FLS 2010: Report of the Working Group on Storage Ring-based Sources

4/6/10

Executive Summary

The charge for the Storage Ring-based Sources working group, co-chaired by Sam Krinsky (BNL) and Bob Hettel (SLAC), was given as:

A. Evaluate light source concepts and architectures that are beyond state-of-the-art and are presently in the conceptual or R&D stage and that would have transformational radiation characteristics.

B. Evaluate concepts that could significantly change the economics of construction and operation of advanced light sources. Assess the cost/performance trade-offs in terms of overall construction and operation cost, accessibility to researchers, etc.

The working group was very well attended and continued the momentum in thinking about future ring implementations developed in two recent workshops: the BES workshop on Accelerator Physics for Future Light Sources (September 15-17, 2009) and the CERN workshop on Low Emittance Rings (LER2010, January 12-15, 2010). The working group program was comprised of four sessions:

1. Lattice Design and Beam Dynamics (Yunhai Cai, SLAC, chair);
2. Machine Operation and Studies on Existing Rings (James Safranek, SSRL/SLAC, chair);
3. New Capabilities, Short Bunches, Exotic Modes, etc.(Dave Robin, ALS/LBNL, chair);
4. Future Ring Technology and Design Issues (Glenn Decker, APS/ANL, chair).

The discussions addressed a broad array of issues critical to the design and performance of synchrotron light sources; however, the overriding interest was in the assessment of the feasibility of the design of a storage ring for a future diffraction limited hard x-ray source. It was the conclusion of the working group that the knowledge gained from the design, construction and operation of recent storage ring sources, together with increasingly powerful simulation lattice optimization programs and computing platforms, provide the necessary foundation for a successful R&D program to pursue the design of a diffraction limited hard x-ray source with energy ~5 GeV, circumference ~2-3 km, horizontal and vertical emittances ~10-pm, and brightness ~10^{23}ph/sec/mm^2/mrad^2. It was recommended that a study be carried out to evaluate the possibility that the innovative design of MAX-IV might be extendable to the larger diffraction limited x-ray source and might offer insights leading to significant cost savings.

Summaries of the working group sessions are presented below.

Session 1: Lattice Design and Beam Dynamics

This session addressed the design of near-future low emittance storage rings, particularly NSLS-II, MAX-IV and the APS upgrade, as well as farther future ultimate rings, including the planned SPring-8 upgrade and the PEP-X ultimate ring at SLAC that is under study. Advanced methods in lattice design, dynamic aperture maximization, and analysis of impedance and collective effects were presented.

The session presentations included:

Christoph Steier, LBNL, "LER 2010 Workshop Summary"

Weiming Guo, BNL, "The Near Future Light Source: NSLS-II"

Simon Leemann, MAX-lab, "The MAX IV 3 GeV Storage Ring"

Yuri Nosochkov, SLAC, "Lattice Design and Performance for PEP-X Light Source"

Takahiro Watanabe, SPring-8, "SPring 8 Upgrade Plan"

Michael Borland, ANL, "Parallel Tracking-Based Optimization of Dynamic Aperture and Lifetime with Application to the APS Upgrade"

Lingyun Yang, BNL, "Multi-Objective Optimization of Dynamic Aperture"

Karl Bane, SLAC, "Impedance and Collective Effects in Future Light Sources"

LER 2010 Workshop

The CERN Workshop on Low Emittance Rings (LER2010) was held in January 2010. The goal of the workshop was to bring together experts from the scientific communities working on low emittance lepton rings including damping rings, test facilities for linear colliders, B-factories and electron storage ring light sources in order to discuss common beam dynamics and technical issues. The workshop included three main topics: 1) design of low emittance lattice, machine tuning, and non-linear dynamics; 2) collective effects including intrabeam scattering, impedance modeling and measurements, and coherent synchrotron radiation; and 3) technology of low emittance rings emphasizing high-field low-period wiggler, kicker system, beam instrumentation, and feedback systems. The content of the workshop was very similar to that of the storage ring working group for FLS2010. The high degree of commonality in the challenges and approaches to solutions related to these topics for the various applications suggests that there is an opportunity for collaboration in design and beam tests between the various communities. It was proposed that these collaborations be pursued in the future and be reported upon at the second workshop in this series.

NSLS-II

An overview of the lattice design of NSLS-II was presented. The lattice consists of 30 double bend achromats in 800-meter circumference. The main feature of the design is to use weak dipoles and damping wigglers to reduce the emittance down to sub-nanometer level at 3-GeV beam energy. An analytical approach to the optimization of dynamic aperture was emphasized in the presentation. In particular, with the formulas derived from the Lie algebra method, it was shown that one can reduce the nonlinear chromatic effects and minimize the geometrical tune spreads while maintaining the control of the third-order resonances driven by the strong sextupoles in the lattice.

MAX-IV

The MAX-IV storage ring is a major part of Sweden's next-generation high-performance synchrotron radiation source. The ring has a 528-m circumference and will be operated at 3 GeV for the generation of high-brightness hard x-rays. This storage ring was designed to meet the requirements of state-of-the-art insertion devices which will be installed in nineteen 5 m long dispersion-free straight sections. The storage ring is based on a novel multibend achromat (MBA) design delivering an unprecedented horizontal bare lattice emittance of 0.33 nm-radian and a vertical emittance below the 8 pm-rad diffraction limit for 1 Å radiation. Aside from the MBA cell, there are several important innovations: 1) the utilization of many compact and combined function, small-aperture magnets to make a compact ring; 2) the use of lower rf frequency, namely 100 MHz, to increase the rf bucket height and therefore increase Touschek lifetime; 3) achieving a very low emittance with sufficient momentum acceptance to significantly increase the Touschek lifetime; and 4) the introduction of octupole magnets to control the tune footprint.

PEP-X

A comprehensive overview of the lattice design for PEP-X as an ultra-low emittance storage ring that could reside in the existing 2.2-km PEP-II tunnel was presented. The design features a hybrid lattice with double bend achromat cells in two arcs and theoretical minimum emittance cells in the remaining four arcs. Damping wigglers are used to reduce the horizontal emittance to 86 pm-rad at zero current for a 4.5-GeV electron beam. The emittance increases by about a factor of two with 1.5-A stored current and coupling to achieve 8-pm-rad vertical emittance. The design could produce photon beams achieving a brightness of 10^{22} (ph/s/mm^{2}mrad^2/0.1% BW) at 10 keV in a 3.5-m conventional planar undulator. It was shown that the optimized lattice has adequate dynamic aperture to accommodate a conventional off-axis injection system.

SPring-8 Upgrade Plan

SPring-8 has a tentative plan to replace the existing ring with one that is diffraction-limited at 1 Å (~10 pm-rad) and that will support an ultra-short bunch mode of operation by circulating short bunches from the XFEL linac . The study so far has focused on an MBA cell having four to nine bends with various emittances and beam energies. Modified (Gaussian) sextupoles have been considered to reduce the nonlinear effects of the strong sextupoles, but only a marginal improvement in dynamic aperture is achieved. The possibility of utilizing non-interlaced sextupoles has also been considered. A scheme using a solenoid magnet to locally produce a diffraction-limited round beam is being considered. Further improvements seemed necessary to achieve a design of diffraction limited ring inside the existing SPring-8 facility.

Multi-Objective and Parallel Tracking-Based Optimization of Dynamic Aperture

Two presentations were made on powerful multi-objective optimization methods to maximize both dynamic and momentum apertures. The first method, used for the APS upgrade, relies on two key ingredients: fast tracking on a parallel super computer or PC cluster and a multi-objective searching genetic algorithm. The method has been successfully applied to the APS upgrade and is mostly effective and robust for searching the solutions with high chromaticity. The method found a good solution of sextupole settings even in asymmetric lattices. Most importantly, several experimental tests validated the method in terms of increasing the beam lifetime in the existing storage rings.

The second method, used for the NSLS-II, also uses a genetic algorithm for multi-objective optimization and has been successfully applied to many areas. In particular, it is highly suitable for maximizing dynamic aperture because of its stochastic nature and several examples of how to optimize both dynamic and momentum apertures in NSLS-II lattice were shown. Although the results were still preliminary, they showed many interesting and promising features such as the partial correlation between dynamic aperture and the resonance driving terms.

Impedance and Collective Effects

The effects of impedance and collective effects in the design of PEP-X were presented as an example of future light source for future light source design. Topics included intra-beam scattering, Touschek lifetime, impedance calculation, and collective instabilities. For calculating the increase of emittance due to intra-beam scattering, it was shown that one has to be careful about a correlation between the longitudinal and transverse planes when there are combined function magnets in the lattice. A method to simplify the impedance calculation for ultra-short bunches based on a simple scaling law was also presented.

Session 1 Summary

Over the past decade, significant progress has been made in the design of the ultra-low emittance storage rings. Analytical understanding of resonances and nonlinear chromatic effects, combined with modern lattice optimization schemes using multi-objective algorithms and ever increasing computing power, allow us to effectively find lattice solutions for the most challenging requirements. Based on the design of NSLS-II and MAX-IV, the Working Group has concluded that a realistic design of a kilometer-sized storage ring having diffraction-limited emittance at 1 Å is a reachable goal within this decade. The design trend for such an “ultimate” ring points toward multi-bend achromat cells with many weak bends, many combined-function magnets, damping wigglers with shorter period and higher fields, stronger sextupoles, a small dynamic aperture, and the possible use of on-axis, bunch-replacement injection to cope with the reduced acceptance (see Session 2 report).

Session 2: Machine Operation and Studies on Existing Rings

This session addressed the progress that has been made toward optimizing the performance of existing storage ring light sources and achieving their full design potential. Also discussed was further experimental work that could be carried out on existing light sources to demonstrate we can achieve the more challenging performance requirements of future ultra-low emittance storage rings. The critical operational issues are: closed orbit control, linear optics control, nonlinear dynamics, injection, and impedance/instabilities.

The session presentations included:

- Laurent Nadolski, Soleil, “Lessons Learned from Machine Studies on Existing Rings”
- Riccardo Bartolini, Diamond, “Experimental Characterization of Nonlinear Optics”
- Louis Emery, ANL “On-axis Injection into Small Dynamic Aperture”
- Johannes Bahrdt, BESSY, “Experience with Insertion Devices at BESSY-II”
- Kathy Harkay, ANL, “Integrated Instability and Lattice Design for Ultimate Rings”
- Yong-Chul Chae, ANL, “Impedance Modeling of the APS Storage Ring: Current and APS Upgrade”

Closed Orbit

Closed orbit control is covered in session 4**, “**Future ring technology and design issues”**.**

Linear Optics

Work at existing storage rings has shown that good algorithms have been developed for controlling linear optics. Orbit response matrix optics correction methods such as the LOCO code are widely used to correct linear optics, so light source storage rings routinely achieve performance very close to design. LOCO has also been used to correct vertical emittance to 2 pm-rad or less, which is below the requirements for future light sources. Analysis of turn-by-turn betatron motion has also proven to be a powerful method for controlling linear optics and coupling.

Insertion devices are a significant source of linear optics distortion. The skew and normal gradient contribution from IDs varies with ID gap, as well as with polarity for EPUs). Successful feed-forward algorithms have been implemented for ID optics correction of both normal and skew focusing. Lessons learned include the importance of designing in linear optics correction. This can include skew gradient correction coils on IDs as well as optics design to ensure effective local optics correction.

There was some discussion of the need for more real-time optics correction than that provided by orbit response matrix analysis, which requires data collection that perturbs the beam for some minutes or more. It would be worthwhile to study the stability of optics in existing rings to see if it meets the tight requirements of future rings. Perhaps it will be necessary to develop real-time optics correction algorithms based on turn-by-turn measurements of betatron oscillations.

Nonlinear Dynamics

Proper understanding and control of nonlinear dynamics is critical for achieving design dynamic aperture, lifetime and injection efficiency. Much progress has been made in experimental techniques for measuring and controlling nonlinear optics. Tune map measurement techniques have been developed at ALS and BESSY. Local orbit bumps have been used to characterize the nonlinear fields in insertion devices and final focus magnets of colliders. Frequency analysis of nonlinear betatron motion has been used to find sextupole errors and to correct resonance strengths, resulting in improved dynamic aperture.

After sextupoles, insertion devices tend to be the strongest source of optics nonlinearity in light sources. This problem will only increase in future light sources with damping wigglers and EPUs. Tracking techniques to accurately model the “dynamic integrals” of insertion devices have been developed, and methods for correcting these nonlinearities are improving.

As a result of these advanced techniques of nonlinear dynamics measurements, improvements have been made in the agreement between model and measurements for dynamic aperture, lifetime and injection efficiency. Nonetheless, many storage rings still show discrepancy between measured and model parameters such as vertical linear and nonlinear chromaticity. It has been shown, at least in some cases, that these discrepancies can be resolved by more accurate modeling of magnet end field roll-off. This lesson should be integrated into future light source design in order to accurately predict the dynamic aperture as the nonlinear dynamics gets pushed harder.

Future light sources will likely have short lifetimes, resulting in increased electron losses over time. Understanding of nonlinear dynamics will need to be sufficient to predict the loss distribution and avoid radiation damage to insertion devices.

The recent work at the APS and elsewhere in which individual sextupoles strengths are varied in computer tracking of storage rings to optimize dynamic aperture appears quite promising (see Session 1 report). Good results have been achieved implementing the optimized sextupole strength distributions at APS and Diamond. This work should be extended to other existing storage rings to further demonstrate its viability for future light sources.

Injection

The strong focusing and optics nonlinearities in ultra-low emittance light sources will result in small dynamic aperture for injection. Work at existing light sources shows that we can control the optics of the injected beam in order to match the small available injected beam aperture. The small injection aperture will require low emittance beams from future light source injectors.

Small dynamic aperture for injection may necessitate novel techniques such as pulsed multipoles. This technique should be fully investigated on existing rings to ensure that they would be feasible for future light sources. The dynamic aperture of a future light source may be sufficiently small that injection accumulation may not be possible. Bunch or bunch train swap out with on-axis injection would be required. Machine studies of on-axis injection should be conducted at existing light sources to determine the practical requirements for such an injection scheme. The studies should be conducted with small dynamic apertures, such as those expected on ultimate storage rings, as well as with relatively large horizontal to vertical coupling. On-axis injection would require kickers with fast rise times as well as stable flat-tops to minimize injection transients seen by photon users.

Impedance and Instabilities

The group discussed the advantage of a thorough "bottoms-up" impedance database for accurate prediction of instability thresholds. APS, DAFNE, and the SLAC damping rings were given as examples of rings with such impedance databases, with impedance models for all significant components. At APS, vertical beam size increase from TMCI limits injection efficiency at high currents. Measurements and model tracking show close agreement for injection efficiency vs. current, demonstrating the accuracy of the impedance model generated from their impedance database. Measurements at APS of bunch length and shape distortion vs. single bunch current as well as energy spread increase from the microwave instability also show good agreement with calculations. Careful design of tapers for small gap insertion devices is critical for storing large single bunch currents. Nonlinear tapers can be effective for reducing impedance for flat or elliptical chambers, though they are not effective for all chamber transverse cross-sections.

The importance of including impedance considerations in the optics design of future light sources was discussed. For example, many existing rings run at higher chromaticities than originally anticipated, so it would be useful to include tracking studies at high chromaticity when designing future light sources. Minimizing betas at locations of impedance can improve the TMCI threshold. The dispersion in dipoles will be very small in future light sources to achieve ultra-low emittance, so the momentum compaction and bunch length will also be small. Low momentum compaction will lead to lower TMCI threshold. Also, the short bunches will sample a broader impedance spectrum, requiring calculations of high-frequency impedance.

Future light sources could benefit from further studies on existing storage rings, including impedance effects for short bunches, CSR impedance, ion instabilities, ID taper impedance, impedance associated with NEG-coated chambers, and intra-beam scattering.

Session 3: New Capabilities, Short Bunches, Exotic Modes, etc.

This session was charged to "evaluate concepts and architectures that are beyond state-of-the-art and are presently in the conceptual or R&D stage and that could have transformational radiation characteristics and/or significantly change the economics and performance of advanced light sources." To address this charge, six presentations were made that covered five areas:

Dao Xiang, SLAC, "Laser-Assisted Emittance Exchange for Ring Lasing"

Ying Wu, Duke, “Storage Ring Compton Light Sources”

Ron Ruth, Lyncean, “Compact Light Sources

Michael Borland, ANL, “Use of Crab Cavities for Short X-ray Pulse Production in Rings”

Xiaobiao Huang, SLAC, “Low Alpha Mode for SPEAR3 and a Potential THz Beamline”

David Robin, LBNL, “Tailored Bunch Operation”

In storage rings, light, for the most part, is generated via spontaneous radiation. Brightness gains are made by increasing either the beam current or reducing the 6D electron beam size. Many of the other sessions in our working group were centered upon reducing the 6D electron beam size to enhance the emission of spontaneous radiation. In this session we focused in on other more exotic modes of operation both looking at brightness a well as other performance parameters.

Lasing and Related Methods

Being able to exploit stimulated (rather than just spontaneous) emission could greatly increase the flux and would be particularly interesting if it could be done at shorter wavelengths (< 1 nm). At present this is not possible due to the relatively large energy spread and low peak current of the beam. On the other hand, it has been shown earlier workshops that an ultimate storage ring might produce “partial lasing” at longer wavelengths (> 3 nm) if the emittance is at the diffraction limit for the wavelength and sufficient peak current can be reached.

One intriguing idea was presented on using laser-assisted emittance exchange (LAEE) where in principle the low emittance of the vertical plane can be partially exchanged with the larger longitudinal emittance in short sections of an electron bunch separated by the laser wavelength to extend lasing to shorter wavelengths – perhaps to 3 nm or less. Conditioning the beam with LAEE could greatly shorten FEL gain lengths. In the example given, the FEL gain length was reduced from 35m to 8m. Such a scheme would probably require the beam to damp back after the lasing and as a result the scheme might only be practical at the kHz level. Nevertheless this might be of interest particularly for experiments where one would want to synchronize with a laser. In addition it was pointed out that LAEE could also allow one to extend the spectrum to higher harmonics. This is interesting and may be realizable in the longer term. But now LAEE is still in a very conceptual stage.

Compton Scattering Sources

Another technique we discussed was the use of Compton scattering to generate higher energy photons. This is not a new idea however there have been significant advances over time. There were two talks about the use present use of Compton scattering. First there was a comprehensive talk showing the results from Duke University where gamma rays are generated by Compton scattering from a tunable storage ring-based FEL (optical klystron). This has been very effective at generating light in the 1 to 100 MeV energies and as such is the brightest source of light in this region. Most of the applications for such radiation are in nuclear physics. In another talk the performance of the lower energy Lyncean compact Compton scattering source were shown. This source of hard tunable (~12 keV) x-rays is not comparable in brightness to the present 3rd generation of x-rays. The advantage of such a source is its compactness and may be of interest for a user who desires a local compact x-ray source with more capabilities than a rotating anode.

Short-Pulse Operation

There were several talks devoted to short-pulse operation. Several rings have compressed the electron bunch length to the picosecond level by operating with a small momentum compaction, but with very low beam current, in so-called low alpha mode. The current is limited by free space impedance that generates a single bunch instability having a threshold that decreases with lower momentum compaction. There appears to be some discrepancy between the predictions and measurements for the beam current thresholds as a function of momentum compaction factor. Nevertheless all see the current versus bunch length limit and this greatly reduces the utility of low alpha operation. This mode is not compatible with high-brightness and high-flux operation, which is the primary community for storage rings, and as a result has only been used in operation in very limited shorter operation periods.

Another technique for generating short x-ray pulses is to create a tilted bunch using RF deflecting (crab cavities). A major difference between this technique and low alpha is that this does not require shortening the bunch. In this scheme a crab cavity is used to give the bunch a tilted kick that changes with time causing the bunch to vertically wobble. This wobble is taken out with another crab cavity somewhere else in the ring. Between the two cavities one can take advantage of the wobble to generate a radiation pulse that is shorter than the bunch length. An advantage of crab mode is that it can be done at high current and as such is potentially compatible with high brightness operation for other users. The APS has extensively modeled this scheme and has plans for implementing it with superconducting crab cavities. The method has yet to be demonstrated on a real machine.

Neither the crab scheme nor the low-alpha method are projected to bring the pulse length down to much less than a picosecond and thus are not ideal for the ultra-short bunch users (< ~1 ps), who might be able to use low repetition-rate femto-slicing sources. On the other hand, both the low-alpha and crab cavity modes target users interested in picosecond pulses with high repetition rate.

Tailored Bunches

Finally a talk was given on “tailored bunch operation”, a mode that enables changing the properties of some bunches compared with other bunches in the ring. The goal of this mode is to simultaneously satisfy different sets of users having different beam property requirements. In particular, two groups of users having very different beam requirements are the high brightness/flux users and the dynamics/time-of-flight users. In many cases these users are required to operate at different times with different filling patterns. Tailored bunch operation is not a new mode of operation. Presently there are operational modes that provide bunches having different charges, variable gaps between bunches to enable timing measurements, and even femto-sliced short bunches produced using a laser to provide an energy “kick” a small portion of a bunch which then generates a short photon pulse in the beam line.

Ideas are being developed to further exploit the idea of tailored bunch operation. At the ALS, a high repetition rate fast kicker magnet has been installed and experiments are underway with the goal of putting a single bunch on a different closed orbit than the other bunches. The results are encouraging, and show that a user can collimate out the light from all but the displaced bunch allowing a quasi-single bunch mode of operation. One can imagine how to further exploit tailored bunch operation in various ways, for example by having bunches with different orbits, different energies, or even different bunch lengths. In principle it even might be possible to have bunches with different momentum compaction factors circulating in the same ring. The more advanced forms of tailored bunch operation are still in a very conceptual stage.

Session 4: Future Ring Technology and Design Issues

This session was charged to "identify present technical limitations for reaching future ring performance goals, evaluate concepts that could significantly change the economics of construction and operation of advanced and future light sources, and assess the cost/performance trade-offs in terms of overall construction and operation cost, accessibility to researchers, etc." The session presentations included:

Glenn Decker, ANL, "Limits to Achievable Beam Stability"

Animesh Jain, BNL, "Alignment and Stability of NSLS-II Magnet System"

Louis Emery, ANL, "Fast switching IDs and experience with the APS Circularly Polarizing Undulator"

Valery Dolgashev, SLAC, "RF Design of Normal Conducting Deflecting Cavity"

Simon Leeman, MAX-lab, "Cost-saving Design Choices for MAX-IV"

Vasili Tsakanov, CANDLE-YSU, "CANDLE Project in Armenia"

Thomas Rabedeau, SLAC, "Photon Source and Optics Considerations"

Beam Stability and Stabilization

Phase space dimensions for an ultimate storage ring are on the order of 10 microns and 1 microradian. This implies stability at the level of sub-micron and 100-nanoradians rms will be required. In terms of AC stability, a number of beam position monitor (bpm) technologies are available which provide noise floors approaching 1 nm / √Hz, corresponding to 10 nm of rms beam motion in the frequency band 1 -100 Hz. This is sufficient to meet AC stability requirements for an ultimate storage ring. Instrumentation Technologies markets such a bpm processing unit (Libera Brilliance), and other FPGA solutions such as the APS-designed BSP-100 module allow comparable performance.

Time-variable insertion device (ID) parameters such as gap or polarization place fundamental limitations on the stability of source position, angle, shape, and size, in addition to beam energy, and arrival phase. Even with perfect electron bpms, the photon beam's trajectory is not collinear with the line connecting the two bpms that straddle an insertion device due to residual uncompensated first- and second-field integrals, at the level of a few microradians and tenths of microns with present technology. Further, the sinusoidal trajectory within the device may deviate on average from a straight line by amounts comparable to the beam size, which may impact source brightness (Fig. 1).

These effects provide significant motivation to develop photon bpms having sub-micron residual systematic errors. First results were shown from a new high-power photon bpm at the APS, based on hard x-ray fluorescence that solves many problems associated with photoemission-based detectors. In addition, future improvements in ID-shimming may be necessary to minimize these effects. Even with such improvements, the most sensitive x-ray experiments likely will require feedback on optical components to stabilize the monochromatic beam for example. This is especially true considering that ID beams will have tens of kilowatts of white beam power which must be apertured and/or filtered down to manageable power levels upstream of the monochromator.

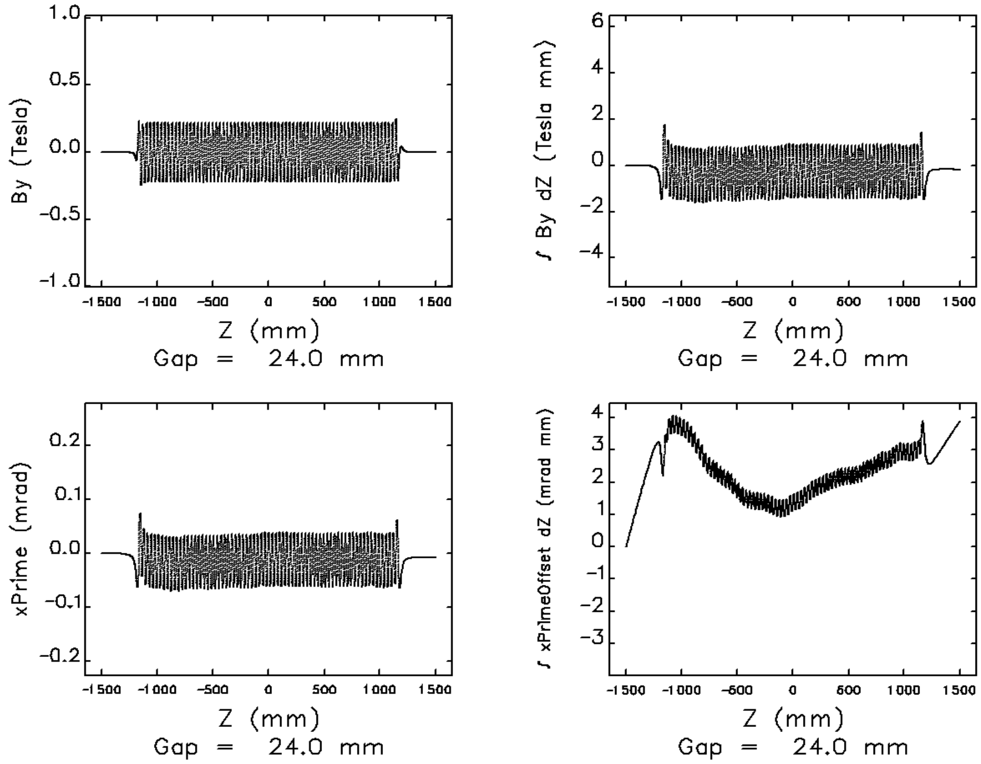

Figure 1. Longitudinal Hall probe scan of a typical APS planar hybrid undulator A. Top left: vertical component of magnetic field. Top right: first field integral in units of Tesla-mm. Bottom left: first field integral in units of milliradians (i.e. divided by beam rigidity 23.3495 T-m for 7 GeV). Bottom right: second field integral in units of microns, i.e. this is the particle beam trajectory.

Accelerator Alignment Technology

Great progress has been made in accelerator alignment technology as demonstrated with implementations for the NSLS-II, now in construction. Using a vibrating wire technique, determination of sextupole magnet center line has been performed at the level of 5 microns absolute. The ability to preserve magnet alignment at this level following girder assembly relocation has also been demonstrated. Quadrupole magnet center line determination is at the level of 2 microns absolute, even though the center line of multipole magnets has been shown to vary at the level of tens of microns depending on magnet excitation.

Fast-Switching Insertion Devices

Advances in magnet control software have made it possible to compensate the effects of fast-switching IDs such as implemented for the APS circularly polarized undulator (CPU). This scheme corrects not only the first- and second field integrals but also the linear and non-linear multipole components using sophisticated feed-forward algorithms. Many obstacles had to be overcome including the effects of hysteresis and eddy current latency. One alternative to rapidly switching the ID fields is to instead rapidly switch between two spatially separated insertion devices with opposite polarity using an orbit bump in combination with fast steering correctors. Experience at the APS with the CPU emphasizes the challenge of maintaining beam stability in the presence of rapidly varying insertion device parameters.

RF Deflecting Cavities

New types of rf frequency devices will be critical to the operation of an ultimate storage ring, with one example being the crab cavity scheme for producing ultra short pulses*. SLAC designs for normal conducting copper s-band and x-band structures were presented. Other important technologies which will need development are superconducting crab cavities, fast kickers to facilitate swap-up injection and tailored bunch operation (see Session 3 report), harmonic cavities for bunch lengthening, and other types of devices allowing fast bunch manipulations.

*Zholents et al., Nucl. Instrum. Methods A 425 (1999) 385-389.

Cost-Saving Technology for MAX-IV

Cost-saving design technology developed for the MAX-IV ring design was described. MAX-IV has a design emittance of 0.25 nm-rad using a multibend achromat lattice. Quadrupole and dipole magnet pole pieces are milled from a single large solid steel block reducing production costs considerably. Such a structure also reduces costs for alignment of individual magnets and forms a solid girder-type structure which is to be mounted on massive concrete supports. This has the additional advantage of moving the lowest vibrational modes up above 100 Hz were there is little ground motion to excite it. The use of relatively low RF frequency (100 MHz) allows for a relatively inexpensive RF system.

CANDLE Light Source

An overview of the Armenian CANDLE light source project, a research institute of the Yerevan State University, was presented. The CANDLE machine uses a double bend achromat lattice and will operate at 3-GeV beam energy. Machine circumference is planned to be 216 meters providing an emittance of 8.4 nm-rad. Design studies are moving forward, including nonlinear dynamics, magnet design and many others. Components for the linac RF systems have been procured. The project is moving forward with land allocated for it and financial commitments in place.

Photon Optics

A design study was presented elaborating on how one might design a beam line to handle a 150-period ID installed in the PEP-X machine that generates 75 kW of radiation. It is a non-trivial exercise to aperture and filter this beam appropriately while at the same time preserving emittance. As an example, present commercially-available mirror technology can provide surface figure at the level of 250 nanoradians which would effectively double the 140 pm-rad PEP-X emittance. Improved metrology will be needed to reliably produce optics with surface figures below a few hundred nanoradians. The power handling of LN2 –cooled silicon monochromator crystals forms another serious limitation owing to the non-negligible thermal expansion coefficient at liquid nitrogen temperatures. Alternative cryogens that operate near 130 K would be near the zero of thermal expansion for silicon and could markedly improve monochromator performance. Materials other than silicon such as diamond should also be explored.

Session 4 Summary

Storage ring technologies are quite mature, including a number of solutions for sub-micron resolution particle beam position monitoring, alignment techniques at the few-micron scale and other technologies. Fundamental limitations impacting the stability of an ultimate storage ring are associated with time-varying properties of IDs such as gap and polarization. Additional work in the area of magnetic measurements and shimming, control methodologies for fast-switching IDs, and photon diagnostics will likely be needed to provide ultimate performance from a diffraction-limited ring.

New operating modes and capabilities involving RF bunch manipulations, such as using crab cavities and other devices for short pulses and tailored bunch operation, are in the early stages of development and close attention to these developments is warranted. These capabilities will require new work in the area of low-level RF control, with phase-matching well below 1 ps required to synchronize pairs of crab cavities for example.

While the technologies to build an ultimate storage ring are available for the most part, beam line technology will require significant work to handle high-power ID x-ray beams while preserving brightness. Developments in optics, monochromators, and metrology will all be needed.

Cost remains a significant challenge for an ultimate storage ring; however there are proof- of-principle examples available, like the existing MAX-III ring and the planned MAX-IV facility. At MAX-lab, many design choices have been driven by cost, while still maintaining excellent performance, with 0.25 nm-rad being the design goal for MAX-IV. How these techniques might scale to a few-kilometer circumference ring remains to be seen. It has been suggested that the cost for such an ultimate ring can be reduced by concentrating IDs and beam lines in a fraction of the total circumference, opening the possibility of implementing a hybrid lattice TME/MBA lattice, where MBA cells with ID straights are used only in the sectors containing IDs.