# Overview of the challenges of the new generation of synchrotron light sources

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# Overview of the challenges of the new generation of synchrotron light sources

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**Abstract**

Synchrotron radiation emitted by circulating electron beams is a powerful and versatile source for probing atomic and molecular structure. The scientific activity around synchrotron radiation sources has grown exponentially from the parasitc use of high energy storage rings to the third generation of dedicated synchrotron light sources presently in design, construction, commissioning or early operation stage throughout the world. This new generation of machines raises numerous challenges associated with the requirements for high brilliance and optimum use of the radiation from insertion devices. In this paper, we will discuss the issues of lattice design and dynamic aperture, beam position stability, radio frequency system and current limitations, vacuum and beam lifetime. The example of the ESRF and other machines being recently operated indicates that most of the challenging target performances set to the third generation synchrotron light sources can be successfully met.

## 1. INTRODUCTION

Synchrotron radiation emitted by circulating electron beams presents an extraordinary combination of different advantages: broad spectral range from infrared to hard X-rays, high flux of radiation and high brilliance thanks to the small source points, polarisation, time structure, ... . These properties have made it a very popular tool for fundamental and applied research in a wide range of domains and has contributed to the exponential growth of the scientific activity around radiation sources since the mid 60s' [1].

The development of synchrotron radiation sources started with the parasitic and then exclusive use of low and intermediate energy synchrotrons and storage rings initially built for elementary particle physics. The first machines used in that way were Tantalus (Wisconsin) and Aco (Orsay) which used the synchrotron light from bending magnets. It took a few years before the second generation of machines dedicated to the production of synchrotron radiation went into operation: SRS (Daresbury), Bessy (Berlin), Max (Lund), Aladdin (Wisconsin), NSLS (Brookhaven), Photon Factory (Tsukuba), etc . These machines were initially designed for photon beamlines from bending magnets before being modified to accommodate special insertions (wigglers and undulators).

The remarkable properties of the radiation emitted by insertion devices has led to the design of a new generation of machines optimized to maximize the brilliance of the radiation from these devices. The design specifications of these machines are based on electron or positron storage rings, very small emittances (in the few nanometer range), large currents and a large number of straight sections to accommodate insertion devices. As shown in Figure 1, machines of the third generation aim at gaining several orders of magnitude in brilliance, compared to second generation machines. The increasing interest for these new machines is illustrated by the numerous projects presently in the design, construction, commissioning or early operation all around the world (more than 10 projects ranging from 1.5 GeV to 6 GeV in Europe [2], ALS (1 - 2 GeV) and APS (7 GeV) in the USA, Spring 8 (8 GeV) in Japan, several rings in Brazil, India, Korea, Taiwan, China, etc.

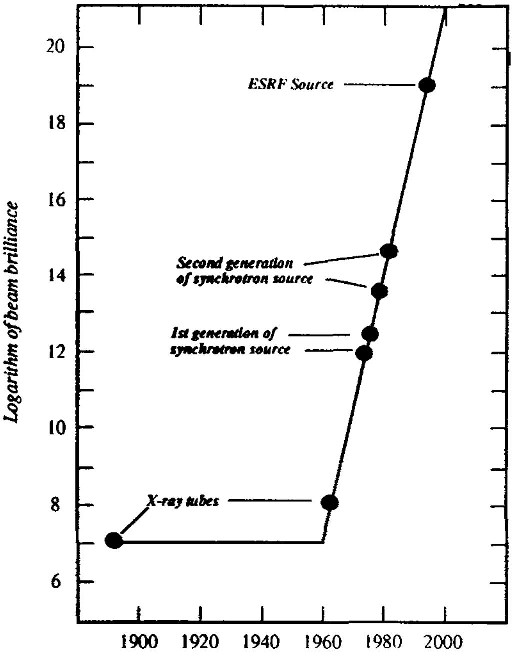



Figure 1. Increase of X-ray beam brilliance over the last decades

Given the extension of the spectrum of photon energies ranging from ultraviolet to hard X-rays, a single source cannot cover the whole spectrum. However similar issues are to be faced by low energy (0.8 GeV to 2 GeV, i.e. a few eV to a few keV) and by high energy (6 to 8 GeV, i.e. 1 keV to 100 keV) machines of the third generation:

- constraints on the lattice design due to the low emittance requirement
- constraints arising from the characteristics of insertion devices (reduced gap vacuum vessels, high power produced by the photon beam, effects on the electron beam)
- stringent tolerances on the photon beam position stability in order to avoid spoiling the small emittances
- ultimate current limits and beam instabilities
- lifetime considerations and vacuum-related problems

## 2. LATTICE ISSUES

### 2.1. Lattice design

Lattice design had led to an intense worldwide activity over the past years [3] in order to fulfil the basic specifications of the third generation of rings: provide long straight sections for the installation of insertion devices and an electron beam with a small emittance. Since the number of beam ports fixes the number of straight sections, the periodicity of the lattice is also determined. The large amount of energy radiated in the insertion devices means that the emittance of the stored beam could depend on the insertion device characteristics unless the straight sections are dispersion-free.

Given the fact that the emittance is determined by the balance between radiation excitation produced in the bending magnets as an electron emits a photon and the damping produced by the RF system, the achievement of a small emittance implies to minimize the amplitude of the excitation which depends on the distribution of the dispersion and the optical functions in the bending magnets.

In particular the small horizontal beta functions required in the bending magnets imply a strong focusing which has adverse effects, as it induces a strong negative natural chromaticity. To prevent beam instabilities, this chromaticity must be corrected or adjusted to a slightly positive value by sextupoles located in the dispersive region of the lattice. As a matter of fact, these sextupoles need to be very strong and introduce aberrations which limit the maximum zone of stable amplitudes of oscillations (known as the dynamic aperture). Therefore, the primary challenge of the low emittance lattices is to provide an adequate dynamic aperture for the injection and accumulation processes and for obtaining a beam lifetime of several hours.

The strong focusing also drastically increases the sensitivity of the lattice to machine imperfections like magnet field and construction errors or alignment errors. The second issue comes from the need to assess the behaviour of the lattice with realistic errors and to estimate the effects of insertion devices.

Several types of lattices had been competing in the past. For high energy machines, it is necessary to operate the bending magnets at low field to limit the power radiated from the dipoles and to minimize the number of RF cavities. This leads to a large number of unit cells and compact structures. The tendency is to use Double Bend Achromat structures. Low energy rings can afford to use less compact structures such as the Triple Bend Achromat. However the high focusing of these lattices necessitates innovative solutions to cope with the enhanced sensitivity to errors, to optimize the dynamic aperture and to define adequate closed orbit correction schemes.

The sensitivity to machine imperfections is illustrated in Figure 2 which shows the expected reduction of dynamic aperture of the ESRF lattice with quadrupole positioning errors of 25 µm. The inclusion of all possible sources of errors with achievable tolerances obviously worsens the situation.

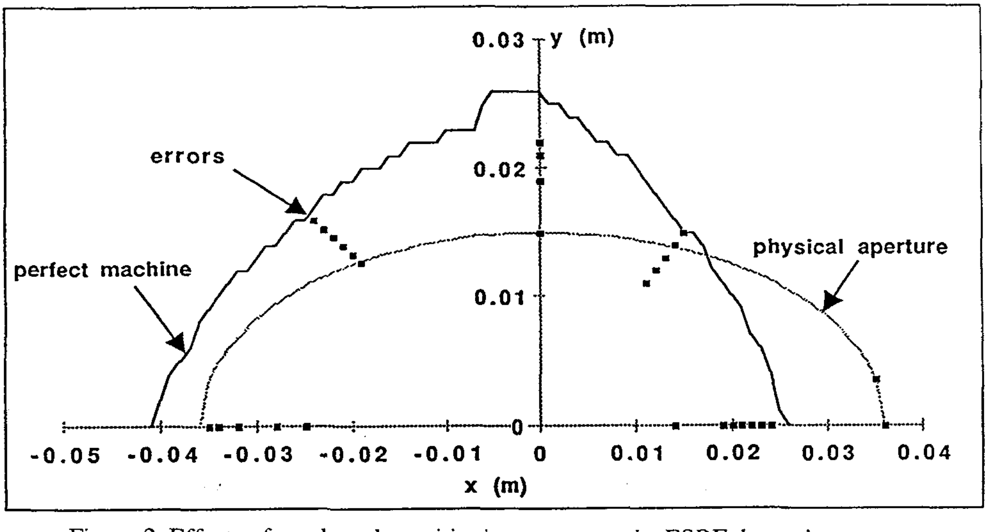



Figure 2. Effects of quadrupole positioning errors on the ESRF dynamic aperture

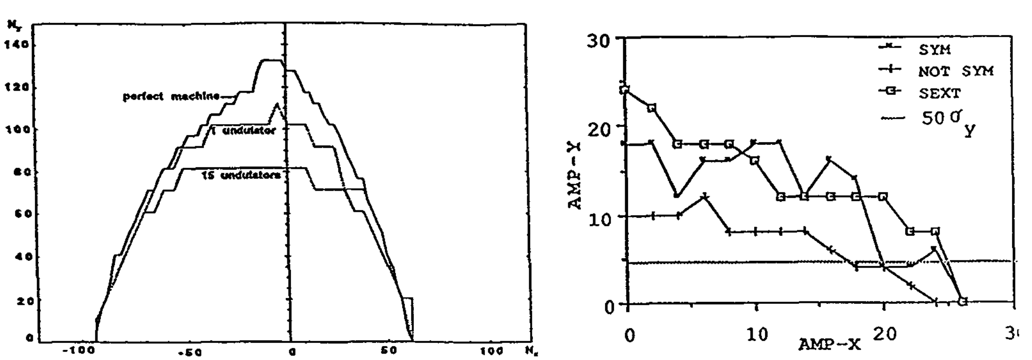
Despite the many precautions taken at the design and construction stages of the new rings (sorting of magnets according to their field quality, optimization of magnet assembly, state-of-the-art alignment on girders to less than 0.1 mm), it was feared that these machines would be very difficult to commission and possibly unable to achieve the target performances. Several scenarios for running a detuned lattice at the early stage of commissioning were envisaged.

Procedures to steer the beam during the first turn transmission appeared more effective, as shown by the rapid obtention of stored beam in the first low emittance lattices commissioned: for example, at the ESRF, a few turns could be transmitted with steerers switched off and the first stored beam obtained one day after. Similar initial success has been reported for the few other third generation sources commissioned afterwards (ALS, ELETTRA, SRRC).

Further experience in commissioning and operating these machines indicates that no problems have been encountered so far due to limited dynamic aperture, such as bad injection efficiency, reduced lifetime, etc. The successful commissioning of several low emittance machines and the rapid obtention of emittances close to specifications demonstrate that the tools and strategies for optimizing these lattices were fully adequate. This also leads to believe that the same tools and strategies are ready to be applied to the design and construction of machines with even smaller emittances, i.e. diffraction limited machines of the fourth generation.

### 2.2. Effects of insertion devices

The electron beam properties can be affected by insertion devices because these devices are intrinsically non-linear and also provide focusing in one or both transverse planes, thus destroying the periodicity of the lattice and causing distortions of the particle motion (distorted closed orbits, tune shifts, modulation of the beta functions around the circumference, excitation of resonances leading to a reduction of the dynamic aperture). Since the strength of the focusing varies as the square of the magnetic field and is inversely proportional to the square of the energy, low energy machines are more sensitive to the inclusion of insertion devices in the lattice. Figure 3 shows a comparison of the predicted reduction in dynamic aperture for a high energy machine (ESRF) [4] and a low energy one (ELETTRA) [5]. In order to minimize the reduction of dynamic aperture, special effort has to be made to provide local compensation schemes with extra quadrupoles in the low energy lattices. Such schemes which had successfully been implemented on machines of the previous generation have not yet been used on the new rings.




ESRF ELETTRA

Figure 3. Effects of insertion devices on dynamic aperture

There are also effects due to the additional radiation emitted by the beam in the insertion device. The radiation damping and the quantum excitation processes can be affected, thus causing changes in the emittance and energy spread of the beam. These effects are produced mainly by wigglers and to a lesser extent by undulators. Some of them could be used to advantage, for instance to reduce the emittance far below that obtainable with other known methods [6].

## 3. BEAM POSITION STABILITY

In these new machines designed for smaller and smaller emittances, the problem of stability of the X-ray beam in position and angle constitutes a key issue for taking advantage of the small emittances of the electron beam.

As seen by the users, any change in change in position or angle of the beam centre of mass with time is equivalent to an enlargement of the source and a macroscopic emittance growth. According to experimental requirements, the position of the X-ray beam should be reproducible from fill to fill and stable to about 1/10 of its dimensions with respect to the beamlines. Given the small vertical emittances (less than 10 % of horizontal emittance), the vertical stability is the most demanding. The typical vertical beam dimensions at the source points (see Table 1) clearly show that the required stability stands in the micron (or micro radian) range for several hours.

| | undulator | wiggler | bending magnet |
|---|---|---|---|
| $\sigma_z$ ($\mu$m) | 90 | 47 | 128 |
| $\sigma'_z$ ($\mu$rad) | 7 | 13 | 7 |

Table 1. ESRF beam sizes at the source points

Therefore, environmental stability is of prime importance and requires the appreciation of a series of new adverse effects and the adoption of technical solutions to combat the hypersensitivity of the machine:

- limitation of temperature changes which cause machine components and experimental equipment to move by regulating the temperature of the tunnel and experimental hall in the °C range.

- minimization of the thermo-mechanical effects linked to the variation of heat load during the current decay which makes the orbit drifting with time. For instance, at the ESRF, with an rms closed orbit in the 0.15 mm rms range, the typical drift could reach 0.1 mm / hour. Sophisticated and permanent closed orbit correction procedures are therefore mandatory to cope with such deviations.

- control of ground vibrations: all sources of vibrations induced by the cultural noise can be transmitted through the ground to the girders supporting the magnets and then amplified. Displacements of quadrupoles are drastically amplified by the strong focusing lattices, with amplification factors standing between 50 and 100. An optimum design of the buildings, infrastructure, slab, magnet supports, etc is essential for these new machines in order to minimize the transmission of mechanical vibrations.

Results reported so far indicate that the measures universally adopted were fully adequate since routinely achieved stabilities significantly below the specified 10 % have been reported for the first sources operated, even those located in a urban environment [7], [8]. The use of local fast feedback systems can even further improve this performance with stabilities in the 1% range, i.e. figures 10 times better than initially required and therefore compatible with 100 times smaller emittances (several $10^{-11}$ meter).

## 4. ULTIMATE CURRENT LIMITATIONS

Brilliance is certainly the most referred to figure of merit. There are many possibilities to increase the brilliance, as shown below:

$$B = \frac{\text{number of photons per second}}{\sigma_x \, \sigma'_x \, \sigma_z \, \sigma'_z} f\,(E, \text{gap})$$

The intensity is one of the parameters which plays a role in the increase of the brilliance of third generation machines. However the effort which is involved for pushing these machines towards their ultimate current is certainly larger than for other parameters.

There are two main operating modes: multibunch mode with a large number of bunches and short single bunch mode with high peak current for time resolved experiments. Typical design performances are: 200 - 400 mA in multibunch, 10 - 30 mA in single bunch. A few bunch mode could be a good compromise to serve a large user community, those who are demanding in terms of intensity profile and those who require time structure.

For all third generation machines, the increase of intensity raises problems in terms of beam behaviour and excitation of instabilities, design of the RF system, engineering. However, the issues are somewhat different for low energy and high energy machines.

Higher Order Modes in RF cavities were considered as a major obstacle for reaching the design current in the multibunch mode of operation. Due the large number of bunches involved, longitudinal and transverse coupled bunch instabilities are much more severe than in colliders. The main source of excitation comes from unwanted high Q resonances in the cavities. The problem is even worsened by the conflicting requirement of using a minimum number of straight sections for the RF, which implies a high accelerating gradient and high shunt impedance at the accelerating frequency but also a large number of strong HOMs which can drive instabilities.

At the ESRF with cavities not at all optimized for a synchrotron light source, simple solutions have been found to nevertheless overcome the HOM limit predicted at 60 mA and go significantly beyond the design current of 100 mA with a best present performance at 175 mA. This demonstrates that contrary to former common belief, machines of the third generation can accommodate rather large HOMs.

A priori, in comparison, low energy machines are more sensitive to HOMs, which fully justifies R&D programmes on HOM-free cavities [9], dampers, feedback systems, etc. However, it is not excluded that similar simple solutions such as partial filling of the circumference or detuning of HOMs by temperature control of the cavities, could also be used. Encouraging intensity performances close to the design current have already been achieved at the first low energy machines like ELETTRA, ALS, SRRC.

With respect to the RF system, high energy machines are more concerned by the beam power which has a direct impact on the number of transmitters and the lifetime of windows, whilst beam loading could be an issue for low energy machines. For both types of machines, R & D programmes are essential for defining the adequate components capable of absorbing the extra power resulting from the increase of current.

For single bunch again, the manifestation of instabilities depend on the energy: microwave instability for low energy machines, fast head-tail for high energy machines. Experimental thresholds are also in good agreement with predictions.

Until now, no new instability mechanisms have been identified at the new third generation sources which could be attributed to the increased transverse density.

## 5. VACUUM - BEAM LIFETIME

The vacuum system is one of the most important components for obtaining design performances. A beam-on operating pressure in the $10^{-9}$ mbar or less is required in order to allow a beam lifetime of several hours. The obtention of a static pressure in the $10^{-10}$ mbar range is rather straightforward, although it implies the use of ultra-vacuum techniques, special care during vacuum vessel manufacturing, in-situ bakeout at 200 ° C, etc.

The third generation light sources are characterized by much lower emittances and smaller undulator gaps than the existing machines. Both factors contribute to the deterioration of the lifetime. The effects which play a major role are the beam gas scattering and the Touschek effect. Their importance is strongly related to the energy of the machine.

Since it is preferable to keep magnetic material outside the vacuum chamber, the impact on the lifetime of the small gaps required for the operation of insertion devices and the corresponding increase of brilliance could be severe. For the time being, typical undulator gaps lie in the 15 - 25 mm range. Gaps in the 5 - 10 mm are envisaged but are still considered as something of an adventure. As a futurist target, one could dream of machines with very small gaps (< 1 mm) and large number of periods (1000) [10]. These reduced machine apertures contribute to substantial lifetime degradation from gas scattering, as predicted in Figure 4 for the ALS [11].

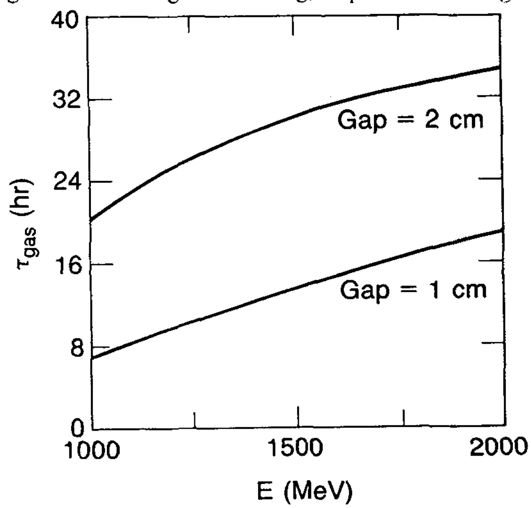



Figure 4. ALS predicted gas scattering lifetime

Another problem comes from the Touschek-related lifetime limitations. The Touschek lifetime is inversely proportional to the particle density and scales as the cube of the machine energy. Therefore, Touschek effects are most severe for short, high-current bunches with low emittance and reduced coupling, which are the main features of the third generation machines. Because of the energy scaling, the effect is more significant for low energy machines. Figure 5 shows an example of the Touschek lifetime as a function of energy in the case of two transverse acceptances [4]. The effect of a small coupling is demonstrated in Figure 6 [11].

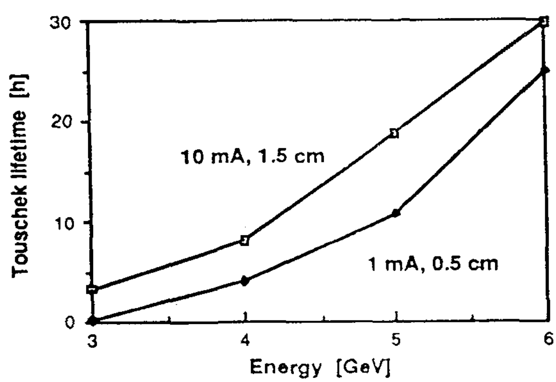



Figure 5

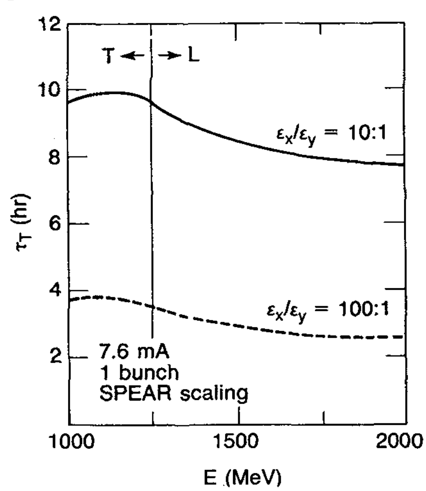



Figure 6

Obviously long lifetime might be conflicting with high brilliance, specially in the low energy sources when operated in the few bunch mode. A possible cure to cope with lifetime limitations in the few hours range might be to operate the machines in top-off injection mode. This however is considered as an ultimate option.

Another challenge for maintaining a good dynamic pressure comes from the emission of synchrotron radiation leading to a large number of photo-desorbed gas molecules to be collected by the pumping system. The vacuum chamber must therefore be properly designed to avoid migration of desorbed molecules to the stored beam region whilst keeping a constant cross section to minimize the vacuum chamber impedance and the excitation of instabilities.

The power density of the photon beam from insertion devices in low energy and high energy machines can exceed 1 kW / cm$^2$ and is therefore equivalent to that of a welding machine. Any misalignment of the photon beam impacting the vacuum vessel might severely damage vacuum vessels in a few tens of ms in case of a mis-steered beam falling on an uncooled surface. A fault on a single steerer can generate such an intolerable orbit distortion. In order to deal with such a scenario, the protection of the vacuum chamber must be ensured by dedicated interlocks. Different solutions are being envisaged (active sensors such as dedicated beam position monitors or tungsten wires [12], limitation of maximum excursion of steerers, etc). The reliability of these diagnostics is essential for the new machines.

## 6. CONCLUSION

Several third generation light sources are now successfully operated with originally adopted options despite several matters of serious concern at the design stage. Most of the challenging target performances initially required for these machines can be successfully met and there is still room for further upgrades.

In the light of preliminary experience with the first third generation machines, even more brilliant machines could be envisaged since no new mechanism has been found that would prevent this. In the medium term, a gain in brilliance by a factor of 10 looks realistic. The further gain in brilliance ($10^7$) is likely to be achieved mostly by a further reduction of the emittance by two orders of magnitude. The adequate tools and design strategy are apparently already available.

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