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Material and surface processing in J-PARC vacuum system

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A B S T R A C T

All systems comprising the Japan Proton Accelerator Research Complex (J-PARC), namely, the 400 MeV linac, 3-GeV rapid-cycling synchrotron, and 50-GeV synchrotron, were completed in 2009 and are now being used to supply high-power proton beams to secondary particle users. In order to minimize maintenance and shorten the pump-down and conditioning period, an ultra-high vacuum of 10^{-5} Pa or lower is required for the vacuum system. Here we present a review of the surface processing methods employed and the results of outgassing measurements for the components used in the vacuum system made from the following materials: electroformed copper, alumina ceramic, titanium, and stainless steel. The vacuum performance of these materials during accelerator operation is also reported.

1. Introduction

The Japan Proton Accelerator Research Complex (J-PARC) comprises a 400 MeV linac, a 3 GeV rapid-cycling synchrotron (RCS) and a 50 GeV synchrotron (Main Ring; MR). The purpose of this facility is to generate a high-power (1 MW) proton beam that can be used to drive the generation of secondary particles such as neutrons and neutrinos, which are widely useful in science and engineering. Beam commissioning of the linac started in 2008, and by December of that year, the RCS had provided a beam to secondary particle users. Neutrinos generated by the beam extracted from the MR were first detected in February 2010 at the Super Kamiokande. Because the accelerator facility will be subjected to high level of radiation as a consequence of the high-power operation, the vacuum system should be constructed using components that have high reliability and long lifetimes so as to minimize the maintenance work required. In addition, a fast pump-down sequence and short conditioning period are required. Maintaining the ultra-high-vacuum necessary requires choosing the correct materials and surface processing methods to minimize outgassing.

Fig. 1 shows a schematic view of the J-PARC, indicating the materials primarily used for each of the beam chambers: electroformed copper-linings in the linac cavities, TiN-coated alumina ceramic for the chambers in the RCS, pure titanium for the chambers in the beam-transports, and electro-polished stainless steel for the chambers in the MR. Details of the surface characteristics and vacuum performance for test tubes made of these materials are published elsewhere [1]. In this report, the surface processing methods and the results of outgassing measurements are reviewed for the beam chambers to be installed in the J-PARC. All outgassing results for the materials are obtained during pump down from atmospheric pressure at room temperature by a conductance-modulation method [2]. The chambers, packed with dry nitrogen or dry air in the manufactures, were exposed to the ambient air of the accelerator tunnel about 1 h for preparing measurement set-up; the relative humidity in the tunnel was kept at about 30%. The vacuum performance of the chambers during accelerator operation is also described.

2. Materials and surface finish

2.1. Electroformed copper lining

Because the rf cavity of the drift-tube linac (DTL), which has a diameter of 0.57 m and length of 9.9 m, is difficult to cast from

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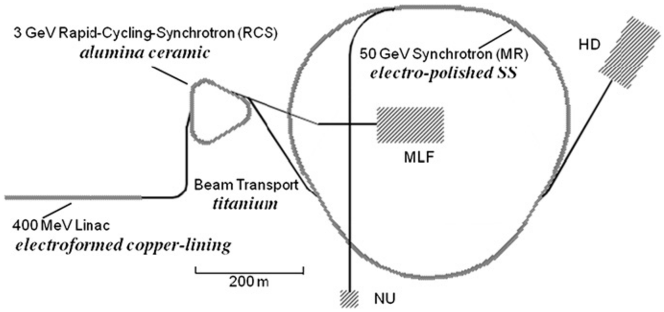

Fig. 1. Layout of the J-PARC and materials to be used for fabricating the cavity and the beam chambers. NU: neutrino to Super Kamiokande, HD: hadron experimental hall, and MLF: material and life science facility.

oxygen-free-copper (OFC), a copper-plated pure iron cavity was used (Fig. 2). The copper lining was formed by first nickel-strike plating the iron surface, followed by cyanide copper plating. A 1-mm-thick layer of copper was electroformed on this surface by using the periodic current-reversing (PR) method [3], which makes the copper grains small and uniform, without requiring the addition of a brightener, resulting in high electrical conductivity and machinability. The lining was then machined by diamond turning to a thickness of 0.5 mm. Surface finishing by electro-polishing was carried out in order to remove the degraded surface layer introduced during machining. Consequently, the average surface roughness was 0.4 μm.

The durability against electric breakdown in vacuum was examined using test electrodes processed by the above-described treatment [4]. The strength of the breakdown field for the first application of high voltage to the electrodes was 41 MV/m, which is higher than that for a conventionally deposited electrode (i.e., with a brightener). Because the operation field in the cavity is 3.5 MV/m or lower, a cavity surface having such a lining is expected to be stable. Fig. 3 shows the pressure distribution in the upper-stream half of the linac; all the cavities from D-1 to S15-B have electroformed copper linings. The distribution does not exhibit a significant increase when rf power is applied to the cavities. The trip rate due to electrical breakdown is, at present, less than once a day.

From Fig. 3, and taking into account the surface area and the effective pumping speed for each cavity, the outgassing rate of the lining surface is estimated to be 8×10^{-7} and 1×10^{-7} Pa m^3 s^{-1} m^{-2}, for D-1 and S15-B, respectively. The measured rate for a cavity by a built-up method was $6{-}8 \times 10^{-8}$ Pa m^3 s^{-1} m^{-2}, before installation. The higher pressures observed in the D-1, D-2, D-3 cavities are possibly due to the outgassing from the O-ring seals made of elastomer, which, in general, has an outgassing rate per unit area that is greater by an order of 3 or 4 than that of a clean metal surface; the total surface area of O-rings used in the D-1 cavity is 0.6 m^2, whereas the area of the cavity is 32 m^2.

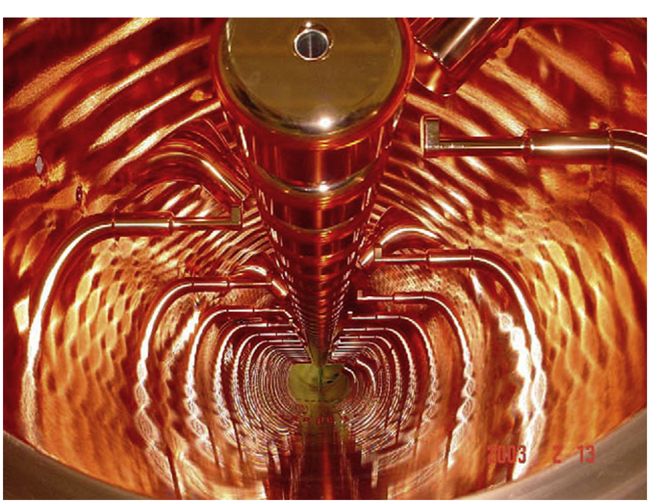

Fig. 2. Cavity of the drift-tube linac.

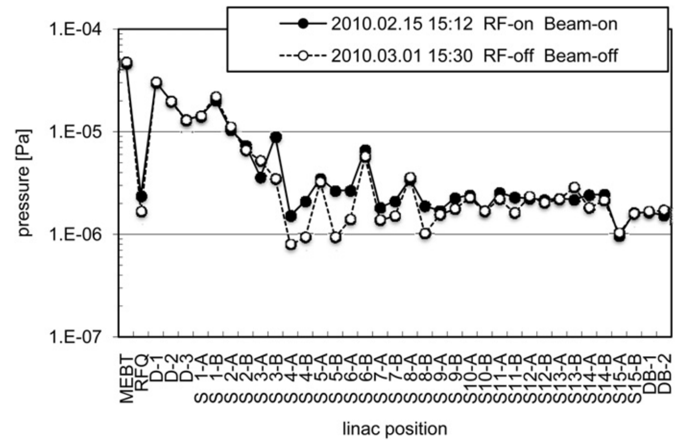

Fig. 3. Pressure distribution of the linac (right: downstream).

2.2. Alumina ceramic

In order to avoid any eddy current effect arising from the rapidly varying magnetic field (25 Hz) in the RCS, the beam chambers were made of an insulating material, namely, alumina ceramic. The total length of the ceramic chambers is about 200 m; the circumference of the RCS is 348.3 m. Fig. 4 shows a chamber of 3.54m in length, having a 15° bend and a racetrack cross-section of 246 × 188 mm, which is to be installed in the dipole magnet. All the ceramic chambers should have an rf shield for lowering impedance, a TiN coating for secondary electron emission suppression, and a non-magnetic metal flange in order to avoid disturbing the magnetic field, as well as adequate mechanical strength and a low outgassing rate.

The production process for the alumina ceramic chamber is as follows [5]:

1) sintering (1600 °C in air) a unit duct of length 0.15–0.8 m;
2) precise grinding of both extremities, cleaning by acid solution and annealing (1500 °C in air);
3) metalizing (1400 °C in wet hydrogen) a 7–10-μm-thick layer comprising Mo–Mn compounds;
4) electroplating a 2–5 μm-thick Ni layer on the metalized surface;
5) coating the inside of the duct with a 15-nm-thick TiN film (260 °C in vacuum);
6) brazing (830 °C in vacuum) between the unit ducts and also Ti sleeve to the duct by Cu–Au eutectic alloy, followed by welding a Ti flange; and
7) electroforming 1.5-mm-thick copper stripes (rf shield) outside the chamber.

Since an alumina ceramic is sintered at high temperature and, originally, a chemically stable oxide material, the surface is considered to have an adsorption energy for water molecules that is lower than that of metal surface. The chambers are, therefore, expected to have a low outgassing rate, if the chambers are handled