LIGHT SOURCE PERFORMANCE ACHIEVEMENTS

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Abstract

More and more third generation light sources (3GLS) have come into operation. All of them were successful in reaching their performances. Some of them, like the ESRF, achieved brilliances up to two orders of magnitude higher than their initial target.

Experience with the operation of existing machines indicates some imperfections and possibilities for new projects to integrate possible corrections in their design. These include : operation at the diffraction limit with even higher brilliances, higher position stability, enhanced Touschek lifetimes with larger momentum acceptances combined with low chromaticity and feedback of coupled bunch transverse resistive wall instability, efficient control of the longitudinal coupled bunch instability, higher currents in single bunch, better signal to noise ratio by localising losses at selected places in the ring and avoiding the emission of high energy bremsthralung photons in the direction of beamlines, possibilities of permanent injection, production of focused photon beams, high quality insertion devices, etc.

1 THIRD GENERATION LIGHT SOURCES WERE A SUCCESS

Third generation light sources were heard of for the first time, almost 20 years ago. In comparison with storage rings of the previous generation, these new rings aimed at gaining a factor of about 10^4 on the brilliance, which became the reference figure of merit with a target in the 10^{18} range. The gain was obtained by optimising the low emittance rings for undulator radiation (rather than for wigglers as was the case for the second generation).

A certain number of problems were feared :

- over sensitivity to magnet errors,
- reduced dynamic aperture due to the necessary large chromaticity sextupoles,
- beamcenter of mass position difficult to stabilise,
- current limitations in multibunch and single bunch
- a short lifetime
- etc…

In fact, the target performances were easily reached and often surpassed. In some cases, brilliances in the 10^{20} range, two orders above initial specifications, were obtained a few years after commissioning.

The exceptional quality of the produced photon beams opened a series of totally new and extremely exciting experimental perspectives and the immediate search for even more speculative performances.
As an example, the availability of coherent X-ray beams was one of the major events for imaging techniques.

2 DIFFRACTION LIMIT

Over the generations, the gain in brilliance was mostly the result of lattices optimised for a lower equilibrium between heating of the particle beam in the horizontal plane by radiation (quantum emission in a dispersive region) and the damping associated with the re-acceleration at the RF location.

$$\varepsilon_H^{3GLS} \approx 3.10^{-9}(m*rad) = 30\varepsilon_H^{2GLS} = 300\varepsilon_H^{1GLS}$$

$$\varepsilon_V^{3GLS} \approx 1.10^{-11}(m*rad) = 300\varepsilon_V^{2GLS} = 3000\varepsilon_V^{1GLS}$$

The relative merits of pure Chasman-Green lattices, Double Bend Achromat, Expanded Chasman-Green, Triple Bend Achromat, Distributed dispersion, damping by Insertion Devices were exhaustively explored. For the most advanced 3GLS. In comparison with the previous generations of rings, we can sketch the gains as follows :

The vertical emittance is now so small that one has to consider the fact that it can compare with the elementary undulator photon beam emittance associated with a single electron :

$$\varepsilon_{RV} \approx \varepsilon_{RH} \approx \lambda / 4$$

When the electron beam emittance is equal to this value, we are used to say that the diffraction limit is reached. If one considers 3 relevant ranges of photon energies : 30 eV in the UV, 1.2 keV in the X-Ray and 12 keV in the hard X-Ray, one gets :

$$\varepsilon_R^{UV} \approx 3.10^{-9}; \varepsilon_R^{X-Rays} \approx .810^{-11}; \varepsilon_R^{hardX-Rays} \approx .810^{-12}$$

The obvious conclusion is that the most advanced 3GLS undulator beams are diffraction limited in both planes for UV beams and at longer wavelengths. They are diffraction limited in the vertical plane only at shorter wavelengths. Based on the present radiation principle in an undulator, the ultimate limit is reached at least in the vertical plane. In other words, it is useless to further decrease the vertical emittance of the electron beam. It will only marginally affect the photon beam emittance.

In the horizontal plane, a factor between 30 and 300 could still be gained for X-Rays and hard X-Rays respectively. Let us notice that for a given ring emittance, the photon beams are more coherent at longer wavelengths.

The photon beam emittance associated with a single electron has a certain orientation in phase space :

$$\beta_R = \frac{L}{4\pi}$$

in which L is the undulator length.

3 MORE HORIZONTAL COHERENCE

Since there is still a possible gain of one or two orders of magnitude, the pending question is whether we can further reduce the horizontal emittance. A lattice expert [1] would suggest to split the dipole magnets in two $\theta_d \Rightarrow \theta_d/2$ while keeping the same radius and consequently to double the number of cells and the circumference in a Chasman-Green structure. A 3 GeV ring emitting in the X-Ray range would then have a circumference of 700 m (nearly the circumference of the ESRF 6 GeV ring). The dispersion in the dipoles and everywhere would be 4 times larger. This would make the sextupoles stronger and the dynamic aperture lower. Heating by radiation would be 4*4=16 times less. Simultaneously, damping time will be 2 times longer due to the longer circumference. The final result is a reduction by a factor 8 (or more generally, a θ_d^3 scaling) for the horizontal emittance. In parallel, the momentum compaction α is divided by 4 and the zero current bunch length is divided by 2. If the vertical emittance is maintained at the diffraction limit by increasing coupling, the reduction of the electron beam volume by 4*2=8 leads to significant intrabeam scattering that makes the reduction of emittance much less effective (3.8 instead of 8). Furthermore, Touschek lifetime is strongly shortened. A second academic case, consists in considering that every straight section (200 m in total out of a 350 m circumference) is filled with damping wigglers ; thus occupying all undulator high brilliance sections. The energy loss per turn in the dipoles will be multiplied by 4. Accordingly, damping time will be 4 times shorter and the emittance 4 times smaller. Intrabeam scattering is less severe than in the previous scenario. However, Touschek lifetime is again dramatically shortened. This second scenario is certainly more suitable for a damping ring than a light source.

The above examples show that the era of gains of 3 orders of magnitude every ten years that we had for the last 30 years, is definitely over. Much less remains to be gained and every tentative to get closer to the diffraction limit will be very expensive. As a consequence, we can predict a saturation of storage ring based light source brilliance in the low 10^{22} range (~100 times the present peak performances) slightly below the diffraction limit in the horizontal plane.

4 POSITION STABILITY IS CRUCIAL

Due to the smaller emittance, stability in the vertical plane is generally more demanding. The typical vertical rms size (divergence) is 5 µm (5 µrad) in the middle of an undulator straight section. It is usually accepted that the beam is stable when the effective size or divergence is less than 110 % of the unperturbed value.

4.1 High frequency vibrations (1 to 100 Hz)

We first assume that the vibration period is short when compared with the data acquisition time. In which case, the effective emittance is obtained from the quadratic sum of the rms size (or divergence) of the unperturbed photon beam and of the rms displacement (or divergence) of the beam center of mass. The tolerable displacement would be 2.3 µm in the suggested example :

$$5^2 + 2.3^2 = (5*1.1)^2$$

With the generally adopted precautions around 3GLS (low cultural noise due to external activity, control of all in-situ sources of vibrations, careful design of girders and slabs, fixation of piping, etc..), such a target can be reached [2]. In addition, the introduction of damping materials and fast feedback can improve the situation. Stability against high frequency vibrations is not the hardest point.

4.2 Low frequency drifts

It is more difficult to prevent the beam center of mass from drifting over the several days necessary for an experiment. Many effects can contribute.

The very basic point is that the measurements and corrections of the orbit assume fixed Beam Position Monitors (BPM). Back to the suggested example, the BPM must be fixed within +/- 0.5 µm over days. This is not trivial. Below, a series of recipes are given.

The concrete tunnel walls have to remain at fixed temperature (inside and outside) even during shutdowns. The inside temperature must be stabilised to +/-0.1°C. The cooling water must be at the temperature of the air of the tunnel and stabilised to +/-0.1°C. The BPM's should be preferably fixed to the girders or the floor of the tunnel and not to the magnets. They should be coupled to a bellow to accommodate longitudinal constraints. It would be wise to fix (+/-0.1°C) their temperature with cooling water. There should be no mechanical constraints on magnets (a sufficient stay clear between the vacuum chamber and the poles of the magnets is recommended), etc.

As of today, we are certain that all 3GLS in operation are not within specifications from this point of view. This challenge is to be faced by forthcoming projects.

5 HIGH BRILLIANCE AT HIGH HARMONICS OF THE UNDULATOR

With the spectrum shimming techniques, undulator field quality would be adequate to cover a large domain of energies between the fundamental and harmonics 13 or 15 with less than a factor 10 reduction of brilliance. Therefore, from this point of view, one could hope to produce high energy undulator photons with a moderate energy of the stored electron beam. However, a large energy spread in the particle beam can make the high harmonics disappear. In other words, the electron bunches must also be dense along the energy axis (5th dimension). Accordingly, all energy widening has to be avoided. The usual sources of widening are coupled bunch longitudinal instabilities in multibunch mode and microwave instability when the ring is filled with a few intense bunches to exploit the pulsed structure of the radiation.

6 COUPLED BUNCH INSTABILITIES

There are some transverse coupled bunch instabilities induced either by the resistivity of the vacuum chamber walls or by some Higher Order Modes (HOM) in the RF cavities. However, they usually happen to be more severe in the longitudinal plane. All sorts of recipes are implemented to increase the threshold current which stands in the several 100’s mA range.

The simplest solution consists in shifting the HOM frequency away from the coupled bunch mode frequency. This can be achieved by fine adjustment of the cavity temperature, or if necessary, by introducing plungers with a view to detune the HOM’s (ESRF, ELETTRA, etc..).

A more elaborated solution consists in designing the cavity with HOM dampers as it was done for the B factories (SLAC, KEK) or Daϕne. In general the impedance of the HOM’s is significantly decreased but the mode is broadened and a feedback is needed to stabilise currents in the 1A range.

At several places, the recipe against coupled bunch instability consists in introducing some sort of Landau damping. It can be an harmonic cavity acting in the bunch lengthening mode (MAX II, ..) and introducing a frequency spread within the bunches. At the ESRF, only 2/3 of the circumference are filled and they make use of the variation of RF voltage at the revolution frequency induced by beam loading, to obtain a spread in synchrotron frequencies of the individual bunches. The same result was obtained by modulating the voltage with an extra RF tuned f_0 (revolution frequency) apart from the fundamental.

The ideal solution would be to have an actual HOM free cavity system. To this end, superconducting cavities were developed at many places (Cornell, B factories, SOLEIL, …). The results look very promising and should allow to go easily beyond the 500 mA level.

To close this paragraph, let us remark that the brilliance is only proportional to the current, and that a large increase in current is not the easy way to obtain more brilliance since it raises other problems such as reliability, power, cooling, etc..

7 HIGHER PEAK BRILLIANCE

At present, light sources are operated for 10 to 20% of the running time in the single bunch or few bunch mode. In general, zero current rms bunch length stands between 15 to 50 ps. There is an excellent scientific case for dynamic studies with very intense and much shorter (1 ps rms or even 100 fs) bunches [3]. We are now trying to increase the bunch density along the time axis (6th dimension). Several approaches were explored during the last few years.

During the 1992 workshop on 4GLS at SSRL [4], many hopes were placed in low emittance lattices and their potential to be pushed further towards the isochronous regime (momentum compaction α very small and even negative), to speculate on very short bunch production. As a matter of fact, the zero current bunch length is given by :

$$\sigma_{l0} \propto \left[\alpha\gamma^3 / \omega_{RF} V_{RF}\right]^{1/2}$$

On existing 3GLS rings, it was possible to retune the expanded Chasman-Green lattices with a view to decrease and change the sign of α. Extensive tests were made principally on ALS, ESRF, Super-ACO, UVSOR, SRRC, … rings. It was possible to achieve α_1 values in the 10^{-6} to 10^{-5} range :

$$dT/T = \alpha_1(\delta E/E) + \alpha_2(\delta E/E)^2$$

The correction of α_2 becomes mandatory in view of maintening a minimum bucket energy acceptance when the linear term α_1 gets smaller and smaller and large deviations in energy are concerned. Three general remarks can be made :

- A low α means a low synchrotron frequency in the few 100’s Hz and a high sensitivity of the beam to noise at these frequencies in the RF system.
- Bunch length measurements in the 1ps range are extremely difficult.

- Bunch widening can qualitatively be detected from the decrease in brilliance of undulator radiation at high harmonics.

Tentative explanations supporting the experiments made at the ESRF can be found in [5].

For positive α values, it was experimentally found that bunch length is in fact independent of α. Above a threshold which corresponds to an extremely low bunch current, the bunch lengthens with the following scaling law :

$$\sigma_l \propto \left[\left(Z_{//} / p \right) I / \omega_{RF} V_{RF} \right]^{1/3}$$

In addition, the bunch widens.

For negative α values, the bunch starts by shortening with increasing current. However, above a threshold (again extremely low in current) a negative mass instability for bunch beams develops and the bunch lengthens. The scaling low is found experimentally to be similar to that measured for positive α values. The other remarkable result is that apparently the widening is larger for negative α values.

From these set of coherent experimental results, one can advance that a small α value positive or negative is not the solution to produce higher peak brilliance. A best performance for a present 3GLS would be a peak current of 1 kA associated with a 10 ps rms bunch length. To meet the 1ps range would require to decrease the impedance $Z_{//}$/p from the present 1 Ω down to 1 m Ω range. Therefore, speculations on isochronous rings were nor founded.

More generally, the single bunch length in a 3GLS ring is an extremely soft function of current, impedance, voltage, etc…[6]. It seems out of question to envisage dramatic evolution of the performances in peak current and peak brilliance. New schemes are to be found.

8 LIFETIME CONSIDERATIONS

There is an obvious difficulty to simultaneously serve and please the different user communities : those who want a very high average brilliance will prefer the multibunch operation. Those who want the maximum time structure will prefer a highly charged single bunch. Depending on the rings, there could be a factor 50 in bunch current between these 2 extreme cases. This means a factor 3.7 in bunch length, a factor 13 in particle density. Obviously Touschek lifetime (that might already dominate the multibunch lifetime) will dramatically increase with the highly charged single bunch to the point that on top of the lower average brilliance, one will have to suffer from the numerous refills imposed by the short lifetime.

In general, for the first set of 3GLS, the energy acceptance of the storage rings was not designed sufficiently large. In this respect, the efforts made by the SLS and SOLEIL projects [7] are remarkable since one can accommodate up to +/- 6% of relative energy deviation within the ring acceptance.

To have a large energy acceptance, one needs obviously to run the ring with a zero chromaticity. Accordingly, transverse

- coupled bunch resistive wall,
- HOM's in cavities,
- Mode coupling in single bunch

have to be corrected by feedback.

9 PERMANENT INJECTION

If one disposes of a full energy injector, the idea was brought (APS, SLS, …[3]) to inject permanently. There is a series of good reasons to consider this proposal very seriously :higher average brilliance,stable heat load on ring components (no discontinuity due to the refill -with closed beamline shutters- and step change of stored current),

- stable heat load on beamline optics,
- compensation of losses due to short lifetime authorising :
  - small dynamic acceptance,
  - small energy acceptance,
  - small physical aperture and ID gaps, etc…

Obviously, this option must be integrated early in the conception phase. It requires a high reliability of the injector (and pre-injector) which becomes a key component as essential as any piece of equipment of the storage ring.

The fact that injection is performed with beamline shutters open, raises a series of new safety related problems.

For the cleanliness of operation, one certainly wants to install collimators all around the ring to localise particle losses at specific locations and avoid a contamination of the ring at unwanted places. Similarly, one would install collimators on the transfer line between the booster and the ring to get sure that only particles in the acceptance would reach the injection septum.

The scheme was tested at several places (ESRF, APS, …) and no major problem was met. Permanent injection must be integrated in the design of all new 3GLS projects.

10 CONCLUSION

The new projects of 3GLS could benefit from the experience gained at facilities already in operation :

- to further push the undulator photon beams closer to the diffraction limit and the ultimate brilliance of 10^{22},

- to get a better position stability and in particular minimise the photon beam center of mass drifts over days to 1/10 of the beam size and divergence,
- to minimise the electron bunch energy widening, so as to extract the highest possible photon energy at harmonics of the undulator for a given electron energy,
- to include at an early stage of their design the possibility to use permanent injection

As far as peak bunch current and rms bunch length, an ambitious objective to be met is 1 kA together 10 ps. For even higher performances, the presently used principles for producing undulator radiation does not seem to be adequate and other schemes such as linac driven FEL's using Self Amplification of Spontaneous Emission (under tests at this moment and reviewed during the conference) are possible candidates.

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