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MAX $4^{\underline{\mathrm{U}}}$: AN UPGRADE OF THE MAX IV 3 GeV RING

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Abstract

The MAX IV 3 GeV storage ring in Lund, Sweden, is the first multibend achromat (MBA) lattice fourth-generation light source worldwide. In order to continue to offer the Swedish and international scientific communities state-of-the-art competitive tools beyond the end of this decade, MAX IV Laboratory launched in 2024 the conceptual design of MAX $4^{\underline{\mathrm{U}}}$, an upgrade of its 3 GeV storage ring aiming at an emittance below 100 pm.rad. This performance boost is to be achieved through a minimum-interference upgrade in which localized interventions in selected subsystems and components are carefully chosen to provide the maximum performance increase with minimum cost and, equally important, minimum dark time for the MAX IV user community. This contribution summarises the accelerator physics and engineering aspects of the MAX $4^{\underline{\mathrm{U}}}$ conceptual design and presents the latest developments.

INTRODUCTION

The successful commissioning in 2015 of the MAX IV 3 GeV storage ring, the first fourth-generation storage ring worldwide, ushered in a new era for science enable by ultrahigh brightness X-ray beams [1]. The critical source performance parameters for many applications are high brightness and transverse coherence, which are in turn determined by the electron beam emittance. The challenge lies in reducing the electron beam emittance to the level of the intrinsic photon beam emittance $\varepsilon_r(\lambda) \simeq \frac{\lambda}{4\pi}$ where λ is the photon wavelength.

Since the inauguration of the MAX IV facility in 2016, the international landscape of storage rings has dramatically changed with four other multibend-achromat-based storage ring facilities now being in operation and several others being under design or construction all over the world (Figure 1). At the same time, the next phase of beamlines that are part of the MAX IV roadmap for the same period foresees up to five new beamlines, which are critically dependent on brightness and coherence. It is imperative therefore to act now so that, by the time these new brightness/coherence-hungry beamlines are in place, our source capabilities can provide appropriate conditions for them as well as for our already existing beamlines to be able to compete with their counterparts in other facilities. To meet that challenge, MAX IV initiated in 2024 work on the conceptual design of MAX $4^{\underline{\mathrm{U}}}$: a major upgrade of its 3 GeV ring. The project aims at a reduction of the 3 GeV ring emittance from the present 328 pm.rad to below 100 pm.rad. This major performance boost must however be realized within strict constraints of cost and time while minimizing the dark time for the user community.

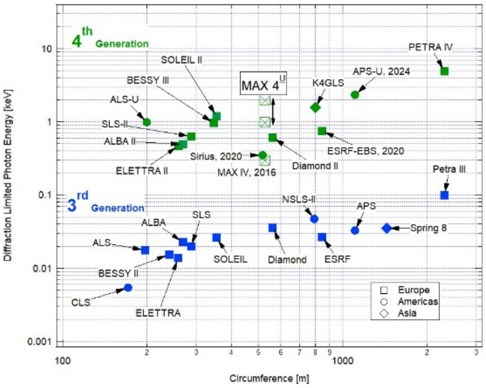

Figure 1: Diffraction-limited photon energy vs size of third and fourth-generation storage rings. The performance of MAX $4^{\underline{\mathrm{U}}}$ is indicated as a range corresponding to electron beam emittance from 100 down to 50 pm.rad.

This requires a highly effective surgical intervention based on innovative solutions that capitalize on upgrade possibilities that were foreseen already at the original design of the MAX IV 3 GeV ring and makes best possible use of techniques developed by the accelerator community over the past years. All of this makes the MAX $4^{\underline{\mathrm{U}}}$ project very special in that the accelerator physics design needs to go hand-in-hand with the engineering design of the various subsystems and engineering considerations need to be factored in at a very early stage.

MAX $4^{\underline{\mathrm{U}}}$ Goals and Boundary Conditions:

- Electron beam emittance $\lesssim$ 100 pm.rad
- Electron beam energy: 3 GeV
- Keep shielding wall
- Keep light source positions
- Keep injector and accumulation capability
- Limited dark period
- Cost-effective
- Realizable until the early part of the next decade

LATTICE DESIGN

Design Strategy

The lattice and the engineering design, including the installation planning, started in parallel with the aim to quickly identify the main cost drivers and design constraints. It immediately and not unexpectedly became

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apparent that interventions in the magnet and vacuum systems are the main drivers of dark time and cost. The design focused on keeping the vacuum system, as well as replacing as few magnet blocks as possible.

For the lattice design work, the main tools were Accelerator Toolbox v2 and Tracy3, the choice of which was made based on team competencies. An evaluation suite was built up using the former, in order to have a common benchmark for all produced lattice candidates. The design work itself proceeded in parallel using the tools of the trade, including computer-aided optimization (e.g. Multi-Objective Genetic Algorithm a.k.a. MOGA [2], ML-MOGA [3]) and robust design methodology keeping resonance driving terms under control [4].

The main change to achieve the desired emittance reduction in the lattice options presented below is the introduction of reverse bends as well as an overall increase of focussing strengths.

100 pm.rad Lattices

The machine function for one of the lattice candidates in the 100 pm.rad region, here referred to Lattice A, can be seen in Fig. 2a. Lattice parameters can be found in Table 1.

Lattice A makes only limited use of reverse bends, which only replace four quadrupoles in the central unit cell. While this concentrates the design orbit changes to a single cell, which would necessitate a controlled deformation of the chamber, the benefit is that large changes to the magnet blocks are avoided except in this single cell. It therefore has the potential to avoid vacuum interventions and extensive magnet manufacturing while still achieving an emittance reduction to just below 100 pm.rad.

50 pm.rad Lattices

The machine function for one of the lattice candidates in the 50 pm.rad region, here referred to Lattice B, can be seen in Figure 2b. Lattice parameters can be found in Table 1.

Unlike the lattice A option, reverse bends are distributed throughout the arc, allowing for a greater emittance reduction. Resonance driving terms are cancelled within the achromat, greatly improving the robustness of the lattice.

While engineering solutions exist for the magnet elements that will provide the required fields, they are far more extensive and appear likely to require changes to the vacuum system as well.

VACUUM SYSTEM

Several of the proposed lattices with ~100 pm.rad emittance require beam orbit offset of up to 8.8 mm in the unit cells, compared to the current ring orbit. Relying on the very good experience with the MAX IV 3 GeV ring Non-Evaporable Getter (NEG) coated vacuum system [5], one scenario is to accommodate the orbit offset by re-using and elastically adapting the geometry of the standard vacuum chambers under vacuum, without venting. This approach was studied and is being validated through simulations, prototyping and testing. If implemented, it will keep the cost, installation and conditioning times to minimum [6].

For lattices with 50 pm.rad emittance, the changes in the vacuum system are likely to require venting the vacuum system and replacing several vacuum components. Solutions for vacuum system design for such scenario are under development [6].

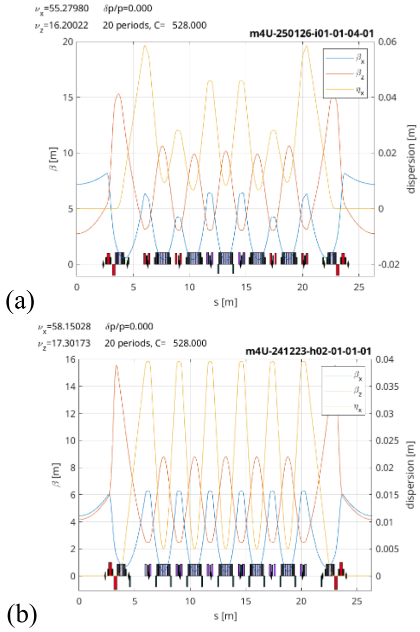

Figure 2: Twiss parameters for a. lattice A (top) and b. lattice B (bottom).

Table 1: MAX $4^{\underline{U}}$ Parameters

Parameter	**Lattice A**	**Lattice B**
Energy (GeV)	3.0	3.0
Emittance (pm.rad)	97	57
Nat. energy spread (10^{-4})	7.54	9.2
Nat. bunch length (mm)	6.5	6.3
Energy loss per turn (keV)	414	529
Tot. defl. angle (deg.)	395	414
Tune	55.20/ 16.28	58.15/ 17.30

MAGNET SYSTEM

The present magnet system for the MAX IV 3 GeV ring consists of twenty 7BA achromats where several individual magnets are incorporated in each of the magnet blocks (see Fig. 3).

Much effort in the search for new magnet lattices, has been put into attempts to keep the present magnet block concept, and all its benefits [7]. Furthermore, the magnet bore radii are kept at 12.5 mm. Within these boundaries comes the quest of increasing the strengths of all multipoles as far as possible, while the dipole strengths stay rather untouched. For the quadrupoles, such an increase can involve different steps, from such as simply increasing the current in the coils, to more elaborate schemes where pole roots are widened and lengthened, and pole tips are exchanged to narrower ones. Coils and cooling circuits are then altered accordingly. All this is possible without exchanging the original iron block. The reverse bends are foreseen to be created from our present quadrupoles, by introducing an asymmetric solution both for pole tips, pole roots and pole coils, where the magnetic centre is shifted up to 5 mm. Prototyping of these converted quadrupoles has already started. For the sextupoles and octupoles an almost doubling of integrated strengths are seen possible with new designs. These multipoles are incorporated in special pockets in the iron block and the whole magnet will be exchanged without the need of a new iron block. The pockets allow for some additional lengthening. The dipole gradients, which are cast in the iron, will be handled with a new type of more powerful water-cooled Pole Face Strips, that allows for a +/- 20 % gradient adjustment.

If stronger magnets are required, such as in some 50 pm.rad lattices, iron blocks may be rebuilt.

INJECTION SYSTEM

The MAX IV Linear Accelerator serves as injector for both the existing storage rings and the Short Pulse Facility (SPF) [8]. For standard storage ring injection and top-up, a thermionic gun used, which produces a train of 1-10 bunches separated by 10 ns, to match the ring RF frequency of 100 MHz. This mode is compatible with the traditional off-axis, on-energy injection scheme [9] but requires a large phase acceptance in the storage ring. For MAX 4$^{\underline{U}}$ a more advanced injection scheme may have to be commissioned. Particularly for very low emittance lattices and small dynamic apertures, the MAX IV linac can switch to its photo cathode gun mode. With the photo gun, up to 200 pC can be injected per linac shot, filling only one 100 MHz ring bucket with a single S-band bunch. The photo gun provides a beam with a small phase extension due to the short bunch length (~5 ps) and low energy spread (0.06%). These characteristics make it suitable for on-axis, off-phase injection schemes which are essential for accumulating beam in lattices with smaller dynamic aperture and for enabling the use of insertion devices with restricted horizontal physical apertures. Due to the full energy linac, photo gun injection capabilities and long ring bunch separation (due to the 100 MHz RF system) the MAX IV facility is in a unique position to implement such a longitudinal injection scheme, as first suggested by [10].

RF SYSTEM

The MAX IV 3 GeV ring is equipped with a 100 MHz RF system. Six individual normal-conducting (NC) capacity-loaded cavities, fed by six 120 kW solid state amplifiers, constitute the backbone of the system [11]. The choice of a relatively low RF system frequency leads to a lower overvoltage (peak voltage to synchronous voltage ratio) and therefore lower power consumption for a given RF momentum acceptance. In addition, one can profit by the commercial availability of robust mass–produced VHF transmitters for the power sources. A harmonic RF system, consisting of two 300 MHz NC passive Harmonic Cavities (HC), is in use. The bunch lengthening reached is in the order of a factor five, which tremendously increases the lifetime of the beam, decreases the heat load deposition from beam image currents on vacuum chamber components, and alleviates Intra Beam Scattering (IBS) that would otherwise blow up both the transverse dimensions of the beam and the beam energy spread. Additionally, instability current thresholds of longitudinal Coupled Bunch Modes (CBM) are pushed to sufficiently high currents. All the features mentioned will be kept for the MAX 4$^{\underline{U}}$ ring.

As an innovative extension of our HC system, MAX IV is also developing a dual HC system, where the passive 300 MHz cavities will be accompanied with one active 500 MHz cavity [12]. With such a system we expect a bunch lengthening factor of around ten, when adjusting to, or nearby, the so-called super-flat condition. For a double harmonic frequency system, the super-flat condition is equivalent to cancelling all derivatives of the total voltage, at the bunch position, up to order four.

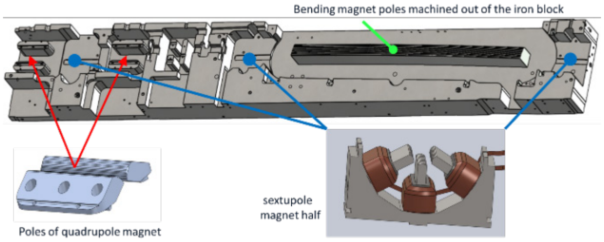

Figure 3: The lower half of a MAX IV magnet block incorporating various functions sharing a common iron yoke.

PLANNING AND INSTALLATION

Installation planning and conceptual/technical design started at the same time and so was done for multiple scenarios. From the alternative schemes that emerged, two extremes were investigated: one containing limited vacuum interventions, and a second requiring vacuum interventions in all achromats.

An important constraint is that the upgrade should not impact user delivery by the two other accelerators at the MAX-IV facility. This limits the available time in the injection region, and so installation planning must respect that. For this reason, installation work within this sensitive region will take place during a regularly scheduled summer shutdown. Work in the remainder of the ring will continue after that. Depending on the installation alternative, the dark period will last no more than one year.

CONCLUSION

The design work of MAX 4$^{\underline{U}}$, an upgrade of MAX IV 3 GeV storage ring aiming at an emittance below 100 pm.rad is progressing. The accelerator physics design goes hand-in-hand with the engineering design. various lattice options and their engineering impact are under studies.

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