively, while the momentum spread is $\sigma_\delta = 1.17 \times 10^{-3}$. Figure 10 shows the fraction of beam lost after injection into the short, tilted bunch for the first 4000 turns from three levels of deflecting voltages. The beam loss is less than 1% for the case with $V_1 = 0.4$ MV and at about 1.5% for $V_1 = 0.5$ MV. It rises sharply to about 4% at $V_1 = 0.6$ MV. The injection loss for the tilted bunch is acceptable. The impact of crab cavities on the long, nontilted bunch is negligible.

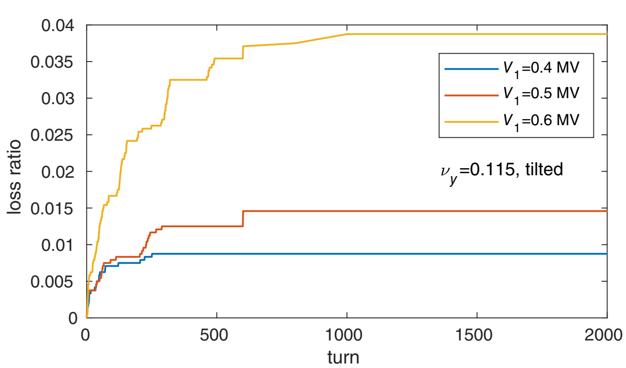

FIG. 10. The injection beam loss for three levels of deflecting voltages for APS-U 2FCC. The betatron tunes are $\nu_x = 95.10$ and $\nu_y = 36.115$.

The crab cavities may also impact the beam lifetime as the Touschek scattered particles undergoing synchrotron motion will shift to a large distance in the longitudinal direction from the bunch center, which is at zero crossing of the crab cavity waveforms (see Fig. 5), and experience vertical kicks by the crab cavities. To evaluate the impact, a tracking simulation is done to obtain the local momentum aperture (LMA) with the crab cavities and the half harmonic cavity included. Figure 11 top plot shows the LMA for half of an APS-U lattice cell for the tilted bucket, with various deflecting voltages, including $V_1 = 0$. Clearly, when powered on, the crab cavities cause a reduction of the LMA throughout the ring. The bottom plot in the figure shows the calculated Touschek lifetime for a 5-mA bunch in the tilted bucket for the corresponding deflecting voltages. The horizontal emittance of the titled bunch is assumed to be $\epsilon_x = 40$ pm, while the vertical emittance varies with deflecting voltage according to the power rule found in Eq. (4), with $\epsilon_y = 10$ pm at $V_1 = 0$ and $\epsilon_y = 22.8$ pm at $V_1 = 0.5$ MV. The bunch length in the calculation is assumed to be $\sigma_z = 3$ mm, which includes a presumed 50% lengthening at 5 mA. Because of the high bunch current and short bunch length, the beam lifetime is only 27 min even with crab cavities off. With the deflecting

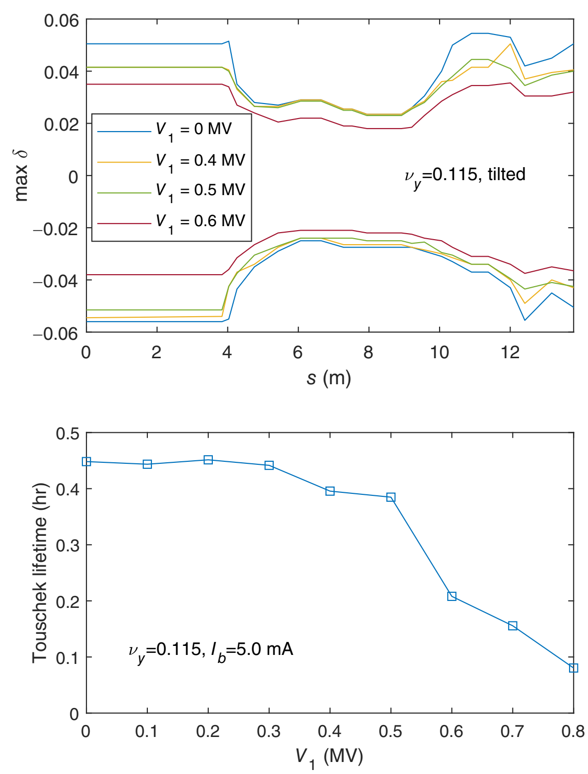

FIG. 11. Top: the local momentum aperture for half of an APS-U cell with 2FCC for beam in a tilted bucket, with $\nu_y = 36.115$. Bottom: the Touschek lifetime calculated for a 5-mA short, tilted bunch. Four levels of deflecting voltage V_1 are shown.

voltage at $V_1 = 0.5$ MV, the Touschek lifetime is 24 min. This would be acceptable; the tilted bunch can be swapped out every 5 min, resulting in an average bunch current of 4.53 mA. It is noted that while the LMA decreases for a larger deflecting voltage, at the same time the vertical emittance increases. The impact on the Touschek lifetime by the two effects cancels out to some degree. However, for $V_1 \geq 0.6$ MV, the reduction of LMA dominates, resulting much lower Touschek lifetime. There is no reduction of LMA for the nontilted bunch for V_1 up to 0.6 MV.

IV. CONCLUSION

We studied the application of the two-frequency crab cavity (2FCC) scheme [6] to fourth generation storage ring light sources for the generation of short x-ray pulses. It was found that the small momentum compaction factor, characteristic to such rings, helps ease the need to choose a high fractional vertical tune, which would be necessary for third generation rings with large momentum compaction factors due to the increase of vertical emittance by the tilted beam distribution [11]. By choosing a lower fractional tune, a lower deflecting voltage is needed to produce the same tilting slopes, which is a substantial advantage. We also found that the bunch lengthening cavities, which are often adopted in the newer rings, cause a large increase to the vertical emittance for the tilted bunch, in part due to nonlinear coupling through vertical chromaticity [13] and in part due to the curvature of the crab cavity waveforms. The large vertical emittance, in addition to the reduced charge density due to bunch lengthening, will substantially degrade the short pulse performance. To combat such an issue, we propose using a half harmonic cavity instead of a harmonic cavity to lengthen the bunches in half of the buckets while compressing the bunch length by a factor of $\sqrt{2}$ for bunches in the other half of the buckets. The buckets with bunch shortening are also the ones tilted by crab cavities. This approach would produce normal high brightness beams in elongated, nontilted form, while simultaneously generating shortened and tilted bunches for short pulse production.

The proposed scheme is applied to the APS-U lattice, assuming a half harmonic cavity with a frequency 4.5 times the fundamental rf frequency. We show that with a modest deflecting voltage of 0.5 MV for the first crab cavity frequency (2.816 GHz) and 0.483 MV for the second frequency (2.993 GHz), the short pulse duration reaches 2 ps (FWHM) and 50% of the flux can be extracted for pulse duration shorter than 7 ps (FWHM). Superconducting and normal conducting crab cavities capable of meeting the operation requirements have been designed [17–19]. Injection beam loss for the tilted bunch is only slightly reduced, while there is no noticeable impact on the nontilted bunch. The Touschek lifetime for a 5 mA shortened and tilted bunch is 24 min, for a coupling emittance ratio of 20% and including vertical emittance increase due to crab cavities.

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