COMMISSIONING OF THE MAX IV LIGHT SOURCE

M. Eriksson, E. Al-Dmour, Å. Andersson, M. Johansson, S.C. Leemann, L. Malmgren, P. F. Tavares, S. Thorin, MAX IV Laboratory, Lund University, Lund, Sweden

Abstract

The first of the so-called diffraction-limited storage rings (DLSRs), MAX IV, has now gone into operation. For this ring, a multibend achromat (MBA) lattice is employed in order to achieve a small electron beam emittance. Several non-conventional technical system solutions have been introduced in order to reduce size, cost, assembly time, installation effort and to increase the ring robustness. Examples of this are solid magnet blocks housing several magnet items, a fully NEG-coated vacuum system and a low frequency RF system.

The commissioning started in late August 2015. Several base-line parameters have now been reached like a sufficiently high stored circulating current, beam lifetime and beam quality for beamline commissioning. The MBA concept and the operation of the non-conventional solutions technical systems are verified.

This article describes some of the technical solutions chosen and the early commissioning results.

THE MBA LANDSCAPE

It is since long a well-known fact that the electron beam emittance in a storage ring decreases as the inverse of the number of ring cells cubed. The MBA concept offers thus the solution to decrease the emittance significantly when a larger number of ring cells is introduced.

Until a few decades ago, the DBA (double-bend achromat) or TBA (triple-bend achromat) lattice types were by far dominating in 3rd-generation storage rings. The technical system solutions for these lattice types were well established and worked extremely well in harmony with each other. The minimum horizontal emittance was generally in the ballpark of 2-5 nm rad. It was also quite clear that MBA lattices could be introduced [1], but when using conventional techniques, the rings tend to be quite big and the cost prohibitive. The MBA-type rings now coming up have generally quite small magnets and a compact lattice so a large number of magnet cells can be squeezed into compact rings.

However, changing one technical system alone doesn't work. A whole set of new problems must be solved simultaneously. Smaller magnets call for smaller vacuum chambers. Limited vacuum conductance becomes an issue, as does the increased chamber impedance. The smaller beam emittance may introduce a strong intrabeam scattering (IBS) effect which may be quite significant, especially in medium-energy rings, and the Touschek beam lifetime may be severely reduced. The smaller beam emittance will also introduce stricter demands on beam stability and diagnostics to mention a few examples.

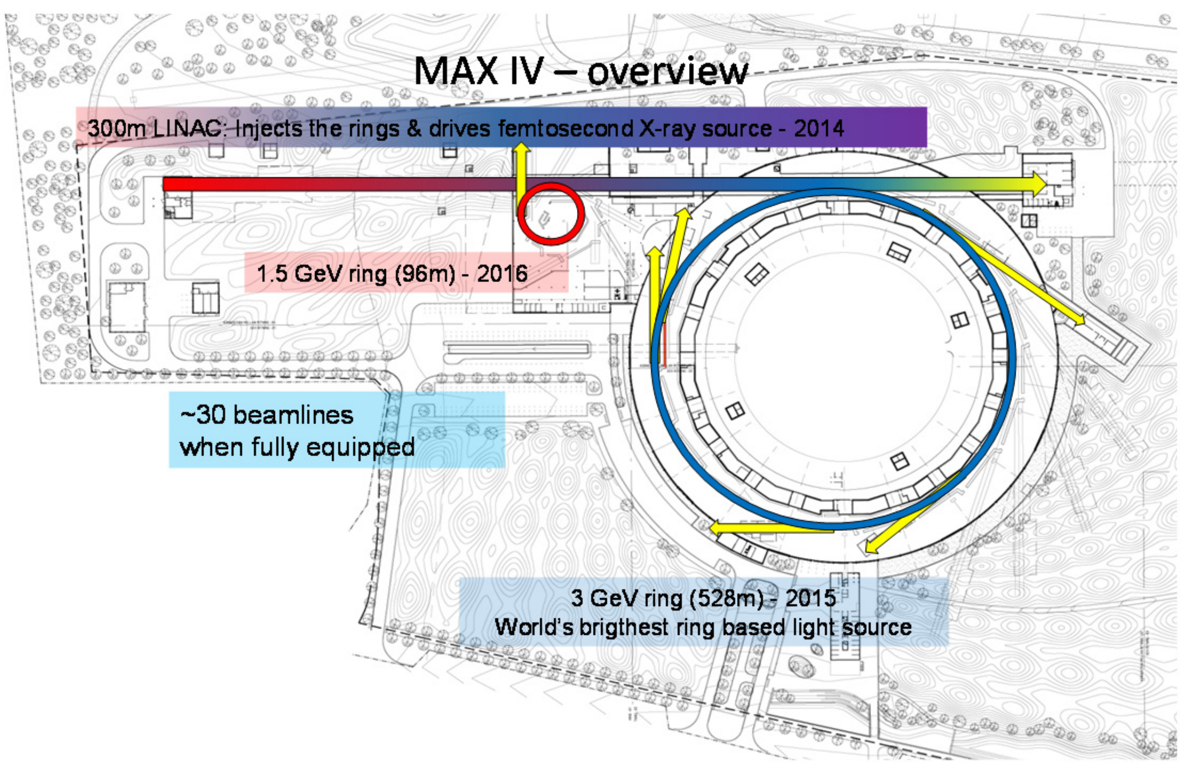

Figure 1: The MAX IV facility.

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The MAX IV ring is still in its commissioning state, although the early results clearly demonstrate the functionality of the new concepts. SIRIUS in Campinas, Brazil is under construction and so is the ESRF Upgrade. Many other are also coming up or are in an advanced planning state like APS-U and ALS-U.

And this seems to be only the beginning. A total of some 10 facilities are now in different states of design for even higher brilliance performance; the ghost has left the bottle.

How come? One strong contributing factor is the development of tracking codes [2] and improved simulations. Also new techniques like on-axis injection, anti-bends [3,4] and the usage of bunch-lengthening schemes are introduced or contemplated. Truly diffraction-limited sources at tens of keVs seem possible.

THE MAX IV FACILITY

The MAX accelerator facility is shown in Fig.1. A more detailed description can be found in [5].

As an injector, a 3 GeV S-band linac has been chosen. Admittedly, a booster synchrotron is a more economical choice as a ring injector, but a linac injector opens up Short-Pulse Facility (SPF) operation [6] (now being commissioned) and also paves the way for possible future Free-Electron Laser operation [7].

A smaller ring operating at 1.5 GeV, MAX V, was also introduced at the laboratory to increase the spectral range of high-quality undulator radiation. This ring will start commissioning in the fall of 2016.

THE LINAC INJECTOR

The 3 GeV injector linac is seen in Fig.2. and described more in detail in [5]. Two electrons guns are used; one thermionic RF gun used for injection into the rings and one photo-cathode RF gun. The motivation for using two guns is that our experience with the former is quite positive regarding robustness and long cathode lifetime while the photo-cathode is required for SPF operation. However, the photo-cathode gun seems quite robust as well, so this may very well be used as an injector gun.

Linac commissioning started in August 2014 when installation of the MAX IV ring started. Linac commissioning was well completed one year later when MAX IV commissioning started. Some parameters for the MAX IV linac can be found in Table 1.

Table 1: Injector Linac Parameter Values

End energy	3 GeV
RF	3 GHz
Field gradient	17 MV/m
Acc cell length	5.2 m
No of structures	39
Bunch compressors	Double achr.

Figure 2: Injector linac.

THE MAX IV STORAGE RING

As mentioned, this ring is described in detail in [5] so only a coarse recapitulation is given here.

3 GeV Storage Ring Beam Dynamics

Lattice & Optics The 3 GeV storage ring was designed to meet the requirements of state-of-the-art insertion devices (IDs) for the generation of high-brightness hard x-rays. Its lattice was therefore based on a novel compact multibend achromat (MBA) delivering 328 pm rad emittance in a circumference of 528 m [8-10]. 20 MBAs provide 19 long straights (4.6 m) for IDs and 40 short straights (1.3 m) for RF and diagnostics. The MAX IV achromat is a 7-bend achromat with 5 unit cells (3°) and 2 matching cells (1.5°). All bends contain a transverse gradient for vertical focusing (J_x=1.85). The matching cell dipoles have a longitudinal gradient as well.

Since the vertical focusing is performed by the gradient bends, only horizontally focusing quadrupoles are contained in the unit cells. In the matching cells at the ends of the arc a quadrupole doublet is included for matching of the arc optics to ID gap and phase settings. Adjustment of the vertical focusing in the arc is performed by exciting currents in the pole-face strips 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 is displayed in Fig.3 and storage ring parameters are given in Table 2.

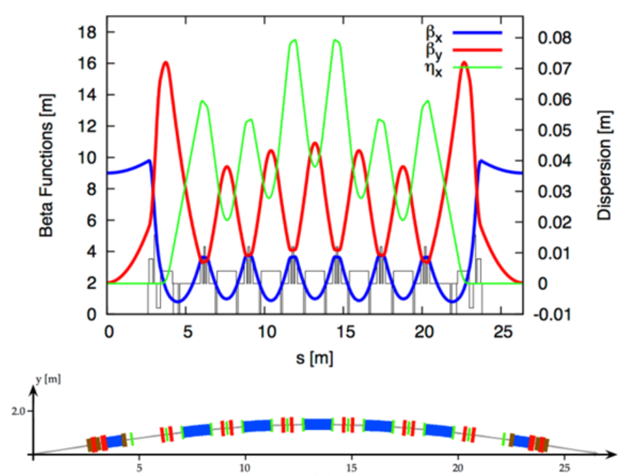

Figure 3: MAX IV 3 GeV achromat and optics.

Table 2: MAX IV 3 GeV Storage Ring Parameters

Operating energy	3 GeV
Circulating current	500 mA
Circumference	528 m
Horizontal emittance (bare lattice)	320 pm rad
Horizontal emittance (incl. IDs) [11]	179 pm rad
Coupling	0.5-2.5%
Total beam lifetime at 500 mA	>10 h
Q_x, Q_y	42.20, 16.28
ξ_x, ξ_y (natural)	-50.0, -50.2
Momentum compaction factor	3.06×10^{-4}
Required momentum acceptance	>4.5 %

The quadrupoles that interleave the dipoles in the unit cells have actually been split to make space for focusing sextupoles in between at optimum beta function ratios. Defocusing sextupoles flank all dipoles. Overall five families of sextupoles correct the large natural chromaticity and minimize resonance driving terms (RDTs) [9]. By distributing many sextupoles throughout the achromat, RDTs are canceled within the achromat, sextupole gradients and length can be reduced, and chromaticity is corrected at the source thus limiting chromatic beta beating. In addition, three octupole families have been added to the matching cells. The octupoles provide the most efficient tuning for amplitude-dependent tune shift [10]. The overall result of the nonlinear optimization is a very compact tune footprint both on and off momentum. This results in large dynamic aperture and momentum acceptance, which in turn provides for good injection efficiency and ample Touschek lifetime.

Thanks to a fully NEG-coated copper vacuum system (cf. the following section), limited vacuum apertures are sufficient, thus enabling small magnet gaps. This allows for large gradients and short magnets which results in strong focusing, low emittance and a compact lattice. The compact optics in turn allows reducing bend angles, i.e. increasing the number of cells, thereby closing the MBA cycle.

In order to reach the diffraction limit at 1 Å the emittance coupling can be set at a very generous 2.5% [12]. Matching of the arc optics to ID gap and phase settings is achieved using the quadrupole doublets in the matching cells as well as skew quadrupole windings installed on all sextupoles and octupoles [13,14].

Emittance & Intrabeam Scattering As typically in ultralow-emittance lattices based on MBAs (where the power radiated in the bending magnets is low compared to ID losses), the equilibrium emittance of the 3 GeV storage ring will depend on the number and type of installed IDs as well as their gap and phase settings [11]. In addition, the overall equilibrium emittance at high stored current is limited by intrabeam scattering (IBS): at natural bunch length a blowup of 45% would be expected at 500 mA. However, three Landau cavities operating at the third harmonic will stretch bunches by roughly a factor five, thereby mitigating the emittance blowup from IBS at high stored current. A moderately ID-equipped ring should achieve an equilibrium emittance at 500 mA of roughly 270 pm rad (incl. IBS and Landau cavities). Once the storage ring is fully equipped with IDs, this figure can be expected to drop to roughly 220 pm rad (compared to a zero-current value of 179 pm rad).

Lifetime & Injection At 500 mA stored current gas scattering lifetimes in the 3 GeV storage ring have been calculated to amount to about 17 hours in total. Touschek lifetime is required to be better than 24 hours so that a total lifetime of 10 hours can be achieved. The Touschek lifetime is high despite the ultralow emittance because of the large momentum acceptance of the storage ring. Furthermore, it will actually increase as the emittance is lowered by additional IDs [11]. Even in a fully ID-equipped ring (with aperture restrictions from narrow-gap chambers and in-vacuum IDs) and at 2 pm rad vertical emittance [11,12] a Touschek lifetime of 27.3 hours at 500 mA including machine imperfections has been derived from tracking simulations. Such lifetime is compatible with top-up injection shots every few minutes keeping storage ring current constant to within roughly 0.5%. Storage ring injection during commissioning has so far been performed with a single dipole kicker [15], but for fully transparent top-up injection during user operation we will soon install a multipole injection kicker [16,17].

Integration of Technical Systems

The magnet block concept is used. One block is shown in Fig.4. Several magnets are CNC-machined in this block. A more detailed report of the magnet production and results is given in [18].

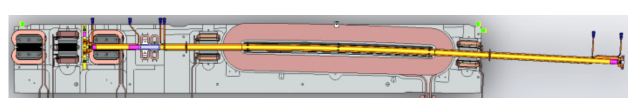

Figure 4: One magnet block in MAX IV.

This magnet concept offers several advantages:

- No special girders are needed. The blocks are installed directly on concrete blocks.
- No assembly procedure is needed. The blocks come wired and plumbed from the contractor.
- The number of magnet units to be installed is reduced one order of magnitude.
- High eigenfrequencies. The rigidity/mass ratio is high.
- High internal alignment precision, some 10 µm [18].

The disadvantage is that eventual errors are harder to correct.

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The vacuum system [19] consists mainly of a round NEG-coated copper tube (Fig. 5). Very few lumped absorbers are used (just one per achromat at the photon beam exit). The synchrotron radiation hits the copper tube at small angles of incidence and the tube is cooled by external water cooling tubes electron beam welded to the vacuum tube.

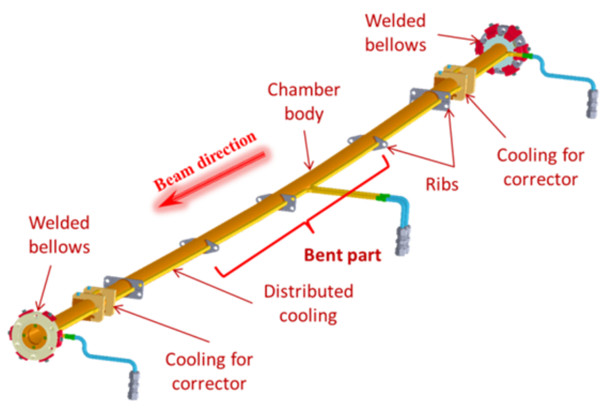

Figure 5: One MAX IV vacuum tube.

The main RF parameters are seen in Table 3. The main motivations for the choice of a low frequency are:

- Long bunches introduce a narrow power spectrum. This reduces the effect of collective instabilities, in some cases significantly.
- The RF voltage needed for a large bucket height is reduced.
- Commercial high efficiency solid state amplifiers (FM band) are on the market to low prices.
- With the 100 MHz RF, we have a 10 ns bunch separation which matches the rise-time of fast stripline injection kickers.

To mitigate coupled bunch instabilities and to reduce the IBS and Touschek effects, a 3rd-harmonic cavity system is used [20].

MAX IV COMMISIONING

Commissioning of the 3 GeV ring was initiated in August 2015 when a 3 GeV electron beam was first brought up the transfer line and into the ring´s injection straight. The beam made the first few turns around the ring without requiring any orbit correctors to be turned on and with all magnets (including sextupoles and octupoles) set to their nominal values according to the design lattice. During those initial stages of commissioning, before the storage ring RF was turned on, the chopper system (based on a stripline kicker) located immediately downstream of the thermionic electron gun was run at 500 MHz (rather than at the storage ring RF frequency) in order to provide a much improved signal-to-noise for the BPM electronics which were used for measuring the first turn trajectory.

Once RF power could be delivered to two of the six 100 MHz cavities, beam capture could be demonstrated at 0.1 mA, which allowed measurements of electron beam optical parameters such as the dispersion function, betatron and synchrotron tunes and the closed orbit. In particular, synchrotron tune measurements allowed proper phasing of the cavities to be performed. Stacking was first demonstrated on October 8 and the stored current rose steadily over the following weeks, finally reaching 120 mA (in multi-bunch mode) by the end of January 2016. During this period further characterization of both the single particle dynamics as well as of coherent collective effects were carried out. These included tests of a slow orbit feedback system, LOCO measurements and aperture scans.

Moreover, the thermionic gun chopper was set to imprint the 100 MHz structure to the injector beam imposed by the storage RF, and injection efficiency beyond 75% was eventually demonstrated. The chopper could also be used to demonstrate injection into a single bucket: up to 8.5 mA could be stored in a single bunch without any signs of transverse instabilities (note that the required current in each bunch when running in multibunch mode is only 500/176=2.84 mA).

Once higher currents could be stored, commissioning and conditioning of the passively operated third-harmonic (Landau) cavities could be initiated. The positive impact of tuning in the harmonic cavities both in terms of beam lifetime as well as in terms of reduced amplitude of coupled-bunch modes could be confirmed.

Table 3: RF Configuration 3.0 GeV Ring

Operation Phase	Commissioning	Final
Energy loss/turn	360 keV	1000 keV
Current	200 mA	500 mA
Total SR power	72 kW	500 kW
Total RF voltage	1.0 MV	1.8 MV
Number of cavities	4	6
Cavity voltage	250 kV	300 kV
Cavity R_{sh} (=V^2/2P)	1.6 Mohm	1.6 Mohm
Total Cu losses	78 kW	169 kW
Coupling (beta)	1.9	4.0
Nr of RF stations	4	6
Minimum RF station power (w. LC losses)	39 kW	114 kW
Total LC voltage	310 kV	490 kV
Number of LC	3	3
LC R_{sh} (=V^2/2P)	2.5 Mohm	2.5 Mohm
Total LC Cu losses	6.3 kW	16 kW
Bunch rms length	60 mm	56 mm

These could be observed on a spectrum analyser as well as with a commercial bunch-by-bunch feedback processor.

First preliminary tests of the bunch-by-bunch feedback system included temperature tuning of the RF cavities and attempts to close the feedback loop for the transverse plane using a short stripline originally intended for tune measurements.

During most of the commissioning, injection was done at 0.5 Hz, due to radiation safety requirements. That rate was eventually raised to 2 Hz leading to an accumulation rate of up to 20 mA/min in the storage ring. In routine operation the injection rate will be further increased to 10 Hz.

In parallel with commissioning, vacuum conditioning of the NEG coated chambers as well as conditioning of the RF cavities allowed the electron beam lifetime to reach in excess of 16 hours at 100 mA stored beam current

In February 2016, the first two insertion devices (two in-vacuum undulators) were installed in the ring. At the time of writing, initial commissioning of the beamline frontends has been initiated and the undulator gaps have been closed to 7 mm.

Currently, emittance measurements to verify the horizontal emittance are carried out [21].

REFERENCES

[1] D. Einfeld et al., “Design of a Diffraction Limited Light Source”; Proceedings: PAC, p 177 (1995).
[2] A. Hofler et al., Phys. Rev. ST Accel. Beams **16**, 010101 (2011).
[3] R. Hettel, “PEP-X: Concepts for a Future Light Source for SSRL”, Synchrotron Radiation News, 23:6, 42-47 (2010).
[4] A. Streun, "The anti-bend cell for ultralow emittance storage ring lattices", NIM-A **737** (2014) 148-154.
[5] The MAX IV Detailed Design Report, available at http://www.maxlab.lu.se/maxlab/max4/index.html
[6] S. Werin, S. Thorin, M. Eriksson and J. Larsson, “Short Pulse Facility for MAX-lab”, NIM-A **601** (2009) 98-107.
[7] Anders Nilsson et al, “The Soft X-Ray Laser@MAX IV, A Science Case for SXL”, Stockholm university, to be published
[8] M.Eriksson et al, "Some Small Emittance Lattices with Multibend Achromats", NIM-A **587** (2008) 221-226.
[9] 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).
[10] S.C. Leemann, A Streun, "Perspectives for future light source lattices incorporating yet uncommon magnets", Phys. Rev. ST Accel. Beams **14**, 030701 (2011).
[11] 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).
[12] S.C. Leemann, M. Eriksson, "Coupling and Brightness Considerations for the MAX IV 3 GeV Storage Ring", MOPHO05, PAC2013, Pasadena, CA, USA, p.243.
[13] E. Wallén, S.C. Leemann, "Strategy for Neutralizing the Impact of Insertion Devices on the MAX IV 3 GeV Storage Ring", TUP235, PAC2011, New York, NY, USA, p.1262.
[14] S.C. Leemann, H. Tarawneh, "Impact of Insertion Devices on the MAX IV Storage Rings", TUPJE038, IPAC2015, Richmond, VA, USA, p.1696.
[15] S.C. Leemann, "Injection with a single dipole kicker into the MAX IV storage rings", NIM-A **693**, p.117, 2012.
[16] S.C. Leemann, "Pulsed sextupole injection for Sweden’s new light source MAX IV", Phys. Rev. ST Accel. Beams **15**, 050705 (2012).
[17] S.C. Leemann, L.O. Dallin, "Progress on Pulsed Multipole Injection for the MAX IV Storage Rings", WEPSM05, PAC2013, Pasadena, CA, USA, p.1052.
[18] M. Johansson, B. Anderberg, L-J. Lindgren, “Magnet Design for a Low-Emittance Storage Ring” J. Synchrotron Rad. **21**, 884-903 (2014).
[19] E. Al-Dmour et al., “Diffraction-limited storage-ring vacuum technology” J. Synchrotron Rad. **21**, 878-883 (2014).
[20] G. Skripka et al, “Commissioning of Passive Harmonic Cavities in the MAX IV 3 GeV Ring”, These proceedings, WEPOW035.
[21] J. Breunlin et al, “Emittance Diagnostics at the MAX IV 3 GeV Storage Ring" .These proceedings, WEPOW034.

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