A Super-Bright Storage Ring Alternative to an Energy Recovery Linac ⋆

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Abstract

One of the promised characteristics of an Energy Recovery Linac (ERL) as a synchrotron light source is the very low emittance of the electron beam. A difficulty with ERLs is that, as yet, no one has demonstrated a gun that delivers average currents comparable to what has been demonstrated in storage rings, i.e., 0.1 to 1 A, with the required emittance and for the long periods of time necessary for a user facility. As an alternative to an ERL, one might consider a super-bright storage ring with short lifetime, requiring fast top-up. We present a possible replacement ring for the Advanced Photon Source with 0.5-micron normalized emittance at 7 GeV, along with a discussion of design challenges and operating considerations.

Key words: synchrotron radiation sources
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1 Introduction

The Advanced Photon Source (APS) is a 7-GeV, third-generation synchrotron radiation facility supplying x-ray beams to approximately 50 experimental stations. Development of the remaining beamlines and build-up of experimental stations will continue into the foreseeable future, resulting in a complex, costly accumulation of facilities and equipment surrounding the APS ring. At present, few APS users are truly limited by the available source properties. However, we expect this to change and that eventually the APS ring will need to be upgraded. One of the options we are exploring is a replacement storage ring with ultra-high brightness.

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The requirements for this ring are that it must fit in the existing APS tunnel and must preserve the existing insertion device (ID) beamlines. This implies that we will have a periodicity of 40, or some multiple thereof, in the lattice. Ideally, we would like to preserve the existing bending magnet beamlines as well.

The goal is to provide a thousand-fold increase in average brightness. We sought to achieve this through a combination of improvements:

- Decreasing the emittance by a factor of about 50. The present effective emittance is 3.1 nm. Rings like APS are capable of operating diffraction-limited in the vertical plane for 1-$\AA$ radiation. Hence, the brightness gain will come mostly from improving the horizontal emittance.
- Allowing for undulators that are at least twice as long as the typical 2.4-m device in use today.
- Assuming that stored current could be increased from the present 100 mA to 1 A. This is less than what is presently achieved in B-factories [1].

In order to maintain the same spectral reach that APS users enjoy today, we have kept the ring energy at 7 GeV. In addition to making high-energy x-rays easier to produce, this energy reduces intrabeam scattering, improves lifetime, and mitigates instabilities. These are highly desirable features when pushing the emittance and current to extreme values.

As might be anticipated, obtaining sufficient dynamic and momentum aperture is very difficult in the proposed ring. At this point, this is an unsolved problem that will be addressed in future publications.

2 Design Concepts

The equilibrium emittance in a storage ring is given by [2]

$$\epsilon = \frac{55}{32\sqrt{3}}\frac{\hbar\gamma^2}{mc}\frac{I_5}{I_2 - I_4}. \tag{1}$$

The relevant radiation integrals I_i are

$$I_2 = \int \frac{1}{\rho^2} ds, \tag{2}$$

$$I_4 = \int \frac{(1-2n)\eta}{\rho^3} ds, \tag{3}$$

and

$$I_5 = \int \frac{H}{|\rho^3|} ds, \tag{4}$$

where

$$H = \frac{1}{\beta} \left(\eta^2 + (\beta\eta' + \alpha\eta)^2 \right). \tag{5}$$

Clearly, a basic requirement is to keep the dispersion as low as possible in order to make H small. Generally, this requires strong focusing and many short, weak dipole magnets. Unfortunately, stronger focusing results in higher natural chromaticity, correction of which requires stronger sextupoles that introduce strong nonlinearities into the lattice. The low dispersion also contributes to the increased strength requirement for the sextupoles.

In addition, it is helpful to use a non-zero field index n in the dipoles in order to make I_4 negative and increase the denominator in equation (1). This will increase the equilibrium energy spread, which is generally not an issue in storage ring light sources unless the energy spread is so large that we have difficulty with lifetime. Of course, if we are seeking to minimize the effective emittance (beam size times divergence) and have dispersion at the observation point, it can become important.

One obvious idea for the APS is to double the number of cells from the present 40 to 80. This allows shorter dipoles and less distance between focusing elements, both of which allow reducing the dispersion and hence reducing the emittance. An example of such a design was reported in [3], providing an improvement of a factor of 10 in the emittance. In this design, we essentially reduced the length of all magnetic elements by 50%. We also added a gradient to the dipole magnets.

This lattice falls short of our goal of a fifty-fold reduction in the emittance. As a result, more speculative concepts were developed. Among the assumptions of these concepts was the use of combined-function permanent magnets in order to allow fitting many short components into the ring. In particular, we envisioned using twelve-pole magnets as combined quadrupole/sextupole magnets. We also envisioned using combined function dipoles including a gradient and sextupole term.

A lattice based on this concept was presented in [3], but the results for this lattice were later found to be incorrect due to a data entry error. Further work resulted in a new lattice that was inspired by the example of the Stanford Linear Collider arcs, which feature long, relatively weak dipole magnets with alternating gradients and an integrated sextupole field [4]. As in the previous work, we assume that twelve-pole magnets are used for combined quadrupole/sextupole magnets.

As an aside, we note that the use of permanent magnets has a distinct advantage for a high-brightness ring, namely, the elimination of power supply ripple as a source of beam motion. The ring will of course still require electromagnetic steering magnets. We assume that these would be incorporated into some number of the twelve-pole magnets.

3 Design Details

The lattice, designated XPS7 (eXtreme Photon Source version 7), was designed using the program `elegant` [5]. The optimization feature of `elegant` allows simultaneous optimization of lattice functions, effective emittance, tunes, chromaticities, and tune shifts with amplitude.

The matching began by optimizing a cell consisting of a vertically-focusing gradient dipole (VD) and a horizontally-focusing quadrupole (QF). The horizontal damping partition number [2] was constrained to $J_x \geq 1$. The length of the cell was chosen as 1.65 m, giving a modest bending radius of about 30 m, somewhat shorter than the present value of 38 m. With six such cells, we have used up 9.9 m of the available 27.6-m sector length.

Bracketing these arc cells are the dispersion and beta function matching modules. We chose to match the dispersion to zero in the straight sections in order to eliminate the dispersion contribution to the effective emittance and to reduce undulator effects on the emittance. The dispersion matching uses a missing-magnet approach: exiting the last regular cell we have a QF-QD-QF-VD′ arrangement, where VD′ is a short dipole with a different gradient than the arc cell dipoles. Following this dipole are four more quadrupoles in a QF-QD-QF-QD arrangement. These are used for beta function matching into the straight section. Except for the arc magnets, we assumed all gradients were individually variable.

In order to enhance the brightness, we sought to optimize the beta functions at the center of the ID straights to provide the best match to the undulator radiation. An undulator of length L emits radiation that has an effective beta function of $L/2\pi$ [6]. For the XPS7, the maximum value for L is about 12 m, requiring a beta function of about 2 m. This is too small to be practical, and we settled on a value of 4 m. With this value, the beta function at the ends of the straight sections will be 14.9 m, not much larger than the minimum achievable value of 13.2 m.

The lattice functions are shown in Figure 1, while Table 1 lists lattice parameters. The equilibrium emittance is 78 pm, which is 40 times smaller than the effective emittance of the APS at present. As might be expected, the tunes and natural chromaticities are very high, while the average dispersion is very low. The normalized emittance of this beam is 0.55 μm, which is less than contemplated for many XFEL and ERL projects.

The quadrupole strengths, listed in Table 2, are very high, but not so high as to be obviously impossible.

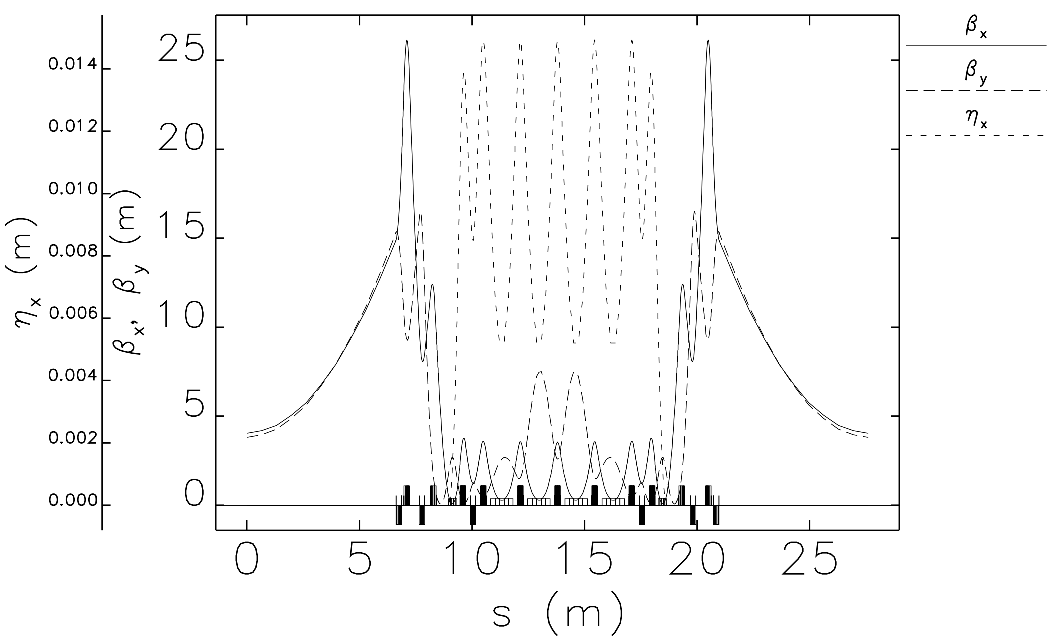

Fig. 1. Lattice functions for the XPS7 design.

4 Collective Effects and Beam Lifetime

We anticipate that the lifetime for this ring will be very short. Even in third-generation storage ring light sources, achieving adequate beam lifetime is a challenge. The dominant lifetime-reducing effect in third-generation rings is Touschek scattering. In the XPS7 ring, we must also be concerned about quantum lifetime, because it will be difficult to obtain large dynamic aperture.

Assuming zero coupling, the horizontal rms beam size at the center of the ID straights is $\sigma_x = 18\mu m$. A dynamic aperture of at least $\pm 6\sigma = \pm 108\mu m$ is required for reasonable lifetime [7]. This may seem disasterously small, but if we use on-axis injection from a high-brightness injector, it should not be a

Table 1
Lattice parameters for the XPS7 design.

Betatron Tunes		
Horizontal	113.121	
Vertical	108.121	
Natural Chromaticities		
Horizontal	-366.190	
Vertical	-312.604	
Lattice functions		
Maximum β_x	23.629	m
Maximum β_y	16.017	m
Maximum η_x	0.015	m
Average β_x	7.359	m
Average β_y	6.704	m
Average η_x	0.006	m
ID β_x	4.044	m
ID β_y	3.811	m
ID η_x	0.000	m
Radiation-integral-related quantities at 7 GeV		
Natural emittance	0.078	nm
Energy spread	0.176	%
Horizontal damping time	3.297	ms
Vertical damping time	5.986	ms
Longitudinal damping time	5.054	ms
Energy loss per turn	8.613	MeV
Miscellaneous parameters		
Momentum compaction	2.836×10^{-5}	
Damping partition J_x	1.816	
Damping partition J_y	1.000	
Damping partition J_δ	1.184	

Table 2
Gradient parameters for quadrupoles and dipoles. The B_{tip} value is the pole-tip field for a pure quadrupole of the given strength and 5-mm bore radius.

Element	Type	Length m	B_1L T	B_{tip} T
QT0	12 pole	0.250	-21.052	-0.421
QT1	12 pole	0.250	37.773	0.755
QT2	12 pole	0.250	-48.328	-0.967
QT3	12 pole	0.250	44.062	0.881
QD1	dipole	0.378	-114.187	-1.511
QFH1	12 pole	0.250	94.284	1.886
QDH2	12 pole	0.250	-99.057	-1.981
QFH0	12 pole	0.250	63.275	1.265
QD0A	dipole	1.000	-46.556	-0.233

problem. To accommodate large vertical coupling for good Touschek lifetime, we need essentially the same aperture in the vertical plane.

The rms energy spread is $\sigma_\delta = 0.18\%$, indicating that a minimum energy aperture of $\pm 6\sigma_\delta = \pm 1.1$A larger momentum aperture is necessary for Touschek lifetime, as we will see.

Before computing the lifetime, we need to examine some basic collective effects. The momentum compaction factor for this ring is 2.8×10^{-5}, a factor of 10 less than the APS. Hence, all other things being equal, we expect single-bunch instability thresholds to be $1/10^{\mathrm{th}}$ of those in the APS. Without feedback, APS can store up to 20 mA in a single bunch. Hence, we anticipate that the XPS ring will be limited to under 2 mA single bunch current. To be conservative, we assume the limit is 1 mA.

We chose an rf voltage of 10 MV and kept the existing rf frequency of 352 MHz, providing a bucket half-height of 3.5% and a zero-current rms bunch length of 4.2 mm. To compute bunch lengthening, we assumed a broadband impedance of 0.5 Ω, about twice the present value for APS [8]. Solution of the Haissinski equation (which `elegantRingAnalysis` [9] does using the `haissinski` program [10]), gives an rms bunch length of 7.9 mm. This is comparable to the present bunch length in the APS with less than 1 mA.

Using this bunch length, we next evaluated intrabeam scattering (IBS) (which `elegantRingAnalysis` performs with the program `ibsEmittance` [10]). Due to the high beam energy and relatively long bunch, IBS effects are modest even when the emittance ratio is very small, as seen in Figure 2.

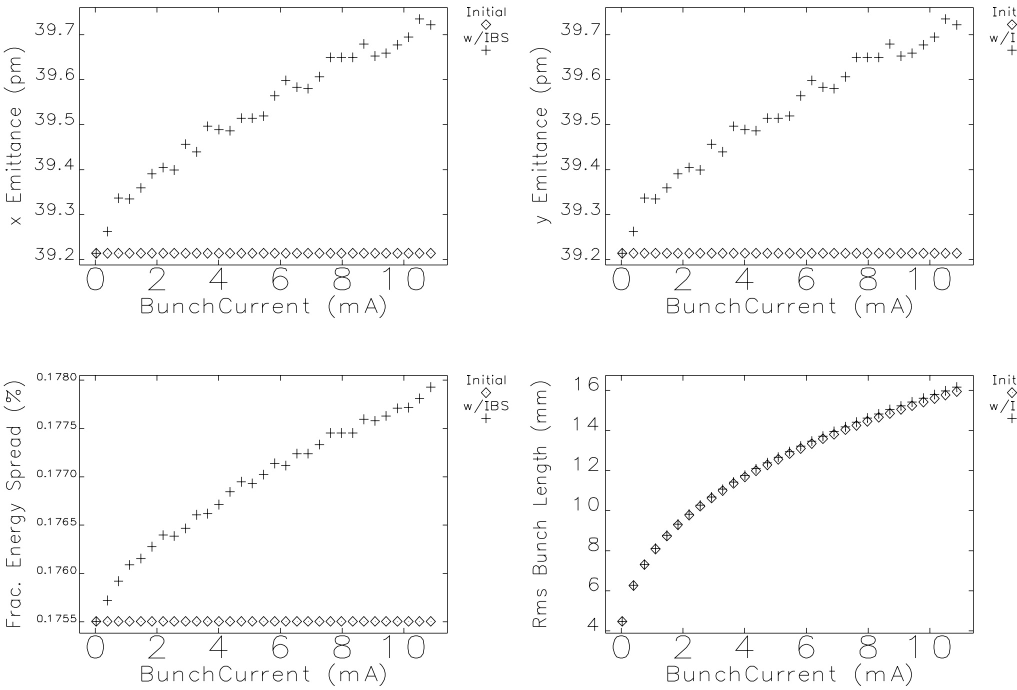

Fig. 2. Intrabeam scattering for XPS7 for 1-mA bunches, including bunch lengthening due to potential well distortion.

The space-charge tune shift was computed for the case of small coupling using [11]

$$\Delta\nu_y = -\frac{Qr_e}{(2\pi)^{\frac{3}{2}}\,\gamma^3\sigma_z}\int\limits_0^C \frac{\beta_y}{\sigma_y(\sigma_x+\sigma_y)}ds. \tag{6}$$

For a vertical-to-horizontal emittance ratio of 10%, this gives 0.006, which is quite small.

Finally, we evaluated the lifetime as a function of energy aperture and emittance ratio. We used the nominal emittance, since IBS is negligible. We assumed a round beam pipe of 5-mm radius, which gives an aperture limit in the horizontal plane, where the beta functions are largest. The lifetime calculations included gas scattering, brehmstrahlung, quantum lifetime, and Touschek scattering. The dominant effect is Touschek scattering, as expected. Figure 3 shows the results for three values of the emittance ratio as a function of the energy aperture.

The achievable energy aperture for the XPS is not yet known. Work to date indicates that $\pm 1.5\%$ is possible, so we've used this value. Assuming 100%

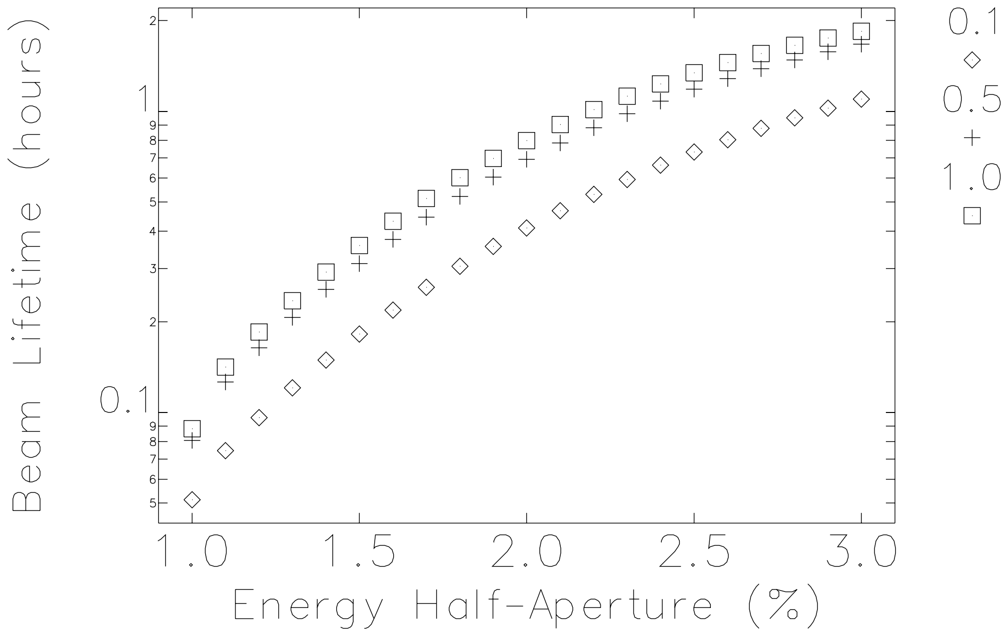

Fig. 3. Lifetime as a function of energy aperture for various ratios of vertical-to-horizontal emittance, including bunch lengthening due to potential well distortion.

coupling, the lifetime is 0.36 hours. Clearly, this machine will require fast top-up or some similar method.

5 Operating Modes

Recently, top-up operation [12] has come into widespread use as a way to deal with short beam lifetimes. However, unless the emittance ratio is large, the lifetime of the XPS ring is likely to be much too short to be practical even with top-up. Running with low emittance ratio is generally advantageous in order to achieve higher brightness. The diffraction limit for 1-$\AA$ photons is 8 pm, so there is little point in running with an emittance ratio under 10%. We used `sddsbrightness` to compute brightness curves for various emittance ratios, assuming an APS "U27" undulator with a period of 2.7 cm, length of 12 m, and maximum K of 2.18 [13]. As seen in Figure 4, we lose little in brightness even when operating with 100% emittance ratio.

Operating the XPS on or near the coupling resonance will not degrade brightness significantly and is necessary for good lifetime. If we perform on-axis injection, rather than accumulation, this should not be an issue. This implies that instead of performing top-up, i.e., instead of adding charge to bunches,

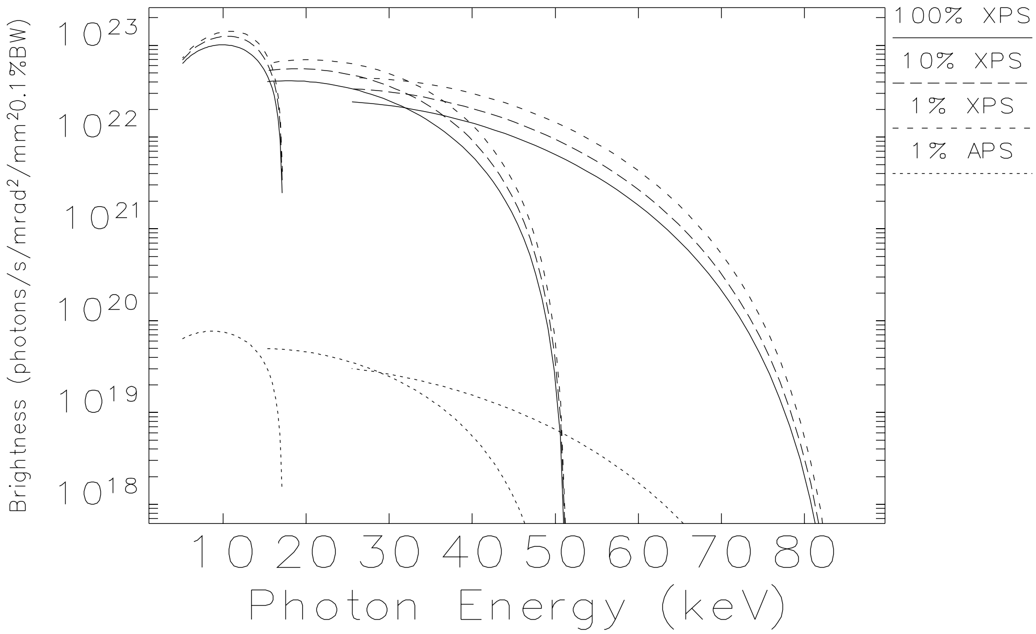

Fig. 4. Average brightness for the XPS with a 12-m undulator with a 2.7-cm period assuming a 1-A stored beam and various emittance ratios. Also shown is the present APS performance with a 2.4-m undulator, with 100 mA, and a 1% emittance ratio.

we will instead replace bunches or the entire fill.

One option [3] is to have a separate ring with sufficient dynamic aperture to allow accumulation, then swap stores between the accumulator and the light source ring. In the case of the XPS, the accumulator ring could be the existing APS ring relocated to the the floor of the tunnel. This approach has several disadvantages. In order to have good dynamic aperture, the accumulator will have to have large emittance compared to the XPS, so that when the stores are swapped, the users will see a transient in the brightness. In addition, if the dynamic aperture of the XPS is very small, we might have beam losses when the stores are swapped. Since the stored current is large, both rings would need careful design to suppress instabilities as well as very high power rf systems to deal with beam loading. Placing one ring below the other in the existing APS tunnel would be mechanically very challenging. The main advantage of this approach is re-use of the stored beam, thus reducing radiation and injector requirements.

Another option is to use a full-energy linac as the injector. If a photoinjector is used, the beam emittance at 7 GeV will be essentially the same as the damped emittance in the XPS, meaning there would be no significant emittance transient. Since we need to fill many bunches in order to avoid single-bunch instabilities and get good lifetime, the linac would need to provide a train of

1000 bunches at 352 MHz. The required pulse length is 2.8 μs, which is not challenging. Photoinjector drive lasers with longer pulses and higher bunch rates are needed, of course, for ERL projects that propose to provide bunches at 1.3 GHz [14].

In both of these options, we must replace the store frequently enough to reduce the stored current variation below $\pm 1\%$, which is the tolerance at APS for top-up operations. The interval at which the store must be replaced is

$$\Delta T_r = \tau \frac{\Delta I}{I}, \tag{7}$$

where τ is the lifetime and $\frac{\Delta I}{I}$ is the allowed peak-to-peak variation. Assuming an energy aperture of $\pm 1.5\%$, we expect a lifetime of 0.36 hours at 1 A with 1000 bunches and 100% emittance ratio. This implies replacing the entire store every 26 s.

Two concerns with the linac scheme are the power handling requirements of the beam dump and the requirements on the injector itself. The average power in the dumped beam is 990 W, which is tolerable. The average beam current required from the injector is 0.13 μA, while the average current during the macropulse is of course 1 A. Both are easily achieved.

The charge per ring bunch is 3.7 nC. The ring rf frequency is 352 MHz, while the linac rf frequency is likely to be 1500 to 3000 MHz. Hence, one might think we could inject 3 to 6 bunches into each ring bucket, reducing the charge per linac bunch from 3.7 nC. However, this needs to be evaluated carefully since the several linac bunches injected into each ring bucket will execute synchrotron oscillations and eventually filament into a long bunch with large energy spread. This may have implications on the requirement for energy aperture and for users.

6 Conclusion

We have presented a design for a replacement ring for the Advanced Photon Source that, while speculative, provides an increase of about 1500 times in the average brightness. This is achieved through a ten-fold increase in beam current, a five-fold increase in the undulator length, and an eighty-fold reduction in the horizontal emittance. The natural emittance of this beam is 78 pm, corresponding to a normalized emittance of 0.55 μm, less than contemplated for many XFEL and ERL projects. We envision using permanent magnet technology, including twelve-pole designs for combined quadrupole/sextupole magnets. Achieving sufficient dynamic and momentum aperture is challenging and will be the subject of a future publication. In addition, the magnet designs will present challenges the degree of which is not presently known. Provided we can achieve energy aperture of $\pm 1.5\%$ and a 6σ dynamic aperture, the expected lifetime is 0.36 hours for a 1-A beam of 1000 bunches. A new operational method is required, namely, completely replacing the stored beam every 26 s. The injector requirements and beam dump power levels are not challenging.

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