Synchrotron Radiation Light Sources

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Abstract

Today, synchrotron radiation from an electron or positron storage ring is widely regarded as a unique scientific tool for basic and applied research in physics, chemistry, biology and their sub-fields. To satisfy the increasing demand for photons, a new generation of dedicated storage rings using state of-the-art accelerator techniques is in project or under construction. This paper will review the major features of these machines with reference to future national and international synchrotron sources and in particular the European Synchrotron Radiation Facility.

Introduction

The scientific activity around synchrotron radiation has grown exponentially. One after the other, high energy physics machines have been made partially or totally available and transformed for synchrotron radiation work:

CESR(CHESS)Ithaca-USA ; DORIS (HASYLAB) Hamburg-Germany; ACO,DCI(LURE) Orsay-France; SPEAR, PEP (SSRL)Stanford-USA; MAX Lund-Sweden ;VEPP-2M,3,4 Novosibirsk-USSR ;ADONE Frascati-Italy; etc.

In parallel, many dedicated sources with more appropriate performances have already been built:

around 0.8 GeV	
ALADDIN	Stoughton-USA,
BESSY	W. Berlin-Germany,
NSLS-VUV	Brookhaven-USA,
SUPERACO	Orsay-France,
TERAS	Tsukuba-Japan,
UVSOR	Okasaki-Japan,
etc.,	
and 2 GeV	
NSLS-XRAY	Brookhaven-USA,
PF	Tsukuba-Japan,
SRS	Daresbury-UK,
etc.	

This non exhaustive list of light sources is already impressive. However, the number of unsatisfied demands for photons is growing at an even higher rate than the development of the facilities. Therefore, a new generation of dedicated machines is being prepared to serve the user's community with more photons beams of higher quality.

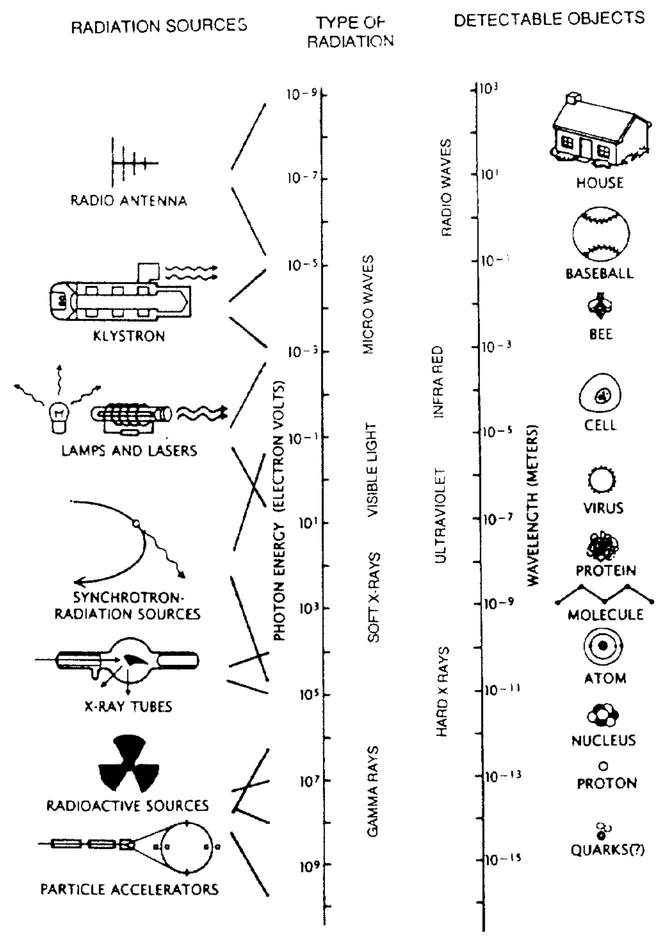

Figure 1
(drawn from "Synchrotron Radiation" by H. Winick, SLAC-SSRL)

Design specifications of the new generation of storage rings

Storage ring energy

The electron energy of storage rings dedicated to production of synchrotron radiation ranges between 0.2 and 7 GeV. Within this electron energy domain, significant flux of synchrotron radiation can be delivered in a large range of photon energies (Fig.1) from infrared (a fraction of eV) up to hard X rays (a few hundred keV).

At present, there is no obvious reason to largely deviate from this energy interval and in particular to envisage synchrotron radiation storage rings at much higher energies. As a matter of fact, photons employed to detect an object must have a wavelength that is equal or less than the object's dimensions.

Therefore, in the range defined above, synchrotron radiation photons are ideal probes to study objects like viruses (ultraviolet) proteins, molecules, atoms (hard X rays). To study more macroscopic objects with longer wavelengths (infra-red), synchrotron radiation enters into competition with standard laser sources and free electron laser oscillators under development. The other end of the scale corresponds to nuclear physics and elementary particle physics. For this kind of physics, medium and high energy particles that are abundantly produced by accelerators, have wavelengths equivalent to γ rays. They are preferred to photons.

A single source is not sufficient to cover the whole useful synchrotron radiation spectrum. In view of this, a minimum of three different storage rings well spread in electron energies at 0.8, 2 and 6 GeV and delivering photons peaked around 0.5 (vacuum ultraviolet), 2.5 (soft x-rays) and 20 keV (hard x-rays) respectively, are needed.

Hereunder a list of future dedicated sources in project or under construction is given. From the table, it can be seen that there is a clear demand for new machines around 2 GeV in the soft X-ray domain. In addition, the first hard X-ray dedicated machines around 6 GeV are under construction.

Name	location	Energy(GeV)	Status
SUPERSOR	Tokyo-Japan	1	Plan
SRRC	Hsin Chu-Taiwan	1.3	Const [1]
ALS	Berkeley-USA	1.5	Const [2]
BESSY II	W. Berlin-FRG	1.5	Plan [3]
DELTA	Dortmund-FRG	1.5	plan [4]
ELETTRA	Trieste-Italy	1.5-2	Const [5]
LNLS	Campinas-Brazil	2-3	Plan [6]
KURCHATOV II	Moscow-USSR	2.5	Const
ESRF	Grenoble-Europe	6	Const [7]
NHT	Hyogo-Japan	6	Plan
APS	Argonne-USA	7	Const [8]

Insertion Devices

Once the stored beam energy and correspondingly the range of achievable photon energy is decided, it is important to specify the characteristics of the source points and their number. The quantity of interest for users is the flux that can be drawn from a source point (number of photons emitted per second in an angle of one mrad (in the orbit plane) and within a relative energy bandwidth of 0.1%). Of course, a large flux is emitted from the bending dipoles all around the machine.

However, experience gained at existing facilities and recent development of Insertion Devices (ID) led to a new set of requirements on the design of future synchrotron radiation sources.

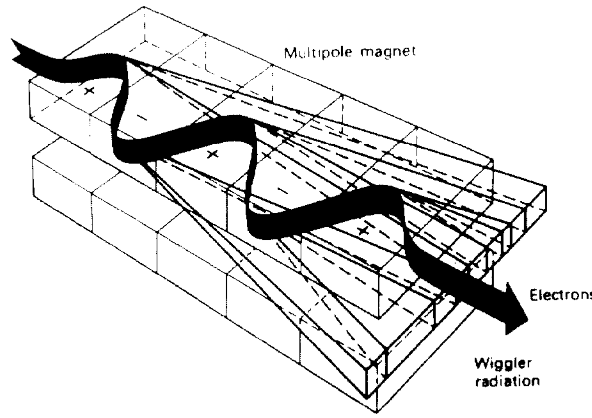

Figure 2
A wiggler consists of a series of dipoles with alternating polarities

Between the main dipoles, one can insert special devices called wigglers in which electrons are made to jiggle on a sinusoidal path. Such an ID consists in a series of dipoles with alternating polarity (Fig.2). It produces a continuous spectrum similar to that produced in a classical bending magnet having the same magnetic field. The main difference is that the flux is multiplied by the number of poles of the wiggler as one cumulates the emission from every arc of the sinusoid. Gains in flux larger than a factor of 20 are easily achieved. For this primary reason, one can easily understand that such ID's are much more attractive than the storage ring dipoles. It is therefore logical that in dedicated modern machines, specifications are essentially given in terms of characteristics of photon beams that can be drawn from ID's. A direct consequence is that the number of straight sections in the lattice, fixes the number of ID's that can be installed.

Development of ID's is very recent. Within a few years, a total of about 35 ID units were installed as radiation sources around the world. Given the special features of these radiation sources, there is no doubt that future lies with all ID-machines. A machine like the European Synchrotron Radiation Facility (ESRF) that will start operation 5 years from now is being built to accommodate up to 29 ID's.

Another obvious advantage of ID's is that in principle one can vary the field to match experimental requirements at best without disturbing machine operation. This flexibility can be achieved provided that two conditions are satisfied :

- since a substantial amount of energy is lost in the straight sections, the emittance of the stored beam could be largely dependent on ID tunings, unless the straight sections are dispersion free.

Therefore, an adequate storage ring lattice will consist of a series of achromatic bends between two successive dispersion free straight sections.

- In addition, correctors should be provided to compensate closed orbit displacements and wave number changes induced by changes of ID parameters.

Usually, from the broad band spectrum that can be drawn from storage ring dipoles or wigglers, experimenters are interested only in a narrow bandwidth around a given photon energy. As a consequence, most of the photon beam power is blocked on monochromators in the beam line, leading to technical problems due to heat load which are not easy to solve. The situation can be substantially improved if the wiggler parameters are changed to work in the undulator mode (Fig.3). In an undulator, the angular deflection caused by each set of poles is smaller than or comparable to the natural emission angle. This is achieved by shortening the magnetic period. In this mode, waves radiated by each electron can be constructive or destructive at certain photon energies and at certain emission angles. The spectrum presents a strong angle-photon energy correlation with an extremely higher flux per solid angle at the enhanced energies. If a small angular aperture is selected near the axis, the spectrum is reduced to a thin line spectrum at harmonics of **the fundamental undulator photon energy.**

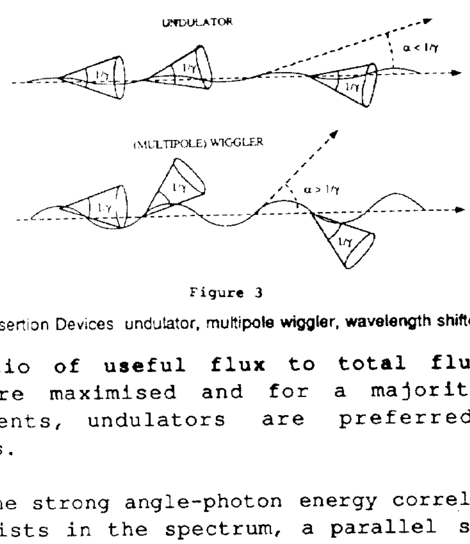

Figure 3

Insertion Devices undulator, multipole wiggler, wavelength shifter

The ratio of useful flux to total flux is therefore maximised and for a majority of experiments, undulators are preferred to wigglers.

Given the strong angle-photon energy correlation that exists in the spectrum, a parallel stored beam is required at undulator locations (high local beta function for the lattice). The angular deflection caused by each set of poles is larger in a wiggler and a large angular spread of the stored beam can therefore be tolerated. In this case, a low local beta function makes the machine less sensitive to the ID. To accommodate both types of ID's, the storage ring lattice must be flexible enough to provide low or high betas in the straight sections.

Flux around a certain wavelength is an important source characteristic. Nevertheless, whenever the beam must be focused at the sample, the true figure of merit is the brilliance (sometimes called brightness or radiance) : the flux divided by the product of the transverse emittances of the source. Far from the diffraction limit, the lower the emittance of the stored beam, the higher the brilliance it produces. Most existing sources operate with horizontal emittances of the order of 100 π nanometer-radians or more. Rings under construction are designed to gain a factor of 10 to 30.

Lattice Design

Given the above constraints, lattice design for the generation of sources to come has led to an intense worldwide activity. The low emittance is obviously achieved by reducing the betatron oscillation induced by photon emission : combination of low beta in the horizontal plane (β_x) and small energy dispersion η in the main dipoles. This implies a very strong focusing and consequently a very large negative natural **chromaticity.**

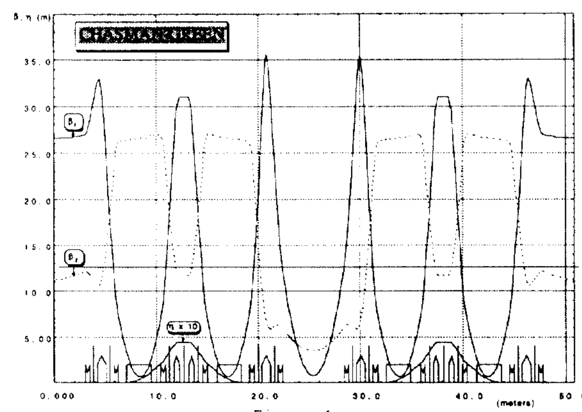

Figure 4
Lattice function for ESRF
Model of extended Chasman-Green lattice

To prevent transverse coherent instabilities, the chromaticity sign must be changed by means of strong sextupoles in the achromat. The induced non-linearities are so large that, a priori, the dynamic aperture is very small and tune shifts with amplitude are unacceptable. It took some time before lattice designers could find adequate first order optics and sextupole schemes. Several achromat designs with emittances ranging between 3 and 7 π nanometer-radians at design energy have been brought to more or less the same level of optimisation with dynamic acceptances of more than 50 rms beam size. Among the different possibilities should be mentioned the double bend achromat (DBA) or extended Chasman-Green for the ESRF (Grenoble) (Fig.4), APS (Argonne) and ELETTRA (Trieste) ; the triple bend achromat (TBA) for the ALS (Berkeley) and SRRC (Taiwan) (Fig 5) ; and the FODO.

All these machines have in common that they require a quite perfect closed orbit to achieve correct performances.

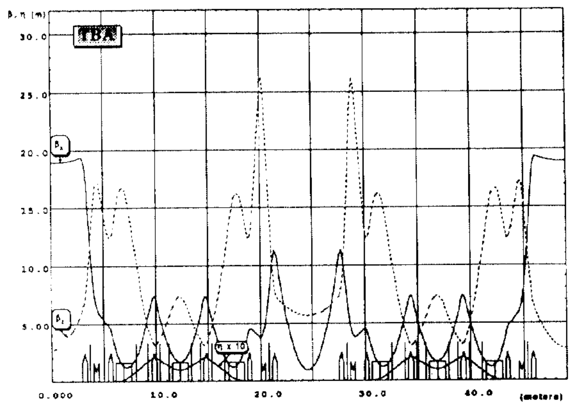

Figure 5
TBA lattice functions

Orbit Stability

Orbit stability has more severe requirements than for other accelerator applications. Typical maximum figures for rms vertical beam dimensions at undulator location are : $\sigma_z = 80$ µm and $\sigma'_z = 6$ µrad (10% coupling). To avoid spoiling the source emittance, the beam center of mass must be kept within ± 4 µm and ± 0.3 µrad all around the machine. In view of this, several measures are almost universally adopted.

- The closed orbit is sensitive to quadrupole center displacements. The amplification factor stands between 50 and 100. The buildings, infrastructure, slab and magnet supports must be designed to minimize transmission of **mechanical vibrations to the storage ring elements.**
- **Standard stored beam position monitors are not sensitive enough to be used to control such** small displacements. Dynamic feedbacks based on actual detectors of the photon spot position will be installed at every undulator beam port. In principle, this is straightforward but can be difficult in practice to avoid coupling among the many beam lines. Furthermore, full flexibility for the users means that the parameters of several tens of ID's (therefore the closed orbit excitation and wave numbers) will be changed during standard operation. The correction scheme must be designed to cope with this severe constraint.
- The storage ring will be operated totally d.c. with full energy injection. This will prevent the unavoidable lack of reproducibility due to magnetic field ramping and leaves exactly invariant the beam characteristics even though the current has to be topped up from time to time.

Vacuum system and ion trapping

The vacuum system is certainly one of the most important components for obtaining optimal performances. To avoid having complex mechanisms under vacuum and to make the vacuum as clean and as possible, it is preferable to reject ID's outside vacuum. This makes it necessary for the minimum undulator gap to be increased (1 cm for the APS - 2 cm or more elsewhere) and costs some extra hundreds MeV of storage ring energy to cover the short wavelength part of the radiation spectrum. Under these conditions the static (no-beam) vacuum of 10^{-10} Torr is not difficult to achieve. The difficulty lies in maintaining a good dynamic vacuum. The wall is flooded with intense synchrotron radiation and becomes an abundant source of photo desorbed gas molecules to be collected by the pumps. The chamber geometry is designed to avoid migration of desorbed molecules to the stored beam region while keeping impedance low.

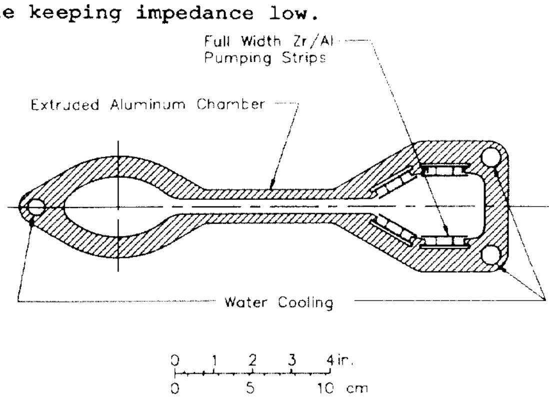

Figure 6
Storage ring vacuum chamber cross-section
(APS - Argonne)

With the exception of straight sections, the chamber is composed of two parts (Fig 6). The stored beam chamber is of constant cross section with shielded bellows and flanges. On the outside, the antechamber contains the absorbers, on which unextracted photons are dumped, and right next to them the high speed pumping system.

The chamber and antechambers communicate via a slot through which synchrotron radiation passes. The power density of the photon beam emitted by insertion devices is very high. The vacuum chamber could be seriously damaged if the photon beam is not perfectly aligned. Mis-steering errors must be avoided by all means.

There are different approaches. Favourite designs consist of an aluminium chamber with distributed pumping. The ESRF has decided to use an all stainless steel system with lumped absorbers and pumps.

Once vacuum problems are settled, there still remains the problems associated with ion trapping for e^- machines. Residual gas atoms are stripped by the electron beam and the resulting ions are trapped along the beam path. The accumulation of ions causes space charge effects with large tune spreads compared to resonance spacing which in turn leads to particle losses.

Improving vacuum can only delay the mechanism. On the other hand, clearing electrodes require space, larger magnetic gaps and contribute to impedance.

Many large emittance machines suffer from ion trapping. For the low emittance machines of the next generation, theory predicts that a correct beam lifetime could be obtained by filling a restricted part of the circumference with a bunch train in order to allow ions to escape before the bunch train passes again.
Nevertheless, the most dramatic way to rid a machine of ion trapping is to use positrons instead of electrons. Most projects plan either to use positrons from the start or at least to implement a positron option at a later stage if necessary.

Current limitation and radio frequency system

The machine will be mainly run in the multibunch mode. However, some experiments of time of flight type will require single short bunch operation. Therefore, the new generation of machines will use high frequency systems at 350 or 500 MHz where power sources are available. In the multibunch mode, due to the large number of bunches involved, coherent coupled bunch longitudinal or transverse instabilities are much more severe than in colliding beam machines. The main sources of unwanted high Q resonators are indeed the Radio frequency (RF) cavities.
For an X-ray source at 6 or 7 GeV, there are two conflicting requirements.
In order to minimise the number of straight sections occupied by the RF, a high accelerating gradient and accordingly a high shunt impedance at the fundamental frequency is required. This is obtained with highly coupled multicell cavities designed with a pronounced nose shape to enhance the accelerating field on beam axis (LEP 5 cell cavities for instance adopted by the ESRF). However, such cavities have a large number of strong transverse and longitudinal higher order modes (HOM) that can drive coupled bunch instabilities and limit the current.
The alternative approach consists in using a large number of independent single cell cavities carefully designed to minimise HOM's. This is the solution adopted by the APS.
For a low energy machine, radiation losses are less and only a few single cells are required
In both cases, a strong research and development programme on HOM suppression in multicell or single cell cavities is underway. Other ways to push the current limit by means of feedback systems or landau damping are being contemplated.
The design multibunch current stands between one hundred and a few hundreds mA.
In the single bunch mode, the threshold is given by the fast head-tail transverse instability resulting from the broadband interaction of the bunch with the environment impedance. Contrary to what happens in large colliders, the main contribution to the impedance comes from the vacuum chamber itself and not from the RF cavities. Bellows, flanges and vertical dimension changes must be carefully shielded taking into account the complicated geometry of the vacuum chamber. A priori, the antechamber does not couple to the main chamber in the frequency range of interest. Nevertheless, to better assess this coupling some theoretical and experimental studies are still underway.
The single bunch design current stands between 5 and 30 mA.

Conclusion

The next generation of synchrotron radiation sources is especially designed to fully exploit the special spectral features from undulators and wigglers. Achievement of very low emittances with very flexible optics, beam stability, beam lifetime, high intensity addresses new challenges to machine builders and makes this branch of accelerators very specific. When compared to existing sources, the expected gain on brilliance stands between 100 and 1000 (Fig. 8).
Experience has shown that with each order of magnitude improvement, novel applications have come. There is no doubt that the new generation of sources will significantly contribute to the already explosive growth of synchrotron radiation activity.
Speculative projects based on diffraction limited sources with emittances in the 0.01 π nanometer-radian range and new types of ID's are being contemplated.

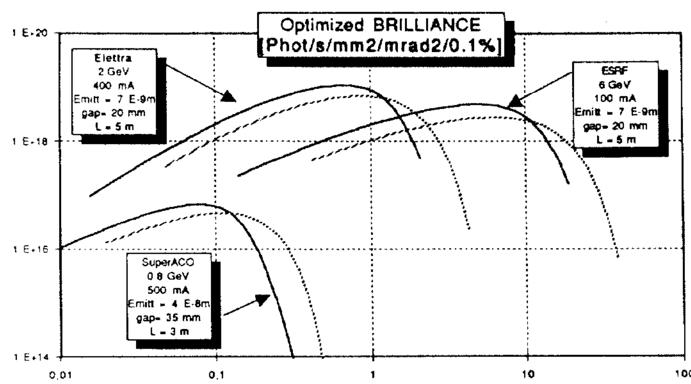

Figure 7
Optimised brilliance achievable with a series of undulators, from two machines of the next generation : Elettra and ESRF compared to SuperAco, the latest low emittance machine of the previous generation

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