Review of APS Upgrade Options

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1 Introduction

In this document we briefly review various major options for APS accelerator upgrades and improvements. The options are as follows:

- ERL@APS: Addition of an energy-recovery-linac (ERL) injector to the APS.
- APS1nm: APS replacement ring with 1nm effective emittance.
- APSx3: APS replacement ring with three straight sections per sector.
- cAPS: APS with various per-sector customizations, such as long straights, split dipoles, stronger dipoles, etc.
- APS-LSS: APS with a long straight section in every sector.
- USR7: Construction of a large, 7 GeV Ultimate Storage Ring.
- XPS: APS multi-bend-achromat replacement ring (eXtreme Photon Source).
- XFEL-O: X-ray FEL oscillator based on a superconducting linac.

Table 1: Table of APS Upgrade Options

Option	Flux	Max. Ave. Brightness	Time Req.	Dark Time	Cost	Tech. Risk
APS today	1	1	none	none	none	none
ERL@APS	0.5	140	10 years	6 months	$$$	Very high
APS1nm	7	40	5 years	1 year	$	Moderate
APSx3	7	18	5 years	1 year	$	Moderate
cAPS	3	2	5 years	none	$	Moderate
APS-LSS	$3 \sim 7$	$4 \sim 10$	6 years	none	$	Very low to moderate
USR7	7	400	5 years	none	$$$$	Moderate
XPS	7	75	7 years	2 years	$$	Very high
XFEL-O	$1 \sim 100$	$10^7 \sim 10^9$	7 years	none	$$	High

2 Definitions

2.1 Flux

Flux is quoted in normalized units, with the reference being the APS today. Specifically, the reference is a 2.4-m-long U33 insertion device with 100 mA stored beam.

2.2 Maxium Average Brightness

Brightness is quoted in normalized units, with the reference being the APS today. Specifically, the reference is a 2-4-m-long U33 insertion device with 100 mA stored beam in the standard low-emittance lattice at 1% coupling. This configuration has 3.1-nm effective horizontal emittance and 25 pm vertical emittance. For each case, we find the maximum average brightness, which is in the first harmonic, typically at about 8 keV.

2.3 Time Required

This is the time required to complete the project after the start of funding. It includes construction, assembly, and commissioning. The durations stated here are mostly educated guesses.

2.4 Dark Time

This is the duration of the time that APS will not provide x-rays. It is included in the total time required. The durations stated here are mostly educated guesses, although in a few cases detailed analysis has been done.

2.5 Technical Risk

This is a measure of the technical uncertainty surrounding the project. It indicates the amount of R&D required and the possible difficulty of commissioning the new machine.

3 ERL@APS

This option entails building a 7 GeV energy recovery linac to provide beam to the APS ring. The "ultimate" concept[27] gives the potential for expanding the APS facility with 48 additional straight sections, each accommodating 8m of undulators, as well as a few beamlines with very long undulators. The facility might also feature a secondary injector providing high peak current pulses at a reduced repetition rate, to support timing experiments [18]. This is facilitated by having the linac point away from the APS, which also motivates having a fairly large, expensive turn-around system for emittance preservation. This turn around system would be used to accommodate the additional beamlines mentioned previuosly.

Drawbacks of this option include: the size, cost, and environmental impact of the facility; low average beam current (25 mA) gives reduced flux, particularly for in-APS beamlines; low bunch charge and 1.3 GHz bunch repetition rate not useful for timing studies.

Many cost-saving options are conceivable for the ERL, including: staging of the ERL concept to initially require no energy recovery [15] (150 μA average current initially); reorientation of the linac to point toward the APS and use of a minimal turn-around arc (as in Stage 2 of [15]); development of a pulsed ERL using multiple guns and mergers [10], to reduce the cryogenic heat load and cathode lifetime requirements; use of a multipass linac to reduce the cost of the linac and its cryogenic system [29]; and use of a split linac to reduce the energy of the turn around to 3.5 GeV. In all of these options, we retain the ability to store beam in the APS and use the existing injector [13].

3.1 Potential Performance

The most likely operating mode for the ERL is the "high-coherence" mode [16], i.e., 25 mA beam current with 6 pm emittances in both planes. With such low emittance, very high brightness and transverse coherence may be expected. Indeed, modeling [8] shows that a 140-fold increase in maximum average brightness may be possible, assuming a 4.8-m-long U33 device. Higher brightness is possible with optimized undulators [26] As mentioned, incorporation of long undulators is possible, which should deliver even higher brightness [22].

This mode does not, of course, provide increased flux compared to present-day APS, since the beam current is only 25% of today's value. This can be partially compensated by doubling the undulator length, as we've assumed here. Another ERL mode is the "high-flux" [16], which assumes 100 mA beam current, but with a 4-fold increase in the emittance. This results in lower brightness.

3.2 Technical Risk

Technical risk for this option is very high. Primary challenges are: producing and maintaining ultra-low emittance electron beams; sustaining high average current electron beams for operationally-useful time periods; controlling beam loss at the parts-per-billion level; developing cavities with very high Q in order to reduce cryogenic power; controlling impact of insertion devices on the beam.

3.3 Time Required

The high level of technical risk in the ERL upgrade necessitates a long period of development, probably on the order of 10 years. To achieve the ultimate performance goals, gun technology must advance by about an order of magnitude on several fronts. There must also be considerable advances in superconducting rf technology.

Ideally, a prototype ERL would be built to develop and demonstrate the required technology. This would be a relatively small machine, operating at perhaps 200 MeV, but would include all of the component parts of a larger machine.

As mentioned above, staging of the ERL concept [15] may cut the development time by reducing initial requirements on the gun average current. The drawback is that we would have only 150 μA average current initially.

3.4 Dark Time

The favored ERL options involve building the ERL itself outside the APS ring, although "infield" designs have also been considered [30]. One advantage of outfield designs is that they result in reduced interference with APS operations. The existing injector, for example, is left intact.

Integration of the ERL into the APS will [13], however, involve dark time. First, one must move a number of rf cavities and their waveguides after first modifying several sectors of the ring to lengthen the straight sections. Second, one must open the shield wall from the outside and build the ERL-related transport lines. Finally, one must perform commissioning. An estimate for the time required to do this is six months. Following this, one may begin a period of initial operation of the ERL interspersed with operation of the APS as a storage ring. Modeling [32] has verified that this should be feasible.

4 APS1nm

This option[2] entails replacing the existing APS storage ring with a triple-bend-achromat design with an effective emittance of 1 nm. Essentially all existing in-tunnel storage ring components would have to be replaced. Exceptions may include the rf cavities and some undulators. By including a gradient in the dipole magnets, we not only achieve lower emittance, but also reduce the number of quadrupoles. By reducing the magnet apertures we are able to make the magnets stronger and therefore shorter. Both steps result in more space available for undulators, increasing the maximum undulator length from 4.8 m to 8.0 m.

Drawbacks of this option include: long dark time for ring installation; disappointing transverse coherence increase.

4.1 Potential Performance

Assuming 200-mA stored beam current and optimized insertion devices, the brightness increases about 40-fold [14], but the transverse coherent fraction increases only 5-fold. These computations assume that an 8-m-long U33 device is used. Further improvements should be possible with customized insertion devices.

Increasing the current to 200 mA and using an 8-m-long device results in a seven-fold increase in flux compared to APS today.

The vacuum chamber will have reduced dimensions in order to allow stronger magnets, which can be shorter, thus saving space. In spite of this, flexible bunch patterns should be possible, as in APS today [35].

4.2 Technical Risk

Technical risk for this option is moderate. Storage ring technology is mature and well understood, so that modern storage rings deliver beam relatively quickly following construction.

Primary challenges are: the need for rapid commissioning to reduce dark time; good control and correction of errors is required in order to achieve acceptable dynamic aperture and momentum aperture, which, respectively, determine injection efficiency and beam lifetime; design, construction, and alignment of dipoles with strong gradients.

4.3 Time Required

This option has a moderate level of technical risk, so the R&D period is not very long. However, to installation dark time, essentially all components must be completed and staged for installation in rapid order. To minimize commissioning time, great care must be taken in measurement, assembly, and alignment of components. We estimate that the total time required, including installation, will not exceed five years.

4.4 Dark Time

Dark time is unavoidable with this option, but can be minimized through careful preparation. The existing storage ring must be removed prior to installation of the new ring. Following this, preassembled storage ring girders must be rapidly moved into place and aligned. Once installation is completed, commissioning will commence. It is estimated that this entire process will take 1 year [31].

5 APSx3

This option [33] evolved from the APS 1nm design following user feedback. It entails replacing the existing APS storage ring with a triple-bend-achromat design with an effective emittance of 1.7 nm. Liek the APS 1nm design, space is created for 8-m undulators by using gradient dipoles and shorter, stronger quadrupoles. Additionally, each sector accommodates two short insertion devices, which could be an undulator or a three-pole wiggler. One of these new straight sections is parallel to the existing BM beamline.

Drawbacks of this option include: long dark time for ring installation; additional insertion devices are only about 1-m long; disappointing transverse coherence increase.

5.1 Potential Performance

As with APS 1nm, we would expect to run at 200 mA with flexible bunch patterns. The brightness improvement, about 18-fold, would be less than that predicted for APS 1nm, since the emittance is 70% higher.

Increasing the current to 200 mA and using an 8-m-long device results in a seven-fold increase in flux compared to APS today.

The vacuum chamber will have reduced dimensions in order to allow stronger magnets, which can be shorter, thus saving space. In spite of this, flexible bunch patterns should be possible, as in APS today [35].

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6 cAPS

This option, "customized APS," takes advantage of the existence of individual quadrupole and sextupole power supplies in the APS, as well as the presence of trim windings on all dipoles. It entails various customizations to the existing APS ring to accommodate specific, sector-by-sector user requirements. These customizations may include long straight sections of various flavors, split dipoles (to accommodate additional IDs), stronger dipoles (for harder bending magnet radiation), and reduced horizontal source size.

Straight sections could be lengthened by up to 6 m (assuming absorber redesign accommodates 1.2T dipoles[21] or beam current is limited to 150 mA). The emittance increases by 0.07 nm per straight for the longest straight option, and is essentially unchanged for the shorter option.

It appears straight sections can also be lengthened by 3.2m while providing reduced horizontal beamsize (120 μm), but at a cost of 0.4 nm emittance increase per sector. 1.3 T dipole fields are required. Another option for reduced horizontal source size [11], down to perhaps 40 μm, is to install a series of strong quadrupoles in a straight section; the implications of this for beam emittance are presently unknown.

Split dipoles[9] would accommodate additional 1-m-long insertion devices, but require 1.7 T dipole fields and hence limiting the beam current (to 210 mA assuming successful redesign of absorbers, or 105 mA otherwise). Depending on the configuration, the emittance would increase by up to 0.13nm per additional ID.

Dipoles with fields up to 2.4 T were explored[4]. With 1.3T fields, the emittance increase is 0.04 nm per dipole, whereas for 2.4 T fields it is 0.17 nm per dipole. (Stronger fields require either lower current, or perhaps longer absorbers, which can be accommodated by the new geometry.)

Drawbacks of this option include: increased emittance, perhaps in the 4 to 5 nm range; lack of symmetry in ring potentially leading to operational problems with injection and lifetime.

6.1 Potential Performance

Because of the many options available and uncertainty as to which would be deployed and in what locations, gauging performance is difficult. We have assumed that longer insertion devices, up to 8 m, would be deployed in at least some locations, boosting the flux by a factor of about 3. An additional boost may come from higher beam current, though how high is feasible is unclear. Because of the likelihood of increased emittance, the brightness improves only two-fold.

6.2 Technical Risk

Technical risk for this option is low to moderate, depending on the customizations implemented. Primary challenges are: achieving sufficient dynamic and momentum aperture for good injection efficiency and lifetime; keeping low emittance; managing evolution of the machine while maintaining solid routine operation.

6.3 Time Required

Ideally, this option would be pursued using only the regular APS shutdowns. This has the advantage of requiring no dark time, but the disadvantage of requiring a drawn out implementation.

6.4 Dark Time

Ideally, this option would be pursued using only the regular APS shutdowns. Hence, there would be no dark time.

7 APS-LSS

This option entails modifying the existing APS ring to have long straight sections [1] in all sectors. This could be done by removing one quadrupole and steering magnet from each side of each straight section. The space available for IDs would increase by 2.9 m. Making the change in all sectors preserves lattice symmetry and alleviates concerns with injection efficiency and lifetime. The emittance increases slightly, from 3.1nm to 3.3nm [32]. We may choose to leave a few sectors unaltered, to preserve the ability to achieve reduced horizontal beamsize, for example.

A variant of this option [17] is to retain the quadrupole triplets, but shorten both the dipoles and quadrupoles. This retains lattice flexibility, but entails gradual replacement of the majority of the magnets and vacuum chambers. Difficulties include maintaining low emittance and high single-bunch current [6].

Drawbacks of this option include: modifications required to every sector; reduction in flexibility for lattice functions at IDs; difficulty maintaining high single-bunch current [19].

7.1 Potential Performance

A factor of more than 3 in flux can be gained in this concept through use of 8-m-long insertion devices compared to the standard 2.4-m-long devices used today. If in addition the current is increased to 200 mA, the total increase is about a factor of 7.

Assuming a U33 device, brightness is expected to increase by a factor of 4 as a result of the longer device and higher current, in spite of the slightly increased emittance. A larger factor, perhaps as much as 10, should be possible with a customized insertion device[17].

7.2 Technical Risk

Technical risk for the basic option is very low, as it can be mocked up in studies and operations by turning off the Q1 quadrupoles; mechanical changes can be staged. In addition, well-established methods of modeling single bunch instabilities [34] will allow predicting and possibly mitigating the impact on the single bunch current limit.

A variant of this concept, mentioned above, is to retain the quadrupole triplets, but shorten both the dipoles and quadrupoles. The risk for this variant is moderate, as it entails replacement of most storage ring components. In this sense, it is similar to APS 1nm and APSx3. However, unlike those concepts, the number of quadrupoles would be unchanged, preserving lattice flexibility. It is thus likely that we could gradually implement this scheme over many shutdowns, which would not be feasible with less flexible lattices. This requires detailed study.

7.3 Time Required

Ideally, this option would be pursued using only the regular APS shutdowns. This has the advantage of requiring no dark time, but the disadvantage of requiring a drawn out implementation.

In the full replacement variant of the concept, the time required is considerable because we only make use of periodic shutdowns. Even for the less ambitious variant, signficant time is required as we must replace several girders and vacuum chambers in each sector.

7.4 Dark Time

Ideally, this option would be pursued using only the regular APS shutdowns. Hence, there would be no dark time.

8 USR7

This option entails building a large 7 GeV storage ring with very low emittance. A preliminary design[7] features a 40-sector ring with a 3.1-km circumference, 8-m undulators, 200 mA stored beam current, and 0.016 nm emittance in both planes.

Drawbacks of this option include: size and cost of the facility; bunch patterns are inflexible (fill essentially every bunch); does not make use of existing APS beamlines.

8.1 Potential Performance

Because of the extremely low emittance and 200 mA beam current, this option promises higher brightness and much higher flux than ERL@APS for the same insertion device. The transverse coherent fraction increases 80-fold compared to APS today.

The ERL has the advantage of potentially accommodating a number of very long undulators, which will give increased brightness.

8.2 Technical Risk

Technical risk for this option appears to be moderate. Primary challenges are: dynamic and momentum apertures are small, requiring a "swap-out" operation scheme [3, 25], which may require very fast kickers; errors must be well controlled and corrected to obtain sufficient aperture and design performance.

8.3 Time Required

In spite of the high level of predicted performance, there is apparently little R&D required. Therefore, the time required is simply what is needed for construction and commissioning.

8.4 Dark Time

Since this facility would be decoupled from the APS, there is no dark time.

9 XPS

This option entails replacing the APS storage ring with a multi-bend achromatic design [12]. An initial design [5] features a 40-sector ring with 8-m undulators and an emittance of 0.2 nm. Like USR7, dynamic aperture is insufficient for accumulation, requiring a switch to swap-out based operation.

Drawbacks of this option include: long dark time for ring installation; brightness gain from long IDs reduced by large energy spread of beam.

9.1 Potential Performance

The brightness gain is about a factor of 80 for U33 devices.

9.2 Technical Risk

Technical risk for this option is very high. Primary challenges are: sextupole strengths are presently unrealistic and it is unclear if this can be resolved, although use of combined function magnets is an option; sextupole fields are also required inside some quadrupole magnets.

Shorter straight sections and other compromises appear required for a workable design. For example, SPRing-8 has a design for replacing their ring [24], achieving an emittance of 0.08 nm. It exhibits good dynamic aperture, albeit in the absence of errors. Unfortunately, it also eliminates half of the existing straight sections and allows only about 5 m for insertion devices.

9.3 Time Required

This project has considerable technical challenges that will require time to address. In addition, a large number of components need to be built, carefully assembled, measured, tested, etc. A guess is that this will take 7 years.

9.4 Dark Time

Dark time will be considerable with this option. First, the existing ring must be removed and the new ring installed. Then, an extended commissioning period will probably be required. A guess is that this will take up to 2 years.

10 XFEL-O

This option [20] entails building a 7 GeV superconducting linac to provide ERL-like beams at a repetition rate of 1 to 100 MHz, in order to drive an oscillator FEL in the x-ray regime. Energy recovery would be unnecessary at the lower end of this range. The FEL cavity would be created using Bragg mirrors.

Drawbacks for this option include: size and cost of the facility; lack of tunability; supports a single user at a time; does not supply improved performance to existing beamlines.

10.1 Potential Performance

This option would provide transversely and longitudinally coherent x-rays at about 1 Å. It is predicted to provide 10^5 to 10^7 higher average brightness than ERL-based and high-gain FEL-based sources, while providing peak spectral brightness comparable to LCLS [20]. The source delivers 10^9 photons/pulse, so that, depending on the repetition rate, the average flux is up to 100 times that of the APS (which is about 10^{15} photons/sec[28]).

10.2 Technical Risk

Technical risk for this option is high. Primary challenges are: producing and maintaining ultra-low emittance electron beams; achieving required electron beam timing stability (about 20 fs [23]); development of x-ray cavity with sufficient mirror reflectivity and stability.

10.3 Time Required

Although not as challenging as the ERL, this project has considerable technical challenges that will require time to address. In addition, the linac is relatively long and will require time for construction and commissioning. A guess is that 7 years should be sufficient.

10.4 Dark Time

Since this facility would be decoupled from the APS, there is no dark time.

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12 Revision Notes

1. Added sentence and reference about continued ability to store beam in ERL@APS. Added acknowledgements section. Revised on 5/5/2008.
2. Additional material on ERL options, including more cost-saving options. Additional material on APS-LSS, particularly the replacement option. Revised on 5/21/2008.
3. Considerable extension of the text for all options. Addition of hypertext links, including links to references.

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