Aluminium ultrahigh vacuum system for the 3 GeV TPS synchrotron light source

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Abstract. The 3-GeV Taiwan Photon Source (TPS) is a large accelerator and synchrotron light source of circumference 518.4 m. The electron storage ring of TPS requires an ultrahigh-vacuum pressure per beam current less than 2×10^{-10} Pa/mA in the beam duct to maintain a long life of the circulating beam without scattering of ions by residual gases. Aluminium alloys used for the beam ducts have a benefit of greater thermal conductivity that simplifies the structure of vacuum vessels built with the cooling components. Machining completely free of oil applied to the aluminium chambers followed by cleaning with ozonized water and welding in house provide a precise dimensional control within 0.3 mm and a clean surface with a small rate ~ 6.4×10^{-12} Pa m/s of thermal outgassing after baking at 150 °C for 24 h. The assembled ion pump with non-evaporable getter pump is capable of evacuating the chamber to a pressure < 1×10^{-9} Pa. The average pressure inside the duct is expected to be sufficiently small. The clean process to manufacture the aluminium ultrahigh vacuum system is described.

1. Introduction

Designed as a third-generation synchrotron light source with electron-beam energy 3 GeV, beam current 400 mA in multi-bunch top-up operation mode, circumference 518.4 m, beam emittance < 2 nm·rad, Taiwan Photon Source (TPS) is under construction and will be installed in 2013. The vacuum system for the electron-storage ring of TPS provides an ultrahigh vacuum of highest quality with average pressure much less than 1×10^{-7} Pa throughout the beam duct to mitigate the effects of gas scattering of the stored electron beam [1]. As the aluminium ultra-high vacuum (UHV) systems for many accelerators have been operated successfully, and as manufacturing techniques for aluminium chambers have been established during the construction of the Taiwan Light Source (TLS) operated since 1993 [2], aluminium alloys were selected for TPS for the beam ducts of the electron-storage ring. For the 3-GeV TPS, the heat load from the synchrotron radiation and the rate of outgassing from photon-stimulated desorption are much greater than for the 1.5-GeV TLS. As the impedance budget for the beam ducts is more stringent, and as the dimensional control of vacuum components is more precise, new manufacturing techniques for the aluminium beam ducts must be developed to fulfill the requirements of the UHV systems for TPS rather than TLS [3]. The design of the aluminium vacuum systems for TPS complies with the following six strategies: (1) to accept the large heat load, the absorbers are located remotely from the radiation source; (2) the beam ducts are designed with inner apertures sufficient to accommodate the dimensions of the beam stay clear; (3) the UHV pumps are located near the gas sources or the absorbers; (4) the structures of vacuum components are modified to be smooth with small impedance; (5) to maintain the clean qualities of surfaces, manufacturing was developed completely free of oil, and (6) there is no baking in situ inside the tunnel. The design of the vacuum system, the manufacturing and the test results are described in the following sections.

2. Design of the vacuum system

The vacuum system for the electron-storage ring is divided into six-fold super-period systems; each comprises four long straight sections, with lengths one 12 m and three 7 m, and four arc-cell bending sections of lengths 13 ~ 14 m. All lattice magnets are gathered in the arc-cell bending sections that yield a limited space to accommodate vacuum chambers and components. Figure 1 illustrates the assembly drawing for a typical one-sextant vacuum system with magnets. The design of the vacuum chambers must hence utilize the entire space between the magnets to accommodate the beam-dynamic apertures and to allocate photon absorbers, beam-position monitors (BPM), vacuum pumps, bellows, flanges, gate valves and supports. Besides the constraint from limited space, the manufacturing tolerance for all components must be precisely controlled and the cleanliness of the surface must be maintained through all manufacturing. The concept of a large bending chamber made of aluminium alloys, with ease of machining capability and increased thermal conductivity, was adopted to optimize the design that fulfills the specified requirements [4]. The layout drawing of a typical vacuum system of a 14-m cell appears in figure 2. To mitigate the impedance and to save space from flanges and bellows, the vacuum chambers in the cell are welded to one piece of 14-m sector with only two bellows joined; two flanges and two sector gate valves (SGV) join both ends.

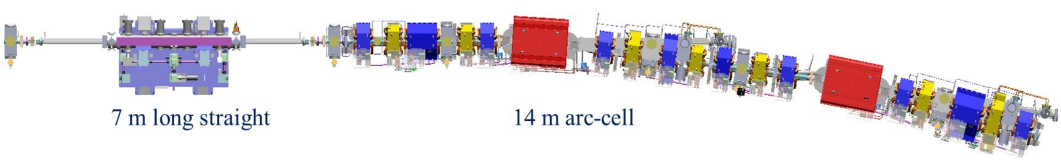


Figure 1. Assembly drawing for a typical sextant super-period vacuum system with magnets.

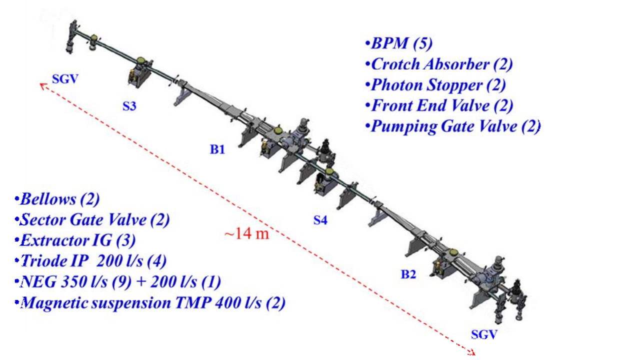


Figure 2. Layout drawing of a 14-m cell vacuum system. The beam ducts are composed of two straight chambers, S3 and S4, and two bending chambers, B1 and B2.

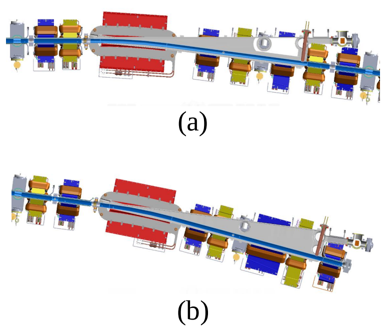


Figure 3. Section drawings inside bending chambers (a) B1 and (b) B2.

Several issues concerning the optimized design of the cell vacuum system are described as follows. The crotch absorber must be located at least 2.3 m from the source of synchrotron radiation emitted from the upstream bending magnet so that the water-cooled OFHC copper material is capable of accepting the thermal load [5]. With this design concept, the bending (B-) chamber has a triangular shape with length about 3 ~ 4 m. The crotch absorber installed downstream from the antechamber that produces molecules outgassing from photon-stimulated desorption (PSD) is confined locally to decrease the gases backfilling the beam channel. The surface of aluminium chambers is readily machined to an overall precision < 0.02 mm. Figure 3 shows section drawings inside the (a) B1- and (b) B2-bending chambers. The long channels (dark blue) represent the orbital channels for the electron beam. Two crotch absorbers and photon stoppers (orange) are located downstream of the B-chambers. The circles shown in the antechambers represent the pumping ports near the absorbers to enhance the localized-pumping efficiency. The back sides of the B-chambers are partially machined away to fit the chambers inside magnets with clearances about 1 ~ 3 mm from the magnetic poles or coils. The orbital channel made with precise machining in the aluminium B-chamber provides a finished smooth surface that minimizes the impedance.

As space between the chambers and magnets is tight, baking the cell vacuum systems in situ without conflicting with the magnets is impractical; all cell vacuum systems must therefore be baked ex situ in the laboratory to achieve an UHV without leakage before installation in the tunnel. Without baking in situ, the design of the vacuum cells can be simplified, which minimizes the quantity of bellows and flanges to mitigate the impedance, to avoid shifting of the BPM from thermal stress, to decrease the risks of leakage through the baking and to save significantly the long working hours in the tunnel for the baking. The cell vacuum systems will be transported from the laboratory to the tunnel and installed on the girders with a conveyance system [6].

The vacuum chambers in the long straight sections comprising pumping-port chambers, primary BPM ducts, bellows, taper chambers and drift chambers, will cooperate with the vacuum systems for insertion devices. All drift chambers will be made with aluminium extrusions. The long straight sections will be installed after positioning the two arc-cell vacuum systems on both ends. Baking in situ will be performed for the long straight sections after installation, which is easier than baking of the cells.

3. Manufacturing

3.1. Manufacturing of the aluminium vacuum chambers

The vacuum beam ducts for the 14-m arc-cell vacuum system are composed of two short straight (S-) chambers, S3 and S4, and two bending (B-) chambers, B1 and B2, as shown in figure 2. As the manufacturing of S-chambers differs from that of B-chambers, the four chambers must be manufactured individually and then welded to form a 14-m sector chamber. Figure 4 shows a design drawing of the four chambers to be prepared before welding. The manufacturing is described in the following subsections.

3.1.1. S-chamber. The S-chamber comprises the drift chamber, the pumping-port chamber, the BPM duct and flanges. All chambers are made of aluminium alloys for welding to one piece of the S-chamber. The straight aluminium tubes other than the BPM duct are made with extrusion. All aluminium extruded parts were cleaned with chemical solvents before welding in the clean room. The manufacturing of the S-chambers follows a procedure similar to that for TLS [7]. The aluminium extruded pipes were machined for pumping holes, cooling channel and welding edges. After the chemical cleaning, the pre-machined pumping port chamber will be inserted into the extruded pipe and welded together with a tungsten-inert-gas (TIG) method to form the drift straight chamber. The aluminium BPM duct is precisely machined with a machine free of oil similar to the manufacturing of the B-chamber to be mentioned in the next section. The drift chambers and the BPM duct will be aligned on pre-aligned supports and welded to the one piece S-chamber, S3 or S4, as shown in figure 4. Photographs of the welded S-chambers appear in figure 5(a).

3.1.2. B-chamber. The B-chambers are made on welding two halves of aluminium plate of length ~ 4 m. The aluminium plates are precisely machined with a machine under numerical control of a computer (CNC) and free of oil in a clean room (class 10000). The ambient temperature is controlled at 25±1 ^{o}C and the relative humidity at < 50 %. All machining tools must be cleaned with alcohol throughout the work. A system to spray pure alcohol (99.5 %) is developed to cool the aluminium working pieces during machining. A system for compressed air free of oil provides super-dry air to the spray system for spraying the alcohol on the working pieces with ultra-low moisture < 10 ppb. The machining of each aluminium plate is divided into three steps -- rough machining to intermediate machining to precise machining with intervening intervals 1 ~ 3 days for stress release. The overall deformation after machining is then controlled < 0.02 mm. Each aluminium plate will be stored in a clean aluminium bag filled with pure dry nitrogen gas and sealed.

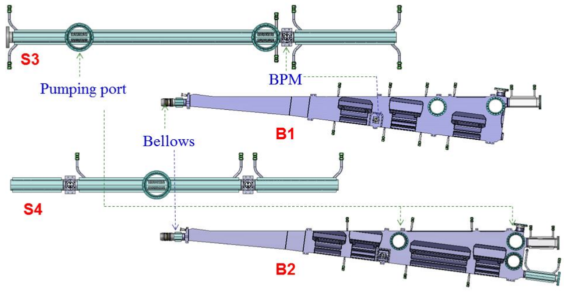


Figure 4. Design drawing of four chambers including two short straight (S-) chambers, S3 and S4, and two bending (B-) chambers, B1 and B2, to be welded to a 14-m sector of an arc-cell vacuum chamber.

Before the welding of a B-chamber, the two halves of machined plates are taken from the sealed dry bag and immersed in a clean vessel filled with the ozonized water (ozone concentration > 20 ppm) for 30 min, then dried with pure nitrogen gas spraying and promptly moved to the clean room. The machining in an environment of pure alcohol is similar to the former process for the aluminium B-chambers in TLS [2], but a recent investigation of cleaning, with ozonized water, of aluminium chambers machined free of oil provides a much smaller rate of thermal outgassing, ~ 6.4×10^{-12} Pa m/s after baking [8] and a smaller yield of photon-stimulated desorption ~ 2×10^{-5} molecules/photon [6] that is applicable for the TPS UHV system. As the cleanliness of the surfaces must be maintained and the rate of growth of oxidation on the aluminium surface must be suppressed throughout the welding process, all welding work must be done in the dry clean room (class 1000) controlled at temperature 25±1 ^{o}C and relative humidity < 50 %. The welding sequence consists of the welding of pumping port with flange, welding of half plate with pumping port, auto-welding of the B-chamber with two half plates, precise machining of the terminal ends of the side ports and welding of B-chamber with the side tube, flanges and bellows. The overall deformation of B-chambers after welding was < 0.1 mm vertical and < 0.3 mm transverse. Each step in the welding sequence must be inspected for leakage [6]. The B-chambers after welding will be promptly evacuated and sealed in vacuum. The photographs of the welded B-chambers and the welding work appear in figure 5(b) and 5(c), respectively.

3.2. Welding of the 14-m vacuum cell

Before joining the chambers, the supports for the chambers are installed on the girders and aligned to precision < 0.1 mm with a laser tracker. All major supports are made of thick aluminium plates. With a precisely machined base plane provided on the girders, the aluminium plates can be well positioned within 0.1 mm without adjustment mechanism. When those supports have been aligned and fixed on the girders, the B1 and B2 chambers are placed on the aluminium supports and fixed with the positioning guide pins near the BPM of B1 and B2 chambers, respectively. The S3 and S4 chambers are then placed on the supports. The four chambers are aligned with a laser tracker to precision < 0.1 mm, then fixed on the supports. As the surfaces of the aluminium chambers and aluminium supports near the adjacent interface are both precisely machined, the positioning of chambers on the pre-aligned supports can be done quickly without adjustment. After positioning the chambers, the TIG welding to join the four chambers to one sector is performed on site on the girders and then evacuated to test the leakage. With this efficient welding, a full cell of a 14-m vacuum chamber proved to be precisely aligned on the girders and leak-tight. The 14-m cell is then exposed to the atmosphere with pure nitrogen gas for the installation of vacuum components including ten BPM flanges, two sector-gate valves (SGV), two front-end valves (FEV), two pumping-gate valves (PGV), four ion pumps (IP), ten non-evaporable getter (NEG) pumps, three extractor ionization gauges (IG), four turbo-molecular pumps (TMP) etc., and evacuated for leak testing. Figure 6 presents photographs of the assembly works for the 14-m vacuum cell on the girders. After installation of two crotch absorbers and two photon stoppers, the vacuum system of the entire cell must be baked at 150 ^{o}C for 24 h to attain the required UHV pressure.

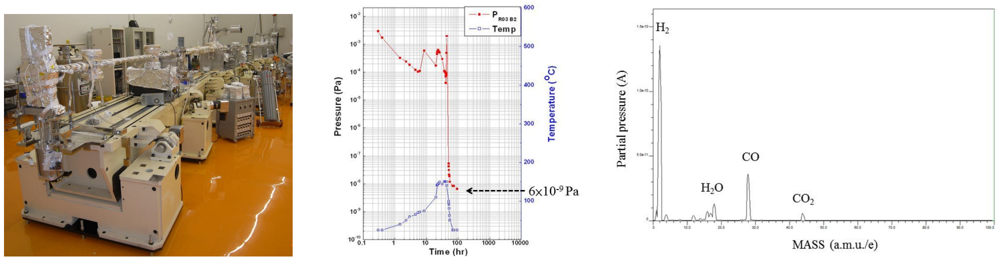
Figure 5. Photographs of (a) welded S-chambers, (b) welded B-chambers, and (c) welding works for the B-chamber.

Figure 6. Assembly work for the 14-m vacuum cell on the girders.

4. Test results

4.1. Baking test for a 14-m vacuum cell

The average pressure in the beam duct is determined by the rate of thermal outgassing of the aluminium vacuum chambers and the efficient pumping performance at UHV. The baking test for a 14-m cell vacuum system is performed on reaching 150 ^{o}C and kept for 24 h for inspection of the outgassing behavior. Before cooling, the IP will be switched on to refresh the cathodes with a high-temperature ion-sputtering effect, and the gauges degassed more than 20 min; all NEG pumps will then be simultaneously activated to 450 ^{o}C for 1 h when all IP must be turned off to avoid pumping contamination from the outgassing of NEG during activation. After the NEG activations the triode IP are switched on and maintained at a fixed mode of high voltage (-7 kV) applied for more efficient discharge-cleaning of the cathodes. The entire system is then cooled uniformly. All bolts and nuts of the flanges will be tested for torque and tightened as required at temperature ~ 60 ^{o}C during cooling. Figure 7 shows a photograph of one cell baking ex situ in the laboratory, the pumping curve through the baking and the mass spectrum after baking. The ultimate pressure after baking attained 6×10^{-9} Pa, indicated in figure 7(b). The major residual gases comprising H_2, CO, H_2O and CO_2 are shown in figure 7(c).

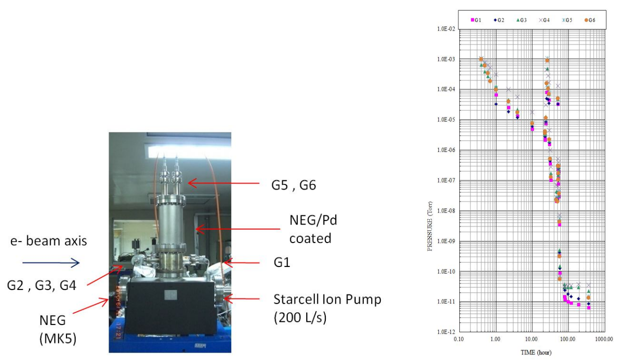


(a) (b) (c)

Figure 7. Baking ex situ of one cell in the laboratory: (a) preparation for baking, (b) pumping curve, (c) mass spectrum after baking.

4.2. Baking test for the IP and NEG pumping assembly

The combination of triode ion pump (IP) (200 L/s) and non-evaporable getter (NEG) pump (350 L/s) was designed to fit in the spaces between the magnets and located nearer the major outgassing sources from the photon absorbers to enhance the highly efficient pumping performance. An experimental system was set up, as shown in figure 8(a), for the UHV-pumping test. The ion pump was connected to the chamber at the bottom. Two side ports of the ion pump were mounted with the NEG pump and the roughing pump. To measure the pressure, an extractor ion gauge, labeled G1 in fig. 8, was installed in the chamber. Vacuum gauges G2 ~ G6 of other kinds were mounted near the chambers for comparison. The performance of pumping and the gauge measurements in the UHV were evaluated through the pumping and the baking. After evacuation of the system, baking for degassing and NEG activation, the ultimate pressure (G1) attained ~ 8×10^{-10} Pa (~ 6×10^{-12} Torr as shown in fig. 8(b)). The major residual gases comprised H_2, CO and CO_2. When the system was isolated from the turbo-molecular pump and the ion pump shut off, the pressure increased to ~ 4×10^{-9} Pa, about five times as great, with the pressure increasing from the residual outgassing of methane (CH_4). The NEG pump actively pumps all gases but noble gases such as CH_4. The pressure recovered to 8×10^{-10} Pa after switching on the IP to reveal the workable pumping at 10^{-10} Pa.



(a) (b)

Figure 8. (a) Experimental setup of vacuum chambers with ion pump, NEG pump, and gauges (G1 ~ G6); (b) Pumping curve.

5. Conclusion

The design concepts, manufacture and test results for the aluminium ultra-high vacuum system for the TPS synchrotron light source are described. CNC machining completely free of oil with a system to spray pure alcohol working for machining the aluminium B-chambers and BPM ducts in a dry clean room provides a precise control of dimension with tolerance < 0.02 mm and a clean surface. After the machining, the machined piece is promptly sealed in a clean aluminium bag filled with pure N_2 gas for storage. The aluminium parts are not removed until the welding process proceeds in the clean room. Cleaning with ozonized water applied for aluminium parts before welding provides a least rate of thermal outgassing, 6.4×10^{-12} Pa m/s. The aluminium chambers for the 14-m cell vacuum systems are welded on the pre-aligned girder supports in the clean room for stringent dimensional control and cleaning quality of the vacuum chambers. The overall tolerance for the deformation and the alignment for the 14-m vacuum chambers is controlled within 0.3 mm. All work for the welding in house and the vacuum assembly were performed in a clean room. The pumping test of an experimental system assembled with IP and NEG and a baking test for the 14-m vacuum cell have attained a pressure less than 6×10^{-9} Pa in UHV. The result proves that the design of the aluminium UHV system is acceptable for the TPS synchrotron light source.

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