LATTICE UPGRADE OPTIONS FOR THE ESRF STORAGE RING

Y. Papaphilippou, A. Ropert, P. Elleaume, L. Farvacque, ESRF, Grenoble, France

Abstract

Several scenarios of lattice upgrade for the ESRF storage ring are under study. In order to minimise the cost, their design is based on the length constraints of the existing tunnel with the ID beam-lines kept in place. The goal is to shrink the emittance in order to increase the undulator brilliance. The two main options are a double bend achromat structure with non-uniform field dipoles and a triple bend achromat lattice. The two designs are detailed and compared with respect to their linear optics solutions, correction of chromatic effects and non-linear dynamics. It is also attempted to reveal the horizontal effective emittance dependence on important design parameters, such as optics functions maxima, chromaticity and dynamic aperture. Technological challenges concerning magnet design with small physical aperture in a reduced space are finally addressed.

INTRODUCTION

Reducing the horizontal emittance of the electron beam is essential for achieving more horizontal coherence. A cost effective strategy at the ESRF for reaching this objective is to replace the existing ring by a new ring located in the existing tunnel while keeping untouched the ID source points. By taking into account the enlargement of the beam size due to the electron energy spread in the case of a finite dispersion at the ID source point, the target goal is to achieve an effective emittance in the 1 nm range for the 6 GeV, 32 cells, 844 m circumference new ring. When considering iso-magnetic lattices, the Double Bend Achromat (DBA) lattice with distributed dispersion is disregarded due to the fact that the minimum effective emittance cannot be smaller than 1.69 nm. Thanks to the cubic dependence of the emittance on the number of dipoles in the achromat, an emittance of 0.63 nm can be achieved with a Triple Bend Achromat (TBA) lattice. Another option would be to use a Double Variable Bend (DVB) structure by incorporating dipoles with variable fields along the beam path so as to further reduce the emittance [1, 2, 3]. In this paper, the two options will be reviewed within the stringent space constraints imposed by the existing tunnel, the magnetic design challenges and finally, the common beam dynamics difficulties encountered when trying to reach the minimum effective emittance.

LATTICE DESIGN CONSIDERATIONS

The number of dipoles in the ring fixes their effective bending angle, which is equal to $\pi/32$ in the case of the DVB and $\theta_1 = \frac{\pi}{16(2+3^{1/3})}$ is the angle of the first TBA dipole with $2\theta_1 + \theta_2 = \pi/16$. By keeping the total bending magnets length approximately equal to 4.8 m, as for the actual storage ring (SR), the effective bending radius and field are fixed, for an energy of 6 GeV. The bending radius influences the equilibrium energy spread $\sigma_\delta^2 = \frac{C_q \gamma^2}{J_s} \frac{\oint \frac{1}{|\rho_x|^3} ds}{\oint \frac{1}{\rho_x^2} ds}$, which is proportional to $1/\sqrt{\rho_x}$ in an iso-magnetic lattice. As shown in Fig. 1, the energy spread has a direct impact in the flux of the photon beam: the flux in 0.1×0.1 at 30 m of harmonic 3 and 5 are plotted as a function of the energy spread, for different horizontal emittances and typical ESRF undulator parameters. The decrease of the flux with the momentum spread is more pronounced the higher the harmonic and the lower the emittance. We have chosen a target energy spread of 1.3×10^{-3} which causes a moderate reduction of 13% in the flux for harmonic 3 at 1 nm. Fixing the energy spread, has important consequences in the maximum field of the variable bend, and consequently, in the achievable minimum emittance of the DVB, as discussed below.

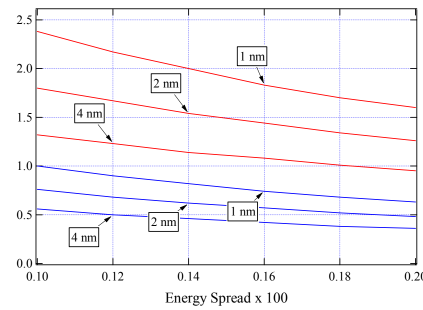

Figure 1: Flux of the photon beam in 0.1×0.1 at 30 m, for the harmonics 3 (red) and 5 (blue) versus the equilibrium energy spread for different horizontal emittances, in an ESRF undulator.

As the interaction points have to be kept intact, the cell length is fixed at 26.4 m. Other important space constraints include the ID drift of around 6 m needed for using the same undulators and a minimum drift space of 0.5 m on either side of the dipole for the absorber. A minimum drift of 0.6 m is imposed on either sides of the quadrupoles, leaving enough space for sextupoles, correctors, diagnostics and vacuum equipment.

In order to employ normal conducting magnets, the maximum gradient of the quadrupoles is fixed at 45 T/m. This can be achieved by reducing the bore radius by a factor of 2 with respect to the actual design. The same constraint is imposed on the integrated field of the sextupoles which should be below 35m^{-2}, in order to avoid saturation [4].

For an ID drift space of 6 m and in order to minimise the vertical losses at the exit of the undulator, the optimal vertical beta function at the ID should be around 2.5 m. The horizontal betas at the IDs keep the actual design (β_x =

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35 m at even ID source points and $\beta_x = 0.5$ m at odd).

The minimum emittance optics conditions at the entrance of the bending magnets imposes a unique horizontal phase advance [5]. It can be demonstrated that a mirror symmetric straight section with initial optics functions β_0, α_0, η_0 and η'_0 has a phase advance for which $\tan(\mu) = \frac{2\eta_0(\beta_0\eta'_0+\alpha_0\eta_0)}{(\beta_0\eta'_0+\alpha_0\eta_0)^2-\eta_0^2}$. For the whole cell, the phase advance depends only on the dipole bending angle and the initial optics functions at its entrance. Indeed, there is a link between the achieved emittance and the cell phase advance. As the optics functions become smaller at the entrance of the dipole, the phase advance becomes higher. For example, the phase advance for achieving the minimum effective emittance of 1.69 nm in the actual ESRF is 293° compared to the actual 205°. The implications of a high phase advance are two-fold: on the one hand, it implies that strong quadrupoles are needed which raise the natural chromaticity; on the other hand, it results in a small dispersion, as $\eta_x(s) \approx \sqrt{\frac{a_c R \beta_x(s)}{\nu_x}}$. The combined effect of low dispersion and increased chromaticity necessitates the use of strong chromatic sextupoles which have a detrimental effect on the dynamic aperture (DA).

Further global optics considerations can be made in a general multiple bend lattice, for reaching the ideal effective emittance, as the four optics functions at the entrance of the dipoles are fixed. In the straight section between the ID and the dipole entrance, there are three constraints that have to be satisfied: two of them imposed by the symmetry point at the ID (optics derivatives should vanish), a third imposed by the fixed beta function at the ID. The dispersion is fixed by the emittance invariance. Hence, considering the drift spaces as parameters, at least three quadrupoles are needed. In the achromat, two constraints are imposed by the symmetry point in the center, thus at least two quadrupoles are needed (one and a half for a completely symmetric cell). Note that this means that there is no control in the vertical plane, but by imposing these conditions, the vertical phase advance is also fixed. Analytic expressions for the quadrupole gradients can be obtained, parameterised with the drift lengths, the initial optics functions and the beta on the IDs. All the optics functions are thus uniquely determined for both planes and can be minimised along with the quad gradients and chromaticity by varying the drifts.

OPTIMISATION OF A TBA LATTICE

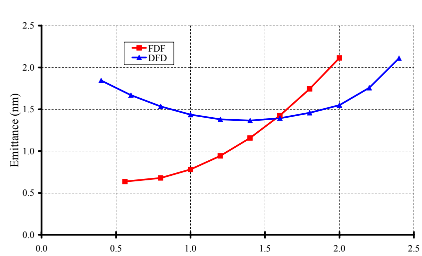

Figure 2: Emittance evolution as a function of the dispersion in the inner dipole.

Despite the fact that a single focusing quadrupole in the achromat is sufficient to shape the dispersion, the required flexibility for adjusting transverse dimensions imposes additional defocusing ones. For both the DBA and the TBA structures, the minimum emittance can only be reached by using the FDF configuration, as opposed to the present DFD structure of the SR. The resulting dispersion in the achromat is very small (5.6 mm in the inner dipole and a maximum of 5 cm). As a consequence, the chromaticity sextupoles are very strong, about 15 times stronger than for the existing lattice. The resulting DA is so small that even with the use of harmonic sextupoles it is impossible to reach a value allowing comfortable injection. Detuning the optimum optics by increasing the dispersion in the inner dipole is therefore mandatory for obtaining a feasible lattice. Fig. 2 shows the resulting increase of the emittance.

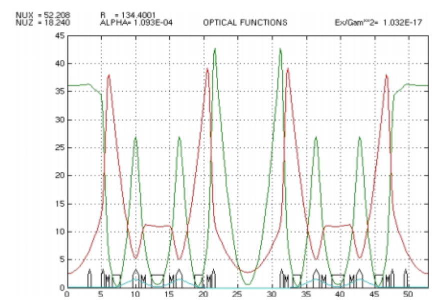

Figure 3: Optical functions of the TBA lattice providing an 1.36 nm emittance.

As the detuning of the achromat does not lead to a significant increase of the maximum dispersion in the FDF configuration, a tuning of the achromat in the DFD configuration has been retained, resulting in an emittance of 1.36 nm and a maximum dispersion of 14 cm. The optical functions providing the required beta functions at the ID source points are shown in Fig. 3. In the achromat, The required phase advance for getting the small emittance drives the choice of the horizontal tune ($Q_x = 52.2$). The vertical tune ($Q_z = 18.24$) is chosen above 16 in order to get smaller β_z and consequently a smaller vertical chromaticity. Seven families of quadrupoles with gradients up to 42 T/m are necessary. Most of them are combined-function magnets providing sextupole components for the correction of the chromaticity and non-linear effects.

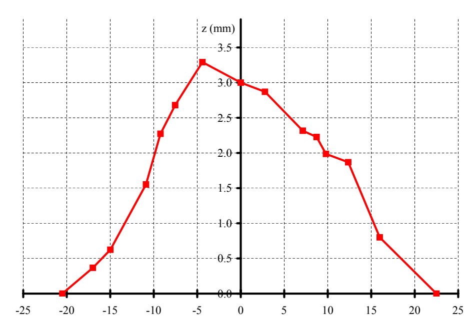

Figure 4: On momentum dynamic aperture of the TBA.

Natural chromaticities are about 70 % larger than for the present ESRF lattice but the much smaller dispersion necessitates chromaticity sextupoles which are up to 4 times larger, resulting in a very small DA. The optimisation of harmonic sextupoles to enlarge the DA while keeping the tune shifts with amplitude small is in progress. The DA currently achieved is shown in Fig. 4.

DOUBLE VARIABLE BEND STRUCTURE

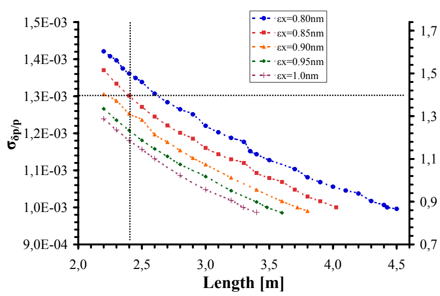

Figure 5: Equilibrium momentum spread (left) and associated maximum dipole field (right) versus the magnet length, for different values of the effective emittance.

The first important consideration for building the DVB structure is the choice of the dipole field profile. Instead of a complicated polynomial profile [1, 2, 3], a simple constant field with three steps was considered as the most feasible solution. Indeed, the actual ESRF dipoles with soft edges follow a two step field profile. It was shown numerically that by fixing the maximum field to 1.7 T, a minimum effective emittance of 0.77 nm can be achieved. Unfortunately, this solution imposes a high energy spread of 1.5×10^{-3}. In fact, raising the maximum field at the entrance of the magnet reduces the emittance but increases the momentum spread, as shown in Fig. 5, where the dependence of the momentum spread and the corresponding maximum bending field are plotted versus the magnet length, for different effective emittances. Thus, in order to achieve a low emittance, the bending field has to be increased, which definitely raises the momentum spread and thereby reduces the flux; otherwise, the magnet has to be much longer thereby decreasing the available space and increasing the beta functions at its exit. In order to have a magnet length almost equal to that at the ESRF (2.4 m) and a momentum spread of 1.3×10^{-3}, the maximum bending field is fixed around 1.4 T, giving a minimum effective emittance of 0.85 nm.

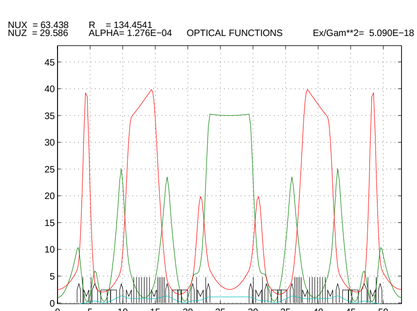

Figure 6: Optics of a DVB lattice giving an effective emittance of 0.96 nm.

The optics was matched for a bending field profile and an effective emittance of 0.96 nm was achieved (0.95 nm in the even and 0.97 nm in the odd ID), with maximum beta values close to the ones of the actual SR. In order to reach such an emittance, the quadrupole gradients have to be pushed to 45 T/m (3 times higher than the actual SR) which results in high phase advances per cell of 357° and 166° (205° and 81° for the SR). At the same time the maximum dispersion is only 0.13 m, 2.5 times lower than the SR. With chromaticities of -169 and -160 (-132, -50 for the SR) the sextupoles have to be pushed to integrated strengths that are 3 times higher than the SR, resulting in a poor DA. In order to keep the chromaticity low, the dipole to quadrupole distance has to be kept at its minimum value of 0.5 m, leaving a large 3 m space in the middle of the achromat, in order to install several sextupoles. Unfortunately, they can only be used to correct vertical chromaticity, as the horizontal beta is quite low in that area. On the other hand, this space can be used for another dipole, showing actually that both TBA and DVB optics solutions converge with each other.

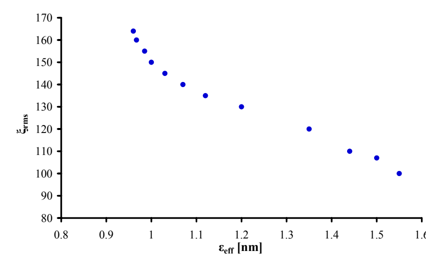

Figure 7: Scaling of the effective emittance with chromaticity.

A more relaxed version of the lattice was designed with an effective emittance of 1.55 nm, and the same chromaticities as that of the actual SR. Even if the dispersion was still 60% of that of the SR, a comfortable DA of more than 30 mm was achieved. In Fig. 7, we show a numerical scaling of the effective emittance with respect to the chromaticity. Indeed, the emittance scales almost linearly with chromaticity. The question which remains to be answered is which is the lowest emittance that can be achieved which leads to a reasonable DA. This preliminary scaling seems to suggest that this emittance may be found around 1.3 nm, as for the TBA. Although top-up could allow a small DA to be coped with, a figure of at least 10 mm (with a small emittance booster) is mandatory for ensuring efficient injection. This major concern is common to the TBA and the DVB lattices and may question their feasibility. In addition, the TBA will have to face a number of challenging technical issues due to a heavily packed structure.

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