MAX IV Emittance Reduction and Brightness Improvement

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MAX IV EMITTANCE REDUCTION AND BRIGHTNESS IMPROVEMENT

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Abstract

With MAX IV construction well underway and storage ring commissioning expected to commence in July 2015, first studies have been launched to improve the optics of the MAX IV 3 GeV storage ring with the goal of further reducing the emittance from the baseline design (328 pm rad) towards 150 pm rad while improving the matching of the electron beam to insertion devices to further improve the resulting photon brightness. We report on progress in the development of this new optics taking into account the strong impact from intrabeam scattering and insertion devices on the resulting equilibrium emittance. We present initial results and sketch a path towards a first MAX IV upgrade.

INTRODUCTION

Construction of the MAX IV facility [1, 2] is progressing well. Commissioning of the MAX IV 3 GeV linac has recently started while beam commissioning of the 3 GeV storage ring [3] is expected to commence in July 2015. Inauguration of the MAX IV facility will be on June 21, 2016 and design specifications of the 3 GeV storage ring should be reached by summer 2017. In view of the accelerator physics development program after this early period, the recently released MAX IV Strategic Plan 2013–2026 [4] 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. The latter has recently been investigated in studies presented in [5], whereas the former shall be investigated in this paper.

As has been previously shown [3, 6], a strong reduction of the horizontal emittance can be achieved by adding damping wigglers (DWs) to the MAX IV 3 GeV storage ring. This is a straightforward approach that has been applied successfully at PETRA III and will also be used at NSLS-II. However, DWs are expensive, raise operational costs considerably, and take up straights that would otherwise be available to user insertion devices (IDs). Therefore, studies at MAX IV have focused on increasing photon brightness through a reduction of lattice emittance as well as an improved matching of the electron beam to the IDs.

STRATEGY AND LIMITATIONS

Both the optics improvements to lower the lattice emittance as well as those to improve the matching of the electron beam to the IDs can be staged. In a first stage the optics are modified so that the present cabling and power supplies can be retained[1]. In a second stage, the exchange of power supplies can be contemplated, therefore allowing more substantial optics variations. Finally, in a third stage, recabling of the magnets can be considered so that existing individual families are broken up into several new families allowing for increased flexibility.

The first stage shall be investigated in this paper. The horizontal focusing in the arcs (cf. Fig.1) can be increased thus reducing the dispersion and hence the lattice emittance [7]. The focusing quadrupoles in the arc and their power supplies

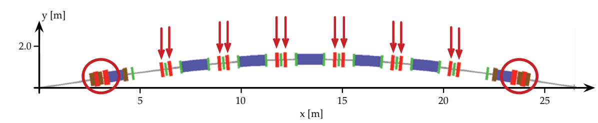

Figure 1: One achromat of the MAX IV 3 GeV storage ring. Quadrupoles are indicated in red. The quadrupole doublets in the straights (circles) and horizontally focusing quadrupoles in the arc (arrows) are highlighted.

offer substantial headroom so that such a tuning is feasible. The quadrupole doublets in the straights also offer enough flexibility to reduce the beta functions in the IDs therefore improving the matching of the electron beam to the intrinsic photon beam from the ID and hence increasing the resulting photon brightness [5]. So far, the achromatic condition in the straights has been retained.

The vertical focusing in the arcs is provided by a gradient in the dipoles. This gradient can, however, be modified by exciting a current in the dipole pole face strips (PFSs). By design the PFSs can vary the vertical focusing by about ±4% of which roughly ±1% will be used to adjust to the design working point. This leaves some headroom for changes to the vertical focusing in the arc. So far, however, this has not been required.

In terms of nonlinear optics, the focus so far has been on retaining the fractional tunes and optimizing chromatic and amplitude-dependent tune shifts in a fashion similar to the design optics [7]. The integer tunes are allowed to move. Sextupole and octupole magnets as well as their power supplies so far appear to offer enough tuning flexibility [8]. The dynamic aperture (DA) requirements are considered unchanged. The vertical requirement is quite relaxed as a consequence of the limited physical acceptance resulting from in-vacuum IDs and narrow-gap ID chambers. The horizontal DA requirement is determined by the injection process [9] where roughly 5–6 mm of residual betatron oscillation amplitude after capture is expected[2].

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[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 controlling the entire family.

[2] Note that this requirement also results from lifetime considerations. In order to retain good Touschek lifetime in an ultralow-emittance storage ring, a large momentum acceptance (MA) is required [6]. For the design optics, the maximum RF bucket height is 7.1% and the horizontal DA required in the straights for the lattice MA to match this RF acceptance is 5–6 mm. Hence, if Touschek lifetime shall be retained, the horizontal

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MODIFIED OPTICS

By increasing the focusing strength of the arc quadrupoles the dispersion and hence the emittance can be reduced. An increase in focusing strength of the straight section quadrupole doublets lowers the beta functions in the IDs. An initial scan of quadrupole parameters indicated that the lattice emittance can be lowered from its design value of 328 pm rad to roughly 270 pm rad in this way while the vertical beta function at the center of the straight can be reduced to half its design value of 2 m or less (cf. Fig. 2). The horizontal beta function at the straight center varies between 7–8 m. In this way the horizontal tune is increased by two integers, while the vertical tune reduces by two. The maximum of the vertical beta function, located in the outermost arc dipoles, grows considerably (25–27 m vs. the design 16 m). However, taking into account narrow-gap chambers in the straight sections, the vertical acceptance of the storage ring is not affected by this increase.

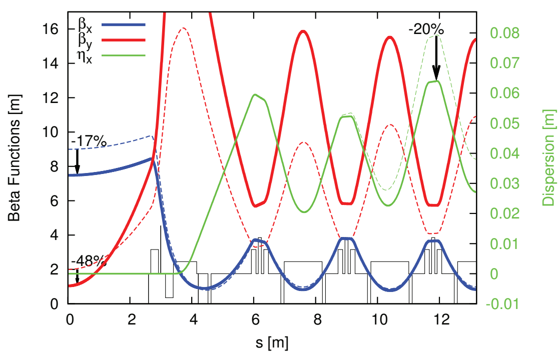

Figure 2: Machine functions for one half of an achromat of the MAX IV 3 GeV storage ring. The design optics are indicated in dashed lines, while the solid lines indicate one possible modified optics.

The peak dispersion drops from 8 cm to 6.4 cm which leads to the emittance reduction, but also to a significant drop in linear momentum compaction α_c. Since the bare lattice losses are determined by the dipoles and therefore remain unchanged at 363.8 keV/turn, the reduction of α_c increases the RF acceptance for a given cavity voltage. Because the lattice acceptance exceeds the RF acceptance in parts of the lattice, this translates to an improved Touschek lifetime in addition to the Touschek lifetime increase from the reduction of emittance [6].

So far reasonable DA has been achieved for candidates where the vertical beta function at the center of the straight has not been reduced below 1 m. In terms of photon brightness an even lower beta function could be desired [5], but sufficient DA is deemed more important at this point. The choice of 7.5 m horizontal beta function at the straight center is a compromise between the desire to lower the beta function to improve the photon brightness and the requirement to preserve the injection scheme. Table 1 compares key parameters for design optics vs. the modified optics shown in Fig. 2.

DA requirement cannot be substantially relaxed by choosing a more aggressive injection scheme.

Table 1: MAX IV 3 GeV storage ring parameters for the design optics and the modified optics.

	Design	Upgrade
ε_0 (bare lattice)	328 pm rad	269 pm rad
ν_x, ν_y	42.20, 16.28	44.20, 14.28
ξ_x, ξ_y (natural)	−50.0, −50.2	−50.7, −76.5
J_x	1.847	1.719
σ_δ (natural)	7.69×10^{-4}	7.29×10^{-4}
α_c (linear)	3.06×10^{-4}	2.60×10^{-4}

A summary of the required strength changes for the different magnet families is shown in Table 2. The only family that requires significantly more gradient is OXX, but since the octupole magnets and power supplies were required to offer lots of headroom by design, the current power supply is sufficient [8]. The resulting on-momentum DA using the standard MAX IV error model [10] is displayed in Fig. 3.

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

	Required Norm. Gradient		
Family	Design	Upgrade	Rel. Change
QF	4.030 m^{-2}	4.296 m^{-2}	+6.6%
QFm	3.774 m^{-2}	3.781 m^{-2}	+0.2%
QFend	3.654 m^{-2}	3.700 m^{-2}	+1.3%
QDend	−2.504 m^{-2}	−2.562 m^{-2}	+2.3%
SFi	207.4 m^{-3}	211.8 m^{-3}	+2.1%
SFo	174.0 m^{-3}	190.0 m^{-3}	+9.2%
SFm	170.0 m^{-3}	190.0 m^{-3}	+11.8%
SD	−116.6 m^{-3}	−129.9 m^{-3}	+11.4%
SDend	−170.0 m^{-3}	−160.0 m^{-3}	−5.9%
OXX	−1649 m^{-4}	−3141 m^{-4}	+90.5%
OXY	3270 m^{-4}	2410 m^{-4}	−26.3%
OYY	−1420 m^{-4}	−944.2 m^{-4}	−33.5%

BRIGHTNESS IMPROVEMENTS & OPERATIONAL CONCERNS

The combination of lowered lattice emittance (−18%) and reduced beta functions in the IDs allows substantially increasing the brightness (+33%) without requiring any new hardware procurement or recabling of the magnets. Figure 4 shows the brightness increase compared to design parameters for various settings of the emittance coupling. The emittance values used here so far are zero-current values and will of course increase when intrabeam scattering (IBS) at 500 mA is included. However, as shown previously [6], this can be mitigated by bunch lengthening from Landau cavities. When bunches are lengthened according to design, the

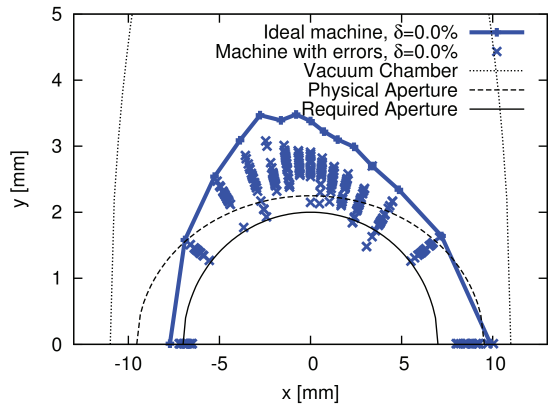

Figure 3: On-momentum DA for the bare lattice using the modified optics. The solid line indicates the ideal DA while the crosses correspond to results for 20 error seeds including misalignments as well as field and multipole errors.

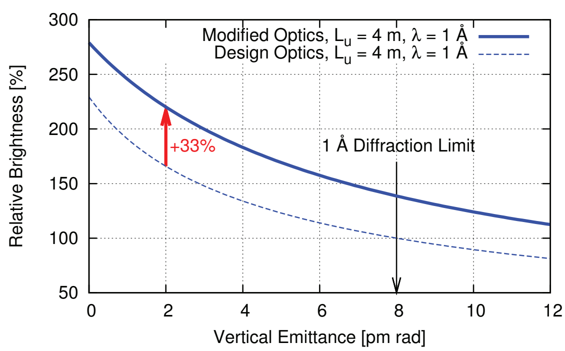

Figure 4: Brightness increase (at 1 Å) from the modified optics compared to the design optics for different settings of emittance coupling in the MAX IV 3 GeV storage ring.

emittance blow-up from IBS is estimated to remain below 27%.

Further studies will be required to include the effect of the overall lowered emittance when operating many IDs. This is an important issue in ultralow-emittance rings where dipole radiation losses are low and hence the equilibrium emittance is determined to large extent by the IDs [6]. First results indicate the new optics together with a moderately ID-equipped ring will give a zero-current emittance on the order of 190 pm rad which will increase to no more than 250 pm rad at full 500 mA stored current (including bunch lengthening form the Landau cavities). In principle one could consider running at reduced current to lower the emittance, but so far, brightness optimization studies indicate that the flux penalty from lowering the current outweighs the brightness increase from overall emittance reduction.

CONCLUSIONS & OUTLOOK

The proposed change to the MAX IV 3 GeV storage ring optics presents a possible upgrade path towards zero-current emittances below 200 pm rad. Although IBS will increase this value during user operation at 500 mA stored current, the bunch lengthening from LCs should ensure overall emittance remains below 250 pm rad. In combination with the improved optics matching to IDs, this should result in a brightness increase on the order of 30% without requiring any new power supplies or changes to magnet cabling. An interesting aspect of this proposed optics improvement is that Touschek lifetime—without requiring changes to the RF system—will actually improve.

So far it appears the injection scheme will require only minor adjustments despite the changes to the optics. Further studies will focus on additional emittance reduction from e.g. splitting up quadrupole families to further increase the horizontal focusing in the arc as well as changes to the vertically focusing gradient in the arc dipoles via PFSs. Finally, in order to achieve larger DA further optimization of the nonlinear optics, possibly including MOGA will be pursued.

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