TOWARDS THE ULTIMATE STORAGE RING-BASED LIGHT SOURCE

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Abstract

Present third generation synchrotron light sources reach brilliances in the 10^{20} phot/s/0.1%BW/mm^2/mrad^2. Even if the trend in brilliance increase achieved over the last thirty years is over, a brilliance enhancement by two orders of magnitude can still be envisaged for an X-ray storage ring-based light source. The ESRF approach to a future machine delivering photons in the 0.5 – 500 keV range is presented in this paper. In particular, the choice of the energy, the comparison of circumference increase versus the use of damping wigglers to reach horizontal emittances in the low 10^{-10} m.rad range, the possible lattices and the challenges made to the RF system by a very high stored current are reviewed.

1 MOTIVATION AND OBJECTIVES

The construction and successful operation of the third generation synchrotron light sources has resulted in a significant improvement in the characteristics of the X-ray beams delivered to the Users. Now that these facilities are mature, it is legitimate to try to evaluate what the ultimate performances one can expect from a storage ring-based synchrotron radiation source are. The evaluation of their present performances and some expectations on their possible evolutions have already been reviewed on different occasions and in particular by A Wrulich [1] and in a recent edition of Synchrotron Radiation News, with H Winick as guest editor [2].

There is presently a general motivation towards the development of linac-based X-ray Free Electron Lasers. The X-ray beam properties and operating modes of these SASE-FEL sources will be very different from those of a storage ring source (ultra-short pulses with high peak power and brilliance). These upcoming fourth generation light sources will have the potential to reach very high average and peak brilliances, several orders of magnitude above what the best performing storage ring sources could ever achieve. But a storage ring-based source provides its brilliance and permanent high flux of photons simultaneously to a large number of user beamlines, with no intrinsic limitation to extend the X-ray energy towards very high values (100 keV). As such, storage ring X-ray sources will stay cost effective, irreplaceable tools, which will be well complemented by the new SASE-FEL facilities once the technological challenges required by the latter have been overcome.

From the experience gained at the ESRF, we have started to investigate in detail how a storage ring X-ray source could be designed to provide the best achievable performances. We have deliberately oriented our study to fulfil the present and future requirements of the majority of the ESRF users. The new facility would have to provide, to at least 40 insertion device beamlines, the maximum constant and stable flux of photons, in the 5 - 50 keV range, with an optimum power ratio on the optical components. Starting from the existing third generation light sources, the main parameters that still can be significantly improved are the horizontal emittance and the beam current. A stored beam current of up to 1 A could have been envisaged (similar to what is expected for the e-/e+ colliders). However, considering the small Touschek lifetime, the difficulties to overcome instabilities and the high heat load on the dipole crotch absorbers, a 0.5A current appeared a more realistic target to aim at. Such current can only be achieved with a very large number of bunches. We therefore excluded the few bunch modes of operation from the scope of our study, which eases the impedance requirements on the vacuum vessel. To further minimise the heat load, the field in the bending magnets was set to a low value (< 0.6 T), which renders them unattractive as radiation sources. In order to keep within a realistic budget envelope, the circumference of the ring was constrained not to exceed 2 km.

The arguments that will be presented below summarise the preliminary outcomes of the study work of an Ultimate Storage Ring Light Source (USRLS) performed by the ESRF Machine group and started a few months ago.

2 DESIGN PARAMETERS

2.1 Undulator technology, electron energy

The selection of the electron energy is deeply related to the spectrum to be covered and to the insertion device technology. The spectrum range is that of the ESRF: 0.5 - 500 keV with a peak around 12 keV. For an optimum performance of the undulators, we want to cover the 5 - 50 keV range with harmonics 1-5 and a K = 2.2 undulator. Assuming a minimum gap of 11 mm, this results in electron energy around 7 GeV. Some in-vacuum undulators with gaps as low as 4 mm will cover the need for undulator radiation of higher energy. Note that 1 GeV lower electron energy could have been selected with a more systematic use of in-vacuum undulators, but lifetime and beam stability considerations are pushing for a higher electron energy. To maintain the size of the ring within 2 km and simplify the design of fixed gap vacuum chambers, the useful undulator length has been limited to 7 m.

2.2 Emittances and beta functions in the IDs

A major issue is the heat load on the optical components in the beamline. It is assumed that almost all beamlines will use an undulator source. The undulator radiation is first collimated by some slits to reduce the power while letting the flux in the narrow central cone go through. To minimise the transmitted power without reducing the flux, the lattice is optimised to provide minimum sizes (σ_x, σ_z) of the radiation at the slit location. Clearly, a reduction of these sizes allows the closing of the slit and a corresponding reduction of the transmitted power to be dissipated in the cryogenically cooled Si crystal or in the diamond crystal. Due to the natural small vertical emittance, the vertical size is limited by the single electron emission $\sigma_z \cong d\left(\dfrac{\lambda}{2L}\right)^{1/2}$ where L is the undulator length, λ the radiation wavelength and d the distance between the undulator and the slit. The horizontal size is the convolution of the electron beam contribution and the single electron emission $\sigma_x \cong \left[\varepsilon_x(\beta_x + \dfrac{d^2}{\beta_x}) + d^2\dfrac{\lambda}{2L}\right]^{1/2}$, where ε_x and β_x are the horizontal emittance and beta function. The minimisation of σ_x calls for $\beta_x \approx d$ and for a small emittance ε_x. For emittances smaller than $\varepsilon_0 = \dfrac{\lambda d}{4L}$, the beam size σ_x is close to the minimum value $\sigma_x \cong d\left(\dfrac{\lambda}{2L}\right)^{1/2}$. A further reduction in the emittance would not benefit the heat load issue but would still allow the refocusing of the radiation to a smaller size. The ultimate limit is the diffraction limit $\varepsilon_1 = \dfrac{\lambda}{4\pi}$. A typical value for ε_0 is ε_0 = 0.18 nm (assuming d = 50 m, L = 7 m, λ = 1 Å). This explains our objective to achieve ε_x = 0.2 nm with β_x = 50 m. In the vertical plane, the beta function is optimised with the criteria of minimising the scraping in the narrow gap undulators, i.e. $\beta_z = \dfrac{L}{2} = 3.5m$. In order to have diffraction limited radiation for any wavelength λ > 1 Å, it is sufficient to reduce the vertical emittance to 8 pm. This corresponds to a conservative 2.7 % coupling. Smaller values would further enhance the Touschek lifetime reduction.

2.3 Characteristics of the radiation

Table 1 presents the total power, the power in the central cone (defined as the power integrated over an aperture of $4\sigma_x * 4\sigma_z$ in which 90% of the flux is collected) and the brilliance at 1 Å computed for an in-air and an in-vacuum undulator compared to those from the best ESRF and SPRING8 undulators.

It is interesting to note that the 2 orders of magnitude gain in brilliance are reached with a very small increase of the power in the central cone. The selected current of 500 mA and undulator length of 7 m is set by the requirement of keeping the power in the central cone reasonable . The present value of 0.65 kW is 30% higher than what has been achieved so far by cryogenic Si crystals [3]. Improving the cooling of the monochromator, one could accept a higher power and achieve a higher brilliance with either a higher current or a longer length of undulator. In this exercise, we assumed that the crystal is placed at a sufficient distance from the source for the power density to be low enough and compatible with engineering requirements.

Table 1: Comparison of power and brilliance from undulators on ESRF, SPRING8 and USRLS

	ESRF	SPRING-8	USRLS	USRLS
Energy [GeV]	6	8	7	7
Current [A]	0.2	0.1	0.5	0.5
Und. Period. [mm]	34	32	33	20
Und. Length [m]	5	25	7	7
Und. Gap [mm]	11	12	11	6
Power [kW]	13	38	53	55
P. Cone [kW]	0.4	1.5	0.65	1.1
$4\sigma_x * 4\sigma_z$ [mm^2]	2 x 0 .5	3.8 x 0.5	1 x 0.8	2 x 0.8
Flux @ 1 Å [ph/s/.1%]	2.0 x 10^{15}	9.0 x 10^{15}	6.5 x 10^{15}	1.7 x 10^{16}
Brilliance @ 1 Å [ph/s/.1%/mm^2/mr^2]	2.9 x 10^{20}	6.7 x 10^{20}	1.5 x 10^{22}	3.7 x 10^{22}

Figure 1 presents the brilliance of an in-air and an in-vacuum undulator as a function of photon energy compared with the best result obtained so far at ESRF.

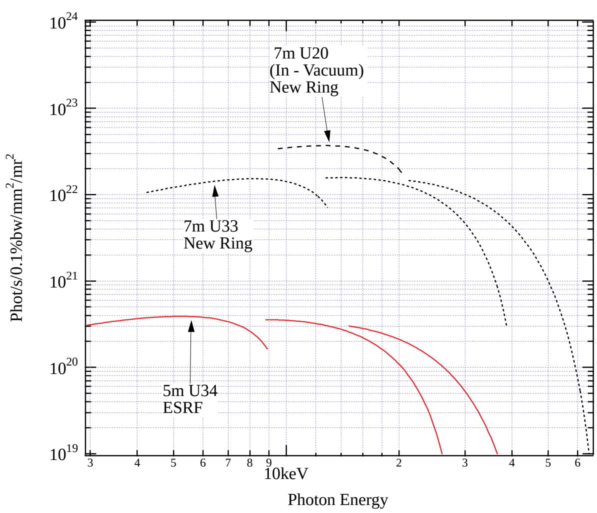

Figure 1: Undulator brilliance on the USRLS compared to the ESRF best achieved figures

3 EVALUATION OF LATTICES

The discussion of key parameters leads to the following specifications for the lattice: 7 GeV ring, horizontal emittance ranging between 0.1 and 0.3 nm, 50 straight sections (40 for ID beamlines and the rest for machine utilities), 10 m long straight sections capable of accommodating 7 m long IDs. The additional constraint of a 2 km circumference is set for budget considerations.

3.1 *Achromat design*

The well-known scaling law $\varepsilon_x = E^2\theta^3 F(lattice)$ dictates the emittance in a synchrotron light source. It shows the dependence on the square of the energy E and the third power of the bending angle θ. F is a weighting factor characterising the chosen optics. Obviously, the choice of 7 GeV energy makes the achievement of an emittance in the 0.1 nm range more challenging.

Since existing high-energy light sources are using DBA lattices, the possibility of extrapolating their performances has been investigated. The theoretical minimum emittance requiring a minimum of the horizontal β-function to occur at 3/8 from the dipole entrance [4] can never be achieved. The symmetry imposed by the achromat build-up is incompatible with this condition. As an example, the minimum emittance of the ESRF operating at 7 GeV would be 8 nm. As shown in Figure 2, operational lattices (ESRF scaled DBA or TBA) cannot fulfil the emittance/number of cells requirement. In the case of the DBA, the additional emittance reduction provided by a distributed dispersion is meaningless: the quantum excitation in insertion devices would take over the damping effect and lead to a dramatic increase in emittance (see Table 2).

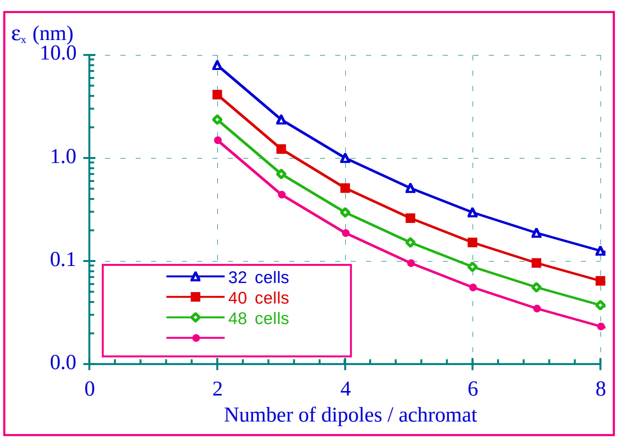

Figure 2: Emittance scaling with the number of cells and of bending magnets

Table 2: Effect of dispersion on horizontal emittance

	zero-dispersion	10 cm dispersion
ε_x with no IDs [nm]	3.96	2.07
ε_x with 40 IDs [nm]	1.98	3.2

These results lead to scenarios with more bending magnets in the achromat. In order to keep the length of the achromat compatible with the overall target circumference whilst fulfilling the emittance goal, structures with 4 magnets per achromat appear adequate. Two examples of such achromats are presently under consideration. The first one is based on FODO cells with a dispersion suppression section (Figure 3, top). The second one is a kind of double DBA structure (Figure 3, bottom). Both types of achromats achieve emittances in the 0.3 nm range. Note that with such small values, optics codes are faced with a precision problem and that the limit of accurate analytical emittance computation is approached. Straight section tuning to the β-functions of the above Section 2 is performed by means of triplet or doublet quadrupoles.

In both cases, the achromat expansion makes the dispersion very small. In order to keep reasonable strengths for the chromaticity correcting sextupoles, the concept of distributed sextupoles with integrating sextupole fields into the focusing elements is being contemplated. However, achieving a reasonable dynamic acceptance with such large sextupoles will be a challenging issue for lattice designers.

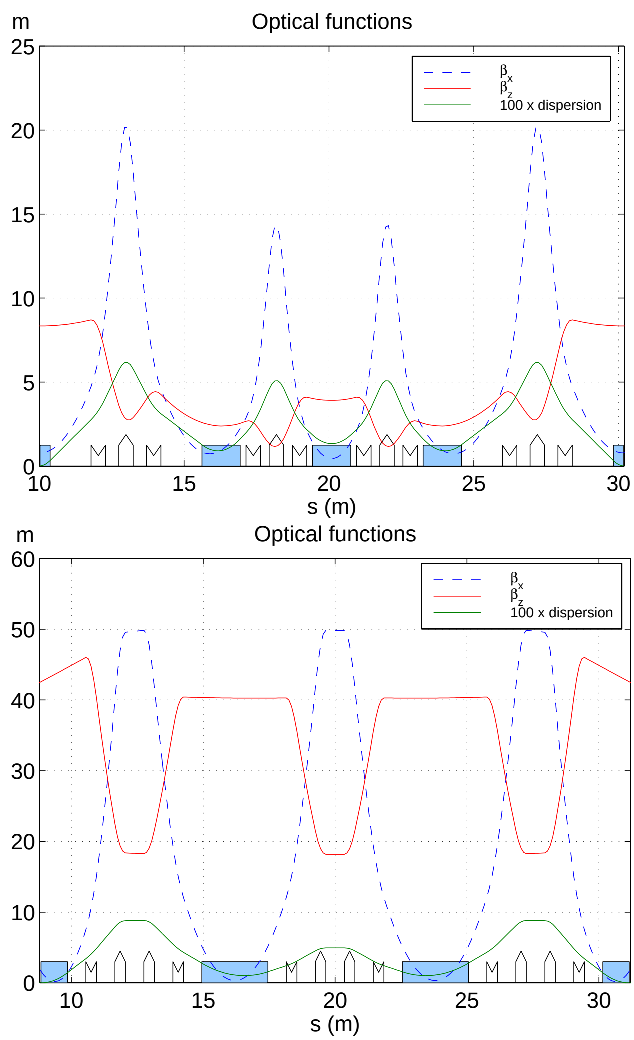

Figure 3: Examples of achromats providing a 0.3 nm emittance at 7 GeV

3.2 *Merits of damping wigglers*

Damping wigglers had been proposed as a means of reducing the emittance of a light source [5], [1]. In the case of the ultimate storage ring-based light source, a gain by a factor of 2 would allow the design of the 4-dipole achromat to be relaxed or the number of dipoles to be reduced to 3 and then the circumference decreased.

The required parameters of the 7 m long damping wigglers (75 mm period, 1.75 T field) bring them at the limit of in-air technology. As shown in Figure 4, at least 10 of these devices would be necessary to provide the expected emittance reduction. In addition, the energy loss would be doubled, thus requiring the number of straight sections for the RF system (Section 4.1) to be doubled. The detrimental effects of damping wigglers (unavailable straight sections, high power (1.2 MW) to be handled, ID technology) exceed by far the added value. Therefore, the use of damping wigglers is not included in the design.

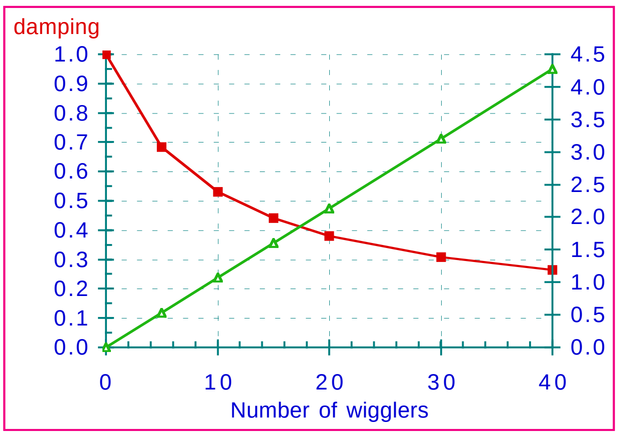

Figure 4: Effects of damping wigglers on emittance and on energy loss per turn increase

3.3 *Effects of Insertion Devices*

On a future storage ring, Insertion Devices will strongly influence the beam parameters since they will contribute significantly to the total radiated power, specially given the trend towards an increased bending radius in order to minimise radiation losses.

For the proposed lattices, the energy loss per turn arising from the standard undulators will be equal or larger than the one arising from the dipoles. The effect is highlighted for standard U33 undulators in Table 3.

Table 3: Effect of U33 undulators on the beam

	Bare lattice	140 m U33	280 m U33
Energy loss [MeV/turn]	4.3	7	9.9
Energy spread	9.1 10^{-4}	9.6 10^{-4}	9.7 10^{-4}
Emittance [nm]	0.30	0.19	0.13

The use of the standard undulators will be sufficient to damp the beam emittance by at least a factor of two. However, as experience has shown that it will take several years to install Insertion Devices after the machine has been built, the lattice should be designed in order to achieve the required emittances without counting on the ID effect. In order to maintain the design emittance whatever the gap movements, a slight dispersion could be introduced in the straight sections.

3.4 *Focusing in straight sections*

The main machine parameters have been optimised to provide the highest brilliance around 12 keV, using 7 m long typical undulators, with a gap of 11 mm. Higher energies can be provided by using smaller gaps. In such a case the vertical β-function must be reduced to keep the same vertical acceptance, and one has to reduce the length of the insertion device accordingly to keep the optimum tuning of $\beta_z = \frac{L}{2}$. The best use of the straight sections can then be achieved by designing an alternate tuning. An additional triplet in the middle of the straight section provides two locations with β_z = 1 m instead of 3.5 m. Such a straight section can accommodate two in-vacuum undulators, 2 m long each. The gap of 5.9 mm results in the same vertical acceptance as a standard 7 m long undulator with 11 mm gap (see Figure 5).

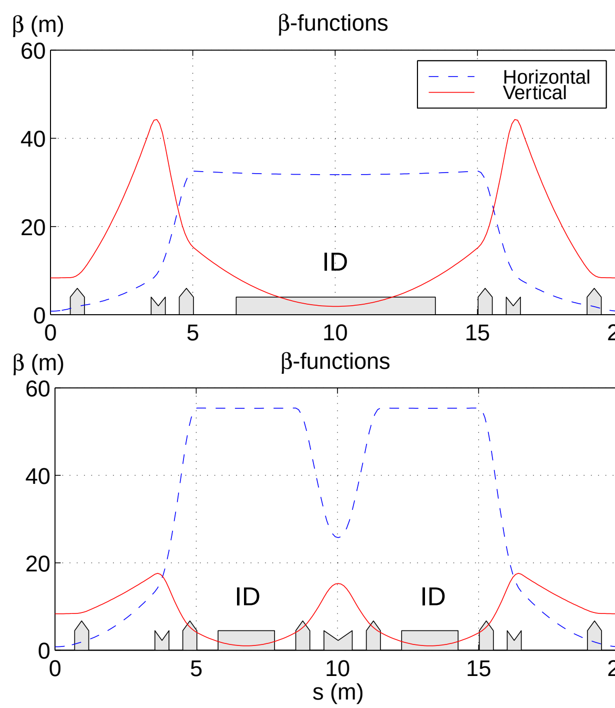

Figure 5: Examples of different vertical focusing solutions in the straight section

4 OTHER CONSIDERATIONS

4.1 *RF System and Instabilities*

Longitudinal and transverse multibunch instabilities must be fully damped as they would spoil the brilliance gained from the low emittance lattice. Even if feedbacks are considered, a moderate gain is required to limit the noise injected into the beam. Therefore, the growth rates of HOM driven oscillations must be minimised by using strongly HOM damped cavities like the superconducting CESR or KEKB cavities [6] or the superconducting cavity designed for SOLEIL [7]. With the lattices of

Section 3 exhibiting a large β_x = 50 m in the straight sections, one 2-cell SOLEIL cavity yields worst longitudinal and transverse instability thresholds of about 100 A and 1 A, respectively. As discussed further below, six such cavities are required to store 500 mA and, for zero chromaticity, the worst remaining transverse HOM could then lead to a 150 mA instability threshold. A transverse feedback should therefore be implemented to damp this instability.

Table 4: RF parameters for a typical lattice, using 6 superconducting SOLEIL 2-cell cavities at 352.2 MHz, I_{beam}=0.5 A, for $\Delta p/p_{RF}$ = 4.5 %

	U_0 [MeV]	V_{RF} [MV]	V/cell [MV]	P/cell [kW]	Q_{ext} (match)
No ID	4.3	7.2	0.6	181	$2\ 10^4$
280 m U33	9.9	13.4	1.1	413	$3.3\ 10^4$

Table 4 illustrates a possible RF acceleration scheme using 6 HOM damped superconducting SOLEIL cavities:

1. Depending on the number of IDs in operation, the energy loss per turn varie**s** by more than a factor 2.
2. As a consequence, the required RF working point (voltage, power and optimum coupling) varies a lot with the user's ID gap settings.
3. At high current it is not the voltage (maximum 2.5 MV/cell for SOLEIL) but the input RF power that imposes the number of cavities to be installed.
4. The input RF coupler is therefore an important issue for such a machine: in this example it should transmit up to 0.5 MW. Two couplers could also be mounted per cell in order to divide the maximum power by 2.
5. One should envisage adapting the coupling factor dynamically in order to adapt the RF working point to the varying beam loading.

Including all intermediate vessels, it should be possible to install four accelerating cells, equivalent to two SOLEIL cavities per 10 m straight section, thereby using a total of 3 straight sections for RF acceleration.

4.2 Lifetime, topping up

Despite the 7 GeV energy, the Touschek lifetime will be the dominant contribution to the beam lifetime, due to the very high bunch density resulting from the very small transverse dimensions. The lattice design will have a determinant influence on Touschek lifetime via the modulation of beam sizes along the machine and the momentum acceptance. For instance the DBA type achromat provides significantly larger Touschek lifetimes than the FODO type thanks to its large βs (more than a factor of 2 for a RF acceptance of 4.5 %). Operating the ring at zero chromaticity will be mandatory for achieving large momentum acceptances. This dictates the choice of vacuum vessel material (copper or aluminium) to minimise the resistive wall impedance and probably requires the use of transverse feedback systems. However the more demanding effort will be the optimisation of the sextupole scheme for obtaining a large momentum acceptance. For the time being, anticipating a 2 % momentum acceptance seems really challenging, given the experience of present machines running with much smaller sextupoles. With the resulting Touschek lifetime (less than 10 h in the best case), frequent re-injections will be necessary to ensure the required thermal stability on both the ring and beamline components. Keeping the stored current within 10 % of its initial value will impose a topping-up (injection with open front-end shutters) every hour.

4.3 Injector

These frequent refills imply having a full energy and reliable injector able to deliver reproducible high quality beam. In addition, if the storage ring does not operate in few bunch mode, the injector could be designed so as to deliver time structured X-rays to some users, but this would require that it be designed with characteristics comparable to those of the present ESRF storage ring.

5 CONCLUSIONS

We have figured out what could be the ultimate performances of a Storage Ring hard X-ray source, and the most promising directions to be followed: a 7 GeV, 50 cell, 2 km long storage ring could achieve a 0.3 nm horizontal emittance. With a 0.5 A stored current, the 7 m long undulators would produce X-rays in the 5 - 50 keV with a brilliance larger than 10^{22}, i.e. 2 orders of magnitude above the present high-energy facilities.

There are however still some open questions such as the lattice optimisation to provide large energy acceptance (which may require a specific magnet design), the design of the vacuum vessel to minimise its impedance to the beam, the layout of the crotch absorbers and of the front-ends which will have to handle the tremendous beam power, the means to provide the required beam stability,.. We will work on these topics in the months to come.

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