Vacuum Technologies in High-Power Proton Accelerators*

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For vacuum systems in high-power proton accelerators, compared with those in conventional particle accelerators, there are more challenging requirements in addition to their basic role owing to the existence of a large number of high-energy protons, rapid cycling of the magnetic field, and high radioactivation. In addition, it is necessary to promptly evacuate from the atmospheric pressure to ultra-high vacuum (UHV) and ensure sufficient pumping speed against an additional gas load because of the desorption of ion-induced molecules from the vacuum wall. The vacuum system of the 3 GeV Rapid Cycling Synchrotron (RCS) at the Japan Proton Accelerator Research Complex fulfills such unique requirements of high-power proton accelerators. Many vacuum devices such as turbo molecular pumps with radiation toughness, beam pipes made of alumina ceramics, and titanium beam pipes and bellows were developed in accordance with the design concept of the system. Treatments to minimize both static and dynamic outgassing were also performed, e.g., surface polishing, coating, and vacuum firing. With regard to the performance of the entire vacuum system, rapid evacuation from atmospheric pressure and assurance of UHV during beam operation have been achieved. Responding to the upgradation of the beam power, continuous improvements of the vacuum system have been performed, e.g., beam loss reduction by improving the beam line pressure, in-situ degassing of the kicker magnet, and magnetic shielding via beam pipes and bellows made of soft magnetic material. This report presents vacuum technologies typically used in high-power proton beam accelerators considering the design concept of the RCS vacuum system, developed components, vacuum performance, and recent upgrades.

1. Introduction

The basic role of vacuum systems in accelerators is to maintain a sufficiently low pressure in a beam area to prevent a beam from being scattered by residual gas molecules. The required pressure for an accelerator depends on the type of accelerated particles, beam energy, necessary beam storage time, acceptable amount of beam loss, and so on. For vacuum systems in high-power proton accelerators, compared with those in conventional particle accelerators, there are more challenging requirements in addition to their basic role because of the existence of a large number of high-energy protons. For example, the size of vacuum devices needs to be large to accommodate the large cross-sectional area of beams, vacuum devices need to have high resistance to radiation, and pumping speeds need to be completely large in anywhere in the beam line to pump down unpredictable gas load caused by the intense beam.

A typical example of such high-intensity proton accelerators is the Japan Proton Accelerator Research Complex (J-PARC) 3 GeV rapid cycling synchrotron (RCS), whose maximum output beam power is 1 MW. The present report introduces vacuum technologies in high-power proton beam accelerators considering the RCS vacuum system. First, the design concept of the vacuum system is presented. Second, an overview of the system and some developed vacuum devices is reported. Third, the achieved vacuum performance is discussed. Finally, some recent upgrades are introduced.

2. Design concept of the J-PARC RCS vacuum system

J-PARC consists of a sequence of three proton accelerators and three experimental facilities1). The first stage of the accelerators is the linear accelerator (Linac), which accelerates H⁺ ions from the ion source up to an energy of 400 MeV. These 400 MeV H⁺ ions are converted to protons by a thin carbon foil at the injection point in the RCS and accelerated to 3 GeV. These 3 GeV protons are dispensed to the Materials and Life Science facility (MLF) and Main Ring (MR). The MLF aims to promote materials science and life science using high-intensity pulsed neutron and muon beams that are produced using the 3 GeV protons. The MR accelerates the 3 GeV protons up to 30 GeV and sends them to the neutrino experimental facility and hadron experimental facility.

The most notable characteristic of the J-PARC accelerator is its high-intensity beam. In particular, the RCS is one of the highest-intensity proton accelerators in the world. It aims to produce a proton beam with 1 MW power. This beam power consists of $8.3 \times 10^{13}$ protons per bunch with 3 GeV energy at 25 Hz repetition rate. These conditions lead to the following unusual situations. First, an enormous number of protons form a large beam size. Next, the rapid repetition rate requires a rapid change rate of the magnetic field, which produces eddy currents in metals. In addition, a very small beam loss leads to a severe radioactivation of devices owing to the existence of a large number of high-energy protons. Furthermore, the additional gas will be continuously desorbed by ion bombardment during high-power beam operation.
To operate the system under such circumstances, the vacuum system of the RCS was constructed according to the following design concepts:

1) Vacuum components in the beam line, such as beam pipes and bellows, should have sufficiently large aperture sizes compared with the cross-section of the beam.
2) The beam line components are required to have a low residual radioactivation characteristic, and the components in the accelerator tunnel should be resistant to radiation.
3) Eddy currents in the beam pipes should be avoided.
4) Outgassing of the vacuum components should be minimized, and a continuously high pumping speed should be ensured over a wide range of pressures.

New vacuum components such as turbo molecular pumps with radiation toughness, large-scale alumina ceramic beam pipes, large-scale titanium bellows, large-scale metal seals, and cables and connectors with radioactive resistance were developed on the basis of these design concepts. Simultaneously, treatments such as surface polishing and vacuum firing of vacuum materials to suppress outgassing were performed. In the next section, a description of the entire RCS vacuum system is presented and several examples of the developed components and the treatments applied to them are introduced.

3. RCS vacuum system

3.1 Overview of the vacuum system

Figure 1 shows a schematic of the RCS vacuum system with the main vacuum components. The RCS has a threefold symmetry with a circumference of 348 m, which consists of three straight and three arc sections. Each straight section has a role: either beam injection, extraction, and acceleration. All-metal gate valves with an inner diameter of 250 mm are installed to isolate each section. There are a total of 60 beam focusing magnets (quadrupole magnets) and 24 beam bending magnets (dipole magnets) in the RCS. Beam pipes made of alumina ceramics are installed in these magnets to prevent eddy currents, which would otherwise be induced by the rapidly changing magnetic field if metal beam pipes are used. The beam pipes and bellows made of titanium are installed between the alumina ceramic beam pipes. Ports for pumps and gauges are mounted on the titanium beam pipes. Ports for pumps and gauges are mounted on the titanium beam pipes.

Turbo molecular pumps and ion pumps are installed around the ring as main pumps for simultaneous use. Turbo molecular pumps are used as the main evacuation pumps for the area that contains devices with large outgassing, such as beam collimators and kicker magnets. Practically, only the turbo molecular pumps are used for the entire area because of the following reasons: 1) rapid evacuation to ultra-high vacuum (UHV) can be achieved using only the turbo molecular pumps, and they have constant pumping speed over wide pressure ranges; 2) the turbo molecular pumps are easier to maintain compared with ion pumps, which must be infrequently baked out for degassing; and 3) ion pumps eject buried gasses, which are ions generated during beam operation via beam-residual gas interactions and/or via the electrical field that is used for acceleration. Dry scroll pumps are used as backing pumps. Because chip seals in the dry scroll pumps do not have tolerance to radiation, they are installed in the maintenance tunnel, where the radiation effect is negligibly small even during beam operation.

Operable components such as valves, pumps, and gauges are controlled by the control system, which consists of nuclear instruments modules (NIM), programmable logic controllers (PLC), and a client-server network. An interlock among the components (programmed in the PLC) is internally used to protect the vacuum devices and externally used to stop the beam in the case of an unusual pressure increase. Figure 2 shows snapshots of the operation screen of the client, from which all vacuum devices can be controlled and all statuses and readings of each device are monitored.

3.2 Developed vacuum components

Titanium duct and bellows with large aperture

The beam pipes and bellows in the RCS are made of pure titanium because it is a low radioactivation material. Titanium is also well suited for use in vacuum because its outgassing rate is very low when it is appropriately treated. The beam pipes and bellows have large aperture sizes of 250–500 mm in diameter to accept a large number of protons without loss.

Figure 1 Schematic of RCS vacuum system with main vacuum components.
Bellows with low spring constants are required for the RCS in order to avoid stress on the nearby alumina ceramic beam pipes. Hydroformed bellows with large apertures generally have high spring constants. Although a relatively low spring constant may be achieved in welded bellows, there is then a potential risk of vacuum leaks caused by the brittleness of a welding line owing to oxygen penetration into the melted part under the welding line. Therefore, flexible bellows without welding were developed. Figure 3 shows a typical titanium bellows with an inner diameter of 400 mm. A narrow pitch of approximately 3 mm was formed by a combination of hydroforming and pressing, thereby typically achieving a spring constant of less than 25 N/mm. As shown in Fig. 3, two bellows are connected through an intermediate pipe. In this configuration, more than 3 mm displacement perpendicular to the central axis can be typically achieved.

A new type of a radio-frequency (RF) shield with a low spring constant is employed in the bellows. This RF shield consists of braided titanium wires, as shown in Fig. 3. This type of RF shield can easily change its shape and smoothly connect different cross-sections. The shield’s spring constant, which depends on the shield shape, is typically has maximum values of 20 N/mm and 60 N/mm for the axial and lateral displacements, respectively. Negligible amounts of dust particles are generated by the movement of the RF contact.

Alumina ceramic beam pipes with large aperture

Alumina ceramic beam pipes were developed to avoid eddy currents induced by the rapid changing of the magnetic field. Alumina ceramics with high purity (99.7%) were used. The cross-sectional diameters of the pipes range from 250 to 500 mm, as is the case for the titanium beam pipes and bellows. There are several cross-sectional shapes corresponding to the various beam shapes. The beam pipes in the dipole and quadrupole/sextupole magnets have racetrack and circular shapes, respectively. The beam pipes in injection magnets have racket, racetrack, and rectangular shapes. Figure 4 shows the alumina ceramic beam pipes for the dipole and quadrupole magnets. To employ one beam pipe, several 0.5–0.8 m unit pipes are brazed with each other after metallizing the edge facet with Mo-Mn compound. At the edges of both sides of the beam pipe, titanium sleeves are brazed, and titanium flanges are welded to the sleeves. As the RF shield, high-purity copper stripes are electrically formed outside the chamber to obtain low impedance and shut off the high-frequency electromagnetic wave induced by a beam. The inner surface of the ceramic pipes is coated with titanium nitride (TiN) to suppress secondary electron emission. The thickness of the TiN coating is controlled within 10–20 nm. This thickness is enough thicker than the maximum escape length of the secondary electrons. Furthermore, the negligible eddy current generates in this thickness. The TiN coating also helps to decrease outgassing by suppressing the adsorption of gas molecules.

Turbo molecular pump with high resistance to radioactivity

A turbo molecular pump with high resistance to radiation...
radioactivity was developed based on a standard magnetically suspended turbo molecular pump TG1300M (provided by Osaka Vacuum, Ltd.)\textsuperscript{31.3). This standard model had no semiconductor devices in its body and was constructed only of metals. Therefore, the model originally had relatively higher resistance to radioactivity. At the first stage of the development, TG1300M was irradiated by gamma rays to survey points to be improved to increase its resistance to radioactivity\textsuperscript{12). As a result, its fluoroelastomer o-ring seals, the Teflon sheath of lead wires, and the epoxy resin insulator of connectors hardened, cracked, and discolored after a gamma ray dosage of 3.5 MGy. Then, the seal material was replaced with metals, the sheath was replaced with polyether ether ketone (PEEK), and the insulator was replaced with alumina ceramics. By the subsequent gamma ray irradiation, the redesigned turbo molecular pump was found to operate until the radiation dosage reached 70 MGy.

Treatments to minimize outgassing sources

Outgassing processes in a normal vacuum system are generally dominated by the thermal desorption of adsorbed molecules on vacuum surfaces. In the vacuum systems of particle accelerators, there are additional outgassing processes such as molecule desorption stimulated by photon, electron, ion, high-energy particles. In high-power proton accelerators such as the RCS, the main additional outgassing source is the molecules desorbed by ions, which are residual gas molecules ionized by a beam. To decrease outgassing during these processes, the vacuum surfaces of the beam pipes and bellows were chemically polished or coated, and the devices were heat treated in high vacuum in the manufacturing processes.

Surface polishing and coating are effective for decreasing the actual surface area and preventing gas molecules from sticking on the surface by forming a chemically stable layer. Inner metal surfaces were mechanically and chemically polished. For example, the titanium bellows were chemically polished after the first hydroforming process, achieving an average roughness of less than 0.05 \( \mu \)m. The inner surfaces of the alumina ceramic beam pipes were coated with TiN to obtain a low secondary electron emission yield, as described above. For a kicker magnet, whose electrodes are made of aluminum alloy with a total surface area of 35 m\(^2\) per magnet, a special type of electropolishing was employed\textsuperscript{13). In this process, hydrogen bubbles, which are produced in chemical reactions and generate pits on the aluminum surface, were removed by the flow of the electropolishing solution. The surface roughness decreased to less than 0.03 \( \mu \)m on average.

Heat treatment in vacuum (called \textquoteleft\textquoteleft vacuum firing\textquoteright\textquoteright) can minimize the amount of atoms dissolved into the interior of metals, which would otherwise diffuse to the surface and be released into vacuum\textsuperscript{14). The minimization of the amount of dissolved atoms near the vacuum surface of metals is also important in an accelerator because dissolved hydrogen would be knocked out by several previously mentioned processes originating from the beam; this would then become an additional outgassing source. As an example of vacuum firing in the RCS, the titanium beam pipes and bellows were heat treated at 750°C and 650°C, respectively, under high vacuum (below \( 10^{-3} \) Pa) to decrease the hydrogen content to less than 1 wt. ppm. This heat treatment was performed after surface polishing because hydrogen would reinvade metals during surface polishing.

4. Vacuum performance

Fast evacuation from atmospheric pressure to UHV is absolutely necessary after both scheduled and unscheduled accelerator maintenance to ensure a user’s experimental time. In the RCS, turbo molecular pumps are generally started after approximately 2 hours of rough pumping by the dry scroll pumps. Figure 5 shows the time dependence of the beam line pressure after starting the turbo molecular pumps. UHV below \( 10^{-5} \) Pa is achieved within a day except for the extraction section, where kicker magnets are installed. The outgassing reduction of the kicker magnets will be described in the following section. Figure 6 shows the pressure distribution with all magnets on and without a beam. Although the pressure in the kicker magnet area is higher than that in other areas, a pressure of the order of \( 10^{-6} \) Pa is achieved in all sections.

As described previously, the pressure increases during beam operation mainly because of ion stimulated molecule desorption. The total flux of desorbed gas per unit length during beam operation, \( Q \), is given by

\[
Q = \eta_{\text{ion}} \sigma \frac{I}{e} + Q_0,
\]

where \( \eta_{\text{ion}} \) is the molecular desorption yield, \( \sigma \) is the ionization cross-section of residual gas molecules, \( I \) is the pressure, \( I \) is the average beam current, \( e \) is the unit charge, and \( Q_0 \) is the thermal outgassing rate from the wall\textsuperscript{15). Considering the equilibrium condition, where the
desorbed gas is balanced with the evacuated gas, the pumping speed \( S \) is given by
\[
PS = \eta_{\text{ion}} \sigma P \frac{I}{e} + Q_0. \tag{2}
\]
Therefore
\[
P = \frac{Q_0}{S \left( 1 - \frac{\eta_{\text{ion}}}{S} \frac{I}{e} \right)} = \frac{Q}{S_{\text{eff}}}, \tag{3}
\]
where \( S_{\text{eff}} \) is the effective pumping speed. The pressure increases as the beam current increases if \( Q_0 \) and \( \eta_{\text{ion}} \) do not change. This phenomenon is shown in Fig. 7, where the short-term dependence of the pressure on the beam power was examined. On the other hand, the \( Q_0 \) and \( \eta_{\text{ion}} \) decrease during long-term operation, which is referred to as beam conditioning effect. Figure 8 shows the long-term beam conditioning effect.

5. Vacuum performance improvements

Figure 9 shows the history of beam power increases in the RCS. Responding to the problems, highlighted through the increased beam power and long-term operation of the vacuum system, upgrades of the vacuum system have been continuously performed. Next, a few examples of vacuum performance improvement are described.

**Pressure improvements to reduce beam losses**

The injection line called the L3BT line (Linac to 3 GeV synchrotron beam transport line), is a section where the beam line pressure notably caused beam losses. Figure 10 shows the layout of L3BT near the injection section of the RCS. H- ions from Linac are normally converted to protons (H+ ions) at the injection point. In this process, two electrons in H- ion are stripped, leaving only proton, by a thin carbon foil. However, H- ions were inconveniently stripped of one electrons, leaving unwanted H0 atoms, because of the interaction between H- ions and residual gas molecules in L3BT line. Such H0 atoms are not bent by injection bending magnets and directly hit the vacuum wall. The residual dose rate around the injection branch was higher than those at other points. To
improve vacuum in this beam line, turbo molecular pumps were additionally installed. Calculation results showed that by installing the two turbo molecular pumps, the average pressure in this area was reduced to $10^{-6}$ Pa, thus achieving a negligibly low charge exchange in this area. Figure 11 shows the measured results of vacuum improvements and beam loss reduction by the additional pumps. The pressure decreased from $10^{-5}$ Pa to $10^{-7}$ Pa near the pumps, and successful beam loss reduction was achieved via vacuum improvement.

**New in-situ degassing method for kicker magnets**

As described above, kicker magnets in vacuum are one of large outgassing components. The role of kicker magnets in the RCS is to extract an accelerated proton beam to a downstream beam transport line. Because 30 kV voltage is applied from the power supply to magnets to generate the necessary magnetic field, kicker magnets are installed in vacuum to prevent discharge. Kicker magnets mainly comprise Ni-Zn ferrites and aluminum alloys. Because of the large surface areas of these materials (more than 5 m$^2$ for ferrites and 35 m$^2$ for aluminum alloys per magnet), total outgassing in the kicker magnet area is larger than those in other areas within the RCS. The main outgassing component is adsorbed water molecules: these molecules were effectively removed by bake-out at temperatures higher than 100°C in vacuum. However, it is undesirable to heat an entire vacuum chamber because the thermal expansion of the chamber would lead to the breakage of, for example, the alumina ceramic pipes installed between the vacuum chamber and pumps for electrical insulation. Thermal expansion is of the order of a few millimeters because of the large chamber size. The problem of thermal expansion can be solved using a new in-situ baking method, which involves installing a heat source between the device and inner wall of the vacuum chamber and inserting several thermal radiation shield plates between the heat source.
and inner wall. In this configuration, most of the heat flux directs toward the kicker magnets while suppressing the heat flux to the vacuum chamber. Thus, the kicker magnets are baked out, limiting the temperature rise of the vacuum chamber\(^{17}\).

Figure 12 shows the experimental setup of the verification test using a prototype kicker magnet and the measured heater power dependence on temperature. The temperature of ferrite cores and aluminum plates exceeded \(120^\circ\text{C}\) for an input power higher than 800 W. The temperature rise of the vacuum chamber wall was maintained below \(30^\circ\text{C}\) over this input heater power range. Figure 13 shows the pressure during the heat-up test of prototype kicker magnet. The pressure decreased by one order of magnitude during 180 hours bake-out. The outgassing rate per unit area after bake-out was estimated to be \(3 \times 10^{-8} \text{ Pa m}^3/\text{s m}^2\). Based on these verification examinations, it is concluded that using the new bake-out method, the kicker magnets are heated to the target temperature with a small rise in the temperature of the vacuum chamber, effectively reducing the outgassing rate.

Graphite was selected as the heater material for practical use; thus, the heater size was sufficiently compact to be inserted via the existing unused port in the vacuum chamber. Figure 14 shows the outgassing rate of graphite used as the heater. The outgassing rate per unit area of graphite was reduced to less than \(1 \times 10^{-8} \text{ Pa m}^3/\text{s m}^2\) after bake-out. Considering the surface area of the graphite heater, the effect of outgassing from the heater on the beam line pressure was negligible.

A preliminary heat-up test was performed using one kicker magnet in the RCS beam line. The kicker magnet was heated while the temperature rise of the vacuum chamber was suppressed. The displacement of fragile parts owing to thermal expansion was negligibly small. By employing this in-situ degassing system to all kicker magnets, the beam line pressure in this section in the RCS beam line is expected to be improved.

**Beam orbit stabilization via high \(\mu\) beam pipes**

One of the main sources of beam loss in synchrotrons is beam orbit distortion caused by unwanted stray magnetic field from magnets at a nearby beam line. In the RCS, the beam orbit was distorted approximately 10 mm from the center of the beam pipes owing to the stray magnetic field (\(\sim 10^{-3} \text{ T}\)) from the magnet at the beam extraction line. The most effective method to shield such a magnetic field is to completely surround the beam region with a magnetic material. This led to the idea...
of manufacturing the vacuum chamber using magnetic materials. Therefore, we developed beam pipes and bellows made of soft magnetic materials, which have good magnetic shielding and vacuum performance18).

**Figure 15** shows the layout of the beam extraction section of the RCS. The beam orbit calculation shows that an amount of the external magnetic field is suppressed to one-tenth in the beam region. **Figure 16** shows the magnetic field calculated under the assumption that each component of the vacuum chambers comprises magnetic materials. It is found that all components, including bellows parts and flange parts as well as pipe parts, that are made of magnetic materials make the magnetic shielding

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**Fig. 15**  Schematic of RCS extraction beam line, where unwanted stray magnetic field from a magnet (B01 dipole magnet) in the extraction beam line leaks into synchrotron beam line.

**Fig. 16**  Magnetic field inside vacuum chamber calculated with assumption that each component of the chamber is a magnetic material. Most effective magnetic shielding is achieved when all components are made of magnetic materials.

**Fig. 17**  (a) Distribution of magnetic flux density inside beam pipe and bellows of soft magnetic materials. External magnetic field of $2.0 \times 10^{-3} \, \text{T}$ is severely shielded.
(b) Pressure when beam pipe of soft magnetic materials with a length of 1000 mm and diameter of 450 mm is pumped by 420 l/s turbo molecular pump. Ultra-high vacuum was easily achieved.

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more effective. For the magnetic materials, permalloy (Ni-Fe alloy) and ferritic stainless steel were selected for thin (pipes and bellows) and thick (flanges) parts, respectively.

Magnetic permeability generally decreases under the internal stress, which is caused by machining. Magnetic permeability can be recovered by annealing. On a separate note, the outgassing of vacuum materials is suppressed by bake-out at a high temperature under high vacuum, as previously described. We performed the heat treatment of the beam pipes and bellows under high vacuum to combine magnetic annealing and outgassing reduction.

**Figure 17** shows the magnetic shielding and vacuum performance. The averaged external magnetic field was successfully suppressed to less than one-tenth inside the beam pipe and bellows. The vacuum characteristics of soft magnetic materials were uncharted; it was found that UHV can be achieved using a vacuum chamber composed of soft magnetic materials.

**Figure 18** shows the measured closed orbit distortion (COD) around the RCS before and after installing the beam pipes and bellows that are made of magnetic materials. Using the beam pipes and bellows of soft magnetic materials, the COD is reduced by 91%. Corresponding to COD reduction, the beam survival ratio also successfully increased by several percent. The application of the beam pipes and bellows of magnetic materials with good magnetic shielding and vacuum performance ensured the beam orbit stabilization of the synchrotron. This is a good example of how the application of a new material to vacuum devices can lead to the improvement of beam characteristics in the synchrotron.

6. Summary

The J-PARC RCS vacuum system was described as a typical example of a vacuum system in a high-power proton accelerator. The RCS vacuum system was constructed according to the design concepts aiming the stable production of a proton beam with 1 MW power. Several examples of the developed vacuum devices such as turbo molecular pumps with radiation toughness, alumina ceramic beam pipes, and titanium beam pipes and bellows were introduced. Treatments such as surface polishing, coating, and vacuum firing to minimize both static and dynamic outgassing were performed. As a result, rapid evacuation from atmospheric pressure and the stable operation of the vacuum system were performed.

Responding to a beam power increase, upgrades have been continuously performed to achieve a better quality of vacuum and beam, e.g., beam loss reduction by the beam line pressure improvement, in-situ degassing of kicker magnets, and magnetic shielding by beam pipes and bellows.

Because vacuum is the environment surrounding the beam and the vacuum wall is the nearest material from the beam, almost all new phenomena in high-power proton accelerators relate to vacuum. Therefore, both cutting-edge and basic vacuum technologies are absolutely indispensable for latest high-power proton accelerators.

**References**

1) High-intensity Proton Accelerator Project Team: JAERI-Tech. 2003–044, KEK Report 2002–13 (2003).
2) N. Ogiwara: Proceedings of the IPAC2011, San Sebastian (2011) p. 971.
3) K. Wada, T. Inohara, M. Iguchi, N. Ogiwara, K. Mio and H. Nakayama: J. Vac. Soc. Jpn., 50 (2007) 452.
4) M. Kinsho, Y. Saito, Z. Kabeya and N. Ogiwara: Vacuum, 81 (2007) 808.
5) M. Lefrancois, J. Montuclard and C. Rouaud: Vacuum, 41 (1999) 1879.
6) K. Mio, N. Ogiwara, F. Furukori, H. Arai, D. Nishizawa, T. Nishidono and Y. Hikichi: JAE-A-Technology, 2009–018 (2009).
7) J. Kamiya, Y. Hikichi, M. Kinsho, N. Ogiwara, M. Fukuda, N. Hamatani, K. Hatanaka, K. Kamakura and K. Takahisa: J. Vac. Sci. Technol. A, 33 (2015) 01365.
8) H. Kurisu, K. Ishizawa, S. Yamamoto, M. Hesaka and Y. Saito: J. Phys. Conf. Ser., 100 (2008) 092002.
9) N. Ogiwara, J. Kamiya, Y. Shobuda, M. Kinsho and O. Koizumi: Proceedings of the IPAC2013, Shanghai (2013) p. 3321.
10) Y. Saito, M. Kinsho and Z. Kabeya: J. Phys. Conf. Ser., 100 (2008) 092020.
11) Z. Kabeya, M. Kinsho and Y. Saito: J. Vac. Soc. Jpn., 49 (2006) 343.
12) M. Kinsho, N. Ogiwara, K. Wada, M. Yoshida, T. Nakayasu and Y. Yamato: Vacuum, 74 (2004) 175.
13) K. Tajiri, Y. Saito, Y. Yamanaka and Z. Kabeya: J. Vac. Sci. Technol. A, 16 (1998) 1196.
14) R. Calder and G. Lewin: Brit. J. Appl. Phys., 18 (1967) 1459.
15) Vacuum technology, CERN accelerator school, ed. S. Turner, CERN99–05 (1999).
16) J. Kamiya, T. Takayanagi and M. Watanabe: Phys. Rev. ST Accel. Beams, 12 (2009) 072401.
17) J. Kamiya, N. Ogiwara, Y. Hikichi, T. Yanagibashi, M. Kinsho and Y. Yasuda: In situ J. Vac. Sci. Technol. A, 34 (2016) 021604.
18) J. Kamiya, N. Ogiwara, H. Hotchi, N. Hayashi and M. Kinsho: Nucl. Instrum. Methods A, 763 (2014) 329.