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Development of Synchrotron Radiation Storage Rings

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Many third-generation light sources have been commissioned over the past ten years, and the soundness of the principal design concepts has been well recognized through experiences at these facilities. Also, technological developments concerning third-generation light sources have been remarkable. With the emittance and current of the beams far exceeding the previous levels, stability requirements of the beams have become much more stringent. In this report the present status of light sources, operational and projected, is summarized, and developments and future prospects of synchrotron radiation storage rings in view of accelerator physics and technology are reviewed.

Keywords: light sources; small emittances; diffraction limits; ultra-short bunches; high-current beams; instability; two-beam instability; damped cavities.

1. Introduction

Small-emittance multi-bunch high-current beams must be achieved at electron or positron storage rings since as high a brilliance as possible is required for light sources. For beams with smaller emittance, stability requirements, including not only orbit stability but also suppression of beam instabilities, become much more stringent.

The guidelines for designing a storage ring for a light source have been well established for many years through experiences gained from many light-source projects. The light source can be thought of as a device with matured technology, at least in the sense that we know in theory what to do when designing a new light source. Requirements for new light-source projects, however, are always at the edge of the frontier of accelerator technologies. Hence, the history of advancement of light sources has continuously brought about technological interests and challenges to accelerator physicists and engineers.

In this report I will try to give my personal view on the important technological trends for synchrotron radiation storage rings at present and in the future. According to tradition, the report will begin with a summary of new light-source projects.

2. Summary of new light-source projects

There are many light sources currently running worldwide. Some were converted from high-energy-physics machines to light sources, and others were constructed as dedicated light sources, which are called the second-generation light sources. At these facilities, for example, at SPEAR of Stanford Synchrotron Radiation Laboratory, many new ideas on light sources, including insertion-device technology, have been implemented.

Many third-generation light sources have appeared over the past ten years. The scientific and technological impacts of the newly operating third-generation light sources have been as big as, or bigger than, those of the second-generation light sources. Storage rings with extremely small emittances have been constructed over the past ten years. In Asia, the TLS at the Synchrotron Radiation Research Centre in Taiwan, the PLS at Pohang Accelerator Laboratory in Korea, and SPring-8 at the Japan Synchrotron Radiation Research Institute were constructed and are in operation. In America, there is the ALS at Lawrence Berkeley National Laboratory and the APS at Argonne National Laboratory in the USA, and the LNLS in Campinas, Brazil. In Europe, there is the ESRF in Grenoble, France, ELETTRA in Trieste, Italy, MAXII in Lund, Sweden, and Siberia-2 in Moscow, Russia.

In addition, there are light-source projects which aim at specific purposes such as industrial applications (ANKA at Karlsruhe, Germany, for example) or free-electron lasers (at Duke University, USA, and the University of Dortmund, Germany, for example). Table 1 shows a list of new light-source projects which are in the construction or planning phase.

Finally, it should be mentioned that emittance upgrade programs have been seriously pursued at some of the second-generation light sources, as shown in Table 2.

3. Technology trends for light-source storage rings

3.1. *Distributed dispersion system*

Up to now almost all the light sources have been designed on the basis of the Chasman–Green lattice which is based on an achromatic bend with a doublet for focusing on each side. It has been recognized for almost ten years

Table 1
New light-source projects.

Country	Facility name	Energy (GeV)	Emittance (nm rad)	Stage
China	SSRF (Shanghai)	2.2	4.3	Planning
France	SOLEIL	2.15	2.0–30	Planning
Germany	BESSY II (Berlin)	0.9–1.9	5	Construction
	ANKA (Karlsruhe)	2.5	39	Construction
India	INDUS-2 (CAT)	2.0	45	Construction
Japan	New Subaru (HIT)	1.0–1.5	30	Construction
	VSX (Tokyo University)	2.0	4.8	Planning
	Tohoko University	1.5	7.3	Planning
Spain	LSB (Barcelona)	2.5	8.5	Planning
Switzerland	SLS (PSI)	2.4	2.5	Construction
Thailand	Siam Photon (SIT)	1.2	72	Construction
UK	DIAMOND	3.0	14	Planning

that by relaxing the constraint of zero-dispersion in the long straight section it is possible to reduce the emittance by a factor of two or three compared with the zero-dispersion system. Actually, this concept has been adopted at MAXII from its design stage. There are also several plans to change the optics to realise the distributed dispersion system. The ESRF has achieved an emittance of 4 nm rad, reduced from the original design value of 7 nm rad, and is attempting to go down to 3 nm rad in the near future. ELETTRA has also succeeded in obtaining a smaller emittance of 3.7 nm rad compared with the original value of 7 nm rad. The new light-source projects tend to adopt this concept.

3.2. *Correction of the coupling factor in the 0.1% range*

It is common to assume in the design stage a coupling factor of 10% between the horizontal emittance and the vertical emittance. In actual operations, however, a coupling factor of a few percent can be achieved without particular corrections if magnets are fabricated and aligned with reasonable quality. As the demand for higher brilliance becomes stronger, the achievement of small vertical emittance has been more seriously considered at many light sources. The NSLS reported a coupling factor of 0.1%, which corresponds to a vertical emittance of 0.1 nm rad. Later, the ESRF achieved a smaller vertical emittance of 0.04 nm rad with a horizontal emittance of 4 nm rad and a coupling factor of 1%. They intend to achieve a horizontal emittance of 3 nm rad and a coupling factor of 0.3%, which corresponds to a vertical emittance of 0.01 nm rad, an extremely small value.

In order to correct the coupling factor, we need the correction of betatron coupling and the correction of spurious vertical dispersion. The correction of betatron coupling is achieved by correcting the nearest coupling resonances and by choosing the proper betatron tunes. The spurious vertical dispersion, on the other hand, is generated by the closed-orbit distortion at the position of the quadrupole and sextupole magnets and by the corrector kicks which are used for correcting the orbit. Therefore, the simultaneous correction of the closed-orbit distortion and the spurious dispersion is quite essential in achieving the effectively small vertical emittance. The rule of thumb for the correction of the spurious vertical dispersion is that it should be of the order of 0.5 cm (r.m.s.) when a coupling factor in the 0.1% range is pursued.

Table 2
Emittance upgrade at second-generation light sources.

PF	100 to 27 nm rad	Conversion in progress
NSLS X	90 to 45 nm rad	Achieved in machine study
SSRL	130 to 18 nm rad	Detailed design study
NSRL (Hefei)	133 to 27 nm rad	Tried

The technique for measuring the emittance is another issue of importance when going down to emittances as small as 0.01 nm rad. Usually the emittance is estimated from the beam size measured using synchrotron light. Since the typical beam size is around 10 μm, a carefully designed measuring system is required to reach this range. The ESRF have used an X-ray pinhole camera to measure a vertical beam size of 86 μm. At the Photon Factory, a novel technique based on the interferometer has been developed. The results of a preliminary experiment are very promising for reaching the 10 μm range.

3.3. *Orbit stability*

As is well recognized, the orbit should be stabilized within 10% of the beam size. This requirement implies an orbit stability of less than 5 μm in the vertical plane.

In the usual design, the beam position monitor is placed near each quadrupole magnet. The orbit correction is categorized into two different modes: (i) global orbit correction and (ii) local bump correction at a source point. For the global orbit correction the simultaneous correction of the orbit and the vertical dispersion is necessary, as already mentioned. A control algorithm has been developed at the respective light sources. The correction speed varies from 0.1 to 10 Hz or higher. Fast correction has become possible by the advent of digital signal processors. The local bump correction at a source point is quite important for the beam-position stabilization. Caution is necessary, however, for the correction at one particular source point not to interfere with the other source points and for the local correction not to affect the orbit globally. As an example, the five-corrector orbit bump is used at ELETTRA in order not to change the orbit length by the local orbit correction. In spite of precautions, interference between various source points may actually bring about complaints from users of different beamlines.

3.4. *Lattice modelling based on orbit response measurements*

Not only for correcting the orbit and the coupling factor, but also for analyzing the beam behaviour or predicting them in advance, it is very important to reproduce an accelerator virtually on computer. This is called lattice modelling. For this purpose, information on the real magnet parameters is required from measurements. Although magnetic measurements are performed on all the magnetic elements before installation, the actual magnet parameters, not only the strengths but also the alignment errors, should be determined by orbit response measurements. This has been possible because of the recent advancements in accurate beam monitoring systems and in fast digital computing systems with large memories. Lattice modelling has been regarded as a standard technique for all the accelerator facilities.

3.5. *Very small aperture at insertion devices*

A recent trend concerning insertion devices is the installation of undulators with very small gaps. At the NSLS, for example, they have small-gap undulators: one with a 6 mm magnet gap and 16 mm period, and one with a 3.3 mm magnet gap and 11 mm period. Actually, they confirmed a long lifetime with a 3 mm full aperture. At the ESRF the present standard vessels are 15 mm high, but will be replaced with 10 mm-high vessels in the near future. At the APS the present vessels have an 8 mm aperture, but a vessel with a 5 mm aperture will be installed for testing in late 1997.

In order not to deteriorate the lifetime with very small aperture undulators, the betatron function at the undulators must be properly selected, and the vacuum pressure must be kept low all around the ring. Also, an approach might be necessary to minimize the impedance seen by the beam. The ESRF is contemplating using copper plating on the surface of the stainless steel chambers.

3.6. *Trial for diffraction-limited beams*

Some of the existing light sources are reaching the diffraction limit in the vertical plane, as they have realised a very small natural emittance and a very small coupling factor. The ESRF will realise a vertical emittance of 0.01 nm rad in the near future. Even now, it has been reported from the ESRF that the mismatch of the emittance ellipse of the electron beam with the radiation emittance ellipse can deteriorate the brilliance by a considerable amount, and that the ESRF has operated with a small value of the vertical betatron function at the insertion device.

At the ESRF an interesting trial for achieving a diffraction-limited beam has been carried out for a couple of years. A diffraction-limited beam is achievable when the ESRF ring is operated at 1 GeV with full coupling. Here the wavelength of light is assumed to be that corresponding to the first harmonic from the undulator. However, as is well known, emittance blow-up may occur with increasing current due to intrabeam scattering. Theoretical simulations show that, even at 10 mA, the electron emittance could be larger than the radiation emittance.

In any case, it is very interesting to investigate how the diffraction-limited beam behaves. In experiments so far, the beam intensity has been limited to 1 mA by the excitation of the longitudinal coupled-bunch instabilities. Further tests are expected to continue in the future with some solutions for overcoming the instabilities.

3.7. *Ultra-short bunch option*

Both from the user's point of view and from the accelerator physics point of view, interest in ultra-short bunches is as strong in diffraction-limited beams as it is in light-source technology. In theory, the method of obtaining a short bunch is clear: by increasing the RF voltage or by accomplishing a low momentum compaction factor, α.

Such experiments have been carried out at various laboratories, for example, at BESSY I, NSLS UV, UVSOR, SPEAR, Super-ACO, ESRF and ALS. To accomplish a low value of α, the correction of the first-order term with lattice quadrupoles, as well as the correction of the second-order term with sextupoles, are necessary. In experiments so far, bunch lengths comparable with theoretical estimates have been obtained at very low currents.

At high currents, however, the bunch length always becomes independent of α. Bunch lengthening is a common feature for high-current storage rings. The wake fields induced by the interaction of the beam with the environment have a strong defocusing effect on the bunch, and, as a result, bunch lengthening takes place. Generally speaking, the reduction of impedance seen by the beam is essential, but from experiences so far, the suppression of bunch lengthening does not seem promising.

3.8. *Coupled-bunch instabilities*

Table 3
Comparison of the currents between B-factories and light sources.

	PEP-II (LER)	KEKB (LER)	ALS	ESRF
Energy (GeV)	3.1	3.5	1.5	5.0
Beam current (A)	2.14	2.6	0.4	0.2

Multi-bunch high-current beams are the fundamental requisite, not only in light sources, but also in particle factories like B- and φ-factories. In practice, in the multi-bunch systems the stored current is limited by coupled-bunch instabilities. Table 3 shows a comparison of the energy and the current of typical B-factories and light sources. In the future, light sources could operate with much higher currents, such as 0.5–1 A. Coupled-bunch instabilities are mainly due to the higher-order modes (HOMs) of accelerating cavities. In addition, the interaction of the beam with environmental particles (electrons or ions) causes anomalous coupled-bunch instabilities. These kinds of instabilities have been called two-beam instabilities.

3.8.1. *Cures for the HOMs of cavities.* There are two ways to cope with the instabilities due to the HOMs of the cavities. The first one is detuning of the HOM frequencies by changing the RF cavity temperature and/or by adding tuners. This method is simple in principle and reliable in operation. Hence, the detuning method has been used extensively at many light sources. However, tuning is sensitive to the tunes of the storage ring (ν_x, ν_y and f_s), and it is not applicable to a large ring in which the revolution frequency is small.

A more genuine method of coping with instabilities due to the HOMs of cavities is to use damped cavities. If we remove the HOM power from the cavity and dissipate it with external loads, the growth rate of the induced fields is reduced within the range that makes feasible the use of broadband feedback systems, which will be described later. Since this system provides very low values of impedance for the HOMs, the damped cavity is also called the HOM 'free' cavity.

The idea of the HOM free cavity is not new, but was proposed more than 15 year ago. Recently, the demand of multi-bunch high-current beams has grown for particle factory projects, and hence developments for damped cavities have progressed appreciably in the new electron–positron collider projects such as PEP-II, KEKB and DAFNE. Many types of damped cavities have been developed: some of them are normal-conducting and others are superconducting. Both have been well developed, and superconducting damped cavities in particular, which have been developed for CESR and KEKB, seem promising for light sources as well. An advantage of superconducting cavities is that a cavity voltage of more than 2 MV may be feasible with a single-cell cavity, while the typical cavity voltage for a normal-conducting single-cell cavity is around 0.5 MV.

It should be mentioned that the Photon Factory, in collaboration with the ISSP, University of Tokyo, has developed a new type of damped cavity, and replaced two of the four old cavities with new damped cavities. This damped cavity is a single-cell cavity made of copper with large beam pipes on both ends to extract the HOMs and with SiC absorbers on the beam pipes. The Photon Factory storage ring was operated in the autumn of 1996 with two damped cavities and two old cavities, and stored the electron beam to a current of 773 mA. It has been reported that no transverse instabilities were observed, while longitudinal signals were seen on the spectrum analyzer. Much more promising results are expected when the remaining old cavities are replaced by damped cavities.

3.8.2. *Two-beam instabilities.* All light sources operating in the multi-bunch mode usually operate in the partial-filling mode. Partial filling can help eliminate ion-trapping effects which produce the vertical beam blow-up. It also can help reduce the longitudinal coupled-bunch instabilities due to the HOMs of cavities, although low-frequency variations of the oscillation amplitude remain. The gap in the bunch train induces modulation in the cavity voltage and the subsequent spread in synchrotron frequencies within the bunch train. This leads to Landau damping on the longitudinal oscillation. Partial filling is a simple and efficient way of curing some kinds of coupled-bunch instabilities.

Recently, a new type of two-beam instability has been observed, which cannot be suppressed by partial filling. One is the photoelectron instability observed when the positron beam is stored, and another is the fast beam-ion instability observed in the case of electron beams.

The photoelectron instability (PEI) was identified for the first time at KEK-PF in 1996. Electrons are produced by the irradiation of the wall of the vacuum chamber with synchrotron radiation, and the secondary emission of electrons may be a source of electrons as well. Experimental observations have shown that if there are some empty buckets between neighbouring bunches, the instability never occurs. This means that the memory of the interaction between a positron bunch and electron clouds disappears within ~10 ns. Partial filling is not effective for overcoming the instability, but Landau damping by octupole magnets is effective.

The fast beam-ion instability (FBII) was first predicted theoretically in 1995, and later observed at the ALS and KEK-AR in 1996. Curiously, however, it has never been observed at the ESRF, for reasons not yet clear.

Ions are produced by the ionization of residual gases by the beam. The ions created by the head of an electron bunch train perturb the tail of the bunch train. According to the observations, the oscillation amplitude starts to increase from the 40th or 50th bunch within the train. The simulation gives qualitatively similar results. A good vacuum is essential for reducing the growth rate.

3.8.3. *Multi-bunch feedback system (active damper).* The complementary cure for damped cavities, capable of damping all the coupled-bunch modes, is the multi-bunch feedback system, or active damper. There are two kinds of damping systems: the mode-by-mode feedback and the bunch-by-bunch feedback.

The mode-by-mode feedback system is a system where a particular mode with a particular frequency is selectively damped. The longitudinal feedback systems based on this principle have been operated at NSLS-VUV and Super-ACO.

In the bunch-by-bunch feedback system a signal proportional to the displacement of each bunch is detected, delayed and amplified to feed power to a kicker. At UVSOR a longitudinal system was developed, and has been operated for many years. Later, both longitudinal and transverse systems have been operated at the ALS. A stable beam has been stored at 400 mA. The PLS installed a transverse system in March 1997 and is planning a longitudinal system in 1998. A transverse system has been operated and a longitudinal system is under development at the TLS. Also, a transverse-system beam test will be carried out hopefully by early 1998 at ELETTRA.

In the near future the active damper will become a standard technique at light sources.

3.9. *Topping-up*

Topping-up is the procedure in which the injection of the beam is repeated at short time intervals with the user's X-ray beam shutter open for the purpose of regulating the stored beam current. The advantages of topping-up are to keep the heat load on X-ray optics constant, to constantly maximize the data rate and to minimize the non-linearity effects in the beam detectors. In addition, it makes possible installation of undulators with extremely small gaps, since nobody worries about a short lifetime.

The APS has been pursuing this idea since the beginning of the project, and radiation measurements were recently performed. The results were reported to look promising.

Readers who need references on the subjects described in the text can refer to the proceedings of accelerator conferences such as the Particle Accelerator Conference, European Particle Accelerator Conference, International Conference on High Energy Accelerators, and other topical conferences and workshops.