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EXPERIENCE WITH THE VACUUM SYSTEM FOR THE FIRST FOURTH GENERATION LIGHT SOURCE: MAX IV

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Abstract

The 3 GeV electron storage ring of the MAX IV laboratory is the first storage-ring-based synchrotron radiation facility with the vacuum system having small aperture and with the inner surface of almost all the vacuum chambers along its circumference coated with non-evaporable getter (NEG) thin film. This concept implies challenges during the whole project from design into operation.

The fast conditioning of the vacuum system and over five years of reliable accelerator operation have demonstrated that the chosen design proved to be good and does not impose limits on the operation. A summary of the vacuum system design, production, installation and performance is presented.

INTRODUCTION

The MAX IV facility in Lund-Sweden is composed of two storage rings with electron energies of 1.5 GeV and 3 GeV. A linear accelerator (LINAC) serves as the full energy injector to the two storage rings as well as a driver for a short pulse facility [1]. The MAX IV 3 GeV ring started delivering light to the users in April 2017.

3 GEV STORAGE RING

The 3 GeV storage ring is the world's first multibend achromat, ultra-low emittance light source. To achieve the low horizontal emittance, a 7 bend achromat lattice was chosen. The storage ring has a 20-fold symmetry and is 528 m in circumference [2].

Each achromat contains seven magnet blocks of two types: five unit cells (U) (with 3° bending magnets) and two matching cells (M) (with 1.5° bending magnets). Each achromat contains two short straight sections (S1 and S2). In addition 19 long straight sections (L) of 4.6 m length are used for the insertion devices (ID) and one long straight section is used as an injection straight. Figure 1 shows one standard 3 GeV ring achromat, including magnet blocks and the vacuum chambers of one achromat.

3 GEV STORAGE RING VACUUM SYSTEM DESIGN AND MANUFACTURING

The vacuum system of the 3 GeV ring is based on chambers which are made of copper and the chamber body is used as distributed absorbers. The inner surface of the vacuum chambers is NEG coated. Four ion pumps per achromat are installed in areas with high outgassing and provide pumping for noble gases (see Fig. 1).

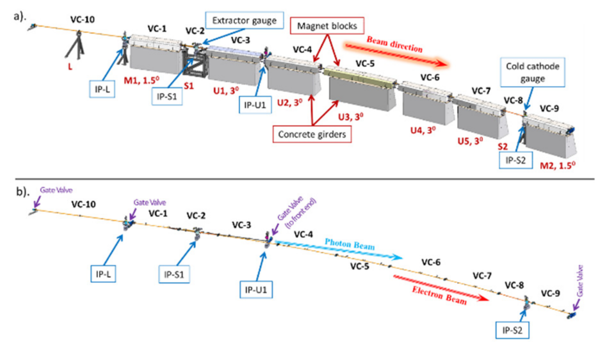

Figure 1: One standard 3 GeV storage ring achromat, a). with the magnet blocks and girders b). the vacuum chambers without the magnet blocks [3].

Vacuum Chamber Design

The vacuum chambers are made of oxygen-free silver-bearing (Ag 0.085%) copper (OFS-C10700). The internal diameter of the vacuum chambers inside the magnet blocks is 22 mm and the chambers have 1 mm wall thickness. The vast majority of the chambers have electron welded water cooling channels on one side.

Ten beam-positon monitors (BPMs) per achromat are installed and mounted directly to the magnet blocks. Bellows with internal RF fingers are located at the extremities of the vacuum chambers, the main purpose of the bellows is to shield the BPM block from any deformation occurring in the vacuum chambers due to heating up from the synchrotron radiation.

Several design challenges were faced, some of which are listed below:

- Effectively extract the photon beam to the front end.
- Avoid interferences with the magnets.
- Provide cooling for the chambers in places with limited access and space.
- Guarantee the mechanical and thermal stability of the BPMs while vacuum chambers are allowed to expand.
- Provide a design that will allow successful implementation of NEG coating on the chamber's inner surface.
- Provide a design that allows easy installation.
- Keep standardization.

To assure the mechanical stability of the BPMs, the bellows' spacers were made from epoxy glass G10, with low thermal conductivity and high radiation resistance (see Fig. 2). The BPM blocks are shadowed by small absorbers at the end of each chamber body, just before the flange.

Finite element analysis (FEA) was performed during the design stage, to study several mechanical and thermal issues related to the vacuum chamber design, such as the deformation, stress and strain of the vacuum chambers, the deformation of the BPM during operation, the design of the

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RF fingers and the insertion device power deposited on the vacuum chambers.

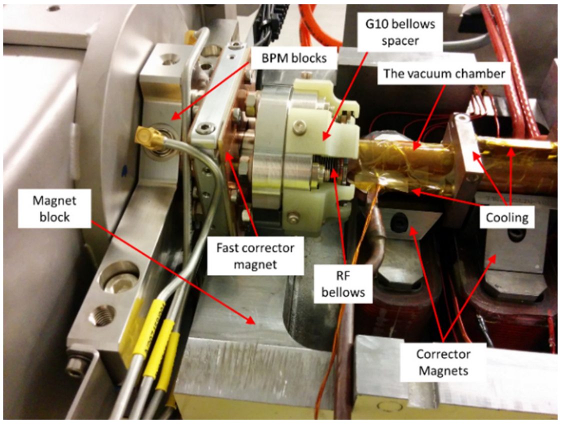

Figure 2: Location of BPM block and bellows.

An example of FEA results performed for the estimation of stress on the RF fingers is shown in Table 1. Such analysis was performed to optimize the shape of the RF fingers, the number of the RF fingers and effect of pre-stressing during assembly. The aim is to keep the stress and strain within the design criteria of the copper-beryllium (CuBe) RF fingers.

Table 1: Stress results for various RF fingers configuration and pre/stressing forces for MAX IV bellows.

Spring configuration	**Pre-stress displacement [mm]**	**Pre-stress force [N/finger]**	**Stress [MPa]**
30 spring	0.1	0.8-1	252
finger	0.25	2.0-2.7	630
flat	0.4	3.9-4.3	1000
30 spring	0.1	1.1-1.6	290
finger	0.25	2.7-4.0	730
curved	0.4	4.4-6.4	1170

The Vacuum Chambers Manufacturing

All the copper extruded tubes used for the production of the vacuum chambers were subjected to surface treatment at CERN [4]. Following this process, the tubes were sent to the manufacturer of the vacuum chambers.

Various manufacturing processes were needed for the production of the vacuum chambers:

- Machining of the chamber parts: flanges, bellows, bellows sleeves, ribs, BPM blocks, cooling tubes …etc.
- Vacuum brazing of stainless steel flanges to transition copper sleeves of the bellows, brazing of the stainless steel ribs to copper transition…etc.
- TIG welding: flanges to the chamber body, ribs assembly to the chamber body…etc.
- Electron beam welding of the cooling tubes to the chamber body.
- Bending of chambers body to the correct radius of curvature.
- Vacuum cleaning.
- Testing: dimensional, vacuum, cooling…etc.

The main challenges during the production process were:

- Assure that the production processes proposed will not affect the NEG coating or its performance.
- Changes in the production that may cause interferences with other systems, e.g. magnets.
- Changes in other accelerator systems that may affect the vacuum system design and production.

NEG Coating

A collaboration between CERN and MAX IV Laboratory has been set up to address and validate challenges in coating long, small aperture, bent vacuum chambers manufactured with various methods [4-6].

The results of the R&D provided input for the series production of the chamber coating, with around 70% of the chambers coated at the manufacturer and the remaining coated at CERN and the ESRF.

THE VACUUM SYSTEM INSTALLATION AND OPERATION

Installation

From the very early stages of the design, it has been decided not to perform in-situ bakeout for the vacuum chambers, the decision was made due to the compactness of the lattice (small gap between the chambers and the magnets and very small space between the magnets for accommodating bellows) [6].

Prior to the start of the installation inside the 3 GeV tunnel, a mock-up was done to check the installation procedure and possible interferences

The installation of the vacuum chambers took place on the assembly tables which were placed over the open magnet blocks, this allowed accurate positioning of the BPM blocks relative to their final position in the achromat. The oven used for the bakeout has been placed over the concrete blocks.

The general installation procedure followed as described in [3].

The installation stage went smoothly, with minor issues being faced: rejection of few chambers due to peel off of the coating or partially uncoated area, damage of a chamber during the manipulation of an achromat and accidental venting of one full achromat after installation.

Operation

The vacuum conditioning is progressing well, this is evident by both the average pressure reduction and by the increase of the total beam lifetime as the accumulated beam dose has increased. Studies performed also indicated that the NEG coating performance after five years of operation is good, with no indication of saturation or peel off [3].

The average base pressure (without beam) before the start of commissioning with electron beam was $2{\cdot}10^{-10}$ mbar. When the first beam was stored, the pressure increased to the high 10^{-9} mbar range.

The average pressure rise normalized to beam current dP_{av}/I [mbar/mA] as a function of the accumulated beam

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dose [Ah] is presented in Fig. 3. The slope of the conditioning curve is comparable to those of other similar machines, and slightly faster.

Figure 4 presents the increase of the normalized total beam lifetime $I{\cdot}\tau$ [A·h] versus accumulated beam dose [A·h]. The increase in the $I{\cdot}\tau$ product is an indication of the vacuum conditioning.

As of July 2021, the storage ring had an accumulated beam dose of 4620 Ah, and the maximum stored beam current was 500 mA. Standard delivery to beamlines is at 300 mA with top-up using multipole injection kicker (MIK) every 10 minutes.

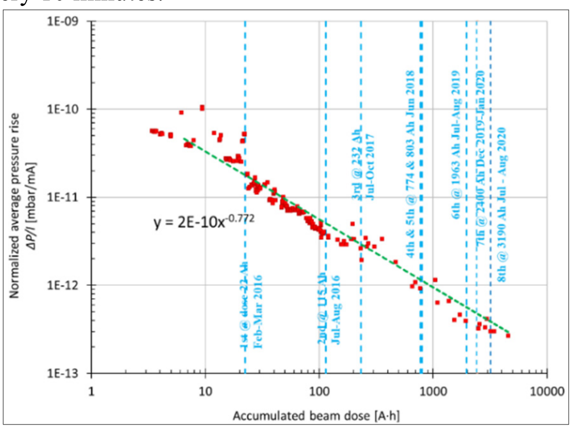

Figure 3: 3 GeV ring: normalized average pressure rise dP_{av}/I [mbar/mA] vs. beam dose [Ah].

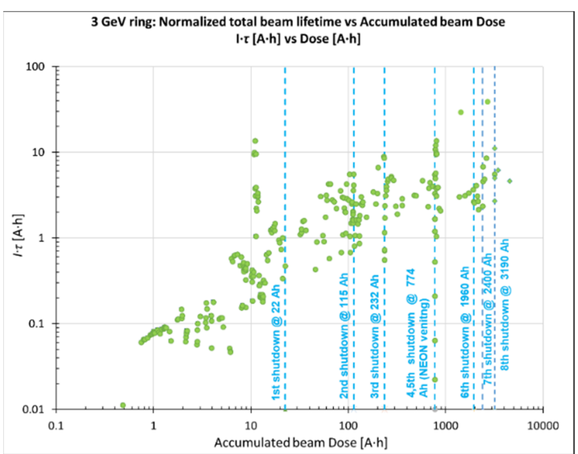

Figure 4: 3 GeV ring: normalized beam lifetime I·τ [A·h] vs. beam dose [Ah] [3].

Operational Issues

Since the start of operation, the vacuum related failures were small. In 2020, there were seven vacuum alarms resulting in beam dumps, contributing 2.7 % of the total machine downtime. The main contributor to downtimes due to vacuum is alarms triggered by pressure spikes from ion pumps or vacuum gauges when a measured pressure reaches the interlock level and results in a beam dump. With the help of around 30 thermocouples installed on the chamber of each achromat, it has been possible to identify few hot spots, where the readings from thermocouples did not correspond to the simulations done during the design stage. Investigation using FEA was done to identify the causes and for trouble shooting. The causes of such problems are summarized below:

- Positioning of the vacuum chambers due to geometrical non-conformity, or deformation.
- Chamber non-conformities: crotch absorbers did not shield as per design, the straightness of the chambers and some tolerances did not meet the technical specifications defined on the drawings.
- Deformed chambers during installation: an example was that a thermocouple placed in the vicinity of the photon beam extraction was mispositioned and glued with an excessive amount of glue, when the magnet in that location was closed, it pressed the chamber through the glued thermocouple and caused deformation of the chamber.

As the production of new chambers would take a while, the hot spot issue was investigated, to verify what the damaged vacuum chamber can structurally withstand by limiting the beam current and the minimum gap of the insertion device. Due to this, FEA was performed, with the goal to match the temperature readings with the simulations results, and accordingly identify the allowed machine operational conditions (beam current, beam bumps minimum allowed insertion device gap).

Figure 5 shows the workflow being used for this analysis. The results from the analysis allowed MAX IV to decide on the allowed operational conditions until a new chamber being manufactured and installed.

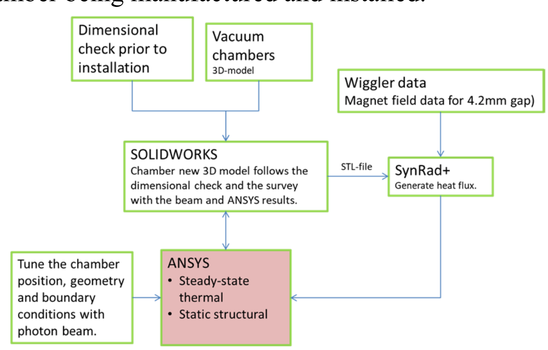

Figure 5: Workflow used to investigate hot spots and validate machine operational conditions.

CONCLUSION

During all the stages of the project, engineering studies, prototyping, mock up and FEA were crucial in validating solutions, investigation and troubleshooting, and provided the needed answers which were essential for the success of the project.

The use of the NEG coating on an unprecedented scale at MAX IV 3 GeV storage ring was a significant challenge. The goal of a simple and reliable ultra-high vacuum system was achieved thanks to careful design, NEG coating validation, appropriate production, installation, operation and precisely planned interventions optimized for the NEG coating. Furthermore, five years of operation ensures that the chosen design is a reliable solution for vacuum systems of new fourth generation, storage ring based light sources.

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