SR-RELATED ACCELERATOR PHYSICS ISSUES

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Abstract

The experience gained with the 3rd generation machines give now good indications on the target performance for future SR-dedicated Storage Rings. Synchrotron Radiation users are still looking for higher brilliance, but also for more coherence of the radiation, both in space and time domains. In terms of accelerator physics, this means smaller emittances, higher currents, shorter bunches. The corresponding limitations are being investigated on operating machines, such as the ESRF [1]. Limits for the next generation of SR Storage Ring sources will be discussed here.

1 INTRODUCTION

Third generation Synchrotron Radiation Sources were supposed to accumulate a number of problems like:

- small dynamic aperture,
- high sensitivity to errors,
- current limitations in single and multi bunch modes…

However these machines reached very easily, and often surpassed their target performance. A workshop recently held by the ICFA was an opportunity to derive, from present experience, realistic goals for a next generation of SR-sources, in accordance with the wishes of the User community. A strong request concerns the coherence of light, in space (Diffraction Limit) and time (Fourier Transform Limit). The need for higher average brilliance is still present. Operational aspects (beam lifetime and stability for instance) should not be compromised in the search for performance.

2 SMALL EMITTANCES

Smaller emittances are necessary to approach the diffraction limit, and are playing an important role in the average brilliance.

2.1 Horizontal emittance

The equilibrium emittance is defined by:

$$\varepsilon_x = \frac{C_q \gamma^2 \left\langle H / |\rho|^3 \right\rangle}{J_x \left\langle 1/\rho^2 \right\rangle}$$

The strong dependence on γ^2 suggests that the easiest gain will be obtained by reducing the energy.

The emittances scale down as γ^2, and at the same time the photon emittance scales like γ^{-2}. Figure 1 shows the evolution of emittances for an ESRF type lattice (circumference 850 m).

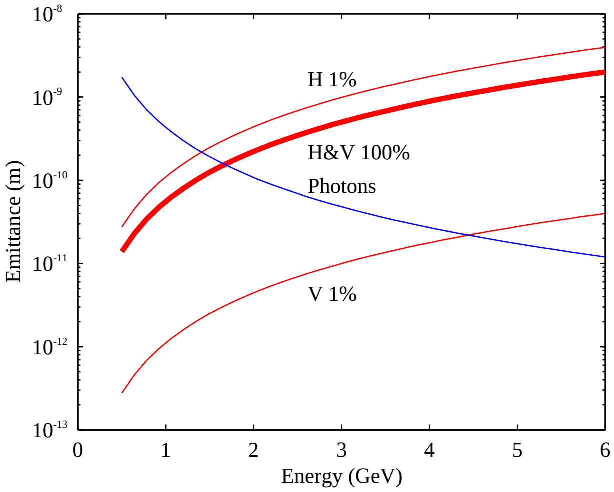

Fig. 1: Electron and diffraction emittances as a function of energy and coupling

Thus for a given machine there is an energy where we reach the diffraction limit. However, at that point the energy is so low and emittances so small that the intrabeam scattering becomes dominant. Therefore a compromise in energy scaling must be chosen [2]. To cover the hard X-ray domain a scaling in size can be studied, giving the following parameter ranges for VUV and hard X-ray machines [3]:

Table 1

	VUV	hard X-ray
Energy (GeV)	2	6
Photon energy (keV)	1	10
Circumference (m)	850	1700
Intensity (mA)	500	500
Emittances (H/V) (pm)	222/222	495/4.95
Ratio to diffraction limit	5	28/1
Brilliance	$1.3\ 10^{21}$	$4.9\ 10^{22}$

Other possibilities to reduce the horizontal emittance have marginal effect: no significant gain is expected from new lattice designs, the use of damping wigglers requires extremely long wiggler sections.

In terms of brilliance, present performances on 3rd generation machines are in the range of 10^{20} to 10^{21} .

The ultimate value is defined by the diffraction limit and is in the order of 10^{23}.

2.2 Vertical emittance

As long as the machine is above the diffraction limit, a reduction of the horizontal/vertical coupling will bring a significant improvement in brilliance. On the other hand, reducing the vertical emittance below the diffraction limit is of no interest, while increasing it may help in fighting intrabeam scattering and Touschek effect. The control of the coupling in a wide range (0.1% to 100%) will therefore be necessary in future machines.

2.3 Beam stability

When dealing with extremely small emittances, the question of beam stability is crucial. According to recent experience [4] it appears that:

- Vibrations should not prevent achieving extremely small emittances, provided care is taken during design and construction phases. The vibration amplitudes measured on 3rd generation machines are still far from the tolerance of 10% of the beam size and should not degrade the performance of diffraction limited machines. Vibration damping materials and feedback systems can further improve the stability.
- The main limitation for beam stability comes from the stability of the beam position monitors themselves. They are subject to thermal and electronic drifts, with time constants of a few hours. Reducing emittances implies significant progress in this domain.

2.4 Limitations

Larger machines will have smaller values of the dispersion function. The correction of chromaticity then requires stronger sextupoles, and yields very likely smaller dynamic apertures. However, with the experience of 3rd generation machines such a reduction does not appear to be a severe problem.

4 TIME STRUCTURE

There is a scientific case for bunch lengths in the range 100 fs – 1 ps. The bunch length at low intensity scales like:

$$\sigma_l = k_1 \cdot \sqrt{\frac{\alpha\gamma^3}{\omega_{RF} V_{RF}}}$$

Synchrotron Radiation Sources have, by design, a rather small momentum compaction factor α and therefore short bunches (tens of picoseconds). One could think of further reducing α to get shorter bunches. Unfortunately, as soon as the intensity increases, the bunch lengthens because of its interaction with the environment (broad band impedance of the vacuum chamber). The asymptotic behavior for an inductive impedance scales like [5]:

$$\sigma_l = k_2 \cdot \left(\frac{\left| Z_{//}/p \right| I}{\omega_{RF} V_{RF}} \right)^{1/3}$$

The bunch length is now independent of α and of the energy. The dependence on V_{RF} and ω_{RF} is also weaker (-1/3 power). This is illustrated in Fig. 2. A realistic broad-band impedance gives the same behavior.

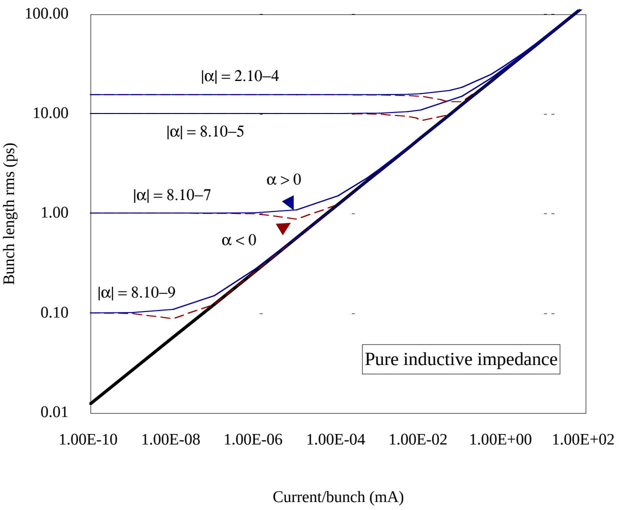

Fig. 2: bunch lengthening with intensity

3.1 Low α

This method has been tested on several machines [6][7][8] but is not very promising since the bunch lengthens (independent of α) because of potential well distortion. The only advantage may be in the production of coherent infra-red radiation, with a very low beam intensity.

3.2 Negative α

With a negative α, the potential well distortion has a tendency to shorten the bunch with increasing intensities. However the behavior is limited to very small intensities, up to the point where a bunced beam negative mass threshold is reached. Above this threshold, lengthening will again occur, but in addition the energy spread will also increase, which is very detrimental for the brilliance. A minor advantage lies in the reduction of the sextupolar strengths.

3.3 Increased V_{RF} and ω_{RF}

Although the dependence on V_{RF} and ω_{RF} is weak, this method may be envisaged, particularly on small machines, using active or passive harmonic cavities. A limit of 1 ps is envisaged.

3.4 Bunch rotation

The addition of strong longitudinal focusing with a pulsed Linac-type RF structure in a Storage Ring can give short bunches after bunch rotation (but with a larger energy spread). The advantage in peak brilliance is balanced by a loss in average brilliance since the large repetition rate of the Storage Ring is lost.

3.5 Limitations

Low α values lead to low synchrotron frequencies: the sensitivity to RF noise is increased. RF power supplies will have to be designed very carefully. Also when reducing α, at some point one might have to minimize the value of α_2.

4 CURRENT LIMITATIONS

The intensity in the multibunch mode of operation used for the highest average brilliance is limited by the Higher Order Modes of RF cavities. These modes will excite coupled bunch instabilities: longitudinally, the increase of the momentum spread is detrimental to the brilliance[9], transversally, the instability can lead to beam losses. Various solutions to push the instability threshold have been successfully experienced:

- Shifting the modes to avoid interaction with the bunch spectrum. Thermal control of the cavities is, for example, routinely used on several machines (ELETTRA, ESRF,…).
- Parasitic mode dampers (example of the SLAC PEPII cavity): It is a complex task, and it is difficult to combine with the HOM detuning since the damping broadens the resonances, and reduces the spacing between the lines.
- Reducing the number of parasitic modes: superconducting RF cavities are being considered for a number of new projects. This looks like an ideal solution, but its reliability still needs to be proven.
- Feedback (Efficiency demonstrated at the ALS): it is the last solution when the beam interaction with the HOMs cannot be avoided .

In addition tricks such as the introduction of an RF voltage modulation inducing Landau damping of the instability can raise the threshold.

5 INSERTION DEVICES

The brilliance and tunability of insertion devices are now tremendously optimized by the “Spectrum” or “Phase” shimming techniques. The use of higher harmonics extends the range of undulators and relaxes the need for higher electron energies. The present technology is so good that:

- The beam quality is dominated by the electron beam properties (emittance and energy spread),
- The influence of insertion devices on the electron beam is negligible, even for low energy machines (except for beam displacements as a function of gap, for which a compensation is necessary).

The present construction and measurement techniques are considered adequate for the next generation of machines. The main tendencies for the future are:

- the reduction of gaps. Values of 8 mm internal/10 mm external are currently planned.
- the production of polarized radiation [10].

The question of the optimum lattice functions for an insertion device is also debated [11]:

- If the emittance is larger than the diffraction limit, the minimum size on the sample (without focusing) calls for large β values (of the order of the distance from the source to the sample). Focusing the electron beam downstream the beamline could even give smaller spot sizes.
- Minimizing the width of harmonics also calls for a large horizontal β (or small angular divergence).
- If the electron beam emittance approaches the diffraction limit, the spot size becomes independent of the electron optics. The maximum brilliance is then achieved when electron and diffraction emittances are matched. This corresponds to small β values (half the undulator length). This applies to the vertical plane, and when the photon beam is focused on the beamline.

6 LIFETIME

All the goals described in the previous sections are detrimental to lifetime: small emittances, shorter bunches, high currents, small gaps. Touschek lifetime will dominate in all cases (this is already true for low energy machines), and rather short lifetimes can be expected.

The “topping-up” mode of operation might then become attractive: it has implications on the machine (availability of the injector), on safety (injection with beamline shutters open) and on the beamlines (shielding, gating of the experiments). But the constant heat load on the beam lines is crucial for stability. Topping-up may also allow a further reduction of the undulator gaps.

7 CONCLUSIONS

The next generation of SR Storage Rings will reach fundamental limits:

- transversally, emittances will be limited by intrabeam scattering before reaching the diffraction limit.
- longitudinally, the bunch length will reach a minimum value imposed by the environment (vacuum chamber impedance).
- The interaction of the beam with the Higher Order Modes of RF cavities limits the beam intensity. Superconducting cavities and feedback systems are expected to give solutions.

- The Touschek effect will limit the lifetime to rather small values.

However, a significant increase in performance above "upgraded" 3rd generation machines will bring the Storage Ring performance, in terms of average brilliance, at a level comparable to the expectations from linac driven FEL projects:

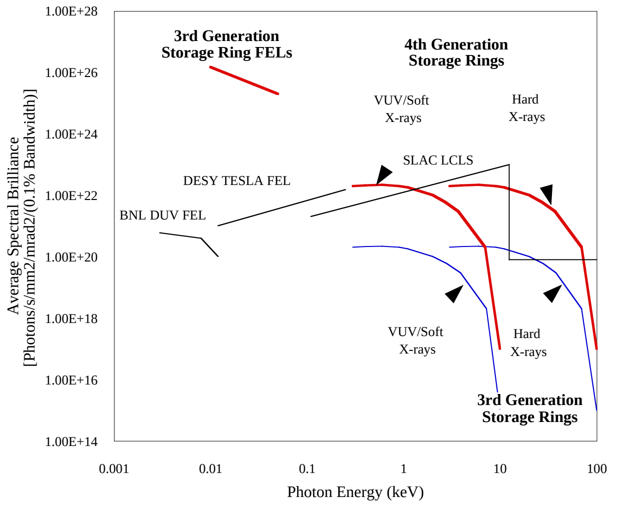

Fig. 3: Average brilliance

Storage Rings will maintain the advantage at photon energies above 10 keV (limit of the SASE mode). At low energies, Storage Ring driven FELs benefit from the high repetition rate of a Storage Ring in order to reach the highest brilliance.

Storage Rings also benefit from a long experience, compared to ambitious Linac projects. On the other hand, for peak brilliance and bunch length, Linac sources are unbeatable.

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