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Generation of picosecond electron bunches in storage rings

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Approaches to generating short X-ray pulses in synchrotron light sources are discussed. In particular, the method of using a superconducting harmonic cavity to generate simultaneously long and short bunches in storage rings and the approach of injecting short bunches from a linac injector into a storage ring for multi-turn circulation are emphasized. If multi-cell superconducting RF (SRF) cavities with frequencies of $\sim$1.5 GHz can be employed in storage rings, it would be possible to generate stable, high-flux, short-pulse X-ray beams with pulse lengths of 1–10 ps (FWHM) in present or future storage rings. However, substantial challenges exist in adapting today's high-gradient SRF cavities for high-current storage ring operation. Another approach to generating short X-ray pulses in a storage ring is injecting short-pulse electron bunches from a high-repetition-rate linac injector for circulation. Its performance is limited by the microbunching instability due to coherent synchrotron radiation. Tracking studies are carried out to evaluate its performance. Challenges and operational considerations for this mode are considered.

Keywords: short pulse; picosecond; storage ring.

1. Introduction

Synchrotron radiation light sources have been a major source of high-flux high-brightness X-rays that are used in scientific research in condensed matter physics, material science, chemistry, environmental science, biology and medical sciences in the last few decades. One trend of synchrotron radiation light source development is to increase the photon beam brightness by reducing the electron beam emittance in the storage rings. New machines under construction will have horizontal emittances near or well below 1 nm (NSLS II, 2006; MAX IV, 2010) for 3 GeV electron beams. With the multi-bend achromat lattice design approach, upgrade lattices for existing facilities with emittances around 100 pm for 6 GeV beams have been proposed (SLAC, 2013). There are also lattice designs that have reached diffraction-limited emittances at lower beam energies (SLAC, 2013). Future machines that implement these lattices would deliver photon beams with 100–1000-fold higher average brightness than presently achieved in storage rings.

There is another direction in the development of synchrotron radiation light sources which is aimed at providing short X-ray pulses to meet the increasing demand for such capability by the user community for time-resolved experiments. X-ray pulses with lengths <10 ps (pulse length FWHM is employed throughout this article) have important applications in the study of fast dynamic processes in many disciplines. Because photon beams from storage rings usually have high repetition rate, high stability, high flux and low peak brightness (and hence linear sample response) compared with X-ray free-electron lasers, there is a unique position for storage rings in short-pulse applications. Developing short-pulse X-ray capability is important for both existing synchrotron radiation light sources and future diffraction-limited storage rings (DLSRs).

Typical pulse lengths in storage rings are 30–200 ps. There are several approaches for generating short pulses with storage rings. The laser slicing technique (Zholents & Zolotorev, 1996; Schoenlein *et al.*, 2000) generates short pulses by modulating a thin slice of the electron bunch with a laser pulse inside a wiggler, propagating the slice to a radiator that is located in a dispersive region and collecting the radiation of the modulated slice which has a considerably larger transverse size due to the increased momentum spread. This method can produce X-ray pulse lengths of 100–300 fs, but the photon flux is very low and the repetition rate is limited to below $\sim$40 kHz. The crab cavity approach (Zholents *et al.*, 1999; APS, 2011) uses a transverse deflecting cavity to apply a time-dependent transverse (*e.g.* vertical) kick to the electron beam bunch and thereby creating a vertical-angle–longitudinal-position correlation for the radiated photons. After a time of flight of 30–50 m, a vertical-position–longitudinal-position correlation in the photon pulse is developed which allows a horizontal slit to select a short pulse to pass through. The crab cavity method can generate pulse lengths of $\sim$1–5 ps with high repetition rate.

The laser slicing and crab cavity methods both pick out the radiation of a thin slice from a long bunch. Short pulses from these schemes are available only at a few photon beamlines following the modulator or the deflecting cavity. There are other methods that shorten the electron bunch lengths and produce short pulses for all photon beamlines. One simple method is to modify the storage ring lattice to reduce the momentum compaction factor (*i.e.* α) (Feikes *et al.*, 2004). In a storage ring, the equilibrium electron bunch length scales with α according to the $\sigma_z \propto \sqrt{\alpha}$ rule. Because it is usually easy to change α at third-generation light sources, the so-called low-α method provides an inexpensive way to generate short pulses. However, low-α mode has a low bunch charge in the steady state, and hence a low short-pulse photon flux, due to the longitudinal microbunching instability. Another drawback is that the low-α lattices usually have higher emittance than the normal lattices which further reduce the brightness of the short-pulse beam.

Another means to shorten the electron bunch is to increase longitudinal focusing with superconducting harmonic cavities. For the same bunch length this mode can reach much higher steady-state bunch charge than the low-α mode without increase of the emittance. With the innovative approach of using two harmonic RF systems with different frequencies (Wüstefeld *et al.*, 2011), short pulses can be simultaneously generated with regular high-charge long bunches. Therefore this is an ideal approach for short-pulse generation for future diffraction-limited storage rings.

If a full-energy high-repetition-rate linac injector is available, there is another potential approach to obtain short pulses in a storage ring. The low-emittance short-pulse beam from the linac can be injected into the storage ring and circulates for one or multiple turns (Huang, 2007; Shoji *et al.*, 2006). As the beam radiates in bending magnets *via* incoherent or coherent synchrotron radiation and tumbles in the longitudinal phase space, the beam emittance and bunch length will both grow. The longitudinal microbunching instability could spoil the beam quality quickly. But still, it is possible that the beam remains useful for a number of turns.

In the following two sections we will examine the prospects of using superconducting harmonic RF cavities and multi-turn circulation in the storage rings to generate short X-ray pulses.

2. Generation of short pulse with superconducting RF cavities

The bunch length σ_t and the relative momentum spread σ_δ of a bunch in equilibrium in a storage ring are related through

$$\sigma_t = \left(\frac{\alpha T_0 E/e}{|\partial V/\partial t|} \right)^{1/2} \sigma_\delta, \tag{1}$$

where T_0 is the revolution period, E/e the beam energy in eV divided by the unit charge, and $\partial V/\partial t$ the time derivative of the RF voltage at the synchronous phase (*i.e.* the RF voltage slope). Because the momentum spread is fixed, the bunch length can be shortened by increasing the RF voltage slope. This may be achieved by adding superconducting harmonic RF cavities to the storage ring. The main advantage of this approach over the low-α method is that, according to the Keil–Schnell–Boussard criterion (Keil & Schnell, 1969; Boussard, 1975), the single-bunch current threshold for the microbunching instability can be higher by the factor of α reduction required to obtain the same bunch length *via* the low-α method. For example, to reduce the bunch length by a factor of ten, one could increase the voltage slope by a factor of 100, or decrease α by a factor of 100. The single-bunch current threshold of the former approach is higher by a factor of 100 than the latter.

If one harmonic RF system is added, all bunches will be shortened. This may not be acceptable because short bunches cause more resistive heating on the vacuum chamber which would prevent the normal high-beam-current operation. A solution is to add a second RF system with a different frequency. If the frequencies of the first and second systems are $nf_{\rm rf}$ and $[n+(1/2)]f_{\rm rf}$, with $f_{\rm rf}$ being the frequency of the fundamental RF system, the voltage slopes of the two systems will add up at half of the original RF buckets and cancel each other at the other half (Wüstefeld *et al.*, 2011). Therefore, half of the buckets can accommodate long bunches. The RF waveforms and longitudinal phase space for this scheme are illustrated in Fig. 1, using the SPEAR3 storage ring at Stanford Synchrotron Radiation Lightsource, USA, as an example.

For low-emittance storage rings the momentum compaction factor is usually small and hence the bunch length is short, which causes a high intra-beam scattering (IBS) rate and, in turn, poor Touschek lifetime and IBS emittance growth. It is often necessary to lengthen the electron beam bunch with harmonic cavities in order to alleviate these issues. The two harmonic RF systems with frequencies $nf_{\rm rf}$ and $[n+(1/2)]f_{\rm rf}$ can be used to simultaneously shorten and lengthen electron bunches. Bunch lengthening (for long bunch buckets) can be achieved by adjusting the voltages or relative phase of the two harmonic RF systems so that the slope cancellation at the long-bunch bucket is not complete but produces a negative sum which reduces the overall voltage slope at the long-bunch buckets.

High harmonic RF voltages are required to substantially shorten the bunch length, particularly for high-energy storage rings. For the 1.7 GeV BESSY-II storage ring, to shorten the bunch by a factor of ten from the present level of 35 ps would require 3 and 3+1/2 harmonic RF cavities with voltages at 25 MV and 21.4 MV, respectively (Wüstefeld *et al.*, 2011). If similar harmonic RF systems are applied to the SPEAR3 3 GeV storage ring, the bunch length reduction factor is about 7 (from 47 ps to 6.6 ps); for the APS 7 GeV storage ring the bunch length reduction factor is only 5 (from 47 ps to 9 ps). The bunch length can be further reduced if the superconducting RF (SRF) harmonic cavity approach is combined with low-α lattices.

Because storage rings usually have limited straight section spaces available for RF cavity installation, high-accelerating-gradient SRF cavities similar to the multi-cell SRF cavities that have been proposed for the energy-recovery linacs

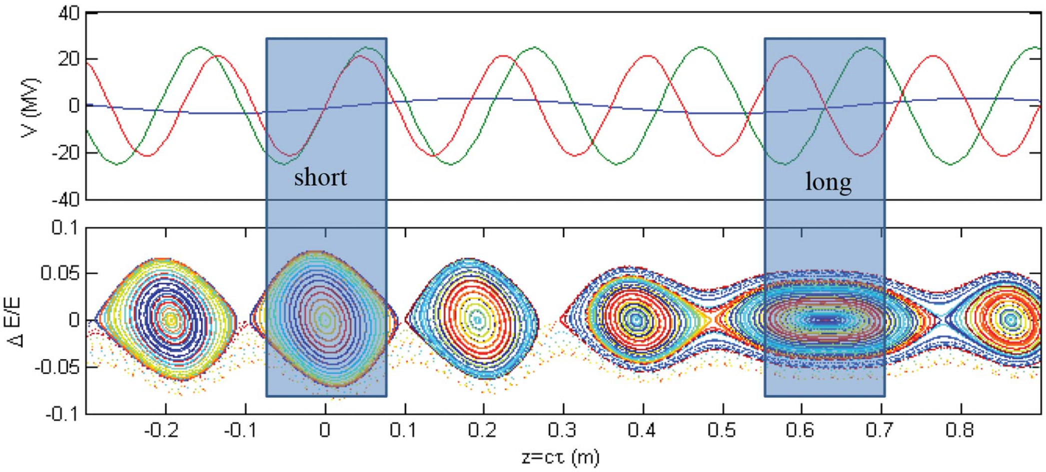

Figure 1
The voltages of the three RF systems (top) and the stable phase space areas obtained by tracking (bottom), assuming SPEAR3 ring parameters and a third-harmonic system with $V_1 = 25$ MV (green curve in top plot) and a 3 + 1/2 harmonic system with $V_2 = 21.4$ MV (red curve). The fundamental RF is at 476.3 MHz with a total gap voltage of $V_0 = 3.2$ MV (blue curve).

(ERLs) (Shemelin, 2009) are required to provide the high voltages in the frequency range. If the aforementioned RF cavities are to be housed in a 5 m-long straight section, the required accelerating voltage gradient for the cavities would be in the 15–20 MV m^{-1} range, considering extra space is needed for cryostats, *etc*. Although the accelerating voltage gradient requirement is not demanding with today's superconducting RF technology, it is challenging to use such cavities in a high-current storage ring. This is because the multi-cell cavities have many unwanted modes other than the fundamental accelerating mode. These modes may be excited by the electron beam to cause resistive heating in the cavity or coupled bunch instabilities for the beam. Mitigation of these effects through cavity design, RF control or beam feedback is critical for the feasibility of the two-harmonic SRF bunch-shortening approach.

3. Multi-turn circulation of short bunches in storage rings

3.1. General considerations

If a high-repetition-rate full energy linac injector is available, an alternative method of obtaining short pulses from a storage ring is to make use of the injected short electron bunch before the beam quality degrades to an unacceptable level. For a linac that simultaneously serves an X-ray free-electron laser (FEL), the initial beam quality is usually high compared with the equilibrium beam in a third-generation light source (*e.g.* the nominal LCLS-II normalized emittance is 0.5 µm, corresponding to 85 pm at 3 GeV, as compared with the equilibrium emittance of the SPEAR3 storage ring of 10 nm). So the short photon pulse would also have high brightness. As the electron bunch circulates in the ring, its emittance will grow due to the quantum excitation of synchrotron radiation. The bunch length would also grow due to momentum spread growth caused by synchrotron radiation and phase slippage. For a short bunch with high charge, the microbunching instability due to coherent synchrotron radiation is likely to occur, which could quickly spoil both horizontal emittance and longitudinal beam distribution. It is therefore necessary to investigate the beam quality evolution during the circulation of the injected beam in a storage ring for the parameter space of interest.

There may be various scenarios for this mode of operation. First, the storage ring can be dedicated to this mode by operating with only the short bunches, or the injected short bunches can be inserted into a gap between the regular bunches of the storage ring. The latter case (which may be referred to as the hybrid mode) is ideal in fully utilizing the potential of the storage ring. But it is more complicated because it would require two injection systems: an on-axis injection system for the short bunches and an off-axis injection system for the regular bunches. Alternatively all bunches could be injected on-axis as discussed below. On-axis injection is required for the short bunches because the injected beam needs to be on the design orbit for its radiation to be directed toward the beamlines. Off-axis injection is needed for the regular bunches if accumulation is required. If the storage ring is a DLSR that has too small a dynamic aperture for accumulation, the same on-axis injection system can be used for both the short bunches and the regular bunches. However, the linac injector has to deliver the injected beam in two different modes: one single pulse for the short bunch and a continuous bunch train for the regular bunches. For the dedicated short-bunch mode, the storage ring lattice can be optimized for short bunches, for example, with an appropriate momentum compaction factor that maintains the bunch length from phase slippage while avoiding significant microbunching in the desired number of turns. However, for the hybrid mode the lattice may have to be optimized for the regular bunches to yield highest brightness.

Because the quality of the injected beam varies each turn, the brightness of the radiated photon beam at each beamline will also vary for each successive pass. This is a major disadvantage of the multi-turn circulation mode. If the repetition rate of the linac injector is very high (*e.g.* 100 kHz to 1 MHz), the injected short bunch can circulate for only one turn before being dumped. In this case the short-pulse photon beam brightness will be stable at each beamline. However, the beam power to be dumped in this mode would be very high, which requires substantial effort in radiation protection. For example, if a 200 pC bunch at 3 GeV is circulated and dumped at 1 MHz, the beam power at the dump would be 0.6 MW.

One of the challenges of the multi-turn circulation of short bunches is that the beam centroid loses energy to coherent synchrotron radiation. If not compensated with RF cavities, the extra energy loss will cause the short bunch to shift in transverse position at the radiation source points if these locations are dispersive and lose synchronism with the photon experiments due to phase slippage. Therefore, for short-pulse and high-charge cases, for which CSR energy loss is significant, the timing of the injected bunch should be chosen so that the energy of the beam centroid is approximately constant for successive turns. Multi-turn circulation also requires precise control of the initial transverse position and angle of the injected beam to avoid oscillation of the photon beam source points.

Special challenges exist if the linac injector is also an FEL driver that operates simultaneously with the multi-turn circulation mode because the beam parameter requirements for the two modes may be different in beam energy, bunch charge, bunch length and momentum spread. Switching between the two modes on the kHz to MHz time scale is very difficult and may be possible only if careful planning is incorporated at the early stage of the linac design. Synchronization between the linac and the storage ring is important and could be challenging if the two systems are not originally designed to work together (such as the SLAC linac and SPEAR3). The transport line between the linac and the storage ring also needs to be carefully designed to minimize beam quality degradation.

3.2. Microbunching instability for the circulating bunch

Under certain conditions, the initial noise on the longitudinal distribution can be exponentially amplified by coherent synchrotron radiation (CSR), causing the so-called CSR microbunching instability. This is not a problem for the regular long bunches in the storage ring because the CSR wake is suppressed by vacuum chamber shielding. However, the microbunching instability is a limiting factor for the performance of the injected short bunch because such a shielding effect is weak or absent. The CSR microbunching instability has been extensively studied in recent years (Huang & Kim, 2002; Stupakov & Heifets, 2002; Bane *et al.*, 2010). In the following we use the approach developed by Huang & Kim (2002) to study the amplification of the bunching factor for a circulating bunch. The bunching factor is defined as

$$b(k;s) = \int \mathrm{d}\mathbf{X} \exp(-ikz) f(\mathbf{X}), \qquad (2)$$

where k is the wavenumber for a mode, s is the path length, $\mathbf{X} = (z, \delta)$ the longitudinal coordinates and $f(\mathbf{X})$ the normal-

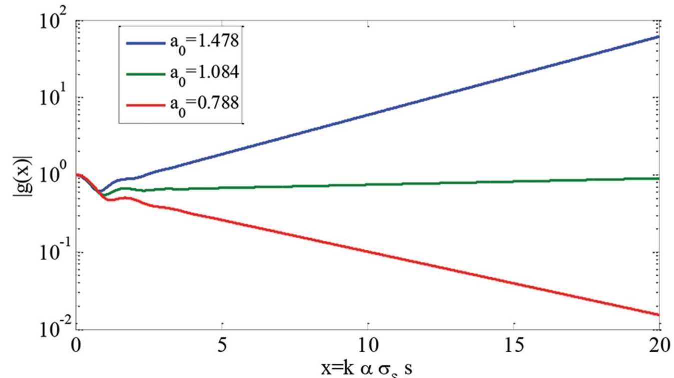

Figure 2
The gain factor by numerically solving equation (3). The scaling parameter $a_0 = (I_0/\gamma I_A \alpha\sigma_\delta^2)[1/(k\rho)^{2/3}]$ is dimensionless.

ized longitudinal phase space distribution. If we consider the beam on a circular orbit such that $R_{56}(s) = \alpha s$ with α being the momentum compaction factor, the integral equation [equation (20) of Huang & Kim (2002)] that governs the evolution of the bunching factor due to initial density modulation becomes

$$g(x) = \exp\left(-x^2/2\right) + a_0 A \int_0^x \mathrm{d}x'(x-x') \exp\left[-(x-x')^2/2\right] g(x'), \qquad (3)$$

where $x = k\alpha\sigma_\delta s$, $A = 1.63i - 0.94$, $a_0 = (I_0/\gamma I_A \alpha\sigma_\delta^2)[1/(k\rho)^{2/3}]$, σ_δ is the relative momentum spread, I_0 is the peak current, I_A = 17045 A the Alfvén current, γ the Lorentz energy factor, ρ the bending radius and $g(x) = b(k;s)/b(k;0)$ the amplification factor of the bunching factor for wavenumber k. Here we assume the initial beam distribution is Gaussian, there is no chirp in the longitudinal distribution and hence no bunch compression, and ignore the transverse effects. Equation (3) can be numerically solved. For the three cases shown in Fig. 2, the initial bunching is either exponentially amplified, stays roughly unchanged for the duration considered, or is suppressed.

The above simplified model gives an estimate of the microbunching instability threshold and the gain of the bunching factor above the threshold. According to the numerical result, the instability threshold is $I_{\rm th} = 1.10\gamma I_A \alpha\sigma_\delta^2 (k\rho)^{2/3}$, which strongly depends on the momentum compaction factor and the momentum spread of the beam. This instability threshold is consistent with the theory of Stupakov & Heifets (2002), with only a modest difference in the numerical factor. For the multi-turn circulation mode, the beam does not have to stay below the instability threshold because it is short-lived. However, because of the exponential growth of the bunching factor, the threshold can be exceeded by only a small fraction. The more turns that the beam is stored, the less the peak current can go above the instability threshold.

3.3. Tracking studies

Numerical tracking can give a more complete picture of the evolution of beam quality during circulation. We conducted tracking studies for several scenarios of short-bunch beam circulation in the SPEAR3 storage ring (see Table 1 for its

Table 1
SPEAR3 nominal parameters.

Circumference	234 m	Beam energy	3 GeV
Horizontal emittance	10 nm	Momentum spread	0.1%
RF frequency	476.3 MHz	Energy loss per turn	1.0 MeV
Bending radius	8.15 m	Momentum compaction	0.0016

parameters). The tracking code *elegant* (Borland, 2000), which is capable of modelling the CSR effect on the beam (Borland, 2001), was used in this study.

To be realistic, the longitudinal distribution of the injected beam is obtained by tracking the LCLS beam and adjusting the linac phase, bunch compressor R_{56} parameter and the laser heater power for desired beam parameters. The number of macro-particles in the simulation is 200000. Because the number of macro-particles is significantly fewer than the actual electron numbers, the CSR simulation results may be pessimistic as artificial noise could be introduced to the longitudinal distribution. The smoothing routine of *elegant* was used to reduce the initial shot noise before tracking. For one of the cases (200 pC charge, 1 ps bunch length, for 20 turns) the simulation was repeated with the number of macro-particles increased to 1×10^6 and the results were very similar. This indicates that the number of macro-particles in our simulation is sufficient. The longitudinal distribution for a bunch length of 1 ps and two levels of slice energy spread are shown in Fig. 3. The slice energy spread is determined by the LCLS laser beam heater. The longitudinal emittance for the case with $\sigma_\delta = 0.3 \times 10^{-4}$ at a bunch length of 1 ps is close to the nominal operating condition of LCLS.

The beam is tracked through two SPEAR3 lattices: the nominal low-emittance lattice (see Table 1) and a low-α lattice for which the momentum compaction factor is $\alpha = 1.46 \times 10^{-4}$ and the horizontal emittance is 35 nm. It is observed that for the low-emittance lattice the bunch lengthens quickly due to a large momentum compaction factor. Even for a weak beam (50 pC) the bunch length grows from 1 ps to 7 ps after ten turns. Therefore the nominal low-emittance lattice is not suitable for multi-turn circulation of short bunches. A moderate reduction of α is chosen for the low-α lattice to avoid large phase slippage-induced bunch lengthening while maintaining reasonable microbunching instability threshold. The evolution of several important beam parameters in 20 turns for a beam with an initial bunch length of 1 ps and three levels of bunch charge is shown in Fig. 4. The results indicate that a bunch with 50 pC charge can circulate 20 turns, and a bunch of 100 pC for ten turns before the bunch length roughly doubles. The horizontal emittance and momentum spread increase for both cases, to a level that is probably acceptable. The longitudinal profile for the 100 pC case after one and several turns is shown in Fig. 5. The microbunching instability for modes with wavelengths of 20–25 μm is clearly seen.

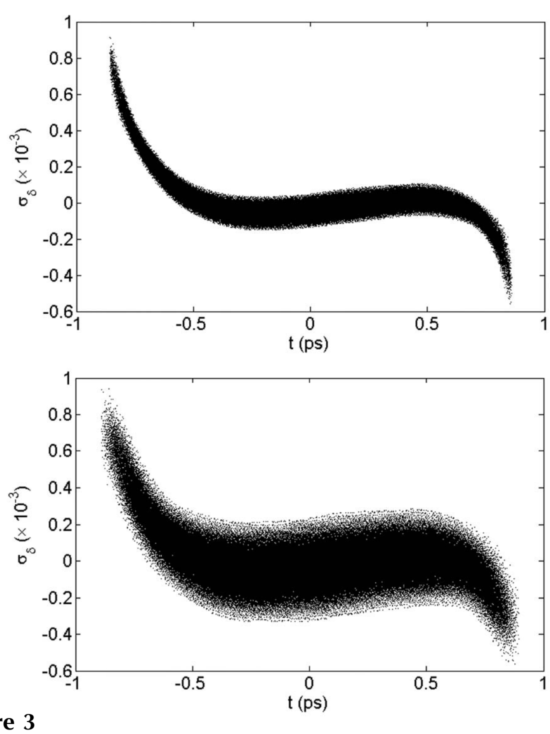

Figure 3
Initial longitudinal distribution of a beam with bunch length of 1 ps and slice energy spread of $\sigma_\delta = 0.3 \times 10^{-4}$ (top) and $\sigma_\delta = 0.9 \times 10^{-4}$ (bottom).

The low-emittance lattice is more suitable for the case when the injected short bunch is used only for one turn. It is preferable to inject high charge in the bunch while keeping emittances low. In Fig. 6 the beam parameters after one turn of circulation as functions of bunch charges are plotted for various initial slice momentum spread. If we require the normalized horizontal emittance to be less than 2 μm, then a bunch charge of 300 pC is possible for an initial slice momentum spread of $\sigma_\delta = 0.3 \times 10^{-4}$. Higher initial momentum spread helps suppress microbunching instability and allows more charge in the bunch. But it would require high laser power for the laser heater, which may reduce the repetition rate of the system.

4. Conclusion

We have discussed two approaches for obtaining short electron bunches in storage rings that can produce short X-ray pulses to all photon beamlines. The approach of using two SRF harmonic cavity systems can support short-pulse capability with pulse lengths from below 1 ps to 10 ps (FWHM) and simultaneous high-flux high-brightness operation. It is ideal for existing and future storage-ring light sources that seek a substantial capability for time-resolved experiments. But a significant R&D effort is required to adapt the present high accelerating gradient SRF technology for high-current storage ring operation by mitigating the effects of unwanted modes of the SRF cavities.

Injecting short electron bunches from a linac injector into a storage ring for one or multiple turns may be an alternative way of generating short X-ray pulses. It is flexible in bunch charge and bunch length. Its performance is severely limited by the CSR-driven microbunching instability which may increase the horizontal beam emittance, momentum spread and in turn the bunch length quickly. Simulation shows that it is possible for a bunch with 100 pC charge, 1 ps (FWHM) bunch length and reasonable slice momentum spread (σ_δ =

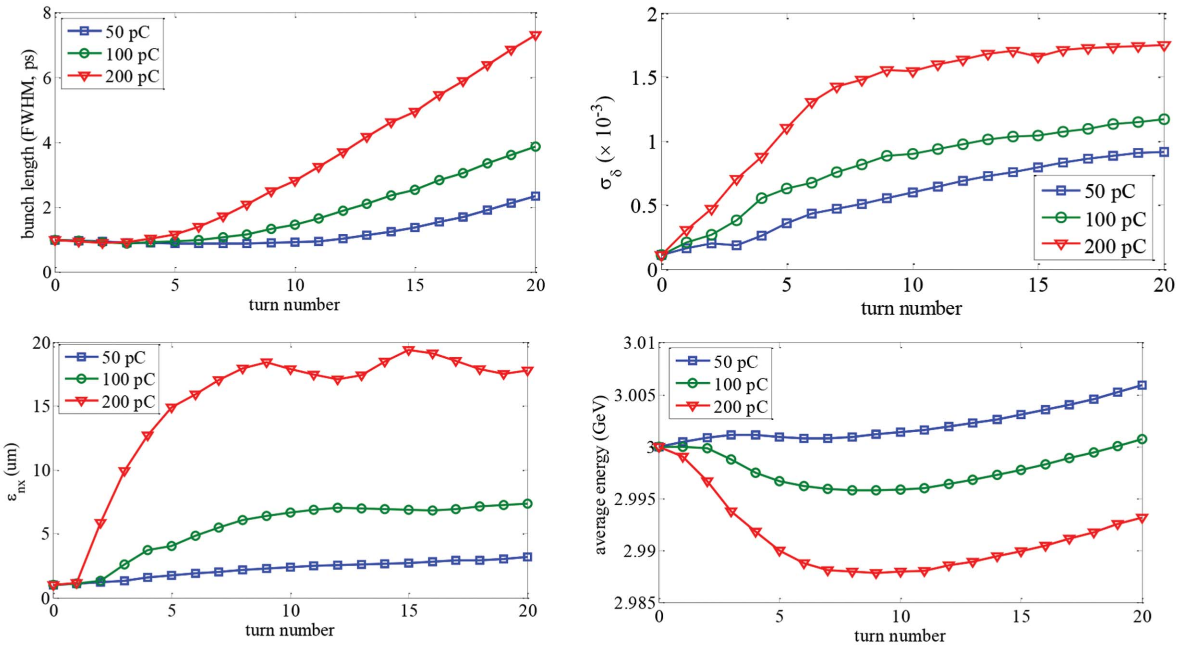

Figure 4
Evolution of beam quality in 20 turns for a bunch with initial length of 1 ps, slice momentum spread $\sigma_\delta = 0.3 \times 10^{-4}$ and normalized emittances (x and y) of 1 µm circulating in the SPEAR3 low-α lattice ($\alpha = 1.46 \times 10^{-4}$). Top left: bunch length; top right: momentum spread; bottom left: normalized horizontal emittance; bottom right: average beam energy.

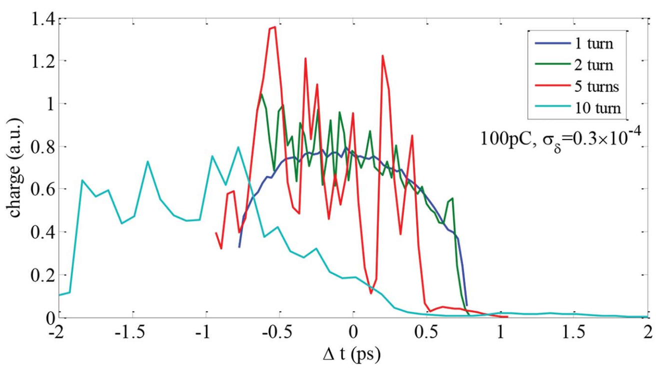

Figure 5
Longitudinal profile of the circulating beam in a low-α lattice after 1, 2, 5 and 10 turns, with bunch charge 100 pC, initial slice momentum spread $\sigma_\delta = 0.3 \times 10^{-4}$ and bunch length 1 ps.

0.3×10^{-4}) to circulate in a SPEAR3-size storage ring and remain usable for about ten turns. If the electron bunch is used for only one turn, the bunch charge can be 300 pC or higher, depending on the emittance growth requirement and initial slice momentum spread. The high beam power to be dumped is a significant challenge in radiation protection. There are also many other challenges in integrating a FEL driver linac and the storage ring for the multi-turn circulation mode, such as resolving the discrepancies in the requirements for beam energy, bunch length and bunch charge by the FEL and the storage ring on a high-repetition-rate basis.

The predicted performance of the two short-pulse schemes discussed above for SPEAR3 is summarized in Table 2 in comparison with the existing capability of the machine.

Table 2
Expected performance of the two short-pulse schemes for SPEAR3.

Machine and mode	Pulse length (ps, FWHM)	Camshaft bunch charge (nC)	Repetition rate (MHz)	Camshaft 8 keV average flux† [photons s^{-1} (0.1% bandwidth)$^{-1}$]
Standard lattice, camshaft 5 mA	54	3.9	5.1	1.6×10^{13}
Low-α, α/34, 100 mA	10	0.106	5.1	4.3×10^{11}
Standard lattice w/SRF upgrade	6.6	2.34	5.1	9.6×10^{12}
Low-α, α/41, w/SRF upgrade	1.3	0.044	5.1	1.8×10^{11}
Low-α, α/550, w/SRF upgrade	0.35	0.0020	5.1	0.8×10^{10}
Ten-turn circulation	1.0	0.10	1.3	1.0×10^{11}
One-turn circulation‡	0.5–1.0	0.15–0.30	1.3	$1.6–3.1 \times 10^{11}$

† SPEAR3 BL12-2 is assumed for flux calculation (λ = 22 mm, 67 periods, $k_{\max}$ = 2.17). ‡ Brightness for the circulation modes is significantly higher than the other modes for the same flux because the horizontal emittance is 30–60 times smaller.

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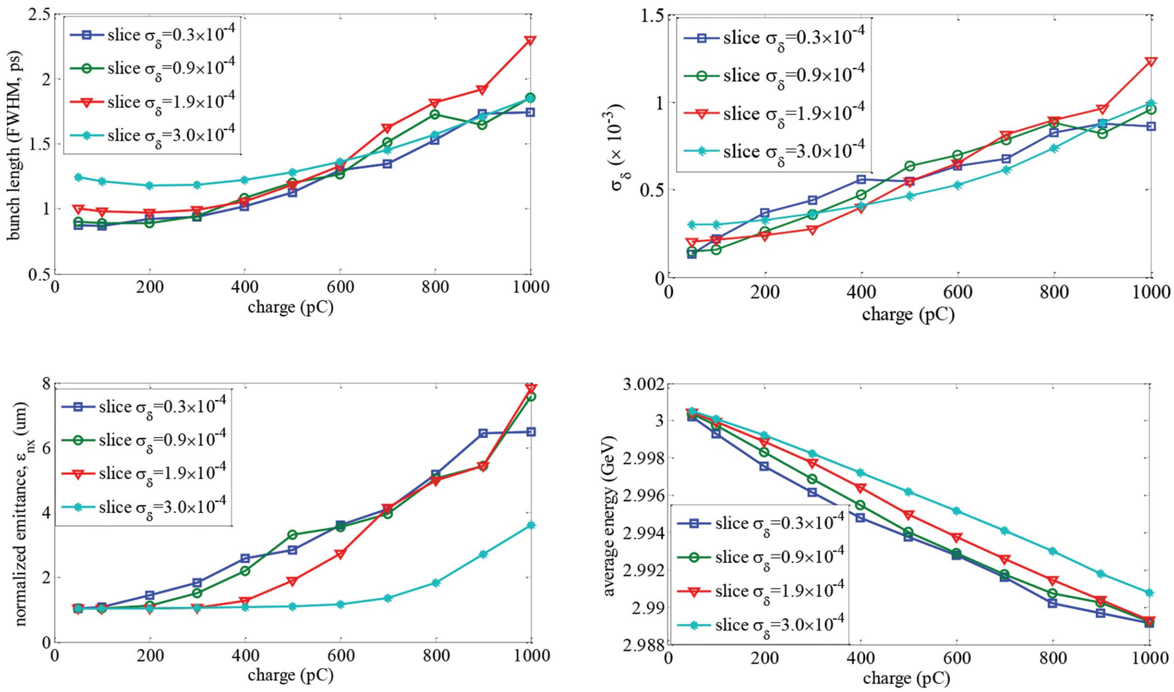

Figure 6
Beam parameters after one turn for a bunch with initial length of 1 ps and normalized emittances (x and y) of 1 μm circulating in the SPEAR3 nominal lattice. The initial slice momentum spread can be changed by adjusting the laser heater power in the linac.

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