Development of UHV systems at UHVTD, RRCAT Indore

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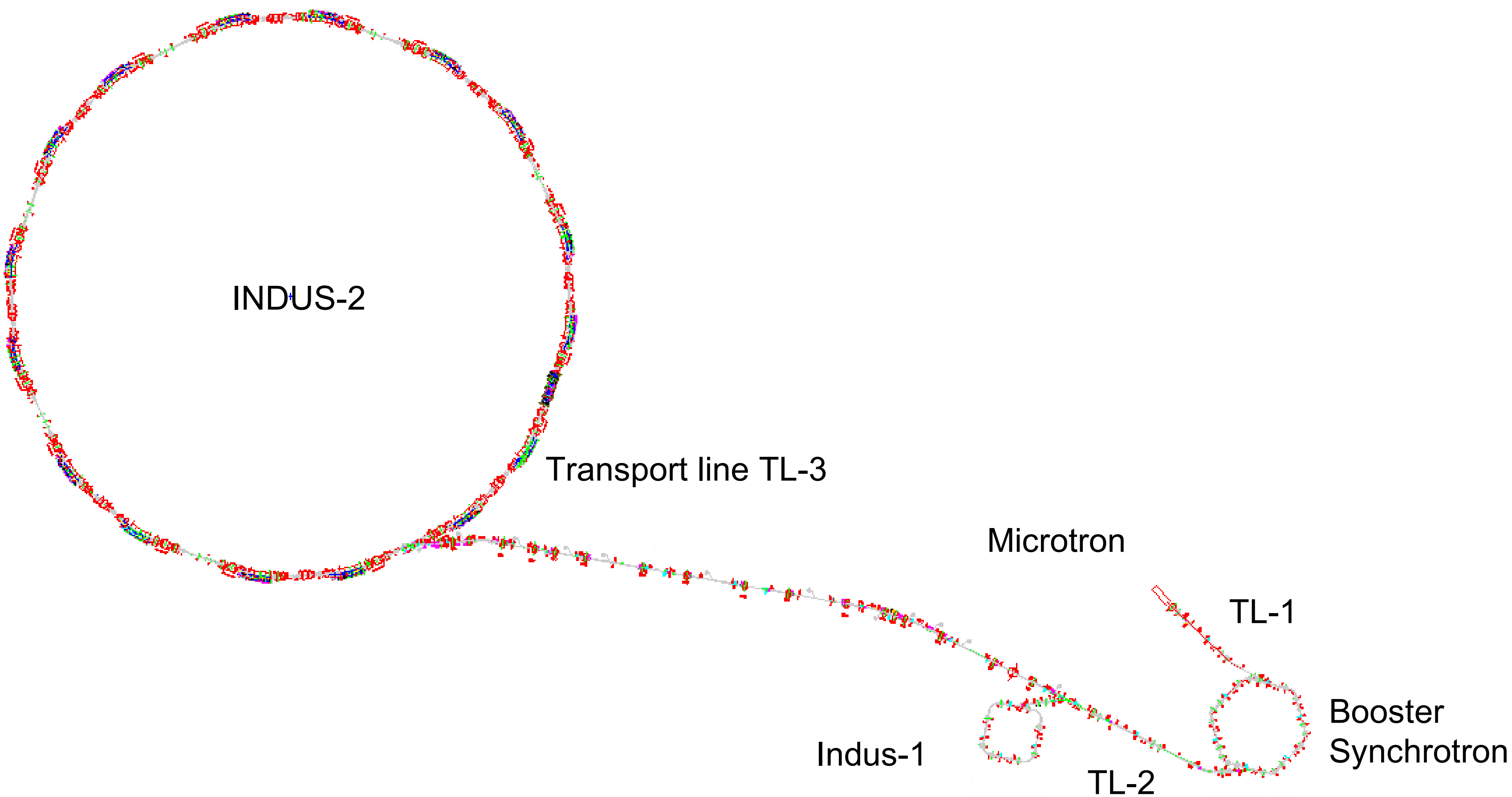
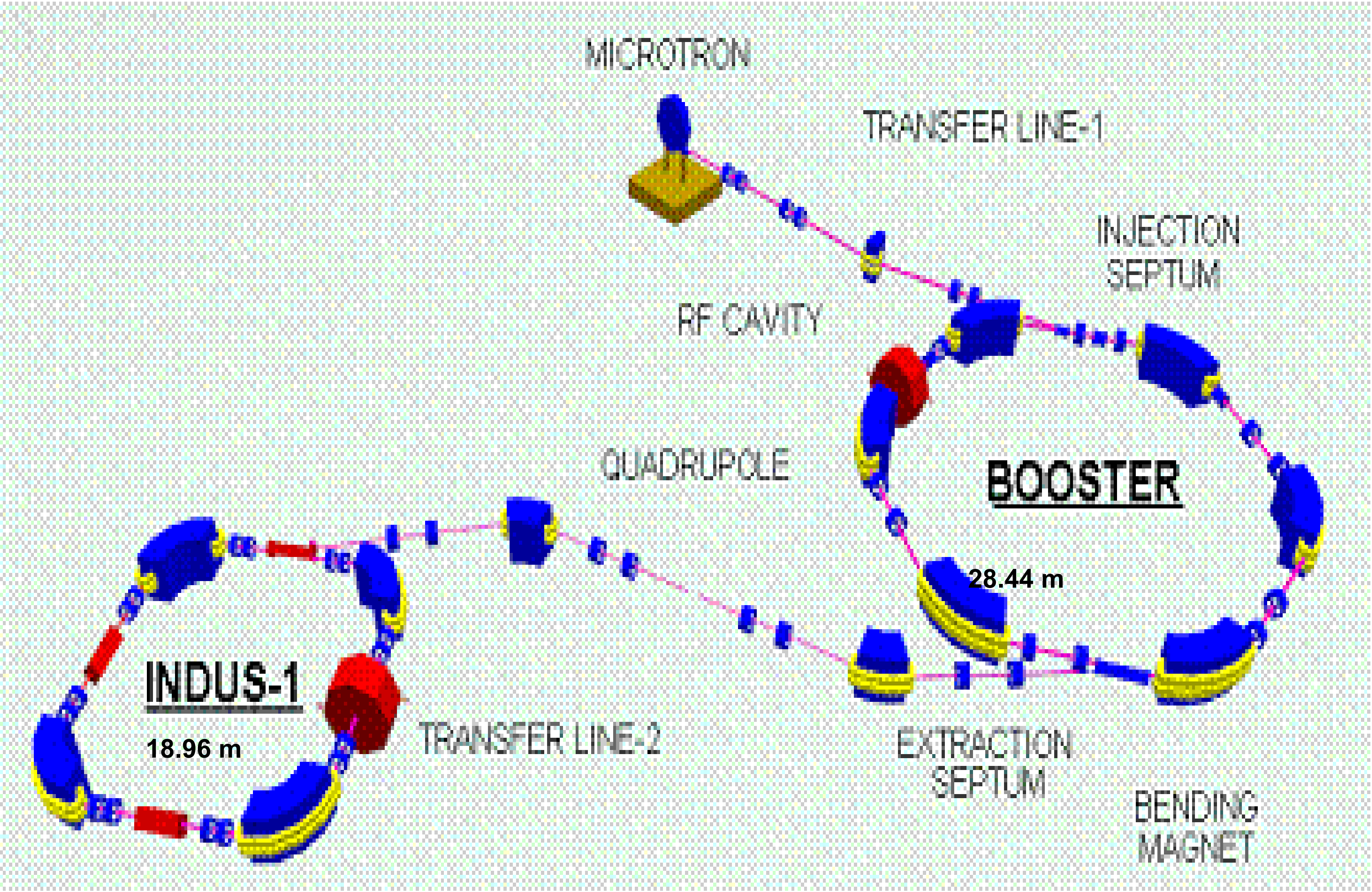
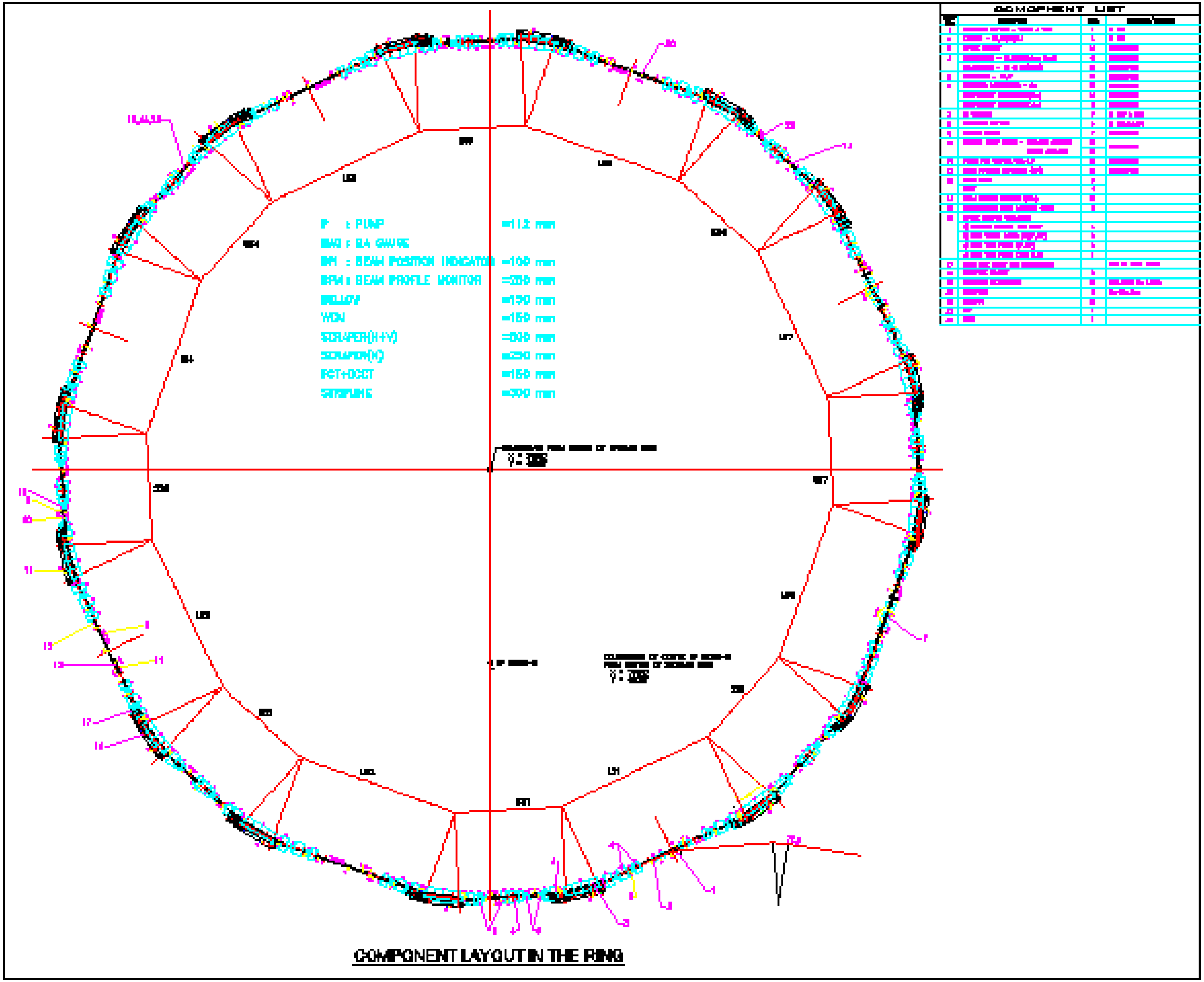
Layout of Accelerators in Indus complex at RRCAT, Indore

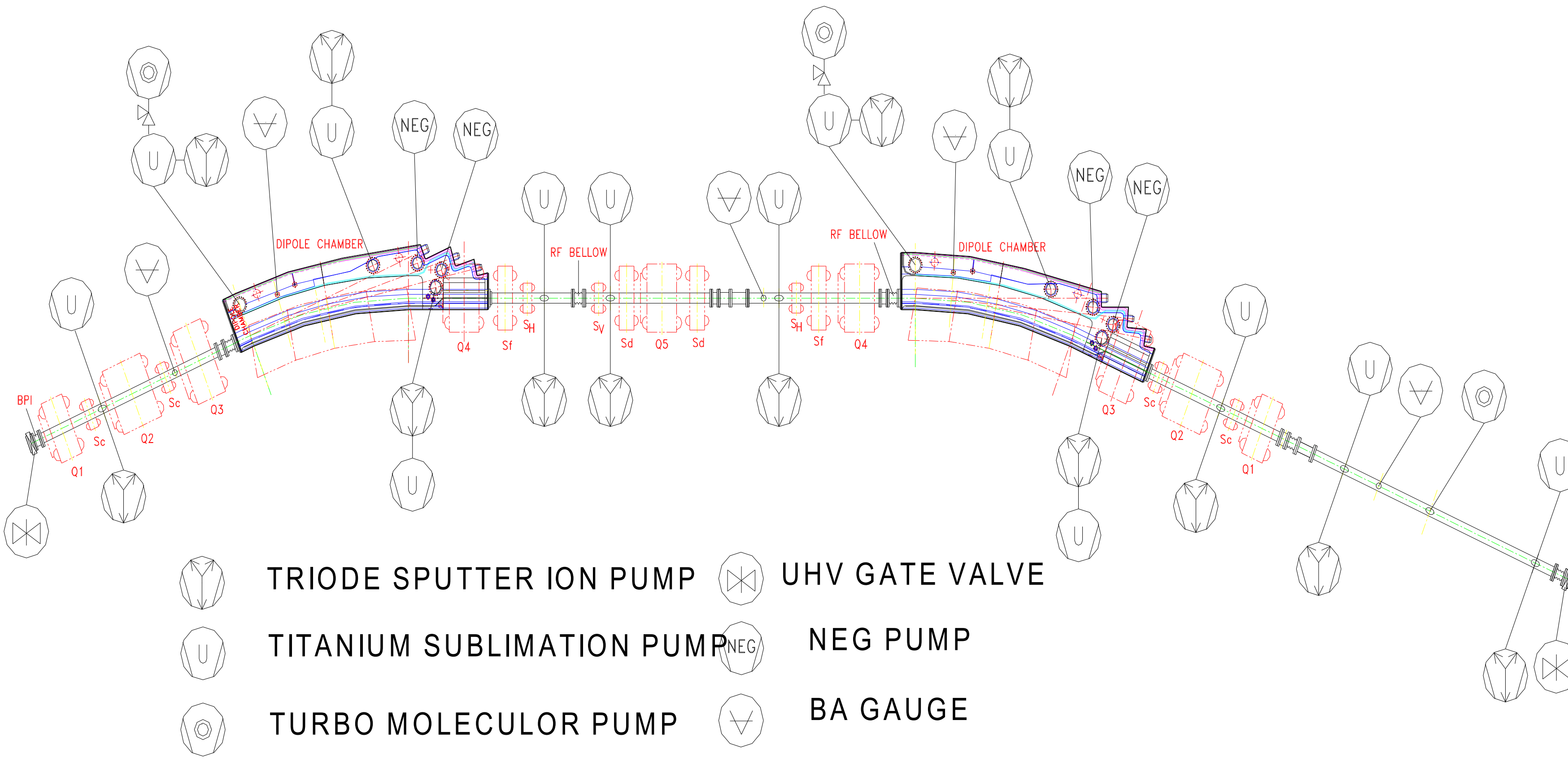


Layout of SR Source Indus-1




COMPONENT LIST
PUMP
BEAM POSITION INDICATOR
BEAM PROFILE MONITOR
COMPONENT LAYOUT IN THE RING

Vacuum components in a unit cell of Indus-2.



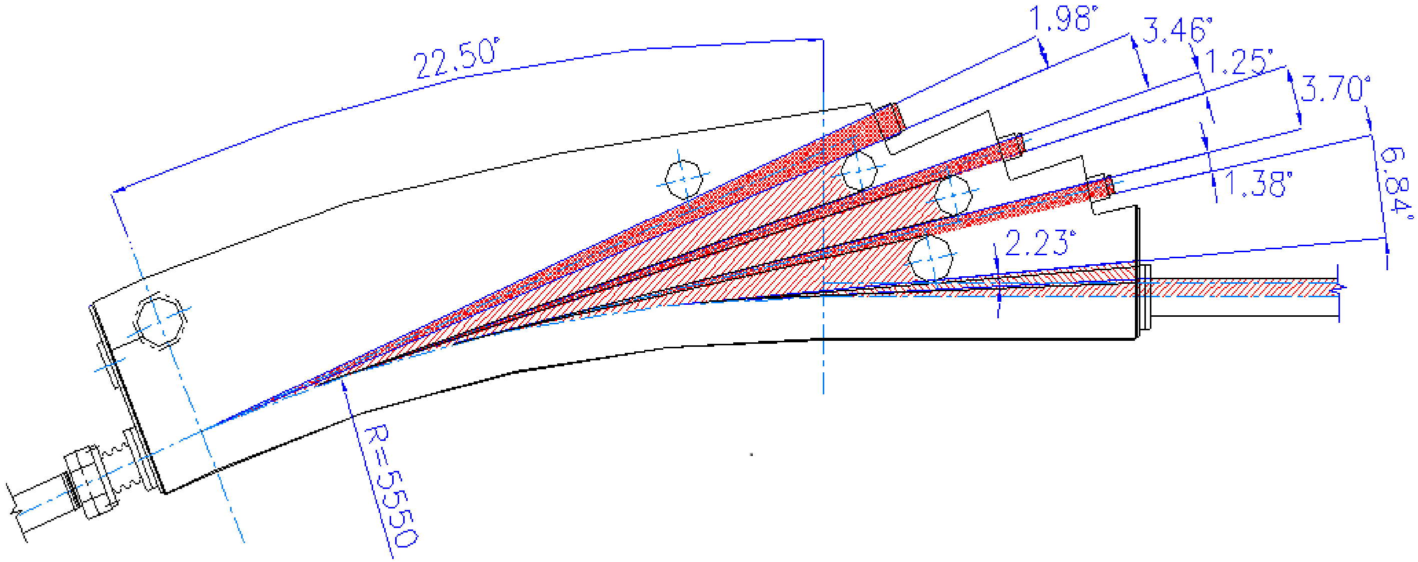
Accelerator – a testing ground for UHV equipment

- **Large quantity of Equipment**.
- **Duration Of continuous Operation** – Many years, preferably without interventions.
- **An extremely high duty factor** – nearly 100%.
- **A very high degree of reliability of Equipment -** Much superior to what is used in other fields of vacuum applications.
- **An unavoidable opening** implies minimum 5 days of loss of machine operation, as the repaired sector must be rebaked and/or reconditioned for 50 to 100 hrs.

Salient features of Indus-2 UHV System

- **Circumference** - **172.3 m**
- **Ultimate vacuum** :- 10^{-10} mbar (w/o beam), $1X10^{-9}$ mbar (with beam)
- **Highly intense Synchrotron radiation** – 187 kW Power & Large PID
- **Same aperture through out the accelerator** to reduce HOM losses. Smooth walls to reduce impedance (implying screened bellows, pumping and gauge ports).
- **Integrated ante chamber in the dipole sections** to facilitate the installation of photon absorbers and vacuum pumps away from electron beam chamber.
- **Aluminium alloy vacuum chambers**
- **Use of Photon absorbers to absorb most of the unused radiation**
- **Indigenously developed R.F Shielded bellows** - To take care of thermal expansion during bake-out and the fabrication / alignment tolerances of chambers.
- **Water cooled End flanges**: To dissipate 30 kW of power channeled onto these flanges, with SR power density 1.2 kW/cm^2.
- **Use of SIP's and the TSP's produced in-house**
- **Glow discharge cleaning (GDC) of all the Aluminum Chambers**
- **Development of indigenous Vacuum Instrumentation**

Distribution of SR power from Bending Magnets



TOTAL RADIATION POWER	= 11.70 KW PER BENDING MAGNET
POWER ABSORBED BY WATER COOLED PHOTON ABSORBERS	= 62.22%
POWER ABSORBED BY BENDING MAGNET CHAMBER (END)	= 10.00% (COOLING PROVIDED)
POWER ABSORBED BY STRAIGHT SECTION CHAMBER	= 2.78%
POWER ABSORBED BY NEXT BENDING MAGNET CHAMBER	= 1.60%
POWER TRANSMITTED TO 5° AND 10° BEAM LINES	= 11.70%

List of Vacuum components in Indus-2

Bending Magnet chambers	16
Straight Section chambers	46
Septum magnet chamber	1
Kicker chambers	4
R.f shielded bellows	44
R.f contact UHV valves	10
Right angle UHV valves	18
Photon absorbers	64
Beam diagnostics components	77
Triode type sputter ion pumps	96
Titanium sublimation pumps	98
NEG pumps	32
BA Gauges	45
Residual Gas Analyzers	12
Thermocouples to monitor temperature	160
Moveable TMP stations fitted with pirani/penning gauges	4

Gas load calculations

- $Q_{total} = Q_{SR} + Q_{Th}$.
- Gas load due to Synchrotron radiation is given by, $$Q_{SR} = 2.n^o.\eta.K$$

Where, No. of photons emitted per sec.= $$n^o = 9.5.x10^{17}.I.E.\left[1-\left(0.01/\varepsilon_c\right)^{1/3}\right]$$

Molecular desorption yield, η=5 x 10^{-6} x$D^{-1/2}$ = 1x10^{-6} Molecule/photon

K = 4.16 x 10^{-20} mbar-l/molecule, I = 300mA, E = 2.5 GeV.

Critical energy, $$\varepsilon_c(keV) = \frac{2.2.E^3(GeV)}{\rho(m)}$$ = 6.244 keV for Indus-2.

- Q_{SR} = 5.24 x 10^{-5} mbar-l/sec and Q_{th} = 0.88 x 10^{-6} mbar-l/sec.
- Area, A = 4.4 X10^{6} cm^2 and q =2 X 10^{-12} mbar-l/sec/ cm^2.
- Thus, Q_{Total} = 6.1 x 10^{-5} mbar-l/sec and to attain operational vacuum of 1X10^{-9} mbar, an effective pumping speed more than 60000 l/s is required.
- However, the installed capacity needs to be much larger due to conductance limitations.

Construction materials

Dipole chambers - 5083 H 321 as per ASTM B 209M rolled aluminum plates. a solid solution alloy and non-heat treatable. Hence, free from residual stress associated with processes.

Composition :- 0.4 % Si, 0.4 % Fe, 0.1% Cu, 0.4 - 1.0 % Mn, 4.0 - 4.9 % Mg, 0.05 - 0.25 % Cr, 0.25% Zn, 0.15% Ti, 0.15% others and the remainder Al.

Temper :- H321, Strengthened by strain hardening and stabilised.

Mechanical properties :- Excellent resistance to corrosion, Excellent weld-ability and good machine-ability.

Extruded chambers - 6063 T6 - good extrudability and welding properties.

Composition :- 0.2 - 0.6% Si, 0.35% Fe, 0.1% Cu, 0.1% Mn, 0.45 - 0.9 % Mg, 0.1% Cr, 0.1% Zn, 0.1% Ti, 0.15% others and the remainder Al.

Temper :-T6, Thermally treated to produce stable tempers. Solution heat treated and artificially aged.

Mechanical properties :- Excellent resistance to corrosion, Excellent weldability and good machinability. Suited for extrusion.

Al flanges - AL 2219 T851 - stronger and harder than the softer gasket materials.

Composition :- 0.2% Si, 0.3% Fe, 5.8 - 6.8% Cu, 0.2 - 0.4% Mn, 0.02% Zn, 0.02% Mg, 0.02 - 0.1% Ti, 0.15% others and the remainder Al.

Temper :-T851. Thermally treated to produce stable tempers.

Available in rolled form. Comparable to T-852, which is forged but costlier by three times.

Mechanical properties :- Very good machinability, Excellent weldability. It has highest strength of all Aluminium alloys at 150^{0}C.

Injection septum chamber, pump bodies, valves etc - AISI 316L - good weld-ability, machine-ability, very low magnetic permeability and corrosion resistance.

Advantages of Al alloy chambers

- Extremely low thermal outgassing rate
- High thermal conductivity, low thermal emissivity and easy bake-ability at 150^{0}C
- Aluminium alloys have tolerable caloric deposition and lesser susceptibility to chamber damage
- High resistance to nuclear radiation, low residual radioactivity and transparency to photons (so no melt down effect).
- Completely non-magnetic
- Easy to fabricate with possibility of extrusions in complicated profiles.

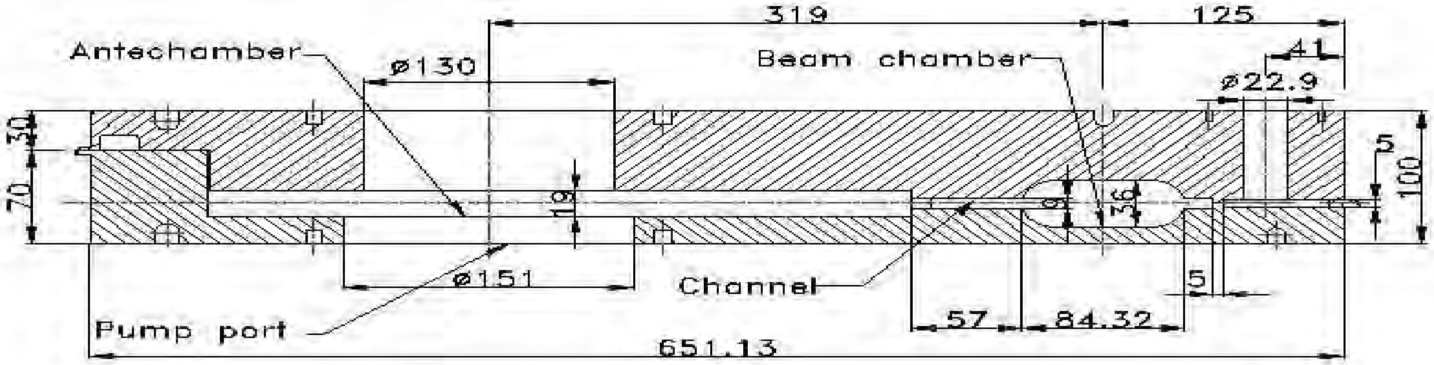
Dipole Chambers for Indus-2

Advantages of Ante-chamber design

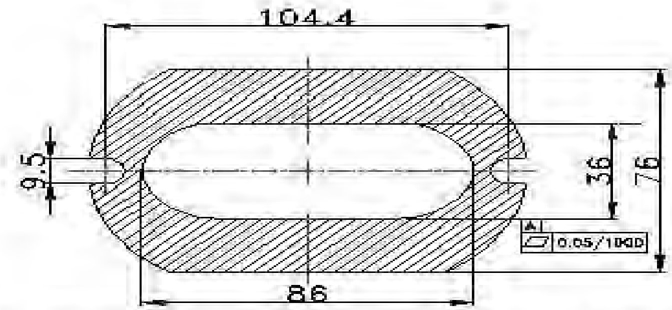
- Improves longitudinal conductance
- Lowers its impedance
- Permits adsorption of photons away from the electron beam close to discrete pumps installed under the photon absorbers.

Short and long straight section chambers

X-sections for Al alloy chambers of Indus-2



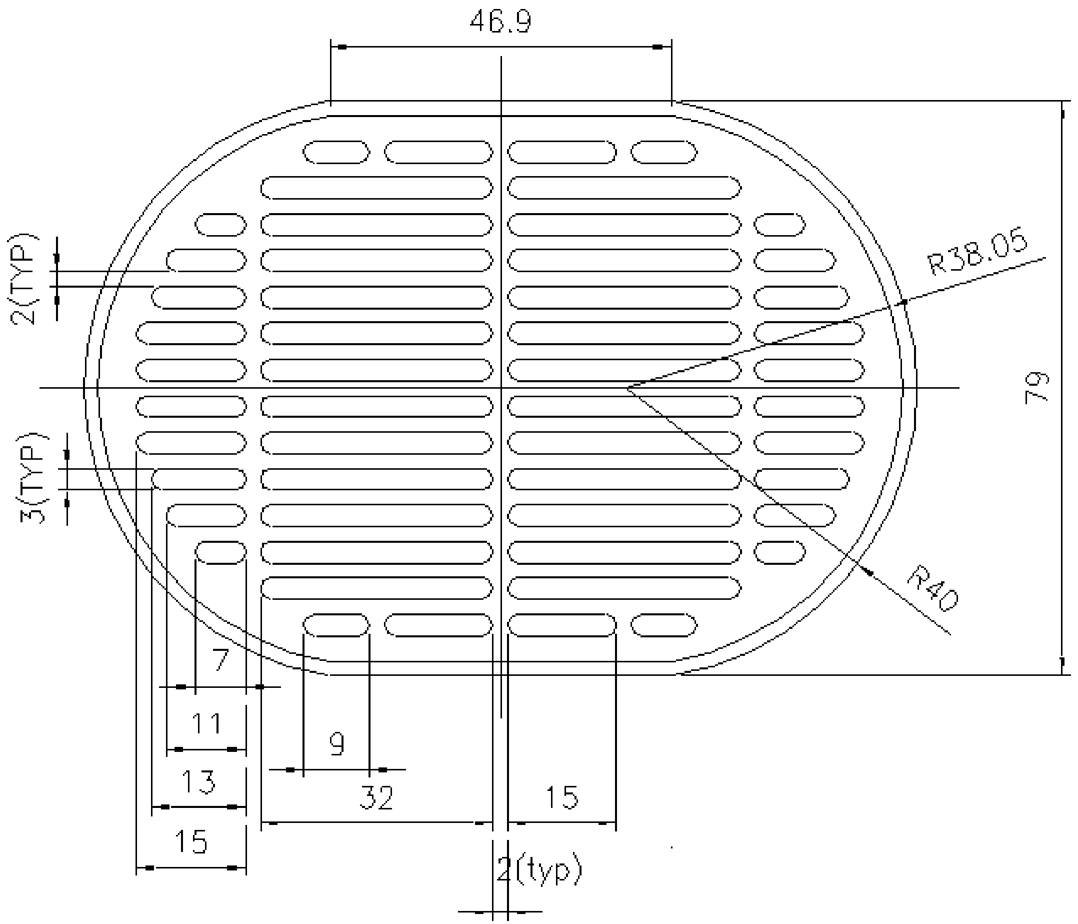
a) DIPOLE CHAMBER



b) STRAIGHT SECTION CHAMBER

Transition joint pipe after end forming

Pumping port mesh on straight section chambers



Fabrication of BM chambers

Top and bottom plates were machined and welded in the midplane. Machining of various ports and contours on both the top and bottom halves was carried out on CNC moving Bridge vertical profiler. Machine was proved for its geometrical and positional accuracies using Laser interferometer.

The welding joints – 2.5 mm thick, 5&8 mm wide lips for fillet welding.

CNC program - using Uni-graphics CAM software.

Suitable fixtures were designed and fabricated to reduce distortion in job. Two negatives of each half chamber were generated for job stabilization on machine. Hard foam jobs were cut on 1:1 size to check the accuracies, suitability of CNC program and dimensions of each half.

Roughing and finishing cut – using sharp lapped Stellite coated tools to get high material removal rates and desirable surface.

Profile machining of beam line path of elliptical section- Ball shaped end-milling cutter with suitable radius compensation in CNC program.

2.5mm thick welding lip was machined all around each half, with the help of form cutter and suitable CNC program. M/s. Hindustan Aeronautics Limited, Nasik, carried out these machining operations.

Vacuum ports and flanges - 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.

Fabrication of Straight Section chambers

- Machining of pump ports and maintaining continuity of beam profile by machining a mesh at these ports.
- Pipes having Al to SS transition joints, obtained by friction-welding technique, were welded on these ports. Elliptical shape of 80.2X 75.5 mm obtained by end forming by using die and punch at Al end of transition joint.
- Localized machining of extruded pipes to accommodate SS chambers in q-pole, s-pole and corrector magnets.
- Machining of SS chambers by using CNC profiler for high accuracy, intricacy and surface roughness $<1.6\ \mu m$.
- Solid carbide cutters to get high material removal rates with good surface finish. CNC program was generated using CAM software and proved on a trial job.
- Machining was carried out at M/s. Hindustan Aeronautics Limited, Nasik.

Fabrication of flanges

- Material - Aluminum alloy AA 2219 for helicoflex, diamond and Al wire seals.
- Usual elliptical aperture chosen for Indus-2.
- Profile accuracy - 50 mm.
- Surface finish - 0.8 micron on sealing surface for leak tight joints.
- Machined in Workshop-A, RRCAT using BMV-40 CNC milling machine to achieve required dimensional accuracy and interchange ability.

Types for Vacuum seals Used In Indus-2

- Aluminum Helicoflex seals - on demountable joints on bending magnets. The bolt holes on BM chambers provided with Be-Cu inserts.
- Aluminum diamond seals - on Al-Al and Al-SS demountable joints along the beam path.
- Standard OFHC copper gaskets - to connect pumps, valves, gauges etc.

Welding Of Aluminum chambers

Problems in welding of Al

- Higher thermal conductivity
- Aluminum oxide layer
- hydrogen embrittlement because of atmospheric moisture.

Welding technique for Aluminum developed at RRCAT workshop

- Relative humidity <40% in the welding room.
- Chemically cleaning, just before welding.
- Hand scrapping of Top and bottom halves of the BM chamber.
- Assembly of weld surfaces using dowel holes within aligned accuracy.
- Manual TIG welding using hard arc with welding current of 70 to 120A, Background current of 35 A, pulse frequency at 7 Hz and pulse ratio at 80%.
- The flow rates of high purity (99.99% pure) argon gas at 8 l/m and 3 l/m for shielding and purging respectively.
- Overlapping of end part of the weld bead by 25-30mm to avoid crater cracking.
- Welding of exit port flanges and end flanges in the final welding operation.
- Filler wire ER 5183 (2 mm dia) in dipole chamber welding and SFA 5.10 ER 4043 in welding of extruded section (AA 6063) with transition joint and extruded section with end flange (AA 2219).

Septum Magnet Chamber - main design features

- Size - A cylindrical vessel ϕ 450 mm X 1558 mm.
- 19 ports of sizes varying from ϕ35 mm to ϕ152 mm, at various angular and longitudinal positions on main shell.
- Material - NB 450, 10 SCH, confirming to ASME SA 312 –TP 316L.
- In vacuum radial movement of septum magnets from atmospheric side.
- Fixed & floating saddle supports to take care of thermal expansion during baking,
- Alignment & diagnostics features- Base trolley with stainless steel spherical ball transfer units to align and for multidirectional rolling action with minimum friction. Diaphragm bellow sealed linear motion feedthroughs of 25 mm stroke, to provide movement to this trolley.
- Al-alloy 6063-T6 dummy chamber of SS section profile was installed inside the main chamber to reduce impedance.
- Be-Cu finger contacts at the end of dummy chamber for continuity of profile
- Detailed engineering design based on ASME pressure vessel code section-VIII, Division-I.

Injection septum chamber with septum magnets.

Assembly of trolley and dummy chamber

Machining of Septum chamber

- Proper geometry of cutting tool, optimum cutting parameters and suitable fixtures to get parallelism of faces within 0.1 mm on shell and to avoid chattering to ensure high surface finish. Length and Parallelism of both ends of the shell achieved by facing on High Speed Precision Lathe (NH-26x3000) using tailor-made HSS tools.
- Rough machining of ports with 25 mm End milling cutter by using circular interpolation on CNC controlled H.B. Machine (AZ-11).
- Final boring of the ports by using high precision micro boring head.
- Machining of Aluminum wire sealed, main flanges of ϕ 580mm x 33.5 mm on VTL (DynaCut-1560) and Radial Drilling M/c (RM-65).

Photon Absorbers

64 water cooled photon absorbers (a heterogeneous structure of OFHC copper and SS) to dissipate 158 kW of Synchrotron radiation power.

Salient features :-

- UHV compatibility
- Absence of water to vacuum joints
- Rectangular finned type water channels for enhanced heat transfer and vacuum brazed joints.
- The wedge shaped profile for grazing incidence of photons reducing power density from 10 - 12 kW/cm^2 to 0.8 to 1.0 kW/cm^2 and to direct PID gas load towards SIPs installed below them.
- Calculated maximum localized temperature 130° C at hot spot and max. temperature 80° C on the cooling side.

3D Sectional view of a photon absorber

Machining of Photon Absorbers

- Tight tolerances are required for the precise capillary gap.
- 5-axis CNC machining centre to machine the profiles of OFHC components. To achieve very tight profile tolerances, flatness, perpendicularity, concentricity & finish on each component, machining was done in two settings only.
- Special carbide end mill cutters with a helix angle of 45° to 60° used to machine the profiles of components. Flatness of surfaces to be brazed was achieved by machining process only.
- SS flanges were also very precisely machined in one setting on CNC lathe while the graphite fixtures were machined by vertical milling m/c.

Vacuum Brazing of photon absorbers

Two stage vacuum furnace brazing to get bright, oxide free, degassed & UHV compatible leak tight assemblies.

Coating of 20 micron thick copper layer on brazing surface of SS pipes

Chemical cleaning by degreasing in TCE for 15 minutes; rinsing with dimineralised water for 5 minutes; pickling in 50% diluted HNO_3 for 5 minutes; rinsing with cold and hot DM water; cleaning with Acetone and drying in oven at 110°C.

Vacuum Annealing- At 600ºC & $5X10^{-5}$ mbar for a soaking time of 30 minutes (to check distortion due to residual stresses & appearance of blisters etc in the Cu coating of SS parts).

Then the components were cleaned in Acetone, filler materials were placed properly & assembly mounted on graphite fixture.

First stage of brazing- subassemblies of SS flange to cover & lid to main body was done at 840ºC using Ag72-Cu28 alloy as filler material. Natural cooling was done inside the furnace.

Second stage of brazing- final joint between cover & lid was done at 740ºC using Ag61.5-Cu24-In14.5 (InCuSil) alloy as filler material

QA - ultrasonic testing of material, inspection of profile on CMM after machining , leak checking after both stages of brazing etc.

Testing of Photon Absorbers

Ultimate vacuum testing w/o SR beam - $2X10^{-10}$ mbar using a 270 l/s SIP, after 8 hour baking at 150°C. The RGA components mostly H_2 and little CH_4, CO and CO_2

Power testing using electron beam - A strip type electron beam gun with specified for E=60 keV and I=100 mA was used. e^- beam irradiated an area of 5mm X 151mm on the central surface of the crotch. The absorber was cooled by water with flow rate of 4.8 l/min. Temperature rise for cooling water was 10°C, for incident power of 2.8 kW.

Surface cleaning effect of e^- beam was also observed, as the initial ultimate vacuum of ~$1X10^{-8}$ mbar improved to ~$3X10^{-9}$ mbar with a 270 l/s SIP. After irradiation for hours, the visual inspection of surface showed absence of any melting effect / erosion.

R.F Shielded Bellow Assembly

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

RF-shielded Bellow

A RF-shielded Bellow Assembly

The rf-shields w/o bellow

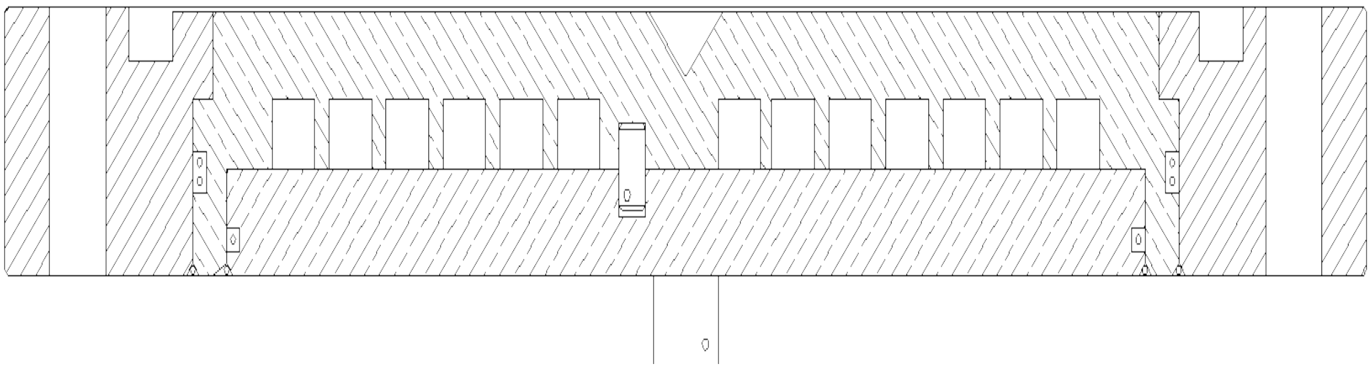
Water cooled End Flanges

Heterogeneous compact structure of OFHC central portion & stainless steel flange on outer portion, installed on BM chambers. 30 kW of power may be channeled onto these flanges, with SR power density 1.2 kW/cm^2.

Salient features - 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.

- Inspection, cleaning procedure and vacuum brazing 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 840ºC.
- All the end flanges were subjected to He leak testing $<2X10^{-10}$ std.cc/s. and ultimate vacuum testing $<1X10^{-9}$ mbar.

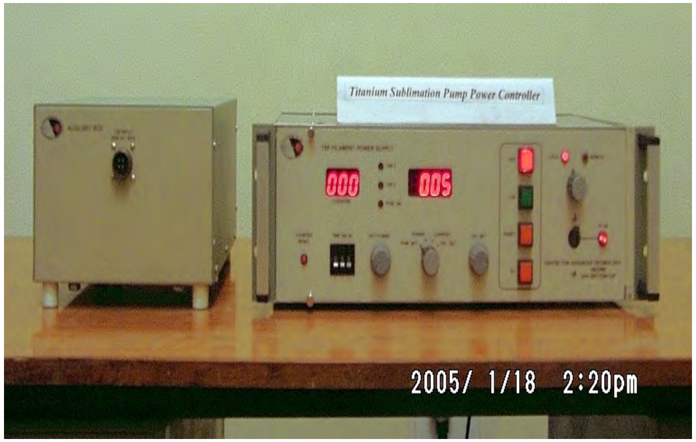
Sectional view of Water Cooled Flange



SIPs ranging from 35 to 1000 l/s pumping speed

Vacuum Instrumentation

Temperature and pressure monitoring units

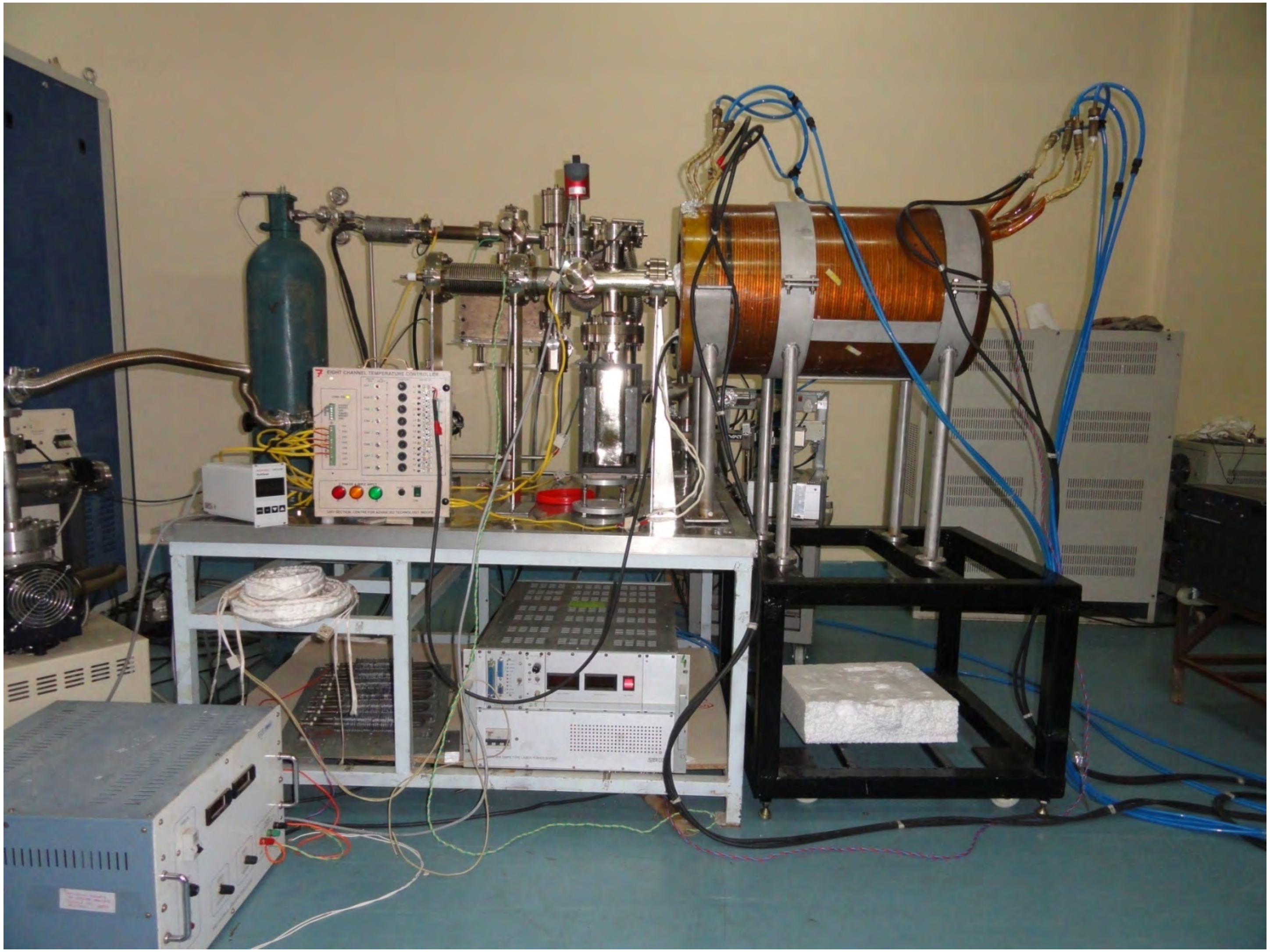


TSP controller for Indus-2

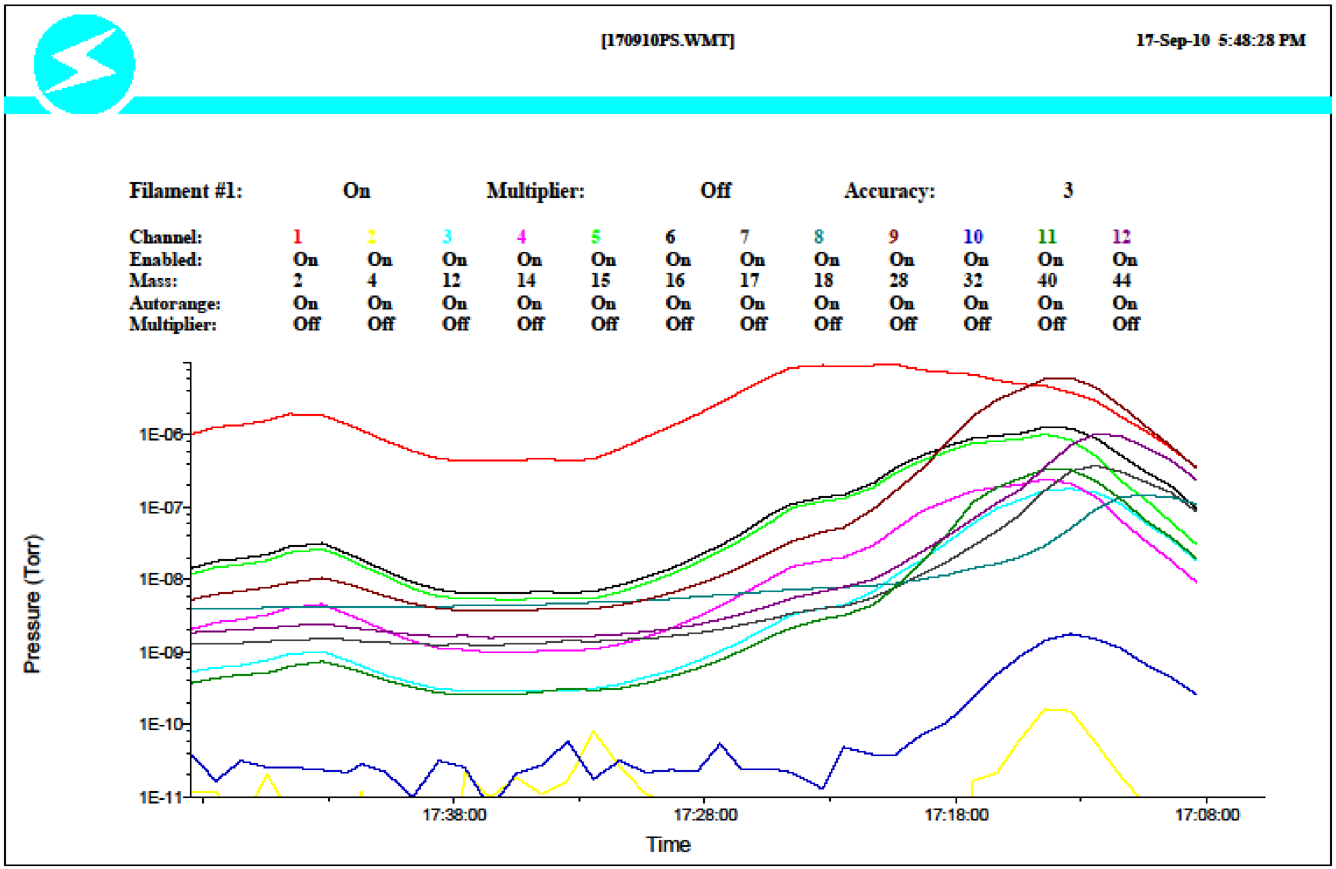
Eight-Channel Temperature controller unit.

Super Heated Water Generator

Cylindrical Magnetron Sputtering System



CO pumping using NEG



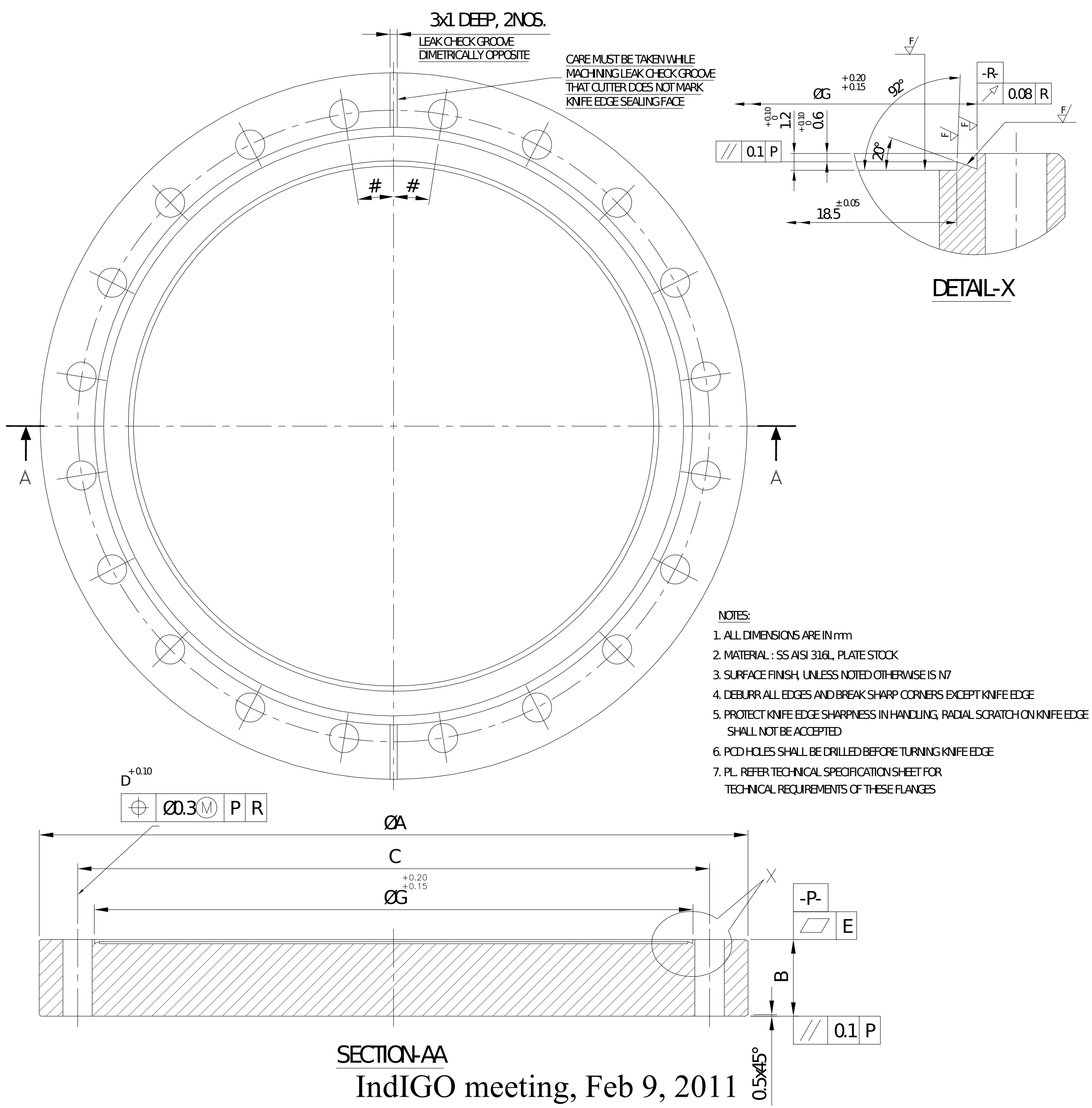
After CO injection, NEG activation was started at 1706 hrs, which continued upto 1750 Hrs. The CO peak reduced by three orders even when the Activation is ON.

Experience, Expertise & Infrastructure

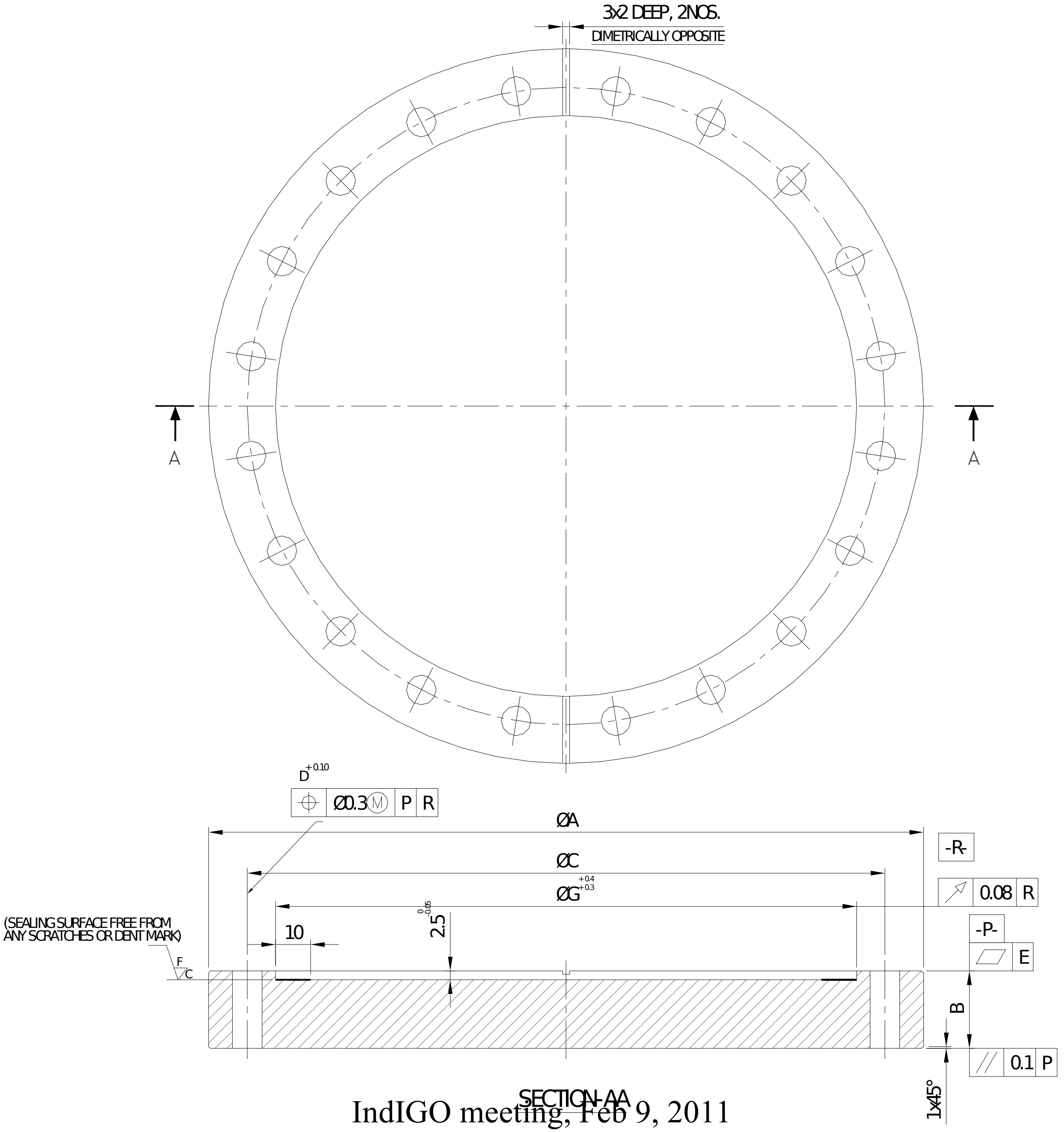
- **Design, development, installation and commissioning of UHV Systems**
  - MICROTRON, BOOSTER SYNCHROTRON
  - SYNCHROTRON RADIATION SOURCES Indus-I & Indus-2
  - ELECTRON BEAM TRANSPORT LINES 1, 2, 3 etc.
- **Computer Simulations of UHV Systems**
- **Vacuum Vessel Design & Fabrication as per ASME Pressure vessel code Sec-VIII, Division – I**
- **Simulation of Thermo-mechanical loading on structures using FEM code ANSYS.**
- **UHV Characterization of vacuum systems.**
- **Development and Production of SIP's and TSP's.**
- **Temperature control and vacuum data logging.**
- **INFRASTRUCTURE** for Outgassing Study, ESD Study , Pumping Speed measurement of SIP's , Glow Discharge cleaning etc
- **Development of NEG Coating system for vacuum chambers.**

THANKS

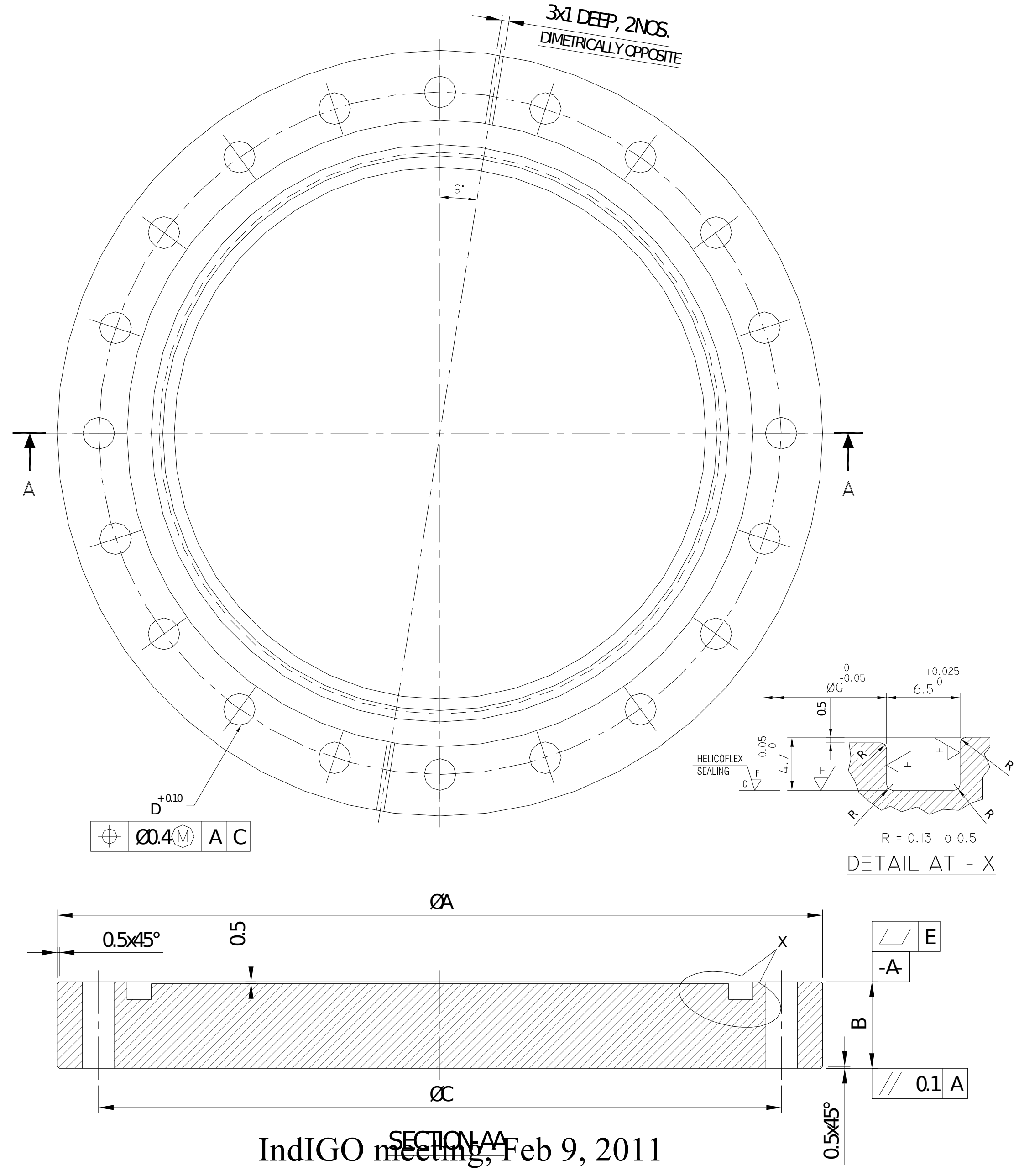
NW160 CF BLANK FLANGE



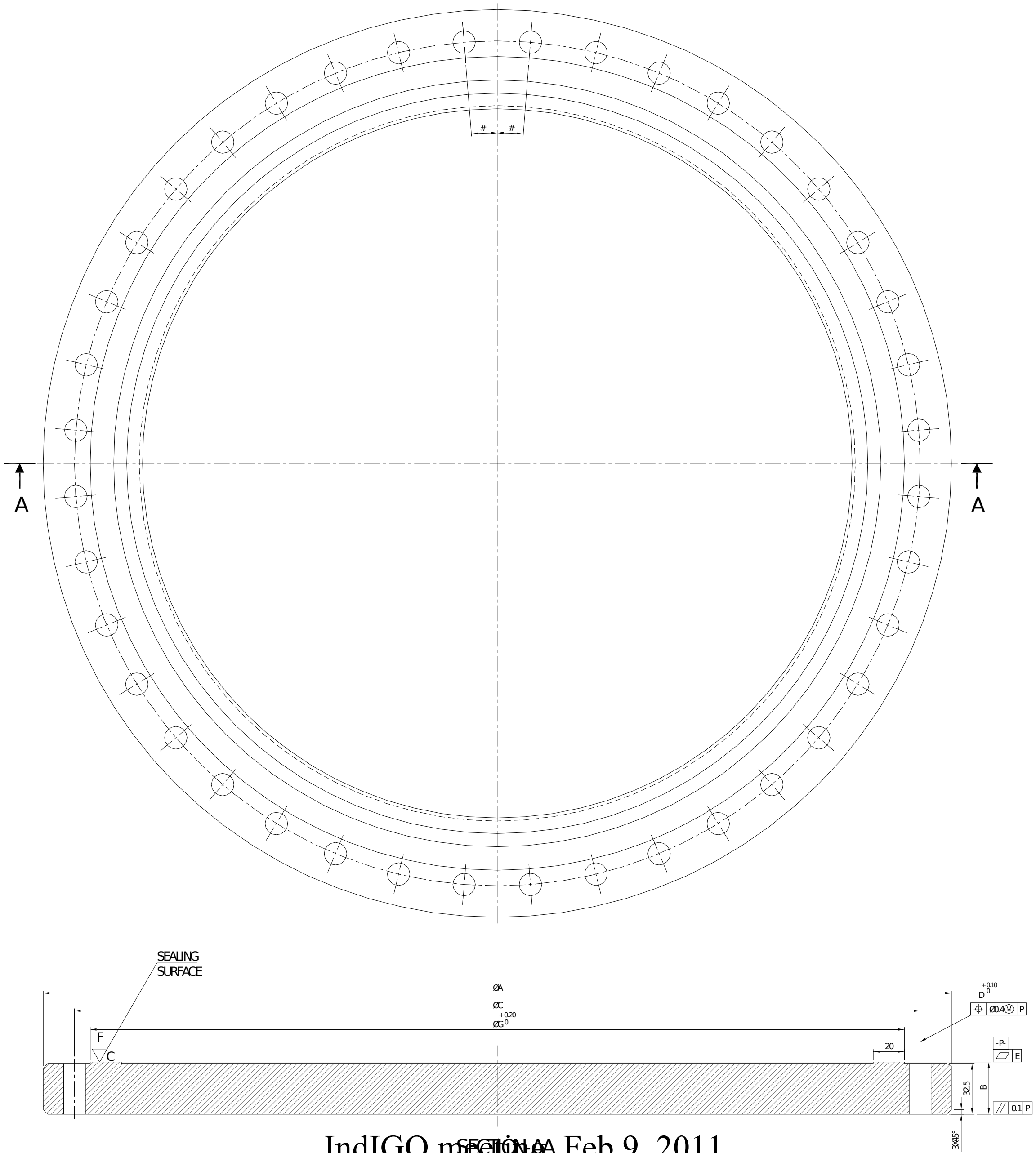
NW160 DS BLANK FLANGE



NW160 HF BLANK FLANGE



NW450 WS BLANK FLANGE



TYPICAL FLANGES USED IN INDUS-2				
DIMENSION	NW160CF	NW160DS	NW160HF	NW450WS
A (OD)	Ø203	Ø203	Ø203	Ø580
B (THICKNESS)	22	22	22	33.5
C (PCD)	181	181	181	540
D (No.OF BOLT HOLES x DIA OF HOLES)	20xØ8.3	20xØ8.3	20xØ8.3	40xØ14.4
E (FLATNESS OF MATTING FACE)	0.02	0.02	0.02	0.05
F (SURFACE FINISH OF SEALING SURFACE)	0.4 TO 0.8	0.4 TO 0.8	0.2 TO 0.4	0.4 TO 0.8
G (GASKET SEATING DIA)	Ø171.4	Ø165	Ø153.1	Ø480

Note: All dimensions above are in mm except surface finish (F). Surface finish is in micron.

Different Types of Gaskets

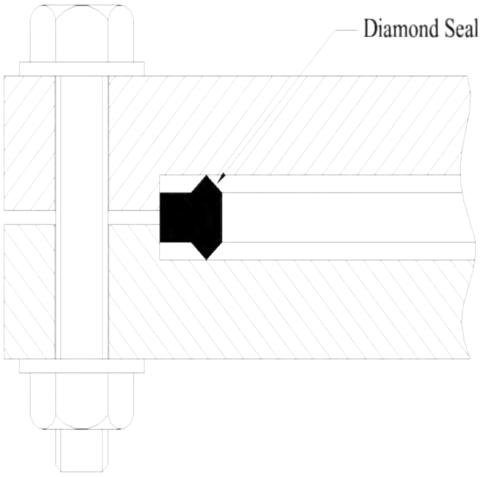
Aluminum Diamond type gaskets

Standard OFHC gaskets for CF flanges

Aluminum Wire gaskets

Helicoflex gaskets

Diamond Seal for Indus-2



Salient Features

- UHV compatible Al-alloy gasket
- Suitable for homogeneous joints between Al 2219 flanges.
- Also suitable for heterogeneous joints between Al 2219 and SS flanges
- Material of construction - Al6063-T5
- highly reliable
- very low cost

Cleaning Procedure for SS at Chemical Cleaning Lab, RRCAT

1) Ultrasonic cleaning and vapour degreasing in Trichloroethylene
2) Alkali Cleaning – NaOH, Na_2CO_3, Trisodium orthophosphate @ Temperature 45 to 55°C, for 35 to 45 minutes
3) Rinsing and washing - 20% HNO_3, 1.5% HF, for 40 to 55 minutes at room temp Rinse
4) Electropolishing – H_2SO_4, H_3PO_4, Gycerol, water at Temp 40 to 50°C for a duration of 1 hr, Current density- 2.5 to 3 Amp/dm^2