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The MAX IV storage ring project

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The MAX IV facility, currently under construction in Lund, Sweden, features two electron storage rings operated at 3 GeV and 1.5 GeV and optimized for the hard X-ray and soft X-ray/VUV spectral ranges, respectively. A 3 GeV linear accelerator serves as a full-energy injector into both rings as well as a driver for a short-pulse facility, in which undulators produce X-ray pulses as short as 100 fs. The 3 GeV ring employs a multibend achromat (MBA) lattice to achieve, in a relatively short circumference of 528 m, a bare lattice emittance of 0.33 nm rad, which reduces to 0.2 nm rad as insertion devices are added. The engineering implementation of the MBA lattice raises several technological problems. The large number of strong magnets per achromat calls for a compact design featuring small-gap combined-function magnets grouped into cells and sharing a common iron yoke. The small apertures lead to a low-conductance vacuum chamber design that relies on the chamber itself as a distributed copper absorber for the heat deposited by synchrotron radiation, while non-evaporable getter (NEG) coating provides for reduced photodesorption yields and distributed pumping. Finally, a low main frequency (100 MHz) is chosen for the RF system yielding long bunches, which are further elongated by passively operated third-harmonic Landau cavities, thus alleviating collective effects, both coherent (*e.g.* resistive wall instabilities) and incoherent (intrabeam scattering). In this paper, we focus on the MAX IV 3 GeV ring and present the lattice design as well as the engineering solutions to the challenges inherent to such a design. As the first realisation of a light source based on the MBA concept, the MAX IV 3 GeV ring offers an opportunity for validation of concepts that are likely to be essential ingredients of future diffraction-limited light sources.

Keywords: storage ring; synchrotron light source; multibend achromat.

1. Introduction

The MAX IV facility, currently under construction in Lund, Sweden, is the first of a new generation of storage-ring-based synchrotron light sources which employ a multibend achromat lattice to reach emittances in the few hundred pm rad range in a circumference of a few hundred metres, thus enabling the realisation of a new class of experiments which are critically dependent on source brightness and transverse coherence.

Central to the MAX IV design concept is the notion that the diverse needs of the user community are difficult to satisfy with a single source without compromising performance. In fact, the scientific case for the MAX IV project (MAX IV, 2006) requires high average brightness over a wide spectral range from infrared to hard X-rays as well as intense short X-ray pulses in the fs range. An analysis (MAX IV, 2006) of alternative solutions to meet those requirements led to the conclusion that storage-ring-based sources are likely to continue to be the workhorse of synchrotron-radiation-based research for the foreseeable future and that recent advances in accelerator lattice design and engineering development in key subsystems indicated the possibility of a substantial decrease in storage ring emittance, bringing those sources closer to the diffraction limit at X-ray wavelengths. Moreover, the growing demand for temporally as well as spatially coherent radiation pointed to the fact that free-electron lasers will also open new research opportunities.

All of those considerations were included in a facility-wide optimization procedure that led to a design (MAX IV, 2010) based on three sources sharing a common site and infrastructure (Fig. 1):

(i) Two electron storage rings operating at different energies (1.5 GeV and 3 GeV) in order to cover a wide photon energy range in an optimized way with short-period insertion devices.

(ii) A linear accelerator which acts as a full-energy injector into both rings and provides electron pulses with duration below 100 fs to produce X-rays by spontaneous emission in the undulators of a short-pulse facility (SPF) (Werin *et al.*, 2009; Thorin *et al.*, 2011). The 3 GeV linear accelerator also allows a

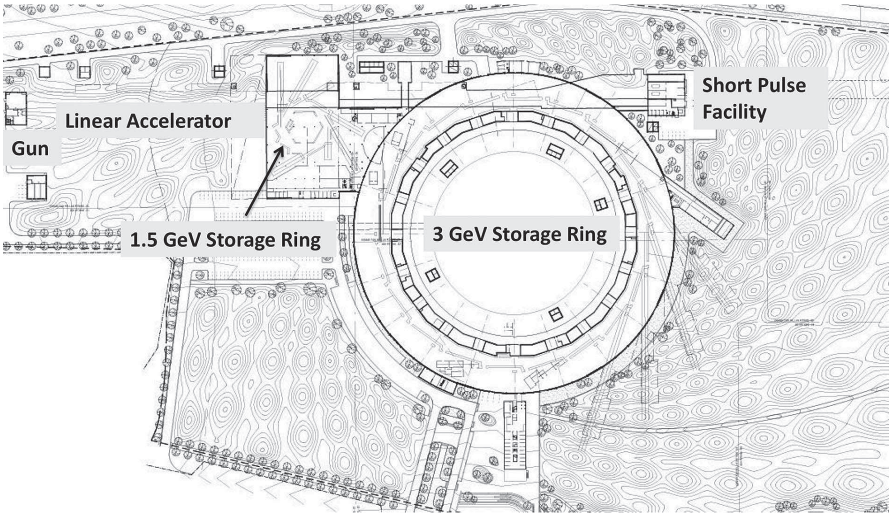

Figure 1
Overview of the MAX IV facility.

future upgrade to a fully coherent free-electron laser source based on seeding and/or cascading (Čutić *et al.*, 2010; Curbis *et al.*, 2013).

The 3 GeV ring (Leemann *et al.*, 2009; Eriksson *et al.*, 2011) is optimized for the production of high-brightness hard X-ray beams and features a 20-fold seven-bend achromat lattice, reaching a bare lattice emittance of 0.33 nm rad, which is further reduced to 0.2 nm rad when insertion devices are added. In order to reach such a low emittance in a circumference of only 528 m, a compact magnet design is mandatory. This implies the use of small magnet gaps (Johansson *et al.*, 2011), which allows reaching larger integrated gradients in shorter magnets and reduces the minimum required distance between consecutive magnets. Moreover, these compact magnets are built as integrated units in which the bending magnet poles and quadrupole pole roots are machined out of a pair of iron blocks, which are assembled together, each unit holding all the magnets of a complete cell. This concept leads to alignment accuracy within a cell being determined by machining and assembly accuracy, rather than fiducialization methods and also makes for high natural vibration frequencies of the units, thus reducing the sensitivity of the magnets to the environmental vibrational noise. Finally, the integrated magnet concept allows for streamlined installation and system testing.

The compact magnet design leads to narrow low-conductance vacuum chambers (Al-Dmour *et al.*, 2011), which necessitate distributed pumping and distributed absorption of the heat load from synchrotron radiation. The heat load problem is dealt with by choosing copper as the chamber material and providing water cooling along the extended region over which the synchrotron radiation heat is deposited, whereas distributed pumping is provided by non-evaporable getter (NEG) coating of the chamber's inner surface. As a result, the number of required lumped pumps and absorbers is significantly reduced with a corresponding reduction in cost and complexity.

The reduced chamber dimensions lead to an increased risk of collective instabilities (Tavares *et al.*, 2011), such as coupled bunch instabilities driven by the resistive wall impedance. A key ingredient in facing that problem is the use of passively operated harmonic cavities, which lengthen the bunches, reduce the electron density, help keep the heat load from beam-induced fields on vacuum components down to acceptable levels, and increase the incoherent synchrotron frequency spread that enhances Landau damping of coherent instabilities.

The RF system (Andersson *et al.*, 2011) operates at 100 MHz and uses capacitive-loaded normal conducting cavities, of the same type as previously developed for MAX II and MAX III. The choice of RF frequency allows a large bucket height with relatively low RF voltage and power to be achieved, which can be obtained from standard high-efficiency RF transmitters largely used in telecommunications, leading to low investment and operation costs. Moreover, the cavity design pushes the frequencies of the first higher-order modes (HOMs) of the cavity to about four times the fundamental mode frequency, so as to reduce the overlap of the cavity impedance spectrum with the spectrum of the lengthened bunches.

The 1.5 GeV ring (MAX IV, 2010; Leemann, 2012*c*) will replace the existing MAX II (Andersson *et al.*, 1994) and MAX III (Sjöström *et al.*, 2009) rings in delivering UV, soft X-ray and infrared radiation. With about the same circumference (96 m) as MAX II, the 1.5 GeV ring will deliver a smaller emittance (6 nm rad) than its predecessor by applying the same compact multipurpose magnet design concept (Johansson, 2011) as in the 3 GeV ring to a 12-fold DBA lattice. Here, two gradient dipole magnets, three combined quadrupole/sextupole magnets as well as four pure sextupoles and four combined trim sextupoles/orbit correctors are all integrated into a single iron block pair comprising a full DBA arc. An exact copy of the 1.5 GeV ring is being built at the Polish laboratory Solaris (Bocchetta *et al.*, 2012).

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 insertion devices (IDs), an ultralow-emittance design was targeted. One simple and robust method to achieve ultralow emittance is the use of a multibend achromat (MBA) lattice (Einfeld & Plesko, 1993; Joho *et al.*, 1994; Einfeld *et al.*, 1995; Kaltchev *et al.*, 1995). The MBA exploits the inverse cubic dependence of emittance on the number of bending magnets.

By choosing a very small bending angle per dipole the emittance can be dramatically reduced. By introducing a vertically focusing gradient in the dipoles the emittance is further reduced (the emittance scales inversely with the horizontal damping partition J_x) while the dispersion is limited to small values without requiring any extra space for vertically focusing quadrupoles. Because of the resulting low dispersion, the MBA lattice allows the use of narrow vacuum chambers without limiting momentum acceptance. This in turn enables narrow magnet gaps and hence magnets with strong gradients can become very compact (additionally, the compact magnets reduce the power consumption and hence the running cost). The compact magnets allow for a shorter unit cell; thus the number of unit cells for a given circumference can be increased. This in turn allows to further reduce the bend angle per unit cell which leads to even lower emittance (and in addition reduces the radiation heat load on the vacuum chamber). Thus, the MBA design approach closes a positive feedback cycle.

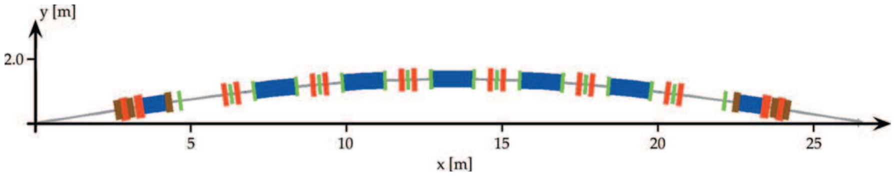

Figure 2
Schematic of one of the 20 achromats of the MAX IV 3 GeV storage ring. Magnets indicated are gradient dipoles (blue), focusing quadrupoles (red), sextupoles (green) and octupoles (brown).

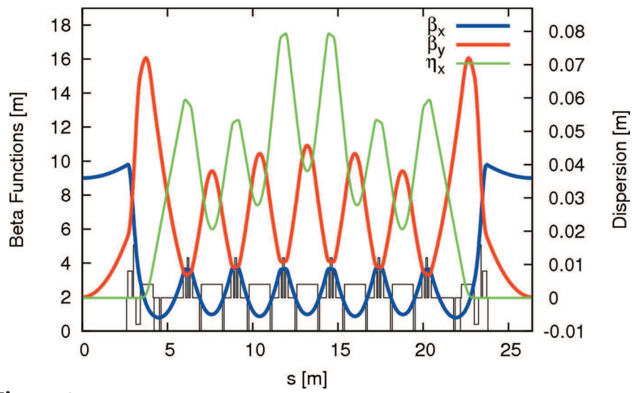

Figure 3
β functions and dispersion for one achromat of the MAX IV 3 GeV storage ring. Magnet positions are indicated at the bottom.

Before the MBA concept was first applied to a light source at MAX IV, this concept had been suggested for booster synchrotrons (Mülhaupt, 1994) of which several operate successfully today (Joho *et al.*, 2006; Georgsson *et al.*, 2004; Benedetti *et al.*, 2008). Distributing many sextupoles and/or making use of combined-function magnets throughout the MBA lattice allows the chromaticity to be corrected where it is generated (Klotz & Mülhaupt, 1992) giving large dynamic aperture and good off-energy performance. By introducing octupoles alongside the many sextupoles and carefully balancing non-linear magnet families, the non-linear optics can be tuned for large momentum acceptance (MA) and dynamic aperture (DA) providing both long Touschek lifetime and high injection efficiency despite the very low emittance (Leemann *et al.*, 2009; Leemann & Streun, 2011).

From its initial proposal in 2002 (Eriksson, 2002), the MAX IV 3 GeV storage ring lattice went through several iterations (Tarawneh *et al.*, 2003; Eriksson *et al.*, 2007, 2008) until a finalized version (Leemann *et al.*, 2009; MAX IV, 2010) was funded in 2010. The optics were subsequently refined (Leemann, 2011*a*,*b*) and a few minor modifications were made as a result of detailed magnet and vacuum systems engineering (Leemann, 2011*c*, 2012*d*). Further optics optimization is ongoing both in terms of choice of operational parameters (Leemann & Eriksson, 2013) as well as further modifications to user optics (Leemann & Eriksson, 2014).

2.1. Linear optics

The MAX IV 3 GeV storage ring consists of 20 seven-bend achromats separated by 4.6 m long straight sections for IDs. An overview of one MAX IV achromat is shown in Fig. 2. Each of the achromats consists of five unit cells and two 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.[1] 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. The short straights are used for RF cavities and diagnostics so that all long straights but the injection straight are available for installation of IDs.

Since the vertical focusing is performed by the gradient dipoles, dedicated quadrupoles are, apart from ID matching (*cf.* §2.3), 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 (PFSs) that are installed in all dipoles. Such a lattice leads to very compact optics with strong focusing, low β functions, and very small peak dispersion. The optics for one achromat are displayed in Fig. 3 and ring parameters are given in Table 1.

The working point was chosen away from systematic resonances so that both fractional tunes are just above the integer

[1] Note that this slightly increases the bare lattice emittance. Longitudinal gradients in bending magnets can be used to reduce the emittance (Nagaoka & Wrulich, 2007; Guo & Raubenheimer, 2002; Streun, 2004; Leemann & Streun, 2011), but this requires the bending radius to grow as the dispersion invariant $\mathcal{H}$ increases. For the soft-end bending magnets in MAX IV the zero-dispersion end of the bend is where the largest bending radii are.

Table 1
Main parameters of the MAX IV 3 GeV storage ring.

Parameter	Value	Unit
Energy, E	3.0	GeV
Circumference, C	528	m
Maximum circulating current, I	500	mA
Main radio frequency, f_{RF}	99.931	MHz
Number of long straights (available for IDs)	20 (19)	
Betatron tunes, $\beta_{x,y}$	42.200, 16.280	
Natural chromaticities, $\xi^{(0)}_{x,y}$	−49.984, −50.198	
Corrected chromaticities, $\xi_{x,y}$	+1.0, +1.0	
Momentum compaction, α_c, α_2	3.06×10^{-4}, 1.40×10^{-4}	
Horizontal damping partition, J_x	1.847	
Bare lattice emittance at zero current, ε_0	328	pm rad
Bare lattice natural energy spread at zero current, σ_δ	0.769×10^{-3}	
Bare lattice radiation losses	363.8	keV per turn

and away from the most dangerous resonances. With the working point held constant during operation (*cf.* §2.3), the non-linear optics can be adjusted to minimize the chromatic and amplitude-dependent tune shifts (ADTSs), therefore keeping the tunes of most stored beam particles clear of dangerous resonances. This shall be explained in the next section.

2.2. Non-linear optics

Despite comparably relaxed linear optics, the non-linear 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 non-linear amplitude-dependent behaviour, which can limit both DA and MA. 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 (Bengtsson, 1988, 1997*a*; Streun, 2012).

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 β function and dispersion. The defocusing sextupoles are installed as close as possible to the maximum of the product of dispersion and vertical β: 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 is created thus limiting chromatic β beating (Mülhaupt, 1994). 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* (Streun, 2010) and *Tracy-3* (Bengtsson, 1997*b*). The linear chromaticities were corrected to +1.0 in both planes[2] and the first-order resonance driving terms along with second- and third-order chromaticity were minimized as detailed by Streun (2012). However, amplitude-dependent tune shifts 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 non-linear optimization in a MBA lattice, three achromatic octupole families were introduced into the matching cells of the 3 GeV achromat in locations with appropriate β-function ratios (Leemann *et al.*, 2009; Leemann & Streun, 2011). 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, the octupoles in the MAX IV MBA were adjusted so the resulting overall ADTS is minimized throughout the physical acceptance (*cf.* Fig. 4).

Because the ADTSs are corrected with the octupoles, the sextupoles are freed up for first-order corrections (linear chromaticity, resonance driving terms). Some extra weight was also added to minimize second- and third-order chromaticity in an attempt to limit the chromatic tune footprint (*cf.* Fig. 5). The result of this non-linear 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 centre of the IDs] and energies covering the required $\pm 4.5\%$ acceptance. This results in large DA and MA (*cf.* Fig. 6 and §3.1), 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.

2.3. Optics matching and orbit correction

With the quadrupole doublets in the matching cells the β functions in the long straights can be tuned over a fairly wide range. This allows matching of the linear optics to individual IDs. The ID matching is performed both locally (β functions are matched to minimize β beat) and globally (phase advances are corrected to restore the design working point). For the

[2] An alternate optics has also been developed with linear chromaticity set to +4.0 as a fallback solution in case of instability issues during commissioning (Olsson & Leemann, 2013).