4336-4338 (2007).

33. I. A. Zagorodnov and T. Weiland, Phys. Rev. ST Accel. Beams, 8:042001 (2005).

34. W. Bruns. The GdfidL Electromagnetic Field Simulator.

35. M. Borland, T. Berenc, L. Emery, and R. Lindberg, "Simultaneous simulation of multi-particle and multi-bunch collective effects for the APS ultra-low emittance upgrade," Proceedings of the 2015 International Computation Accelerator Physics conference, 61-65 (2015).

36. L. Emery, M. Borland, T. Berenc, and R. Lindberg, "Multi-bunch stability analysis of the Advanced Photon Source upgrade including the higher-harmonic cavity," Proceedings of the 2015 International Particle Accelerator Conference, 1784-1786 (2015).

5.2 Lattice Design for the MAX IV Storage Rings

Simon C. Leemann

MAX IV Laboratory, Lund University, 22100 Lund, Sweden

Mail to: simon.leemann@maxiv.lu.se

5.2.1 Introduction

The MAX IV synchrotron radiation facility [1] will be officially inaugurated on June 21, 2016. At the time of writing the MAX IV 3 GeV linac has been commissioned and is routinely serving as both top-up injector to the MAX IV 3 GeV storage ring and driver for the MAX IV Short Pulse Facility. The MAX IV 3 GeV storage ring is presently being commissioned with its first two in-vacuum undulators installed and producing photons for beamline commissioning. The MAX IV 1.5 GeV storage ring has been almost completely installed and commissioning is scheduled to commence in September 2016.

Once the MAX IV facility is 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 at 3 GeV [2] and 1.5 GeV [3] as well as a linac-driven short pulse facility (SPF) [4,5] which will be upgraded to an FEL in a second phase [6,7]. In addition to serving as a driver for the SPF/FEL, the MAX IV 3 GeV linac also acts as the full-energy injector to both storage rings therefore enabling top-up operation at a constant 500 mA in both rings.

This article will focus on the lattice design, optics, and electron beam properties of the two MAX IV storage rings. The following Section 5.2.2 is dedicated to the 3 GeV storage ring and is followed by Section 5.2.3 focusing on the 1.5 GeV storage ring.

5.2.2 **Lattice Design for the MAX IV 3 GeV Storage Ring**

The MAX IV 3 GeV storage ring is the world's first multibend achromat (MBA) storage ring to go into operation. It will serve as the main radiation source of the MAX IV synchrotron radiation facility. In order to generate high-brightness hard x-rays with state-of-the-art insertion devices (IDs), an ultralow-emittance design was targeted from the very start [8,9]. One simple and robust method to achieve ultralow emittance is the use of an MBA lattice [10-13]. The MBA exploits the inverse cubic dependence of emittance on the number of bending magnets. By choosing a very small bending angle per dipole, introducing a vertically focusing gradient in the dipoles (the emittance scales inversely with the horizontal damping partition J_x), and strong horizontal focusing between dipoles, the dispersion can be limited to very small values which leads to a dramatic reduction of emittance. The low dispersion allows the use of narrow vacuum chambers and compact magnets with strong gradients. In addition to reducing the power consumption and running cost, the compact high-gradient magnets in turn allow for a denser lattice thus closing a positive feedback, the *"MBA cycle"* [14]. Finally, by adding several families of properly optimized 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 [2,15,16].

The 3 GeV storage ring's 20-fold MBA lattice results in 528 m circumference and an equilibrium zero-current emittance of 328 pm rad. This emittance is further reduced when IDs are added so that ultimately about 200 pm rad horizontal emittance is expected at 500 mA (i.e. including intrabeam scattering). Moderate coupling will ensure vertical beam sizes in the IDs below the 1 Å diffraction limit. With a stored current of 500 mA held constant by continuous top-up operation, the 3 GeV storage ring is expected to become the brightest storage ring-based light source in the world.

5.2.2.1 ***Linear Optics***

The MAX IV 3 GeV storage ring[2] is based on an entirely novel 7-bend achromat lattice [2]. Its 20 MBAs provide 19 user straights of 4.6 m length for IDs. An overview of one 3 GeV storage ring achromat is shown in Fig.1. Each of the achromats consists of five unit cells and two matching cells. The unit cells have a 3º bending magnet, while the matching cells at the ends of the achromat have a 1.5º soft-end bending magnet. In these soft-end dipoles, the magnetic field drop-off towards the long straight reduces the amount of high-energy radiation hitting a downstream ID therefore facilitating the

[2] Lattice files available at https://www.maxiv.lu.se/publications/

design of superconducting IDs. All dipoles contain a vertically focusing gradient. The lattice models both types of dipoles as arrays of gradient dipole slices so that each segment of the dipoles contains bending magnet field and vertically focusing gradients that match results from magnetic field measurements[3] [17]. In this way both the proper longitudinal gradient and the longitudinal evolution of the transverse gradients are included in modeling and beam dynamics studies.

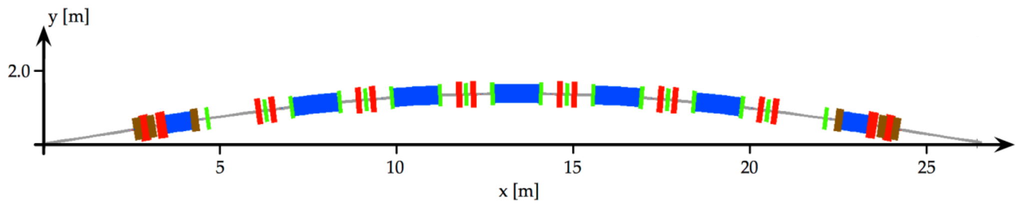

Figure 1: Schematic of one of the 20 achromats of the 3 GeV storage ring. Magnets indicated are gradient dipoles (blue), focusing quadrupoles (red), sextupoles (green), and octupoles (brown).

The matching cells at the ends of the achromat 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 are used for RF cavities and diagnostics so that all long straights but the injection straight are available for IDs. 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 dipoles in pairs with a short space in between for 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 (PFSs) that are installed in all dipoles (up to ±4% gradient variation). This results in a very compact optics with strong focusing, low beta functions, and very small peak dispersion. The optics for one achromat is displayed in Fig.2 and storage ring parameters are given in Table 1.

[3] In fact, even the measured multipole content evolution along the dipoles has been added to individual dipole slices in the lattice error model.

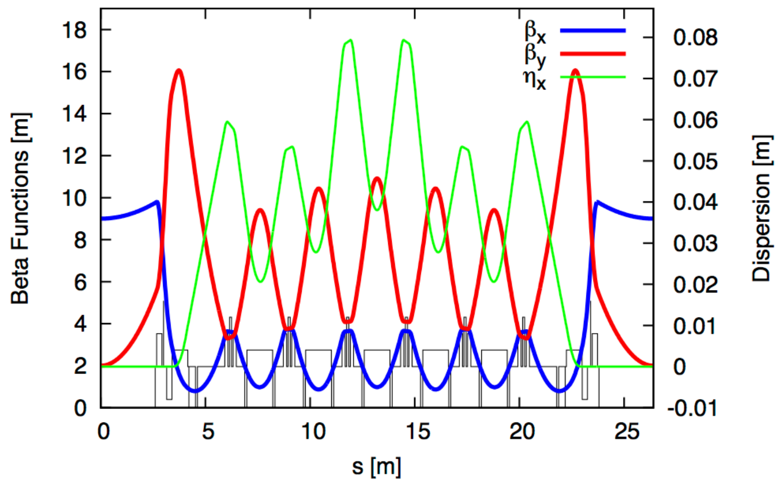

Figure 2: Beta functions and dispersion for one achromat of the 3 GeV storage ring. Magnet positions are indicated in black at the bottom.

Table 1: Parameters for the 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 (straights available for IDs)	…	20 (19)
Betatron tunes (H/V)	…	42.20 / 16.28
Natural chromaticities (H/V)	…	–49.98 / –50.20
Corrected chromaticities (H/V)	…	+1.0 / +1.0
Momentum compaction factor α_c, α_2	…	3.06×10^{-4}, 1.40×10^{-4}
Horizontal damping partition	…	1.85
Horizontal emittance (bare lattice)	pm rad	328
Radiation losses per turn (bare lattice)	keV	363.8
Natural energy spread (bare lattice)	…	7.69×10^{-4}
Required momentum acceptance	…	>4.5%

The optics in the long straight sections (cf. Fig.2) has been chosen according to injection and ID requirements. In the horizontal, a beta function of 9 m at the long straight center has been selected to enable off-axis injection. In this configuration the overall horizontal acceptance is determined by the septum blade at –10 mm. In the vertical, the beta function can be selected so as to maximize photon brightness [18]. However, because of the vertical acceptance limitations this entails (up to 4 m long IDs targeting 1 Å radiation), a vertical beta function of 2 m at the center of the long straight has been chosen instead. This choice maximizes the vertical acceptance of the machine when in-vacuum undulators (IVUs) are being operated with fully closed gaps [18].

Finally, the working point was chosen away from systematic resonances such 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.

5.2.2.2 *Nonlinear Optics*

Despite comparably relaxed linear optics, the nonlinear optics of such an MBA lattice is 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 (DA) and momentum acceptance (MA). The approach followed for the 3 GeV storage ring hinges on an idea first presented in 1992 for the ESRF [19,20]: correct chromaticity where it is generated by using many distributed sextupoles thus limiting chromatic beta beating. In addition, the nonlinear lattice design separates sextupole families by appropriate phase advances in order to cancel resonance driving terms (RDTs) and limit chromatic tune shifts [21-23].

The 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. Because of the large number of installed sextupoles and the small magnet gap, the sextupoles can be kept short and the pole-tip fields are far from saturation.

Sextupole optimization was performed with the codes OPA [24] and Tracy-3 [25]. The linear chromaticities were corrected to +1.0 in both planes (an alternative nonlinear optics for chromaticities corrected to +4 has also been developed [26]) and the first-order RDTs along with second- and third-order chromaticity were minimized as detailed in [23]. However, amplitude-dependent tune shifts (ADTSs) 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 IDs, 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 [2,15]. 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 ADTSs that result from an octupole in the lattice. This system can be inverted to calculate octupole strengths that give the desired ADTSs. Rather than setting the linear ADTS to zero, however, the octupoles in the achromat were adjusted so the resulting overall ADTS is minimized throughout the physical acceptance (cf. Fig.3). Because the ADTS is corrected with the octupoles, the sextupoles are freed up for first-order corrections (linear chromaticity, RDTs). Some extra weight was added to minimize second- and third-order chromaticity in an attempt to limit the chromatic tune footprint (cf. Fig.4).

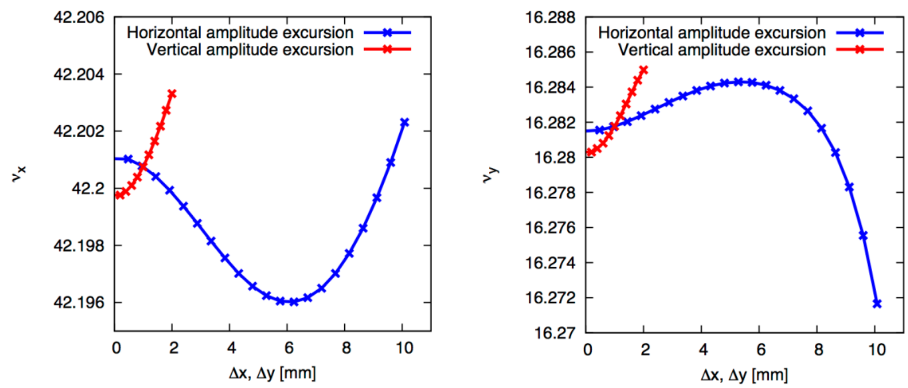

Figure 3: Amplitude-dependent tune shift in the 3 GeV storage ring with octupoles at design strength.

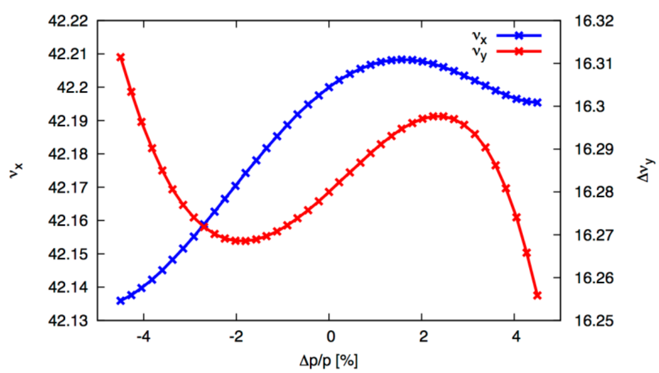

Figure 4: Chromaticity in the 3 GeV storage ring with octupoles at design strength.

The result of this nonlinear optimization is a very limited tune footprint for particles with a range of amplitudes covering the physically accessible aperture (at the center of the IDs roughly 10 mm horizontally and 2 mm vertically) and energies covering the required ±4.5% acceptance. This results in large DA and MA (cf. Fig.5 and Section 5.2.2.4), which ensure high injection efficiency and good Touschek lifetime. Frequency map analysis confirms 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.

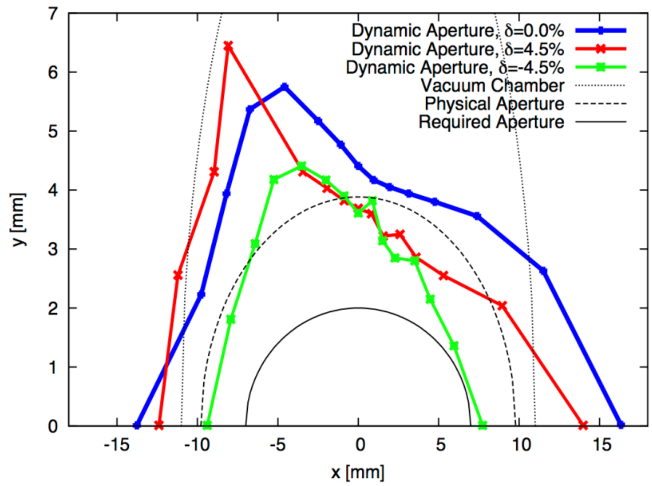

Figure 5: Dynamic aperture at the center of the long straight section in the 3 GeV storage ring (bare lattice). Tracking was performed with Tracy-3 in 6D for one synchrotron period. For comparison, the vacuum chamber, physical aperture (projection of vacuum chamber to the track point), and min. required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

5.2.2.3 *Optics 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) [27, 28]. For the global correction the PFSs 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 [27], neither sextupoles nor octupoles have to be adjusted with ID gap movement. In addition, skew quadrupole windings on all octupoles flanking IDs can be employed in a feed-forward scheme to compensate locally for the coupling induced by elliptically polarizing undulators (EPUs) operated in various modes and at various gaps. Tracking studies with Tracy-3 using kick maps reveal that, in the storage ring equipped with many strong in-vacuum undulators and EPUs, the DA is not substantially reduced as long as the proposed ID matching is properly performed [28].

Since all octupoles and sextupoles in the 3 GeV storage ring have been equipped with extra windings that can be powered in different ways, dispersive and non-dispersive skew quadrupoles can be added to the lattice for coupling control and removal of spurious vertical dispersion. An additional mode allows powering of the extra windings as auxiliary sextupoles in order to restore the design symmetry of the nonlinear optics [23]. Finally, these windings can also be powered as upright quadrupoles, which is routinely used to calibrate BPM offsets to the magnetic centers of the adjacent sextupoles and octupoles.

Each achromat also contains 10 horizontal and 9 vertical dipole correctors as well as 10 BPMs that are 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 [29,30]. Tracking studies have revealed that adequate DA remains when expected misalignments and multipole errors are added to the lattice and the orbit is corrected according to the proposed orbit feedback scheme [31]. This also holds if IDs are included and ID matching is performed as detailed above. Figure 6 shows an example for the DA resulting in such a case where, in addition to alignment, field, and multipole errors, ten 3.7-m long IVUs (18.5 mm period, 4.2 mm gap, 1.1 T effective magnetic field) have been added to the 3 GeV storage ring lattice. The resulting on-energy DA including the effect of all IDs and errors still roughly matches the physical aperture of the ring and therefore exceeds requirements based on injection and lifetime concerns.

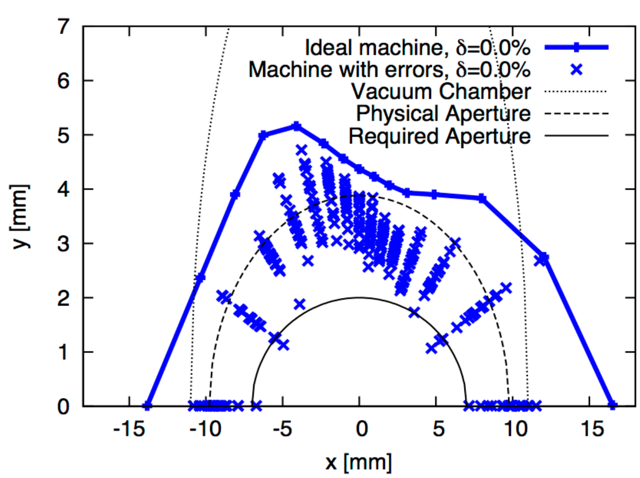

Figure 6: On-energy DA at the center of a long straight section in the 3 GeV storage ring where ten IVUs have been to the lattice. The plot shows the ideal lattice and results for 20 seeds with field and multipole errors as well as misalignments. Tracking was performed with Tracy-3 in 6D for one synchrotron period.

5.2.2.4 *Enabling Technology*

The 3 GeV storage ring lattice gives an ultralow emittance, but it requires strong magnets and compact optics, which leave little space for a conventional vacuum system. Therefore, several less conventional technology choices have been made in the 3 GeV storage ring, such as solid-iron integrated magnet blocks, a fully NEG-coated copper vacuum system, and a 100 MHz main RF system.

The magnets for the 3 GeV storage ring [32] have been designed using a technology already successfully demonstrated at MAX III [33]. The dipoles (28 mm pole gap) and quadrupoles (25 mm bore diameter) for each cell are precision-machined out of just two solid blocks of iron (CNC milling). 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 7 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 high alignment accuracy. Furthermore, misalignments of magnets tend to be correlated [34] and can be minimized using beam-based realignment of the blocks as demonstrated at MAX III [35]. The blocks are installed on massive concrete supports at low height, which pushes vibrational eigenfrequencies of the assembly to higher frequencies thus improving beam stability.

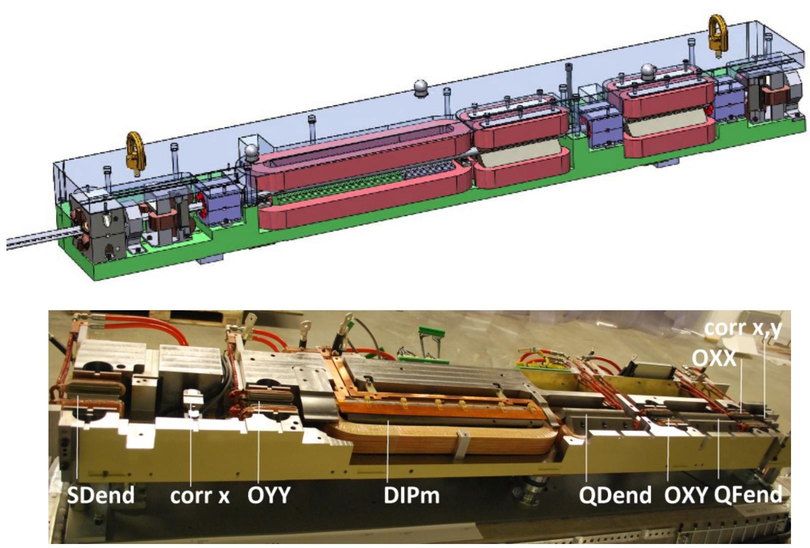

Figure 7: Top: schematic of a matching cell magnet block with soft-end gradient dipole, quadrupole doublet, defocusing sextupole (far left), three octupoles (blue), and two dipole corrector pairs. Bottom: photo [17] of an actual lower half of a matching cell magnet block.

The small magnet apertures of the 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 [36]. Lumped absorbers can be avoided as synchrotron radiation is distributed along long sections of the chamber. A cooling channel is electron beam-welded 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 have been installed in straight sections. Narrow-gap chambers (8 mm full vertical aperture) for EPUs and in-vacuum IDs (4 mm minimum gap) 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.

Since users are provided with short pulses from the dedicated MAX IV SPF, 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 therefore use a warm 100 MHz main RF system and passive Landau cavities at the third harmonic for additional bunch lengthening [37,30]. The six main cavities are an improved version of the 100 MHz cavities used in MAX II and III [38]. 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 up to 7.1% depending on number and type of operated IDs. The minimum required MA was specified at 4.5% which corresponds to running the cavities at 1.02 MV total gap voltage (bare lattice). Figure 8 shows the RF and lattice MA in the achromat. The lattice MA exceeds the RF acceptance except if a bare lattice is combined with maximum cavity voltage.

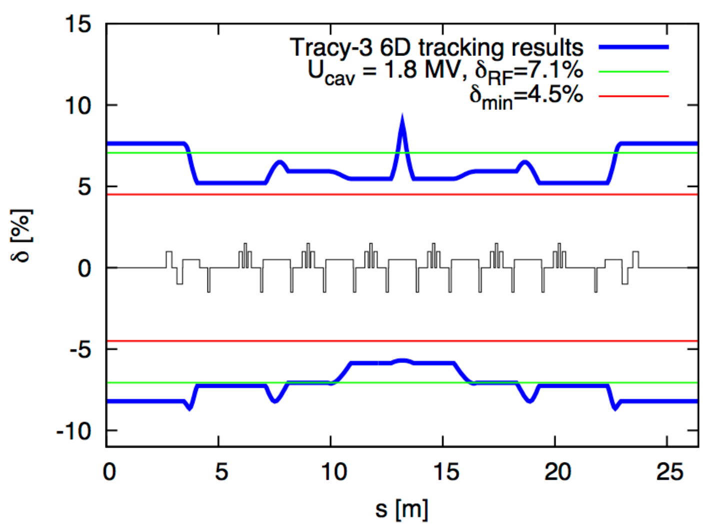

Figure 8: Lattice MA for one achromat of the 3 GeV storage ring. A bare lattice with actual vacuum chamber apertures has been used. The solid blue line shows lattice MA from 6D tracking with Tracy-3 for one synchrotron period. For comparison, the RF acceptance is also shown for cavities at maximum voltage 1.8 MV.

The Landau cavities are a new in-house development based on the main cavities' capacity-loaded design. Three warm and passive Landau cavities allow for roughly 600 kV gap voltage, thus stretching bunches by a little more than a factor of five. Not only do such long bunches increase Touschek lifetime (cf. Section 5.2.2.6) and reduce emittance growth from intrabeam scattering (cf. Section 5.2.2.5), they also make the ring more tolerant against coupled-bunch instabilities.

5.2.2.5 *Emittance and Intrabeam Scattering*

The ultralow emittance of the 3 GeV storage ring will depend on the number and type of installed IDs [16]. This is a general property of ultralow-emittance lattices based on MBAs where the power radiated in the bending magnets is low compared to ID losses. In addition, the overall equilibrium emittance at high stored current is limited by intrabeam scattering (IBS). The 3 GeV storage ring bare lattice has an equilibrium emittance of 328 pm rad, but at the shortest bunch length (i.e. at maximum cavity voltage and without Landau cavities) of 9 mm, IBS at 500 mA (even fill, 5 nC/bunch) blows up the emittance by 45%. Once the Landau cavities are tuned in and the bunches lengthened to ~50 mm as foreseen by the design, the IBS blow-up results in an emittance of 372 pm rad, i.e. 13% above the zero-current bare lattice emittance. 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 roughly 270 pm rad. This figure can be further lowered by reducing the RF cavity overvoltage. On the other hand, a decrease of vertical emittance from its 8 pm rad design value will lead to an increased IBS blowup of the horizontal emittance [16]. The strong IBS mechanism in the 3 GeV storage ring results in a situation where bunch lengthening Landau cavities are not only required for lifetime and stability reasons, but most importantly also to guarantee the ultralow lattice emittance can be maintained even when storing large amounts of current.

5.2.2.6 *Lifetime*

Gas scattering lifetimes in the 3 GeV storage ring including in-vacuum IDs at 500 mA have been estimated at roughly 25 hours (elastic) and 56 hours (inelastic) where the latter has been calculated assuming a MA of only 4.5% [1]. 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 [16]. Even factoring in alignment, field, and multipole errors as well as narrow vertical apertures from IVUs and narrow-gap EPU chambers, the Touschek lifetime should remain at 66 hours (assuming proper bunch lengthening from the Landau cavities). Overall this results in a total lifetime of about 14 hours, which equates to one top-up injection every seven minutes if a 0.5% top-up deadband is chosen.

Despite the ultralow emittance of the 3 GeV storage ring, lifetime is very good. This is the result of large MA achieved with the nonlinear optics optimization (cf. Fig.8), 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 [16]. A nice example for this behavior is the observation that, as IDs are added to the 3 GeV storage ring, the emittance (including IBS) decreases, but Touschek lifetime actually improves (cf. Fig.9).

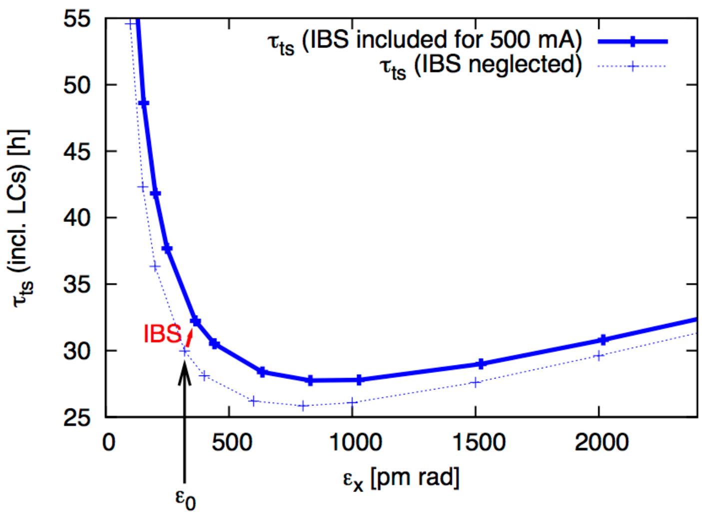

Figure 9: Touschek lifetime (including the effect of LCs) at 500 mA from 6D tracking with Tracy-3 as a function of equilibrium emittance assuming the lattice emittance could be adjusted freely while keeping the energy spread constant. The overall MA has been set to 4.5% while the vertical emittance is adjusted to 8 pm rad. The effect of IBS at 500 mA is also displayed.

Studies have indicated that the change of Touschek lifetime behavior with emittance occurs around 0.7 nm rad for the 3 GeV lattice (cf. Fig.9). Since all operation conditions foresee emittances below this value, an emittance reduction should always lead to a Touschek lifetime improvement in the 3 GeV storage ring. In consequence, having many strong IDs in the 3 GeV storage ring should not only lead to lowest emittance, but also to best lifetime. Once the 3 GeV storage ring is fully equipped with IVUs (rendering in total 213 pm rad horizontal emittance at 500 mA of stored current) 38 hours of Touschek lifetime can be expected when including the effect of errors and narrow vertical apertures [16].

5.2.2.7 *Injection*

Top-up injection into the 3 GeV storage ring will be performed by the 3 GeV linac via an achromatic vertical transfer line that connects the underground linac with the storage ring. The 3 GeV linac today routinely delivers roughly 250 pC of charge per top-up shot (a train of S-band bunches that is injected in up to ten consecutive storage ring buckets). Top-up injection can occur at 10 Hz (governed by a storage ring damping time on the order of 15 ms), thus, up to 0.3% of the storage ring current can be replenished per second—at the expected lifetime in the storage ring this will occur once every three minutes. Originally, injection into the 3 GeV storage ring was designed using a closed four-kicker injection bump around a DC Lambertson septum in the first long straight [1]. In light of the very tight beam stability requirements in the 3 GeV storage ring there was considerable doubt that four injection kickers could be aligned, balanced, and synchronized well enough to prevent perturbation of the stored beam beyond the limits of these stability requirements. Furthermore, since the injection bump would have contained strong sextupoles and octupoles, the bump could not be closed properly for all amplitudes and all particles in the bunch.

As a result, the four-kicker injection bump was abandoned and instead an injection based on pulsed multipole injection was pursued. A first design [39] was based on a pulsed sextupole magnet (PSM) following pioneering work at KEK. Tracking studies confirmed that capture in the storage ring can be highly efficient since the emittance of the linac bunches at 3 GeV is extremely small compared to the storage ring acceptance. Meanwhile stored bunches in the ring are not perturbed beyond tolerances by the pulsed multipole as long as it is properly aligned to the stored beam. Further studies finally led to the choice of pulsed multipole injection [40,30] using a multipole injection kicker (MIK) based on a stripline-like design similar to a prototype developed for BESSY II. In this kicker the induced field around the stored beam is octupole-like, hence no kick is given to the stored beam at the magnetic center. The injected beam is, as in the case of a PSM, injected into the storage ring's acceptance within a single turn. This MIK is presently being assembled and tested [41] within a collaboration between MAX IV, SOLEIL, and HZB/BESSY. Installation into the 3 GeV storage ring is presently foreseen to take place at the end of 2016.

For commissioning purposes a single dipole kicker was retained from the original closed-bump injection scheme. This dipole kicker [42] has enabled injection, capture, and accumulation of up to 160 mA during commissioning so far. It is also used in top-up mode to ensure constant high current during machine shifts, however, since it causes considerable perturbation to the stored beam during accumulation, it is not considered compatible with user top-up operation. It will therefore be replaced by the MIK for user operation and from then on used only as a horizontal pinger during machine studies.

5.2.2.8 ***Outlook***

Commissioning of the 3 GeV storage ring has progressed quite well so far [43]. The rather unconventional magnet and vacuum systems have both proven viable solutions for an ultralow-emittance storage ring. A peak stored current of 160 mA has so far been achieved. The 100 MHz main RF system and the three 300 MHz Landau cavities have been commissioned and are operating well: the resulting bunch lengthening as well as the damping of instabilities have both been demonstrated [44]. The first of two diagnostic beamlines, where transverse emittances, energy spread, and longitudinal bunch profiles are measured, has also been taken into operation [45]. The first two IVUs in the 3 GeV storage ring are now routinely producing photons for ID, beamline, and endstation commissioning. During the summer shutdown the first in-vacuum wiggler will be installed as well as the first two EPUs. These devices shall undergo commissioning starting in September 2016. Dedicated user operation at the 3 GeV storage ring is expected to commence in 2017. By the end of 2017 the first seven beamlines (funded within the two first beamline phases) at the 3 GeV storage ring are expected to be in operation.

In terms of further machine development, several improvements have been studied and will hopefully be implemented soon after commissioning. The vertical emittance of the 3 GeV storage ring was originally set at 8 pm rad corresponding to the 1 Å diffraction limit. This calls for a rather generous 2.5% emittance coupling. Studies have shown, however, that both brightness and coherence in the vicinity of 1 Å can be substantially increased by lowering the vertical emittance to roughly 2 pm rad (0.6% emittance coupling) [18]. Ample skew quadrupoles are available in the 3 GeV storage ring for this purpose. Including imperfections, Touschek lifetime should remain beyond 27 hours even at lower coupling [16] as long as sufficient bunch lengthening from the Landau cavities is ensured. Furthermore, studies have also shown that using the many skew quadrupoles available in the 3 GeV storage ring allows adjusting the vertical emittance quite freely over a large range [46]: by exciting vertical dispersion only in the arcs, a large Touschek lifetime can be ensured while nevertheless limiting betatron coupling at the ID source points, thereby simultaneously ensuring high photon brightness and good lifetime.

Other studies have just started to investigate how timing experiments can be accommodated in the MAX IV storage rings [47,48]. While the MAX IV SPF caters to short-pulse users at 100 Hz, some high-brightness users at the storage rings are interested in synchronization, which is difficult considering that the 3 GeV storage ring has been designed to run with an even fill in multi-bunch mode using passive Landau cavities without any gaps or camshaft bunches. These recent studies have started to investigate alternate filling patterns, their effect on the storage ring, and other options to accommodate timing users at the MAX IV storage rings.

Finally, several studies have been initiated to investigate optics improvements throughout the 3 GeV storage ring. A first study [49] assumed that magnets and power supplies would be retained. By adjusting the optics in the arc to reduce the dispersion and by improving the optics matching to IDs in the long straights, the lattice emittance can be dropped by 18% and the photon brightness at 1 Å can be increased by 33%. Ongoing studies assume existing quadrupole families could be broken up and power supplies exchanged. This allows a further emittance reduction to the roughly 200 pm rad level. Lastly, first MOGA studies indicate that if DA requirements are lowered (enabled eg. by switching to on-axis injection using a ~20 ns dipole kicker to remain compatible with user top-up), we should ultimately be able to reach roughly 150 pm rad in the 3 GeV storage ring with IDs.

5.2.3 **Lattice Design for the MAX IV 1.5 GeV Storage Ring**

The MAX IV 1.5 GeV storage ring has a 96 m circumference, 10 user straights, and 6 nm rad emittance. It is essentially a modernized and upgraded design of the recently decommissioned MAX II storage ring [50], but employing the fully integrated magnet design first demonstrated in the MAX III storage ring [33] and now also used in the MAX IV 3 GeV storage ring (cf. Section 5.2.2.4). The MAX IV 1.5 GeV storage ring has actually been built twice: once in Lund for the MAX IV facility [1,3] and once in

Krakow, Poland for the Solaris Project [51]. While it will be injected at 1.5 GeV from the MAX IV linac in top-up mode, at Solaris injection from the linac occurs at 500 MeV and the ring is then ramped to 1.5 GeV. At MAX IV, the 1.5 GeV storage ring will serve as the source for UV and soft x-rays. In fact, a few beamlines from the recently decommissioned MAX II and III are being moved to this new storage ring.

5.2.3.1 *Linear Optics*

The MAX IV 1.5 GeV storage ring[4] is based on a double-bend achromat (DBA) lattice [3,52]. Its twelve identical DBA cells provide 10 user straights of 3.5 m length for IDs. An overview of one achromat of the 1.5 GeV storage ring is shown in Fig.10. Each of the achromats consists of two 15º bending magnets flanked by horizontally focusing quadrupoles. The dipoles contain a transverse gradient that provides vertical focusing while the quadrupoles contain a sextupole gradient for nonlinear correction. The lattice models both dipoles and quadrupoles as arrays of consecutive combined-function magnets in order to properly resolve fringe fields as well as longitudinal variations of the ratio between the design multipole components.

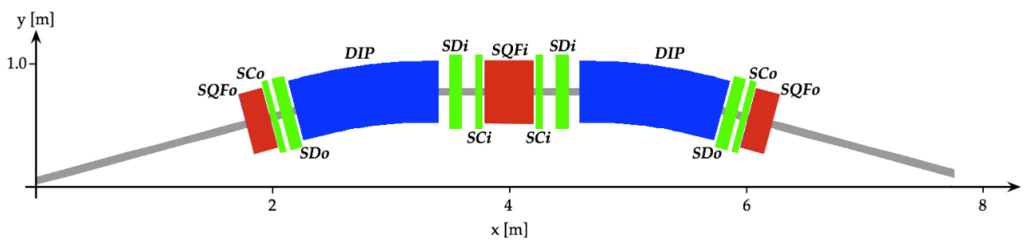

Figure 10: Schematic of one of the 12 achromats of the 1.5 GeV storage ring. Magnets indicated are gradient dipoles (blue), focusing quadrupoles with a sextupole gradient (red), and discrete sextupoles (green).

The quadrupoles are split up into two families: the SQFi family for the "inner" quadrupoles (i.e. those between the two dipoles in the arc) and the SQFo family for the "outer" quadrupoles (i.e. those in the straights). The lattice does not contain any dedicated vertically focusing quadrupoles as this is performed entirely by the transverse gradient in the dipoles. Matching of the arc optics to IDs in the straights is performed by adjusting the SQFo quadrupoles. In order to also vary the vertical focusing in the straight, the dipoles contain PFSs that allow roughly ±5% gradient variation at full excitation. 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. The optics for one achromat is displayed in Fig.11 and storage ring parameters are given in Table 2.

[4] Lattice files available at https://www.maxiv.lu.se/publications/

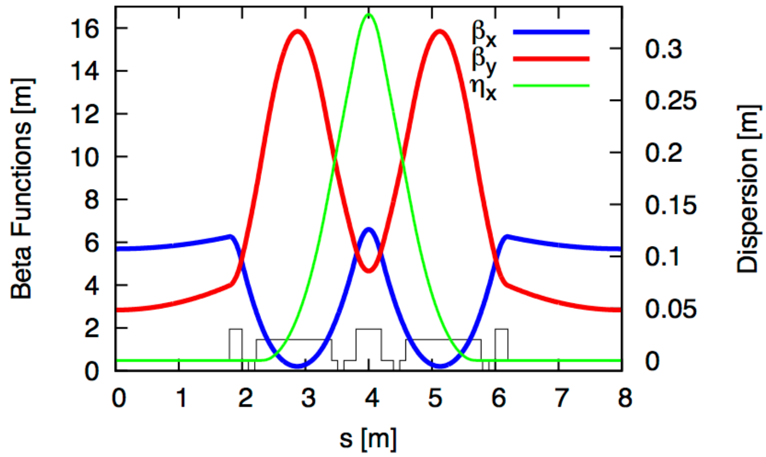

Figure 11: Beta functions and dispersion for one achromat of the 1.5 GeV storage ring. Magnet positions are indicated in black at the bottom.

The magnet design of the 1.5 GeV storage ring is very similar to the 3 GeV storage ring with two considerable differences: magnet gaps can be larger (lower gradients required by the DBA optics) and increased use of combined-function magnets, i.e. combining focusing sextupole gradients into the horizontally focusing quadrupoles. The resulting magnet design [53,54] can therefore rely on the same magnet block concept used in the 3 GeV storage ring, while a much more conventional vacuum design can be retained since magnet gaps are roughly twice the size of their 3 GeV storage ring counterparts. Figure 12 shows a schematic of the magnet block containing all magnets of one DBA of the 1.5 GeV storage ring. With this optics and magnet design the 1.5 GeV storage ring can provide two additional ID straights as well as lower emittance compared to the MAX II storage ring within essentially the same space.

Table 2: Parameters for the 1.5 GeV storage ring.

Parameter	***Unit***	***Value***
Energy	GeV	1.5
Main radio frequency	MHz	99.931
Circulating current	mA	500
Circumference	m	96
Number of achromats (straights available for IDs)	…	12 (10)
Betatron tunes (H/V)	…	11.22 / 3.15
Natural chromaticities (H/V)	…	–22.98 / –17.14

Corrected chromaticities (H/V)	…	+1.0 / +1.0
Momentum compaction factor α_c, α_2	…	3.06×10^{-3}, 6.41×10^{-3}
Horizontal damping partition	…	1.46
Horizontal emittance (bare lattice)	nm rad	5.98
Radiation losses per turn (bare lattice)	keV	114.1
Natural energy spread (bare lattice)	…	7.45×10^{-4}
Required momentum acceptance	…	>3.5%

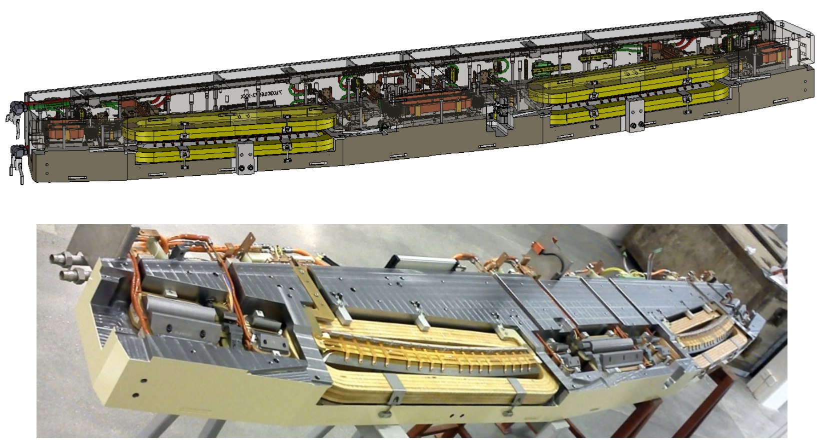

Figure 12: Top: schematic of one of the twelve magnet blocks in the 1.5 GeV storage ring. The block consists of two solid iron halves into which magnet pole faces have been machined: gradient dipoles (yellow coils), quadrupoles with sextupole gradient (red coils) as well as discrete sextupoles and dipole correctors in between. Bottom: photo of an actual lower half of a magnet block. Courtesy M. Johansson.

5.2.3.2 *Nonlinear Optics*

At least two families of sextupoles are required to correct the natural chromaticity of the lattice. In order to achieve a compact lattice, the sextupoles for the 1.5 GeV storage ring were integrated into the quadrupoles where possible. This has led to a design where both types of horizontal focusing quadrupoles contain a focusing sextupole gradient. Since only one of these quadrupoles is dispersive, only this sextupole component can be used for chromatic correction. The sextupole component in the SQFo family, is considered a harmonic sextupole and used for minimization of the RDTs and tailoring of the ADTS. The defocusing sextupoles have on the other hand been realized as discrete sextupoles. One family (SDi) is installed between the dipoles and the SQFi quadrupoles at the center of the DBA. The other defocusing family (SDo) is placed between the dipoles and the SQFo quadrupoles. In these locations both defocusing sextupoles see beta function ratios that reduce the required sextupole gradient. Again, since only the SDi is dispersive, it is used for chromatic corrections, while the SDo family is employed for RDT minimization and tailoring of the ADTS.

Since the focusing sextupoles are realized as gradients in quadrupole magnets, an additional means of sextupole tuning is required. This has been realized by inserting thin additional sextupoles: the SCi family flanks the SQFi at the center of the DBA, whereas the SCo is installed right next to the SQFo. The underlying strategy is to use the built-in gradient of the SQFi to correct the bulk of the natural chromaticity while using the dedicated SCi for adjustments of the corrected chromaticity over a narrower range. The SCi and SCo trim sextupoles also carry three additional sets of windings: a skew quadrupole winding for correction of spurious vertical dispersion and tuning of the betatron coupling as well as dedicated coils for horizontal and vertical dipole correction that are used by the slow orbit feedback running at 10 Hz [1].

The nonlinear optics foresees correction of the linear chromaticities to +2 "in iron", i.e. using the sextupole gradient in the combined-function SQFi family and the SDi. By additionally exciting the SCi family and adjusting the SDi family, the linear chromaticities can be adjusted by roughly ±2. In the production nonlinear optics [52] this is used to set the corrected chromaticities to their design values of +1 in both planes (an alternative nonlinear optics for chromaticities corrected to +4 has also been developed [55]). The sextupole gradient in the combined-function SQFo and the setting of the SDo have been optimized in order to reduce first-order RDTs and adjust the ADTS footprint to avoid potentially dangerous resonances. This optics results in a tune footprint as shown in Figs.13 and 14. As a consequence of the very compact tune footprint and the limited RDTs, the DA both on and off energy becomes large. This is demonstrated in Fig.15.

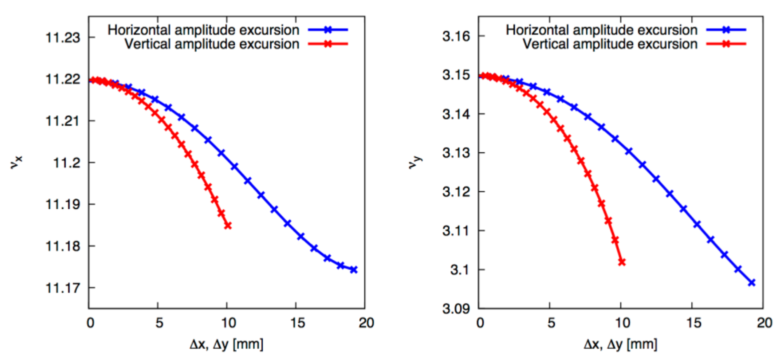

Figure 13: Amplitude-dependent tune shift in the 1.5 GeV storage ring with the design optics correcting linear chromaticities to +1 in both planes.

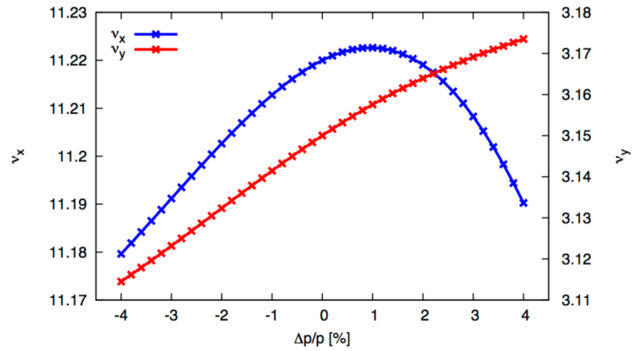

Figure 14: Chromaticity in the 1.5 GeV storage ring with the design optics correcting linear chromaticities to +1 in both planes.

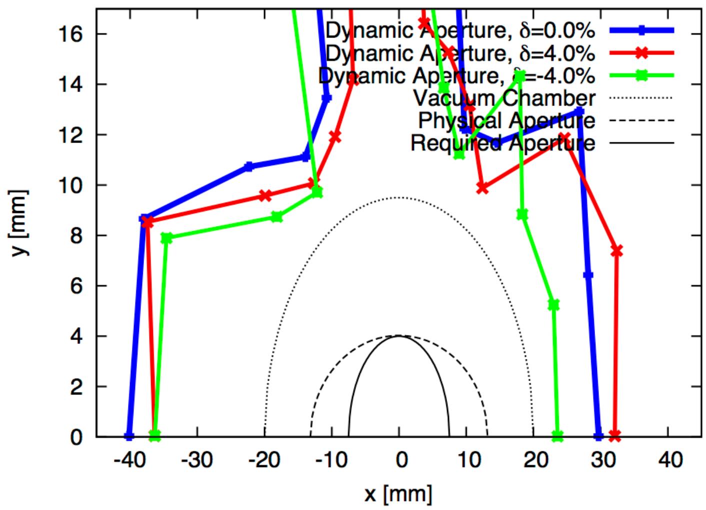

Figure 15: Dynamic aperture at the center of an ID straight in the 1.5 GeV storage ring (bare lattice). Tracking was performed with Tracy-3 in 6D for one synchrotron period. For comparison, the vacuum chamber, physical aperture (projection of vacuum chamber to the track point), and min. required aperture (injection, lifetime) are also indicated in the plot.

Similar to the approach taken for the 3 GeV storage ring, the optics in the 1.5 GeV storage ring will be matched to strong IDs [28]. PFSs and SQFo on either side of an ID can be used to match the arc optics to the ID gap and phase setting. Since changing the focusing in SQFo will also modify its sextupole gradient, the SCo can be used to compensate for this shift in the nonlinear optics if required. Skew quadrupole coils are readily available to compensate for coupling induced by EPUs in addition to cancelation of spurious vertical dispersion and the adjustment of the betatron coupling. Tracking studies with various error sources such as misalignments, field, and multipole errors in addition to adding various types of IDs to the 1.5 GeV storage ring indicate that sufficient on- and off-energy DA can be retained as long as orbit correction and ID compensation are carried out according to design (cf. Fig.16).

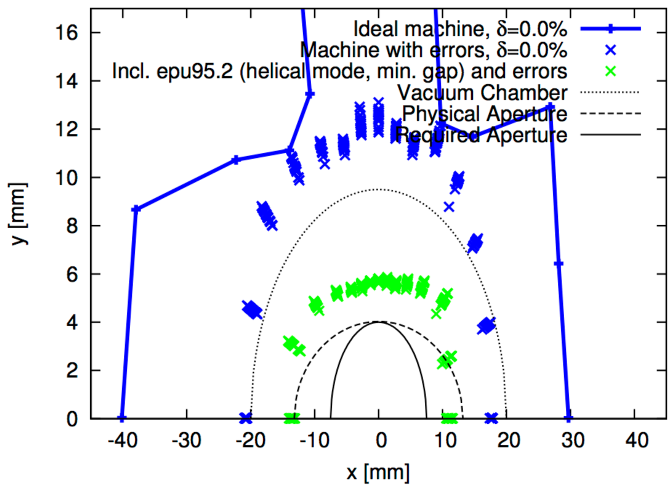

Figure 16: On-energy DA at the center of an ID straight section in the 1.5 GeV storage ring. The plot shows the ideal lattice and results for 20 seeds with field and multipole errors as well as misalignments. For comparison, results when adding an EPU (95.2 mm period, 2.6 m length, 14 mm magnetic gap) to the ring are included. In this case the EPU is assumed operating in helical mode at minimum gap (modelled with a kick map) [28]. Tracking was performed with Tracy-3 in 6D for one synchrotron period.

5.2.3.3 *RF, Lifetime & Injection*

The large off-momentum DA in conjunction with an RF system supplying sufficient RF acceptance allows for a large overall MA. The vacuum apertures at the center of the DBA were increased[5] to match the growing dispersion and in this way ensure that the overall MA remains beyond the minimum requirement of 3.5% even at the center of the DBA. The RF system makes use of the same 100 MHz cavities used in the 3 GeV storage ring. Two such cavities are installed for a maximum accelerating voltage of 560 kV which renders a maximum RF acceptance of 4.13% well matched to the lattice MA (cf. Fig.17).

[5] The standard full apertures at the ends of the DBA are 40 mm × 20 mm whereas towards the middle of the DBA where dispersion peaks they are increased to 56 mm x 28 mm.

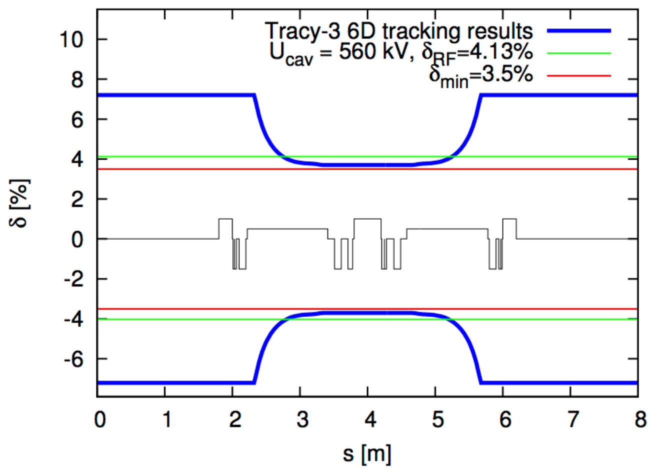

Figure 17: Lattice MA for one DBA in the 1.5 GeV storage ring. A bare lattice with actual vacuum chamber apertures has been used. The solid blue line shows lattice MA from 6D tracking with Tracy-3 for one synchrotron period. For comparison, the RF acceptance is also shown for cavities at maximum voltage 560 kV.

As a result of the large overall MA, decent Touschek lifetime despite 500 mA of stored current can be expected. To increase the resulting Touschek lifetime, two 300 MHz Landau cavities (identical to the Landau cavities in the 3 GeV storage ring) will be installed. Both 100 MHz main cavities and the two Landau cavities can be installed in a single straight section so that—together with the injection straight—only two straights cannot host IDs. The two 300 MHz Landau cavities should stretch bunches in the 1.5 GeV storage ring by roughly a factor of four. Tracking studies indicate this should result in a Touschek lifetime (at 500 mA stored current and 1% emittance coupling) between 23–34 hours depending on the exact settings of the RF cavities as well as the installed IDs and their gap settings. Together with the assumed gas lifetime of around 19 h [1], this gives an overall lifetime beyond 10 h. This is compatible with top-up injections from the MAX IV linac occurring every few minutes keeping stored current in the ring constant to within 0.5%.

Injection into the 1.5 GeV storage ring will make use of the vertical achromatic transfer line between the 1.5 GeV extraction point of the underground linac and a DC Lambertson septum in the injection straight of the storage ring. As in the 3 GeV storage ring, we have decided to avoid a four-kicker injection bump and instead inject into the ring using a single injection kicker. In the commissioning phase this will be a dipole kicker magnet [42] installed in the third straight section (capture of injected bunches is not feasible in the second straight section). This dipole kicker will allow both on-axis and off-axis injection as well as accumulation. Since it perturbs the stored beam considerably during accumulation, it will after commissioning be replaced by a MIK [39,40] to enable transparent top-up injection during user operation. The dipole kicker will then be moved to the upstream end of the injection straight where it will serve as a horizontal pinger magnet for machine studies. Since both the dipole kicker and the proposed MIK are short, the third straight remains available for a roughly 2.5 m long ID. The dipole kicker, manufactured by BINP, has already been installed in the 1.5 GeV storage ring whereas the MIK for this ring is presently being developed within the scope of the MAX IV – SOLEIL – HZB/BESSY collaboration designing and building the MIK for the 3 GeV storage ring.

5.2.3.4 ***Outlook***

At the time of writing most of the installations in the 1.5 GeV storage ring are complete. During the summer shutdown (July & August 2016) the last missing pieces will be installed: the remaineder of the 1.5 GeV transfer line from the linac as well as the last DBA before the injection straight. Once these last pieces have been installed the remaining subsystem tests can be completed so that commissioning of the 1.5 GeV storage ring should be able to commence in September 2016. Initial commissioning will be carried out with dummy chambers in the straight sections. In early 2017 the first EPU chambers will be installed so that commissioning of the first two EPUs in the 1.5 GeV storage ring can start by March 2017.

As in the 3 GeV storage ring, the 1.5 GeV storage ring was designed to operate with an even fill in constant multi-bunch mode at 500 mA with top-up injection. First studies [47, 48] have started investigating how users interested in timing and synchronization could be accommodated at the 1.5 GeV storage ring. In the meantime, the first five beamlines (funded within the two first beamline phases) will be installed and brought into operation throughout 2017.

5.2.4 **References**

1. The MAX IV Detailed Design Report.

   https://www.maxiv.lu.se/publications/

2. S.C. Leemann et al., "Beam dynamics and expected performance of Sweden's new storage-ring light source: MAX IV", Phys. Rev. ST Accel. Beams **12**, 120701 (2009).

3. S.C. Leemann, "Recent Progress on the MAX IV 1.5 GeV Storage Ring Lattice and Optics", Proceedings of IPAC'12, New Orleans, LA, USA, p.1662.

4. S. Werin, S. Thorin, M. Eriksson, J. Larsson, "Short pulse facility for MAX-lab", Nucl. Instr. and Meth. A **601**, 98 (2009).

5. S. Thorin et al., "Design of the MAX IV Ring Injector and SPF/FEL Driver", Proceedings of PAC'11, New York, USA, p.2447.

6. N. Cutic et al., "The MAX IV Injector as a Soft X-Ray FEL Driver", Proceedings of FEL2010, Malmö, Sweden, p.382.

7. F. Curbis et al., "Simulation Studies for an X-ray FEL Based on an Extension of the MAX IV Linac", Proceedings of FEL2013, New York, NY, USA, p.510.

8. H. Tarawneh, M. Eriksson, L.-J. Lindgren, B. Anderberg, "MAX-IV lattice,

dynamic properties and magnet system", Nucl. Instr. and Meth. A **508** (2003) 480.

9. M. Eriksson, et al., "Some small-emittance light-source lattices with multi-bend achromats", Nucl. Instr. and Meth. A **587** (2008) 221.

10. D. Einfeld, M. Plesko, "Design of a diffraction-limited light source", Proc. SPIE, **2013**, pp.201-212, 1993.

11. W. Joho, P. Marchand, L. Rivkin, A. Streun, "Design of a Swiss Light Source (SLS)", Proceedings of EPAC 1994, London, England, p.627.

12. D. Einfeld, J. Schaper, M. Plesko, "Design of a Diffraction Limited Light Source (DIFL)", Proceedings of PAC 1995, Dallas TX, USA, p.177.

13. D. Kaltchev, R.V. Servranckx, M.K. Craddock, W. Joho, "Lattice Studies for a High-brightness Light Source", Proceedings of PAC 1995, Dallas TX, USA, p.2823.

14. An MBA cycle schematic by A. Streun (PSI) can be found on slide 10 in https://agenda.infn.it/getFile.py/access?contribId=20&resId=1&materialId=slides&confId=9137

15. S.C. Leemann, A. Streun, "Perspectives for future light source lattices incorporating yet uncommon magnets", Phys. Rev. ST Accel. Beams **14**, 030701 (2011).

16. S.C. Leemann, "Interplay of Touschek scattering, intrabeam scattering, and rf cavities in ultralow-emittance storage rings", Phys. Rev. ST Accel. Beams **17**, 050705 (2014).

17. M. Johansson, L.-J. Lindgren, M. Sjöström, P.F. Tavares, "MAX IV 3 GeV Storage Ring Magnet Block Production Series Measurement Results", Proceedings of IPAC2016, Busan, Korea, p.1157.

18. S.C. Leemann, M. Eriksson, "Coupling and Brightness Considerations for the MAX IV 3 GeV Storage Ring", Proceedings of PAC2013, Pasadena, CA, USA, p.243.

19. W. Klotz, G. Mülhaupt, Proceeding of the Workshop on 4th Generation Light Sources, Stanford, CA, USA, 1992.

20. G. Mülhaupt, Technical Report No. ESRF/Mach-INJ/94-13, ESRF, Grenoble, France, 1994.

21. J. Bengtsson, Technical Report CER 88-05, CERN, Geneva, Switzerland, 1988.

22. J. Bengtsson, "The Sextupole Scheme for the Swiss Light Source (SLS): An Analytic Approach", PSI Internal Report SLS-TME-TA-1997-0009, PSI, Villigen, Switzerland, 1988.

23. A. Streun, "A standard method of nonlinear lattice optimization and application to the Swiss Light Source storage ring", ICFA Beam Dynamics Newsletter, Volume 57, pp.95-104, April 2012.

24. OPA lattice design code, http://ados.web.psi.ch/opa/

25. J. Bengtsson, Tracy-2 User's Manual (unpublished).

26. T. Olsson, S.C. Leemann, "High-Chromaticity Optics for the MAX IV 3 GeV Storage Ring", Proceedings of PAC2013, Pasadena, CA, USA, p.592

27. E. Wallén, S.C. Leemann, "Strategy for Neutralizing the Impact of Insertion Devices on the MAX IV 3 GeV Ring", Proceedings of PAC'11, New York, USA, p.1262.

28. S.C. Leemann, H. Tarawneh, "Impact of Insertion Devices on the MAX IV Storage Rings", Proceedings of IPAC2015, Richmond, VA, USA, p.1696.

29. M. Sjöström et al., "Orbit Feedback System for the MAX IV 3 GeV Storage Ring", Proceedings of IPAC'11, San Sebastián, Spain, p.499.

30. P.F. Tavares, S.C. Leemann, M. Sjöström, Å. Andersson, "The MAX IV storage ring project", J. Synchrotron Rad., **21**, 862-877 (2014).

31. S.C. Leemann, "Updates to the MAX IV 3 GeV Storage Ring Lattice", MAX-lab internal note 20110117, https://www.maxiv.lu.se/publications/

32. M. Johansson, B. Anderberg, L.-J. Lindgren, "Magnet design for a low-emittance storage ring", J. Synchrotron Rad., **21**, 884-903 (2014).

33. M. Sjöström, E. Wallén, M. Eriksson, L.-J. Lindgren, "The MAX III storage ring", Nucl. Instr. and Meth. A **601**, 229 (2009).

34. J. Björklund Svensson, M. Johansson, "Relative Alignment Within the MAX IV 3 GeV Storage Ring Magnet Blocks", Proceedings of IPAC2015, Richmond, VA, USA, p.57.

35. M. Sjöström, E. Wallén, M. Eriksson, L.-J. Lindgren, "Corrector-based magnet alignment procedure", Nucl. Instr. and Meth. A **597**, 170 (2008).

36. E. Al-Dmour et al., "Diffraction-limited storage-ring vacuum technology", J. Synchrotron Rad., **21**, 878-883 (2014).

37. Å. Andersson et al., "The 100 MHz RF System for the MAX IV Storage Rings",

Proceedings of IPAC'11, San Sebastián, Spain, p.193.

38. Å. Andersson et al., "The 100 MHz RF System for MAX-II and MAX-III", Proceedings of EPAC 2002, Paris, France, p.2118.

39. S.C. Leemann, "Pulsed sextupole injection for Sweden's new light source MAX IV", Phys. Rev. ST Accel. Beams **15**, 050705 (2012).

40. S.C. Leemann, L.O. Dallin, "Progress on Pulsed Multipole Injection for the MAX IV Storage Rings", Proceedings of PAC2013, Pasadena, CA, USA, p.1052.

41. S.C. Leemann, "Pulsed Multipole Injection for the MAX IV Storage Rings", 5th Low Emittance Rings Workshop, ESRF, Grenoble, France, 2015, http://indico.cern.ch/event/395487/contribution/946547/attachments/1155707/1661128/MAX_IV_Multipole_Injection_LER2015

42. S.C. Leemann, "Injection with a single dipole kicker into the MAX IV storage rings", Nucl. Instr. and Meth. A **693**, 117 (2012).

43. M. Eriksson et al., "Commissioning of the MAX IV Light Source", Proceedings of IPAC2016, Busan, Korea, p.11.

44. G. Skripka et al., "Commissioning of the Harmonic Cavities in the MAX IV 3 GeV Ring", Proceedings of IPAC2016, Busan, Korea, p.2911.

45. J. Breunlin, Å. Andersson, "Emittance Diagnostics at the MAX IV 3 GeV Storage Ring", Proceedings of IPAC2016, Busan, Korea, p.2908.

46. J. Breunlin, S.C. Leemann, Å. Andersson, "Improving Touschek lifetime in ultralow-emittance lattices through systematic application of successive closed vertical dispersion bumps", Phys. Rev. Accel. Beams **19**, 060701 (2016)

47. S.L. Sörensen, T. Olsson, C. Stråhlman, S.C. Leemann, "Workshop on Timing Modes for Low-Emittance Storage Rings", Synchrotron Radiation News Vol.28, No.5, 2015.

48. C. Stråhlman, T. Olsson, S.C. Leemann, R. Sankari, S.L. Sörensen, "Preparing the MAX IV Storage Rings for Timing-based Experiments", Proceedings of SRI 2015, in print, http://lup.lub.lu.se/record/7791594

49. S.C. Leemann, M. Eriksson, "MAX IV Emittance Reduction and Brightness Improvement", Proceedings of IPAC2014, Dresden, Germany, p.1615.

50. Å. Andersson et al., "The MAX II synchrotron radiation storage ring", Nucl. Instr. and Meth. A **343**, 644 (1994).

51. C.J. Bocchetta et al., "Project Status of the Polish Synchrotron Radiation Facility Solaris", Proceedings of IPAC'11, San Sebastián, Spain, p.3014.

52. S.C. Leemann, "Updates to the MAX IV 1.5 GeV Storage Ring Lattice", MAX-lab internal note 20120904, https://www.maxiv.lu.se/publications/

53. M. Johansson, "Design of the MAX IV/Solaris 1.5 GeV Storage Ring Magnets", Proceedings of IPAC'11, San Sebastián, Spain, p.2430.

54. M. Johansson, "The MAX IV 1.5 GeV Storage Ring Magnet Design", MAX-lab internal note 20130712, https://www.maxiv.lu.se/publications/

55. T. Olsson, S.C. Leemann, "High-chromaticity Optics for the MAX IV 1.5 GeV Storage Ring", Proceedings of IPAC2014, Dresden, Germany, p.30

5.3 Upgrade of the Swiss Light Source storage ring based on a lattice combining longitudinal gradient bends and anti-bends

Andreas Streun, Masamitsu Aiba, Michael Böge, Michael Ehrlichman,

Ángela Saá Hernández, Haisheng Xu

Paul Scherrer Institut, 5232 Villigen, Switzerland

Mail to: andreas.streun@psi.ch

5.3.1 **Introduction**

The emergence of new or upgraded light source storage rings providing 1-2 orders of magnitude higher brightness and coherent flux than 3rd generation light sources obliges existing facilities, among them the Swiss Light Source (SLS), to consider upgrades too in order to stay competitive in future.

The SLS started user operation in 2001 already. The storage ring is built from 12 triple bend achromats (TBA) in a circumference of 288 m and provides an emittance of 5 nm at 2.4 GeV. An upgrade, called SLS-2, is envisaged for the period 2021-24 and should reduce the emittance by a factor of 30. This enterprise is challenged by the comparatively small circumference of the SLS storage ring, because emittance scales approximately inversely with the 3rd power of the machine circumference.

Longitudinal gradient bends (LGB), i.e. magnets where the bending field varies along the beam path, can provide significantly lower emittance than homogeneous bends, if the optical functions are properly matched. Anti-bends (AB) are small bends of opposite field polarity than the main bend and located in some distance. ABs can bring the optical functions closer to the conditions for lowest emittance in any type of main bend, and in particular, they help to exploit the emittance reduction potential of an LGB in a periodic cell structure. A multi-bend achromat (MBA) based on a LGB-AB-