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VACUUM SYSTEM PERFORMANCE OF THE 3 GeV ELECTRON STORAGE RING AT MAX IV LABORATORY

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Abstract

The 3 GeV electron storage ring at MAX IV laboratory is the first synchrotron light source with compact multi-bend achromat (MBA) magnet lattice to achieve ultra-low emittance. The vacuum system of the accelerator is fully coated with non-evaporable getter (NEG) thin film to ensure low gas density. The storage ring started commissioning in August 2015 and currently delivers photon beams from insertion devices (IDs) to 9 beamlines that are in user operation or commissioning. After over 6 years of operation, the NEG coated vacuum system continues to be reliable, is conditioning well and do not pose any limitation to the accelerator operation. The average dynamic pressure is lower than the design value (below 3×10^{-10} mbar) and is reducing with the accumulated beam dose. The vacuum beam lifetime is greater than 39 Ah, and the total beam lifetime is above the design value of 5 Ah - thus is not limited by the residual gas density. Several successful interventions to install new vacuum components were performed on few achromats in the storage ring during shutdowns. Some of them were done utilizing purified neon gas to vent the vacuum system, thus avoiding the need of re-activation of the NEG coating and saving intervention time without compromising the storage ring performance.

INTRODUCTION

MAX IV laboratory consists of 1.5 GeV and 3 GeV storage rings and a full-energy linear accelerator that injects electrons at 3 GeV to the rings and drives short-pulse facility. The injector operates at repetition rate of 10 Hz.

The 1.5 GeV storage ring has delivery beam current of 400 mA, with average total beam lifetime approximately 20 h and delivers photon beams from Insertion Devices (IDs) to 5 beamlines.

The 3 GeV storage ring operates at beam current of 300 mA and deliver photons through IDs to nine beamlines. The electron injection to the ring is done with top-up every 10 minutes. Typical total beam lifetime is 16 h.

3 GEV STORAGE RING VACUUM SYSTEM LAYOUT

The vacuum system of the 3 GeV storage ring follows the geometry of the seven-bend achromat magnet lattice, having 20 fold symmetry. There are 20 long straight sections from which 19 are available for IDs and one is devoted to injection. The main accelerator parameters are listed in Table 1. The detailed design of the vacuum system is described in detail in [1].

Table 1: 3 GeV Storage Ring Main Parameters

Parameter	Value
Energy	3 GeV
Design beam current	500 mA
Horizontal natural emittance	328 pm rad
Circumference	528 m
Number of achromats	20
ID straight section length	4.5 m

3 GeV Storage Ring Layout

The layout of the storage ring is presented in Fig. 1.

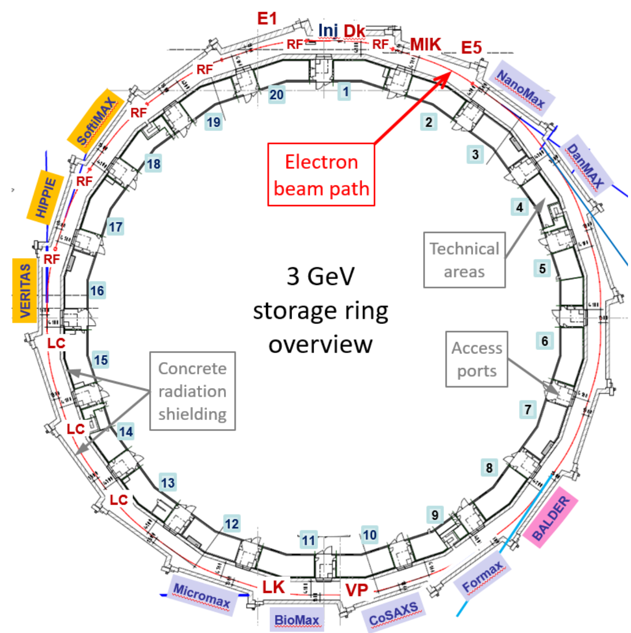

Figure 1: 3 GeV storage ring layout, with marked insertion device/beamline names and main accelerator systems: Inj - Injection straight; Dk - Dipole kicker; MIK - Multipole Injection Kicker; E1, E5 - Diagnostic beamlines for emittance measurement; RF - 100 MHz RF cavities, LC - 300 MHz Landau RF cavities, LK - Longitudinal kicker cavity; VP - Vertical Pinger.

Currently there are 10 insertion devices installed in straight sections (9 of them are delivering photons to beamlines) as indicated in Fig. 1:

- 3 Elliptically Polarized Undulators (EPU) Veritas, Hippie, Softimax.
- 6 In Vacuum Undulators (IVU): Nanomax, Danmax, Formax, Cosaxs, Biomax, Micromax (first light to be delivered in 2022),
- 1 In Vacuum Wiggler (IVW): Balder.

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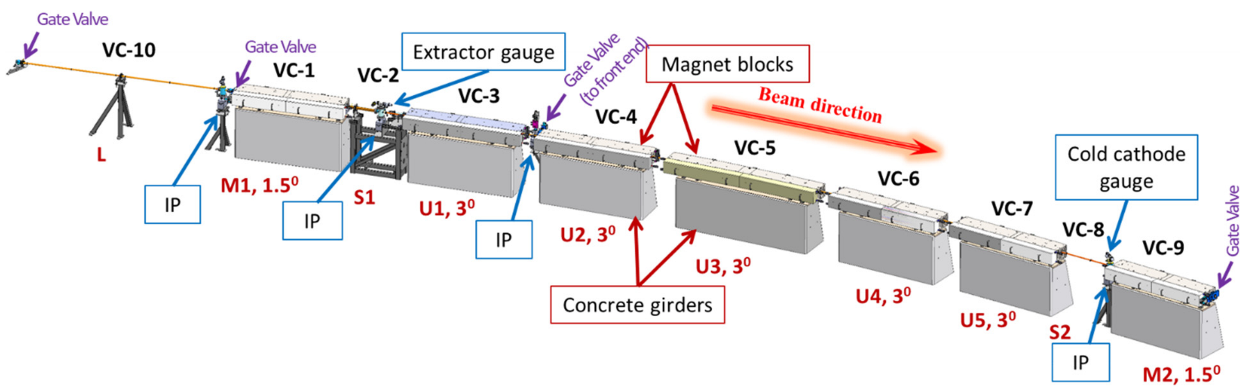

Figure 2: Standard achromat layout of the 3 GeV storage ring with visible magnet blocks, supports and concrete girders. L – Long straight section (for IDs); S1, S2 – Short straight section 1 and 2 (for crotch absorber, RF and diagnostics); M1, M2 – Matching cell magnet blocks; U1-U5 – Units cell magnet blocks. IP - Ion pumps, VC - vacuum chamber types, vacuum gauge and valve distribution.

Vacuum System Layout

In each standard vacuum achromat the following components are installed: one crotch absorber (in S1) to enable the extraction of synchrotron radiation to the beamlines, four sputter ion pumps (noble diode type), two vacuum gauges and three vacuum gate valves.

The vacuum system layout of a standard achromat (26.4 m long) is presented in Fig. 2.

INTERVENTIONS ON VACUUM SYSTEM

Since the start of commissioning in 2015 there were several interventions and upgrades done on the storage ring. The most recent major activity was performed in summer 2020: in place of several straight vacuum chambers two additional vacuum gate valves were installed with dummy chambers in between. This was done to reserve space for future installations without the need to vent the whole achromat again.

This intervention was done by venting of the achromat with purified neon gas following a special procedure. Neon is a noble gas and is not pumped by the NEG coating, thus allows to vent a vacuum section without the subsequent need to re-activate the NEG film by baking. Other intervention using the neon venting were previously performed in 2018 to replace vacuum chambers in two achromats. Both times the interventions were successful and the accelerator could come back to operation without any limitations within few Ah of beam time. The intervention is described in more details in [3].

Spare Vacuum Achromat

In case of unexpected problems with vacuum equipment in an achromat of the 3 GeV storage ring, depending on the issue (and in case the use of neon venting deemed ineffective or unsuitable), the fastest solution instead of exchanging separate pieces, might be to replace the complete vacuum achromat at once. In order to prepare for such event, in summer 2021, one standard, vacuum achromat was assembled inside the 3 GeV storage ring tunnel, and will be kept as a spare. To complete it, all the needed components for one complete vacuum achromat were installed, pumped down, tested, baked and the NEG coated vacuum chambers were activated with a baking oven in-situ. The assembly was prepared on a movable transport structure (as shown in Fig. 3), which can be rolled inside the accelerator tunnel to a specific location when needed.

In case a vacuum achromat needs to be exchanged, the following procedure will be performed:

- Remove the seven top magnet halves of the achromat.
- Vent and disconnect upstream/downstream straight sections and corresponding front end (if needed).
- Vent, remove and place the faulty vacuum achromat on the second transport structure.
- Move the pre-conditioned spare vacuum achromat to the faulty achromat and lift with the strongback.
- Lower with the strongback the spare vacuum achromat to the final location on the lower magnets blocks.
- Reconnect, pump down and condition the upstream/downstream straight sections and the front end (if applicable).
- Place back and connect all the top magnet blocks.

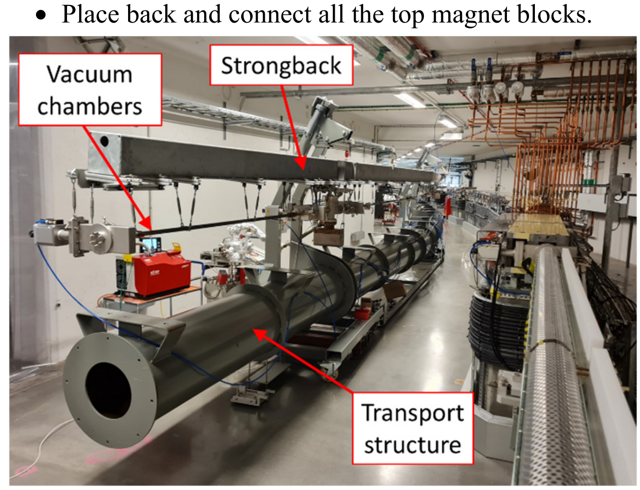

Figure 3: One spare vacuum achromat assembled on a transport structure inside the 3 GeV storage ring tunnel.

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VACUUM SYSTEM PERFORMANCE

Since the start of the storage ring commissioning in 2015 the vacuum system is conditioning fast: the dynamic pressure was reducing fast with the increase of accumulated beam dose and is still observable, as presented in Fig. 4. Current accumulated beam dose is 5860 Ah (June 2022).

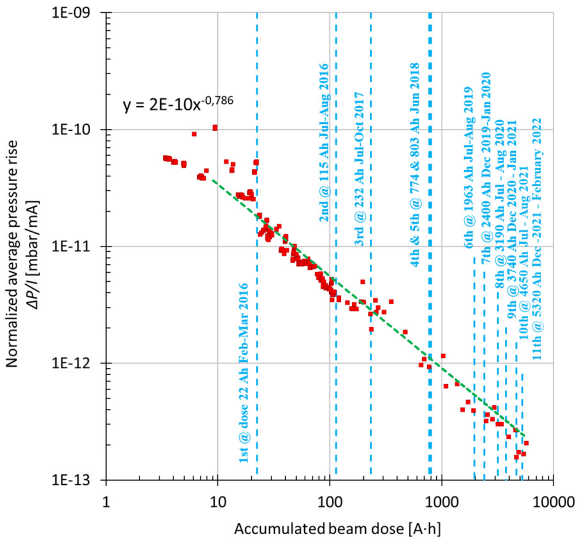

Figure 4: The normalized average pressure rise [mbar/mA] versus the accumulated beam dose [Ah]. Blue vertical lines mark shutdowns with corresponding beam dose and date.

To obtain the vacuum conditioning curve the data points were fitted to the following power function: $y = 2\times10^{-10} x^{-0.786}$. As indicated on Fig. 4 the absolute value of the slope of the vacuum conditioning curve is 0.786.

From the start of commissioning the trend in total beam lifetime increase is observable as shown in Fig. 5, during standard delivery total beam lifetime is around 5 Ah.

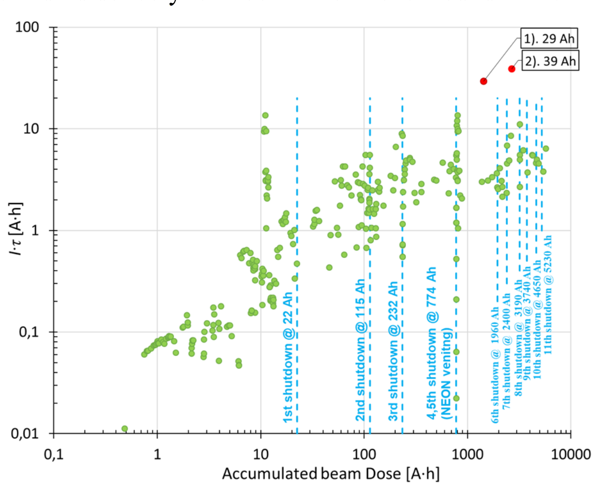

Figure 5: Normalized total beam lifetime I·τ [Ah] vs accumulated beam dose.

In order to determine vacuum related beam lifetime, tests were performed by detuning the RF cavities, enlarging the beam longitudinally thus increasing the Touschek lifetime and minimizing its contribution to the total beam lifetime. Such measurements were performed at accumulated beam dose of 1430 and 2690 Ah, measured lifetime was 29 and 39 Ah respectively. These values are considered as lower limit for vacuum beam lifetime (marked in red in Fig. 5).

Operational Vacuum Issues

There were few operational issues related to the vacuum system (however never related to the NEG coating), nevertheless they did not limit the ring operation.

Several chambers and a crotch absorber in section S1 had geometrical non-conformities due to mechanical deformation during initial installation or manufacturing problems and had to be exchanged during shutdowns. In 2017 vacuum chambers in two achromats were exchanged and the NEG coating was re-activated by baking at 190° C. In 2018 two more components were exchanged in two other achromats, however, without the need of NEG film re-activation as the achromats were vented with purified neon gas in a special way. More details are described in [3].

Table 2 summarizes vacuum related downtimes in the 3 GeV storage ring over several years.

Table 2: 3 GeV Storage Ring Racuum Related Downtimes with Mean Time Before Failure (MTBF) per Year, * until June 2022

Year	# of vacuum downtimes	vacuum contribution [%]	Uptime [%]	MTBF [h]
2022*	0	0	98.74	116.34
2021	1	0.5	96.88	78.85
2020	6	2.7	97.4	38.89
2019	2	1.2	97.28	39.72
2018	8	2.4	n/a	n/a
2017	1	0.3	n/a	n/a

CONCLUSION

The design of the MAX IV 3 GeV storage ring vacuum system proved to be sound with the NEG coating being a reliable solution for the conductance limited vacuum chambers. The performance of the storage ring is very good, the dynamic pressure is low (3×10^{-10} mbar during standard beam delivery) and vacuum related lifetime is long. Several interventions and installations on the vacuum system were performed without jeopardizing the accelerator performance. The method of venting with purified neon was proven to be effective without the need of NEG film re-activation.

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