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FIRST OPTIONS FOR AN EUROPEAN SYNCHROTRON RADIATION FACILITY EXTREMELY BRILLIANT SOURCE UPGRADE LATTICE

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Abstract

New lattice options are proposed as preliminary candidates for the next generation European Synchrotron Radiation Facility (ESRF) Storage Ring (SR). These new lattices would feature lower emittance, matched optics at all Insertion Devices (ID), transparency conditions for symmetry breaking straight sections and an overall net gain in brilliance, coherence and flux. To allow for high efficiency transparent injection in reduced dynamic aperture and low gaps insertions, on-axis injection and low emittance injected beam are considered.

INTRODUCTION

The European Synchrotron Radiation Facility Extremely Brilliant Source (ESRF-EBS) presently operates with the Hybrid Multi-Bend Achromat (HMBA) lattice at a total beam current of 200 mA [1]. The main parameters of the ESRF-EBS storage ring are shown in Table 1.

Table 1: Main Parameters of the ESRF HMBA Lattice at 200 mA with All Gaps Open [2]

	Units	HMBA
Energy (E)	GeV	6
Circumference	m	843.98
β-function at IDs ($\beta_{x,y}$)	m	6.9, 2.7
Emittance ($\epsilon_{x,y}$)	pm rad	140, 10
Energy spread (δ_p)	%	0.094
Bunch length (σ_s)	mm	4.6
Total beam current	mA	200
Energy loss per turn (U_0)	MeV	2.53
RF Voltage (V_{RF})	MV	5.5

In 2020, when ESRF resumed physics operation after the commissioning was successfully completed, the storage ring was running at record low emittance for machines operating in this range of energies [3]. Since then, more recent projects reaching even lower emittances, such as APS-U [4], HEPS [5] or PETRA-IV [6], have been put in operation or have been planned for construction. As seen in Fig.1, when PETRA-IV will be put in operation (expected for 2032), ESRF-EBS equilibrium emittance will be one of the largest world-wide. In order to ensure long-term competitiveness and avoid obsolescence of the ESRF-EBS, new lattice options are studied to match state-of-the art performance for storage ring light sources. This paper presents the results of these preliminary studies and provides insight on possible options for future ESRF storage ring upgrades.

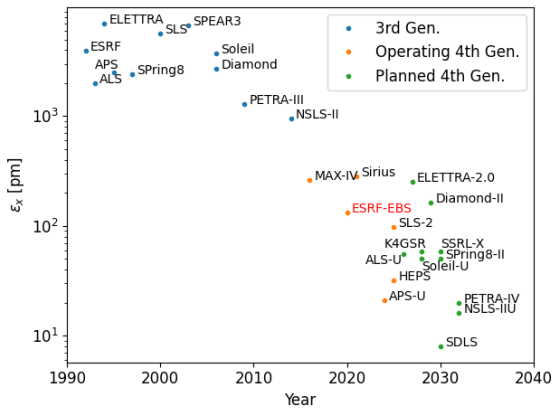


Figure 1: Horizontal equilibrium emittance of storage ring light sources. Data taken from Ref. [7].

PROPOSED STRATEGY

Short term improvement have been studied at ESRF to locally increase the brilliance of selected beam lines [8, 9]. These will nevertheless not provide sufficient gain to maintain competitiveness over the long-term. To achieve this while providing cost effective solutions, several design goals can therefore be defined for possible upgrade of the ESRF storage ring light source:

- Maintain the ring circumference and number of cells such that the present infrastructure can be re-used and optimize power consumption to reduce the operation cost of the facility
- Reduce the present horizontal emittance by at least an order of magnitude, down to 10 pm in both planes or 20 pm flat beam, while maintaining or reducing the energy spread and preserve or increase the photon energy reach of the light source
- Provide high efficiency transparent top-up injection and allow for ultra low-gap insertions in the straight sections
- Maintain the present ESRF flexibility in term of filling modes and bunch current

With these goals set, it is seen that achieving the desired emittance in both planes while preserving the energy spread, photon energy and circumference of the present machine requires to entirely reconsider the machine parameters and layout. We therefore propose in this report to reduce the ring energy to 5 GeV. The reduction of energy not only reduces significantly the equilibrium emittance ($\epsilon \propto \gamma^2$) but also the energy consumption of the machine since the energy loss per turn will be significantly smaller. An immediate two-fold

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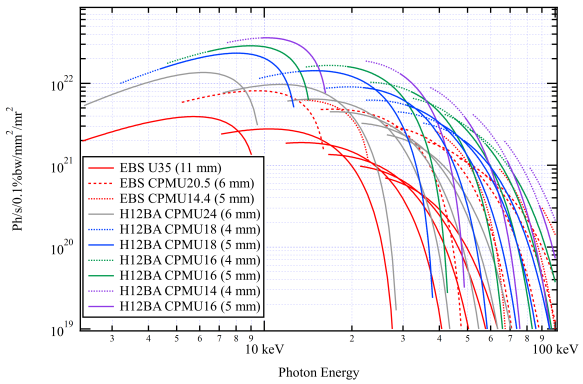


Figure 2: Tuning curves of different undlator configuration for the ESRF-EBS (6 GeV) and H12BA (5 GeV) lattices.

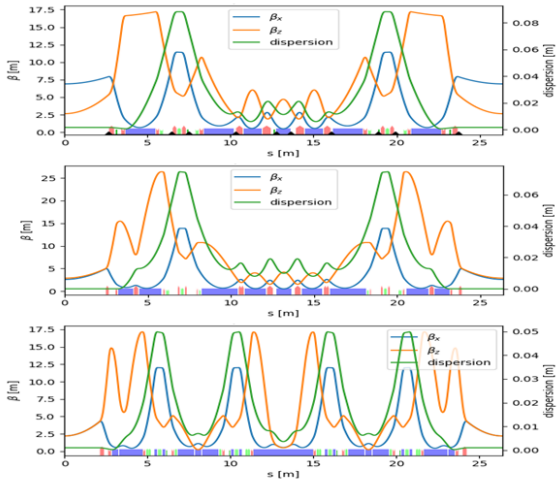


Figure 3: Optics funtions and layout of the three lattice options: top H7BA, middle H9BA, bottom H12BA.

improvement with no additional complication in terms of lattice design is therefore provided. However, reducing the beam energy has an impact on the photon beam properties and dedicated short period low gap insertion devices would be needed to restore or improve these characteristics.

This is shown in Fig. 2 where it is seen that migration to low gap in-vacuum CPMU undulators would allow to both increase the overall brilliance and the photon energy reach of the machine. Depending on the beam line specificity, tailored, cost effective solution will have to be determined. Alternatively high temperature superconducting materials (HTS) shall be considered to adjust the gap or energy reach of the beam line. Finally, high efficiency transparent top-up injection in ultra-low insertion device gaps can only be achieved using an on-axis injection scheme with low emittance injectors chain. This is even more relevant if operation on the coupling resonance is considered. This scheme has to allow for accumulation to maintain the present ESRF filling modes using high single bunch current. Alternatives to the present off-axis injection scheme have already been proposed for ESRF-EBS and are considered as potential upgrades [10, 11]. At ESRF, the vertical gap size is presently limited by transverse halo particle oscillating at large amplitude [12] and lost on the undulators gaps. New lattice designs would therefore have to minimize this effect.

LATTICE OPTIONS

To simplify the comparison, we will use 32-fold symmetric lattices with circumferences of approximately 844 m and beam energy of 5 GeV, the RF voltage is set such that the ratio of energy loss per turn and the voltage remains constant for all the lattices, the reference is the present ESRF-EBS lattice operation settings. We consider 3 cell versions. i) The ESRF-EBS H7BA standard cell, that includes 7 bending magnets [1]. ii) An H9BA cell, that includes 9 bending magnets [13]. This cell was scaled to the ESRF cell length from a shorter version without further optimizations and may feature degraded non-linear dynamics. iii) An H12BA, that consists in 2 compact H6BA [14] with 12 bending magnets. For the H12BA we propose 3 variants, one using a central dipole for all Bending Magnet (BM) beam lines (l_0), one removing this central dipole but with high horizontal emittance (l_1) and one removing the central dipole but preserving the horizontal emittance at the cost of non-zero dispersion in ID straight sections (l_2). The main interest in removing the central dipole is to free a second short straight in the cell and give more flexibility on the photon source type that BM beam lines could use (single bend or wiggler for example). Figure 3 shows the optics functions and layout of the three lattice options proposed in the paper. In the figure, only the H12BA including the central magnet is shown. It is seen that the H12BA cell is in reality a combination of two H6BA, therefore featuring two $-I$ transforms separated by a central dipole. To further reduce the emittance, some quadrupoles are also integrating a bending angle as seen in the chromaticity correction section where the two short blue bars located in the vicinity of the sextupoles (in green) represent focusing quadrupoles with bending angle (either through an offset or via a specific design). For both H12BA and H9BA, an additional focusing quadrupole is inserted in the first dipole to allow the matching of transparency conditions [14] and allow for the insertion of special straight sections such as the injection sections without impacting performance. Table 2 summarizes the main performance parameters of the three lattices options.

Both the H7BA and H9BA offer advantageous characteristics in terms of energy spread and energy loss per turn, however, the transverse emittance is far from the design goal of 10 pm in both planes even assuming this lattice would run on the coupling resonance (shared emittance). The H12BA is approaching this goal while maintaining low energy loss per turn. The energy spread is nevertheless increased when removing the central bending magnet. It should be noted that no linear optics matching was performed for any for these lattices, only bending magnet angles were adjusted to correct the dispersion beating and total bending angle

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Table 2: Main performance parameters of the three lattice options. Values provided in the table are given for zero current. The chromaticities were matched to (10, 8) as presently used in operation for ESRF-EBS. The values in parenthesis for the H12BA correspond to the 3 variants.

	H7BA	**H9BA**	**H12BA ($l_{0,1,2}$)**
E [GeV]	5	5	5
$\beta_{x,y}$ [m]	6.9, 2.7	2.7, 2.7	2.5, 2.5
ϵ_x [pm rad]	92	53	(31, 42, 31)
δ_p [‰]	0.78	0.82	(0.86, 0.96, 1.08)
σ_s [mm]	4.9	4.5	(3.1, 2.8, 3.4)
U_0 [MeV]	1.22	0.95	(1.07, 1.3, 1.22)
V_{RF} [MV]	2.65	2.1	(2.3, 2.8, 2.7)
K_{1max} [Tm^{-1}]	74	105	99
K_{2max} [Tm^{-2}]	1373	2295	$\approx$ 2600

leaving potential margin for improvement in several aspects. Finally, the ID gaps contribute to the total energy loss per turn, and may contribute to a further reduction of emittance and energy spread. For example, taking the H12BA$_{l2}$ and 100 kW radiated power from IDs (typical value for ESRF-EBS) the energy spread would reduce from 1.08×10^{-3} to 0.97×10^{-3} and the emittance from 31 pm to 29 pm. This illustrates an additional interest of inserting free straight sections to host damping wigglers and achieve the design emittance [14].

TRANSVERSE DYNAMIC AND MOMENTUM APERTURE

The lifetime and dynamic aperture values strongly depend on non-linear optimizations. For this preliminary study we consider three sextupole families (one focusing and two defocusing) and one defocusing octupole family. Two sextupole families are used to fix the chromaticity at (10, 8), and the other is used as a free parameter to optimize lifetime and dynamic aperture (DA). The octupole family is set such that the horizontal amplitude detuning is minimized for the optimal sextupole settings. These may not represent the optimal settings but provide a common basis for comparison of the various lattices. Figure 4 shows the momentum aperture (MA) and normalized transverse DA at the center of the straight section for the 5 cases considered. The DA of the H7BA lattice is twice as large as the one of the other lattices while the H12BA lattices have much larger momentum aperture. The H9BA is under-performing in all aspects with respect the other lattices most likely because it was not optimized for the ESRF-EBS cell length. Further optimizations may provide better performance but this initial evaluation clearly favors the H12BA lattice. On-axis injection with low emittance injectors could be required to be able to inject in the smaller DA. Figure 5 shows the momentum aperture and lifetime for the optimized lattices. The lifetime calculation assumes ESRF-EBS effective impedance and bunch

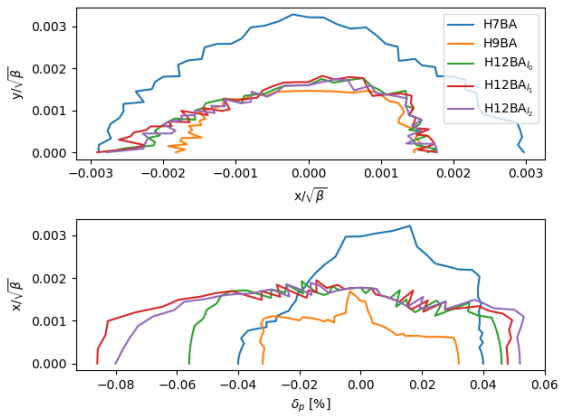


Figure 4: Normalized transverse dynamic and momentum aperture at the center of the straight section.

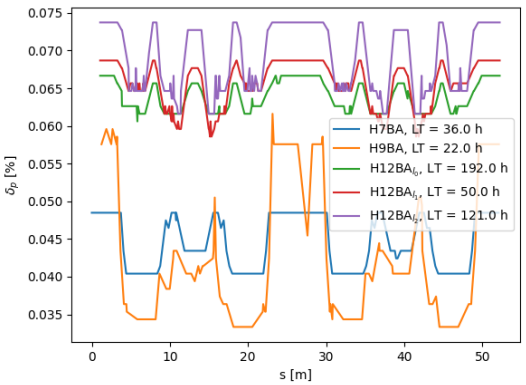


Figure 5: Momentum aperture over one cell and lifetime of the optimized lattices.

current (0.35 Ω and 0.2 mA). The results shown in Fig. 4 are confirmed with the H12BA options largely outperforming other alternatives. The removal of the central magnet affects the lifetime but the low emittance (l_2) version still provides excellent MA and lifetime.

SUMMARY

In approximately a decade from now, the ESRF-EBS will feature one of the largest equilibrium emittance for high energy storage ring light sources. Possible alternatives for the ESRF storage ring lattice have been studied with the goal to maintain state-of-art performance over the long-term. While no solution would provide the desired order of magnitude reduction of emittance, a 5 GeV H12BA lattice provides very promising results assuming it is possible to produce insertion devices that would compensate for the reduced energy. Iteration on the lattice design and optimization of the non-linear dynamics will be performed to probe its limits and determine whether all design goals could be achieved with this lattice proposal.

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