

VACUUM SYSTEM OF MAX 4^U – AN UPGRADE OF THE MAX IV 3 GeV STORAGE RING

M. Grabski[†], K. Åhnberg, E. Al-Dmour, Å. Andersson, A. M. Carboneres, P. S. Navarro
S. M. Scolari, P. F. Tavares, MAX IV Laboratory, Lund University, Lund, Sweden

Abstract

MAX 4^U is an upgrade project of the MAX IV 3 GeV storage ring, to be realized by the early 2030's in Lund, Sweden. The goal of the upgrade is to reduce the horizontal electron beam emittance to below 100 pm.rad. A new magnet lattice will be used, thus the vacuum system will have to be adapted to follow the new beam orbit of MAX 4^U.

Several lattices imposing the most severe changes to the beam orbit were studied. One proposal for the MAX 4^U vacuum system is to re-use and adapt under vacuum the shape of the MAX IV 3 GeV ring vacuum chambers (coated with non-evaporable getter (NEG) thin film) by bending-to fit to the new magnet lattice. In such scenario, the vacuum system will not be vented, thus the NEG coating will not have to be re-activated. Such approach is very cost-effective and reduces the installation and commissioning time to the minimum. This scenario is presented here, together with the performed simulations, validation studies and tests.

INTRODUCTION

The work on the lattice design, and the engineering design is going in parallel. Several lattices were studied and conceptual vacuum system designs were investigated.

As set by the project boundary conditions, the layout of the MAX 4^U storage ring will correspond to the existing MAX IV 3 GeV ring [1], [2]. The MAX 4^U ring is divided into 20 cells: arc section is 21.6 m long and the straight section is 4.5 m long. The basic MAX 4^U parameters are summarized in Table 1.

The magnet layout and magnet apertures of MAX 4^U will be similar to the MAX IV lattice 7 Bend Achromat (7BA) and take advantage of the closed magnet block design concept.

Table 1: MAX 4^U 3 GeV Storage Ring Main Parameters

Parameter	Value
Energy	3 GeV
Design beam current	500 mA
Horizontal bare emittance	<100 pm.rad
Circumference	528 m
Number of achromats	20
Straight section length	4.5 m

VACUUM SYSTEM REQUIREMENTS

The vacuum system requirements for the upgrade are typical for a 4th generation storage ring based light source. Taking into consideration the boundary conditions for the

MAX 4^U project [1], the most critical vacuum requirements are:

- 500 mA electron beam design current.
- Nitrogen equivalent, average, dynamic pressure less than 1×10^{-9} mbar. Corresponding to > 40 hours gas lifetime (assuming the same apertures as for the existing ring).
- Fast vacuum conditioning.
- Maximum reuse of the existing vacuum chambers, pumps, instrumentation, and infrastructure.

The requirement of fast vacuum system conditioning is particularly important as the dark time should be limited to the minimum and has to include enough time for efficient commissioning of the accelerator.

VACUUM SYSTEM DESIGN SCENARIOS

Three possible vacuum system scenarios were identified depending on the chosen MAX 4^U lattice and its impact on the beam orbit:

- Scenario A: minor changes to the electron beam orbit are made compared to the existing MAX IV, 3 GeV ring orbit. Vacuum chambers will be reused, with their geometry adapted, under vacuum without venting. Only a few achromats might be vented to install special vacuum chambers (for example: collimators or stripline kickers).
- Scenario B: larger localized changes to the electron beam orbit (compared to scenario A). One or a few short chambers in the arc sections will be installed, implying that all the achromats will need to be vented (using noble gas). With this scenario, no NEG activation by baking is foreseen.
- Scenario C: the impact on the vacuum system is large, many vacuum chambers will have to be exchanged with new units, thus all the vacuum section of the 20 achromats will need to be vented and reactivated by using a baking oven (following the same procedure as for the first installation in 2014-2015).

VACUUM SYSTEM DESIGN CONCEPT

A conceptual vacuum system design that follows scenario A, was developed for a candidate lattice type of ~95 pm.rad emittance (lattice type code bxx_03). The main difference between bxx_03 and the current MAX IV lattice is the introduction of 4 reverse bending magnets as shown in Fig. 1. The described concept of adapting the vacuum chambers geometry under vacuum can be also used for several other potential lattices under study, where the maximum orbit offset is around 8.8 mm in standard vacuum chambers (i.e. in unit cell magnet blocks – the five central magnet blocks).

[†] marek.grabski@maxiv.lu.se

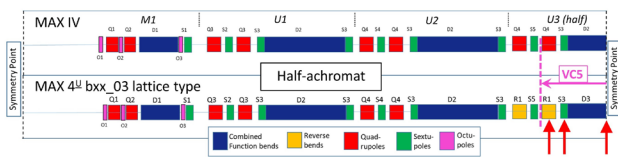


Figure 1: MAX IV and MAX 4^U bxx_03 type lattice (half achromat). The three red arrows at R1, S3, D3 magnets indicate the locations where the vacuum chamber (VC5 – marked in magenta) is bent to fit to the new lattice.

The bxx_03 lattice type imposes a beam closed orbit that is 8.8 mm offset radially compared to the existing orbit at the centre of the achromat as shown in Fig. 3. The orbit offset is the result of introducing 4 reverse bends. The vacuum chamber centre coincides with the beam centre and centre of magnet bore apertures.

Considering that the MAX IV standard vacuum chambers (presented in Fig. 2 and 3) are compact and flexible (made of 1 mm thick copper pipe of circular cross-section), accommodating such beam offset by adapting their shape to the new geometry, was studied and validated.

ADAPTING VACUUM CHAMBER GEOMETRY WITHOUT VENTING

The beam offset for the bxx_03 lattice is concentrated in the middle of the achromat mostly along a single vacuum chamber VC5 as shown in Fig. 2.

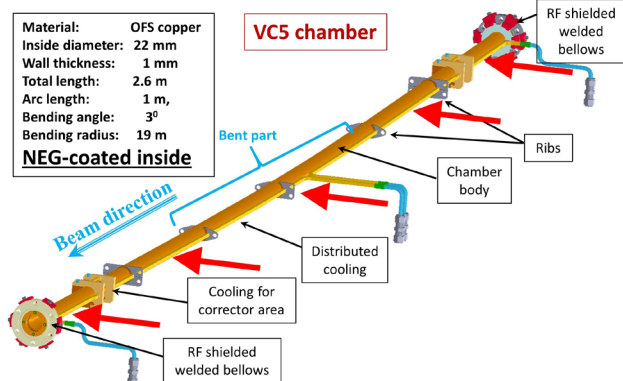


Figure 2: VC5 vacuum chamber located in the middle of a standard achromat. The five red arrows are the locations where the chamber is bent to fit the new lattice

To follow the orbit of the proposed bxx_03 lattice the shape of vacuum chamber (VC5) is bent elastically by applying forces of up to 50 N in 5 positions as indicated in Fig. 1, 2 and 5. The forces are applied with a bending rig (after the magnet block is removed), then the new magnet is mounted, and the new position of the chamber is ensured by installing spacers and supports in the 5 locations that define the orbit trajectory.

VALIDATION STUDIES OF ADAPTED VACUUM CHAMBERS

To ensure that the NEG coated, copper vacuum chambers can operate for extended period of time and to be able to safely bend the chambers under vacuum, the following

aspects were addressed and validation studies performed for the MAX 4^U lattice.

- NEG thin film coating condition in terms of pumping speed, saturation and adhesion.
- Raytracing and thermal simulations to ensure the chamber can cope with additional beam power.
- Mechanical simulations of the chamber body and RF-shielded bellows deformation.
- Bending tests simulating the final condition of the chamber adapted to the bxx_03 lattice.
- Mock-up of the manipulation and integration with magnets.
- Water cooling channel corrosion.

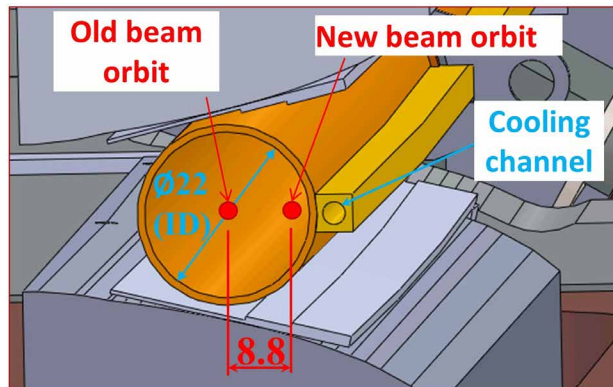


Figure 3: Cross-section of a standard vacuum chamber (VC5) in the achromat centre, with highlighted 8.8 mm shift of the chamber to fit to the MAX 4^U lattice bxx_03.

NEG Thin Film Coating Condition

The NEG coating condition of the MAX IV vacuum chambers was evaluated by analysing average pressure around the storage ring and beam lifetime. The average pressure reduction with accumulated beam dose confirms good health of the vacuum system [2]. The normalized average pressure rise is around 1×10^{-13} mbar/mA for beam dose of 16331 Ah (20th April 2025). The total beam lifetime is above 5 Ah.

Vacuum measurements were performed in 2024 by injecting known amount of gasses: H₂, CO, CH₄ and Ar (leak rates of approximately 1×10^{-6} mbar.l/s) to the vacuum system of the MAX IV ring with and without beam. The injection of H₂ and CO (gases pumped by the NEG) demonstrated that locally the NEG coating film might be saturated but over several meters distance it provides good pumping capacity and ensures UHV conditions for the beam (closest possible measurement points are 2 m apart). Injection of Ar gas demonstrated that it can be pumped out with ion pumps and does not disturb the operation afterwards.

The adhesion of NEG thin film coating was studied to ensure that the coating will not peel off and accordingly impact the machine operation after bending. A sample was prepared from a 2 m long NEG coated long straight section vacuum chamber, which was cut into pieces as shown in Fig. 4.

Cross-hatch with a sharp blade was introduced on the NEG surface to ease potential film peel-off (Fig. 4 b)). The

sample underwent 200 bending cycles (in reality, the chamber will be bent once) of up to 3.5 mm and the coating adhesion was tested with adhesive tape (similar to ASTM D3359 tape tests for coating adhesion). The test results demonstrated that the sample did not show any signs of coating peel-off. Therefore, the NEG film is stable from the adhesion point of view.

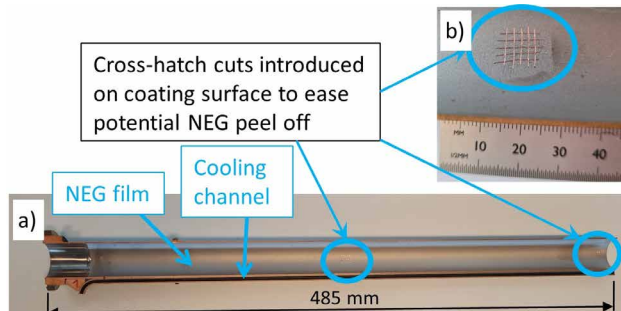


Figure 4: Sample used for NEG coating adhesion test. a) sample overview, b) detail of cross-hatch.

Raytracing and Thermal Simulations

The total power per one achromat emitted from the bending magnets of MAX 4^U lattice bxx_03 is 10355 W (for the existing MAX IV lattice it is 9096 W).

The maximum power density increased from 10 W/mm² to 26 W/mm² in the dipole magnet area where the synchrotron radiation flux is the highest.

Raytracing studies confirmed that all sensitive areas (Beam Positions Monitors, RF fingers, flanges) are shadowed from radiation and that the chambers can cope with the additional power load. In case of bxx_03 lattice there is no power deposited on the inboard wall of the vacuum chambers.

Mechanical Studies

The transversal and longitudinal strokes of the Radio Frequency (RF) shielded bellows welded to both ends of VC5 chamber as shown in Fig. 2, were studied for the new lattice and are feasible when bending the vacuum chamber by the required amount. The difference in the position of the two chamber ends before and after bending is around 0.5 mm (within the stroke of the bellows).

Structural simulations of several vacuum chambers were performed. The studies included bending of the chambers (VC5 shown in Fig. 5), and adding additional power from the reverse bending magnets according to the proposed lattice bxx_03.

In the most conservative case (taking into account defects in cooling channels welds) the maximum temperature of the chamber is 110°C over several square centimetres (near special cooling for corrector magnets - as shown in Fig. 2). Most of the chamber body is below 50°C.

The peak von Mises stress of 49 MPa occurs around the same location as the maximal temperature, but drops quickly to 19 MPa. The bending of the chambers occurs only in the elastic region of the material.

The chamber after bending and with higher power load from the bending magnets is mechanically stable and can operate reliably.

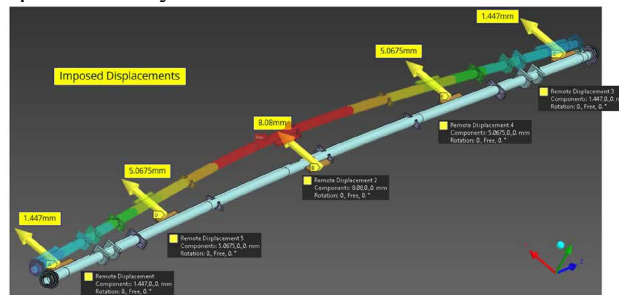


Figure 5: Imposed vacuum chamber displacements (yellow arrows) at five magnet locations (R1, S3, D3) to deform the vacuum chamber to fit the MAX 4^U lattice bxx_03.

Bending Tests

Physical tests were performed to validate the bending process as per simulations: the chamber body was bent under vacuum to fit the bxx_03 lattice with applied displacements as per Fig. 5 in the locations indicated by yellow arrows (red arrows in Fig. 1 and 2). The reaction force in the chamber centre was simulated and measured as 50 N. Magnets dummies as per lattice bxx_03 were used as hard stops. The chamber remained leak tight and can be bent to fit the proposed lattice.

Water Cooling Channel Corrosion

Water cooling channel condition of installed vacuum components was studied. Several chambers and absorbers were removed from the ring, cut and analysed. No significant corrosion was observed.

OTHER LATTICES

There are other lattice candidates considered aiming for the emittance of ~50 pm.rad. To fit the vacuum system to those lattices by adapting the geometry of all the existing vacuum chambers will most likely not be feasible and new vacuum chambers might have to be designed as described in scenario C. This case will need more resources, and time for installation and conditioning of the vacuum system than scenario A.

CONCLUSION

In this article a vacuum system design of MAX 4^U was presented that proposes a scenario where the geometry of MAX IV vacuum chambers is adapted under vacuum (without venting) to fit to a potential MAX 4^U lattice. In this design case, almost all the existing vacuum chambers can be re-used. Such approach keeps the cost of vacuum system to minimum and reduces the vacuum installation and conditioning times to minimum.

ACKNOWLEDGEMENTS

The authors would like to thank MAX IV staff, for the discussions, creative ideas and all the work on the developments of the conceptual design of MAX 4^U.

REFERENCES

- [1] E. Al-Dmour *et al.*, “MAX 4U: an upgrade of the MAX IV 3 GeV Ring”, presented at IPAC’25, Taipei, Taiwan, June 2025, paper MOPS061 this conference.
- [2] M. Grabski and E. Al-Dmour, “Commissioning and operation status of the MAX IV 3 GeV storage ring vacuum system,” *Journal of Synchrotron Radiation*, vol. 28, no. 3, pp. 718–731, Apr. 2021. doi:10.1107/s1600577521002599