ULTRAHIGH VACUUM FOR HIGH INTENSITY PROTON ACCELERATORS: EXEMPLIFIED BY THE 3 GEV RCS IN THE J-PARC

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Abstract

The 3 GeV rapid cycling synchrotron (RCS) in the Japan Accelerator Research Complex (J-PARC) project accelerates a proton beam up to 3 GeV. At a 25-Hz repetition rate, the RCS generates a high-power beam of 1 MW. The cumulative energy dosage is of the order of 100 MGy over 30 years of operation. To minimize the radiation exposure during maintenance, it is necessary to construct a vacuum system with reliable components that can operate for a long time in this high level of radiation. In addition, it is essential that the beam be operated in an ultrahigh vacuum (UHV) in order to suppress pressure instability, due mainly to ion-induced desorption. Thus, we need to design the vacuum system such that it can cope with the additional gas load during beam operation. At the same time, effective pre-treatments that can reduce outgassing from the beam components also need to be developed. A fast pump-down performance after every vent for maintenance is also required in order to obtain long beam-operation times. However, it is not practicable to bake-out the entire system.

To fulfill the above requirements, we developed turbo-molecular pumps (TMPs) for evacuating the large outgassing regions. In addition, ceramic ducts for use in the rapidly varying magnetic field and beam transport ducts, as well as bellows made of Ti, were successfully developed. We subsequently reviewed and examined various surface treatments of Ti, Al, and stainless steel to see how well they reduced outgassing. We polished the inside surface such that it became smooth, to reduce the hydrogen content and to present a superficial barrier to hydrogen diffusion.

This procedure enabled us to realize the UHV without baking-out the RCS and, to date, has resulted in successful beam operation.

INTRODUCTION

The goal of the Japan Proton Accelerator Research Complex (J-PARC) project is to utilize the secondary beams of neutrons, muons, neutrinos, and so on that are produced when proton beams are generated at high power. The accelerator facility consists of a 400-MeV linear accelerator (linac), a 3 GeV rapid cycling synchrotron (RCS), and a 50-GeV synchrotron ring [1]. The 3 GeV RCS is currently being used to accelerate a 181 MeV proton beam from the linac up to 3 GeV, at which point, it is supplied to both the 50 GeV ring and a neutron production target. The aim is to generate a high-power beam of 1 MW at a repetition rate of 25 Hz and a rate of acceleration of 8.3×10^{13} protons per acceleration.

The vacuum requirements for this system are described as follows [2]:

(1) The inevitable loss of even a small fraction of the proton beam generates secondary radiation such as neutrons and beta and gamma rays. The cumulative energy dosage from radiation is roughly estimated to be 30–100 MGy over 30 years of operation [3]. To minimize exposure of operators to radiation, the vacuum system should be made up of low-maintenance, reliable components that can withstand the high levels of radiation.

(2) It is also essential that the beam be operated in an ultrahigh vacuum (UHV) in order to suppress pressure instability, due mainly to ion-induced desorption, even though the specifics of the outgassing mechanism during beam operation are not yet well understood. Thus, we have to design the system in such a way as to enable it to cope with the additional gas load (that may appear at higher beam powers in the future) during beam operation.

(3) A fast pump-down performance after every air intake for maintenance is required every few days in order to realize a long beam operation time of the accelerator. However, it is not practicable to bake-out the entire system due to the small gap between the ducts and the magnets. Therefore, effective pre-treatments have to be developed to minimize outgassing from the beam components.

The above criteria were utilized in the design of the vacuum system. To realize the system, key components such as large-aperture ceramic ducts, titanium bellows, and TMPs with high resistance to radioactivity were developed. In addition, several heat treatments were applied to reduce outgassing from beam components such as the ferrite blocks for the fast kicker magnets and the Cu blocks for halo collection. On the basis of the results of the research and development outlined above, we realized the UHV without baking-out the RCS. To date, this beam operation has been successful. This paper describes the structure of the vacuum system of the 3 GeV RCS and looks at its performance.

OUTLINE OF THE VACUUM SYSTEM

The configuration of the RCS is depicted schematically in Fig. 1. The main vacuum components for the RCS are also listed in the figure. The RCS has a circumference of 348.3 m, and is in three-fold symmetry, as a result of having three divisions called "super-periods." Each

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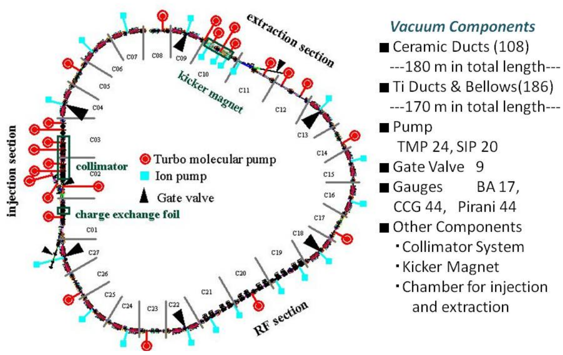

Figure 1: Schematic configuration of the RCS

division consists of a "straight" and an "arc" section. The straight sections are devoted to beam injection, RF acceleration, and beam extraction. Each straight section is isolable using in-line isolation valves at each end, and can be evacuated independently. Each arc section contains eight bending magnets and twelve focusing magnets. These magnets are operated at 25 Hz. To avoid eddy currents [4] in the ducts in the magnets, ceramic ducts are employed. The ceramic ducts are connected to the Ti ducts for beam transport, and bellows with RF contacts are placed between. The pumps and gauges are attached to the Ti ducts. The TMPs with "dry" roughing pumps are used not only for rough pumping but also for evacuating the UHV [2,5]. All the pumps and gauges are installed in the main hall, except for the dry backing pumps. Since the backing pump has a Teflon sealing chip, it is placed in the maintenance tunnel, where the cumulative energy dosage from radiation is roughly estimated to be less than 1 MGy [3]. The two isolation valves between the TMP and the backing pump are set in series. The one closest to the TMP closes when backing pressures exceed 400 Pa in order to protect the TMP from exposure, while the other valve, just on the backing pump, is open only when the backing pump is in operation.

During beam operation, the arc is designed to be evacuated using a combination of four bakeable ion pumps and two TMPs. The nitrogen-equivalent pumping speeds are 0.7 m3/s for the ion pump and 1.3 m3/s for the TMP.

The straight section for beam injection is evacuated by the TMPs because this is the largest outgassing area in the RCS. A collimator system, which consists of eight chambers, localizes most of the beam losses in the restricted area and reduces the average beam losses in the

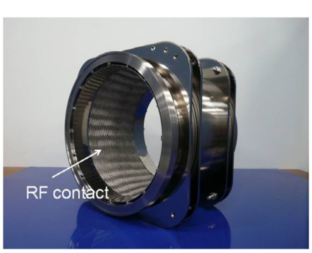

Figure 2: A new type of RF contact which was set in the bellows. This contact is made of Ti braid.

other area [6]. A TMP is attached to each collimator chamber. The straight section for beam extraction is also evacuated by TMPs. The kicker magnets [7] are independently pumped by the combination of TMPs and ion pumps in order to maintain an ultrahigh vacuum during operation. On the other hand, the straight section for RF acceleration seems to be a rather low outgassing region; therefore, it was designed to be independently evacuated using only four ion pumps and one TMP.

DEVELOPMENT OF THE VACUUM COMPONENTS

Turbo-Molecular Pump with High Radioactive-Resistance

To evacuate the large outgassing area, we successfully developed a TMP with a high resistance to radioactivity. The details have already been presented elsewhere [8–10]. Therefore, we will only present a brief outline of its development here. This TMP was developed with high resistance to radioactivity by improving the magnetically suspended molecular pump, TG1300M, produced by Osaka Vacuum Ltd., which endures high backing pressures up to 400 Pa.

First, the TMP was irradiated with gamma rays in order to determine the radiation damage to its constituent parts. Taking the damage observations into consideration, the TMP was re-designed. Subsequent gamma irradiation experiments on this re-designed TMP revealed that it can operate even if the absorbed dosage exceeds 75 MGy.

Finally, in order to ascertain how well the TMPs performed in the accelerator, we examined the effect of magnetic fields on them. It was discovered that rotor temperature rose by less than 100°C in an orthogonal magnetic field of 0.003 T [11,12].

Large-Scale Ti Bellows with a New Type of RF Contact

In the 3 GeV RCS, pure Ti was used for the bellows because of its small residual radioactivity. Large-scale bellows were necessary to adjust the gap between the ceramic ducts and/or between the ceramic duct and the transport Ti duct. Ti bellows with long welding traces are risky for vacuum leaks because the penetration of a small amount of oxygen into the melted part under the welding causes the welded part to be become brittle [13]. We therefore decided to make hydro-formed bellows that were as flexible as welded bellows [14]. A prototype bellows with an inner diameter of 400 mm and a free length of 100 mm performed suitably: (1) The movable displacement parallel to the axis was ±24 mm, and the vertical displacement was 5 mm due to the universal bellows expansion joint. (2) The spring rate was 14 N/mm. (3) The endurance test showed a fatigue life of more than 10^6 cycles with a displacement of 20 mm. Thus, we succeeded in developing a hydro-formed bellows with the same flexibility as that of its welded counterpart.

The prototype bare bellows should be hidden from the beam to short out induced RF fields. Because the beryllium-copper spring finger contacts were found to be very hard (roughly 1000 N/mm) owing to the large size, we developed another type of RF contact. Figure 2 shows the new type of RF contact that was set in the bellows. This contact is made of Ti braid, which consists of wires with a diameter of 0.3 mm. This RF contact is a kind of basket (with two ports) made with the braids. Because of the spring effect, the contact can change shape easily. In addition, the contact can easily connect the different cross sections in a smooth fashion.

Finally, the inner surfaces of the bellows were polished with a newly developed wet-mechanical polish [14]. The average roughness factor, Ra, was set to less than 0.2 µm. The wires from which the RF shield is made were also chemically polished. We then vacuum-fired the entire Ti bellows in order to reduce the hydrogen content in the Ti bulk. The details of the treatments will be discussed later.

Large-Scale Ceramic Ducts

To avoid eddy current effects, a ceramic chamber was developed for use in the dipole and quadrupole magnets. Various types of ducts have been developed. The details related to the development of this chamber have already been reported elsewhere [15–18], so only a brief outline will be given here.

The ceramic chamber has an RF shield that reduces duct impedance (thereby stabilizing the beam). The RF shield is composed of copper strips and capacitors, and is formed on the outer surface of the duct. The copper strips are electroformed on the ceramic surface. One of each of the copper strips is connected to the Ti flange and the other is connected to the other flange via a capacitor, to interrupt eddy current loops. In addition, all the inner surfaces of the ceramic ducts are coated with TiN as a means of precluding any build-up of charge and also to reduce secondary electron emission.

Vacuum Gauges

We employed three types of gauges in the operation of the RCS vacuum system. Pirani and inverted magnetron gauges were used to control the combination of a TMP with a foreline pump, while BA gauges were used to monitor the pressure along the ring. All the gauges in the RCS had to be highly reliable and long lasting; as these qualities would help in minimizing any damage caused from exposure to radiation during maintenance. The Pirani gauge, in particular, had to be highly resistant to radiation, vibration, and abrupt air intakes. In addition, it should preferably be capable of measuring pressures from 0.1 Pa to 10^3 Pa, so that the vacuum conditions of the ring can be ascertained and the back pressure of the TMP can be monitored. Almost no the Pirani-type gauges available in the market could satisfy both these requirements. As a result, we had to develop our own Pirani-type gauge that could satisfy them [5,19–21].

PRETREATMENT FOR WALL MATERIALS, FERRITE MAGNETS, AND CU BLOCKS

Wall Materials

We adopted pure Ti not only for the bellows, but also for the transport and pumping ducts, because of its small residual radioactivity. Another merit of pure Ti is the possibility of low outgassing surface. In order to realize fast pump-down performance, it is necessary to clean and make the surfaces of materials passive [13]. Some researchers have investigated the outgassing characteristics of Ti after various surface treatments [22,23]. From their investigations, we know that after a surface treatment such as electrical polishing, an outgassing rate of less than 10^{-12} Pam/s occurs in the static state (at room temperature, with no beams) [24].

In the case of accelerators, the outgassing may occur through the following three mechanisms, which have been reviewed extensively in relation to plasma-wall interaction in fusion machines [25]: (a) thermal desorption of the gas adsorbed on the walls, (b) impact desorption by high-energy particle such as ions and electrons, and (c) chemical reactions that release gases such as water and methane. These three processes may also be combined. In these cases, if neither gas species nor atoms such as hydrogen and carbon that consist of gas species are present, outgassing should not occur [26–28].

As a result, we employed the following procedures:

(1) We polished the inner surfaces of the Ti ducts and bellows in order to remove the degraded surface layer and to make the resulting surface smooth. For polishing the duct's inner surface, a chemical polish was employed, and a newly developed wet-mechanical polish [14] was employed for polishing the inner surface of the bellows. The average roughness factor, Ra, was set to less than 0.2 µm.

(2) In order to suppress the gas desorption induced by the high-energy particles such as ions and electrons, reduction of hydrogen content (the main residual gas species) in the Ti bulk (especially near the surface) was important, although the outgassing mechanism during proton beam operation has not yet been properly investigated. Therefore, we vacuum-fired the Ti ducts and bellows. The conditions for vacuum firing were extensively examined [29], and special attention was paid to changes in mechanical strength. Using these results, the ducts and bellows were baked-out in a vacuum of less than 10^{-5} Pa at 750°C for 8 h, and at 650°C for 8 h, respectively. These heat treatments were applied after surface polishing, because hydrogen is re-introduced through surface treatments.

(3) Finally, in order to present a chemically stable surface that is passive to water-molecule adsorption, the Ti surface was oxidized by a dry treatment so as to form an amorphous oxide layer with a thickness of 2–3 nm [30]. This oxidized layer reportedly prevents bulk

hydrogen diffusion, which leads to the extremely low outgassing rate for the Ti [24].

The other wall material was magnetic stainless steel for the ducts at the beam entrance and extraction [2,31]. First, this material was baked-out in vacuum at 850°C for 2 h after buffing for reduction of H content. Then, TiN with was coated on it forming a layer of 1-μm thickness in order to obtain a smooth surface and to present the diffusion barrier against hydrogen in the bulk. Thus, the ducts at the entrance and extraction have an outgassing rate of less than 10^{-9} Pa m/s. For the accelerator, this TiN coating is perhaps one of the best surface treatments because of its low secondary electron emission yield [32], as well as its low outgassing rate [33]. The TiN coating was also employed in the treatment of the inner wall of the collimator chambers in order to reduce the electron-cloud effect [32,34].

Ferrite Cores and Cu Blocks

Because the kickers are installed in a vacuum to prevent discharge, it is important to reduce the outgassing of water vapor from the ferrite cores and Al plates. It is very effective to bake out the cores in vacuum at approximately 200°C. After bake out for 300 h, the outgassing rate decreases to less than 1×10^{-7} Pa m/s [35]. An Al surface was finished by employing pit-free electro-polishing, leading to a very low outgassing rate of 10^{-10} Pa m/s after a bake out at 150°C for 25 h [36]. Adopting the above treatments kept the outgassing rate from the kicker system for the RCS remarkably low. The collimator system is used to localize most beam losses in the restricted area (collimator region) [6]. Most of the cut-off beam is absorbed by the five particle absorbers made of highly oxygen-free Cu. Therefore, thermal and particle-induced desorption of the hydrogen from the absorbers should be reduced. We sought to exhaust the H content in the absorbers by vacuum firing at 600°C for 40 hours. The quantity of exhausted hydrogen revealed that the H-content of the Cu block was reduced from the initial value of 0.5 ppm (wt.) to less than 0.1 ppm [2]. Accumulation and re-release of hydrogen in the Cu block should be examined in future.

PERFORMANCES

Pump-Down

A typical pumping-down curve from atmospheric pressure is shown in Fig. 3 (a) for the early stage of operations (2007 Oct.) and (b) for the most recent operation (2010 Dec). In our system, the TMPs with dry roughing pumps have been used not only for rough pumping but also for evacuation in the UHV. Usually, the pressure level reached less than 10-5 Pa in one day [2]. The ion pumps were baked out at around 200°C for 1–2 days in the early stages. Although we spent several days completing preparations for beam operation in the early stages, as mentioned above, since Oct. 2008 we have evacuated the ring using only TMPs, mainly because we have been getting longer beam-operation times. We can start the beam operation in two days just after pumping from atmospheric pressure.

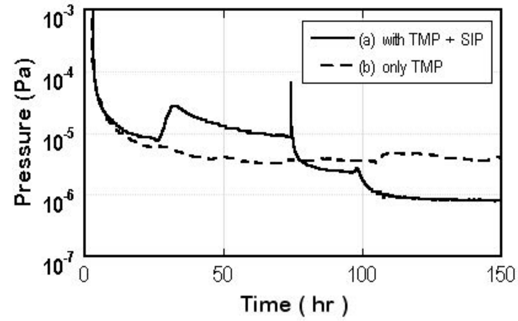

Figure 3: Typical pumping down curves; (a) with ion pumps, and (b) without ion pumps.

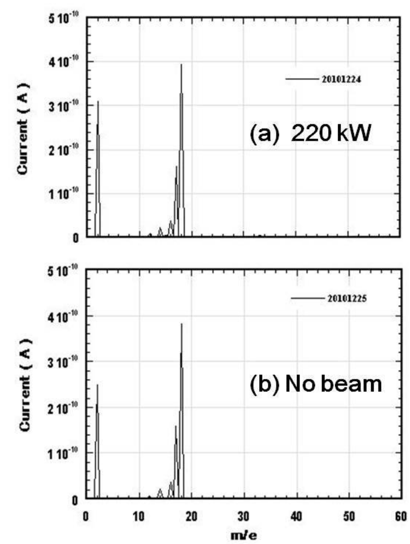

Figure 4: Changes in the residual gas spectra; (a) during the beam operation with the power of 220 kW (24 Dec 2010), and (b) after the beam operation at 220 kW (25 Dec 2010).

The basic pressure distribution using only TMPs is not so different from that with all pumps. The average outgassing rate is roughly estimated to be less than 10-8 Pa m/s, although our system is not bakeable. This vacuum level is not a problem for beam operation with a power of up to 220 kW.

Outgassing During Beam Operation

After a long-time shutdown, there is a rather large amount of outgassing with the beam operation everywhere except the collimator section. Then, the pressure decreases and reaches to the base pressure as a function of operation time. This is independent of the beam power up to 220 kW. The pressure around the collimator is constantly low, because the collimator section is vacuum-sealed with the gate valves during the shutdown. Thus, the pressure distribution during the beam operation saturates to the pressure distribution at the steady state without the beam.

Residual gases were also monitored during the beam operation. With the beam operation, H_2 and H_2O were considerably released at first. Then the both gases gradually decreased and saturated to the base value. The cleaning effect by the beam up to 220 kW was clearly observed through the residual gas analysis. These features are well demonstrated in Fig. 4. In the saturated state, the spectra during beam operation with the power of 220 kW was not so different from the spectra after the beam operation.

After all, there is little outgassing during beam operation with the beam power up to 220 kW in the RCS. The outgassing after a long-time shutdown during the beam operation is supposed to originate from the adsorbed gases on the surface.

SUMMARY

In this paper, the structure of the 3 GeV RCS vacuum system was outlined and its performance described.

The concluding remarks are as follows:

(1) The 3 GeV RCS vacuum system was designed and fabricated on the basis of the following requirements: (a) The system should be composed of reliable, long-lasting components able to withstand high levels of radiation. (b) In order to suppress pressure instability, the system should be able to cope with additional gas load mainly due to ion-induced desorption during beam operation. (c) A fast pump-down performance after every vent is also required to obtain a long beam-operation time.

(2) We developed TMPs for evacuating the large outgassing regions and gauges. In addition, ceramic ducts for use in the rapidly varying magnetic field and beam transport ducts, as well as bellows made of Ti, were successfully developed.

(3) Various surface treatments of Ti, and magnetic stainless steel were reviewed and examined to see how well they reduced outgassing. We also smoothed the surface of the vacuum, by polishing it, to reduce the hydrogen content and to introduce a superficial barrier to hydrogen diffusion.

(4) Cu blocks in the collimator, and Al plates and ferrite cores in the kicker magnets, which influence the vacuum properties of the RCS, were also vacuum-fired before installation in order to reduce outgassing.

(5) Finally, on the basis of the research and development outlined above, we realized the UHV without baking-out the RCS. The beam operation has been successful to date.

(6) Although there is a rather large amount of outgassing during the beam operation after a long-time shutdown, the outgassing decreases gradually and becomes negligibly small as a function of operation time. It is seemed this outgassing originates from the adsorbed gases on the surface. After all, an obvious outgassing due to high-energy particle induced desorption has not been observed with the beam power of up to 220 kW.

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