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OPTIONS FOR A LIGHT UPGRADE OF ESRF BOOSTER SYNCHROTRON LATTICE

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Abstract

The EBS 6 GeV electron storage ring recently commissioned at ESRF, in Grenoble, France, is still operated using the old injector hardware. It is now one of the limiting factor of the facility. The large horizontal emittance of the booster beam affects injection efficiency, preventing from reaching 100% transfer efficiency between the 299.8 m long booster and the storage ring. Different lattice modifications going from minor optics changes to full machine renewal are considered [1] . In this paper we will discuss different options of a "light" upgrade of the FODO lattice, keeping the RF system, vacuum chamber, power supplies, and most of the magnets. The upgrade then consists in creating a few new quadrupole families in the straight section vicinity and remove them from the main QF/QD families.

"LIGHT" UPGRADE AND IT'S LIMITATIONS

PS Limitations

The ESRF booster synchrotron is accelerating electrons from 0.2 Gev to 6 Gev following a 250 ms cycle driven by a ramped power supply (PS) feeding all magnets. This PS is based on H bridge rectifiers using IGBT's switches, and feeds three different magnet chains: Dipoles (D), Focussing Quadrupoles (QF) and Defocussing Quadrupoles (QD). The power supply, commissioned in 2015, has been tailored to the present booster layout and offers very little flexibility for improvement of output current/voltage (presently 500 A/1500 V) and number of output channels. The light version of the upgrade uses of current magnets type, with eventually minor modifications in the design of quadrupoles. It enables to keep most of present magnets, girders and vacuum chambers. New families can then be obtained either by removing some quadrupoles from the present chains, and feed them via dedicated PS, or by introducing magnets with different designs in the same chain. Expected saturation curve for current magnets is presented in Fig. 1.

Magnet Design Limitations

Additional quadrupole families can be obtained by modifying the number of turns on the coils in the magnet design. Sevral families can then be powered by a single chanel output of the ramped PS and no additional PS is requiered. Comsol [2] simulations have been performed to evaluate the impact of magnet saturation. It was coherent with the PS limitation of 500 A. These simulations were used as well to evaluate the field errors induced by a non even distribution of excitation coils. Modification of coils can only be done by removing, or adding, a full turn. Present coils have 12 turns fixing the discreet step in gradient change to 8.3% of the initial value. Removing one turn on only two over the four coils of the magnet, this step is reduced by a factor 2. The field quality is then slightly degraded because of the different current repartition in the coils. Harmonic analysis performed on a circle of 50 mm diameter, for the pole and coil geometry of Fig. 2 indeed shows the presence of a skew octupole for the geometry presented in Fig. 2. Nevertheless the relative amplitude of this component with respect to the main quadrupole gradient is of 4×10^{-4} even for the saturated case (as shown in Fig. 3). It is therefore negligible with respect to other sources of errors. For non uniform chains of magnets, saturation is a concern as well because, for this configuration, it cannot be compensate for all magnets via the power supply waveform anymore.

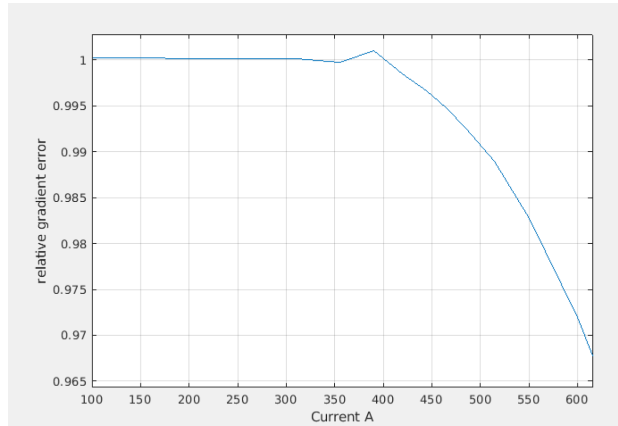

Figure 1: Simulated normalised gradient as a function of current for the present booster quadrupoles.

Extraction

Extraction hardware and layout is strongly lattice dependent. For a given lattice the ability to extract properly the beam using existing layout/hardware must be assessed and potential modifications are foreseen.

LATTICES TO BE COMPARED

Figure 4 displays how the new magnet families are labeled. The figure shows 1/6 of booster circumference. Three new lattices (PR, 3F, and 5F) with new families are compared with two lattices that do not require any hardware change: the one in operation (OP) today, and the same one with an increased horizontal tune (HT). For each lattice, analysis is done considering a 40 kHz shift on the RF frequency. Indeed EBS machine length is not in accordance with booster

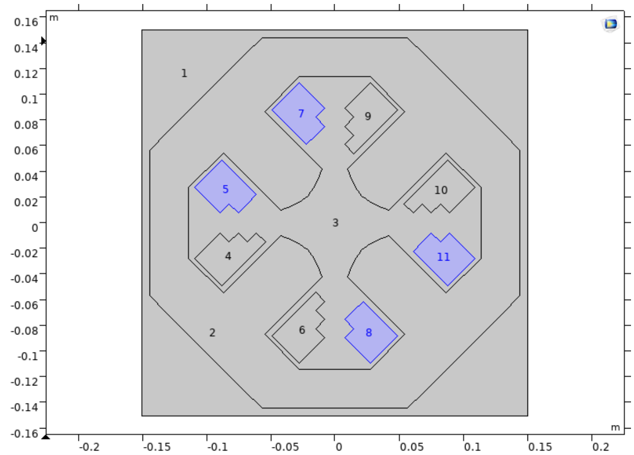

Figure 2: Geometry used for asymmetric coils. The coils in purple have only 11 turns while the others have 12.

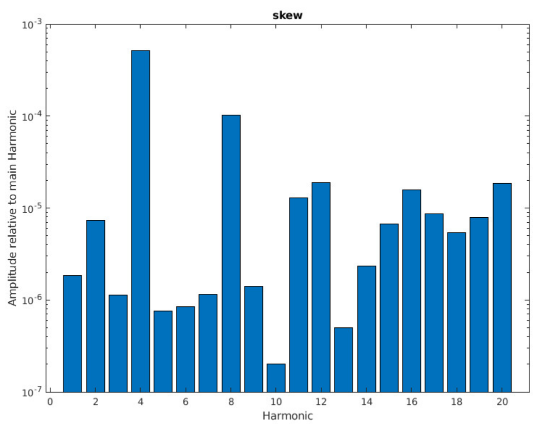

Figure 3: Simulated skew harmonic amplitude relative to main quadrupole for the asymmetric case. Results are given for relative amplitudes measured at 25 mm from the magnet center.

circumference. Therefore ESRF booster runs off energy with a 40 kHz mismatch between machine length and RF frequency [3]. We do benefit from this mismatch as it lowers the H emittance to the cost of bunch lengthening on closed orbit distortion.

OP: Operation lattice as of today with tunes of 11.7/9.6 (h/h). It involves only two families for the quadrupoles, focussing and defocussing. K values in the quadrupoles are: 0.73 m^{-2}/–0.653 m^{-2} corresponding to an excitation current of 446/404 A.

HT: Increasing the horizontal tune by one integer, horizontal emittance can be reduced. For this setpoint, K values will be 0.77 m^{-2}/0.66 m^{-2} corresponding to maximum currents of 469 A / 407 A.

PR: The lattice proposed by P. Raimondi has higher QF strength and lower QD strength so to increase H tune without reaching the 500 A limit for the QF. Tunes are

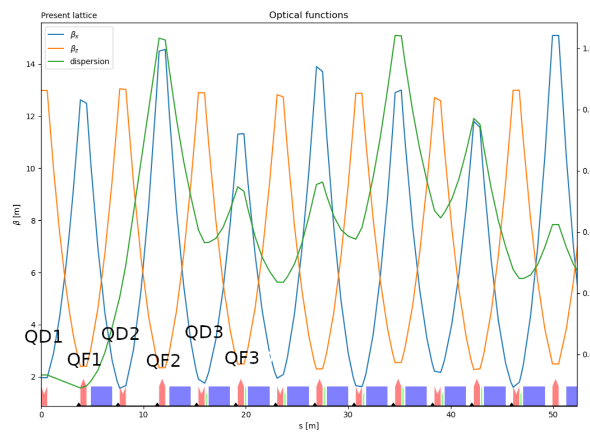

Figure 4: 1/6 of present booster lattice, with quadrupole labeling.

(h/v) 13.4/4.2. Lower vertical tune helps keeping the sextupolar power required for chromaticity correction low. Therefore transverse dynamic aperture is still large. Three new families for QF1, QF2 and QD1 are used to match the straight sections optics to the arcs, and keep extraction possible. It would nevertheless require the refurbishment of the first extraction septum.

3F: It follows the same principle of lowering V tune and enhancing H tune, but keeping all QD's in one family and adding 3 QF families that can be obtained by coil manipulations: $KQF1 = 10/12 * KQF$, $KQF2 = 11/12 * KQF$, $QF3 = 11.5/12 * KQF$ with $KQF = 0.7902$ and $KQD = -0.51$. This option allows to limit the increase of focussing quads in the extraction section. Present extraction hardware is then sufficient to fully transfer the beam from the booster to the transfer line. In this case we would have 18 magnets having different coils than the usual one.

5F: In this case 5 new magnet families including 36 magnets altogether are introduced. Again the new families can be powered in series with the main QF/QD family, and the gradient is tuned by changing the number of turns on the coils. $KQF1 = 9/12 * KQF$, $KQF2 = 11/12 * KQF$, $QF3 = 11.5/12 * KQF$, $QD1 = 13/12 * KQD$, $QD2 = QD3 = 12.5/12 * KQD$. With $KQD = -0.4562$ and $KQF = 0.7981$. This lattice would require the modification of 38 quadrupoles, and the modification of extraction elements. The resulting Twiss parameters for this lattice are presented on Fig. 5.

From these five lattices, two correspond to what is feasible with the present layout (OP and HT). The PR one corresponds to the first version proposed by P. Raimondi following a quick optimisation. It is promising, but as already mentioned, this lattice still has extraction issues. The 3F lattice is optimised considering a limit of three families to

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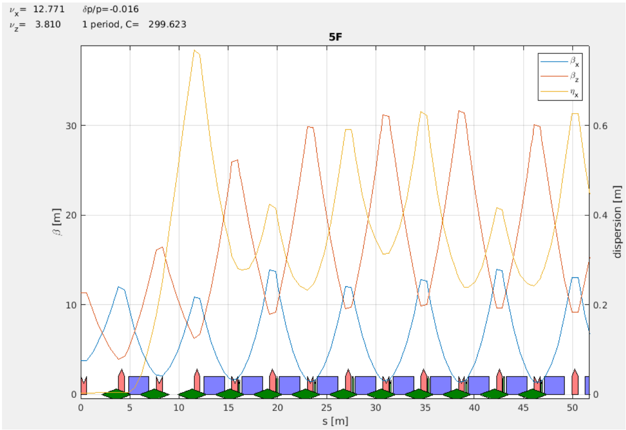

Figure 5: Twiss parameters for the 5F lattice.

be modified and the constraint to use the present extraction layout. The last lattice (5F) is an extension of the 3F lattice with more quadrupole families involved in the upgrade. It is a realistic case requiring more effort for its implementation that the 3F one, and should be close to the optimum we can expect if no major refurbishment of dipoles, power supplies and vacuum chambers is foreseen.

Lattice Performances

All tracking simulations have been performed using AT [4] and pyAT [5].

The lattice performances are evaluated in terms of:

- Horizontal emittance (ϵh): the lower the better, it allows to improve injection efficiency in the SR.
- Bunch Length: The longitudinal matching is not good between the booster and the storage ring. A shorter bunch length would improve longitudinal matching and thus the injection efficiency.
- Injection efficiency (IE): As a result of the lattice parameters optimisation it is expected to increase. Optimising injection efficiency is the main purpose of this upgrade.
- Dynamic aperture: The larger the better, it is strongly linked to the maximum charge the booster can capture.

The comparison for normalised dynamic apertures is presented on Fig. 6 and simulated at the QD1 center. For the upgraded lattices, the dynamic aperture of the 5F lattice is the largest while the HT lattice has a reduced aperture underlining the limits of increasing the H tune with the present layout. All other parameters are summarised in Table 1. They will be compared as well to the preliminary results obtained by scaling the Diamond project for an upgraded booster to the ESRF tunnel which has a horizontal emittance of 15 nm rad. We consider this case as the minimum emittance achievable if the ESRF booster could be fully upgraded fixing only the machine length so to fit in the present tunnel.

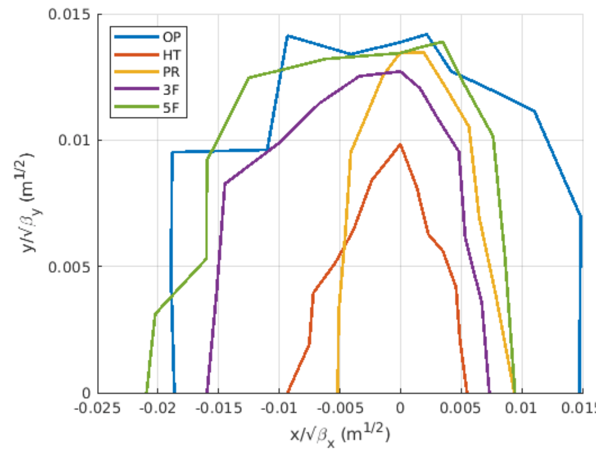

Figure 6: Comparison of normalised dynamic apertures for the 5 presented lattices. No errors are introduced except the eddy current in the dipole VC.

Table 1: Comparison of the Different Lattices Considered

Lattice	ϵ h (nm.rad)	Bunch Length (mm)	IE %
OP	85.1	23.4	86
HT	66.5	21.5	92
PR	55	19.1	95
3F	58.7	19.9	94
5F	55.7	19.2	95
"Diamond like"	15	11.7	100

CONCLUSION

Different options have been presented for a light booster upgrade. The HT lattice, which does not require any hardware upgrade shows its limit as it allows a relevant emittance reduction but at the cost of a small dynamic aperture. The PR lattice is attractive but requires hardware refurbishment for the extraction septum. The two last options, the 3F and 5F could be implemented by keeping two chains of quadrupole magnets fed by the two dedicated PS channels and by changing the number of turns in the coils for 18 (3F) or 36 (5F) magnets. The 5F one would require some modifications of the extraction section. The emittance reduction expected is limited to a factor 1.5, and would allow to reach 95% injection efficiency according to our si mulations. The improvement expect from the light upgrade can be compared to preliminary simulations done for a completely new booster with a lattice similar to the one studied at the Diamond light source in Oxford. This later one would enable a 100% transmission from booster to the storage ring. Another path under study is to have additional families is to use new power supplies for the new families. It would be the most attractive solution due to the increased flexibility it would provide compared to the coils manipulation.

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