Evaluation of the Possibility of Upgrading APS to an Energy-Recovery-Linac-Based X-ray Source

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Introduction

One of the concepts now being explored for a next-generation x-ray source is the Energy Recovery Linac (ERL) [1,2]. Such a source would consist of a high-energy superconducting linac and two recirculation arcs. The arcs would have a cell structure similar to that of the APS, i.e., a series of cells with dipoles and straight sections for insertion devices. A high-brightness electron beam from the linac would be sent through these arcs, producing x-rays for users. Figure 1 shows a schematic of such a light source.

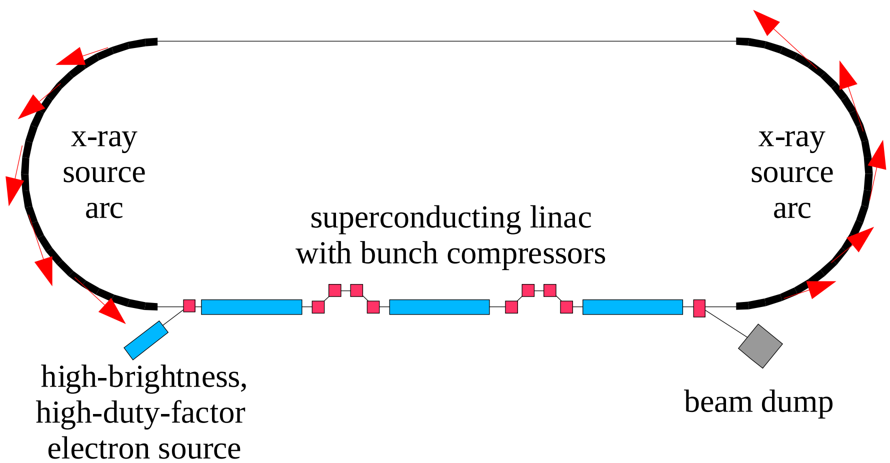

Figure 1: A schematic of an ERL-based x-ray source.

One early paper on this subject [1] used the APS lattice as a model for evaluating emittance growth due to quantum excitation in the arcs. In early 2001, after discussions with John Galayda, I was curious to check their calculations and also look at the impact of coherent synchrotron radiation (CSR). In the process of setting up these simulations, I realized that one could just as easily inject such a beam into the APS ring, instead of building an entirely new facility. The beam could circulate once and then be extracted. Also, since APS is a ring, I was interested in whether the beam could circulate several turns without excessive degradation. If so, then the demanding requirement of 100mA continuous beam from the linac could be relaxed. This paper revises and updates the early simulations I did of this concept [3].

Figure 2 shows a concept for what this machine might look like. Immediately there is one obvious advantage. In the ERL shown in Figure 1, the recirculated beam must enter the low-energy end of the linac and get decelerated. Hence, the optics must accomodate two beams of vastly different energies, which will make for difficult operation. By using a ring and the geometry shown in Figure 2, this problem is avoided. The return beam enters the linac at the downstream end. It always has the same energy as it had the first time through. Note that because the return beam is going in the other direction, all dipoles bend the opposite way, necessitating the odd-looking chicanes.   Another advantage of this concept is that the x-ray beamlines would all be in the same area, rather than being separated by the length of the 7 GeV linac (several hundred meters).

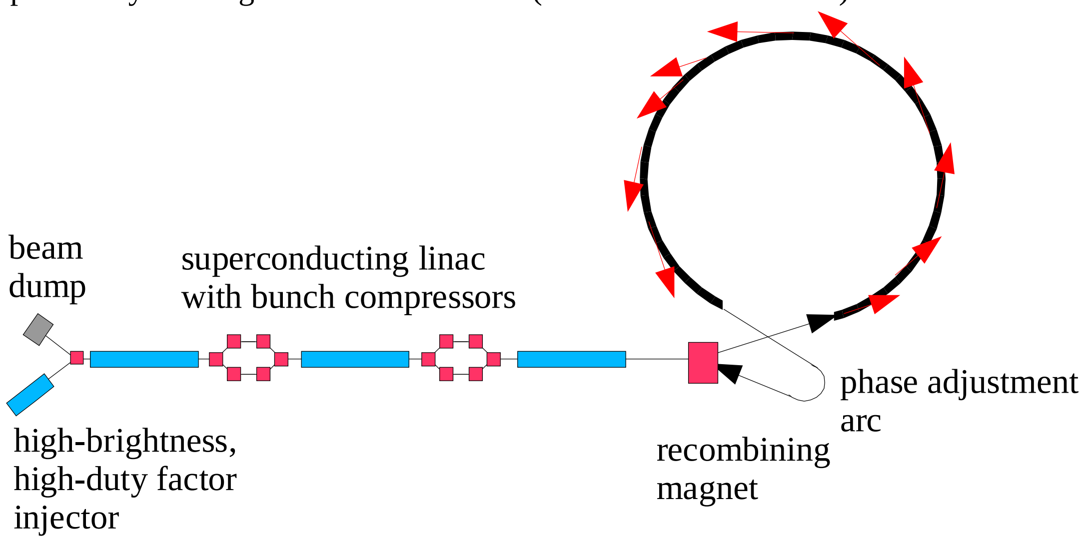

Figure 2: Schematic of a possible geometry for an ERL using the APS ring

One disadvantage of this machine is that all steering magnets will steer in the opposite direction for the two beams. This is acceptable if steering magnets are only needed to correct kicks from misaligned quadrupoles. However, if steering is needed to avoid misaligned apertures, then one beam would be steered into the aperture while the other was steered away. Fortunately, the apetures in superconducting linacs are quite large, so this shouldn't be a problem. Obviously, this issue needs to be investigated with simulations.

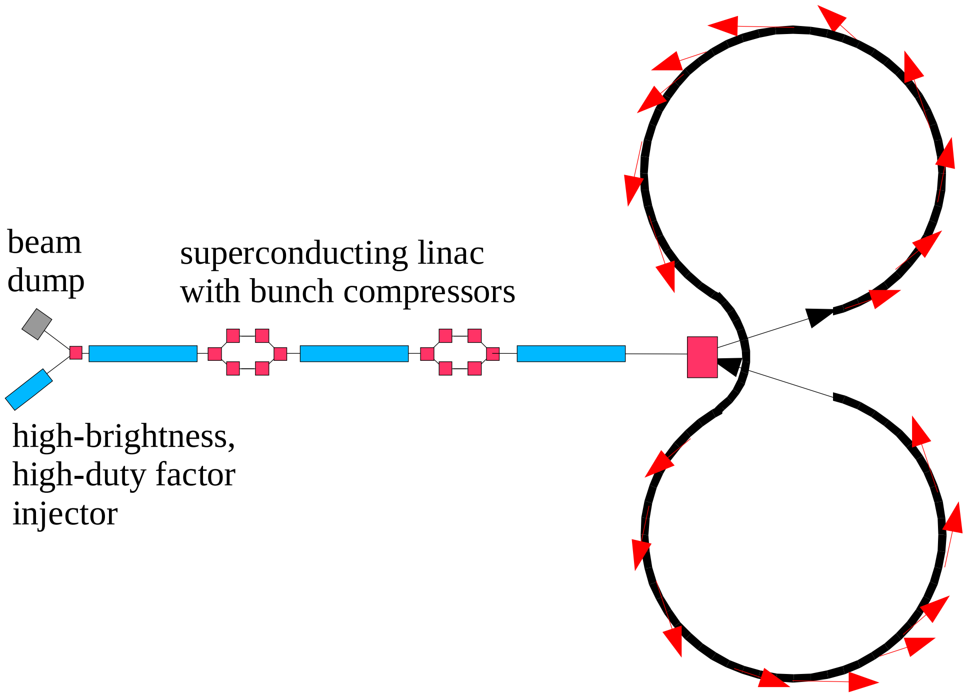

Figure 3: Concept for return arc providing double the number of x-ray beamlines.

Another disadvantage of this scheme is that the beamline to return the beam to the linac will not be small, unlike what is shown in the Figure 2. In order to bend a 7 GeV beam through such a large angle, a substantial number of strong dipoles will be needed. One could take advantage of this to create additional beamlines, perhaps with special characteristics not possible in the existing ring (e.g., long IDs). Figure 3 shows a possible geometry that would dramatically increase the number of beamlines. The total cost of this project would be about the same as the project shown in Figure 1, with the important difference that all the existing APS beamlines would also see a dramatic improvement in beam quality. We would essentially get two ERLs for the price of one. Of course, the beam quality in the second ring might be less than the first, but it might still be much better than the present APS beam quality.

For the present article, I will look only at the beam quality in the first ring. For the properties of the beam from the linac, I have used the following values, which are similar to those in the PERL proposal [2]: charge per bunch of ~100 pC, rms bunch length of ~50 µm (170 fs), normalized emittance of 1 µm in each plane, and rms energy spread of 0.01%. In these studies, I will assume that the beam is gaussian in all dimensions, which is almost certainly a bad assumption. A model of the injector, linac, and bunch compressors would be needed to make a more accurate simulation of beam in the arcs.

The small energy spread is needed to prevent excessive bunch lengthening as the beam travels around the ring. This can be relaxed if the bunch length requirement is relaxed. Indeed, the Cornell paper assumed an energy spread of 0.1% and a bunch length of 300 μm (1 ps), which greatly reduces the effects of CSR, as I will show below.

Simulation Results for Three Possible Ring Lattices

Beyond the usual problems of appropriate beta functions and matching the chromaticity, the principle worries for the beam in the arcs are

1. Coherent synchrotron radiation (CSR)
2. Incoherent synchrotron radiation (ISR), i.e., quantum excitation
3. Wakefields, primarily due to insertion device chambers and transitions.

The present simulations look at the first two effects. Also included is the average beam energy loss due to classical synchrotron radiation. CSR effects will almost certainly be underestimated due to use of a gaussian distribution.

To show the feasibility of this concept, it is necessary to verify that the emittance, energy spread, and bunch length do not degrade excessively in one turn. I have looked at three possible lattices for the ring. These lattices differ by their equilibrium emittances, which provides a convenient measure of the emittance growth rate. Of course, the beam will not be in the ring long enough to approach the equilibrium emittance.

1. Lattice "LE": A low-emittance lattice having an equilibrium normalized emittance of about 34 μm (2.5 nm geometric). This is close to the minimum emittance one can achieve with the existing magnets. This lattice has dispersion in the ID straight sections. The x and y tunes are 36.26 and 19.36, respectively. This is the "lower emittance" lattice now being prepared for user operations.
2. Lattice "ZD": A high-emittance lattice with zero dispersion in the straight sections, having an equilibrium normalized emittance of about 104 μm (7.7 nm geometric). The x and y tunes are 35.25 and 19.35, respectively. This is the standard high-emittance lattice used at APS.
3. Lattice "ISO": An isochronous lattice with large emittance and dispersion in the straight sections. This might prove useful for larger energy spread beams, but has a very large equilibrium normalized emittance of 343 μm. Unfortunately, in a double-bend system one cannot have a low-emittance isochronous lattice. The x and y tunes are 32.09 and 19.61, respectively.

The LE lattice will, of course, have the least emittance growth due to quantum excitation. One anticipates that it will also have minimum CSR problems, because the emittance growth due to CSR is also mediated by the H function[4].

Figures 4-6 show the emittance, energy spread, and bunch length vs distance in the absence of CSR for the three lattices. (These figures and those that follow show beam properties at the centers of the ID straights only.) The ISO lattice is clearly much worse than the others, except, not surprisingly, for the bunch length. What may be surprising is that the LE lattice is worse than the ZD lattice. The reason is that the emittance shown includes the effect of dispersion and energy spread, making the effective emittance, defined as $\sigma_x \sigma_{x'}$, bigger in the case of the LE lattice. The emittance growth rate for the ZD lattice is slightly larger, as one would have expected. On the other hand, in the presence of energy jitter, the LE lattice might prove unacceptable as energy jitter from the linac would translate into position jitter at the source points.

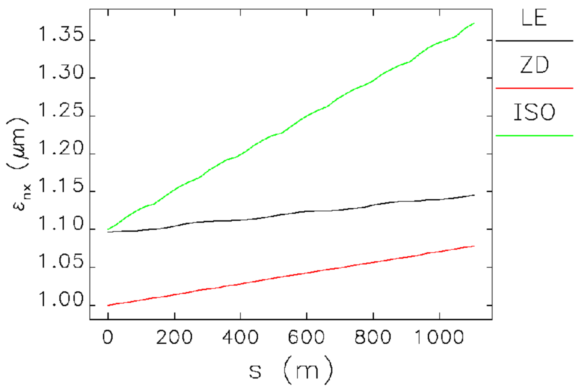

Figure 4: Emittance vs distance in the absence of CSR for three lattices.

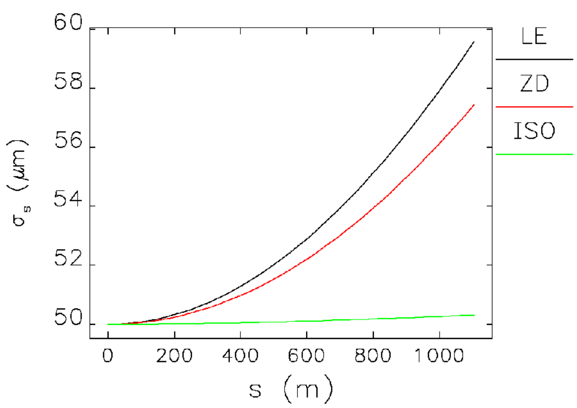

Figure 5: Bunch length vs distance in the absence of CSR for three lattices.

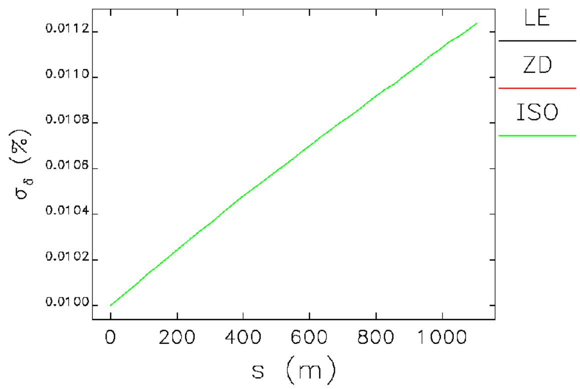

Figure 6: Energy spread vs distance in the absence of CSR for three lattices. (All are identical, as expected.)

Figures 7-9 show the emittance, energy spread, and bunch length vs distance for the three lattices with 50 pC per bunch. These simulations include CSR effects. I used 200k particles with 3-sigma gaussian distributions. The longitudinal distribution was generated using a quiet-start method based on Halton sequences, whereas the transverse distributions used pseudo-random numbers. For the CSR simulation[5], I used 600 bins and a smoothing parameter of 1, which is the same as what I use for LCLS simulations[6,7] for 50k particles. A future study should vary these parameters to verify that they are optimal.

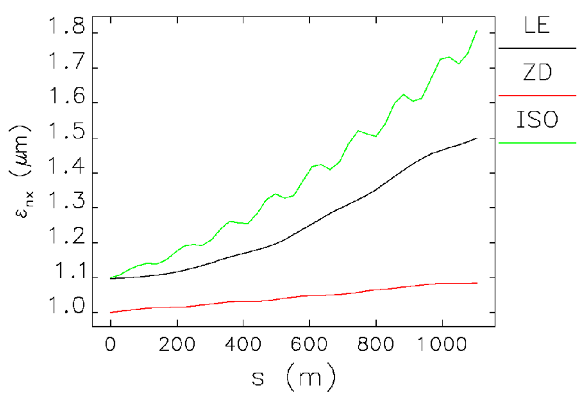

Figure 7: Normalized emittance vs distance for three lattices with CSR, for 50pC charge, 0.01% initial rms energy spread, 1µm initial emittance, and 50µm initial bunch length.

In terms of emittance growth, the ZD lattice is the clear winner. Presumably this is because, unlike in the LE lattice, in the ZD lattice energy spread generated upstream of a given sector does not turn into effective emittance at the ID source point. If one looked at the "corrected emittance" (emittance with dispersion-like correlations removed), as I did in my original study[3], one would conclude that the LE lattice is superior. However, the users don't see the corrected emittance.

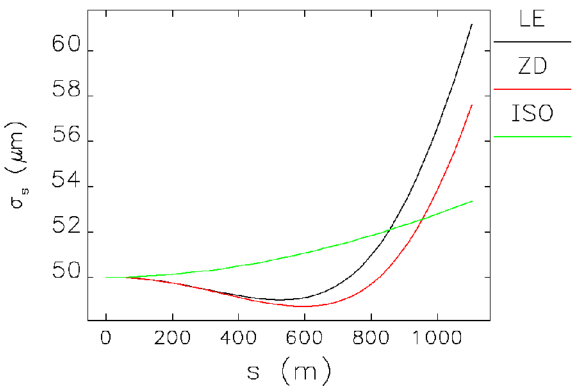

Figure 8: RMS bunch length vs distance for three lattices with CSR, for 50pC charge, 0.01% initial rms energy spread, 1µm initial emittance, and 50µm initial bunch length.

The curves for bunch length and energy spread follow the expected patterns. Not surprisingly, the ISO lattice is best at maintaining the bunch length. The differences in the energy spread curves almost certainly result from differences in the bunch length.

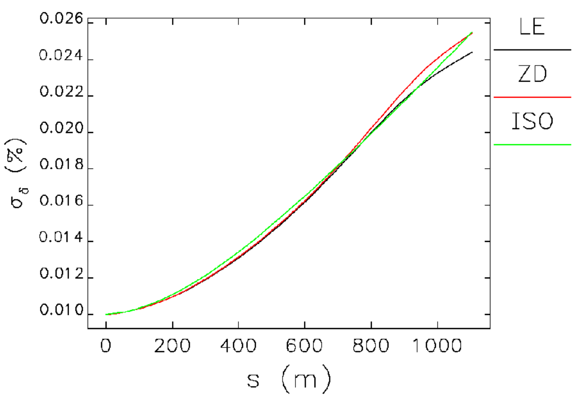

Figure 9: RMS energy spread vs distance for three lattices with CSR, for 50pC charge, 0.01% initial rms energy spread, 1µm initial emittance, and 50µm initial bunch length.

Since the ZD configuration is clearly better, I'll confine myself to that configuration from here on. Figures 10-12 show the behavior as the charge is varied from 0 to 200pC per bunch, with 0.01% initial energy spread, 1µm initial emittances, and 50µm initial bunch length. The effects of CSR increase dramatically for 100pC and above. However, it in all cases (up to 200pC) the beam quality exceeds that of the APS: the normalized effective emittance of the APS is 53 µm in low-emittance mode, while the energy spread is 0.095% and the bunch length ~10mm. This advantage may well decrease significantly when a more realistic input beam is modeled.

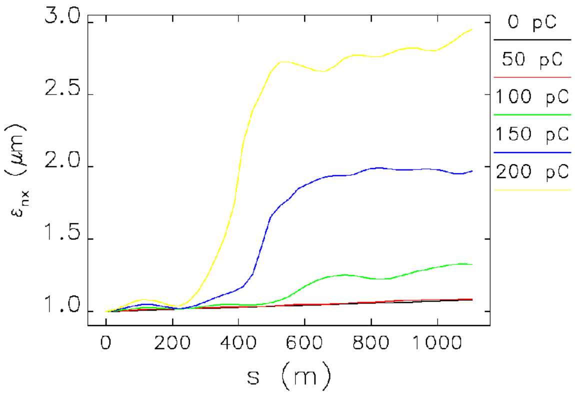

Figure 10: Emittance vs distance for ZD lattice for various charge levels.

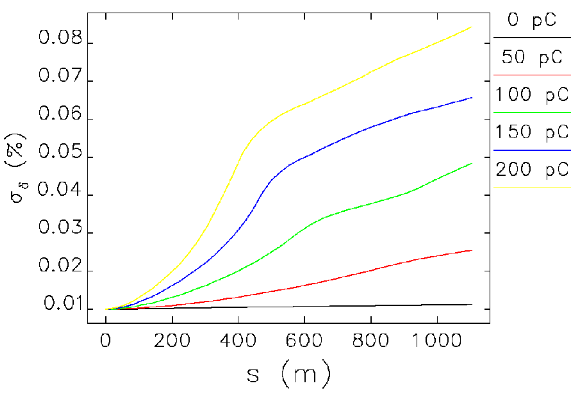

Figure 12: RMS bunch length vs distance for ZD lattice for various charge levels.

The longitudinal distributions for higher charge levels show evidence of the CSR microbunching instability[6,7]. Figure 13 shows data for three cases for various levels of charge. Suppresion of this instability by adding incoherent energy spread (as done in the LCLS design[4]) is not possible because the additional energy spread will stretch the bunch. It is more sensible to start with a long bunch.

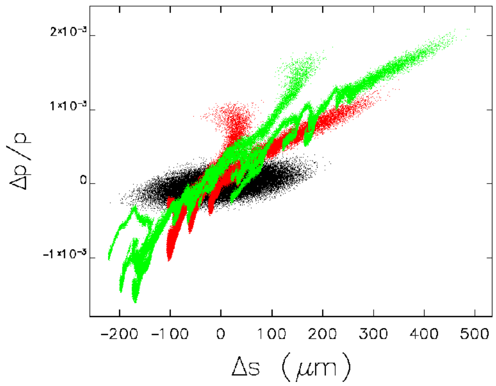

Figure 13: Final longitudinal phase space for three cases: 0 pC (black), 100 pC (red), and 200 pC (green).

As discussed above, the original ERL white paper proposed using a relatively long bunch and relatively large energy spread. This allows higher charge, flux, and brightness, at the expense of some experiments that may need ultrashort x-ray pulses. (These experiments might use a form of x-ray pulse compression such as that discussed for SASE FEL projects, wherein the electron beam is chirped to provide a time-wavelength correlation in the x-ray pulse.) Figures 14-16 show the behavior as the bunch length is varied from 50 to 300 μm rms, for 100pC charge. Clearly, there is a dramatic improvement just from increasing the bunch length from 50 to 100 μm.

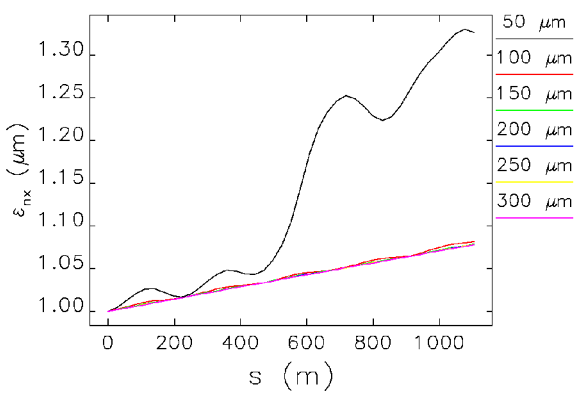

Figure 14: Emittance vs distance for various bunch length and 100 pC charge.

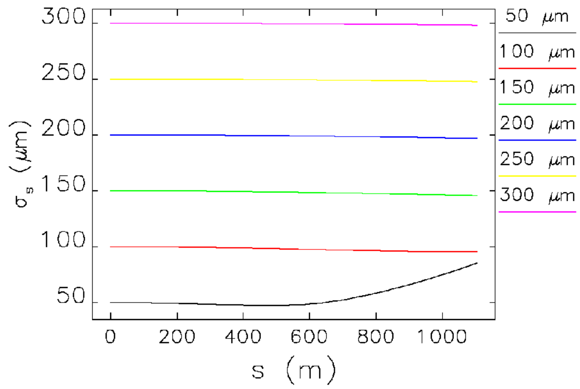

Figure 15: Bunch length vs distance for various initial bunch lengths and 100 pC charge.

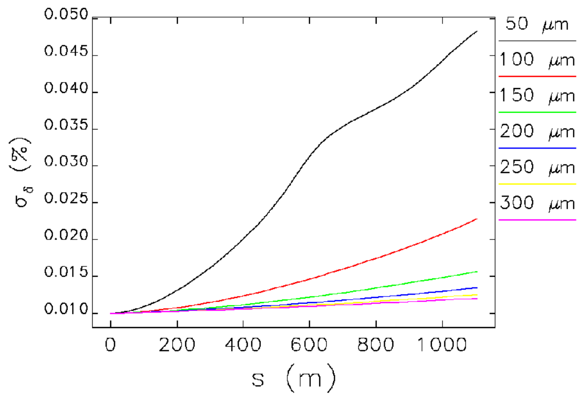

Figure 16: Energy spread vs distance for various bunch lengths and 100 pC charge.

Discussion

These simulations show that using the APS as part of an ERL is apparently feasible, provided that the injector can really deliver the required beam. This is by far the most dubious part of the entire idea. Start-to-end simulations [6,7] with and without jitter are clearly needed, particularly if a photoinjector will be used as the source of particles and if several stages of bunch compression are required.

As mentioned above, the demands on the injector would be considerably lessened if the beam could be circulated several times in the ring. This could only be done if the charge was low or the bunch length was long. Reference 3 shows some examples of simulations with 10 turns. It is clear that a long bunch is necessary even for 50-100 pC.

Using a long bunch and multiturn operation is an attractive choice, as it keeps the flux high while reducing CSR effects, thus maintaining the transverse brightness. Of course, rf systems would be needed to maintain the energy and prevent excessive debunching. This approach would, however, complicate the injection and extraction processes, and result in transients in the x-ray intensity unless beam was extracted and injected simultaneously. While the long bunch case appears to be relatively easy, and we can almost certainly circulate many turns, an important question is how much user interest there is in the 100 μm and longer regime.

Future studies should return to simulation of the multiturn option and consideration of how injection and extraction might be handled. The most obvious way to handle this is to inject a train of bunches that occupies a quarter of the ring circumference. The stored beam would be extracted at one location while injection occurred on the opposite side of the ring. The kickers would need to turn on and reach a flat-top in 1.8 μs. The flat-top would need to be 0.9 μs long, followed by turn-off in less than 0.9 μs. The primary problem here is likely to be making the flat-top uniform enough to prevent spoiling the overall emittance of the bunch train.

As noted above, I did not include any simulation of wakefield effects. This would require Green functions for the chamber transitions and other components, which we do not have at this time. Because of the likelihood that the ERL would run with very closely spaced bunches, we also need to look at the possibility of bunch-train instabilities due to the impedance of the ring. This would require a different characterization of the impedance, in terms of frequencies, Q's, and shunt impedances.

Of the lattices examined here, the zero-dispersion lattice is clearly the best, as it partially insulates the users from the CSR effects. There are reports [8] that cancellation of CSR effects can be obtained with judicious choice of phase advance between dipoles. My initial reaction to this was that it would not work for realistic beam distributions. However, upon reconsideration, I believe that if the lattice is quasi-isochronous, then should work. What is needed, then, is a quasi-isochronous lattice with reasonable quantum excitation, zero dispersion in the straight sections, and 180° horizontal betatron phase advance between dipoles. I doubt this can be accomplished with the ring configuration we have now.

Returning to Figure 3, the following idea is suggested: the upper ring, into which beam is injected first, could be a new design with optics that are optimal for control of CSR and ISR effects. The lower ring could be the existing APS, operated in the ZD lattice. The upper ring, presumably, would have little impact on the beam emittance and energy spread.

Acknowledgement

I acknowledge S. Milton for bringing this idea to my attention again.

References

[1] S. Gruner, D. Bilderback, and M. Tigner, "Synchrotron Radiation Sources for the Future", white paper, available at http://erl.chess.cornell.edu/Papers/Papers.htm

[2] I. Ben-Zvi et al., "Photoinjected Energy Recovery Linac Upgrade for the National Synchrotron Light Source," Proceedings of the 2001 PAC.

[3] See the following links for the original set of simulation runs. These were done with a simpler CSR model, but gave comparable results.
http://www.aps4.anl.gov/FEL@APS/report-7-9-01.html
http://www.aps4.anl.gov/FEL@APS/report-7-23-01.html

[4] P. Emma, private communication.

[5] M. Borland, "Simple method for particle tracking with coherent synchrotron radiation," Phys. Rev. ST Accel. Beams, 4, 070701 (2001).

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[8] J.H. Wu et al., "Coherent Synchrotron Radiation Analysis for the PERL and UVFEL Projects at the NSLS," Proceedings of PAC 2001.