Report of the 07/27-28/05 Cornell meeting on light-source upgrades

October 7, 2005

Abstract

During a two day meeting at Cornell, Ivan Bazarov, Don Bilderback, Michael Borland, Joe Choi, Sol Gruner, Georg Hoffstaetter, Dave Sagan, Vadim Sajaev, Charlie Sinclair, and Maury Tigner discussed possibilities for upgrading existing x-ray storage rings to higher spectral brightness. The charge and and the agenda of the meeting are attached as appendices. Two options for upgrading the APS to lower emittances and higher currents have been presented. The first, 2*APS, is based on reducing the length of most magnets by a factor of 2, especially the length of dipoles. For nominal parameters this leads to a spectral brightness increase of about 500 over the APS performance of 2005. The second, XPS7, pushes permanent magnet technology and rapid top-up injection and would result in another factor of 3. The Cornell ERL upgrade to CESR has been presented which nominally leads to similar average spectral brightnesses by adding an ERL to CESR and by adjusting CESR's optics appropriately. Furthermore the addition of an ERL to the APS was presented. This was based on a different assumption, namely, that the APS ring was not modified but merely supplemented with a full-energy recirculating linac injector. Whereas the upgraded rings, at the other extreme, strongly modify or totally rebuild the accelerator in the APS tunnel. The beam parameters, which are different for each of the presented accelerators, were compared in detail. It was found that different computer codes with which the spectral brightnesses and other x-ray parameters were computed do not agree very well with each other, and a code comparison was therefore started during the meeting. While many ideas were exchanged and computations were compared, it became clear that there are several areas in which the participants have similar interests and in which future collaboration could be very fruitful. Ideas of studies were collected for each accelerator. This exchange was particularly useful since many of the suggested studies need to be performed before one of the presented accelerators could be proposed and built.

1 Common subjects

1.1 X-ray parameter calculations

The program SPECTRA and the different x-ray routines available in `sddsbrightness` were compared by calculating the average spectral brightness in the first undulator harmonic for the parameters listed in Tab. 1. The average spectral brightness was calculated for the listed nominal values, and for the 9 scenarios where successively one of the parameters was set to the alternative

Table 1: Beam and undulator parameters for an x-ray code comparison.

Parameter	Nominal value	Alternative value
Energy	5GeV	
Current	100mA	
Normalized ϵ_x	1μm	0.1μm
Normalized ϵ_y	1μm	0.1μm
rms Energy spread	$10^{-}4$	10^{-3}
Lattice parameter β_x	12.5m	4m
Lattice parameter β_y	12.5m	4m
Dispersion D at the center	0.01m	0.1m
Slop of the dispersion D'	0.01	0.1
Undulator period	17mm	10mm
Undulator length	25m	3m

value that is also listed in Tab. 1. Average spectral brightnesses are listed in Tab. 2 where this quantity was computed for the undulator k-value for which it is maximal. The photon energy at that maximum is also listed. This table is completed by numbers obtained with simplified analytic formulas. These formulas are described in appendix C.

It was discussed that the effects that a realistic program should at least take into account are: (a) energy spread of the electron beam, (b) the horizontal and vertical electron beam size and divergence, (c) the segmentation of undulators, possibly with quadrupoles between segments, (d) phase errors within an undulator and between segments.

Since the spectral brightness was computed for the k-value for which it is maximal, i.e. its k-derivative is zero, a small error in its determination can lead to a large error in the k-value and therefore in the photon energy. The large variation in the photon energies computed with different codes is therefore a result of the different spectral brightnesses that these codes produce. While it is clear that all the used formalisms take each of the used parameters, e.g. the energy spread, into account in some way, nevertheless the spectral brightnesses that are listed differ by many times 10% between codes. No more than one of the algorithms is therefore accurate and this should be analyzed since a trustworthy algorithm should be used for the design of x-ray sources. All participants have a joint interest in this subject.

1.2 Upgrading existing rings to ERL-based light sources

A study ("ERL@APS") was presented that showed that injecting a beam from a bunch-compressed, e.g. 300fs, ERL into the current or a slightly modified APS lattice does not produce the large increase in spectral brightness that one might want to produce with an ERL. Many complications arise from CSR as the short bunches are conveyed around the full ring. It would therefore be very useful to study ERL technologies by developing an ERL upgrade of the APS that is optimally adapted to ERL capabilities. Such a study would be of mutual benefit for the APS and the Cornell team, since ideas from CESR could be adopted at the APS and vice versa.

Such a study should allow for a working mode with longer bunches but high spectral brightness. A working mode with sub-ps pulses (in the 100fs regime) could have larger emittances. Furthermore such short pulses might be obtained by injecting longer bunches that are compressed close to some

Table 2: Average spectral brightness in standard units of 10^{22} for the undulator k-value for which it is maximal and the associated photon energy in keV, as computed by the code SPECTRA and by the three methods that are available in `sddsbrightness`.

PARAMETER	SPECTRA		DEJUS		WALKER		BORLAND		appr. formula	
	(10^{22})	(keV)	(10^{22})	(keV)	(10^{22})	(keV)	(10^{22})	(keV)	(10^{22})	(keV)
nominal values	1.023	5.94	1.62	6.59	1.63	6.61	1.04	5.80	1.97	5.72
alternative ϵ_x	4.622	7.38	4.96	8.05	5.04	7.918	3.99	7.56	7.92	7.02
alternative ϵ_y	4.378	7.17	4.89	8.05	4.97	8.019	3.63	7.33	8.46	7.23
alternative δ_E	0.210	6.53	0.22	7.14	0.21	7.207	0.049	5.29	0.11	4.94
alternative λ_u	2.136	9.51	3.20	10.70	3.21	10.50	1.51	8.59	3.06	8.60
alternative L_u	0.048	7.51	0.059	8.04	0.059	7.81	0.063	7.22	0.096	7.43
alternative β_x	1.270	5.77	1.82	6.59	1.85	6.406	0.998	5.89	2.19	5.51
alternative β_y	1.246	5.68	1.79	6.59	1.83	6.406	1.03	5.98	2.14	5.64
alternative D	1.083	5.86	1.57	6.59	1.58	6.608	1.01	5.80	1.90	5.72
alternative D'	0.403	5.19	0.61	5.84	0.619	5.90	0.35	5.29	0.69	4.95

Table 3: Parameters for a long-bunch ERL upgrade to the APS.

Machine energy	7 GeV
Machine current	100 mA
Normalized emittance in x and y	0.1μm
Momentum spread	0.0002
rms bunch length	2ps
Undulators	Optimized length and k
Optics	Optimized beta function at undulators
Lattice	Zero-dispersion in undulators

undulators. Table 3 shows parameters that could be used for such a study. These are similar to computations presented at the meeting, with the exception of the long bunch.

1.3 Low-emittance and low-emittance-growth lattices

By contrast with the ERL@APS simulations presented at the meeting, the 2*APS and the XPS7 are based on ultra-low emittance lattices that necessarily involve full optimization of the APS ring. Such lattices produce a low equilibrium emittance, but they also produce low emittance growth during one turn. Therefore, similar lattices might be useful for the return loop of an ERL where the ERL's small emittance should not be degraded significantly by incoherent synchrotron radiation.

1.4 Accelerator tests

Several components of an ultra-low emittance storage ring and of an ERL upgrade of a storage ring are very similar. The low-emittance and low-emittance growth optics could lead to similar optics and magnet designs, and undulators for similarly small emittances could be designed similarly. The undulators of an ERL with its small energy spread might be longer than those for a ring, but questions of tolerances, small pole distances, associated heating issues, problems with phasing between poles and between segments could all be studied to mutual benefit. It would be good to collaborate on hardware tests in existing accelerators to address some of these issues, e.g. a magnet string test of a low-emittance-growth lattice.

2 Storage ring x-ray sources

The two storage ring x-ray sources that were discussed, the 2*APS and the XPS7, have overlapping concerns.

Magnet technology (XPS7 only): Permanent magnets can be produced with high precision when highly homogeneous material is used. In a high radiation environment, yet more specialized materials are required. For this reason it should be analyzed how seriously the permanent magnets required for XPS7 drive the cost of this light source. Superimposing permanent magnets multipoles and mechanisms of making their strength tunable will certainly add to the cost and to the field errors that have to be expected.

Tolerances: Since the magnets in 2*APS and particularly in XPS7 are very strong, the dynamic aperture can become very small and sensitive to misalignments and field errors. It has been observed, for example with the CESR final focus permanent magnets, that temperature changes and even temperature gradients can significantly influence the permanent magnet performance. Tolerances for temperature fluctuations should therefore be derived. This study should include turn on and turn off effects and not only heating during a regular top off injection cycle, but also include hysteretic temperature effects.

Tight optical tolerances are not only expected due to dynamic aperture considerations but also because beta and dispersion beats can lead to a disturbance of the optimal matching in undulators. Even more important might be the tolerance on optics errors when considering injection matching for on-axis injection. These tolerances do not only concern the ring but also the optics in the injection linac and transfer line. Of course, they will apply equally to an ERL concept that relies on a low-emittance ring design to control emittance growth.

Tuneability (XPS7): When permanent magnets are tuned, either by correction coils or by mechanically changing the magnet arrangement, the magnet hysteresis might become important and complicate field adjustments significantly. It should also be considered that mechanically tuning permanent magnets adds a dead-band of tuneability, since the tuning current will need to surpass a threshold for any change of the fields produced by the magnets.

Radiation effects: Since the lifetime in the analyzed rings is very low, particle radiation can become a significant radiation hazard, especially for permanent magnets of the beamline and for undulators. Satisfactory collimation sections need to be designed, which has proved to be hard in the past.

Injector needs: Frequent high current injection might lead to challenging injector needs (power, rep rate, high current within a short batch) for the different injection scenarios for XPS7 and 2*APS. Tolerances on injector stability and optics control should be studied in order to avoid mismatch to the ring and associated beam-loss at the very limited dynamic aperture. Furthermore it has to be ascertained that the injector achieves small enough emittances to inject into the very limited dynamic aperture.

Beam dynamics: Beam instabilities have to be analyzed for the different working modes and fill patterns in an upgraded APS. Which instabilities can be compensated by feedback, such as dipole modes, and which cannot, such as some higher instability modes. Ion effects and requirements on the vacuum system also need to be analyzed since the induced focusing errors can be very significant for ultra low emittances. Bunch lengthening effects for high charges per bunch can produce a larger energy spread than estimated, which has implications for undulator performance, and longitudinal phase space dynamics thus has to be understood in detail.

Others: XPS7 requires large improvements in many parameters over existing storage rings or over PETRA III, each one of these factors could be a large development effort in their own right. What loss in quality is to be expected if each of the many improvements fall a little short. (High current, very low emittance, precision permanent magnetics, all of the above, are there material considerations for strong combined function magnets, on axis injection, fast kicker, etc.) It is also worthwhile to investigate whether ultra-low emittance rings have the potential for upgrade options.

3 Comments pertaining to the Cornell ERL

Code integration: While many calculations and simulation were presented, the simulations were not integrated. For example, the brightness calculations did not include all of the emittance growth effects found in the simulations of the injector or transport systems. In some cases, numbers were copied by hand from one program to another. The entire process should be simulated using a sequence of connected codes. For example, beam production in an electron gun is usually simulated by ASTRA or PARMELA, propagation of particles in accelerator is simulated by other set of codes (elegant, bmad), and synchrotron radiation is calculated by yet another set of codes. Different parts of the simulation process should talk to each other in order to minimize possible errors when transferring results from one stage of simulation to the next one. One good example of such communication is the set of SDDS compliant codes developed at APS.

Start-to-End Modeling: It is particularly important to get quick and routine start-to-end simulations. Start-to-end modeling is an outcome of proper code integration. Routine, automated start-to-end modeling has several advantages: (1) It allows combining the strengths of different codes (PARMELA, ASTRA, `elegant`, `sddsbrightness`, etc). (2) It enable optimization of x-ray parameters directly using the well-developed optimization tools used already for the injector design. (3) It avoids serious errors that may occur when Gaussian beams are used in coherent synchrotron radiation and longitudinal space charge simulations.

Beam Quality Preservation: Given the very low emittances (0.1 μm) and energy spreads (0.02%) needed to achieve high brightness with an ERL, beam quality preservation must be looked at very carefully. Suggestions include:
(1) Full start-to-end modeling of the system from gun to undulator, to ensure that collective effects are not driven by non-Gaussian, nonsmooth distributions. It is very important to use a realistic input beam distribution because using a smooth Gaussian will understate coherent synchrotron radiation, longitudinal space charge, and wakefields.
(2) Longitudinal space charge effects turned out to be much bigger problem that CSR in LCLS. This question should not be overlooked. Double check CSR simulations to ensure sufficient number of particles (100k to 1MP), sufficient number of bins (500 to 1000 typical), and that you are using transient-mode CSR. Cross check against steady-state case.
(3) Study CSR effects with 3D codes and investigate Kohltenbah's 1D formalism, which is better at low energies than Saldin's formalism.
(4) Ensure that second-order or kick elements are used for all beamline elements.
(5) Include incoherent synchrotron radiation when tracking. This can be done in `elegant` for dipoles, quadrupoles, and sextupoles.
(6) Look at space charge effects using 3D codes.

Synchrotron Radiation Codes: Benchmark synchrotron radiation parameters calculation codes SPECTRA, XOP, and `sddsbrightness`, and basic analytical formulas described in appendix C. This could be done by making up a benchmark example. Investigate and understand the differences. Are the codes capable of performing brightness calculations with multi-segment devices, including focusing elements between the devices?

Undulator Tuning: ERLs rely heavily on long undulators to take advantage of the low energy spread. What are requirements for undulator tuning? When APS recently installed two undulators in one straight section, it was found the radiation didn't overlap to the required degree. The reason of the problem is not understood yet, but undulator tuning could be one explanation. Both undulators were tuned according to standard APS procedure and passed required tests. But could it be due to cross-talk between multiple segments?

Typical requirements on trajectory wander inside the undulator are presumably 10% of beam size. Is this achievable with present tuning techniques?

What magnets and what instrumentation are required between segments of a long undulator? This question could be investigated using present and future LCLS experience. Note: having extensive diagnostics between undulator sections was crucial to LEUTL FEL success.

What are the requirements on phasing of the undulator segments and phase errors within segments?

Simulations with Errors: Simulations with errors are needed for any highly optimized system.
(1) Errors should include pulse-to-pulse rf voltage and phase errors, alignment and steering, and magnet strength tolerances.
(2) Consider cathode non-uniformity, witch can be time-dependent.
(3) Add pulse-to-pulse variation in drive laser pulse shape, energy, and timing. How do these impact the highly-optimized configuration and CSR/LSC instabilities?

(4) What is the required smoothness/flatness of laser pulse to avoid seeding CSR and LSC instabilities?
(5) Will the cathode and gun survive for a useful period of time at such high current? As the cathode degrades, at what point will the system no longer be optimized?
(6) An ERL will have greater issues than a ring with linac and transfer line matching due to the fact that the entire system is a transport line. Simulation of magnet errors and correction schemes is a necessity. Development of techniques similar to LOCO for high-precision correction of transport line optics may be necessary.

Lattice: The following are suggestions for the lattice in CESR.
(1) Design a low emittance lattice to control quantum excitation. Compared to a 5 GeV linac, some upgrades to CESR itself could be a minor additional cost.
(2) The lattice functions in CESR seem very large and irregular. Will there be any wakefield problems from this? The ring lattice should have flexibility to accommodate users' needs: larger or smaller spot sizes may be requested.

Other: Consider using spectral fluctuations to measure longitudinal bunch profile. It could provide independent nondestructive measurement of bunch length and profile (see V. Sajaev, EPAC 2000)

4 Summary

We listened to and learned from presentations about the Cornell ERL, the 2*APS and the XPS7 rings. It became clear that the papers presented at the ERL workshop for the XPS7 and an ERL injecting into the APS could not be taken as a comparative study of ERL and ring performance limits. While XPS7 pushes all technologies of a totally new accelerator in the APS tunnel, the ERL study assumed minimal changes to the existing APS. It would be helpful for all participants to see how an ERL together with an upgraded accelerator in the APS tunnel would perform. There are also several other fields where a collaborative effort would be very helpful. Examples are: (1) Efforts to understand and possibly improve x-ray parameter calculations, (2) upgrade of codes to SDDS on the Cornell side with support and documentation from APS, e.g. an IMPACT to SDDS filter, (3) development of long undulator specifications and tolerances for high brightness beams, (4) start to end simulations for ERL, (5) use of accelerator markup language, (6) low emittance lattice development. We exchanged extensive and valuable lists of study suggestions for each of the presented projects, and all concluded that this meeting was a valuable effort to find out the performance limit of storage-ring and ERL x-ray sources.

Appendix A: Charge

Future light sources with exceptionally good parameters have been proposed that are either based on advanced storage-ring designs or on Energy Recovery Linacs. Notably there is the ERL@CESR design that upgrades CESR by adding an ERL and there is a design for an upgraded APS (XPS7) that has been presented at the 2005 ERL workshop. Also the PETRA-III design should be mentioned as a reference since PETRA is soon undergoing a well prepared upgrade program. In this meeting both designs should be presented and it should be identified which questions have to be addressed and what R&D has to be completed before each design can credibly be proposed. Furthermore, parameter lists for an ERL light-source and for a future ring light source should that can currently be proposed with limited and well understood uncertainties should be developed. These parameter list should then be used to computed x-ray beam parameters with the same well understood and well documented computer codes. Finally a writeup should be produced that contains: (a) the list of outstanding research issues for each design, (b) the requirements for simulation programs to compare designs, (c) a minimal parameter list for both light source scenarios and the resulting x-ray beam parameters with which all participants feel comfortable, (d) an aggressive list for both scenarios with which the developers feel comfortable and which's realization is subject to list (a). By bringing our two groups of individuals together, we hope to 1) get to know and learn from each other, both in the accelerator as well as the x-ray physics aspects, 2) create a climate of mutual respect for the work that each group has done, 3) to experience first hand, the excitement of each development group for their possible visions of future x-ray sources, and 4) to respectfully sharpen our understanding of each others work. A written document that summarizes the areas of agreement (as well as any few areas of disagreement) will help to clarify the position of each group in the larger developmental context of future x-ray sources and will help to provide further perspective for future R&D beyond this meeting.

Appendix B: Program

Wednesday 07/27/05
08:30-09:00 Breakfast together in the CHESS seminar room in Wilson Lab
09:00-09:45 (incl. discu.) ERL@CESR layout and optics (Georg)
09:45-10:30 (incl. discu.) Injector simulations and status (Ivan)
10:30-11:15 (incl. discu.) X-ray parameter simulations (Ivan for Ken)
11:15-11:30 Break
11:30-12:15 (incl. discu.) Performance of an ERL upgrade to APS (Michael)
12:15-13:00 Working Lunch: Performance of an upgraded APS ring (Michael)
13:00-14:00 ERL@CESR Meeting
14:00-14:45 (incl. discu.) X-ray parameter calculations (Vadim)
14:45-15:30 Discussion of code features and capabilities (all, computations run by Ivan)
15:30-16:30 Writeup of things that should be computed and what codes can do the job.
16:30-17:15 List of required studies for super APS (Cornell)
17:15-18:00 List of required studies for ERL@CESR (APS)

Thursday 07/28/05
08:30-09:00 Breakfast together in CHESS seminar room
09:00-09:30 Presentation of writeup of required studies for super APS (Georg)
09:30-10:00 Presentation of writeup of recommended parameters for ERL@APS (Don)
10:00-10:30 Presentation of writeup of required studies for ERL@CESR (Michael)
10:30-12:00 Presentation of writeup of code requirements (Ivan and Vadim)
12:00-13:00 Lunch with discussion on parameters (Ivan may be able to run programs)
13:00-14:15 Writeup about suitable parameters for ERL@CESR and XPS7 (distri. labor)

Appendix C: Approximate Analytical Formulas for Spectral Brightness

Here the formulas are described that were used for Tab. (2). According to [1] the flux of the n-th harmonic integrated over the central cone from a planar undulator is given by

$$F_n[\text{ph/s/0.1\%BW}] = 1.431 \times 10^{14} N_p Q_n(K) I[\text{A}], \tag{1}$$

with N_p being the number of undulator periods, I the current of the electron beam, $Q_n(K) = nK^2[JJ]/(1 + 0.5K^2)$ with $[JJ] = [J_{(n-1)/2}(x) - J_{(n+1)/2}(x)]^2$ and $x = nK^2/(4 + 2K^2)$.

The wavelength of the radiation in the forward direction is

$$\lambda = \frac{\lambda_p}{2n\gamma^2}(1 + K^2/2) \tag{2}$$

with λ_p being the undulator period and $\gamma = E/mc^2$ for the electrons.

In case of an ideal electron beam, the effective source size and divergence of the undulator source is given by

$$\sigma_r = \sqrt{2N_p\lambda_p\lambda}/(4\pi)\ , \quad \sigma_{r'} = \sqrt{\lambda/(2N_p\lambda_p)}\ , \tag{3}$$

with the product of the two being equal to the diffraction limit $\epsilon_{\text{ph}} = \sigma_r\sigma_{r'} = \lambda/(4\pi)$.

The bandwidth of x-rays in the central cone is determined by the number of periods in the undulator such that its FWHM is given by [2]: $\frac{0.9}{nN_p}$.

The spectral brightness in such an ideal case would be given by $B_0 = \frac{F_n}{(2\pi)^2\epsilon_{\text{ph},x}\epsilon_{\text{ph},y}}$,

$$B_0[\text{ph/s/mm}^2/\text{mrad}^2/0.1\%\text{BW}] = \frac{F_n[\text{ph/s/0.1\%BW}]}{(\lambda[\text{Å}]/2)^2} \times 10^8\ . \tag{4}$$

Finite electron emittance and energy spread are taken into account to give the following estimate of the x-ray spectral brightness:

$$B = \frac{F_n}{(2\pi)^2\sigma_{Tx}\sigma_{Tx'}\sigma_{Ty}\sigma_{Ty'}}\frac{1}{\sqrt{1 + (N_p/N_\delta)^2}}\ , \tag{5}$$

where the effective source sizes and divergences are given by

$$\sigma_{Tx} = \sqrt{\sigma_r^2 + \epsilon_x\beta_x + (\delta\eta_x)^2 + (\lambda_p K/(2\pi\gamma))^2}\ , \quad \sigma_{Tx'} = \sqrt{\sigma_{r'}^2 + \epsilon_x/\beta_x + (\delta\eta'_x)^2} \tag{6}$$

$$\sigma_{Ty} = \sqrt{\sigma_r^2 + \epsilon_y\beta_y + (\delta\eta_y)^2}\ , \quad \sigma_{Ty'} = \sqrt{\sigma_{r'}^2 + \epsilon_y/\beta_y + (\delta\eta'_y)^2}\ . \tag{7}$$

Here the β-function as well as the dispersion η and its derivative are taken at the center of the undulator (waist). N_δ which represents the energy sprectrum broadening due to the electron beam's (rms) energy spread δ is given by

$$N_\delta = \frac{0.9}{2 \times 2.35 N_p n\delta} = \frac{0.19}{N_p n\delta}. \tag{8}$$

B is smaller than B_0 by the following factor:

$$\frac{\epsilon_{\text{ph}}}{\sigma_{Tx}\sigma_{Tx'}}\frac{\epsilon_{\text{ph}}}{\sigma_{Ty}\sigma_{Ty'}}\frac{1}{\sqrt{1 + (N_p/N_\delta)^2}}\ . \tag{9}$$

References

[1] X-ray Data Booklet, LBNL/PUB-490 Rev. 2

[2] K.J. Kim, AIP Conf. Proc. paper on undulator radiation (1989)