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# FIRST COMMISSIONING OF VACUUM SYSTEM OF POSITRON DAMPING RING FOR SuperKEKB

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*Abstract*

A new damping ring (DR) was constructed in an upgraded injector system for SuperKEKB. It took more than two weeks from the start of the evacuation process from atmospheric pressure to the end of the activation of the non-evaporable getter (NEG) pumps, which are primarily used in the DR, because of the small conductance of the beam pipes. The commissioning of the DR commenced in February 2017. Vacuum scrubbing progressed smoothly thus far, and a beam lifetime of longer than 1000 s was obtained with a stored beam current of 8 mA, when the beam dose was 0.7 Ah. This corresponds to a photon dose of $3.6\times10^{22}$ photon·m$^{-1}$. The residual gas composition during the beam operation was typical of that expected for a vacuum system pumped by NEG pumps. The photon stimulated desorption (PSD) rate of the beam pipe at that time was roughly estimated to be ~$1\times10^{-4}$ molec.·photon$^{-1}$ using Moflfow+.

## INTRODUCTION

The SuperKEKB [1], which is an upgrade of the KEKB B-factory (KEKB), is a high-luminosity electron-positron collider. The design luminosity is $8.0\times10^{35}$ cm$^{-2}$·s$^{-1}$, which is approximately 40 times the KEKB's record. Many upgrades were performed, including the construction of the DR [2] in the upgraded injector system to generate a low-emittance positron beam, to achieve this challenging goal with the SuperKEKB. The DR is a racetrack-shaped storage ring with a circumference of 135.5 m. The positron beam is extracted from the injector linac with an energy of 1.1 GeV. It is stored in the DR for more than 40 ms (~$8.8\times10^{4}$ turns), where the beam emittance is damped. Subsequently, the low-emittance beam is extracted and sent back to the linac to be accelerated to 4 GeV and injected into the SuperKEKB low energy ring (LER). The maximum stored beam current of the DR is 70.8 mA.

The first commissioning of the SuperKEKB without the DR (Phase-1) was carried out in 2016 [3]. During and after Phase-1, upgrade work required to commence the next commissioning with the Belle II detector (Phase-2) was performed, and the construction of the DR was completed by the end of January 2017, and the commissioning commenced in February 2017.

## OVERVIEW OF VACUUM SYSTEM [4]

The vacuum system of the DR is divided into five sections. Main sections are two arc sections (east and west arc sections) with a length of ~110 m in total. The length of other sections (north and south straight sections, RF section) is ~25 m in total. Since there is synchrotron radiation (SR) irradiation in the arc sections (critical energy: 0.8~0.9 keV, maximum total power: 7.2 kW), the pressure in the arc sections is much higher than that in the straight sections during beam operation. In addition, since the arc sections are much longer than the straight sections, the average pressure over the entire ring is determined mainly by the pressure of the arc sections. Therefore, we will focus on the arc sections in this report. Figure 1 shows two types of beam pipes in one reverse-FODO cell of the arc sections (Type-I and II) and their cross-section. The material of the beam pipes is an aluminum alloy. They have antechambers on both sides of the beam channel because the SR is irradiated on both side surfaces of the beam pipe.

The required beam lifetime determined by the residual gas scattering is longer than 1000 sec and it is expected that the average pressure should be lower than $1\times10^{-5}$ Pa. NEG pumps are mainly used with auxiliary ion pumps (IPs). In one cell, two NEG pumps (C50-ST707, effective pumping speed $S_{eff}$ = 0.014 m$^3$·s$^{-1}$ for CO just after activation, SAES GETTERS Co. Ltd.) are installed in the Type-I beam pipe, and one NEG pump or IP ($S_{eff}$ = 0.008 m$^3$·s$^{-1}$ for CO) is installed alternately in the Type-II beam pipe. The IP is connected to the pumping port via a manifold, to which a rough pumping unit (RPU) consisting of a turbo-molecular pump (TMP) and a scroll pump are also connected via an angle valve. The average distance between the pumps is 0.7 m and the pressure is estimated mainly from the discharge current of the IPs, which are installed every 6 m. In each section, one cold cathode gauge (CCG) is installed at the manifold between the beam pipe and the IP. One quadrupole mass analyzer (QMA) is also installed in the manifold only in the east arc section.

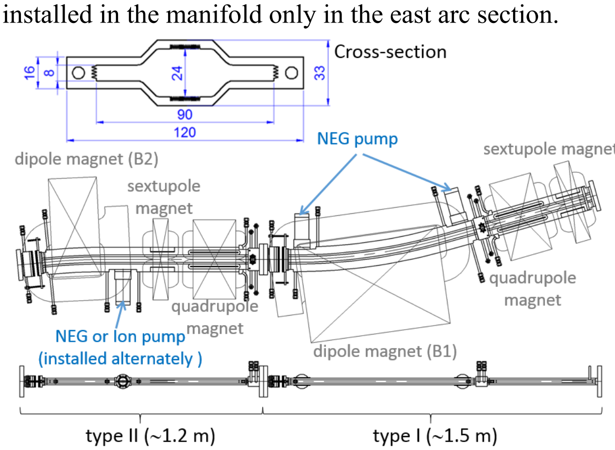


Figure 1: Two types of beam pipes for one cell of the arc sections and their cross-section.

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## CONSTRUCTION

The installation of the beam pipes into the DR tunnel commenced in May 2016 and was completed in January 2018. Almost all beam pipes were coated with titanium nitride (TiN) film ('200 nm) as a countermeasure against the electron cloud issue and baked (150 °C, 24 hours) at the laboratory before the installation [5]. *In-situ* baking was not performed after the installation.

### *NEG Activation*

After the installation, each section was evacuated using RPUs from atmospheric pressure. Figure 2 shows pressure from the start of the evacuation process until the end of the NEG activation in the east arc section. The evacuation with IPs was initiated when the pressure decreased to less than $1\times10^{-4}$ Pa. When the pressure was further decreased to ~$10^{-5}$ Pa, NEG activation was initiated. After NEG activation, RPUs were isolated by angle valves and removed before beam operation. The pressure was monitored using vacuum gauges installed in the RPUs, and also by IPs after they were started. Since the conductance of the beam pipes is small, it took a few days before the commencement of NEG activation. The heating power for NEG activation was controlled so that the monitored pressure did not exceed ~$2\times10^{-4}$ Pa during NEG activation. It took more than two weeks from the start of the evacuation to the end of NEG activation. After NEG activation, the pressure monitored by IPs reached ~$10^{-8}$ Pa.

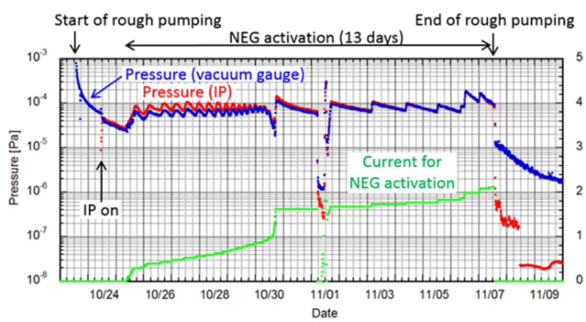


Figure 2: Pressure reading from the start of the evacuation process until the end of NEG activation in the east arc section.

## COMMISIONING STATUS

### *Pressure with Stored Beam*

The commissioning of the DR commenced on February 8, 2018. Figure 3 shows a history of the stored beam current and the average pressure of the arc sections as measured by the IPs. Although there were two long interruptions due to equipment and facility breakdowns, the commissioning has progressed smoothly. When the beam was accumulated for the first time, the pressure measured by IPs exceeded $1\times10^{-5}$ Pa with a beam current of ~1.5 mA. However, the pressure decreased quickly below $1\times10^{-5}$ Pa. Subsequently, the pressure decreased gradually while the beam current was increased. The maximum stored current reached 11 mA on February 23, for which the beam dose was ~0.7 Ah. When the stored beam current was 11 mA, the maximum pressure measured by the CCG was about $4\times10^{-6}$ Pa, which indicates that the average pressure in the beam channel is approximately $1.3\times10^{-5}$ Pa (= $4\times10^{-6}$ Pa × 3.3, see below). After beam tuning of the DR, beam injection into the SuperKEKB LER (Phase-2) commenced on March 27. By April 10, the beam dose exceeded 0.9 Ah.

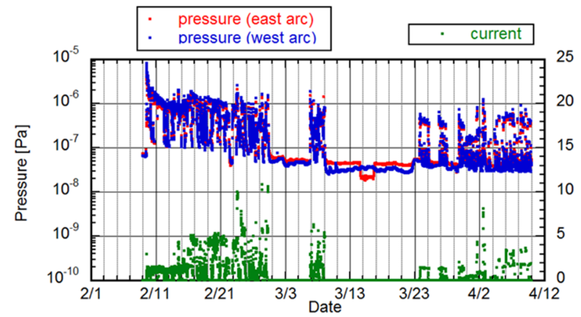


Figure 3: History of the stored beam current and the average pressure measured by the IPs of the arc sections.

### *Vacuum Scrubbing Status*

Figure 4 shows the average pressure normalized by a unit beam current ($p/I$ [Pa·mA$^{-1}$]) for the arc sections as a function of the beam dose. In the graph, the upper horizontal axis represents the photon dose (i.e., the integrated numbers of photons per unit length [photons·m$^{-1}$]). The beam dose of 1 Ah corresponds to the photon dose of $5.2\times10^{22}$ photon·m$^{-1}$. Vacuum scrubbing has progressed smoothly to date.

Figure 5(a) shows the beam lifetime ($\tau$ [s]) and the stored current when the beam dose was 0.7 Ah (corresponding photon dose: $3.6\times10^{22}$ photon·m$^{-1}$). During this measurement, the beam was stored in the DR without beam injection and extraction. When the beam current was 8 mA, the beam lifetime was larger than 1000 s, which is the required value for beam operation. Figure 5(b) shows $1/\tau$ as a function of the average pressure of the arc sections measured by the CCGs. $1/\tau$ is almost proportional to the pressure, which indicates that the lifetime is almost entirely determined by the average pressure.

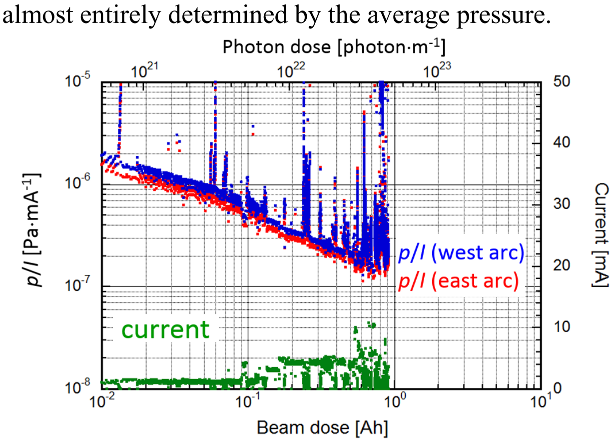


Figure 4: Average pressure normalized by a unit beam current ($p/I$ [Pa·mA$^{-1}$]) for the arc sections as a function of the beam dose.

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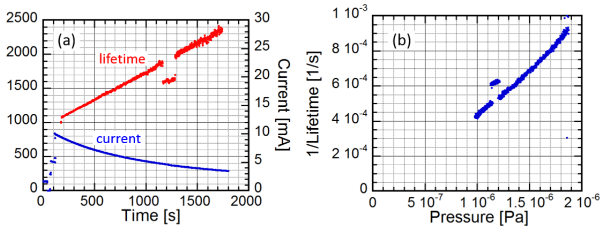


Figure 5: (a) The beam lifetime ($\tau$ [s]) and stored current when the beam dose was 0.7 Ah. (b) 1/$\tau$ as a function of the average pressure of the arc sections.

### Residual Gases

During the commissioning, the residual gases were monitored using the QMA in the east arc section. Figure 6 shows the mass spectrum of the pressure with a beam current of 9.8 mA (average pressure: $1.4\times10^{-6}$ Pa) and the pressure without a beam current (average pressure: $4.3\times10^{-7}$ Pa) when the beam dose was about 0.7 Ah. The residual gas composition of the pressure with the stored beam is typical of that expected for a vacuum system pumped by NEG pumps, i.e., $H_2$, CO and $CO_2$ as leading gas, and the presence of $CH_4$ due to the absence of chemical pumping.

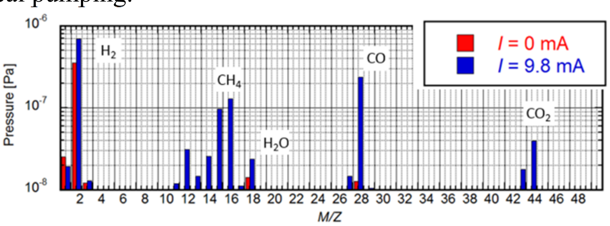


Figure 6: The mass spectrum of pressure with a beam current of 9.8 mA (average pressure: $1.4\times10^{-6}$ Pa) and pressure without a beam current (average pressure: $4.3\times10^{-7}$ Pa) when the beam dose was about 0.7 Ah.

### PSD Rate Estimation

In order to estimate the PSD rate of the beam pipe, the pressure distribution in the beam pipes was calculated using the Molflow+ [6] varying PSD rate. In this simulation, it was assumed that the SR irradiates both sides of the antechambers evenly and the residual gas is CO. The model and parameters used for Molflow+ analysis to obtain the results listed in Table 1 are described below;

- Model: two beam pipes (Type-I and II) with three pumping ports and one manifold. They have no bellows, no beam position monitors, and no groove surfaces. Bent parts are modeled as straight parts.
- Pumping speed: 0.05 m3·s-1 for the NEG pump for the Type-I and 0.04 m3·s-1 for the IP at the manifold connected to the Type-II.
- Temperature: 25 °C.
- Linear photon density: 1.3×1017 photons·s-1·m-1, which corresponds to a PSD rate of 1×10-4 molec.·photon-1 and a stored beam current of 8.9 mA.
- Thermal gas desorption rate: 1×10-9 Pam3·s-1·m-2.

In Table 1 the pressure values at the CCG ($p_{ccg}$) and the average pressure on the top surface of the beam channel ($p_{bc}$) obtained using the simulation in addition to the pressure measured by the CCG when the beam dose was 0.7 Ah, and the beam current was 8.9 mA are listed. Since the calculated pressure is close to the measured one, it is estimated that the PSD rate for CO was reduced to ~$1\times10^{-4}$ molec.·photon$^{-1}$ when the beam dose was 0.7 Ah. From this calculation, it is also estimated that the average pressure in the beam channel can be obtained by multiplying the pressure measured by the CCG by a factor of 3.3.

Table 1: Calculated and Measured Pressure Values when the Beam Dose was 0.7 Ah and the Beam Current was 8.9 mA

| | Calculated (for CO) | Measured |
|---|---|---|
| $p_{ccg}$ | $1.2\times10^{-6}$ Pa | 1~$2\times10^{-6}$ Pa |
| $p_{bc}$ | $4.1\times10^{-6}$ Pa | |
| $p_{bc}/p_{ccg}$ | 3.3 | |

## CONCLUSION

The commissioning of the DR commenced on February 8, 2018, and no problems have been identified for the vacuum system to date. The vacuum scrubbing progressed smoothly, and a beam lifetime larger than 1000 s was obtained with a stored beam current of 8 mA, when the beam dose was 0.7 Ah (corresponding photon dose: $3.6\times10^{22}$ photon·m$^{-1}$). The estimated PSD rate at that time was $1\times10^{-4}$ molec.·photon$^{-1}$. Although ~10 times the beam dose is required to achieve sufficient lifetime with the designed beam current (70.8 mA), it is expected that this value will be achieved during Phase-2 operation. There is no indication of a decrease in the NEG pumping speed, and it is expected that re-activation of the NEG will not be required until the next long shutdown in the summer of 2018. Electron cloud instability has not been observed so far, and this will be continuously monitored to establish if this occurs as the stored beam current increases.

## ACKNOWLEDGEMENTS

The authors would like to thank colleagues in the SuperKEKB team.

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