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Pushing the MAX IV 3 GeV storage ring brightness and coherence towards the limit of its magnetic lattice

S.C. Leemann [a,*], W.A. Wurtz [b]

[a] MAX IV Laboratory, Lund University, 22100 Lund, Sweden
[b] Canadian Light Source, Saskatoon, SK, S7N 2V3, Canada

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ABSTRACT

The MAX IV 3 GeV storage ring is presently being commissioned and crucial parameters such as machine functions, emittance, and stored current have either already been reached or are approaching their design specifications. Once the baseline performance has been achieved, a campaign will be launched to further improve the brightness and coherence of this storage ring for typical X-ray users. During recent years, several such improvements have been designed. Common to these approaches is that they attempt to improve the storage ring performance using existing hardware provided for the baseline design. Such improvements therefore present more short-term upgrades. In this paper, however, we investigate medium-term improvements assuming power supplies can be exchanged in an attempt to push the brightness and coherence of the storage ring to the limit of what can be achieved without exchanging the magnetic lattice itself. We outline optics requirements, the optics optimization process, and summarize achievable parameters and expected performance.

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1. Introduction & background

The MAX IV 3 GeV storage ring is the first light source to make use of a multibend achromat lattice to reach ultralow emittance [1–8]. As the commissioning of this storage ring progresses, crucial parameters such as machine functions, emittance, and stored current have either already been reached or are approaching their design specifications [9]. Once the design parameters are achieved, the electron beam brightness will be unmatched thanks to top-off injection keeping stored current constant at 500 mA and a bare lattice emittance of 328 pm rad that is expected to reduce towards $\approx$ 190 pm rad as additional insertion devices (IDs) are added and ID gaps are closed [10].

In view of the accelerator physics development program for the period following commissioning, the MAX IV Strategic Plan 2013–2026 [11] sets four key upgrade goals for the MAX IV 3 GeV storage ring. The first two are related to an increase of brightness and coherence: lattice/optics improvements and coupling optimization. An increase of brightness and coherence can be achieved by an improved matching of the electron beam to the intrinsic photon beam emerging from an ID as well as by reducing the bare lattice emittance. The former has already been investigated in [12], whereas first studies related to the latter have been reported in [13] as a short-term upgrade plan. Such upgrade efforts shall now be extended and complemented by the investigations reported in this paper which present a more medium-term upgrade option.

For the increase of brightness and coherence through lattice/optics improvements in the MAX IV 3 GeV storage ring, we pursue a staged approach. In a first stage a harder focusing optics was established while retaining achromaticity, all existing power supplies, and magnet cabling.[1] The results from this first stage [13] showed how the horizontal focusing in the arcs can be increased thus reducing the dispersion and hence the lattice emittance. The achromatic character of the arcs was retained, and the transverse focusing gradients in the dipoles[2] were left unchanged. In a second stage, an even harder focusing optics is pursued where only the existing magnets are retained, but new stronger power supplies are foreseen, thereby allowing for more substantial optics variations. Finally, in a third stage, recabling of the magnets can also be considered so that existing individual families are broken up into several new families allowing for increased flexibility.

[1] This is an important restriction in the MAX IV 3 GeV storage ring because most magnets in the achromat are connected in series to a common power supply for the entire family.

[2] The transverse focusing gradients are provided by the shape of the dipole iron poles, however, the pole-face strips (PFSs) installed in each dipole allow a $\pm$4% variation of this gradient, sufficient to move about $\pm$0.5 in tune space.

* New permanent address: Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA.
E-mail address: SCLeemann@lbl.gov (S.C. Leemann).

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So far, studies have not yet revealed substantial gains from such a modification. However, further nonlinear optimization might benefit from such freedom. In this paper we now detail the continued efforts to increase the brightness and coherence of the MAX IV 3 GeV storage ring in the context of the second stage of the upgrade approach.

2. Global search for an improved linear optics

Following the GLASS procedure [14] using the optics code `elegant` [15] we first attempt to vary all horizontally focusing quadrupole gradients along with the pole-face strips (PFSs), which allow varying the vertically focusing gradient otherwise provided by the pole shape of the dipoles. GLASS is a brute-force technique for optimizing an accelerator lattice by examining all possible configurations of the linear lattice. GLASS has the advantage that it does not get stuck in a local minimum but has the disadvantage that it becomes computationally prohibitive if there are more than a few adjustable parameters. For a lattice with few degrees of freedom and relatively simple nonlinear dynamics, such as the Canadian Light Source lattice, GLASS is sufficient to explore the entire configuration space [16]. However, for a lattice such as the MAX IV 3 GeV storage ring, GLASS provides a first step only, where we begin a coarse study of possible linear configurations. The GLASS scan can then seed a stochastic optimization algorithm which can do both linear and nonlinear optimization, and would be the natural next step from this study.

For this search we assume maximum focusing gradients provided by either saturation in the magnet or current limitation or temperature increase limits defined by the magnet coils [17] as we assume these are given boundary conditions. We neglect, however, the current limits given by the present power supplies since we assume these can be exchanged in this upgrade phase. For the MAX IV 3 GeV storage ring this amounts to five free parameters. Along with these parameters come a set of obvious boundary constraints: $J_x > 0$, $J_\delta > 0$, and beta functions exist. Initially we distinguish between solutions providing $\beta_x^* > 4.5\,\mathrm{m}$, i.e. at the center of the long straight (in the vicinity of the injection septum) and those that require smaller β_x^*.

In order to speed up the calculations, instead of the standard Tracy-3 lattice, we use a simplified lattice where the slice models for the dipoles with longitudinal and transverse gradients have been replaced with a single hard-edge dipole and the lattice optics retuned in such a way as to preserve crucial optics parameters such as beta functions and dispersion. The grid spacing for these five parameters is not equal. We have chosen a coarser grid for the PFSs since their excitation results in a far more limited variation of the vertically focusing gradient compared to the horizontally focusing provided by dedicated quadrupoles.

As expected, a decrease of the bare lattice emittance is a necessary but not sufficient condition to maximizing brightness. This is illustrated by Fig. 1. For the brightness calculations we use `sddsbrightness` [18] and have assumed a typical MAX IV in-vacuum undulator (IVU) "pmu18p5" [19] with an 18.5 mm period, 3.8 m length, and effective K value of 0.4 to 1.92. We have decided to focus on the 7th harmonic for the production of 1 Å X-rays. Studies have however shown this is equivalent to maximizing brightness at the 5th harmonic[3] as demonstrated by the very high correlation depicted in Fig. 2.

First studies have indicated that a bare lattice emittance as low as 99 pm rad (less than 1/3 of the design optics value) can be achieved in simulation, however, this comes at the expense of a peak β_y on the order of 700 m, which is considered unworkable in terms of natural chromaticity, vertical acceptance, and hence lifetime. These same first studies also indicate that the most substantial increase of brightness is only possible for $\beta_x^* < 4.5\,\mathrm{m}$ (cf. Fig. 3) which quite clearly indicates that off-axis injection in its present implementation [20] would need to be replaced. Finally, these GLASS studies also reveal that leaking a small amount of dispersion into the long straights is necessary to achieve highest brightness. Fig. 4 demonstrates this quite clearly. Typically

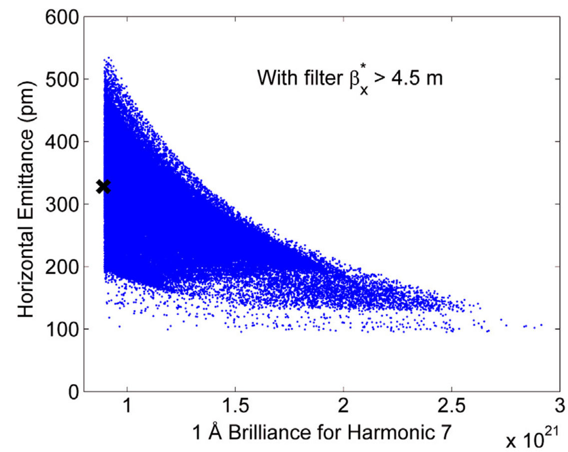

Fig. 1. GLASS solutions showing that maximizing brightness requires minimizing bare lattice emittance. The black cross indicates the baseline design optics.

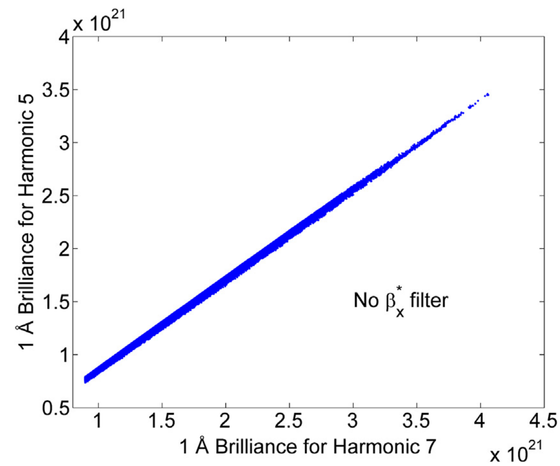

Fig. 2. GLASS solutions showing equivalence of brightness optimizations at the 7th and 5th harmonic of a typical MAX IV IVU.

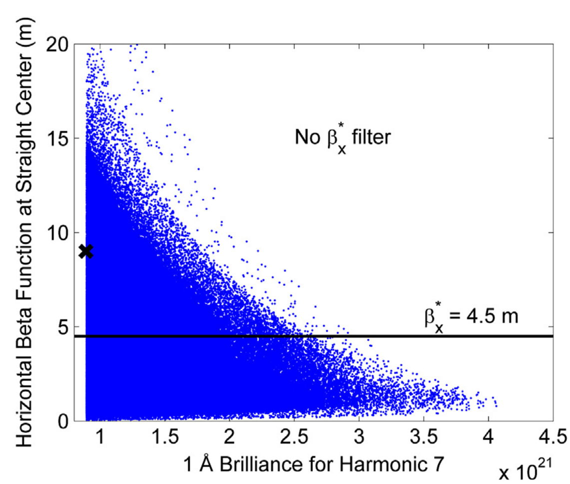

Fig. 3. GLASS solutions showing that maximizing brightness requires reducing the horizontal beta function in the long straights β_x^*. The black cross indicates the baseline design optics.

[3] For reference, at 500 mA stored current and $\epsilon_y = 2\,\mathrm{pm\,rad}$ [12], the design optics gives a brightness of 8.95×10^{20} photons/s/mm^2/mrad^2/0.1% BW and 7.84×10^{20} photons/s/mm^2/mrad^2/0.1% BW for the 7th and 5th harmonics, respectively.

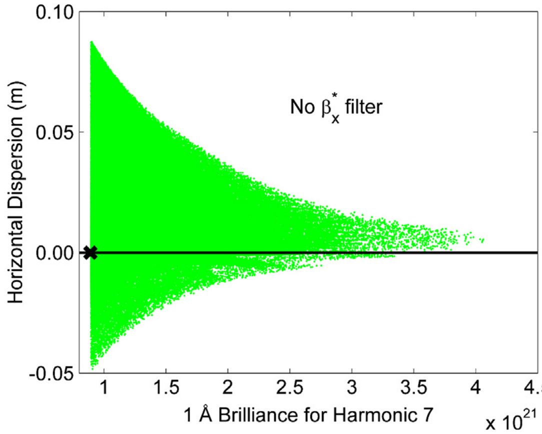

Fig. 4. GLASS solutions showing that maximizing brightness requires a small amount of dispersion leaked into the long straights η_x^*. The black cross indicates the baseline design optics.

required values are on the order of $\eta_x^* \approx 10$ mm which, however, translates to a beam size increase at the source of only 3% which is considered entirely manageable.

In an attempt to retain off-axis injection, a second parameter study was carried out where, in addition to the boundary constraints detailed above, two cuts were added, namely $\epsilon_x < 340$ pm rad and $\beta_x^* > 4.5$ m. For the four families of quadrupoles, Fig. 5 shows the scan region and the resulting bare lattice emittance. Only a single solution emerges with a brightness greater than 2.2×10^{21} photons/s/mm^2/mrad^2/0.1% BW. Fig. 6 shows brightness curves and indicates the roughly 2.5-fold increase of brightness at 1 Å compared to the baseline design optics. This solution renders a bare lattice emittance of 170 pm rad and $\beta_y^* \approx 2$ m. However, the peak vertical beta function becomes very large resulting in $\xi_y = -325$.

On the other hand, there exist solutions that still double the brightness without entailing strong growth of natural chromaticity. As Fig. 7 illustrates, we can find solutions which double the design brightness while retaining natural chromaticity larger than −100. As a consequence, the minimum achievable emittance will be between 100 and 200 pm rad. These solutions are all slightly achromatic, show a strong increase of ν_x while ν_y remains almost constant, and provide $\beta_x^* < 8$ m.

Finally, in a third study we investigate two options still compatible with off-axis injection: we require peak $\beta_y < 50$ m as well as $\beta_x^* = 7$ m or 6 m. The latter two options both lead to the same 221 pm rad bare lattice emittance, however, the leaked dispersion and vertical beta function at the source are rather different: $\eta_x^* = 5$ mm or 11 mm as well as $\beta_y^* = 0.46$ m or 0.54 m. The solution with $\beta_x^* = 7$ m is further pursued. With this solution we can increase the brightness by about 80% compared to the design. Fig. 8 shows the optics that result from this solution. The strong suppression of β_y in the long straights as well as the drop in horizontal dispersion that lead to the emittance reduction are clearly visible. Typical beam sizes at the ID source points are 39 μm in the horizontal and 1 μm in the vertical (at $\epsilon_y = 2$ pm rad). The most important lattice parameters for the design optics and this modified optics are summarized in Table 1.

3. Nonlinear optics & beam dynamics

In a next step the nonlinear optics of the upgrade lattice was optimized following the well established procedure used during the original MAX IV design studies [2,3]. Boundary constraints for the gradients are considered determined by magnet and cabling limits alone [17]. Power supplies are assumed exchangeable. While the resulting lattice momentum acceptance appears sufficient in terms of Touschek lifetime,

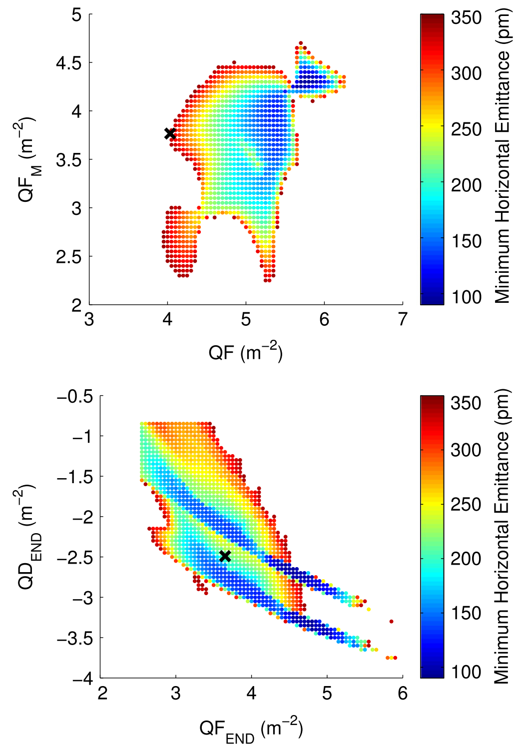

Fig. 5. GLASS solutions showing the minimum bare lattice emittance as a function of settings of the quadrupoles. Top: arc quadrupoles. Bottom: ID straight section doublets. The black cross indicates the design lattice settings.

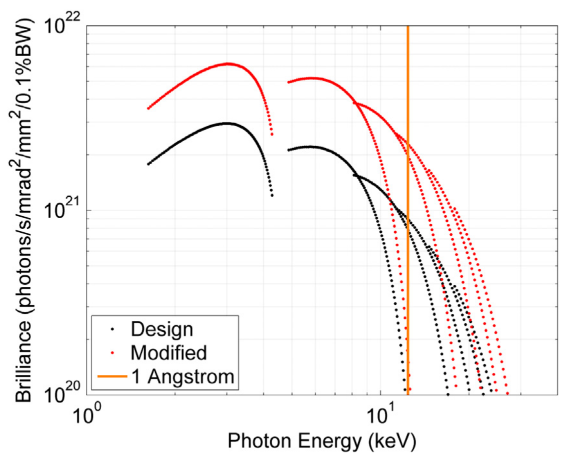

Fig. 6. A roughly 2.5-fold brightness increase at 1 Å (at the 7th harmonic) from the modified optics compared to the design optics in the MAX IV 3 GeV storage ring.

the on-momentum dynamic aperture (DA) is still not quite at the level desired for off-axis injection (cf. Fig. 9). The limited DA at the injection point on the ring outside is not an immediate concern because injection occurs from the ring inside,[4] however, the resulting ≈ 5 mm DA on the inside does not quite offer enough headroom once all imperfections are included. This can be recognized by comparison with the DA including machine imperfections that resulted from the short-term (1st stage) upgrade optics [13]. While the level of machine imperfections (which

[4] Note also, since the injected beam comes from the full-energy MAX IV linac, the emittances (and beam sizes) of the injected beam are actually comparable to those of the stored beam [21].

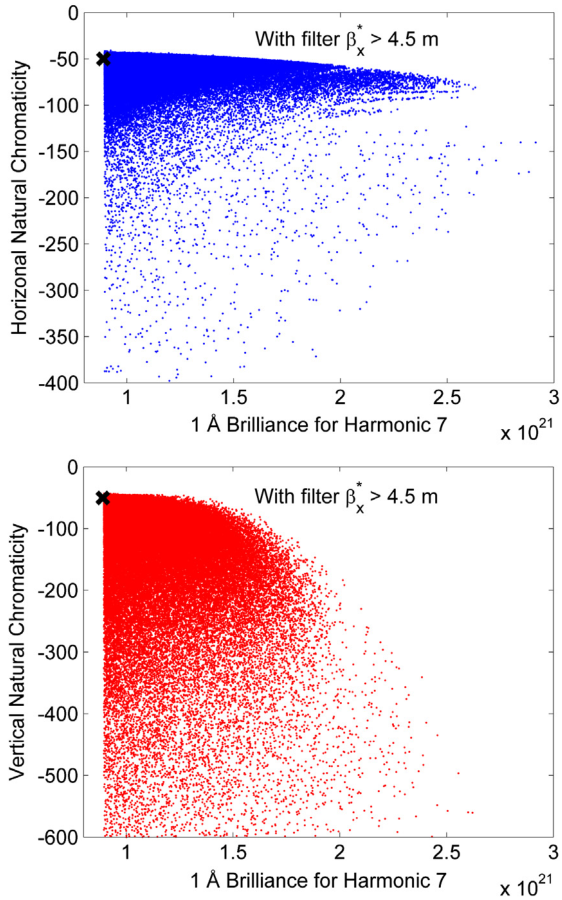

Fig. 7. GLASS solutions showing the resulting natural horizontal (top) and vertical (bottom) chromaticity vs. brightness. The black cross indicates the baseline design optics.

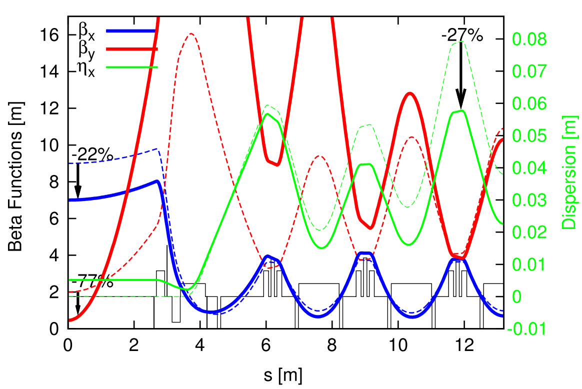

Fig. 8. Machine functions for one half of an achromat of the MAX IV 3 GeV storage ring. The design optics are indicated in dashed lines, while the solid lines indicate the modified optics. The black lines at the bottom depict the various magnetic elements.

appear to match the actually encountered situation during commissioning quite well [9]) does not substantially reduce DA at injection, it does indicate that about 6 mm of DA are required to ensure that roughly 5 mm remain available as required for injection on the ring inside [20–22]. Further nonlinear optimization (possibly including breaking up the existing five sextupole families as per the 3rd upgrade stage) is expected to add the roughly 1 mm still needed and thus demonstrate feasibility of the proposed upgrade optics.

For the sake of completeness, magnet family settings for the design optics and the modified optics are given in Table 2. All required gradients are within the thermal limits of the coils and the magnet iron.

Table 1
MAX IV 3 GeV storage ring parameters for the design optics and the modified optics. Details for the ID-loaded configuration are given in [10].

	Design	Upgrade
ε_0 (bare lattice)	328 pm rad	221 pm rad
ε_0 (fully ID-loaded)	190 pm rad	130 pm rad
ν_x, ν_y	42.20, 16.28	47.20, 15.28
ξ_x, ξ_y (natural)	−50.0, −50.2	−56.5, −127.8
J_x	1.85	1.57
σ_δ (natural)	7.69×10^{-4}	7.01×10^{-4}
α_c (linear)	3.06×10^{-4}	2.05×10^{-4}

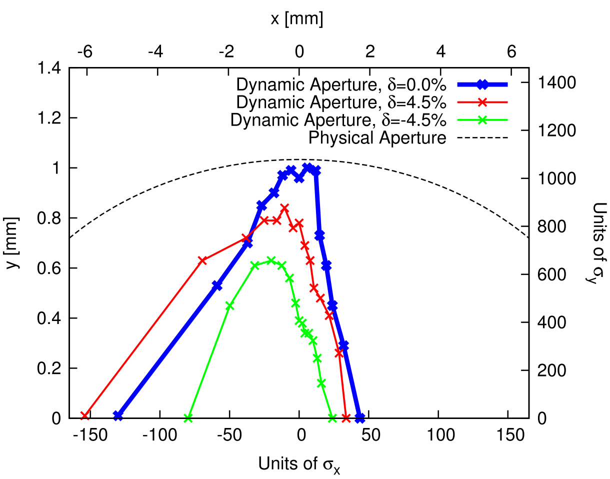

Fig. 9. On- and off-momentum DA for the bare lattice using the modified optics. The dashed line indicates the overall available physical aperture determined by vacuum chamber and ID apertures.

Table 2
Gradient strengths in the MAX IV 3 GeV storage ring magnets according to design along with required changes for the modified optics.

Family	Required Norm. Gradient		Rel. Change
	Design	Upgrade	
DIP	$-0.865\,\mathrm{m}^{-2}$	$-0.882\,\mathrm{m}^{-2}$	+2.0%
DIPm	$-0.871\,\mathrm{m}^{-2}$	$-0.888\,\mathrm{m}^{-2}$	+2.0%
QF	$4.033\,\mathrm{m}^{-2}$	$4.634\,\mathrm{m}^{-2}$	+14.9%
QFm	$3.766\,\mathrm{m}^{-2}$	$3.935\,\mathrm{m}^{-2}$	+4.5%
QFend	$3.651\,\mathrm{m}^{-2}$	$3.798\,\mathrm{m}^{-2}$	+4.0%
QDend	$-2.491\,\mathrm{m}^{-2}$	$-2.709\,\mathrm{m}^{-2}$	+8.8%
SFi	$208.7\,\mathrm{m}^{-3}$	$333.0\,\mathrm{m}^{-3}$	+59.6%
SFo	$174.0\,\mathrm{m}^{-3}$	$171.0\,\mathrm{m}^{-3}$	−1.7%
SFm	$170.0\,\mathrm{m}^{-3}$	$177.0\,\mathrm{m}^{-3}$	+4.1%
SD	$-117.0\,\mathrm{m}^{-3}$	$-163.8\,\mathrm{m}^{-3}$	+40.0%
SDend	$-170.0\,\mathrm{m}^{-3}$	$-194.0\,\mathrm{m}^{-3}$	+14.1%
OXX	$-1681\,\mathrm{m}^{-4}$	$8900\,\mathrm{m}^{-4}$	+429.4%
OXY	$3263\,\mathrm{m}^{-4}$	$-6367\,\mathrm{m}^{-4}$	+95.1%
OYY	$-1428\,\mathrm{m}^{-4}$	$1933\,\mathrm{m}^{-4}$	+35.4%

The strongest change of excitation is clearly required for the octupoles (note also the sign change to counteract the different detuning with amplitude). However, the MAX IV octupoles were originally specified for a ±100% tuning range, so ample octupole gradients strength is available.

4. Analysis & outlook

A possible upgrade optics has been developed for the MAX IV 3 GeV storage ring, that retains the magnetic lattice while delivering a typical brightness about twice the design value. As IDs are added to the storage ring, this optics will eventually enable a zero-current emittance around 130 pm rad, rendering a brightness (including the effects of IBS and harmonic cavities) about three times higher than in the original design. This proposed optics appears in terms of achievable emittance about as low as can be expected without exchanging the actual magnets and/or giving up off-axis injection.

The linear optics reveals that a split up of the horizontally focusing quadrupole family QF in the arc could allow lowering the beating of the dispersion peaks in the arc, thus further lowering the emittance. Studies have so far, however, shown only limited benefit. In hindsight we have to realize that it would have been advantageous to realize the transverse gradient dipoles with exchangeable pole faces (as was done for all other magnets in the MAX IV 3 GeV storage ring) so that the vertical focusing in the arc could be adjusted by more than the limited range provided by the PFSs (note the reduction of J_x in Table 1).

The resulting momentum compaction is rather low which entails bunch shortening and a Touschek lifetime penalty, however, since the RF acceptance also increases with the lowered momentum compaction (and since the lattice acceptance in parts of the lattice exceeds the design RF acceptance), the overall lifetime penalty remains limited. In the case that in connection with a lower coupling [12] the Touschek lifetime does become too low [10], excitation of dispersion bumps throughout the arcs only [23] remains a suitable method to increase Touschek lifetime without sacrificing user brightness.

Further optimization could be carried out using stochastic optimization (e.g. multi-objective genetic algorithms or particle swarm algorithms), which can simultaneously optimize the linear and nonlinear dynamics of the lattice. Our GLASS study has mapped out the basic parameter space that can be used to seed such optimization algorithms.

If we are prepared to give up off-axis injection, we can contemplate solutions with substantially lower β_x^* as long as they do not lead to excessive natural chromaticities. Such solutions should allow for maximum brightness within the limits of the existing magnetic lattice. Since the MAX IV 3 GeV storage ring offers a large longitudinal acceptance, on-axis off-energy injection can be contemplated [24]. Such an injection scheme would be compatible with very limited dynamic aperture while at the same time exploiting a key MAX IV advantage: the 100 MHz RF system renders a 10 ns intra-bunch spacing and hence, an on-axis dipole kicker with a rise and fall time of several ns allows for user operation with transparent single-bunch top-off injection[5] without the need for any gaps in the fill pattern or swap-out of bunch trains. Such a fast kicker incidentally also opens up several interesting possibilities for timing experiments at the storage ring [25–27] without requiring a single-bunch or hybrid fill pattern (e.g. pseudo-single bunch [28]). Furthermore, an aggressive upgrade optics with small dynamic aperture, but compatible with on-axis top-off injection also opens up very interesting possibilities for round beams and/or novel types of insertion devices (e.g. Delta or double-helical undulators).

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