COMMISSIONING OF THE MAX IV LIGHT SOURCE

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

Abstract

The MAX IV facility, currently under commissioning 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.

In this paper, we briefly review the overall facility layout and design concepts and focus on recent results obtained in commissioning of the accelerators with an emphasis on the ultralow-emittance 3 GeV storage ring, the first light source using a multibend achromat.

INTRODUCTION

A central aspect of 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. The MAX IV approach to the common dilemma of simultaneously providing high brightness hard and soft radiation as well as extremely short radiation pulses consists in having a facility featuring three different accelerators, each of which is optimized for a different range of applications (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).

The 3 GeV storage ring [1-3] employs a multibend achromat (MBA) lattice to achieve a bare lattice emittance of 0.33 nm rad. The technical implementation of the MBA lattice raises several engineering challenges: the large number of strong magnets per achromat requires a compact design with small-gap combined-function magnets and 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 cavities. These long bunches are a crucial ingredient to overcome both incoherent (intrabeam scattering) and coherent collective effects and allow operation at high currents while maintaining good Touschek lifetime [4].

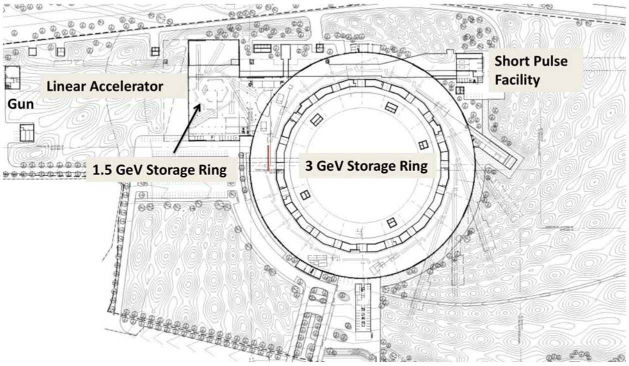

Figure 1: Overview of the MAX IV facility.

The 1.5 GeV storage ring [1] replaces the MAX II and MAX III rings, whose operation was officially concluded on December 15th, 2015 after nearly two decades of continuous service to the scientific community. Despite having about the same circumference as MAX II, the 1.5 GeV storage ring delivers a smaller emittance through the use of the same compact magnet design as in the 3 GeV storage ring. An exact copy of the 1.5 GeV storage ring was built and successfully commissioned at the Polish laboratory Solaris [5].

In this paper, we focus on commissioning results and operational experience with those accelerator subsystems that present most of the innovations brought about by the MAX IV design. In fact, as the first realisation of a light source based on the MBA concept, the MAX IV 3 GeV storage ring offers an opportunity for validation of concepts that are likely to be important ingredients of future diffraction-limited light sources.

INJECTOR LINAC

The MAX IV linear accelerator [2] is used for both full energy injection and top-up to the storage rings and as a high brightness driver for a Short Pulse Facility (SPF) [6]. It consists of 39 warm S-band linac sections together with 18 RF units, each consisting of a 35MW klystron and a solid state modulator and a SLED energy doubler.

For injection to the storage rings a thermionic gun with a pulse train chopper system is used [7]. The chopper can be used to either produce a 500 MHz time structure convenient to enhance the signal-to-noise ratio for single pass beam position monitor electronics during early commis-

---

† pedro.fernandes_tavares@maxiv.lu.se

sioning or to deliver a 100 MHz structure that matches the 100 MHz RF buckets in the rings.

In high brightness mode, we use a 1.6 cell photo cathode gun capable of producing an emittance of 0.4 mm mrad at a charge of 100 pC [8]. The gun is operated together with a kHz Ti:sapphire laser at 263 nm. The same laser is used for timing and synchronisation of the whole accelerator and the SPF.

During August 2015, the linac started operations for 3 GeV storage ring injection and has today reached an injection efficiency of up to 90 % and injection rates of up to 20 mA/minute at 2 Hz repetition rate (Fig. 2). The design goal for injection repetition rate is 10 Hz, which depends on an outstanding permit from radiation safety authorities.

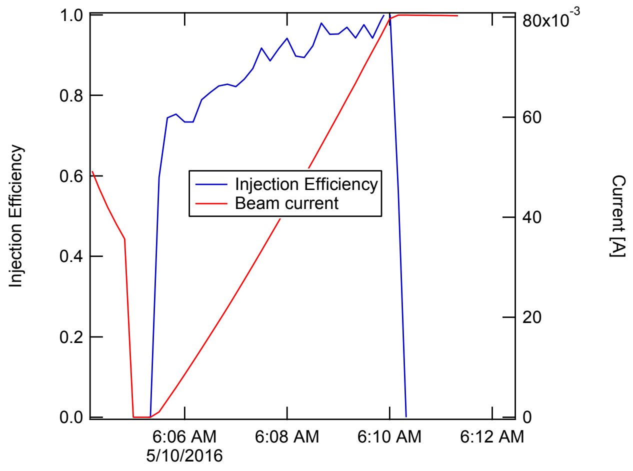

Figure 2: Current accumulation and injection efficiency in the 3 GeV storage ring.

1.5 GEV STORAGE RING

Beam commissioning in the 1.5 GeV storage ring began on September 5th, 2016 and is ongoing. The beam was threaded through the transfer line connecting the injector to the ring and first turn was achieved on September 14th. After a short interruption of the beam commissioning, stored beam and beam accumulation was achieved on September 30th. At the time of writing, 1.6 mA stored beam has been achieved. The first narrow-gap chambers for elliptically polarizing undulators are planned to be installed during the first half of 2017 thus enabling commissioning of the first 1.5 GeV storage ring beamlines.

3 GEV STORAGE RING

Beam Commissioning

A brief account of the early commissioning efforts can be found in [9]. Here, we provide further details as well as an update on the commissioning results.

The first few turns in the ring were achieved without the need for any orbit correctors excitation and with all magnets (including sextupoles and octupoles) set to their nominal values according to the design lattice and magnetic measurement data (Fig. 3).

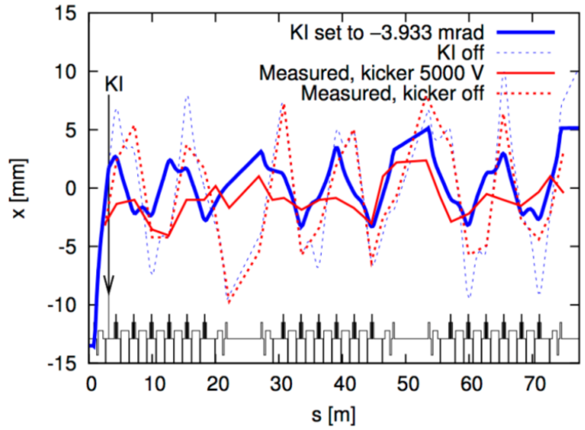

Figure 3: Calculated and measured first turn trajectory in the 3 GeV storage ring along the first three achromats.

Once RF power could be delivered to two of the six 100 MHz cavities, beam capture with a single dipole magnet [10] could be demonstrated, which allowed measurements of electron beam optical parameters such as the dispersion function, betatron and synchrotron tunes and the closed orbit. An additional confirmation that the expected alignment tolerances had been achieved with the magnet block concept could be obtained by measurement of the closed orbit with all vertical correctors at zero excitation current. Response matrix measurements (Fig. 4) were used to confirm the integer tunes and later to perform first LOCO measurements and correction (Fig. 5).

Once stacking was demonstrated, the stored current rose steadily over the following months, finally reaching 198 mA (in multibunch mode) by July 2016. Accumulation up to these current levels was still achieved using only a single dipole injection kicker.

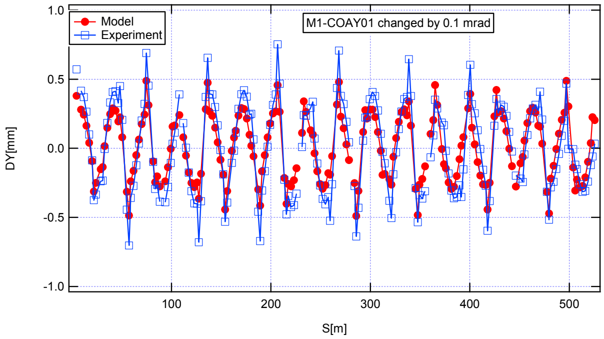

Figure 4: Change of the vertical closed orbit resulting from changing the strength of a single vertical corrector.

A slow orbit feedback system, based on a MATLAB application was tested and used to maintain stable beam position during photon beam delivery for the commissioning of the first two beamlines (Fig. 6).

Scraper measurements in both planes together with local beta function measurements allowed comparing the storage ring's effective acceptance with design studies. Compared to simulations, the vertical acceptance of

2.2 mm mrad (corresponding to ~2.1 mm at the ID source points) is in excellent agreement [11]. In the horizontal, an acceptance of only 2.5 mm mrad (corresponding to ~4.8 mm at the center of the injection straight) indicates that, although injection with high efficiency has already been demonstrated, further optics studies and corrections are required.

The thermionic gun chopper was used to demonstrate injection into a single bucket: up to 8.5 mA could be stored in a single bunch without signs of transverse or longitudinal instabilities (note that the required current in each bunch when running in multibunch mode is only 500 mA/176=2.84 mA).

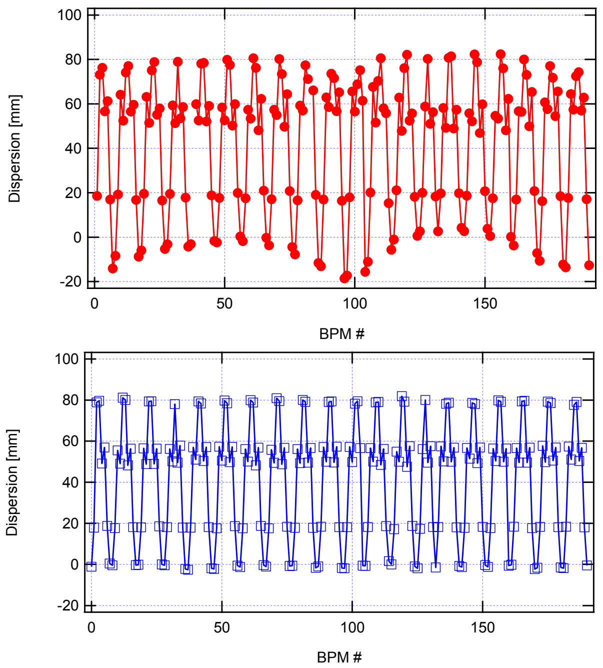

Figure 5: Example of the application of LOCO to correct the linear optics. Top: dispersion function before LOCO correction showing significant beating. Bottom: dispersion beating is reduced after LOCO.

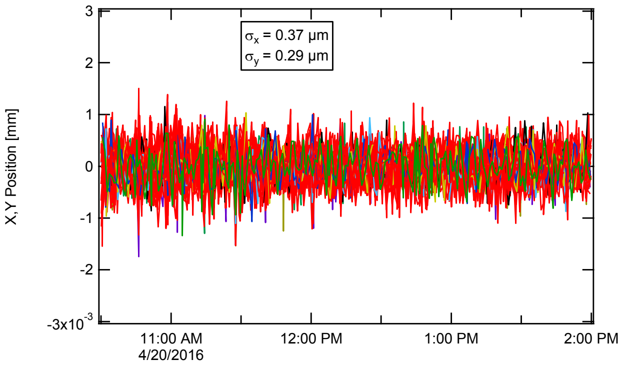

Figure 6: Horizontal and vertical beam positions measured at BPMs around insertion device straights as a function of time with closed slow orbit feedback.

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 [12,13].

A bunch-by-bunch feedback system using 30-cm long striplines was commissioned allowing to achieve a stable beam in all three planes, with the striplines being used as a weak longitudinal kicker when driven in common mode. The diagnostic capabilities of the bunch-by-bunch system allowed for temperature tuning of the RF cavities as well as to handling transverse instabilities (Fig. 7).

A diagnostic beamline imaging visible and near infrared synchrotron radiation from a bending magnet was used to characterize both the bunch length (using an optical sampling oscilloscope) and the transverse beam profile. The measurements carried out so far [14,15] point to a horizontal emittance below 400 pm rad and further improvements to both the experimental setup and the machine models are needed to provide more accurate results.

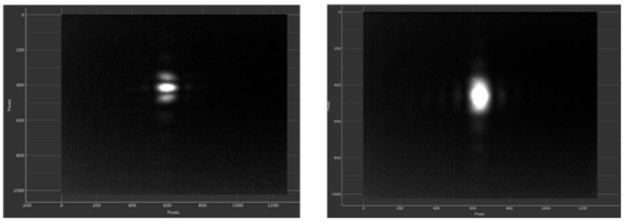

Figure 7: Suppression of transverse instabilities as observed on the beam image monitor of the diagnostic beamline.

In February 2016, the first two insertion devices (two in-vacuum undulators with 18 mm period) were installed in the ring and subsequently commissioned allowing the first experiments using X rays to be performed at the MAX IV 3 GeV storage ring: these were the determination of protein structures at the BioMAX beamline. Another three insertion devices (two elliptically polarizing undulators and one in-vacuum wiggler) were installed during the 2016 summer shutdown and are expected to be brought into operation during the next months.

Magnet System

After installation [16], before start of beam commissioning, a comprehensive test program was carried out for all 3 GeV storage ring magnet blocks, consisting of

- Polarity check by hand held Hall probe, for each individual magnet element (1320 pcs), through inspection ports in the magnet yoke included for this purpose.
- Logged steady state temperature rise at full current for each individual water cooled magnet (940 pcs).

After the testing, we have not in beam commissioning found any single case of wrong magnet polarity. A few cases of blocked cooling channels were found and corrected during testing, but after that we have had no instances of interlocks caused by overheating coils in the first year of operating the 3 GeV storage ring. One issue that was discovered during the full current testing was that the thermoswitch placement in our design was not good enough to safely interlock magnet power supplies in case of a fully blocked cooling channel, due to too long distances between coil body and placement on coil exit leads. Therefore it was necessary to add more thermoswitches, with improved placement and/or rating, but we were able to do this without impact to the commissioning time schedule.

As calibration of magnet field strength vs current in the 3 GeV storage ring control system, we are using the field measurement data from the magnet suppliers [17]. Current set values calculated from this data were used as starting point for beam commissioning, and we were able to achieve many turns with these settings. It can be noted the magnet blocks are built with the possibility to passively adjust all individual magnet element strengths by shunt resistors [18], but as of yet this has not been used.

Vacuum System

The 3 GeV storage ring vacuum system [19] is following the magnetic lattice design, which is divided into 20 vacuum achromats sealed by gate valves. Each achromat is ~26 m long, including 4.5-m long straight section (L) where insertion devices are installed. In order to cope with the low conductance imposed by the small apertures, all the vacuum chambers including Beam Position Monitors (BPMs) were coated with 1 µm thick NEG (Non-evaporable getter - Ti, Zr, V alloy) film all along the electron beam path. The main vacuum chambers are made of extruded silver bearing oxygen-free (OFS) copper, have 1 mm wall thickness and inside diameter of 22 mm in order to fit the magnet aperture of 25 mm in diameter. The vacuum system integrated with magnets is presented in Fig. 8.

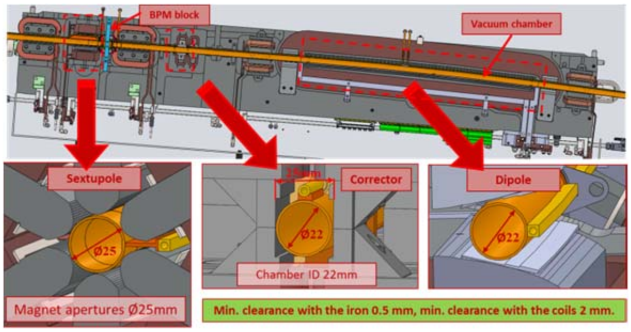

Figure 8: Top view of one opened magnet block with the vacuum pipe placed and detailed views of cross-sections of sextupole, corrector and dipole magnets.

In each achromat there are two short straight sections (S1 and S2), each ~1.5 m long. The first one (S1) is located where the photon and electron beams split. At that location the synchrotron radiation is intercepted by an uncoated, copper crotch absorber under which an ion pump is placed. The second short straight section (S2) is devoted mainly to RF cavities which also accommodate ion pumps. The long straight sections (L) where no insertion devices (ID) are installed accommodate one pumping port with an ion pump. Therefore, there are 3 ion pumps per achromat and each port is shielded from the electron beam path with a mesh.

The average base pressure (without beam) in the ring is 2x10^{-10} mbar (nitrogen equivalent), measured by penning and extractor gauges placed in short straight sections S1 and S2. Since the start of the ring operation, the total beam lifetime is increasing confirming vacuum conditioning of the system. The normalized total beam lifetime evolution versus the beam dose is shown in Fig. 9.

The evaluation of the vacuum performance of the machine is mostly limited to the locations where vacuum sensors are installed. The vacuum conditioning curve, presenting average pressure rise normalized to machine current versus accumulated beam dose is shown in Fig. 10. These pressure values were recorded by penning gauges placed in S2 (nitrogen equivalent). The slope of the conditioning curve is -0.75, which is similar to the vacuum conditioning performance of the Soleil storage ring where 56% of the vacuum system is NEG-coated [20], as well as with the measurements of the MAX IV 3 GeV storage ring vacuum chambers performed at ESRF at D31 beamline in 2014 during the production phase.

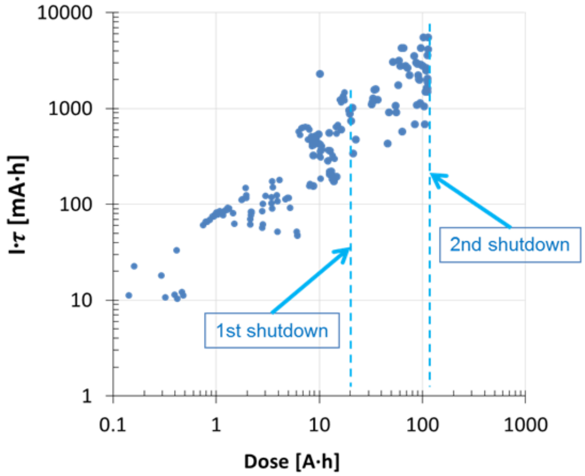

Figure 9: Normalized total beam lifetime versus beam dose.

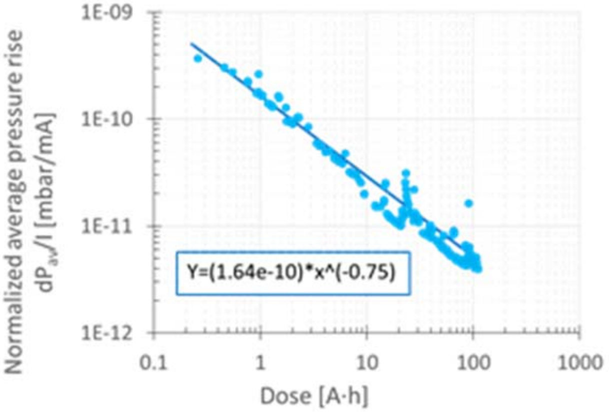

Figure 10: Normalized average pressure versus accumulated beam dose.

Beam lifetime measurements as a function of vertical aperture (defined by a movable scraper) performed at the beam dose of 40 Ah indicate that the average total pressure along the electron beam path was on the range of $5x10^{-9}$ mbar with the beam current of 70 mA.

There have been no major machine downtimes due to intervention on the vacuum system. However, one incident occurred when one of the 100 MHz RF cavities was vented (with closed gate valves) through a broken high power ceramic feedthrough. The cavity was removed from the ring and a dummy chamber has been installed.

In a number of S1 locations, where the photon beam is extracted from the ring, due to mispositioning of the pumping port, the synchrotron radiation is being deposited on a stainless steel surface that should be shadowed. This issue is being investigated and pends mitigation.

RF System

The RF system for the 3 GeV storage ring is described in [21] and in [1]. A relatively low frequency, 100 MHz, has been chosen with normal conducting, capacity loaded copper cavities. The shunt impedance amounts to 1.6 MΩ per cavity and six cavities are foreseen for the final operation, with estimated SR losses of 1 MV/turn, or 500 kW, at the design current. An RF energy acceptance of 4.5%, is then reached with an overvoltage of only 1.8, so copper losses are only 169 kW. To keep a high degree of modularity, one RF station feeds each cavity. The choice fell on a combination of two 60 kW solid state amplifiers, with a 70% efficiency. A 120 kW circulator is installed to isolate the cavity from the RF station.

Even though six main cavities were installed already before commissioning, on average only three cavities were operational during the first half year. Vacuum related issues such as multipacting and even real leaks (in ceramic windows) hampered the operation. During the second half year we operated more routinely five cavities at around 250 kV each. The amplitude and phase loops were during most of the commissioning regulating on the forward fields in the transmission line. This was a safety precaution to avoid that a cavity field break down would not be followed by an excessive transmitter output power. Only recently have we started regulating on the cavity fields. This was necessary when careful cavity temperature tuning was initiated to combat longitudinal coupled bunch mode instabilities driven by HOMs in the cavities.

CONCLUSION

Commissioning of all three accelerators that make up the MAX IV facility is now well under way and the performance demonstrated so far for the 3 GeV storage ring gives enhanced support to several aspects of the multibend achromat design concept and its technical implementation. Examples are the confirmation with beam of the good internal alignment provided by the magnet block design, the fact that close to 200 mA could be stored with off-axis injection (indicating adequate aperture) and a healthy improvement of beam lifetime as vacuum conditioning proceeds, which confirms the proper functioning of the NEG coating. Nevertheless, much remains to be done, including a deeper understanding of the beam dynamics and a full demonstration of all DDR performance parameters.

ACKNOWLEDGEMENT

The MAX accelerators are the result of a collective effort of skilful and enthusiastic staff and collaborators in many labs and companies worldwide.

REFERENCES

[1] MAX IV Detailed Design Report, Technical Report, MAX-Lab, Lund, Sweden, 2010 (available online at `http://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*, vol. 12, p. 120701, 2009.

[3] P.F. Tavares *et al.*, “The MAX IV storage ring project”, *J. Synchrotron Rad.*, vol. 21, pp. 862-877, 2014.

[4] S.C. Leemann, “Interplay of Touschek scattering, intrabeam scattering, and rf cavities in ultralow-emittance storage rings”, *Phys. Rev. ST Accel. Beams*, vol. 17, p. 050705, 2014.

[5] A.I. Wawrzyniak *et al.*, “Solaris Storage Ring Commissioning”, in *Proc. of IPAC 2016*, Busan, Korea, 2016, paper WEPOW029, p. 2895.

[6] S. Werin *et al.*, “Short pulse facility for MAX-lab,” *Nucl. Instr. and Meth. in Phys. Res. A*, vol. 601, pp. 98-107, 2009.

[7] D. Olsson *et al.*, “A chopper system for the MAXIV thermionic pre-injector”, *Nucl. Instr. and Methods in Physics Research A*, vol. 759, pp. 29-35, 2014.

[8] J. Andersson *et al.*, “Beam Performance of the Photocathode Gun for the MAX IV Linac”, in *Proc. of FEL2014*, Basel, Switzerland, 2014, THP037, p. 799.

[9] M. Eriksson *et al.*, “Commissioning of the MAX IV Light Source”, in *Proc. of IPAC2016*, Busan, Korea, 2014, paper MOYAA01, pp. 11-15.

[10] S.C. Leemann, “Injection with a single dipole kicker into the MAX IV storage rings”, *Nucl. Instr. and Meth. in Phys. Res. A*, vol. 693, pp. 117-129, 2012.

[11] S.C. Leemann, MAX-lab Internal Note 20121107, available at `http://www.maxiv.lu.se/publications/`

[12] G. Skripka *et al.*, “Commissioning of the Harmonic Cavities in the Max IV 3 GeV Ring”, in *Proc. of IPAC2016*, Busan , Korea, 2016, paper WEPOW035, pp. 2911-2913.

[13] F. Cullinan *et al.*, “Impedance Characterization and Collective Effects in the MAX IV 3 GeV Ring”, presented at NAPAC2016, Chicago, IL, paper WEA3CO04, this conference.

[14] Å. Andersson *et al.*, “Diagnostics at The MAX IV 3 GeV Storage Ring During Commissioning”, in *Proc. of IBIC 2016*, Barcelona, Spain, 2016, paper MOAL02.

[15] J. Breunlin *et al.*, "Emittance Diagnostics at the MAX IV 3 GeV Storage Ring", in *Proc. of IPAC2016*, 2016, Busan, Korea, paper WEPOW034, p. 2908.

[16] K. Åhnberg *et al.*, "MAX IV Storage Ring Magnets Installation Procedure", these proceedings.

[17] M. Johansson *et al.*, "MAX IV 3 GeV Storage Ring Magnet Block Production Series Measurement Results", in Proc. of IPAC 2016, Busan, Korea, 2016, paper TUPMB023, p. 1157.

[18] M. Johansson, B. Anderberg, L-J. Lindgren, "Magnet Design for a Low-Emittance Storage Ring," *J. Synchrotron Rad.*, vol. 21, pp. 884-903, 2014.

[19] E. Al-Dmour *et al.*, *J. Synchrotron Rad.*, vol. 21, pp. 878-883, 2014.

[20] C. Herbeaux *et al.*, "Vacuum conditioning of the Soleil storage ring with extensive use of NEG coating", in *Proc. of EPAC08*, Genoa, Italy, 2008, pp. 3696-3698.

[21] Å. Andersson *et al.*, "The 100 MHz RF System for the MAX IV Storage Rings", in *Proc. of IPAC 2011*, San Sebastián, Spain, 2011, pp. 193-195.