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IMPROVED EMITTANCE AND BRIGHTNESS FOR THE MAX IV 3 GeV STORAGE RING

M. Apollonio*, Å. Andersson, M. Brosi, R. Lindvall, D. K. Olsson,
M. Sjöström, R. Svärd, P. F. Tavares,
MAX IV Laboratory, Lund University, Lund, Sweden

Abstract

At MAX IV Laboratory, the Swedish Synchrotron Radiation (SR) facility, the largest of two rings operates at 3 GeV with a bare lattice emittance of 330 pmrad. Upgrade plans are under consideration aiming at a gradual reduction of the emittance, in three stages: a short-term with an emittance reduction of 20% to 40%, a mid-term with an emittance reduction of more than 50% and a long-term with an emittance in the range of the diffraction limit for hard X-rays (10 keV). In this paper we focus on the short-term case, resuming previous work on a proposed lattice that can reach 270 pmrad emittance, with only minor modifications to the gradients of the magnets of the present ring, *i.e.* without any hardware changes and all within the present power supply limits. Linear lattice characterisation and calculations of key performance parameters, such as dynamic aperture and momentum aperture with errors, are described and compared to the present operating lattice. Experimental tests of injection into this lattice are also shown.

INTRODUCTION

The MAX IV complex in Lund, Sweden, comprises a LINAC used for injection and also feeding a Short Pulse Facility (SPF), and two storage rings (SR) operating at 1.5 GeV (R1) and 3 GeV (R3). Made of 20 7BA achromats with a circumference of 528 m, R3 is credited to be the first 4th generation electron SR, with a nominal bare-lattice equilibrium emittance of 330 pmrad [1]. The R3 ring provides daily synchrotron light to 10 beamlines at 300 mA, in a 10 minutes top-up mode, with a typical lifetime of 20 hours. Since its first light delivery to beamlines in 2016 [2], studies were made towards a further improvement in its performances. The time has come to consider a testable reduction in emittance and increase in brightness at the ID straights in an operating machine. This paper takes inspiration from a study dating back to 2014 [3] and, after a revision of the case, focuses on the implementation of a lattice into the present ring. For this study only the currents of quadrupoles, sextupoles and octupoles were altered, with no hardware modification. We first discuss the drive behind the linear characterization, illustrating the optimisation procedure towards a lower emittance and the differences in dynamics between the new and the baseline lattice. After that we describe how the new lattice is implemented in the real machine, and the threading technique adopted to capture the first beam. We then discuss the LOCO fits used to define the lattice in the ring, and conclude with the present status of the implementation and with a discussion of the possible further steps.

* marco.apollonio@maxiv.lu.se

LATTICE DESIGN

The main drive in the characterization of the new lattice is the reduction of the natural emittance. Another desirable parameter to consider, not directly targeted in the optimisation, is the brightness at the ID straights. The strategy adopted was to start from the present machine and act on four quadrupole families (QF, QDE, QFE, QFM) to gradually reduce the natural emittance while preserving the non-integer parts of the tunes. The process utilized the MAX IV cluster to exploit the parallel optimisation capabilities of the tracking code elegant [4]. The obtained results, with Twiss parameters shown in Fig. 1, were surprisingly well matched to the initial studies, confirming a natural tendency of the system when optimsation is driven by only the four aforementioned quadrupole families. The code OPA [5] was utilized to tune sextupoles and octupoles in order to improve the non-linear dynamics of the lattice, such as the dynamic aperture (DA), the control of the tune shift with amplitude and with energy deviation. Table 1 summarizes the result of this process, as compared to the present lattice[1]. Magnet variations for quadrupoles, sextupoles and octupoles can be found in Table 2. Figure 2 shows a calculation of DA over 10 seeds with the tracking code elegant [4], where errors on magnet gradients and positions were introduced, and a physical aperture of 22 mm diameter was considered. The DA of the new lattice is clearly penalized in both planes. For the vertical one this is due to the 25 m beta function at both edges of the achromat, a typical feature of the new lattice, together with an important reduction of the horizontal dispersion inside the achromat

Table 1: Comparison of the R3 Parameters for the Baseline Lattice and the Low-Emittance Case

R3	**baseline**	**low-emittance**
ϵ (pm rad)	328.18	269.14
ν	(42.20, 16.28)	(44.1997, 14.2793)
ξ (natural)	(-49.98, -50.08)	(-50.72, -76.47)
α_C ($\times 10^6$)	305.97	259.69
$\tau_{x,y,E}$ (ms)	15.7, 29.0, 25.2	16.9, 29.0, 22.7
$\beta^{\text{straight}}_{\text{x,y}}$ (m)	9.0, 2.0	7.47, 1.04
brightness increase (%)	-	+22
RF_{height}(1.2 MV) (%)	5.19	5.64

[1] brightness increase computed for a 4m long 1Å source

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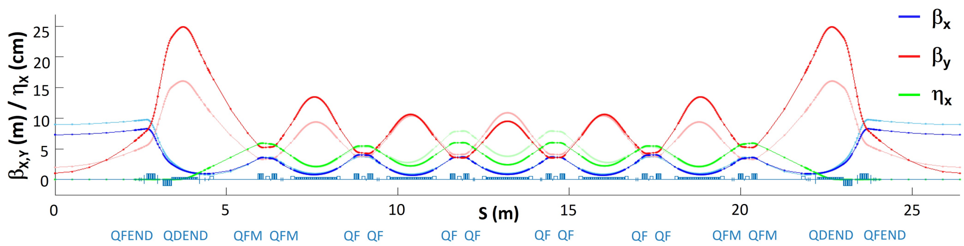

Figure 1: Comparison of the optical functions in one achromat cell of the MAX IV 3 GeV ring. Light colors: baseline lattice (330 pmrad). Strong colors: the newly designed low emittance case (270 pmrad).

Table 2: Variation of Quadrupole, Sextupole and Octupole Gradients between the Baseline and Low-Emittance Lattice

element quadrupoles	**baseline** (m^{-2})	**low emittance** (m^{-2})	**Delta** (%)
QF	4.03	4.296	+6.60
QFE	3.654	3.700	+1.26
QDE	-2.504	-2.562	+2.31
QFM	3.774	3.781	+0.18
sextupoles	(m^{-3})	(m^{-3})	
SFi	207.4	212.1	+2.26
SFo	174.0	189.5	+8.91
SFm	170.0	190.5	+11.20
SD	-116.6	-130.2	+11.16
SDend	-170.0	-159.7	-6.05
octupoles	(m^{-4})	(m^{-4})	
OXX	-1649	-3137	+90.23
OXY	3270	2421	-25.96
OYY	-1420	-948	-33.24

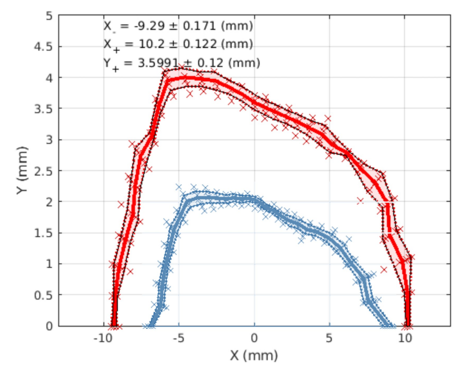

Figure 2: Computed DA for the baseline (red) and for the low-emittance lattice (blue), showing a clear reduction in both planes.

driving the 60 pmrad reduction in natural emittance. The bucket size increase in the new lattice should entail a larger local momentum aperture (LMA), especially at low RF voltages. At 1.2 MV the calculated Touschek Lifetime (TLT) after LMA multi-seed simulations improves by about 1 hour, even though the effect of lattice errors is remarkably higher in the low-emittance case resulting in a TLT of 22.7 ± 5.9 hours against the 21.9 ± 0.2 hours for the baseline lattice. All these predictions point at a new lattice with an important reduction in DA and a comparable TLT.

Implementation of the Lattice in the 3 GeV Ring

From the previous paragraph, we anticipate a significant impact on the injection into the new lattice due to the DA reduction. Injection in R3 is performed by means of a Multipole Kicker (MIK) placed 28 m downstream the first straight [6]. R3 is also equipped with a Dipole Kicker (DK) [7], 3.5 m downstream the injection straight, thoroughly used during commissioning and in the early years of operation, prior to the advent of the MIK. Unfortunately, the phase advance in the low emittance case causes the beam to reach the MIK position almost at the centre of the device, making it ineffective. This aspect was soon noticed in the early calculations and also confirmed during the first unfruitful attempts in the machine. We therefore adopted the DK in order to simplify the injection process, well aware that this might entail the loss of the beam stored in the ring. The first attempts at injecting into the machine with the DK were also unsuccessful, with a penetration of only few BPMs into the ring. The issue was mitigated with a manual tuning of the machine correctors, allowing a single turn at large amplitudes, and prompted a new line of study to thread the incoming beam, eventually closing the orbit to capture it.

Injection, Threading and Beam Capture

Following the idea described in [8] and [9] we developed a Matlab-AT [10,11] based threading algorithm (TA) relying on a one-pass triangular response matrix, making use of the trajectory seen by the BPMs in single-pass mode. This operational feature requires changes in the way BPMs are read-out and also an adjustment in the chopper system used to discard those off-energy electrons that will not make it through the LINAC, creating a good signal to noise ratio in the ADC counts at each BPM. Care must be taken to ensure the injection trigger is well aligned with the Libera ADC buffers, a fundamental requirement when working in single-pass mode acquisition. In order to get a first capture inside R3, the DK voltage was gradually increased, while injecting into the machine with a closed valve at achromat 20. The single-pass recorded track was used by the TA to generate the new steer-

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ing values. After ten threading iterations at V_{DK} = 4.7 kV (3.6 mrad, close to theoretical on-axis condition), a dozen turns were observed in the lattice when opening the valve. The threading procedure was repeated for a further twenty iterations, producing better trajectories in both planes, as testimonied in Fig. 3 for the vertical plane. Reducing beam

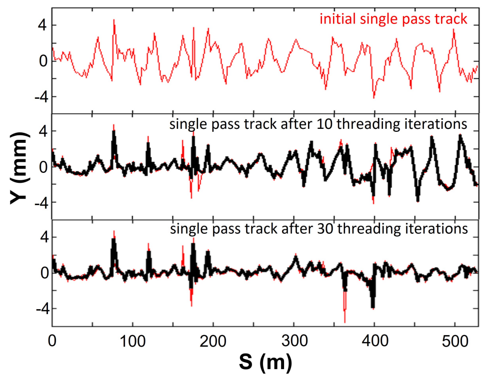

Figure 3: Vertical trajectory improvements when injecting while running the TA. Top, initial vertical single-pass trajectory (red). Middle, trajectory after ten TA iterations, where the black trace is the average of twenty single-pass samples (red). After thirty iterations (bottom), the trajectory appears considerably reduced also in the second half of the ring.

oscillations from a few mm to few hundred μm, crucially allows the first electron capture: after re-opening achromat 20 valve it was possible to observe about 125 turns in R3 (see

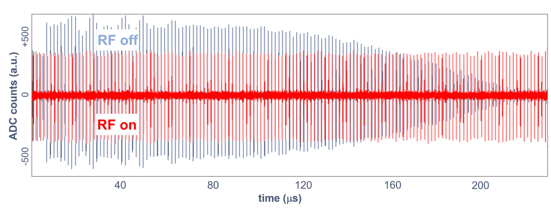

Figure 4: Blue graph: a convincing number of turns in the machine is observed without RF after thirthy TA iterations. Red graph: RF on allows beam to be captured.

Fig. 4, blue graph). When RF was set on, we observed the first beam capture. By tuning the TR3 transfer line we reach a typical value of 0.23 mA, with peaks up to 0.29 mA[2].

First Characterization of the Optics

The small captured current was sufficient to correct the orbit with the slow orbit feedback, measure and correct tune and chromaticity and measure the dispersion in both planes. Several iterations of LOCO [12] were carried out, pushing down the residual β-beat from an initial 50% in both planes to slighlty above 10%, while the horizontal dispersion gradually moved towards the pattern indicated by the low-emittance model (see Fig. 5). A few important considerations are due. LOCO implementations often caused the

[2] these results point at a 100% capture efficiency from the LINAC

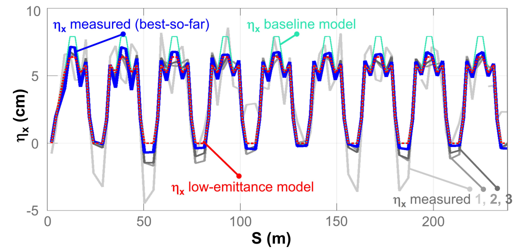

Figure 5: Measured horizontal dispersion after several LOCO iterations (gray colors), as compared to the model for the standard (green) and the low-emittance (red) lattices. The blue curve is the best-so-far measured solution.

beam to dump, imposing fractional changes of the gradients, typically half of the suggested variations. QF and QFM current limits turned out to be too small, requiring a change in the software tolerances and also a review of the cycling procedure for the magnets. Due to the lack of proper calibration curves above the present limits, magnet cycling still happens within the default maximal current values. This may be a reason for the difficulty in reproducing results at different times. Sextupoles too reached their limits when trying to correct chromaticity, found very close to zero and negative, to the (1,1) intended value. The small DA limits our ability to stack charge. A combination of tune scans, introduction of bumps at the injection point and TR3 tuning allowed us to reduce the needed DK voltage to about 3.9 kV (2.99 mrad), with the stored beam typically lost above 1.2 kV (0.91 mrad). We measured 50 beam size samples and inferred the emittance for this new lattice using the LOCO fitting prior to this measurement, suggesting a β-beat of -4.1% at source point. With a measured dispersion of −5.3 mm and assuming the theoretical δ_E = 0.73 ‰, we get $\epsilon_x = 295 \pm 10$ pm rad. The result, showing only statistical errors, should be taken with a word of caution, since the systematic uncertainties are still undefined. However, together with the previously described result for the horizontal dispersion, all seems to point at the establishment of the new lattice.

CONCLUSIONS

In the framework of the short-term development for low emittance lattices at MAX IV, we have implemented a case originally studied for R3 prior to commissioning. To do this we refined the single-pass acquistion and developed a TA allowing the first capture of the beam. We are presently engaged in refining the linear optics which should facilitate the process of acceptance sharing when injecting with the DK. First indications suggest a horizontal dispersion close to the model and a measured emittance pointing at the expected value for the new lattice. Further LOCO campaigns and online optimization of the TR3 parameters with algorithms like RCDS [13], tune and chromaticity scans, and time shift of the DK pulse are among the techniques we aim at deploying in order to reach a better optics and to mitigate the limited dynamic acceptance presently hampering stacking.

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