Critical review of Target Specifications for Third Generation Synchrotron Radiation Light Sources

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Abstract

Subsequent to the early operating experience of the ESRF [1] and to the conclusions of a workshop attended by representatives of all European storage ring based synchrotron radiation light sources [2], a critical review is made of the target specifications for the third generation light sources. Major themes include: figures of merit; storage ring lattices including sensitivity to errors, achievement of low emittances, and beam centre of mass position stability; advanced techniques for insertion devices; current limits; beam lifetime; injector aspects including electrons versus positrons. We will discuss whether the users of a source of such unprecedented quality are ready to make full use of the excellent beam made available. Following this review, an attempt will be made to derive a realistic set of target performances for storage ring machines of the next generation.

1. FIGURE OF MERIT

In the aim of being able to compare different synchrotron radiation sources, it is essential to search for a figure of merit applicable to all types of sources from VUV to hard X-rays and to all types of experiments.

For certain experiments, flux could be a good candidate for such a quantity of interest . However, Brilliance is the figure of merit the most referred to, in particular for the most modern machines of the third generation.

Brilliance is defined by the following formula :

$$B = \frac{d^6 n}{d\Omega \; dS \; \frac{d\lambda}{\lambda} \; dt}$$

usually expressed in units of number of photons/sec/mrad^2/mm^2/0.1% of the relative photon energy bandwidth, and in which S is the source area.

It can also be expressed in terms of electron beam and insertion device parameters :

$$B \sim \frac{I}{\kappa \varepsilon_x^2} \; f(g, E, B_{ID}, \text{etc...})$$

in which

I = electron beam current $\quad \kappa = \frac{\varepsilon_z}{\varepsilon_x}$ = coupling factor

ε_x = horizontal emittance $\quad$ E = electron beam energy

g, B_{ID} = gap and magnetic field of the Insertion Device

In the above units, the performance of the third generation sources is situated in the 10^{19} range, 4 orders of magnitude higher than the second generation ones, and 11 orders of magnitude above most modern rotating anode X-ray tubes.

High Brilliance implies an intense beam of photons (and consequently of electrons) confined within small transverse emittances. If one adds the usual additional request for very short bunches to satisfy experiments using the time structure of the radiation, then the longitudinal emittance has to be small as well. This means that all conditions are united for beam instabilities to develop and for lifetime to be limited by Touschek intra-beam scattering. The inherent contradiction "high Brilliance versus beam stability and long lifetime" is a real dilemma for low energy machines. Therefore, a relatively high energy of the storage ring is necessary to overcome these conflicting aspects.

2. LATTICES - BEAM POSITION STABILITY

All the machines of the third generation aim at gaining several orders of magnitude in Brilliance compared to second generation ones, mainly by lowering the beam emittance in the few to several nanometer range (1 to 6 nm).

A few years ago, it was feared that these new lattices for third generation Light Sources would be extremely sensitive to errors, due to the high focusing required to obtain a low emittance and the necessity to compensate for the subsequently large chromaticity. Consequently these new machines were reputed to be very difficult to commission and possibly unable to achieve the target performances.

The successful commissioning of several low emittance machines (ESRF, SRRC, ALS, ELETTRA) [3][4][5], and the rapid obtention of emittances close to specifications, demonstrate that the tools and strategies for optimizing these lattices were fully adequate. This is very encouraging for the projects now under design for machines of the third generation. This also leads us to believe that the same tools and strategies are ready to be applied to the design and construction of machines with even smaller emittances.

Stability of the X-ray beam in position and angle to better than 10 % of beam size and divergence constituted a key issue for high brilliance Light Sources. Routinely achieved stabilities with figures significantly below the specified 10 % have been reported for some sources, even those located in an urban environment. Accordingly, the evaluation which has been made of a series of new adverse effects (ground settlement, temperature effects, amplification of vibrations,...) and the tèchnical solutions that have been adopted to combat them, appear to be completely adequate.

Successful feasibility tests of a stability in the 1 % of the beam size range have been performed on the ESRF machine using fast feedback systems.(i.e. stability figures 10 times better than initially required and therefore compatible with significantly smaller emittances).

The ESRF design goal for emittances was $\varepsilon_x = 6\ 10^{-9}$ horizontally , and one tenth of that, $\varepsilon_z = 6\ 10^{-10}$ vertically. The achieved stability with feedback would be compatible with a figure such as $\varepsilon_z = 6\ 10^{-12}$ vertically and a few times this value horizontally. which would lead to a factor of several 10^4 in brilliance, if the current were to be maintained at the same level.

At the ESRF, we will use this better than required stability to lower the coupling factor from 10% to 1%. In addition, we will change the lattice working point to gain a factor of 2 on the horizontal emittance, which, combined with the gain on the coupling factor, would lead to a factor of ~ 40 on the brilliance (ie $\varepsilon_x = 3.5\ 10^{-9}$, $\varepsilon_z = 7\ 10^{-11}$)[6].

Even with this upgrading, we will still be a long way from what could be ultimately asked for, ie to reach the diffraction limit at 12 keV (λ = 1 Å), our central photon energy. This would correspond to a horizontal emittance of

$$\varepsilon_x = \frac{\lambda}{4\pi} \sim 8\ 10^{-12}$$

Going this far should be considered as a long way off although from the stability point of view, current state of the art techniques look almost adequate.

To sum up, in the light of our early experience with 3rd generation machine behaviour and the achieved stability, there is no particular reason not to believe that the present ring design tools and technology could not allow both transverse emittance to be pushed down by one further order of magnitude ($\varepsilon_x = 6\ 10^{-10}$, $\varepsilon_z = 6\ 10^{-11}$). A large circumference of the ring is necessary to accommodate the large number of dipoles. This would lead to a gain of up to 2 orders of magnitude in photon Brilliance provided the longitudinal emittance remains untouched.

3. INSERTION DEVICES

In parallel with the evolution of the accelerator techniques which have been implemented to obtain better electron beams, remarkable progress has also been made in the construction of Insertion Devices, which also have a role to play in the contribution to higher brilliance. Several laboratories have developed state of the art and cost-effective techniques (magnet block sorting, mechanical assembly, shimming) to produce permanent magnet insertion devices within the required, extremely tight, field tolerances.

For high Brilliance, an undulator is the best choice on the low energy side of the photon spectrum while at higher energies, a wiggler is the only choice. The transition between the two types of Insertion Devices depends on the highest useful undulator harmonic. Without special precautions, this transition is between harmonic numbers 5 and 7 of the undulator.

Routine spectrum shimming techniques recently developed at the ESRF have pushed this limit to harmonic number 15 [7]. Clearly, for a given storage ring, this extends to significantly higher energies the high Brilliance from undulators, a performance which would otherwise require either an increase in the energy of the storage ring or a reduction in the undulator gap.

In this respect, the ESRF started with a rather conservative 20 mm minimum Insertion Device gap, but there is no fundamental reason to believe that this figure couldn't have been lowered to 15 mm. We have plans to test even smaller gaps, of the order of 7 mm, with the idea of implementing a few such undulators around the ring, but not to adopt 7 mm as a standard minimum gap. Such values are definitely excluded for low energy machines, because of the adverse consequences on dynamic aperture and lifetime. There is an interesting experience to be tried out in Japan by our SPring-8 colleagues, consisting of placing more than 100 metre of undulators entirely under vacuum.

4. CURRENT LIMITS

For all third generation storage rings, progress by several orders of magnitude in brilliance was based on the decrease in the stored beam emittances. The target currents were set at reasonably high values in line with what had already been achieved on the most advanced machines of the second generation. Higher Order Modes in RF cavities were considered as a major obstacle for reaching higher currents in the multibunch mode of operation.

At the ESRF, with cavities copied from LEP (CERN) and not at all optimized for a Synchrotron Radiation source, simple solutions have been found to nevertheless overcome the predicted HOM limit and go significantly beyond the design current. This demonstrates that contrary to former common belief, machines of the third generation can accommodate rather large HOMs in their RF cavities [8].

A priori, in comparison, low energy machines are more sensitive to HOMs, which justifies R&D programmes on HOM-free cavities, dampers, 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 at the design current have been already recorded at the first low energy machines of the third generation such as ELETTRA, ALS, SRRC .

For the ESRF machine with its stainless steel ID vacuum vessels of small vertical aperture, large positive (and not only slightly positive) chromaticities ξ were necessary to combat the resistive wall instability. Fortunately, the lattice proved to be flexible enough in terms of dynamic acceptance to accommodate very large sextupoles.

Operation at higher currents could be helped by feedback systems similar to those developed for B meson factories. However, the expected gain in Brilliance cannot be exceptional and is likely to be to the detriment of lifetime.

5 LIFETIME AND ION TRAPPING

For high brilliance sources, the heat load on instruments is a key issue for experimentalists. If this can fortunately be solved in dc operation, ie infinite lifetime, or extremely slow decay of the current, given the stabilisation time, this becomes extremely problematic if the lifetime only lasts a couple of hours. In most cases, almost the only solution can be found by increasing the energy of the stored beam. In addition, an energy higher than the minimum required makes the machine less prone to instabilities.

When compared to 2nd generation machines, with their low emittance and high current, third generation machines can produce an unstable over-focusing of light ions. The recent experience of the ESRF is fully in line with these predictions, to the extent that it is presently nearly impossible to provoke ion-related effects even in the most favorable conditions at low current. Preliminary results from ALS tend to support similar conclusions. On the other hand, as reported during this conference, ions are being observed in ELETTRA.

LURE has a long experience with positrons and has had the opportunity on many occasions of comparing them with electrons. It has definitely been demonstrated that both DCI and SuperACO work better with positrons.

Obviously, more experimental data is needed to possibly reach general recommendations for the generation of machines to come although this is a "mere" question of budget and in general, the addition of a positron option to a project has a moderate financial impact.

6 INJECTOR

Ramping the magnets between the injection energy and the operation energy has always been a concern in view of reproducing the beam position after a refill. Accordingly, a safe attitude was to build a full energy injector and run the storage ring totally dc. Nevertheless, preliminary results from the first third generation storage rings indicate good to excellent results on beam position reproducibility. Therefore, from this point of view, the necessity of having a full energy injector could possibly be reconsidered.

On the other hand, in order to compensate for a short lifetime resulting from Touschek scattering or operation with minigaps for instance, it is being suggested by our American colleagues from APS, Argonne, to continuously top up the current by an almost permanent injection. This involves practical problems mainly related with personnel radiation safety that will require finding satisfactory solutions before this idea can be realistically implemented : presently, it is required to close the experimental beam line shutters during injection. However, the time might have come to thoroughly test this concept. Experiments are currently planned at the ESRF.

7 BEAMLINE INSTRUMENTATION

Orders of magnitude in Brilliance have been effectively gained on previous generation machines and synchrotron light beams of unprecedented quality have been made available to the scientific community. Nevertheless, one should keep in mind that with this new generation of sources, the task of beamline builders was at least as challenging as that of machine builders. The relevant question is therefore whether beamline instrumentation has been developed to the point at which it can immediately and fully benefit from these photon beams.

If this was not the case a few years ago, during the past five years there has been exceptional progress made on basic beamline optical elements which can sustain heat load and transmit the beam to the sample without spoiling its characteristics. This is the case for monochromators made of light elements such as diamond, for adaptive mirrors which compensate dynamically for the induced mechanical distortion of the surface, and also for focusing elements such as Bragg-Fresnel lenses, etc...

Therefore, the answer is definitely "yes". Today for most beamlines in their present state at the ESRF, instrumentation can fully benefit from these photon beams. Accordingly, Machine Physicists have a very busy future.

8. CONCLUSION

The global conclusion is that the construction of the third generation light sources is definitely a big success. Most of the challenging target performances initially required have been successfully met and there is still room for some further upgrades. In the light of preliminary experience with the behaviour of these new machines, we are certain that even more brilliant machines can be envisaged, since the existing tools for design appear to be perfectly adequate. In addition, no new mechanism has been found that would prevent us from speculating as to the feasibility of even higher performances.

A further gain of a factor of 10 in both emittances ; $\varepsilon_x = 6\ 10^{-10}$ horizontally , and one tenth of that, $\varepsilon_z = 6\ 10^{11}$ vertically (an even lower coupling factor is not excluded), or 100 in brilliance, is a short term reality, to be incorporated into all new designs, combined with a gain on Insertion Devices. The above step in the direction of higher Brilliance must be successfully reached first. The far objective of diffraction limited machines with emittances in the 8 10^{-12} range, in both planes could be attacked then.

9. REFERENCES

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