THE CHALLENGES OF THIRD-GENERATION SYNCHROTRON LIGHT SOURCES*

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Abstract Third-generation synchrotron light sources are specifically designed to operate with long insertion devices that produce very high brightness beams of synchrotron radiation. There are many such facilities now under construction, or in the design stage, all over the world. After a brief review of the main properties of the low emittance storage rings that form the heart of these facilities, we will discuss the particular challenges that accompany their design. These include: the effects of the strong sextupoles required for chromatic correction of the low emittance lattices; impact of machine imperfections on the dynamic aperture; the effects of the linear and nonlinear magnetic fields of the undulators; impedance consequences of long, narrow, undulator vacuum vessels; injection; and beam lifetime. As examples, we take the Advanced Light Source, currently under construction at the Lawrence Berkeley Laboratory, U.S.A., and the European Synchrotron Radiation Facility under construction in Grenoble, France.

INTRODUCTION

The last decade has seen a tremendous growth in dedicated, second-generation synchrotron light sources throughout the world¹. During this development the role of undulator radiation has played an increasingly important part as its unique properties of high brightness, collimation, tunability, and laserlike coherence (for example, in the development of the x-ray microprobe), have become more widely utilized. Third-generation synchrotron light sources are designed specifically to optimize the output from undulators. They are based on electron, or positron (hereafter generically referred to as "electron"), storage rings having very small beam emittance (<10 nm-rad) and large current (0.1 to 1.0 amperes), which together give high brightness, and long (about 6 m), dispersion free straight sections, to accommodate the undulators.

The unique challenges associated with the design of third-generation sources arise directly from the requirement for low emittance and from the characteristics of the undulator magnetic fields, their associated narrow gap vacuum vessels, and the intense beams of radiation that they produce. Because of the dependence of the undulator radiation wavelength on the undulator period length and electron beam energy (see below), storage rings in two energy ranges have evolved to cover the radiation spectrum of interest. This is evident from the parameters of the third-generation sources planned, or under construction, listed in Table 1. Rings with energies in the 0.8-2 GeV range provide undulator radiation from a few eV to few keV (serving the vacuum ultraviolet and

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soft x-ray user community), whereas rings in the energy range 6-8 GeV provide undulator radiation from 1 keV to 100 keV, for the x-ray user community.

Here we discuss the challenges of these sources as they apply to both the low and high energy machines. The issues covered are:

- Lattice design
- Dynamic aperture
- Beam lifetime
- Current limitations
- Vacuum chamber protection.

We take, as specific examples, the 1-2 GeV Advanced Light Source², currently under construction at the Lawrence Berkeley Laboratory, U.S.A., and the 6 GeV European Synchrotron Radiation Facility³ (ESRF) under construction in Grenoble, France.

There are many more challenges associated with, but not unique to, third-generation light sources, which are beyond the scope of this report. We shall merely list a few of them, comment briefly, and assure the reader that their solutions are under study by many investigators:

- Bunch length: Some users require short bunches ($\sigma_t < 10$ ps). This requires a small longitudinal vacuum chamber impedance ($|Z/n| < \text{few ohms}$) if single-bunch currents in excess of a few tenths of milliamperes are needed.

- Multibunch instabilities: These arise due to coupling through high-Q structures in the vacuum vessel, particularly higher order modes in the rf cavities. They cause problems in time resolved experiments, and increase the effective emittance of the beam. Also, they can limit the amount of current that can be accumulated in the injection process due to the effective increase in the stored beam momentum spread.

TABLE 1 Third-Generation Synchrotron Light Sources

Location	Ring	Energy (GeV)	Phase
Brazil (Campinas)	LNLS	2.0	Authorized
China (Hefei)	HESYRL	0.8	Commissioning
France (Grenoble)	ESRF	6.0	Construction
(Orsay)	Super-ACO	0.8	Operational
Germany (W. Berlin)	BESSY II	1.5 - 2.0	Design
India (Indore)	INDUS II	1.4	Authorized
Italy (Trieste)	ELETTRA	1.5 - 2.0	Construction
Japan (Kansai)	STA	8.0	Design
Korea (Pohang)	PLS	2.0	Authorized
ROC (Hsinchu)	SRRC	1.3	Construction
Sweden (Lund)	MAX II	1.5	Design
UK (Daresbury)	DAPS	?	Design
USA (Argonne)	APS	7.0	Design
(Berkeley)	ALS	1.0 - 1.9	Construction
USSR (Moscow)	SIBERIA II	2.5	Construction

- **Ion-trapping:** This phenomenon arises when residual gas atoms and molecules are positively ionized through their interaction with the electron and photon beams, and become trapped in the electrostatic potential created by the electron beam. The result is an increase vertical beam size (leading to a reduction in brightness), and an increase in the gas density seen by the beam (leading to a reduction in beam lifetime). The effect can be ameliorated by inclusion of clearing electrodes in the vacuum chamber or by leaving a gap in the train of electron bunches, as demonstrated in the NSLS and PF rings.

- **Environmental stability:** Temperature changes and gradients cause machine components to move, thereby changing the position of the electron and/or photon beams. Experimental requirements call for beam stability of a few microns (about 10% of the beam size) over many hours, therefore, environmental stability is essential. Similarly, ground vibration is transmitted to the accelerator and the experimental equipment. Care must be exercised in choosing a suitable site, and in isolating any local sources of vibration.

SOME RELEVANT PROPERTIES OF UNDULATOR RADIATION

Undulator radiation is created when an electron experiences the sinusoidally varying field of an undulator magnet. The radiation is emitted into narrow spectral features, as shown in Fig. 1, centered at photon energies given by:

$$\epsilon_i = \frac{hc}{\lambda_i}, \quad \lambda_i = \frac{\lambda_u}{2i\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right), \quad i = 1, 3, 5, \dots$$

where λ_u is the undulator period, i is the harmonic number, γ is the electron energy (in units of its rest mass), K ($= 0.934 B [T] \lambda_u [cm]$) is the "deflection parameter", and θ is the polar viewing angle with respect to the undulator axis.

For a low emittance beam, and proper care in the design of the undulator, radiation up to and including the fifth harmonic should be useful, with a line width given by $1/iN$, where N is the number of undulator periods. Tuning (wavelength scanning) of a spectral feature is normally accomplished by changing K (via the magnetic field B). Note that the shorter wavelengths (higher energies) are generated as the magnetic field is reduced.

FIGURE 1 Undulator radiation energy spectrum

LATTICE DESIGN OF LOW EMITTANCE STORAGE RINGS

As mentioned in the introduction, lattice designs of third-generation light sources must provide long, dispersion-free straight sections for the undulator magnets, and an electron beam with a low natural emittance. In order to achieve the latter, the lattice must produce small values of the dispersion function, horizontal beta functions, and their derivatives, in the bend magnets. Unfortunately, these same characteristics also lead to a requirement for strong sextupole fields, for chromatic correction. These nonlinear fields perturb the betatron motion of the electron trajectories, which become unstable at an amplitude that defines the "dynamic aperture." Since adequate aperture (a few cm) is required for the injection/accumulation process, and for a beam lifetime of many hours, the design of a lattice with low emittance and sufficient dynamic aperture constitutes the primary challenge in the design of third-generation synchrotron light sources. In some cases, particularly those based on the Chasman-Green concept, extra families of sextupoles, the so-called harmonic sextupoles, have been found to be necessary in order to achieve sufficient dynamic aperture. These sextupoles, situated in the dispersion-free regions of the lattice, do not contribute to chromatic correction, but rather compensate locally for the perturbation created by the chromatic sextupoles.

In the initial stages of lattice design, there are many optimization trade-offs between the number of unit cells, bend magnet field strength, rf parameters, cost, etc. A fundamental decision concerns the choice of the bend magnet field, since the power emitted into synchrotron radiation from the bend magnets (at a given electron energy) increases as the square of this value. In the case of low-energy rings, it is possible to optimize the lattice design with high field bend magnets. As a consequence of the resulting small bend radius, it is then practical to incorporate focusing into the bend magnets through pole shaping or edge-angle effects, or both. This option permits some flexibility in the design of the low-energy (0.8-2 GeV) third-generation sources, as is evident from the variety of structures developed for such machines. Fig. 2 shows the unit cells of several of the designs now operating or being built, together with a few of their more important parameters.

For the higher energy machines, it is necessary to operate the bend magnets at lower fields, in order to limit the total power radiated from the bend magnets. This approach minimizes the number of rf stations required, thereby keeping the project cost, impedance seen by the beam, and subsequent power bills down. It also results in the utilization of a larger number of unit cells (leading to smaller beam emittance) to close the circumference. In these cases the efficacy of both field gradients in the bends, and of edge focusing, is reduced substantially and a single lattice structure, based on the Chasman-Green concept, has emerged as the lattice of choice. Fig. 3 shows the structure of the 6 GeV ESRF; other high-energy machines differ only in small details, and in the number of unit cells employed.

Having established a lattice that gives adequate dynamic aperture, it is necessary to check its sensitivity to predictable perturbations (such as construction and installation imperfections), and to the properties of the undulator. It is well known⁴ that the undulator acts as a focusing element, and that the strength of the focusing varies as the square of the undulator field. Since the dynamic aperture of low emittance machines is sensitive to the betatron tune of the lattice, it is necessary to provide tune compensation. Further, since the fields of the undulator may be varied during a machine fill (in order to "tune" the output wavelength of the radiation, as described above), dynamic tune compensation schemes must be developed. These, and other issues raised by the inclusion of undulators in the lattice are discussed in the following sections.

FIGURE 2 Unit cells and major parameters of representative low-energy third-generation synchrotron radiation sources

FIGURE 3 Unit cells and major parameters of the ESRF

DYNAMIC APERTURE - EFFECTS OF MACHINE IMPERFECTIONS AND UNDULATORS

We have found, through computer simulations, that the dynamic aperture of a low-emittance lattice is particularly sensitive to machine imperfections and undulator fields⁵. The first-order effects of these errors are to produce a distorted closed orbit, tune variations, and beta-function modulation around the circumference. The first two effects can, of course, be corrected. Given a sufficient number of monitors and correctors, closed-orbit correction down to a few tenths of a millimeter is expected from computer simulations, a level that has already been demonstrated on existing machines. The degree to which correction is achievable appears to be limited by the absolute accuracy with which the orbit distortion can be measured, and how well the machine can be modeled. The working point (tune) of the machine can be set to the accuracy with which it can be measured, i.e., to at least the third decimal place. What remains is the beta-function modulation - sometimes called "beta-beat" - and, to our knowledge, no machine of this type has an algorithm developed specifically to minimize this function. The result is that the high periodicity of the machine, which is a design feature that maintains a large spacing between dangerous structure resonances in tune space, is broken. The consequence of this symmetry breaking is to bring non-structure resonances into play in the beam dynamics. This, in combination with the strong sextupole fields, and the higher order field components in the magnets (both systematic and random) leads to the second-order effect, a reduction in the dynamic aperture.

Fig. 4 shows the reduction in dynamic aperture caused by the anticipated errors in the ESRF and ALS. The types of imperfections taken into account in such simulations are: magnet misalignments and rotations, systematic and random magnetic field errors, monitor misalignments, and correction magnet field errors. It should be noted that, although the effects are dramatic, the resulting apertures are sufficient for injection and good beam lifetime in both cases.

FIGURE 4 Effect of Machine Imperfections on the dynamic aperture

By systematically "switching off" the sources of errors in the simulations, it has been shown that the major effect on the dynamic aperture is due to those errors that cause the beta-beat, i.e., random gradient errors and closed-orbit distortions in the sextupole magnets. Thus, special effort must be made to minimize these aspects in the production and installation phases, and in developing algorithms for orbit control.

Unfortunately, the inclusion of undulators in the lattice also gives rise to a beta-beat, unless provision is made, from the outset, to include a sufficient number of quadrupoles (four pairs) in the insertion straight section. To date no such provision has been made in any of the lattice designs described in Table 1. The result is a further degradation in the dynamic aperture. Since the focusing effect of insertion devices scales inversely as the square of the electron beam energy, the consequences are more severe for the lower

energy machines. Fig. 5 shows the effects of undulators on the dynamic apertures of the ERSF and ALS. It should be noted that the machine acceptance, in each case, is limited by the physical vacuum aperture, rather than the dynamic aperture.

FIGURE 5 Effect of undulators on the dynamic aperture

A related, but as yet not well understood phenomenon, is the effect of errors and undulators on the momentum acceptance of the storage ring. In simulation studies of single particle dynamics including synchrotron oscillations in the ALS⁶, it has been observed that the momentum acceptance is reduced significantly, from 3.3% (the rf acceptance) to between 1.5% and 2.5%, depending, very sensitively, on machine tune. The impact of this effect on machine performance is discussed in the next section.

BEAM LIFETIME

As in all electron storage rings, the beam lifetime is determined by gas scattering (both elastic and inelastic), quantum excitation and by Touschek scattering.

In the case of elastic gas scattering the lifetime is determined by the machine acceptance, which scales as the square of the machine aperture (the smaller of the physical aperture and the dynamic aperture). As we saw in the previous section, the aperture in third-generation storage rings is typically limited by the small physical vacuum gap required for the operation of the undulators, rather than by the dynamic aperture. At the nanotorr pressures being specified for this generation of storage rings, the elastic scattering lifetimes are typically 10-30 hours.

The inelastic scattering, or bremsstrahlung, lifetime depends on the momentum acceptance of the ring, through the natural logarithm of this parameter. With pressures in the nanotorr range, the inelastic gas scattering lifetimes are typically 50-100 hours. Therefore, the effect of momentum acceptance variations in the range of a factor of two, discussed in the last section, on the inelastic scattering component of the overall lifetime, is negligible.

The quantum lifetime is a strongly varying function of the "over-voltage", i.e., the ratio of the peak rf voltage to the energy lost per turn by an electron. In third-generation rings the lifetime is typically greater than 1000 hours, and varies exponentially with rf voltage. It is, therefore, not usually an issue.

The Touschek lifetime scales inversely with electron beam density, as the cube of the beam energy, and as the cube of the momentum acceptance. Since the object of all third-generation sources is to produce low emittance beams with short bunch lengths, the Touschek effect is an issue. Because of the energy scaling, the effect is more significant for the lower energy machines. For example, the variation in momentum acceptance found in studies of the ALS, discussed above, would have a profound impact on that machine's performance, indicated in Fig.6. Here the different beam decay profiles are determined almost exclusively by the impact of momentum acceptance on the Touschek effect.

FIGURE 6 Variation in current decay in the ALS as a function of the momentum acceptance

CURRENT LIMITATIONS

Current limitations in third-generation storage rings will be set by the transverse mode-coupling instability (TMCI), multibunch instabilities (as mentioned in the introduction), or by trade-offs between current, bunch length and beam lifetime. In the ALS, the threshold for the TMCI is calculated to be more than 40 mA per bunch, and is not an issue. However, bunch lengthening due to the microwave instability is estimated to set in above 1 mA per bunch, see Fig. 7, and some compromise must be reached between acceptable current, bunch length, and beam lifetime. Other low-energy machines will have similar characteristics.

FIGURE 7 Predicted ALS bunch length

In the case of the higher energy machines, where there is greater transverse impedance (generated by the larger number of rf cavities required and the larger number of chamber discontinuities around the circumference), the limit imposed by the TMCI on the single-bunch current *is* an issue. For example, in experiments on PEP (SLAC, USA), operating in a special low emittance mode for synchrotron light, thresholds of about 2 mA per bunch were measured⁷, see Fig. 8. Also, recent work at Argonne National Laboratory (USA) on the 7 GeV APS lattice, suggests that the mode coupling threshold could set in as low as 2 mA per bunch, if the option of 8 mm gap insertion device chambers is pursued.

FIGURE 8 Single bunch thresholds of the PEP low-emittance

VACUUM CHAMBER PROTECTION

The power densities produced by photon beams from undulators in both the low and high energy storage rings can exceed 1 kW per cm², i.e., that provided by an electron beam welder. Calculations show that such beams, falling onto an uncooled aluminum surface can puncture the vacuum chamber in a few seconds. It is, therefore, essential that such a circumstance be protected against. In simulations it has been shown that the sudden loss of a single correction element can result in a closed orbit that illuminates the vacuum vessel with undulator radiation. Two solutions are proposed to deal with such possibilities. The first⁸ is to utilize active trips that sense unacceptable beam motion (both electron and photon), and temperature and/or pressure increases in the sensitive regions of the chamber. The second is to use the passive technique of limiting the maximum excursion of the correction magnet power supplies. Orbit correction beyond this range is accomplished by moving quadrupoles. Both solutions have their drawbacks: the first will lead to a large number of false trips until an appropriate "coincidence-gate" arrangement is established. The second will require a large number of magnet survey and alignments in the early years, until the machine has settled down.

SUMMARY

Third-generation synchrotron light sources face particularly difficult challenges in their design and operation. The requirements for low emittance and adequate dynamic aperture place severe constraints on the lattice design. The sensitivity of these lattices to imperfections, and to the undulators themselves, demands critical analysis of the chosen design. The issues of dynamic aperture, beam lifetime, beam instabilities, and photon beam stability require careful attention through all phases of the design, construction, installation and operation of these facilities. Many of the innovative solutions that have

been conceived to meet these challenges will be tested in the heat of commissioning in the next few years. As a result of the simulations of beam dynamics carried out for these machines, and the careful effort that has gone into their engineering designs, we feel confident that the facilities will fully meet their specifications.

We look forward to the successful operation of these facilities, and to the challenges that will be raised by the fourth-generation synchrotron light sources.

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