T.2 Technological developments for the UHV system of Indus-2

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1. Introduction

Indus-2 is a 2.5 GeV energy electron storage ring built at our centre. It is divided into 8 unit cells. The vacuum envelope of this 172.278 m circumference storage ring consists of 16 bending magnet (BM) chambers, 46 straight section chambers, a septum magnet chamber, 4 kicker magnet chambers, 44 r.f. shielded bellows, 10 r.f contact UHV valves, 24 right angle UHV valves, 64 photo absorbers and 50 beam diagnostics components. 112 triode type sputter ion pumps (SIP), 128 titanium sublimation pumps (TSP) and 32 NEG pumps serve as the main pumps. 33 BAG's and 16 residual gas analysers (RGA) monitor the vacuum. 160 thermocouples are used to monitor temperature at important locations. Moveable turbo molecular pump stations fitted with pirani/penning gauges are used for sector-wise roughing and baking. Fig T.2.1. shows the a unit cell along with its vacuum components.

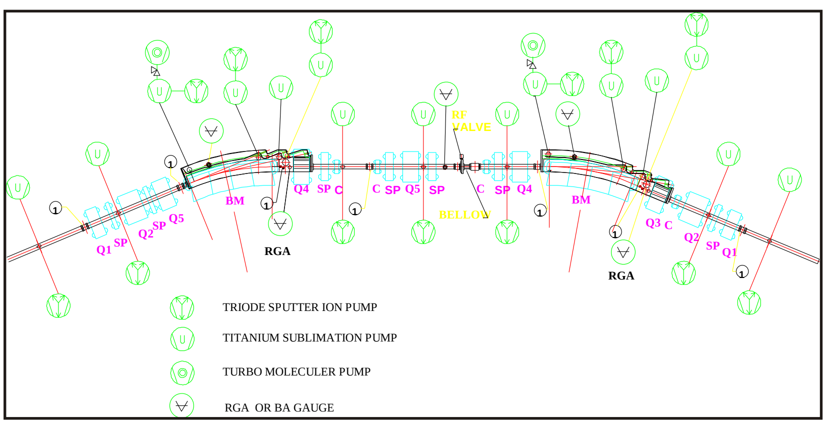

Fig T.2.1 Vacuum components in a unit cell of Indus-2

2. Selection of construction material

At 300mA the radiated power in Indus-2 is 187kW and most of the x-ray part of synchrotron radiation fan is concentrated into a 0.2mrad vertical angle. Only few % of this radiation is channelled into experimental beam lines and more than 85% has to be handled around the exit end of BM chambers. This high power can cause material damage to the chamber walls. Therefore, aluminium alloys, having high caloric tolerance and low susceptibility to chamber damage, were chosen as construction material for vacuum envelope. Besides extremely low outgassing rate, Al alloys also have high thermal conductivity, low thermal emissivity and easy bake-ability at 150°C, high resistance to nuclear radiation, low residual radioactivity and transparency to photons. They are completely non-magnetic, easy to fabricate with the possibility of extrusions in complicated profiles.

Dipole chambers were made out of 5083 H 321 rolled aluminium plates. It is free from residual stress associated with processes. Al flanges were made of AL 2219 T851, which is stronger and harder than the softer gasket materials. SS316L has good weld-ability, machine-ability, very low magnetic permeability and corrosion resistance. Al Helicoflex seals were used on demountable joints on bending magnets. The bolt holes on BM chambers were provided with Be-Cu inserts. Al diamond seals were used on Al-Al and Al-SS demountable joints along the beam path. To minimise impedance, silver plated Be-Cu, r.f contacts were used between flanges along beam path. Standard OFHC copper gaskets were used to connect pumps, valves, gauges etc.

3. Vacuum envelope

The cross section of the vacuum envelope was restricted by pole gap of magnets. Minimum requirement for aperture of vacuum envelope was 34mm (vertical) x 64mm (horizontal). Accordingly an elliptical cross section of 36mm X 86mm was adopted for beam path. This profile for beam path was kept same through out the accelerator. The BM chamber was extended laterally to have an antechamber. The aperture between beam chamber and antechamber was optimized to minimize the RF leakage. An antechamber type vacuum chamber improves longitudinal

Fig T.2.2 *Assembled BM chamber*

conductance; lowers its impedance; permits adsorption of photons away from the electron beam and close to discrete pumps installed under the photon absorbers. The BM chamber was extended to cover up to first quadrupole magnet down the beam path, in the straight section. Each BM chambers is 3.560m long and 635mm wide and 100mm high. Fig T.2.2 shows a BM chamber installed in dipole and quadrupole magnet.

4. Fabrication of BM chambers

A BM chamber is a complex mechanical component. BM chamber was made in two halves. The top and bottom plates were machined and welded in the midplane. The welding joints consisted of 2.5mm thick lips all along the midplane, with 5mm and 8mm width respectively in the two halves. A fillet was formed at the junction to fillet weld all along. A light finishing cut with sharp lapped tool enabled the tolerances to be met and a much finer finished surface was obtained. Machining of various ports and contours on both the top and bottom halves was carried out on CNC moving bridge vertical profiler using Uni-graphics CAM software. Hard foam jobs were cut on 1:1 size to check the accuracies, suitability of CNC program and dimensions of each half. Two negatives of each half chamber were generated for job stabilization on the machine. M/s. Hindustan Aeronautics Limited, Nasik, carried out these machining jobs.

All vacuum ports and flanges were final machined on AZ 11 CNC HB machine using single point tool with fly cutter to achieve high surface finish on all sealing surfaces. End cover plates were fabricated from the 36mm thickness plate of grade AA5083 H321 using CNC BMV-40 and UME-600 milling machines. The end cover plates have sizes 646 x 203 x 33mm and 416 x 203 x 33mm. They have 203mm diameter flanges with regular profile and one 152mm diameter flange with rectangular opening.

5. Fabrication of straight chambers

To accommodate straight section chambers in the apertures of the quadrupole, sextupole and corrector magnets, the extruded pipes were locally machined. Pipes having Al to SS transition joints, obtained by friction-welding technique, were welded. In order to get elliptical shape of size 802mm X 75.5mm, the end forming was carried at Al end of transition pipes. The technique involved chemical cleaning and heating of Al. pipes and subsequent forming of ends using die and punch. The end forming technique and fixture were developed in house. The machining was carried out at M/s. Hindustan Aeronautics Limited, Nasik. Fig T.2.3 shows the completed straight section chambers. Various types of aluminium alloy (AA 2219) flanges, suitable for helicoflex, diamond and wire seals, were machined for vacuum chambers at CAT.

Fig T.2.3 Short and long straight section chambers

6. Welding of aluminium chambers

The welding of Al chamber is difficult due to high thermal conductivity, Al oxide layer and hydrogen embrittlement caused by atmospheric moisture. The welding technique for Al was developed indigenously at CAT. The relative humidity was maintained <40% in the welding room. Just before welding, the jobs were chemically cleaned. Manual TIG welding using hard arc was adopted with welding current of 70 to 120A, background current of 35A, pulse frequency at 7Hz and pulse ratio at 80%. The flow rates of high purity (99.99% pure) argon gas were maintained at 8 l/m and 3 l/m for shielding and purging respectively. End part of the weld bead was overlapped by 25-30mm to avoid crater cracking. The exit port flanges and end flanges were welded in the final welding operation. 2mm diameter Filler wire ER 5183 was used in dipole chamber welding. Filler wire SFA 5.10 ER 4043 was used in welding of extruded section (AA 6063) with transition joint and extruded section with end flange (AA 2219).

7. Septum magnet chamber

Septum magnets have a cylindrical housing of f 450mm X 1558mm. The main shell was made of NB 450, 10 SCH, conforming to ASME SA 312 –TP 316L. It had 19 ports of sizes varying from f 35mm to f 152mm, at various angular and longitudinal positions on main shell. Fig T.2.4 shows the chamber without end blank flanges.

***Fig T.2.4** Injection septum chamber with septum magnets*

Critical design requirements included in vacuum radial movement of septum magnets from atmospheric side, fixed and floating saddle supports for taking care of thermal expansion during baking, r.f-shielding to reduce beam impedance, alignment and diagnostics features etc. To align magnets and to facilitate multidirectional rolling action with minimum friction, a base trolley with stainless steel spherical ball transfer units was provided. To provide movement to this trolley, diaphragm bellow sealed linear motion feed through of 25mm stroke length were installed. Machining of Septum chamber was done on high-speed precision lathe (NH-26x3000) using tailor-made HSS tools. Final boring of the ports was carried out by using high precision micro boring head. Al wire sealing, main flanges of f 580mm x 33.5 mm were machined on VTL (DynaCut-150) and Radial Drilling M/c (RM-65).

8. Gas load calculations

Gases evolved due to thermal out gassing from the surfaces exposed to vacuum and those desorbed due to synchrotron radiation in the BM chamber constitute main gas loads. The gas load due to photon induced desorption (PID), is given by,

$Q_{SR} \;=\; 2n^{o} h\,K$

where, the number of photons emitted per sec, n^{o} is given by

$n^{o} = 9.5 \times 10^{17}$ IE $[\,1 - (0.01/\,e_c)^{1/3}\,]$

Molecular desorption yield, h, is given by,

$h = 5 \times 10^{-6} \times D^{-1/2} = 5 \times 10^{-6}$ moles/photon, after 25A.Hrs.

$K = 4.16 \times 10^{-20}$ mbar-l/molecule.

I = beam current in mA= 300

E = beam energy in GeV = 2.5

D = accumulated beam dose in ampere-hours

e_c = Critical energy of photons = $2.218\ E^3/r$ = 6.244KeV, for Indus-2.

r = Bending radius = 5.555m.

Hence, $n^{o} = 6.3 \times 10^{20}$ photons/sec &

$Q_{SR} = 5.24 \times 10^{-5}$ mbar-l/sec.

Thermal outgassing, $Q_{th} = A \times q = 0.88 \times 10^{-5}$ mbar-l/sec

where, $A = 4.4\ X10^{6}\,cm^{2}$

q = Sp. thermal outgassing rate = $2\ X\ 10^{-12}$ mbar-l/sec/ cm^2.

Total gas load = $Q_{total} = Q_{SR} + Q_{Th} = 6.1 \times 10^{-5}$ mbar-l/sec

Therefore, an effective pumping speed more than 60000 l/s is required to attain operational vacuum of $1X10^{-9}$ mbar.

9. Computer Simulations

Computer simulations were carried out for a unit cell of Indus-2, by using electrical equivalent of vacuum system. Whole of unit cell was divided into 672 elements. The pressure profile shown in fig-T.2.5 indicated that base vacuum in 10^{-10} mbar range can be obtained. Computer simulations were also done to simulate dynamic PID gas load and for cleaning effect of circulating beam. Results are plotted in fig T.2.6, for 300mA stored current circulating up to 5000Hrs. This indicates that after 150AHr the specified vacuum of 10^{-9} mbar with beam might be obtained. However, this dose may reduce substantially because of almost permanent cleaning effect of GDC, as the initial ESD yield should reduce to 10^{-3} mole/photon, after GDC.

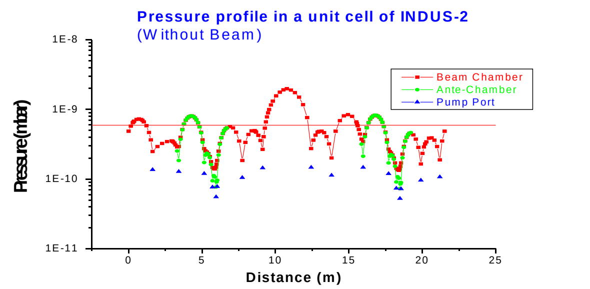

Fig T.2.5 *Pressure profile in a unit cell without beam*

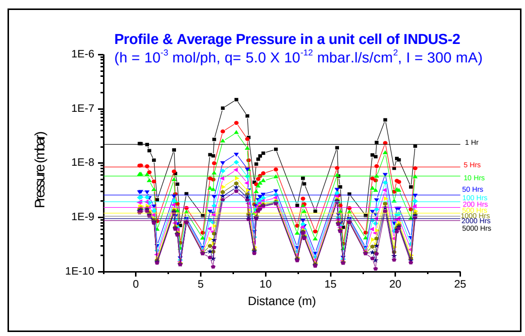

Fig T.2.6 *Average pressure with varying beam dose*

10. Photon absorbers

64 water-cooled photon absorbers dissipate 158 kW of SR power, which makes them a critical component in Indus-2. Besides UHV compatibility, absence of water to vacuum joints, rectangular finned type water channels for enhanced heat transfer and vacuum brazed joints were its salient features. It was a heterogeneous structure of OFHC copper and stainless steel. The wedge shaped profile for grazing incidence of photons reduces power density from 10 - 12kW/cm^2 to 0.8 to 1.0kW/cm^2. It also directs PID gas load towards SIPs installed below them. To get the temperature profile during operation, finite element analysis was done. Maximum localized temperature at hot spot, where photons are directly incident was calculated to be 130°C while the maximum temperature on the cooling side was 80°C.

Two-stage vacuum furnace brazing was used to get bright, oxide free, degassed & UHV compatible leak tight assemblies. To get successful brazing, 20-micron thick copper layer was coated on brazing surface of SS pipes and the parts were chemically cleaned. To check the distortion in components due to residual stresses & appearance of blisters etc in the Cu coating of SS parts, vacuum annealing was carried out at 600ºC in vacuum furnace at $5X10^{-5}$ mbar for a soaking time of 30 minutes. After vacuum annealing, components were cleaned in Acetone, filler materials were placed properly & assembly was mounted on graphite fixture. In first stage of brazing, subassemblies of SS flange to cover & lid to main body was done at 840 ºC using Ag72-Cu28 alloy as filler material. Natural cooling was done inside the furnace. In second stage of brazing, final joint between cover and lid was done at 740ºC using Ag61.5-Cu24-In14.5 (InCuSil) alloy as filler material Since the photon absorbers were sensitive components, strict quality assurance was done by ultrasonic testing of material, inspection of profile on CMM after machining , leak checking after both stages of brazing etc.

All the absorbers were tested for ultimate vacuum without SR beam. After 8 hour baking at 150 °C ultimate vacuum achieved is ~ $2X10^{-10}$mbar with the help of a 270 l/s SIP. The residual gas components were also measured after the bake out & the most abundant gas component was H_2. Other main gases were CH_4, CO and CO_2. Power testing was done by using a strip type electron beam gun with E=60keV and I=100mA. E-beam irradiated an area of 5mm X 151mm on the central surface of the crotch.

11. End flanges

48 water-cooled end flanges were installed on BM chambers to dissipate SR power. 30kW of power is channelled onto these flanges, with SR power density 1.2kW/cm^2. These are heterogeneous compact structure of OFHC copper central portion & stainless steel flange on outer portion. Salient features include absence of water to vacuum joints; vacuum brazed joints; rectangular finned type water channels for enhanced heat transfer; inclined face for incident photons to substantially reduce heat flux density. Machining operations for profiles on OFHC, flanges etc, were similar to those carried out on photon absorbers. Inspection, cleaning procedure and vacuum brazing were also similar to those of photon absorbers except that the entire assembly was brazed in single stage. Ag72-Cu28 alloy was used as filler material for vacuum brazing at 920 ºC. All the end flanges were subjected to He leak testing <$2X10^{-10}$std.cc/s. and ultimate vacuum testing <$1X10^{-9}$mbar.

12. RF shielded bellows

RF shielded bellows were developed to take care of thermal expansion during bake-out and the fabrication/alignment tolerances of chambers. The RF-shield is a flexible mechanical structure that screens corrugations of bellows from bunched beams and allows smooth flow of wall current and reduces excitation of higher order modes (HOM). A typical 150mm long bellow assembly was designed to absorb an axial stroke of 20mm compression, 10mm expansion, transverse offset of 1mm & 15mrad of angular misalignment. The photograph of a typical bellow assembly developed for Indus-2 is shown in fig T.2.7.

Fig T.2.7 *RF-shielded bellow assembly*

The main components of the RF-shield sub-assembly were contact finger, cantilever spring finger & inner tube. The step size was also driven by two features viz. mechanical stability of the inner tube wall and the rounded contact surface at the tip. Rounded tip ensured that the shield finger did not make a secondary contact on the inner tube. Contact force and finger slit size were the two important parameters of the finger type RF-shield. Lower contact force leads to heating & arcing at the contact points, whereas, larger contact force gives rise to intense abrasion leading to dust trapping problem. Contact force ~100 g/finger was used for the design. The contact finger is 0.3 mm thick & has a width of 4.9 mm & gap of 0.5 mm. The thickness of the contact finger is chosen such that the finger did not kink (buckle) throughout the stroke.

Fingers were fabricated from beryllium-copper (C17200)–¼ Hard sheet metal with tensile strength ~ 550 MPa. After heat treatment, this alloy retains elasticity up to about 200°C and also has relatively good thermal and electrical conductivity (about ¼ th of copper). However, Be-Cu being highly toxic material required proper exhaust system during production. Various stages of fabrication include EDM wire cutting to get burr free profile of fingers, press forming by die and punch operation on hydraulic press and precipitation heat treatment at 315°C for 90 minutes in vacuum to get clean, degassed and scale free components. To avoid intense abrasion silver coating was done on Be-Cu contact finger, rhodium coating on SS inner tube while the Be- Cu spring finger was kept uncoated. Static inner flange was subjected to silver coating.

13. Production of sputter ion pumps and titanium sublimation pumps

All the sputter ion pumps (SIP), titanium sublimation pumps (TSP) were produced in house. In all 250 SIP of 35l/s, 140 l/s, 270 l/s were fabricated, cleaned and tested for their ultimate vacuum performance in the range of 10^{-10} mbar. 150 TSP 's were also fabricated and tested. SIP of 1000 l/s was specifically developed for pumping of gas load in septum magnet chamber, as the septum magnet cores are made from 0.3 mm laminations and have very large surface area.

14. Cleaning procedures and surface treatment

Surfaces exposed to vacuum play dominant role in achieving UHV. Thick and porous oxide films formed on aluminium during fabrication stages It was necessary to remove this thick oxide film by chemical cleaning. To suit the requirement of welding and UHV compatibility of AL6063, 2219 flanges chemical cleaning processes were developed. Cleaning process employed were:

(a) Ultrasonic cleaning and vapour degreasing in trichloroethylene.

(b) Strong etching in NaOH and washing with water.

(c) Cleaning in nitric acid, washing with cold and hot demineralised water and dried.

Necessary infrastructure was developed for cleaning, rinsing and pressure washing by jet spray, as the job sizes were very large.

In order to reduce initial PID yield, experiments were conducted to fix GDC dose. GDC was done in an atmosphere of Ar / 10% O_2 at 10^{-2} mbar. To get adequate cleaning, the ion dose was optimised by measuring ESD yield and the carbon peak in RGA spectra. It was found that at a dose of 10^{19} ions/cm^2 the carbon peak gets stabilized ESD yield in the range of 10^{-3} mole/electron was achieved. All the Al chambers were subjected to this GDC treatment.

15. Vacuum instrumentation

All the SIP controllers and BAG controllers, used in Indus-2 were developed indigenously.

TSP controllers power two pumps in a sequential manner. The idle time between these pulses may be varied from 1 – 999 minutes. The supply was designed to deliver a maximum 300watt power to filaments. Apart from the pulse mode operation, power supply can be operated for degassing the titanium filaments of the two pumps simultaneously.

An intelligent, distributed microcontroller based system was developed. Each module unit (TCU) had provision for 8 channels. TCU was capable of monitoring as well as controlling the temperature. 16 modules in multidrop mode can be connected and effectively 128 channels can be controlled, using three wires. Graphical user interfacing software was developed using Visual Basic. Isolated RS485-RS232 converter was developed for giving interface to PC.

In Indus-2, temperature of 148 channels will be monitored at vital locations like photon absorbers, end flanges and chamber walls etc. Temperature monitoring units (TMU) were developed. In all 160 channels may be monitored by using 20 TMU's. Each TMU was having a TRIP Relay.

During baking as well as after completing the baking, Penning and BA gauges are used to monitor pressure in the system. Each PMU can monitor pressure of 8 channels and support RS485 communication.

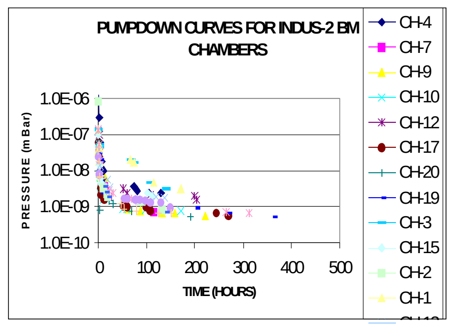

Fig T.2.8 Pump down curves for BM chambers

The pump down curves for BM chambers is shown in fig T.2.8 during testing in the laboratory. The chambers were subjected to 48 hrs of baking at 150 °C. During first baking approx 30% chamber had leaks in welding. However, during second baking, the failure rate was less than 5%. The pump down curves also indicated that within 100hrs most of the chambers attained vacuum less than 2x10^{-9}mbar. The baking of chambers after GDC, resulted in ultimate vacuum in 10^{-10} mbar range for most of the chambers. These extensive testing exercises gave confidence that the specified vacuum conditions will be attained in Indus-2.

16. Conclusion

The UHV system for Indus-2 is in final stage of installation and the pump down results for chambers indicate that the design goals would be achieved without much problem. However, it is to be stressed that during whole of this development, the strict compliance of quality control during fabrication, cleaning, installation and subsequent testing was adhered to. The components were doubly checked for their performance.