T.2: Recent developments in the activities of ultra-high vacuum technologies at RRCAT

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Abstract

Ultra-High Vacuum (UHV) Technology Section (UHVTS) pursues various activities to cater to various needs of accelerators in RRCAT. Various systems have been developed with in-house capabilities. The article highlights some of the major achievements, contributions to Indus accelerators and technological developments at RRCAT in the recent years.

1. Contributions to Indus accelerators

In order to reduce the scattering of electrons in Indus accelerators, starting from the injector microtron up to the storage rings Indus-1 and Indus-2, vacuum envelope is provided throughout the electron path. The storage rings are maintained at ultra-high vacuum of the order of 10^{-10} mbar. The transport line TL3 is also in the range of 10^{-10} mbar and remaining electron beam path is maintained in the range of 10^{-8} mbar. Indus accelerators and the transport lines are provided with indigenously developed UHV compatible chambers/envelope, vacuum pumps and vacuum instruments. Various kinds of transition joints were adopted in Indus accelerators. Some of the seals were also developed in-house, for instance the aluminium alloy diamond seal, which was developed to cater to the requirements to seal between stainless steel-to-aluminium alloy. In this section, recent contributions to Indus accelerators are summarized.

1.1 Alumina ceramic chambers for kicker magnets

UHV compatible alumina ceramic vacuum chambers with improved and more reliable design features of ceramic to metal joint were designed, developed and installed [1], replacing defective alumina ceramic chambers initially installed, in Indus-2 ring. Alumina ceramic chambers are used as vacuum envelopes inside the four injection kicker magnets. Alumina is chosen to avoid the effects of eddy current induced by the pulsed magnetic field generated by the kicker magnets. Salient design features of new chamber are: monolithic flanged alumina tube, ceramic-to-metal joint free from tensile loading, RF continuity, reduced tightening torque for leak tight metal sealing and UHV compatibility. Sintered and ground tube was subjected to Mo-Mn metallization followed by protective nickel plating of areas to be brazed with Kovar. Vacuum brazing technique was used to braze metallized alumina to Kovar joint using BVAg-8 brazing alloy. Inner surface of alumina tube was coated with ~1 micron thick titanium thin film to provide conducting path to image current. Helium leak tightness of the ceramic-to-metal joint was better than 2 x 10^{-10} mbar l/sec, before and after bake-out at 150 °C for 24 hours. After bake-out, ultimate vacuum ~5 x 10^{-10} mbar was achieved. The residual gas analyzer (RGA) spectrum of ultimate vacuum shows abundance of mainly H_2 as residual gas inside the chamber. Ti coated alumina ceramic chamber and its ceramic-to-metal joint design schematic are shown in Figure T.2.1 and Figure T.2.2, respectively.

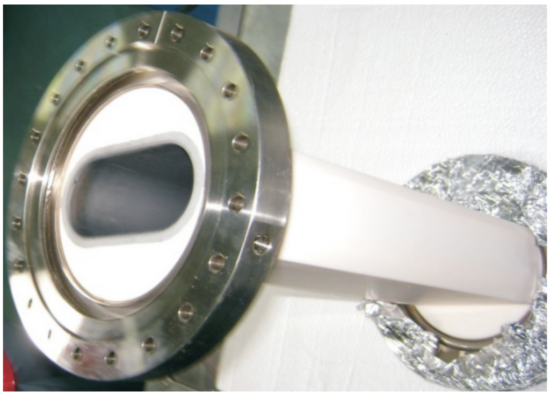


Fig. T.2.1: Titanium coated alumina ceramic chamber.

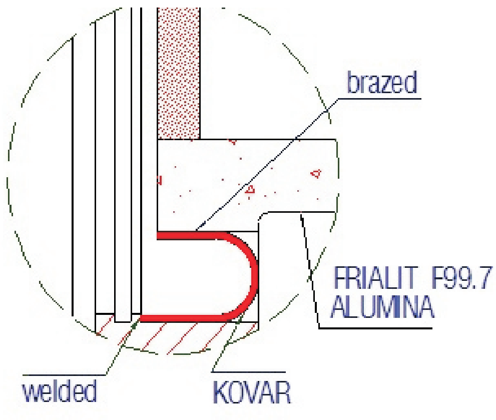


Fig. T.2.2: Ceramic-to-metal joint design.

1.2 Upgradation of UHV system of Indus-2 for undulators

Three undulators, namely U1, U2 and U3 were developed, installed and commissioned in Indus-2 storage ring [2], [3]. With these three insertion devices, a major enhancement in the performance of the Indus-2 synchrotron light source was accomplished. Compatible vacuum systems for these undulators were designed, developed and installed along with undulators. Design of vacuum systems for these undulators are identical. 3D layout of undulator vacuum segment is shown in Figure T.2.3. Total length of undulator vacuum system including RF-shielded bellows is 4325 mm. Undulator vacuum sector is isolated by two sector gate valves for maintenance purpose. Operating pressure of ~5.0 x 10^{-10} mbar is routinely maintained which facilitates a beam life time of more than 24 hours.

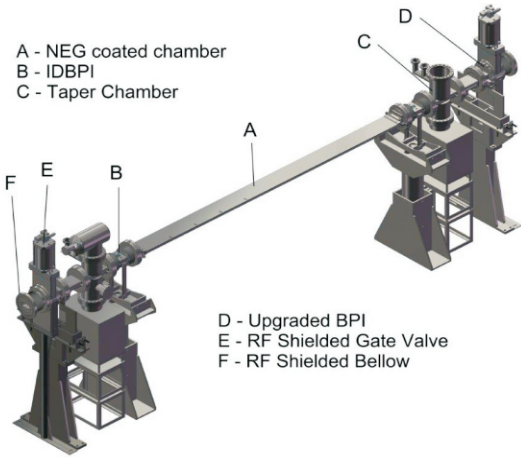


Fig. T.2.3: 3D view of undulator vacuum segment.

1.3 NEG coated vacuum chamber

Undulator vacuum chamber cross section height is decided by the minimum pole gap limit of undulators. Minimum pole gap of undulators in Indus-2 is 23 mm. Due to this constraint, vacuum chamber cross section height is limited to 21 mm keeping 1 mm clearance on both sides for straightness tolerance. Beam dynamics requires minimum 16 mm vacuum height for good field region of e-beam during beam injection. This constraint led to narrow aperture vacuum chamber with reduction of gas conductance in molecular flow condition. Achieving required level of UHV for longer beam life time becomes quite difficult with conventional room temperature UHV pumps. To counter this problem, non-evaporable getter (NEG) thin film coating, as advanced pumping solution, was deployed in the Al alloy 6060-T6 undulator chambers for the first time in Indus-2 ring. NEG film, once activated, acts as in-situ distributed getter pump for achieving required level of UHV in these narrow gap chambers. Average static pressure of ~ 1 X 10^{-10} mbar (without electron beam) was achieved in the undulator vacuum sectors after in-situ bakeout at 150 °C and subsequent activation at 180 °C x 24 hours of NEG coating [4]. Cross section of NEG coated vacuum chamber is shown in Figure T.2.4.

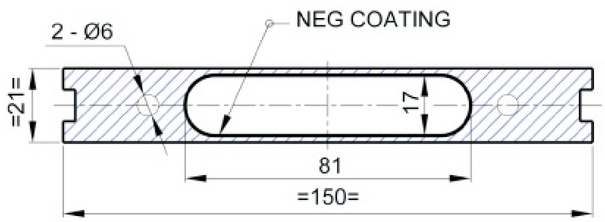


Fig. T.2.4: Cross section of the NEG coated chamber.

1.4 Taper chamber

Taper chamber, as shown in Figure T.2.5, is basically a transition chamber which provides smooth transition of undulator chamber internal cross section at one end to normal quadrupole chamber internal cross section at another end. It minimizes the RF impedance to the circulating electron beam. Apart from providing smooth passage to the image current, it also houses ports for connection to vacuum pumps, Bayard-Alpert (BA) gauge and RGA. Pump ports on top and bottom surfaces of taper body are having staggered smaller slits, also called the RF-screen. Design of RF-screen is optimized for minimum RF impedance for circulating e-beam and adequate molecular flow gas conductance. Water cooling channel, sidewise, is provided for conduction of SR heat due to beam mis-steering.

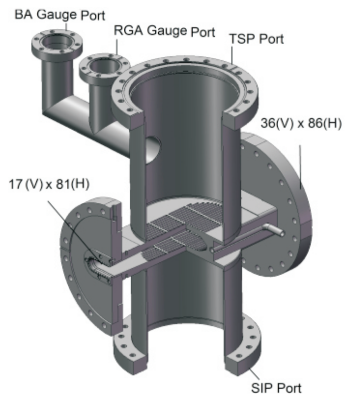


Fig. T.2.5: 3D sectional view of taper chamber.

Salient design features of these water cooled tapers are: (i) Material of construction : SS316L with copper plating of internal surface of beam duct for passage of image current (ii) ports for connecting standard UHV pumps, namely sputter ion pump (SIP) on bottom and titanium sublimation pump (TSP) on top, BA gauge and RGA (iii) smooth taper well within 10% limit of internationally adopted value (iv) optimized design of screened ports to satisfy two conflicting requirements of low RF impedance and higher gas conductance for efficient pumping (v) no water-to-vacuum joints (vi) silver plated beryllium-copper inter-flange contacts at both flange ends for minimizing the beam impedance problem because of step formation due to placement of gaskets in between two mating flanges.

2. Technology development

2.1 NEG coating development

NEG is a porous alloy of getter elements Ti, Zr and V. NEG coated stainless steel (SS) and aluminium alloy vacuum chambers work as a getter pump. It is very useful to produce the vacuum in 10^{-10} mbar range, in the insertion device low conductance vacuum chambers of storage ring. A UHV compatible cylindrical DC magnetron sputter deposition system was designed and developed for NEG coating of circular SS and small cross section racetrack profile (17 mm x 81 mm) aluminium alloy 6063-T6 chambers. The best pumping speed achieved was 1.85 l/s/cm^2 for CO gas for 1.6 µm thick NEG coated SS vacuum chamber. Aluminium racetrack profile low gap vacuum chambers were also NEG coated using the argon gas at -600 V discharge voltage, 100 mA discharge current at 100 °C substrate temperature, 400 G magnetic field and almost 0.5 µm thin film of chemical composition 36%-Ti, 26%-Zr 38%-V (atm%) was formed [5] [6]. The morphology of the NEG coated aluminium substrate having cauliflower structure shown in Figure T.2.6. This development would go a long way in making the vacuum envelope of very low conductance for future accelerators.

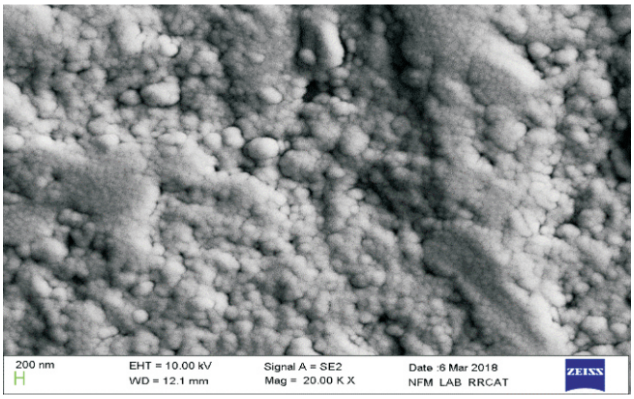


Fig. T.2.6: Surface morphology of NEG coated aluminium sample.

2.2 Large coating setup

A vertically oriented large coating system with overall size of 1300 mm x 1200 mm x 5500 mm height was indigenously developed, installed and commissioned in UHV Lab. Actual photograph of the installed system is shown in Figure T.2.7. This coating system, based on DC magnetron sputtering technique, will be used for coating of NEG film on low gap (conductance limited) vacuum chambers used in insertion devices of Indus-2/future low emittance storage ring, for UHV pumping requirement and TiN coating of vacuum chambers of accumulator ring of Indian Spallation Neutron Source (ISNS) for low secondary electron yield (SEY) requirement. Various sub-systems of this coating setup are: All metal bakeable vacuum system, gas (Ar/Kr) delivery system, water cooled solenoids: 360 and 250 mm IDs x 1000 mm length, power converter: 250 A/50 V for water cooled solenoids, high voltage DC power supply: 2 kV / 6 A for gas discharge, custom built motorized solenoid lift of 3750 mm stroke height and water chiller. Motorized solenoid lift consists of precision lead screw mechanism which provides linear speed of 300 mm/minute (bi-directional) to solenoid. Vacuum chambers with cross section dimension falling within uniform solenoid field of diameter 290 mm and length up to 3500 mm can be accommodated for coating in this set up. All metal bakeable vacuum system consists of 270 l/s SIP, UHV gauge and RGA.

After erection and integration of various systems, an Al alloy 6063-T6 scale down prototype of Indus-2 undulator chamber of 1000 mm length having race-track internal profile of 17 mm x 81 mm (H x W) was assembled along with target cathode wires (intertwisted 1 mm diameter each of Ti, Zr, and V) for functional testing. A steady-state discharge was observed at 500 V discharge voltage, 100 mA discharge current and 1.2 x 10^{-2} mbar dynamic argon gas pressure.

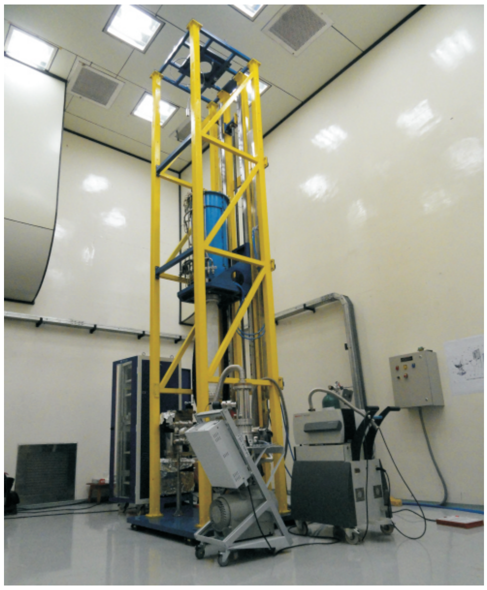


Fig. T.2.7: Photograph of large coating setup.

This development saved considerable amount of foreign exchange and indigenous expertise was gained for design and development of similar systems.

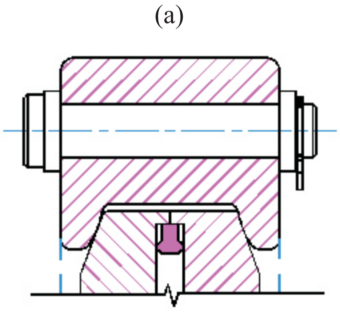
2.3 Water cooled aluminium extrusions

Aluminium alloy chambers, used for undulators and downstream of upcoming superconducting insertion devices in Indus-2, require integrated water cooling holes adjacent to electron beam channel for efficient transfer of SR heat generated on side walls. Minimum pole gap setting of undulator requires straightness of the undulator vacuum chamber ~ 0.1 mm/m. In view of this requirement, precision extrusion aluminium alloy 6063-T6 extrusions with integrated water cooling holes were indigenously developed conforming to EN 12020-2. Racetrack internal aperture of extrusion, for circulating electron beam, is 81 mm (H) x 17 mm (V). Water cooling holes on both sides of the beam channel are of diameter 6 mm each. After machining, straightness of the extrusion was measured and found to be ~ 0.1 mm /m. This extrusion is presently used for the vacuum chamber of IRFEL undulator.

2.4 Quick disconnect flange joint

In the accumulator ring of ISNS, the operating pressure of 10^{-9} mbar is needed to minimize proton beam loss due to beam-residual gas interaction. In several locations with potentially high background radiation, such as the injection, extraction and collimator regions, quick-disconnect type flange is used for minimizing the radiation exposure to workers during machine maintenance periods.

(a)



(b)

Fig. T.2.8: (a) Photograph of the QDF joint. (b) Cross section sketch of the QDF joint.

Indigenous development of UHV compatible all metal quick disconnect type sealing technology was successfully carried out which will be useful in ISNS [7]. Salient features of this demountable joint are:

- Material of construction: flange Ti Gr-5, chain clamp: AA7075-T652 and SS316
- Sizes: NW40/160/200/250/300/350
- Helium leak rate < 2 X10^{-10} mbar l/s
- UHV compatible
- Radiation resistant
- Quick assembly and disassembly (6 to 8 minutes for assembly and 3 to 4 minutes in disassembly for typical NW160 size flange joint)

Photograph of QDF joint and its cross section sketch are shown in Figure T.2.8 (a) and (b), respectively.

2.5 Alumina to titanium brazed joint

To overcome the issue of eddy current effects, alumina ceramic chambers are required for pulsed kicker magnets of accumulator ring of ISNS. Titanium as end flange for UHV sealing of alumina ceramic chamber is preferred due to its compatibility with respect to co-efficient of thermal expansion of alumina, non-magnetic nature and extremely short radioactive half-life. A major technological advancement has been accomplished by successful vacuum brazing and testing of UHV compatible un-metalized alumina (99.7% pure) to titanium-Gr-5 joints. Brazed specimen as per standard ASTM F19 is shown in Figure T.2.9. Brazed joints showed helium leak rate better than 2 x 10^{-10} mbar l/s even after 6 nos. of baking cycles at 150 °C for 8 hour soaking time. Brazing parameters were: brazing alloy - BVAg-8, vacuum ~ 4 X 10^{-04} mbar, temperature: 830 °C, soaking time: 3 minutes.

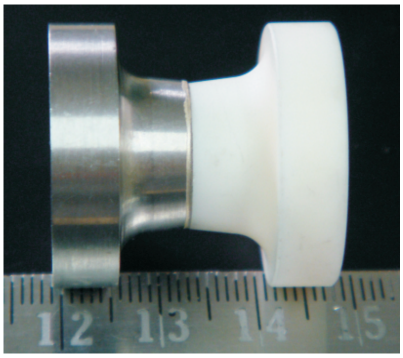


Fig. T.2.9: ASTM F19 brazed specimen.

Microscopic examination of alumina/titanium brazed joints revealed sound interface between the two dissimilar parts as shown in Figure T.2.10. The brazed joint exhibited a two-phase microstructure comprising of an Ag-rich light phase and Cu-Ti-V grey phase. Formation of a thin continuous

Ti-Cu-Al-V film on the alumina surface appears to be responsible for satisfactory wetting of alumina by the brazing alloy. Mechanical characterization of brazed joints was also carried out. 4-point bend test of brazed sample as per ASTM C1161 showed bending strength > 50 MPa, an international benchmark of bend strength of ceramic to metal joint.

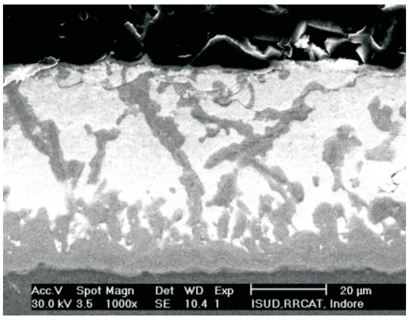


Fig. T.2.10: Micrograph of brazed joint (Top-Al_2O_3; bottom – titanium).

3. Vacuum instrumentation

UHV instrumentation is an essential component of UHV systems and comprises a variety of pump controllers, gauge controllers, valve controllers, baking systems, temperature controller units, pressure monitoring units and associated software, all developed in-house.

3.1 Dual channel digital power controller for SIP

The dual channel digital power controller for SIP is designed to add some additional useful features and to overcome the problematic features of the existing design. These are:

a) Optimization of the power rating of the controller so that just enough power is delivered to the SIPs of ratings normally used in UHV systems. This has helped in reducing the weight and size of the main high voltage transformer considerably.

b) This has also enabled to have dual channel individually switchable design and offers the facility of operating 2 SIPs simultaneously. Parameter measurement is also done individually.

c) The scheme chosen is a combination of linear HV module plus microcontroller based interface and display. Linear design is retained to minimize conducted noise, whereas, apart from control, the microcontroller enables simultaneous display of parameters of both the channels such as voltage, current and pressure. Also, remote status of the controller is available by means of RS232 interface.

The main specifications of this controller are:

Input: 230 VAC, 50 Hz
Output:
Independent outputs: 2 nos.
No load voltage: -6200 VDC
Current (maximum): 520 mA
Power (maximum): 800 W
Protect period: 5 minutes
Overcurrent trip settable: 30 mA/50 mA/100 mA
Thermal protection: 55 ºC on transformer winding surface
Process set points potential free contacts 2 nos.
Protection against open ground loop.
Display: LCD 20 characters x 4 lines
Communication: RS232, GUI: VB.net

3.2 Upgradation and development of BA gauge controller

The controllers for BA gauges are vital instruments and must work reliably on continuous basis especially considering generation of signal for the interlock of machine safety. After study and observations it was found that the existing controller needs to be updated for overcoming several limitations. The development of BAG controllers mainly includes features such as modular distribution of cards for maintenance, additional protections to enhance life of filaments thereby improving reliability, immunity of pressure measurement to ambient temperature variations, additional process control channel, isolated analog voltage and current outputs for remote monitoring, etc. Also, the new design is 40% less in weight and size to the previous one [8]. The photograph of newly developed BA gauge controller is shown in Figure T.2.11.

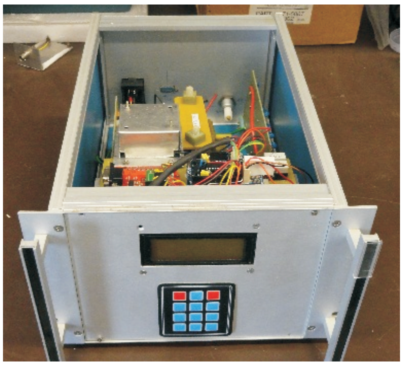
Fig. T.2.11: Photograph of newly developed BA gauge controller.

Technical Specifications

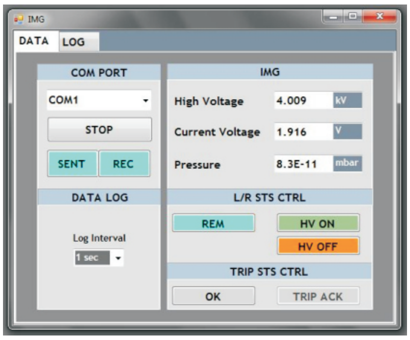
1) Pressure Range: 10^{-3} mbar To 10^{-11} mbar
2) Emission: 0.1 mA, 1.0 mA, 4.0 mA, Dual Filament
3) Degassing: 10 W to 36 W continuously variable
4) Protection: Low/Over emission current, grid to filament short, grid to GND short, degas trip can be set from 75 mA to 150 mA, over pressure protection
5) Gauge head sensitivity: Step variable 10, 15, 19, 20, 25 mbar-1
6) Analog output: a) 0 V To 8 V respectively for 10^{-11} mbar to 10^{-3} m, b) Isolated output voltage: 0 V To 8 V and c) Isolated output current : 4 to 20 mA, respectively
7) Remote control: Local/Remote status, emission reset, process control status through 15 Pin D type connector at rear panel.
8) 2 channels of process control
9) Modular approach to ease the maintenance and the trouble shooting.

3.3 Prototype development of inverted magnetron gauge controller

A switch-mode power supply (SMPS) and microcontroller based inverted magnetron gauge controller (IMG) is indigenously designed and developed. Photographs of newly developed IMG controller and screenshot of its data logger software are shown in Figure T.2.12: (a) and (b), respectively.



(a)



(b)

Fig. T.2.12: (a) Photograph of newly developed IMG controller (b) Screenshot of data logger software of newly developed IMG controller.

The SMPS consists of PWM, power amplifier, step up transformer and 5-stage voltage multiplier and is rated for 3.3 kV, 100 µA to power the gauge head. The high voltage applied is sensed and processed suitably before being sent to a microcontroller. Similarly, the ionization current measured over the range of 6 decades is compressed using a log amp, processed suitably before being sent to the microcontroller. The micro-controller based system converts the ionization current proportional values to corresponding pressure values with the help of a look up table. Pressure, high voltage and ionization current are displayed on a LCD. Operation of gauge controller in local and remote mode is possible using keyboard interface or serial communication respectively. The controller displays under range if the pressure goes below 5E-11 mbar. It provides and displays over pressure trip at 1E-05 mbar for the protection of HV power supply. A GUI has also been developed for data logging and remote operation of the gauge. It is housed in a half sub-rack of dimensions 19 inch, 3U, 305 mm depth.

3.4 Pneumatic sector and gate valve (GV0) controller in Indus-2

Indus-2 is sectored in thirteen vacuum sectors using pneumatically operated RF-shielded gate valves. Also, 19 nos. of all metal gate valves are installed in the beam lines and TL-3. These valves are opened when the vacuum condition in the whole ring is satisfactory and beam filling is to be done. The valves are to be closed in case of failure of vacuum interlock. The valves are also to be closed for required modifications or repair work or during baking.

The opening and closing of the valves is done by means of valve controllers which are developed indigenously. The controllers enable safe opening of these valves with interlocks for avoiding any accidental venting of the machine. The controller is microcontroller based aiding easy modifications for interlocking scheme, software de-bouncing and multiple status indication by the LED without modification in hardware. It also helps to add features of serial communication (RS232 and RS485) along with hardwired potential free relay contacts. Provision of key-switch is kept for selection of LOCAL/REMOTE mode for avoiding unauthorized access of the unit. Failsafe operation is in the sense that any breakage in the interlock cables, solenoid coil wire or power failure should result in the closing of the valve. The unit supports operation of 24 V/230 V solenoids.

For providing safety to the valve, the status of valve is also integrated with the Machine Safety Interlock System (MSIS) which dumps the beam if the valve is not found in open condition during machine operation. Modular valve controllers with front and back panel views are shown in Figure T.2.13.

Fig. T.2.13: Modular valve controllers with front and back panels view.

3.5 Baking system

Optimized bake-out procedures are very important for overall reliability of any vacuum system. In order to achieve this, an intelligent ON/OFF control system is designed and developed incorporating modular baking system with distributed controls [9].

This system contains Temperature Controller Unit (TCU), Pressure Monitoring Unit (PMU), as well as Baking Application GUI. Each TCU is an eight channel temperature controlling unit. A PMU is an eight channel pressure monitoring unit to which analog data from various gauges like Penning gauges, BA gauges are fed. Baking Application is a user interface software developed for controlling up to 6 TCUs. In this way, 48 channel temperature data logging and control, along with eight channel pressure monitoring is realized.

Each TCU has a provision of 8 channels. It is capable of monitoring as well as controlling the temperature and is able to communicate to computer through half-duplex RS485 network. K-type thermocouples are used temperature sensors. TCU temperature measurement range is up to 500 ºC, with a resolution of 1 ºC. Each channel is able to handle grounded as well as ungrounded thermocouple. In input section, differential as well as common mode RC filter is used.

3.5.1 Software for baking application

The process of conducting baking cycles on regular basis has been simplified and made more reliable with in-house developed distributed 48-channel temperature controlling system [10], which includes six 8-channel TCU and one 8-channel PMU distributed over RS-485 multi-drop network. For overall supervision and control and data logging of temperature and vacuum, a GUI is developed. The pressure monitoring unit is used for providing data logging of vacuum in the system supporting various types of pressure gauges. The GUI for this setup is completely redesigned and redeveloped for adding more user friendly features using VB.NET.

In a typical baking cycle, the temperature of a component is elevated to a desired level with required ramping rate. It is maintained at the elevated temperature for about 24 - 48 hours. The temperature is then ramped down to room temperature. In this period turbo molecular pump is kept on which evacuates the vacuum system bringing down the pressure to a level around 1.0E-06 mbar. The vacuum level is further improved by using sputter ion pumps.

User can configure eight sets of profiles defining starting and maximum temperature. Additional settings like ramp time, temperature band, free fall temperature, need to be set before starting of the cycle. Any channel can be configured for one of the eight suitable profiles, before or during running of the cycle. After starting of the cycle, the set point for each channel is updated automatically for full cycle as per selected profile, at the same time maintaining temperature difference between all channels within required limits. The software also auto detects serial port to which system is connected, the number of units connected at start, minimising further inputs required from operator. Data is logged in .CSV format. This helps in removing dependency on specific spreadsheet processing software and limitation of installation of old software on a PC with higher version of OS. The software has more user friendly features like observing serial data communication status and information, data logging status etc. Any channel can be set for one of the profiles and if required, switching between the profiles during operation of cycle is also possible. The state of cycle and running time duration including delay required for holding the cycle for restricting the temperature difference between all channels is also displayed. Provision is kept for saving operator notes, channel names and for configuring auto set point or manual set point for any channel. The channels which are used only for temperature monitoring must be set to manual mode. The PMU interface now supports selection among eleven types of various vacuum measuring gauges used in UHV Lab.

Power failure is automatically detected by the software, which also provides option of auto-reloading after restarting.

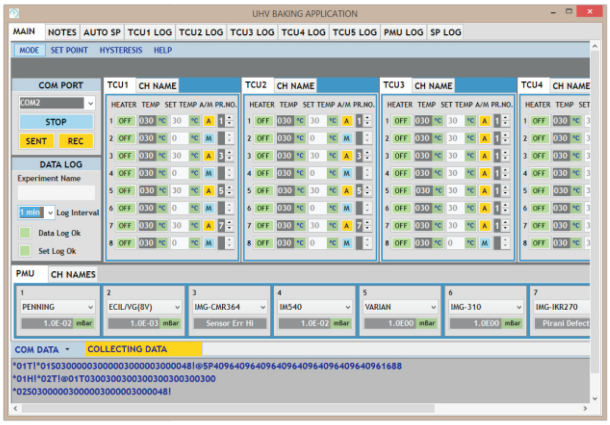


Fig. T.2.14: Screenshot of software showing overall GUI.

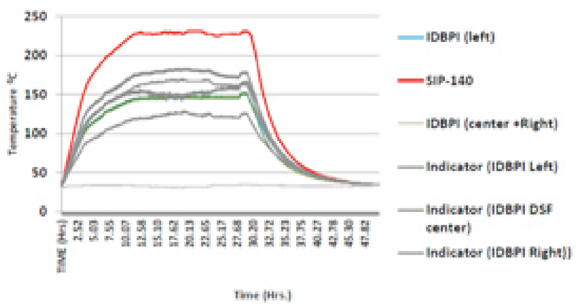


Fig. T.2.15: Result of a baking cycle conducted for ID BPI.

The software restores all the previous settings, channel names and starts appending data log in the original file, if a user opts to reload the software. This software has been successfully used in the baking cycles conducted during commissioning of the undulators U1, U2 and U3 in Indus-2 as well as in various setups for performing vacuum qualification tests in UHV Lab. Screenshot of software showing overall GUI is shown in Figure T.2.14. Result of a baking cycle conducted for ID BPI is shown in Figure T.2.15.

3.5.2 Development of 16-channel temperature controller

The present Temperature Monitoring Unit (TMU) is a 8-channel temperature monitoring unit, using K-type thermocouple for the span of 0-500 ºC at the resolution of 1 ºC. Temperature was monitored on the vital parts of vacuum envelope, such as dipole chambers, photon absorbers and end flanges having possibility of temperature rise over trip set point. In the control room, an alarm is generated and interlock is activated after temperature crossing the respective set points. These units have feature of open sensor detection and isolated RS485 communication. Due to the requirement of additional demand of temperature monitoring especially after installation of undulators, development of 16-channel temperature monitoring unit was taken up and tested successfully. The size was reduced almost to half of earlier unit considering limited space available for installation in Indus-2 tunnel. This unit supports quick replacement and onsite firmware upgradation for reducing maintenance time as required.

4. Summary

State-of-the-art UHV system is required for the reliable operation of particle accelerator and storage ring. UHVTS, RRCAT has acquired the expertise of design, development, installation, commissioning and reliable operation of large UHV systems of Indus machines. This article summarizes the recent upgradation of Indus-2 storage ring and technological developments in UHV domain related to Indus and future accelerators.

5. Acknowledgment

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