A LOW-EMITTANCE LATTICE FOR THE E.S.R.F.

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Abstract

In the framework of its upgrade, the ESRF is looking at a new lattice to replace the present Double-Bend Achromat structure. This new lattice must have the same length and periodicity as the present one and keep the beamline source points unchanged. We will describe our design of an 844 m long lattice based on a 7-bend achromat. It is optimized for minimizing operation costs, in particular the wall-plug power, provides a large dynamic aperture allowing off-axis injection with the present ESRF injector, and gives an horizontal emittance of less than 200 pm at 6 GeV, thus considerably improving the brilliance and transverse coherence of the ESRF.

BASIC PROJECT CONSTRAINTS

The project of a new lattice for the ESRF is part of the Phase II of the ESRF upgrade [1]. Among other points listed in a White Paper produced in November 2012 [2], it has to fulfill the following requirements:

- Reduce the horizontal emittance from 4 nm to less than 200 pm,
- Keep the insertion device (ID) source points in their current locations and maintain the existing bending-magnet beamlines,
- Preserve the present multibunch and time structure operation,
- Keep the injector and injection scheme unchanged,
- Minimize the energy loss, and consequently operation costs.

LINEAR LATTICE

As a consequence of requirement 2 above, the lattice has the following properties:

- Circumference around 844 m
- Energy kept at 6 GeV
- 32 periods. We abandon the alternating high-β (even cells) and low-β (odd cells) straight sections, and move to a 32 superperiods lattice
- Useful straight section length set at 5 m, corresponding to the length of a present standard straight section

We introduced two additional constraints related to the magnet technology:

- The quadrupole strength less than 100 T/m
- The sextupole strength less than 1500 T/m^2

The requirement to minimize the energy loss leads to the minimum dipole field being compatible with the fixed available cell length. However, bending-magnet beam lines require a source point at 0.86 T and another one at around 0.4 T. This sets very specific constraints on the dipoles.

Standard Cell

A common guideline for reducing the horizontal emittance is to increase the number of bending magnets per cell, as shown on the MAX-IV lattice using 7 bends. But it is also well known that this scheme applied to large machines leads to very small bending angles, and so to a very small dispersion. As a consequence, chromaticity correction needs very strong sextupoles, inducing difficulties to achieve a large dynamic aperture. In order to mitigate these difficulties, the ESRF lattice uses a variation of the multi-bend scheme, inspired by the Super-B lattice [3]: starting from a 7-bend lattice, additional space is left between dipoles 1-2 and 6-7, where the β-functions and dispersion are allowed to grow. Chromaticity correction is provided by 2 sextupole families located in these high-β locations, ensuring a high efficiency of the sextupoles. The phase advance between the sextupoles at both ends of the cell is set to 3π in the horizontal plane and π in the vertical plane to get a –I transformation between the sextupoles within each cell, thus eliminating most of the undesirable effects of the sextupoles. This layout, referred to as a Hybrid Multi-Bend lattice (HMB), is illustrated on Fig. 1. The central part of the cell is a standard multi-bend structure, alternating high-gradient bending magnets (dipoles 3, 4, 5) providing the vertical focusing and high-gradient horizontally focusing quadrupoles. The bending magnetic field is set in these magnets at the values requested by the bending-magnet beamlines (0.86 and 0.4 T). At both ends of the cell, we use dipoles with longitudinally varying field, as long as possible to reduce the radiated power. A doublet at each end of the straight section sets the β-values at its centre to 3.6 m vertically (matching the length of the straight section), and 3.6 m horizontally (intermediate between the present values of 37.6 and 0.35 m respectively in high and low-β sections).

Injection

The injection into the new lattice will be done using off-axis injection from the present injector, mostly unchanged. Since the horizontal β in standard cells is only 3.6 m, it is not suited for standard injection. Therefore a special injection cell is foreseen, where the horizontal β-value reaches 17 m. In order to minimize the symmetry breaking, this cell has the same phase advance as the standard cell, and almost the same sextupole configuration. The only difference is the local contribution to the chromaticity. The injection bump is provided by two kickers at π phase advance, with no sextupole inside the bump, which maintains a perfect closure of the bumps during the rise-time and fall-time of the kickers.

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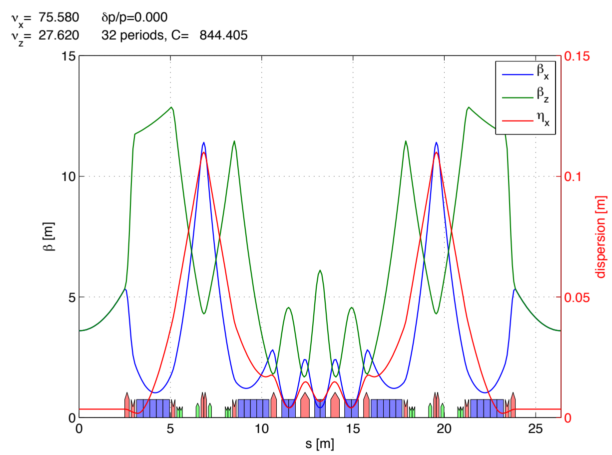


Figure 1: Optical function in the standard cell.

Corrections

The slow orbit correction will be provided by 7 horizontal steerers per cell located in the main dipoles and sextupoles, and 6 vertical steerers per cell, located in quadrupoles and sextupoles. Fast steerers will be combined into the sextupoles. The correction of focusing errors will be done using the individual power supplies of all the quadrupole. Coupling correction will use skew quadrupole correctors in the sextupoles.

NON-LINEAR TUNING

The upgraded ESRF Storage Ring will use the present injector complex (Linac and Booster synchrotron), so the dynamic aperture of the new lattice must accommodate the present off-axis injection scheme.

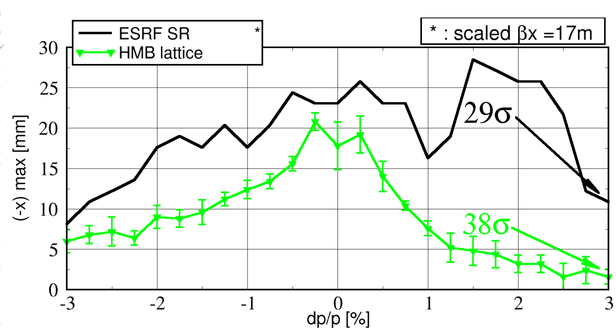


Figure 2: Dynamic aperture of the new lattice compared to the present one.

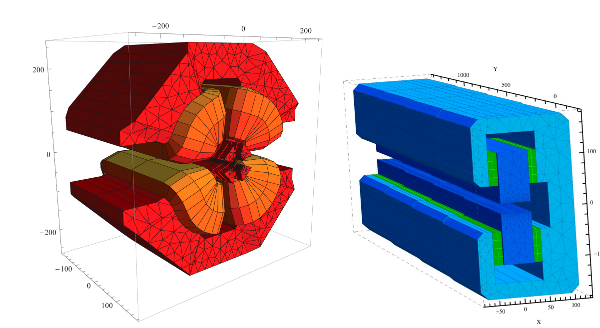
Thanks to the low β-values, the natural chromaticities of the new lattice are comparable to the ones of the present lattice in spite of the much stronger focusing. The sextupole configuration described above provides an efficient chromaticity correction while cancelling most of sextupole perturbations and results in a good dynamic aperture for a perfect machine. However the tune shifts with amplitude are unacceptable. This can be improved by slightly breaking the phase advance condition, and by adding octupoles to the lattice. In addition, we also need an off-momentum aperture large enough to ensure a sufficient Touschek lifetime, as shown on Fig. 2.

MAGNET SYSTEM

The magnet technology represents one of the main challenges in building the new ESRF lattice. The strengths of the quadrupoles range from 55 T/m up to 100 T/m and the bore radius has been set to 11 mm. Massive iron yokes are being investigated to simplify the mechanical design and to fulfill the stringent tolerances (Fig. 3a). The power consumption of these magnets has been optimized to reduce the operation costs. A prototype high-gradient quadrupole magnet is being designed.

The seven dipoles of each cell consist of two families. Three magnets include combined dipole-quadrupole functions (0.34 T and 0.86 T with a transverse gradient of 45-50 T/m). They also build up the source points for the bending magnet beamlines. The study of these magnets will take place in the second part of 2013 with the aim of building a prototype in 2014. The four remaining dipoles include a longitudinally varying field ranging typically from 0.6 T to 0.15 T with a magnetic gap of 22 mm. For these latter magnets, a structure based on high-stability permanent magnet material (Sm_2Co_{17}) is under study (Figure 3b). The 2 m long structure is segmented into 5 similar modules with different amounts of permanent magnet volumes to achieve the longitudinal field gradient. The magnetic yoke of each module is expected to be built out of solid low-carbon steel. A small coil installed on the magnet will allow the tuning of the total deviation angle by ± 2 %. Beside an obvious positive impact on running costs, such a structure is well in line with the required high longitudinal compactness of the magnet lattice.

Sextupole magnets with field gradient up to 1500 T/m and magnetic length lower than 300 mm are also required. Under magnetic study, the sextupole will integrate different types of correctors suitable for fast and slow corrections. The magnetic yoke will therefore be based on laminated material.



(a) (b)

Figure 3: Magnetic design of a 100 T/m quadrupole prototype (a) and of a permanent magnet dipole with longitudinal gradient (b).

The fiducialization of these magnets will be a delicate task. The classical alignment methods rely on the positions of reference cones fastened on the magnets. The transfer of the magnetic axis position to these reference cones dominates the alignment error budget. For some of the magnets, better alignment tolerances can be obtained using an *in situ* stretched wire measurement bench. *In situ* alignment methods have already been investigated during the first phase of the ESRF upgrade.

RF REQUIREMENTS

Thanks to the low magnetic field in the dipoles, the energy loss per turn is 3.32 MeV, significantly smaller than now. An accelerating voltage limited to 6 MV will still give a momentum acceptance of 4.7 % while significantly reducing the operating costs. Because of the longer damping times, the new lattice will be more sensitive to higher order mode (HOM) driven longitudinal coupled-bunch instabilities and the use of HOM-damped single-cell cavities is mandatory. The prototypes presently being tested on the ESRF ring are perfectly adapted to new lattice, which will need a total number of 12 such cavities [4]. These could be accommodated in two straight sections, but the flexibility of individually powering each single-cell cavity with a solid-state amplifier (SSA) allows any other convenient redistribution.

The constraint of keeping the ID source points unchanged when moving to a 7-bend achromat results in a shorter circumference of the ring. The resulting increase of the RF frequency by 155 kHz is acceptable for both the cavities and RF transmitters. However the ESRF booster is presently powered at the same frequency as the Storage Ring. Different solutions are envisaged to cope with this, such as using different frequencies in both rings, or proportionally shortening the Booster circumference.

COLLECTIVE EFFECTS

Intra-beam Scattering and Touschek Lifetime

Given the small emittance achieved, intra-beam scattering and Touschek lifetime are expected to have a strong impact. Table 1 shows the estimations for the 3 main operating modes, with a momentum acceptance set at 4% and a vertical emittance of 3 pm.

Table 1: emittance growth induced by intra-beam scattering and Touschek lifetime in different operating conditions

	Multib.	16-b.	4-b.
Total current [mA]	200	90	40
Nb. Bunches	868	16	4
Emittance growth	3%	19%	24%
Bunch length [ps]	23	61	74
Energy spread	$1.06\ 10^{-3}$	$1.6\ 10^{-3}$	$2\ 10^{-3}$
Touschek Lifetime [h]	16	2.4	1.7

Transverse Resistive Wall Impedance

The threshold of the transverse resistive-wall instability is similar to the present ESRF one. It is measured at 20 mA and is compensated by an increase of the vertical chromaticity. A similar situation is foreseen with the new lattice.

RING PARAMETERS

Table 2 summarizes the main Storage Ring parameters, in the standard conditions of multibunch operation mode, at 200 mA. Table 3 summarizes the properties of the insertion device source points.

Table 2: Main Storage Ring Parameters

Parameter		
Energy, E	6.04	GeV
Circumference, C	844	m
Horizontal Emittance ε_x	150	pm.rad
Vertical Emittance ε_z	3	pm.rad
Bunch length, σ_τ	12	ps
Energy spread, σ_δ	$1.06\ 10^{-3}$	
Tunes, ν_x , ν_z , ν_s	75.58, 25.62, 0.0033	
Momentum compaction	$8.2\ 10^{-5}$	
Damping time, τ_x , τ_z , τ_s	7.4 , 10 , 6.3	ms
Natural chromaticity, ξ_x, ξ_z	-96, -72	
Energy loss per turn, U_0	3.34	MeV
RF voltage, V_{RF}	6	MV
RF frequency, f_{RF}	352.2	MHz
Harmonic number	992	

Table 3: Insertion Device Source Points

	Horizontal	Vertical
Beta [m]	3.6	3.6
Beam size [μm]	24	3.3
Beam divergence [μrad]	6.4	0.91

CONCLUSION

The lattice design for the ESRF upgrade is progressing. The present design fulfills the basic requirements in terms of photon source properties and performance. This lattice is extremely compact, and next steps will consist of making it compatible with engineering constraints, concerning the available space for vacuum equipment, diagnostics…

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