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3.2 The MAX IV 3 GeV Storage Ring

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3.2.1 Introduction

The MAX IV facility [1], which is presently under construction in southern Sweden, will become fully operational in 2015. Once complete, it will provide users with synchrotron radiation covering a spectral range from infrared to hard X-rays and time structures from ~ 30 fs to ~ 200 ns. In addition to spontaneous radiation, spatially and temporally coherent radiation will eventually also be produced. Early on in the design process, it was established that not all of the user requirements of an advanced synchrotron radiation source can be equally fulfilled by a single machine. Instead, a global optimization of the facility based on the wide range of user demands was performed, resulting in a solution using two separate storage rings (3 GeV and 1.5 GeV) [2-4] and a linac-driven short-pulse facility (SPF) [5,6] which will be upgraded to a FEL in a second phase. This 3.5 GeV linac also serves as a full-energy injector to both storage rings therefore enabling top-up operation at a constant 500 mA in both rings.

The 1.5 GeV storage ring is a fairly conventional DBA design with 96 m circumference, 10 user straights, and 6 nm rad equilibrium emittance. It is essentially an upgraded version of the existing MAX II storage ring using the fully integrated magnet design demonstrated in MAX III. This ring will replace the old MAX II and MAX III storage rings as the source for IR and UV radiation at MAX-lab and a few present-day beamlines will move to this new storage ring. This ring will be built twice: once in Lund for the MAX IV facility and once in Krakow, Poland for the Solaris Project [7].

The 3 GeV storage ring on the other hand, is a entirely novel design based on a 20-fold multibend achromat lattice offering 19 user straights with an equilibrium emittance below 300 pm rad. Moderate coupling will ensure vertical beam sizes in the insertion devices (ID's) below the 1 Å diffraction limit. With a constant stored current of 500 mA, the MAX IV 3 GeV storage ring is expected to become the brightest storage ring-based light source worldwide when it goes into operation in 2015. Not only does this storage ring deliver unprecedented ultralow emittance, it makes use of several less conventional technologies. The rest of this article will focus on the design and expected performance of this storage ring.

3.2.2 Lattice and Optics

The 3 GeV storage ring will serve as the main radiation source of the MAX IV facility. In order to generate high-brightness hard X-rays with state-of-the-art ID's an ultralow-emittance design was targeted [8,9]. One simple and robust method to achieve ultralow emittance is the use of a multibend achromat (MBA) lattice [10-12]. The MBA exploits the inverse cubic dependence of emittance on the number of bending magnets. By choosing a very small bending angle per dipole and introducing a vertically focusing gradient in the dipoles (the emittance scales inversely with the horizontal damping partition J_x), the emittance can be dramatically reduced while the dispersion is limited to small values. This in turn allows the use of narrow vacuum chambers and compact magnets with strong gradients. Finally, by adding properly balanced sextupoles and octupoles, the nonlinear optics can be tuned for large momentum acceptance and dynamic aperture rendering long Touschek lifetime and high injection efficiency despite the very low emittance [13].

3.2.2.1 *Linear Optics*

The MAX IV 3 GeV storage ring consists of twenty 7-bend achromats separated by 4.6 m long straight sections for ID's. An overview of one MAX IV achromat is shown in Fig.1. Each of the achromats consists of 5 unit cells and 2 matching cells. The unit cells have a 3° bending magnet, while the matching cells at the ends of the achromat have a 1.5° soft-end bending magnet. In these soft-end dipoles, the magnetic field drop-off towards the long straight reduces the amount of radiation hitting a downstream ID therefore facilitating the design of superconducting IDs. All dipoles contain a vertically focusing gradient. The matching cells contain dedicated quadrupole doublets in order to match the achromat optics to the ID in the long straight. Each achromat also contains two 1.3 m short straights that separate the matching cells from the unit cells. These short straights can be used for RF cavities and diagnostics so that all long straights but the injection straight are available for installation of IDs.

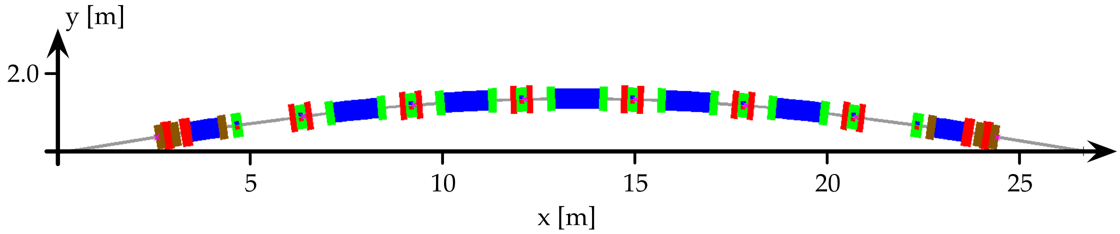

Figure 1: Schematic of one of the 20 achromats of the MAX IV 3 GeV storage ring. Magnets indicated are gradient dipoles (blue), focusing quadrupoles (red), sextupoles (green), and octupoles (brown).

Since the vertical focusing is performed by the gradient dipoles, dedicated quadrupoles are, apart from ID matching, only required for horizontal focusing. Horizontally focusing quadrupoles are installed between the cells of the achromat in pairs of two where the two quadrupoles are installed on either side of a sextupole magnet. There are two families of focusing quadrupoles, one in the unit cells and one in the matching cells. Adjustment of the vertical focusing is performed by exciting a current in the pole-face strips (PFS's) that are installed in all dipoles. This results in a very compact optics with strong focusing, low beta functions, and very small peak dispersion. The optics for one achromat are displayed in Fig.2 and ring parameters are given in Table 1.

The working point was chosen away from systematic resonances and so that both fractional tunes are just above the integer and away from the most dangerous resonances. With the working point held constant during operation, the nonlinear optics can be set to minimize the chromatic and amplitude-dependent tune shifts therefore keeping the tunes of most stored beam particles clear of dangerous resonances. This shall be explained in the next section.

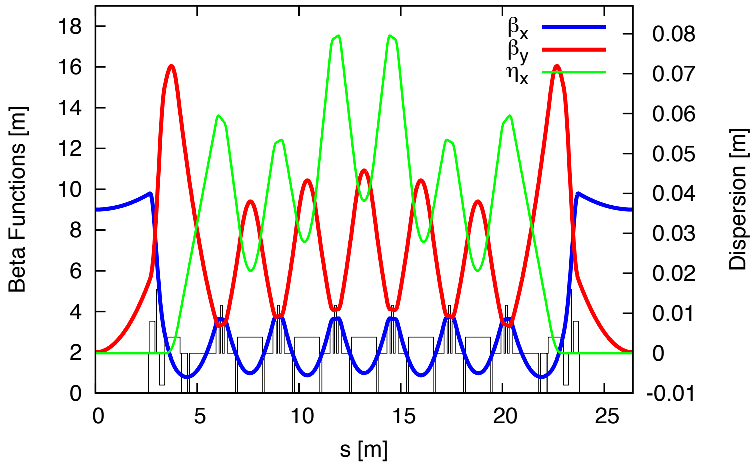

Figure 2: Beta functions and dispersion for one achromat of the MAX IV 3 GeV storage ring. Magnet positions are indicated at the bottom.

Table 1: Parameters for the MAX IV 3 GeV storage ring.

Parameter	***Unit***	***Value***
Energy	GeV	3.0
Main radio frequency	MHz	99.931
Circulating current	mA	500
Circumference	m	528
Number of achromats	…	20
Number of long straights available for IDs	…	19
Betatron tunes (H/V)	…	42.20 / 16.28
Natural chromaticities (H/V)	…	-50.0 / -50.2
Corrected chromaticities (H/V)	…	+1.0 / +1.0
Momentum compaction factor	…	3.07×10^{-4}
Horizontal damping partition	…	1.85
Horizontal emittance (bare lattice)	nm·rad	0.326
Radiation losses per turn (bare lattice)	keV	360.0
Natural energy spread	…	0.077%
Required momentum acceptance	…	4.5%

3.2.2.2 *Nonlinear Optics*

Despite comparably relaxed linear optics, the nonlinear optics of such a MBA lattice are demanding. The strong focusing gives rise to large negative natural chromaticities that need to be corrected to prevent head-tail instability. This can be performed with chromatic sextupoles. Because of the low dispersion in the MBA these sextupoles tend to become very strong. Although this is not a concern for the magnet design (the 25 mm nominal magnet bore allows strong gradients), it presents an optics design challenge as such strong sextupoles give rise to pronounced nonlinear, amplitude-dependent behavior, which can limit both dynamic aperture and momentum acceptance. The most common approach is to install several additional families of sextupoles separated by appropriate phase advances in an attempt to cancel resonance driving terms and limit chromatic tune shifts [14].

The MAX IV 3 GeV storage ring contains five sextupole families, three focusing and two defocusing. The focusing sextupoles are installed between the focusing quadrupoles in the unit cells. This puts these sextupoles at locations with comparably large horizontal beta function and dispersion. The defocusing sextupoles are installed as close as possible to the maximum of the product of dispersion and vertical beta: unit cell dipoles are flanked on either side by a defocusing sextupole of one family while the defocusing sextupoles in the matching cells are installed in the short straights right next to the matching cell soft-end dipole. In this way, sextupoles compensate chromaticity where it's created thus limiting chromatic beta beating. Because of the large number of installed sextupoles and the small magnet gap, the sextupoles can be kept short.

Sextupole optimization was performed with the codes OPA [15] and Tracy-3 [16]. The linear chromaticities were corrected to +1.0 in both planes and the first-order resonance driving terms along with second and third-order chromaticity were minimized as detailed in [14]. However, amplitude-dependent tune shifts (ADTS's) are only corrected as a second-order effect in sextupoles therefore requiring a lot of sextupole gradient strength and in turn driving resonances and chromatic tune shifts. This can necessitate extra sextupoles and/or increased sextupole gradients in order to keep first-order terms in check. Apart from leading to a potential run-away problem, this is a delicate balance that is easily disturbed by ID's, alignment errors, and higher-order multipoles — all of which exist in a real machine. In an attempt to solve this fundamental challenge of nonlinear optimization in a MBA lattice, three achromatic octupole families were introduced into the matching cells of the 3 GeV achromat in locations with appropriate beta function ratios [2,13]. These octupoles correct the three terms for ADTS *to first order*. Analogous to the linear system, which is solved to find sextupole strengths that give a certain chromaticity, a linear system can be set up to describe the ADTS's that result from an octupole in the lattice. This system can be inverted to calculate octupole strengths that give the desired ADTS's. Rather than setting the linear ADTS to zero, the octupoles in the MAX IV MBA were adjusted so the resulting overall ADTS is minimized throughout the physical acceptance (cf. Fig.3).

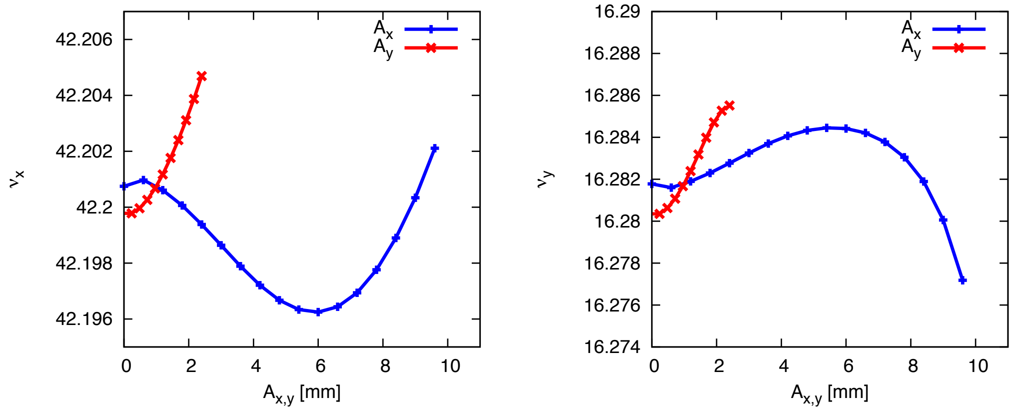

Figure 3: Amplitude-dependent tune shift in the MAX IV 3 GeV storage ring with octupoles at design strength.

Because the ADTS is corrected with the octupoles, the sextupoles are freed up for first-order corrections (linear chromaticity, resonance driving terms). Some extra weight was added to minimize second and third-order chromaticity in an attempt to limit the chromatic tune footprint (cf. Fig.4).

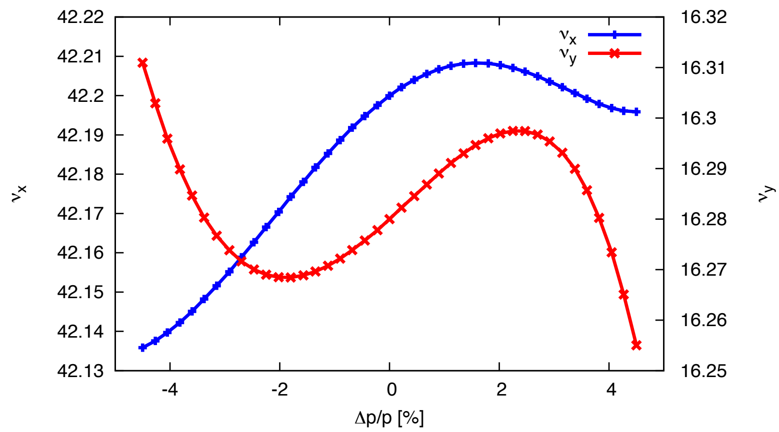

Figure 4: Chromaticity in the MAX IV 3 GeV storage ring with octupoles at design strength.

The result of this nonlinear optimization is a very limited tune footprint for particles with a range of amplitudes covering the physically accessible aperture (roughly 9 mm / 2 mm [H/V] at the center of the ID's) and energies covering the required ±4.5% acceptance. This results in large dynamic aperture and momentum acceptance (cf. Fig.5 and Section 3.1.3.3), which ensure high injection efficiency and good Touschek lifetime. Frequency map analysis confirmed the "wrap-up" of tune shifts around the working point which results in this compact tune footprint. This holds also for a realistic machine, i.e. a storage ring with errors, misalignments, and IDs. This shall be discussed in the next section.

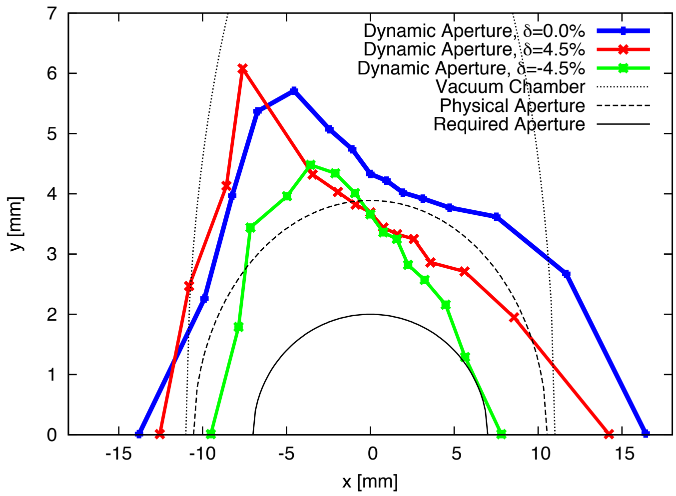

Figure 5: Dynamic aperture at the center of the long straight section in the MAX IV 3 GeV storage ring (bare lattice). Tracking was performed with Tracy-3 in 6D for half a synchrotron period. For comparison, the vacuum chamber and physical aperture (projection of vacuum chamber to the track point) are also indicated in the plot.

3.2.2.3 *Matching and Correction*

With the quadrupole doublets in the matching cells the beta functions in the long straights can be tuned over a fairly wide range. This allows matching of the linear optics to the ID. The ID matching is performed both locally (beta functions are matched to prevent beta beats) and globally (phase advances are corrected to restore the design working point). For the global correction the PFS's in the dipoles are used to adjust the vertical focusing. Because this matching results in restoring the design linear optics within the achromat, the nonlinear optics optimization is left almost undisturbed. If the multipolar content of the IDs is limited to specified values [17], neither sextupoles nor octupoles have to be adjusted with ID gap movement. Tracking studies (with Tracy-3 using kick maps) reveal that, in the storage ring equipped with many strong in-vacuum undulators, the dynamic aperture is not substantially reduced if the ID matching is properly performed.

All octupoles and sextupoles are equipped with extra windings that can be powered in different ways. This allows adding dispersive and non-dispersive skew quadrupoles for coupling control and removal of spurious vertical dispersion as well as auxiliary sextupoles in order to restore the design symmetry of the nonlinear optics [14]. These windings can also be powered as upright quadrupoles, which will be used to calibrate BPMs to the magnetic centers of the adjacent sextupoles.

Finally, each achromat also contains 10 horizontal and 9 vertical dipole correctors as well as 10 BPMs that will be included in a slow orbit feedback. Because of the vertical beam size in the user straights reaching values as low as 2 μm rms, beam stability is crucial. There are 4 dedicated fast correctors installed around each user straight which, together with the BPM system, will allow operation of a fast orbit feedback in order to cancel beam motion effectively up to roughly 100 Hz [18]. Tracking studies have revealed that adequate dynamic aperture remains when expected misalignments are added to the lattice and the orbit is corrected using the dipole correctors [20]. This also holds if multipole errors are added to all magnets.

3.2.3 Technology

The MBA gives a very low emittance, but it requires strong magnets and compact optics, which leave little space for a conventional vacuum. Therefore, several less conventional technology choices have been made for the MAX IV 3 GeV storage ring. These shall be presented briefly in this section.

3.2.3.1 *Magnets*

The magnets for the 3 GeV storage ring are designed using a technology already successfully demonstrated at MAX III [20]. The dipoles and quadrupoles for each cell are machined out of just two solid blocks of iron. The sextupoles, octupoles, and dipole correctors are installed into precision-machined grooves in these blocks. Each achromat cell is then built up of a lower and upper block that are brought together around the vacuum chamber. Figure 6 shows this magnet design using the matching cell as an example. This magnet technology integrates girder and magnet design, which results in reduced cost and higher alignment accuracy. Furthermore, misalignments of magnets tend to be correlated and can be minimized using beam-based realignment of the blocks as demonstrated at MAX III. The blocks are installed on massive concrete supports at low height, which pushes vibrational eigenfrequencies of the assembly beyond 100 Hz thus improving beam stability.

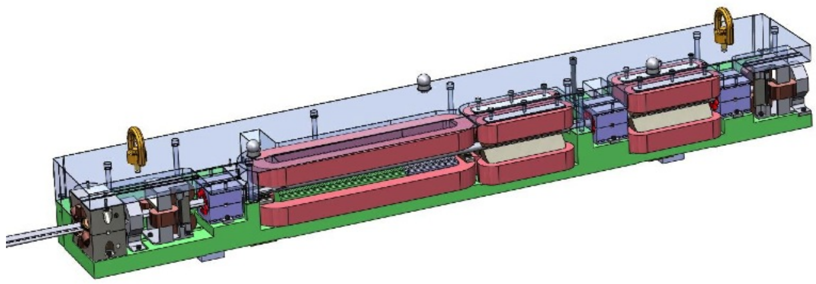

Figure 6: Drawing of a matching cell magnet block with soft-end gradient dipole, quadrupole doublet, defocusing sextupole (far left), three octupoles (blue), and two dipole corrector pairs.

3.2.3.2 *Vacuum System*

The small magnets of the MAX IV 3 GeV storage ring require a narrow vacuum chamber. Such systems are often plagued by poor vacuum conductance. In addition, because of the very compact optics of the storage ring, there is no space for lumped absorbers or distributed pumping. Instead, the 3 GeV storage ring makes use of a 22/24 mm (ID/OD) circular copper tube which is uniformly NEG-coated around the entire machine (as demonstrated [21] in two sectors of MAX II) [22]. Lumped absorbers can be avoided as synchrotron radiation is distributed along long sections of the chamber. A cooling channel is brazed to the outside of the vacuum chamber. The magnet block design foresees simple removal of the chamber for activation bake-outs in the tunnel. Few small discrete pumps will be installed in straight sections. Narrow-gap chambers and in-vacuum IDs (5 mm full vertical aperture) are foreseen in user straights. Short tapers make the transition from the circular standard vacuum chamber to the ID chambers. Bellows and valves are RF-shielded. Bellows and BPM bodies (which are rigidly fastened to the magnet blocks) are manufactured from stainless steel. These bellows are also used for mounting of the fast orbit correctors, as the copper chamber is unsuited because of strong Eddy currents.

3.2.3.3 *RF System*

Since users are provided with short pulses from the dedicated MAX IV short-pulse facility, the MAX IV storage rings can be operated with long bunches. Without increasing the chromaticity to large values (possibly limiting the energy acceptance), this alleviates instability issues that often arise when using narrow vacuum chambers. The MAX IV storage rings will therefore use a warm 100 MHz main RF system and Landau cavities at the third harmonic for additional bunch lengthening [23]. The six main cavities are an improved version of the present-day MAX II and III cavities. They are of capacity-loaded type and are HOM-damped. RF power is delivered by six stations with two 60 kW tetrode amplifiers each. This is considered a modular and cost-effective approach. The main cavities offer a maximum total gap voltage of 1.8 MV, which corresponds to an RF acceptance of between 4.5% and 7% depending on number and type of operated IDs. Figure 7 shows the RF and lattice acceptances in the achromat. The lattice momentum acceptance exceeds the RF acceptance except when a bare lattice is combined with maximum cavity voltage.

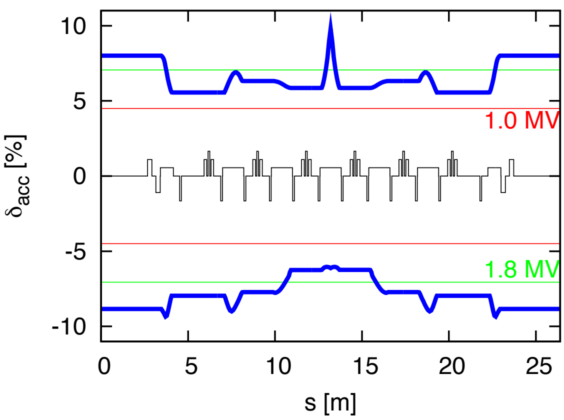

Figure 7: Momentum acceptance for one achromat of the MAX IV 3 GeV storage ring. A bare lattice and cavities at maximum voltage 1.8 MV have been assumed (green line, corresponds to 7% MA). For comparison, the red line shows 1.02 MV which corresponds to 4.5% MA in this configuration. The blue line shows overall MA, calculated from tracking with Tracy-3 for half a synchrotron period.

The Landau cavities are a new in-house development based on the main cavities' capacity-loaded design. Three warm and passive Landau cavities deliver roughly 500 kV gap voltage, which is expected to stretch bunches by a factor 5-6. Not only do these long bunches increase Touschek lifetime (cf. Section 3.1.4.2) and reduce IBS-related emittance growth (cf. Section 3.1.4.1), they also make the ring more tolerant against coupled-bunch instabilities.

3.2.3.4 *Injection*

Injection via a vertical transfer line from the linac is performed with a DC Lambertson septum in the storage ring. Originally it was foreseen to use a closed four-kicker injection bump, but subsequent studies have shown that injection with very high efficiency can be performed with a single pulsed multipole magnet [24]. Only a single dipole kicker remains in the storage ring to provide a simple and robust injection during early commissioning and later, for use as a horizontal pinger magnet. Pulsed multipole injection not only facilitates alignment and synchronization, it also reduces residual perturbations of the stored beam during injection. It is therefore an ideal injection method for top-up injection into an ultralow-emittance storage ring with very tight beam stability tolerance.

3.2.4 **Expected Performance**

3.2.4.1 *Emittance and Intrabeam Scattering*

The ultralow emittance of the 3 GeV storage ring depends on the number and type of installed ID's and is limited by intrabeam scattering (IBS). The bare lattice has an equilibrium emittance of 326 pm rad, but at the shortest bunch length (i.e. at maximum cavity voltage and without Landau cavities) of 9 mm, IBS blows up the emittance by 46% (calculated with ZAP and Tracy-3). Once the Landau cavities are tuned in and the bunches lengthened to 54 mm, the IBS blow-up results in an emittance of 370 pm rad, i.e. 13% above the lattice emittance [19]. For a moderately ID-equipped ring with cavities running at maximum voltage (giving an RF acceptance of 6%), the emittance including the effect of IBS and Landau cavities is expected to lie at about 270 pm rad. This figure can be lowered further by reducing the RF cavity voltage. The IBS calculations are performed assuming an even filling to 500 mA (5 nC / bunch) as well as coupling adjusted for a vertical emittance of 8 pm rad corresponding to the 1 Å diffraction limit. Since this is a very generous coupling and skew quadrupoles are available for coupling adjustment, the vertical emittance can be reduced to around 2 pm rad if required by users. Damping wigglers were also considered in order to reduce the emittance even further and to increase the energy spread, thus mitigating emittance blow-up from IBS.

3.2.4.2 *Lifetime*

Gas scattering lifetimes in the 3 GeV ring including in-vacuum IDs have been estimated at roughly 25 hours (elastic) and 56 hours (inelastic) where the latter has been calculated assuming a momentum acceptance of only 4.5%. The Touschek lifetime of the moderately ID-equipped ring at 270 pm rad is 21 hours at natural bunch length and 114 hours with Landau cavities tuned in (6D tracking in Tracy-3) [19]. If the vertical emittance is reduced to 2 pm rad (0.7% coupling), the Touschek lifetime with Landau cavities is still above 50 hours. This results in a total lifetime of about 13 hours, which equates to one top-up injection every four minutes (0.5% top-up deadband).

Despite the ultralow emittance of the MAX IV 3 GeV storage ring, the lifetime is very good. This is the result of large momentum acceptance achieved with the nonlinear optics optimization, but also of a peculiarity of Touschek lifetime at ultralow emittance. At ultralow emittance, there are only few particles in the bunch with sufficient transverse momentum to generate Touschek losses; most of the scattering events are

IBS, which blows up the emittance, but does not lead to particle loss from the RF bucket. A nice example for this behavior is the observation that, as ID's are added to the 3 GeV storage ring, the emittance (including IBS) decreases, but Touschek lifetime actually improves. Studies have indicated that the change of Touschek lifetime behavior with emittance occurs around 0.7 nm rad for the MAX IV 3 GeV lattice [2]. Since all operation conditions foresee emittances below this value, an emittance reduction should always lead to a Touschek lifetime improvement in the 3 GeV ring. The consequence is that having as many strong ID's (and possibly damping wigglers) in the storage ring not only leads to lowest emittance, but also to best lifetime.

3.2.4.3 *Insertion Device Radiation*

To conclude this article, a performance outlook shall be given for the synchrotron radiation generated by a typical ID in the MAX IV 3 GeV storage ring. Figure 8 shows spectral brightness as calculated by SPECTRA [25] for a 3.3 m in-vacuum undulator of hybrid type (18 mm period, 4 mm gap, $B_{eff} = 1.15$ T) installed in the storage ring where the vertical emittance has been set to 8 pm rad [2 pm rad]. After matching the achromat optics to this ID, the rms beam size at the ID center is 49 μm / 4 μm [2 μm] (H/V).

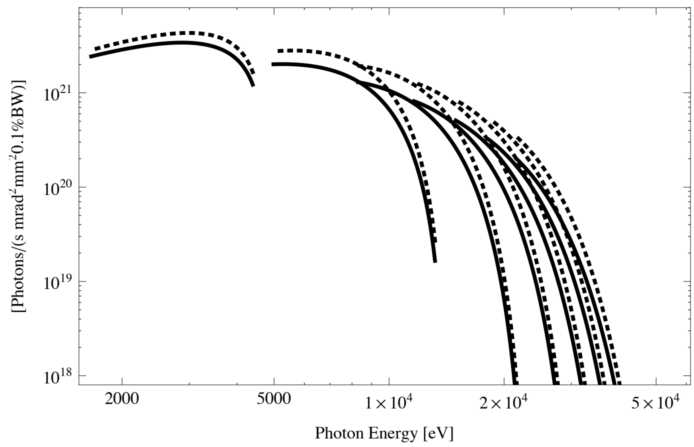

Figure 8: Spectral brightness at peak energy of a typical in-vacuum undulator installed in the MAX IV 3 GeV storage ring with 500 mA stored current and vertical emittance set to 8 pm rad (solid line) and 2 pm rad (dashed line) [26].

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3.3 Lattice Design of a Very Low Emittance Storage Ring for the SPring-8 Upgrade Plan

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3.3.1 Introduction

The SPring-8 storage ring is a third generation synchrotron light source with the electron energy of 8 GeV and the circumference of 1436 m located in Hyogo, Japan (see Fig. 1). The ring stores a nominal current of 100 mA and has provided brilliant hard X-rays of the order of 10^{20} (photons/sec/mm^2/mrad^2/0.1%B.W.) to users since