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APS Machine Advisory Committee November 15/16 2006

Review of options for APS upgrades

Executive Summary

The committee received information on 4 basic upgrade options, namely an Outfield ERL, an Infield ERL, and 2 Storage Ring Upgrades, APSx3 and APS 1nm. In addition, the committee believed that an incremental upgrade of the existing ring is worthy of consideration. Each of these options has been evaluated against the predefined charge to the committee which was:-

- Can the option deliver the claimed technical performance?
- Is the claimed performance technically revolutionary and how does it compare to a "green field" option?
- What are the technical R&D challenges?
- What mitigation of risk is possible?
- Does the option put the APS at state-of-the-art in following decades?

The proposed Outfield ERL is considered to be an extremely exciting light source which builds on the investment in beam lines and infrastructure already at the APS. It would provide a factor of about 150 increase in brightness compared to the existing APS in addition to increasing the coherent fraction of the x-ray beam and significantly reducing the bunch length. The claimed performance is not demonstrated at the present time and would rely on significant improvements to both the current and emittance delivered by high brightness electron guns. The committee is not able to guarantee that these improvements will be delivered, but is optimistic in the light of on going R&D at several institutes. Technically the claimed performance is revolutionary in comparison to present day light sources and will enable new areas of scientific research to be opened up. There are other R&D challenges posed by development of a suitable superconducting RF system at an appropriate frequency, by the design of magnetic transport systems which minimize emittance growth, and by the achievement of positional stability at 10% of an 8 μm beam size. But the committee is confident that these issues can be resolved. Additional risks arise from the possibility of Beam-Break-Up instability, and from reducing beam losses to the extremely low levels imposed by the already installed shielding. These risks merit further study. The disruption that construction would impact on the continued operation of the storage ring is estimated to be about half a year, but that estimate is considered to be quite approximate and needs further refinement. At that level it is probably acceptable to the User community in view of the improved performance that would follow. The APS would then be positioned for state-of-the art light source performance for coming decades especially with the potential to develop Free Electron Lasers.

The committee suggests that the Outfield ERL option could also be configured to use lower energy linacs in a multi-pass arrangement and that there could be considerable cost savings in such an approach whilst still retaining the outfield advantages but at an increased risk.

For the Infield ERL the committee makes identical comments as for the Outfield ERL, except that the constraints imposed by the limited space for the system inside the APS ring building has a serious impact on the positioning of the facility to remain state-of-the-art in coming decades. This is because the development of FELs would be severely limited. The risk from HOM effects in the linac structure is also greater in a multi-pass system.

The storage ring upgrade APSx3 is considered to provide an expansion of existing APS capacity by creating additional locations for undulators together with an increased brightness from a reduced emittance and doubling of the electron current. The existing undulator straights would be extended from 5 to 8 m which would bring the spectral brightness increase to about an order of magnitude. There is a high degree of confidence that the claimed level of performance can be achieved and with no significant risks or R&D challenges, although very high gradient magnets with suitable field quality will have to be developed. It is not believed that the APSx3 option would position APS at state-of-the-art in coming decades and with a disruption of service of about a year to the existing research program it is questionable that the cost and effort would be justified.

The 1nm upgrade to APS attracts virtually the same comments as the APSx3 option, except that it is noted that the dynamic aperture is smaller which implies a somewhat greater risk. The spectral brightness would be increased by about a factor of 40. Neither APSx3 nor APS 1nm is seen as giving state-of-the-art performance for coming decades. The assumed re-commissioning time which was put forward to the committee of 8 weeks is probably over optimistic.

The question of injection into both ring upgrade options from the existing booster should be revisited using alternative matching schemes which may remove the requirement to reduce the booster emittance.

The existing APS is capable of receiving further incremental upgrades which could be cost effective and accomplished with little disruption. An increase of the beam current to perhaps 300 mA and an increase of some IDs to 8 m should be considered.

The committee noted the current activities to generate ps pulses at 120 Hz repetition rate from the APS using crab cavity techniques. This work whilst not specific to any one particular accelerator upgrade option is important underpinning work that will help to strengthen a key user community and generate strength in an R&D area that may contribute to pushing the boundaries of ERL designs.

The assumption that all options for upgrades should use a beam energy of 7 GeV was not entirely justified in the view of the committee. It is accepted that other energy scenarios have been examined by APS staff but it is recommended that the data be compiled into a suitable document.

Introduction

An invited Machine Advisory Committee, constituted as follows, met at the APS on November 15 & 16 to consider outline proposals for APS Upgrade options.

Klaus Balewski (DESY); Max Cornacchia (emeritus SLAC); John Galayda (SLAC); Georg Hoffstaetter (Cornell); Andrew Hutton (JLAB); Sam Krinsky (NSLS); Annick Ropert (ESRF); Elaine Seddon (Daresbury); Vic Suller, Chairperson (LSU). John Galayda was unable to be present but participated by telephone link throughout the meeting.

The committee was charged with evaluating each accelerator upgrade option against the following criteria:-

- Can it deliver the technical performance claimed?
- Is the claimed performance technically revolutionary, and how does it compare to "Greenfield" proposals?
- What are the technical R&D challenges needed to successfully deliver the upgrade?
- What is the expected disruption to users associated with implementing each option, and what can be done to mitigate risk?
- Does a proposed option position APS to remain at the state-of-the-art for the following decades?
- Are there any other proposals that should be considered?

On the first day the committee received a total of 14 presentations from APS staff on various upgrade options and issues related to those options. Later the same day and on the morning of the following day the committee was able to hold both closed sessions and discussions with APS staff to clarify issues raised in the presentations. The committee was very impressed by the quality of the presentations and by the obvious scientific and technical prowess which had been applied to the work on which they were based.

The consensus of opinion from the committee is distilled in the Executive Summary which forms the first pages of this report. The following paragraphs contain more detailed comments.

An Outfield ERL

An extension of the APS by a single-path ERL outside the APS ring was presented. A high-current, low-emittance electron injector would send beam into a straight 7GeV CW superconducting linac headed north, away from the APS ring. The beam would be sent through a loop that is approximately as large as the APS ring and through a transport line to the South into the APS ring. The electron beam would be used for x-ray production in APS straight sections, some of which could be upgraded to accommodate 8m long insertion devices delivering a spectral brightness of up to 10^{22} photons/s/mm^2/mr^2/0.1% with a coherent fraction of more than 90%. The beam would then be energy-recovered and dumped at the north end of the linac.

Risks

While no fundamental flaws or show-stoppers can be identified in the single-path ERL extension of the APS, there are significant risks and uncertainties. These mostly involve the following areas:

1) Gun and injector linac: Can the proposed small emittances, short bunch lengths, and high currents be achieved simultaneously?
2) RF system: The timing and stability requirements are very stringent and have to be verified.
3) Emittance growth: The ERL relies on the transport of extremely small emittances through a very long beam-transport system. Emittance growth effects have been studied extensively, including CSR, nonlinear beam dynamics, cavity misalignments and spurious dispersion from other misalignments. 3D space charge and coupler kick contributions to emittance growth should also be studied.
4) Stability: The APS has achieved a remarkable stability of beam position and energy. An ERL will require slightly higher stability due to smaller emittances. Stabilization strategies and feedback developments are therefore critical, and have to take into account that there are two beams of different energy in the linac simultaneously.
5) Ion effects: Ions accumulate close to the extremely narrow beam of the ERL and create a very steep potential, disturbing the electron dynamics. A strategy for ion removal has to be developed and tested.
6) Beam loss and beam halo: What halo develops in the injector system and to how much beam loss will this lead to, especially in the deceleration process where the relative energy spread increases dramatically?
7) X-ray beamlines and optics have to be developed that can adequately handle the high coherence of the ERL beam. Initially the current APS beamlines could be used, but only after upgrades could full advantage be taken of the high spectral brightness that an ERL offers.

Because the ERL concept still has notable risks and requires significant R&D, its improvements to APS performance will be available later than those of other upgrade options. Improvements of the APS in the interim time should obviously take future ERL requirements into account.

Disruption

The estimated disruption or dark time for installing an ERL was given as 26 weeks. The engineering task of opening the tunnel wall, building the connection between linac hall and ring, and connecting the two accelerators is a very large task and 26 weeks does not seem very generous. Since one of the advantages of any ERL option is the reduction of dark time with respect to a ring upgrade, it is important to develop dark-time estimates for all upgrade options that are easily comparable and make similar assumptions in terms of risk and manpower needs.

Future potential

Several design choices of the single-path ERL option have been made with upgradeability in mind. For example, the linac accelerates particles to the North and has to transport them a long distance and through about 400 degrees of bending before reaching beamlines in the APS. This has been preferred over a linac that accelerates south directly into the APS in order to allow for undulators in the North return loop as a later upgrade option. The return loop is as large as the

APS and provides space for such upgrades. A smaller radius would limit this upgradeability. Additionally, a linac that accelerates northward can, at a later point, be used to feed an FEL.

The committee believes that the upgradeability of the single-path ERL extension should be developed in detail and contrasted to a more compact design with a smaller return loop at half the final energy and two linacs in one tunnel, one accelerating to the North and the other to the South, as developed at Cornell University. Both, the single-linac and the two-linac ERL should include spaces for longer undulators that take full advantage of the low energy spread from an ERL.

An Infield ERL

Two options were presented for the infield option. Option 1 has two 2.33 GeV linacs with an effective gradient of 13.7 MV/m (cavity gradient 22.8 MV/m and a 60% filling factor). Option 2 has a single linac with an effective gradient of 15.6 MV/m (cavity gradient 26 MV/m and a 60% filling factor). Option 2 requires fewer cavities but the effective gradient imposed by the location seems high and will translate to higher cryogenic power.

Both options require two passes of the beam in at least one of the linacs. In addition, several beamlines are required to recirculate the beams and to bring them to and from the ring. This leads to an increase in the emittance that is similar to the values for the out field option (factor 1.35 – 1.85 in the APS).

Can it deliver the technical performance claimed?

The performance relies on achieving the energy, the current (harder to achieve than the outfield option (see below)), the emittance, and the bunch length (about 10% greater than the outfield option). The higher order modes will be large and can lead to beam break-up (BBU) if these modes are not properly damped. There are ways to address the BBU issues, but a recirculated linac will inherently have twice the higher mode power than a single pass linac, requiring stronger damping. The energy is already difficult to achieve given the tight space available for the linacs and it is not obvious that there is enough space for the higher mode damping that will be required. The second infield option is more extreme than the first infield option in this respect and is probably not a viable option. Given the way that the beamlines are laid out, feedback systems are possible by measuring in one arc and correcting in another. This is an advantage of the recirculated linacs.

Overall, the technical performance of the recirculated options will be harder to reach than in the single-pass outfield option.

Is the claimed performance technically revolutionary, and how does it compare with "green-field" proposals?

The claimed performance would make a revolutionary change in the APS performance, and there are ways to incorporate an FEL at a later date (see below). The difference with the "green-field" proposal are the recirculated linacs (cheaper but with more risk) and the beam lines which negatively impact the bunch length and the emittance to a small degree.

What are the technical R&D challenges needed to successfully deliver the upgrade?

Reaching the current from the gun is a pre-requisite but there are many groups working on this and it is likely that the required performance will have been demonstrated ahead of time. Higher order modes in the SRF cavities cause excess heating and instabilities. Recirculating the beam through the linac would double the higher-order mode power and makes this difficult problem worse compared to the outfield option. Calculating the fraction of higher mode power that is trapped in the cavities would lead to an R&D program to damp the relevant modes and extract the higher mode power to higher temperature than 2K.

What is the expected disruption to users associated with implementing this option, and what can be done to mitigate risk?

The disruption is fairly large because of the amount of civil construction required in an area where there are currently a concentration of utilities. It will be difficult to carry out most of the construction without impacting operations, and it is not clear that all of the work can be contained within the maintenance periods. The changes required to the existing infrastructure are well contained and should be completed within the 26 week shut-down presented for the outfield option. We estimate that the overall dark time for the infield option is similar to the ring replacement options (about 1 year), twice that of the outfield option.

Does the proposed upgrade position APS to remain at the state-of-the-art for the following decades?

The infield ERL option, like the outfield option, would ensure state-of-the-art performance for the APS. An FEL could possibly be associated with the infield option by taking the injected beam out of the ring and putting the FEL between the ring and the cooling towers on the North side of the ring.

The option of an outfield recirculated linac (not presented) has more advantages compared to the infield option presented, both from the disruption point of view, the cost (outfield linacs are shorter as beams can travel twice through both linacs instead of only one in the case of the infield option), and also the technical risk (can completely test acceleration to 7 GeV and energy recovery down to 10 MeV while the ring remains untouched). The FEL position between the ring and the cooling towers would also be available for future upgrades in this layout. There are no technical advantages to the infield option other than minimizing the environmental impact on the Argonne site.

Risk versus performance

The single pass ERL has the highest performance potential of the options presented. The recirculated ERL options have similar performance potential, but higher risk and a lower cost. The ring options have lower performance potential, low risk, but a high price for the estimated performance, both in dollars and in dark-time.

Green Field ERL

In order to provide a benchmark for the alternative designs for an ERL “injector” to the APS, a design for a “green field” ERL (GFERL) was presented to the Committee. The GFERL design incorporates isochronous “turn-around” arcs with a generous 230m effective radius. Below is a table showing basic electron beam parameters of the GFERL as compared to the "infield" ERL (IFERL) and the "outfield" ERL (OFERL). All three designs assume identical beam properties at 10 MeV: a normalized emittance of 0.1 mm-mr and an energy spread of 2 x 10^{-4}. "Starting" emittance and energy spread refer to the properties of the 7 GeV beam emerging from the linac. "First arc" data refer to the beam properties at the input and output ends of the first arc, "APS" data refer to the beam properties at the beginning and the end of passage through the APS ring. "Return arc" data refer to the beam properties at beginning and end of passage through the second turn-around arc which brings the electrons back to the linac for deceleration.

	GFERL	IFERL	OFERL (75m arc)
Starting emittance, mm-mr	0.10	0.10	0.10
Starting energy spread, (10^{-4})	1.79	1.00	1.81
First arc angle and radius	180^o, R=230m	127^o, R=80m	$+270^o$-90^o, R=230m
	Input Output	Input Output	Input Output
First arc emittance	0.10 - 0.11	0.10 - 0.12	0.10 - 0.13
First arc energy spread	1.79 1.81	2.00 2.03	1.82 1.84
First arc CSR	minimal	minimal	minimal
		Input Output	Input Output
APS emittance		0.13 - 0.18	0.14 - 0.18
APS energy spread		2.05 - 2.11	1.90 - 1.96
APS CSR		minimal	minimal
Return arc angle and radius	180^o, R=230m	127^o, R=80m	90^o, R=75m
	Input Output	Input Output	Input Output
Return arc emittance	0.11 - 0.13	0.19 - 0.22	0.18 - 0.20
Return arc energy spread	1.81 - 1.83	2.12 - 2.16	1.96 - 2.00
End CSR	minimal	minimal	minimal

The "first arc" designs of the GFERL and OFERL make use of identical design unit cells, and differ only in total bend angle. Therefore it is to be expected that the electron beam properties in first arc of the GFERL and OFERL are essentially identical, as the simulations indicate. Both the GFERL and OFERL "first arcs" are ideal sites for incorporation of the highest performance undulator sources. The R=80m first arc of the IFERL causes only slightly more emittance growth than the GFERL.

Some degradation in emittance at the input to the APS Storage Ring is evident in both the IFERL and OFERL designs, when compared to beam parameters at the end of the first arc of the GFERL. However this is simply the result of adding transport lines for APS Ring injection/extraction, which are absent in the GFERL. Making allowance for this, one can conclude that the IFERL and OFERL are near-ideal sources for the APS ring.

The GFERL requires about 16MW for the cryogenic refrigeration system. This is a very large plant, and it consumes almost as much power as the entire APS facility including accelerators, lab/offices and air conditioning. Optimization of a GFERL design might favor a longer linac with lower gradient.

The IFERL is essentially equal to the OFERL in delivered APS performance, and is likely to be cheaper to build. Perhaps the IFERL could be constructed in the "outfield" to reduce costs.

The presentations of GFERL, IFERL and OFERL, as presented to the Review Committee, placed primary emphasis on performance of the APS Ring. Little emphasis was placed on source characteristics of an FEL (mentioned for the OFERL) or additional high-performance sources of undulator radiation that could be incorporated in the transport lines to/from the APS.

It is recommended that APS staff develop a more complete comparison of the relative merits of alternative ERL designs that includes an assessment of optimum gradient in the linac, technical risks of multi-pass acceleration and the scientific merit of higher-performance radiation sources located outside the APS Ring.

APSx3 Lattice Upgrade

The study of the APSx3 lattice design is very interesting and provides an approach that increases the length of the existing insertion device straight sections from 5 to 8 meters, while providing additional 2m-straights for short insertion devices. In addition, the emittance is reduced to one-half of that of the existing APS storage ring. Obtaining a satisfactory lattice design required a sophisticated optimization of a very nonlinear lattice. This challenging task was successfully accomplished and the calculations presented show that the dynamic aperture is very tight but is sufficient for injection using the existing booster.

In order to implement this new lattice, it will be necessary to replace the existing storage ring magnets by new elements, requiring a shutdown of one year. One must ask whether the improvements in performance provided by the APSx3 lattice justify the large effort in replacing the ring components and the consequent disruption to the user program. The new lattice will provide an order-of-magnitude increase of brightness for the best sources. It will also make available many new sources which will have sufficient brightness to be useful for important classes of research such as protein crystallography. Although these improvements certainly provide an enhancement to the facility they may not be sufficient to properly position the APS to maintain its leadership position as a premier source of hard x-rays over the next decades.

APS 1nm Lattice Upgrade

Reducing the emittance of the electron stored beam is essential for achieving more horizontal coherence. The lattice upgrade scenarios presented to the Committee are based on the boundary condition of keeping untouched the ID source point and running a 200 mA beam at 7 GeV. The presented option uses a Triple Bend lattice, which takes advantage of the cubic dependence of the emittance on the number of dipoles in the cell to achieve an effective emittance of 1 nm, as compared to the current figure of 3.1 nm. In order to increase the available space for insertion devices from the current 5 m to 8 m, the number of quadrupoles in the unit cell is reduced by using bending magnets with gradients and quadrupole doublets in the straight sections instead of triplets. Two versions of this lattice have been studied: a symmetrical one and one with 4 low beta straight sections around the ring. It was noted that the horizontal beta function at the ID source points is significantly different from the present value (~ 8 m instead of 20 m). Could this be a problem for users? Also the vertical acceptance is not optimal since betay= 6 m instead of the ID length/2 optimal value. This may induce more losses at the ID location and an increase of Bremsstrahlung into the beamline.

In these low emittance lattices, correction of the aberrations induced by the increased focusing implies the use of much stronger sextupoles which reduces the dynamic aperture to values that may be insufficient to ensure a correct injection efficiency. In the case of the 1 nm lattice, an upgrade of the booster emittance by at least a factor of 2 would be mandatory to cope with the small dynamic aperture obtained. Confidence in the models and their predictions of the real dynamic aperture of the machine is essential to minimize the operational risks linked to insufficient injection efficiency.

The proposed upgrade would use conventional technologies that are pushed to a realistic limit. Some R&D work on the magnet design is required to ensure the feasibility of a quadrupole with 20 mm bore radius and that the field quality of the combined bending magnet is correct.

The performance upgrade is less than one order of magnitude as compared to the possible intensity and ID length increase of the existing APS and will imply a significant disruption to users with at least one year of shutdown. Even if the dismounting/installation time could be reduced with increased resources, the foreseen commissioning time of 8 weeks for the injector and storage ring looks somewhat underestimated. Although the performance improvement is significant, it may be insufficient to maintain APS at the state-of-the-art for the following decades.

Other lattice upgrade scenarios

Another option to reduce the horizontal emittance would be to use a Double Variable Bend (DVB) structure by incorporating dipoles with variable fields along the beam path. A simple field with a three-step profile is considered as the most feasible solution instead of a complicated polynomial profile. Whether the DVB could, in addition to the emittance reduction, provide extra space in the achromat for insertion devices like the APSx3 is worth investigating.

A much more ambitious project would involve the construction of a completely new storage ring, providing an electron beam of much smaller emittance and hence X-ray beams of much higher brightness than currently possible. The "ultimate storage ring" scheme developed in other laboratories could be revisited with damping wigglers incorporated to provide a reduction in emittance by one order of magnitude and give far better performances than the storage ring upgrades in the existing tunnel. Some consideration of this topic was presented but APS staff feel that all treatments to date are incomplete.

Instability Estimates for the APS Upgrade

Instability estimates for the upgrade of the APS storage ring as well as for the ERL-option were presented.

The boundary conditions for the upgrade of the storage ring are as follows

- The single bunch current limit should be larger than 16 mA.
- Stable operation with 200 mA in multibunch mode should be possible.

In the present APS machine more than 200 mA can be stored in multibunch mode.
Any kind of transverse coupled bunch instability is normally cured by raising the chromaticity. To get rid of longitudinal modes part of the cavities would be equipped with improved higher order mode dampers.

The planned installation of a transverse broad-band feedback system is the right way to get rid of transverse instabilities and has been demonstrated at several laboratories. A careful look at the noise budget of the feedback system is advisable because otherwise the emittance can be spoiled by the feedback system. In summary, there should be no fundamental problems to a current of 200 mA in multibunch mode in the upgrade.

In the present APS machine different kinds of single bunch instabilities have been observed. The longitudinal microwave instability threshold of 6 mA is not a serious limitation because one can accept the larger energy spread. A severe limitation is given by the transverse mode coupling instability in the vertical plane which limits the current to a few mA. The installation of ID chambers with a 5 mm clearance made this problem even more severe. This instability is combated by raising the chromaticity to about 10 which allows up to 20 mA to be stored. The simulated thresholds agree very well with the measurements so there exists a realistic model of the impedance of the existing APS.

Based on this model an estimate was made for the threshold current in the upgraded APS. In terms of impedance the major change comes from the fact that the dimensions of the vacuum vessels will be smaller by a factor of two for the upgraded machines. This will certainly increase the resistive wall contribution but the contribution from transitions should be smaller because they are smoother. The wakes of all relevant components were recalculated and it was found that the total wake is even smaller than for the present APS. But the assumption was made that all 5mm gap chambers will be taken out. The committee questions if this is a good assumption because low gap chambers may be installed in a later phase. It is recommended that the contribution of small gap chambers to the impedance budget should be determined. The single bunch current limit based on the above mentioned assumptions is about 19 mA, which is above the requirement of 16 mA. As for the present APS this can only be achieved with a high chromaticity of 10. Whether this is a good way to fight this instability for both the APSx3 and APS 1nm upgrades is questionable because this may reduce the momentum acceptance to an unacceptably low value.

The other option to cure this instability by using the above mentioned feedback system has to be investigated in detail. It has been tried at several laboratories to increase the threshold current for the transverse mode coupling instability by applying feedback but this has never been satisfactory. It is recommended to investigate this strategy by simulation and by doing machine experiments with the planned prototype of the feedback system. In summary, there is some risk that the current in the upgraded lattices will be limited to a value less than 16 mA.

For the ERL option a program was set up to study wake field effects. There are hints from studies in connection with the ILC that transitions in the vacuum chambers close to the ID's will have a negative impact on the short bunches. The committee also recommends investigation of restive wall heating by the short bunches. Investigating these effects is difficult as the wakes have to be computed for a very short bunch-length (1ps or even less) and the existing codes do not allow an accurate calculation of these wakes. The decision to develop a new code in collaboration with other institutes is endorsed as well as taking part in the ILC collaboration on collimator design.

Superconducting RF system

The ERL options require the development of expertise in superconducting RF technology at the APS. This represents a major effort, but it should benefit from collaboration and the R&D already performed at other institutions (Cornell, Daresbury, DESY, Jefferson Laboratory). The presentation to the Committee touched upon the major technical issues and options confronting the design.

The choice of RF frequency must be based on a detailed study, possibly taking into account the need for synchronization with the APS RF frequency should the hybrid mode be a desirable experimental goal. The cavity design should draw upon the studies being carried out at other laboratories that employ CW operation; the experience of the ILC appears less relevant, since it utilizes a pulsed system.

The power of the higher order modes is an important issue. It must be removed from the 2 K environment. This requires a cavity design without trapped modes. The design of this system presents a considerable challenge.

The power estimate should be refined, and the accelerating voltage should be optimized based on a reliable statistics of breakdown occurrences. The cryomodule design and construction will require appropriate resources; the magnitude of this work should not be underestimated.

Booster upgrade

An upgraded booster has received attention due to the requirement for efficient (low loss) injection into both storage ring upgrade options. The efficiency is likely to be reduced from the presently experienced level of close to 100% because of the reduced dynamic aperture in both the APSx3 and APS 1nm options. Simulations for the case of matched betatron functions between the incoming beam and the storage ring have been made for both options with a variety of randomized errors. With the 65 nm emittance delivered by the existing booster efficiencies of over 90% are found for APSx3 and 75% for the symmetric version of APS 1nm. Unfortunately the low beta version of APS 1nm shows injection efficiency of only 20%.

It is commonly found that best injection can be achieved for unmatched conditions and the committee recommends that simulations using such set-ups be examined before concluding that a booster upgrade is necessary. It may also be found helpful to rotate the horizontal and vertical planes of the beam in the transport line from the booster.

Short X–ray Pulses from the APS

The committee was informed about the current activities to generate ps pulses at 120 Hz repetition rate on the APS using crab cavity techniques. This work whilst not specific to any one particular accelerator upgrade option is important underpinning work that will help to strengthen a key user community and generate strength in an R&D area that may contribute to pushing the boundaries of ERL designs.

The current beam diagnostics activity was presented together with options for the use of slits or x-ray compression optics using asymmetric cut crystals. The plans for developing this work towards 1 kHz operation were summarized. In the longer term work on CW deflecting cavities are of great interest to 3rd generation machines world-wide. Clearly the APS would have the lead with others following. The development/enhancement of SCRF expertise would be in line with other developments necessary for ERL development.

Whilst it is clear that there is much exciting science to be done in the ps regime, shorter pulses should form part of the remit for revolutionary performance.

Compression in the ERL arcs is not being considered but would be a worthwhile topic for the future. The idea of a separate 1nC gun, bunch compression and in-line undulator was liked as a means of generating sub ps pulses and was deemed worthy of further study.