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TECHNOLOGICAL CHALLENGES OF THIRD GENERATION SYNCHROTRON RADIATION SOURCES*

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New "third generation" synchrotron radiation research facilities are now in construction in France, Italy, Japan, Taiwan and the USA. Designs for such facilities are being developed in several other countries. Third generation facilities are based on storage rings with low electron beam emittance and space for many undulator magnets to produce radiation with extremely high brightness and coherent power. Photon beam from these rings will greatly extend present research capabilities and open up new opportunities in imaging, spectroscopy, structural and dynamic studies and other applications.

The technological problems of the third generation of synchrotron radiation facilities are reviewed. These machines are designed to emit radiation of very high intensity, extreme brightness, very short pulses, and partial coherence. These performance goals put severe requirements on the quality of the electron or positron beams. Phenomena affecting the injection process and the beam lifetime are discussed. Gas desorption by synchrotron radiation and collective effects play an important role. Low emittance lattices are more sensitive to quadrupole movements and at the same time, in order not to lose the benefits of high brilliance, require tighter tolerances on the allowed movement of the photon beam source.

We discuss some of the ways that should be considered to extend the performance capabilities of the facilities in the future.

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1. INTRODUCTION

The design and construction of large, high energy storage rings as dedicated synchrotron radiation UV and x-ray sources is now well underway in Europe (the 1.5–2.0 GeV Elettra machine in Trieste, Italy, the 6 GeV European Synchrotron Radiation Facility, ESRF, in Grenoble, France), Japan (the 8 GeV Super Photon ring, SPring-8 in Harima Science City) and the US (the 1.5–2.0 GeV Advanced Light Source, ALS, at Lawrence Berkeley Laboratory and the 7 GeV Advanced Photon Source, APS, in Argonne). These are third generation synchrotron radiation facilities in the sense that they aim for a lower electron beam emittance and more straight sections for insertion devices than previous rings built as dedicated light sources; e.g. the second generation facilities such as the Synchrotron Radiation Source (SRS) in England, Photon Factory in Tsukuba and the National Synchrotron Light Source at Brookhaven National Laboratory. Remarkably, some first generation light sources (e.g. rings built for high energy physics research) have the ability to function as very low emittance sources because of their large circumference (e.g. PEP at Stanford and Tristan in Tsukuba).

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Third generation synchrotron radiation sources are characterized by an increased emphasis on the *quality* of the photon beam, expressed in terms of its *spectral brightness*. A high spectral brightness is achieved with photon beam intensity, narrow spectral distribution and ease of focusing onto a small spot. A high photon brightness implies a *low emittance* of the electron beam. Another important feature of third generation light sources is the presence of a large number of long insertion devices. These wigglers and undulators constitute a strong perturbation to the lattice, and their linear and nonlinear effects must be taken into account in the design and operation of the storage rings.

In Sections 2 and 3 we discuss the challenges and the problems that the designers of the new high-brightness sources have to overcome to meet the design objectives. The issues considered in this report are common to both UV (1.5–2.0 GeV storage rings) and x-ray facilities (6–8 GeV storage rings). We will not discuss the important problem of ion trapping, caused by the potential well of a circulating electron beam. Some x-ray facilities now under construction (APS and SPring-8) have avoided this problem by circulating positrons instead of electrons.

In Section 4 we examine some of the ways in which performance parameters can be improved in future synchrotron radiation sources.

2. STORAGE RING CHALLENGES

There are many technical challenges that must be met by the large third generation synchrotron radiation facilities. Broadly, these may be divided into three categories: the storage ring itself, the insertion devices and the beam lines. In this paper we mainly discuss the storage ring.

2.1 General Considerations

The goal of most large storage rings now being designed and constructed is to achieve a brightness around 10^{18} to 10^{19} photons/(s, mm^2, mrad^2) within a 0.1% bandwidth at photon energies of 5–40 keV. This can be reached with 5-m-long undulators in 6–10 GeV rings operating at about 100 mA with an emittance of about 5–10 nm-rad.

The main technical challenge facing the designer of large storage rings is to achieve an emittance low enough to optimize the performance of undulators with many periods (perhaps one hundred or more periods) while providing adequate dynamic aperture.

Since the emittance grows in the bending magnets, the desired low emittance is achieved in lattices which use relatively short bending magnets separated by quadrupole magnets. In fact, the emittance increases as the third power of the bending angle, leading to rings with many repeating cells and a high degree of symmetry, suitable for accommodating many insertion devices in the straight sections between the magnetic elements of each cell. For a given cell length the emittance can be reduced by increasing the strength of the quadrupole magnets, resulting in stronger focusing optics.

The study and understanding of low emittance lattices has made great progress over the last few years: optics like the Chasman-Green, FODO, enlarged Chasman-Green, Triple-Bend Achromat, have been studied in great depth *(1)*. All these lattices are characterized by the fact that, in order to achieve a low emittance, a strong focusing optics is required. A strong focusing optics has the disadvantage of requiring strong chromaticity correction sextupoles and increased sensitivity to quadrupole misalignment and movement. Strong chromaticity correction sextupoles have a negative effect on the maximum amplitude of stable betatron oscillations that can be sustained in the vacuum chamber, and this may negatively impact the electron beam lifetime. An increased sensitivity to quadrupole movement may lead to movement of the source: the benefits of high brilliance are therefore compromised if the photon source moves. Thus, we see that the challenge of the new generation of light sources is that the same optics characteristics that produce a low emittance beam impose a difficult task on obtaining a long beam lifetime.

2.2 Aperture Requirements

The aperture requirements (i.e. the maximum amplitude of betatron and momentum oscillations for which the motion is bounded within the physical dimensions of the vacuum chamber) are determined by the following processes:

- *Quantum emission of photons* causes the particle to lose energy in discreet quantities and excites betatron oscillations. If the associated oscillation amplitudes fall outside the acceptance of the storage ring, the particle is lost and the beam lifetime is reduced *(2)*.
- The *injection process* requires aperture to accommodate the initial oscillations of the injected beam (typically, of the order of 10–15 mm). A good injection efficiency is required to achieve the design beam intensity in reasonably short time (of the order of a few minutes).
- *Elastic and inelastic Coulomb scattering* of electrons against the *residual gas* requires aperture in order not to lose the scattered particles, a necessary requirement for a long lifetime.
- *Inelastic scattering* between particles in the same beam [*Touschek effect (3)*] and against the *residual gas* requires both momentum acceptance and physical aperture in order not to lose the scattered particles. This is, again, a necessary condition for a long lifetime.

If the betatron motion was purely linear, the available aperture would be determined by the physical aperture (vacuum chamber). Sextupole magnets, nonlinear elements, are required to avoid the "head-tail" instability and to prevent betatron resonance crossing and loss of particles subject to inelastic collisions. Because of the sextupole field, the equations of motion are not linear.

The nonlinear nature of the motion represents the main problem facing the machine designers. As the oscillation amplitude of the particle increases due to the effects described above (quantum excitation, Coulomb scattering, injection process), the motion becomes progressively more distorted compared to the linear situation, until the "chaotic limit" is reached. At this amplitude the particle is lost in a few turns. Accelerator designers try to make this "maximum stable amplitude" at least as large as half the vacuum chamber aperture (typically, 2-3 cm).

Figure 1 illustrates the fact that new generation of light sources have to deal with smaller dynamic aperture compared to older and more conservative machines.

2.3 Vacuum Requirements

For a beam lifetime of several hours (implying uninterrupted experimental runs of several hours) a vacuum of the order 1×10^{-9} Torr is required *(4,5)*. To reach this vacuum level in the presence of synchrotron radiation bombardment of the chamber wall represents one of the major challenges of the new generation of synchrotron radiation sources.

Photons emitted by synchrotron radiation produce photoelectrons when they strike the vacuum chamber walls. The photoelectrons desorb gas.

Because of the high vacuum requirement, the low vacuum conductivity of a small vacuum chamber (necessary to accommodate the high magnetic gradient required for strong focusing), and the photon bombardment causing gas desorption, conventional vacuum techniques are not applicable to the new generation of light sources. One widely adopted solution consists of letting the photon

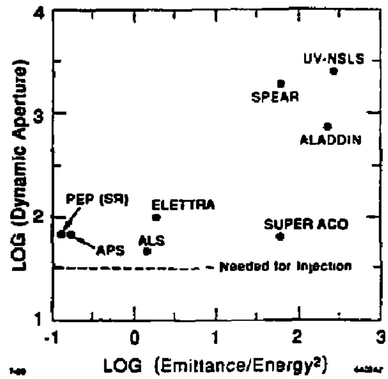

Figure 1. Dynamic aperture of new generation (ALS, Elettra, Super ACO, PEP as a synchrotron radiation (SR) source, i.e., with a high brilliance optics, APS) and older machines (SPEAR, UV-NSLS, Aladdin). The decimal logarithm of the dynamic aperture (in mm mrad) is plotted against the decimal logarithm of the emittance (in 10^3 mm mrad) divided by the square of the energy in GeV. The square energy factor normalizes the dependence of the emittance with energy. The broken line is meant to give an approximate idea of the acceptance needed for injection.

beam intercept the chamber only at selected discreet locations where water-cooled photon absorbers are located. This is, for instance, the solution adopted by the Advanced Light Source, the Taiwan Light Source, the Advanced Photon Source and the ESRF machine. A very careful control of the orbit is required to prevent the photon beam from accidentally hitting the vacuum chamber at unwanted locations.

2.4 Collective Instabilities

These are instabilities that are not directly related to the available aperture of the accelerator. Of these, coupled bunch oscillations *(6)*, bunch lengthening, *(7)* and transverse single bunch instabilities *(8)* have been observed in most electron storage rings.

In order to achieve high brilliance, accelerator designers strive to design machines that can store a large amount of beam current. Because of the limit on the number of electrons that can be packed in a single bunch, the design tries to accommodate as many circulating bunches as possible. As the number of bunches increases, the electromagnetic field of "long memory" resonant objects tends to couple the motion of the circulating bunches. Under certain conditions, a positive feedback develops by which the voltage induced by the beam interacts with the beam itself leading to instability.

The instability can be longitudinal or transverse and is driven by the Fourier harmonics of the beam current that can resonate with the cavity-like objects distributed around the ring. These objects are given by any type of discontinuity that gives a sudden change in vacuum chamber cross section: RF cavities, beam position pick ups, bellows, etc. The instability develops when its growth time is shorter than the natural damping times of the beam due to the emission of synchrotron radiation. Several measures can be taken to increase the beam current threshold for the instability. The most effective one is to limit the impedance of the ring by careful design of the vacuum chamber, the RF cavities and other discontinuities.

The most widely used method to damp coupled bunch oscillations is the feedback system. In the longitudinal plane, a beam pickup detects the displacement due to energy or phase oscillations and feeds the signal to a special radio frequency cavity. In the transverse plane, the betatron amplitude is detected and fed back to a transversely deflecting device. The technological problem here lies in the fact that, in order to act on each individual bunch, the bandwidth of the system must be large, of the order of the bunch repetition frequency (up to 500 MHz). This, coupled with the high gain normally required for fast damping, poses a limit to the minimum bunch separation, thus to the total number of bunches, and hence the maximum current, that can be achieved.

2.5 Positional Stability of the Photon Beam

Movement of the ground or local temperature changes causes the magnet support structure to move. As a consequence, the magnets also move, and so do the electron beam and the emitted photon beam. In the new generation of light sources, the problem is exacerbated by the fact that these machines are characterized by small electron beam size. A small photon spot size leads to a tight orbit stability tolerance, since the latter is normally required to be a fraction of the former. At the same time, there is an increased sensitivity to quadrupole movement because of the stronger electron focusing optics.

Thus, it appears that the problem of the stability of the photon beam scales like the square of the photon brilliance. The position and angle changes of the electron beam result in similar changes in the photon beam. As a consequence, at the end of the beam line the experimenter sees less flux and possibly a shift in wavelength.

The main causes of magnet movement are:

a) Ground movement (seismic motion, ground settlement, traffic, cranes, heavy machinery, etc.).

b) Temperature effects (temperature changes and gradient in magnet support structure, thermal distortions in mirrors and monochromators).

c) Electrical disturbances (Power supply ripple, Booster synchrotron cycling, long-term drift of magnetic field).

d) Magnetic effects on orbit (Hystereses after orbit changes, ramping, magnet cycling). Changes of insertion device field strength.

e) Electron beam *instabilities* (coupled bunch oscillation, ion trapping).

Several measures are being taken to reduce this problem. To reduce the magnetic effect listed above (ramping), most third generation machines inject at the operating energy of the storage ring.

Care is taken in the design of the magnet support structure: the mechanical resonant frequencies are damped where necessary or designed for resonant frequencies far from ground vibration frequencies. Also, effort is put to reduce the temperature gradient in the magnet supports. Air conditioning (local or global) may be required.

After all of the above is done, however, it is unlikely that the quadrupoles will not move by more than allowed. For this reason, nearly all modern synchrotron radiation sources use orbit feedback systems to stabilize the orbit.

3. Undulator and Beam Line Challenge

In order for the undulators to produce radiation with the brightness potential offered by large, low emittance storage rings, they will have to be built to tighter tolerances than necessary on presently operating rings. Similarly, the beam lines and experimental stations face new challenges in dealing with the high power density and counting rates.

Field quality requirements on undulators have been addressed by several authors. It is shown *(9)* that tolerance requirements increase in severity with increasing harmonic number.

The power densities that will be produced by long undulators on large, low emittance synchrotron radiation facilities will place severe thermal loads on beam line front ends, mirrors, monochromators, etc. The problems are most severe for optical elements which must not distort significantly under this thermal loading.

4. Consideration for Extension of Performance

From the above discussion it can be seen that achieving the design goal for high brightness UV and x-ray sources will not be easy. Is spite of this, it is important that consideration be given, even in the conceptual design stage, to ways in which these goals can be extended in the future. The high cost and the long time it takes to design, construct and commission a high brightness facility make it necessary to consider design features which can be used at a later date to extend the performance to meet new experimental needs. Some examples of such consideration are given below:

a) Reduction of the emittance below the original design goal may be desirable in the future, for example to increase brightness and coherent power levels. This may be accomplished by adding devices called damping wigglers to the ring *(10)*. Reduction of the emittance can also be achieved by changing the damping partition *(11)*

b) Possibility of accommodating stronger optics to achieve emittance reduction. The dynamic aperture problems in the future may be alleviated by replacing the chromaticity sextupoles with "modified sextupoles." These are magnets that have sextupole form near the magnetic axis and become more linear at large amplitudes. It has been shown *(12)* that, with these magnets, a large increase in dynamic aperture can be obtained.

c) A bypass to a part of the ring *(13)* adds flexibility by providing am alternate path for the stored beam. This could be used for testing insertion devices before installing them in the main ring and also for special runs to operate devices which may compromise other users.

Alternatively, the bypass could have a very low beta optics suitable for a short, small gap, short period micropole undulator which could produce very high energy photon beams. One could also consider a bypass into which the beam is switched after injection and possibly switched back into the main ring after a certain period, which could be one or a few turns. This would make it possible to use beams at higher photon energies and would possibly open the way for achieving amplification, extremely high peak power and other special results.

d) Ultrashort bunches (down to a few picoseconds) might be achieved with the use of a pulse compressor (14). Because such a device may compromise the ring aperture, it might best be located in a bypass.

e) Consideration should be given to extracting a beam from the ring and injecting it into another ring, which might be located in the same tunnel if enough space is provided If the entire beam could be rapidly extracted from the ring it could be injected into the second ring in one shot, using on-axis injection. By eliminating the oscillations inherent in off-axis injection schemes, the second ring could operate with reduced dynamic aperture, particularly if the vacuum in the second ring could also be improved to reduce the dynamic aperture required to maintain adequate Coulomb-scattering lifetime.

f) The site for the facility should enable the use of very long beam lines, perhaps up to 1 km (for x-ray facilities). Such long lines might prove to be necessary to effectively utilize the high power and power density that can be produced by some insertion devices. They could also facilitate experiments which seek to utilize the coherent part of the radiation, which is concentrated in a very small angular opening.

The above are some of the ways that should be considered to extend the performance capability of the facility in the future. The decision on how far to go in including these options in the initial design must come from a balancing of the potential future benefits against increased cost, complications and possible compromise of initial performance.

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