PROSPECTS FOR A LONG-TERM LATTICE UPGRADE AT THE ESRF

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Abstract

Twelve years after commissioning, the ESRF routinely delivers X-rays 100 times more brilliant than the design target, to 45 beamlines. Further long-term improvements to the storage ring performance concern the reduction of the horizontal emittance leading to an increase in the brilliance and/or an increase in the number of beamlines from insertion device source points. In this paper, we review the different scenarios that can be envisaged while keeping the existing tunnel and beamlines untouched. Among them the concept of the Double DBA structure, which combines the reduction of emittance (a factor of 8) and the increase of the number of straight sections (64 instead of 32), looks very challenging. Some of the challenging issues of the different scenarios (squeezed space between magnets, innovative combined function magnets of unprecedented small aperture, small dynamic aperture…) will be discussed.

INTRODUCTION

The present optics of the ESRF storage ring provides an effective horizontal emittance of 4 nm and a coupling of 0.7 %. This is achieved by allowing dispersion in the 32 straight sections of a Double Bend Achromat (DBA) lattice. Lifetimes of 80 hours are obtained with a stored current of 200 mA in the uniform filling mode. Brilliances in the $4x10^{20}$ photons/s//0.1BW/mm^2/mrad^2 are currently achieved with two in-vacuum undulators operated at a gap of 6 mm.

Further upgrades of the X-ray source over the next ten to twenty years may include an increased beam current requiring new cavities and new lattice configuration providing decreased horizontal emittance and/or an increased number of insertion device source points.

A 2 km ring had recently been proposed to fulfil these requirements [1]. A much lower cost and more realistic alternative involving the replacement of the storage ring by a new ring located in the existing tunnel is being investigated. The goal would be to gain at least a factor of 10 in brilliance by combining an increase in current and the reduction in emittance.

Some scenarios that can be envisaged and their technical difficulties are presented.

MAGNET DESIGN ISSUES

Indeed the boundary condition of keeping the new machine within the given perimeter imposes severe constraints since the increased focusing required to achieve smaller emittances implies a large number of stronger and therefore longer quadrupoles. Large sextupole strengths are induced by the higher chromaticities and the reduced dispersion in the achromat. A number of technically challenging magnet design issues have been identified for such new lattices:

i) Smaller bore radii than the existing ESRF quadrupoles are considered (16 mm instead of 32 mm) in order to achieve high gradients (values of the order of 50 T/m are contemplated). Beam stay-clear requirements are imposed by the injection process, which is based on the same mechanism as presently, using an off-axis injection with either a closed bump or a shared oscillation. Provided a low emittance booster and a first turn orbit control are operated, the required beam stay-clear is compatible with these unprecedented small apertures.

These small apertures, in addition to the beam current increase and the emittance reduction, will have a detrimental impact on the lifetime, imposing the adoption of a continuous topping-up system. It appears at this stage that the existing booster and linac injection system could be kept essentially unmodified while operating in topping-up mode.

ii) Using the concept of combined-function magnets in order to add a significant sextupolar component to the quadrupolar field. This looks like an attractive solution for coping with the anticipated space limitation. A preliminary design of such magnets has been produced [2]. Figure 1 shows the maximum achievable sextupolar component G6, as a function of the gradient G4. It can be seen that in the intermediate part of the curve ($35 \leq G4 \leq 42$), a small reduction of the gradient enables a significant increase of the sextupolar component.

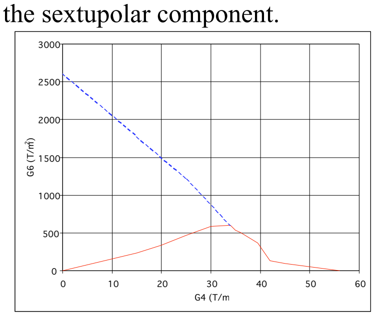

Figure 1: Achievable G6/ G4 for a bore radius of 16 mm

iii) Design of a bending magnet with longitudinal and / or transverse gradient

INCREASING THE NUMBER OF INSERTION DEVICE BEAMLINES

Double Bend Achromat

The easiest way to increase the number of straight sections for beamlines within the given perimeter consists in redistributing the magnets within each cell by drifting apart the two focusing quadrupoles in the achromat of the present DBA in order to create new straight sections for insertion devices. A total of 64 IDs of about 3 m in length could be made available. Such a concept has already been applied to light sources [3]. It presents a minimum of technical challenges since it re-uses proven operational lattice schemes without pushing any components to the limit. Figure 2 shows the lattice functions.

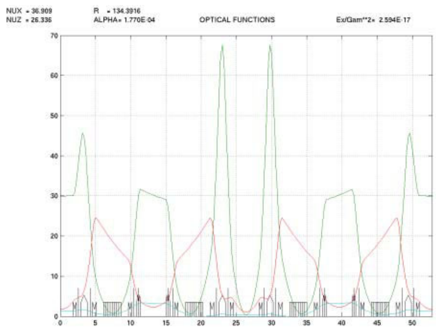

Figure 2: Lattice functions of a DBA optics with straight sections for IDs in the achromat

The performance of the future ring could be further improved by using gradient bending magnets and thereby decreasing the emittance by about 40 % with respect to the present lattice.

Double DBA structure

A more ambitious and challenging approach consists in doubling the number of ID straight sections while reducing the emittance by a factor of 8. The basic idea consists in starting from the existing DBA lattice, dividing all lengths by a factor of 2 and building a new cell from the two created subsections. An effective emittance is 0.47 nm is obtained. Figure 3 shows the lattice functions.

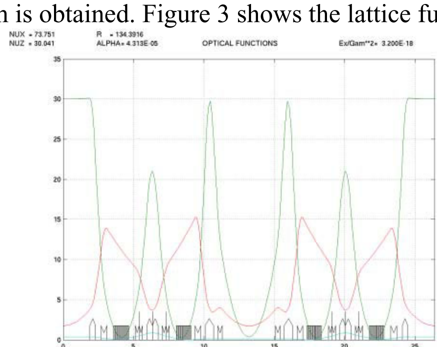

Figure 3: Lattice functions of the double DBA structure

MINIMISING THE HORIZONTAL EMITTANCE

Strategy

The equilibrium emittance can be expressed as:

$$\varepsilon_x = C_q \gamma^2 \frac{\oint \frac{\gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta'_x + \beta_x \eta'^2_x}{\rho^3} ds}{\oint \frac{1}{\rho^2} ds - \oint \frac{[1-2n]\eta_x}{\rho^3} ds}$$

where $C_q = 3.84 \times 10^{-13}$

γ is the machine energy in mass units,

ρ is the bending radius

In the case of an isomagnetic lattice, this expression simplifies and can be scaled as $\varepsilon_x \approx \frac{\gamma^2}{J_x}\left(\frac{2\pi}{N}\right)^3$, showing that the horizontal emittance can be reduced by acting on the damping partition number J_x (while introducing some gradient in the dipoles) or more efficiently by increasing the number N of dipoles in the achromat (going from a Double Bend Achromat to a Triple Bend Achromat or to a four-bend achromat QBA). Table 1 gives the ultimate performances of these lattices for the ESRF.

Lattice type		Number of dipoles	Minimum emittance (nm)
DBA	$\eta_x = 0$	64	3.23
	$\eta_x \neq 0$	64	1.08
TBA	$\theta_2 = 3^{\frac{1}{3}} \theta_1$	96	0.63
QBA	$\theta_2 = 3^{\frac{1}{3}} \theta_1$	128	0.22

Table 1: Comparison of emittances for different lattice types, with $J_x = 1$ and optimum sharing of bending angle between outer (index 1) and inner (index 2) dipoles

Effective emittance and longitudinal field varying dipoles

Minimising the emittance in a DBA lattice necessitates non-zero dispersion in the ID straight section, which results in an enlargement of the beam size through the electron energy spread σ_δ [4]. The brilliance is obtained by replacing the betatron emittance ε_x by the effective emittance $\varepsilon_{eff} = \sqrt{\varepsilon_x{}^2 + H_{ID}\sigma_\delta^2 \varepsilon_x}$, where H_{ID} is the function $H(s) = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta'_x + \beta_x \eta'^2_x$ expressed at the ID location, which is invariant outside the bending magnets. In the particular case of constant field and setting the longitudinal partition number $J_s = 2J_x$, the minimum effective emittance can be expressed as $\varepsilon_{eff} = \frac{0.033 C_q \gamma^2 \theta^3}{J_x}$, i.e. a factor 1.55 higher than the absolute minimum betatron emittance $\varepsilon_x = \frac{1}{4\sqrt{15}} \frac{C_q \gamma^2 \theta^3}{J_x}$. This results in an effective emittance of 1.69 nm for an ESRF DBA (64 dipoles 6 GeV).

An idea, originally proposed by Wrulich [5] and applied to the lattice of SOLEIL [5] and the NLC damping ring [6], is to set the bending field higher where $H(s)$ is lower and vice versa, so as to further minimize the emittance. For a given dipole field model, it is possible to derive the necessary conditions analytically, for which ε_x is minimised. In Figure 4, the minimum betatron emittance is plotted for an ESRF-type DBA lattice and a bending radius following the law $\rho = \frac{(1+as)^m}{b}$, as proposed in [5]. The parameters a and b

can be eliminated by fixing the bending angle to $\pi/32$ and imposing the peak field to be lower than 1.8 T (twice the bending field of the actual ESRF dipoles). The minimum emittance falls rapidly from 1.08 nm for $m = 0$ (constant field) to 0.48 nm for $m > 2$. In particular for $m = 1$, the minimum emittance is equal to 0.54 nm. Raising the maximum bending field and adding a quadrupole gradient can further reduce the emittance. Similarly, minimising the effective emittance under the conditions of a fixed bending angle and a maximum field of 1.8 T gives a minimum effective emittance of 0.8 nm. The quadrupole matching sections still remain to be found, while ensuring the optimum effective emittance.

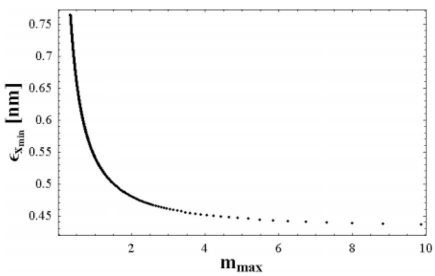

Figure 4:Minimum betatron emittance versus a field parameter, for a model with 64 ESRF type dipoles and a maximum dipole field of 1.8 T

Isomagnetic lattices

The main first-order design difficulty comes from the fact that the optics becomes more and more densely packed due to the additional bending magnets and the subsequent focusing elements. For instance, a large number (32) of short (25 cm) and high gradient (50 T/m) quadrupoles are required in the case of the QBA. These magnets are likely to be at the limit of the technology, more especially as combined quadrupole-sextupole magnets with high sextupolar components are required.

For the TBA optics, the constraints put on the magnet and vacuum chamber design look less unrealistic. However the design of the crotch absorber will require an innovative concept due the space available at the exit of the dipole (30 to 40 cm). Since drift spaces between magnets will only be in the 20 cm range, interferences between the magnetic fields of the different magnets will have to be carefully monitored. Gradients of 50 T/m are also necessary as for the QBA but with magnets of reasonable length (60 cm). Very small values of β_x and η are required at the symmetry point (β_x = 26.5 cm, η = 7 mm) to obtain the minimum emittance for a 2π /32 bending angle / cell and a bending radius of 25 m. Figure 5 shows the lattice functions of the ideal TBA optics which provides an emittance of 0.63 nm.

It is anticipated that the non-linear dynamics in these super low emittance lattices will be a critical issue. The increasingly lower dispersion (Figure 6) makes the chromaticity sextupoles stronger and stronger and the compensation of their detrimental effects more and more questionable.

For the ideal TBA, the maximum dispersion is reduced by a factor of 10 as compared to to the DBA. This is likely to make the achievement of a reasonable dynamic aperture an impossible challenge. One has therefore to relax the optimum conditions in the inner dipole. In the detuned TBA example, the significant increase of the emittance induced by the increase of the dispersion in the inner dipole can be partly cancelled by using gradient in the dipoles to increase the partition number. With J_x = 1.58, an emittance of 1.1 nm is obtained. The feasibility of the required gradient of 12 T /m needs to be assessed.

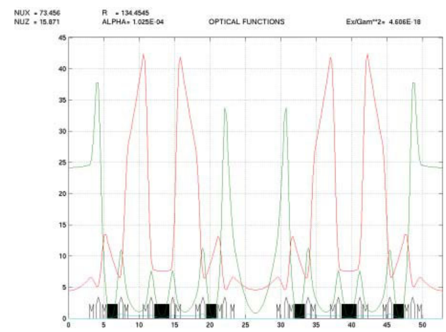

Figure 5: Lattice functions of the ideal TBA optics

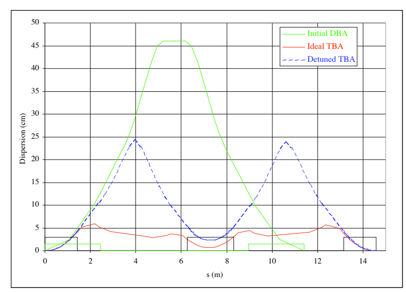

Figure 6: Comparison of dispersion in various achromats

CONCLUSIONS

A number of technological areas will need further R&D work before assessing the feasibility of these new lattice concepts for the ESRF. In particular, the achievement of a reasonable dynamic aperture is likely to be the most critical issue.

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