Simulation Studies of Vacuum System for Indus-2

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Abstract: Due to eight fold symmetry of lattice, the 172.4 meters circumference of Indus-2 was divided into eight unit cells. The location of vacuum pumps was restricted by location of more important components like magnets, beam diagnostic components etc. The minimum permissible beam aperture, restricted by apertures of magnets, rendered the vacuum envelope highly conductance limited. Main sources of gas loads viz the outgassing and the photon induced desorption (PID) were also highly location specific, because of location of photon absorbers, and the specific nature of vacuum components. Therefore, the computer simulation of a unit cell was important to have a feel for ultimate results obtained by a particular configuration of pump installation. The vacuum system for a unit cell was studied using electrical equivalent network for the vacuum system. The entire circuit was analyzed by using commercial software used for electronics circuit analysis. Since the synchrotron radiation leads to cleaning effect and the PID yield reduces with accumulated dose of beam current, system’s behaviour with beam current was also studied by using computer program obtained from BESSY Berlin. This provided an estimate of dose necessary for achieving the specified operation of UHV system for Indus-2. The calculations also helped in optimizing the initial cleaning of chambers by glow discharge cleaning etc. This paper presents the results obtained by computer simulations of a unit cell of Indus-2, carried out by both the methods.

1. Introduction
In a large synchrotron radiation source like Indus-2, the performance and ultimate pressure of the vacuum system depends on the pumping speed, outgassing rate of vacuum chamber material and other additional gas sources like photon induced desorption etc. The conventional approach of using discrete lumped pumps was adopted for Indus-2. This approach led to minima at location of pumps and maxima at the location in between the adjacent pumps. The inherent conductance limitations did not favor high speed pumps. During the operation of the storage ring, the PID gas load at the locations of discrete photon absorbers also resulted in large pressure bumps if sufficient pumping was not installed at these locations. Therefore, the selection of pumps, their locations and installation in the storage ring were also important factors for achieving uniformly good vacuum. For a large UHV system like Indus-2, it became necessary that the performance of actual system is studied by simulating it on a computer.

2. Description
The Indus-2 vacuum system was made from very large number of vacuum components. There were 16 numbers of dipole chambers, interspersed with 46 numbers of straight section chambers. The r.f cavity sections and injection section constituted special sections reserved for r.f cavities, the septum magnets and kicker magnets. Seventy-seven numbers of diagnostic components like Beam Position Indicators, Beam position monitors, Fast current transformers, Direct current transformers etc also formed part of
storage ring vacuum envelope. Fifty six numbers of r.f shielded bellows were used to ease system installation and to take care of thermal expansion during baking. Sixty four numbers of photon absorbers were installed on dipole chamber to absorb unused synchrotron radiation. All these components had different vacuum characteristics. Their outgassing rates were also variable with scrubbing of chamber walls by synchrotron radiation.

In order to facilitate easier evacuation, the Indus-2 vacuum system was divided in eight vacuum segments each having a length of approximately 21.58 meters. Two dipole chambers, six straight section chambers, beam diagnostic components, bellows, valves etc formed each vacuum segment, which were isolated by two r.f contact UHV gate valves at the ends. Figure 1 shows one of the vacuum segments, used for computer simulations.

![Figure 1: A Vacuum Segment for Indus-2](image)

The cross section of straight sections of Indus-2 was relatively simple and the pumps were directly mounted using ports having aluminum to stainless steel transition joints. But the dipole chamber was a complex structure, having an antechamber all along the beam chamber. The antechamber was separated from beam chamber throughout the length by using a 57 mm wide, 9 mm high channel. The cross sections of straight section and dipole chambers are shown in Figure 2.

![Figure 2: Cross Section for Vacuum Chambers of Indus-2](image)
On dipole chamber, vacuum pumps were installed at the antechamber and the pumping of beam duct was obtained through the narrow channel. The discrete photon absorbers were also installed on the antechamber and they were located just above the pumps to take care of PID gas loads near its origin. Each of these dipole chambers was pumped by three numbers of Sputter Ion Pumps (SIP) with nominal pumping speed of 270 l/s each. Three Titanium sublimation pumps (TSPs) were also attached to them in series. There were provisions for two NEG pumps to be installed on each dipole chambers. The straight sections were provided with SIPs and TSPs connected in parallel. The pumping scheme envisaged achieving the base vacuum in $10^{-10}$ mbar range by using SIPs only. The TSPs were planned to be used during first phase of commissioning, especially to take care of additional gas load due to PID. Finally NEG pumps will be installed after the first stage of commissioning and stabilization of operation, when the opening of storage ring for interventions will be rare phenomenon. Important input parameters for Indus-2 are tabulated below.

| Parameter                                           | Value                      |
|-----------------------------------------------------|----------------------------|
| Electron Beam Energy                                | 2.5 GeV                    |
| Electron Beam Current                               | 300 mA                     |
| Circumference of storage ring                       | 172.43 meters              |
| Radius of curvature for beam in dipole magnets      | 5.55 meters                |
| Ultimate vacuum                                     | $< 2 \times 10^{-10}$ mbar |
| Required operating vacuum, with the specified beam  | $1 \times 10^{-9}$ mbar    |
| Construction materials for chambers                 | Al alloys                  |
| Construction material for other components exposed to vacuum | AISI316L SS, OFHC, Be-copper etc |
| Circumference of Straight Section aperture           | 21.06 cm                   |
| Area of X-section for SS chambers                   | 27.70 cm²                  |
| Circumference of BM aperture                        | 106.255 cm                 |
| Total Area of X-section for BM chambers             | 116.70 cm²                 |
| Linear conductance of SS Chamber                    | 2314.28 l/s per cm         |
| Linear conductance of BM Chamber                    | 5525 l/s per cm            |
| Volume of Straight section Chamber                  | 0.0277 l/cm                |
| Volume of BM Chamber                                | 0.1067 l/cm                |
| Total PID gas load, with $\eta = 10^{-6}$ molecules/photon, | $5.235 \times 10^{-5}$ mbar.l/s |
| PID gas load with $\eta = 10^{-3}$ molecules/photon  | $1.45 \times 10^{-4}$ mbar.l/s per degree |

**SR distribution**

- Into the 0° Beam line: 0.99 degree
- On Absorber-2: 3.46 degree
- Into the 5° Beam line: 1.25 degree
- On Absorber-3: 3.7 degree
- Into the 10° Beam line: 1.38 degree
- On Absorber-4: 6.84 degree
- On the exit walls of dipole chamber: 2.23 degree
- On SS chamber i.e on a length of 905.97 cm in LSS & 550.232 cm SSS: 2.21 degree
- On the next dipole chamber in between BAG on dipole and Absorber-1: 0.45 degree

To simulate the vacuum system of Indus-2 two types of calculations (viz in static conditions without electron beam and in dynamic conditions with electron beam circulating in storage ring), were carried out. Electrical equivalent network simulation method was used for static calculations [1]. The reduction of PID yield with SR dose and ensuing beam cleaning was very important to study vacuum
system behavior, when the electron beam was circulating in the storage ring. The computer program obtained from BESSY, Berlin was used for these dynamic gas load calculations. This program had also been used at APS and ESRF for simulation of their vacuum systems [2, 3].

3. Computer analysis for static gas load

3.1. Electrical equivalent network

In this method of calculations, the beam chamber was divided into number of elements and every element was a source of gas current desorbing from surface of its walls. These gas currents flowed into the pumps and led to superposition of gas currents in every element. Due to the resistance offered by beam tube to the gas currents, pressure gradient developed along the beam. The pressure gradient, $P$ is given by,

$$\Delta P = \frac{1}{C} \frac{dQ}{dt}$$

Where C is conductance and the outgassing rate is the gas current per unit area. i.e.

$$q = \frac{1}{A} \frac{dQ}{dt}$$

In order to simulate one vacuum segment of Indus-2, its length of 21.58 meters, having dipole chambers, straight section chambers, bellows, beam diagnostics components, valves etc was divided into 160 elements along the length of beam chamber. Each of the dipole chambers was divided into 36 elements along beam tube; 36 elements on antechamber and another 36 elements across the pumping channel between the beam chamber and the antechamber. The conductance, surface area, gas loads etc were calculated for each of these elements and the vacuum system was transformed into an electrical network, where the inverse of conductance was equivalent to a resistor. The vacuum pump corresponded to a resistor having resistance value equal to inverse of pumping speed. The gas flow was equivalent to constant current sources. The solution of this electrical network provided voltage at every node, which corresponded to the pressure at that point. Commercial software ORCAD was used to simulate the network. Figure 3 shows a small part of electrical equivalent network for Indus-2 vacuum segment. Various configurations and situations were analyzed by utilizing this network.

3.2. Optimisation of pumping speed for SIPS:

Since the storage ring vacuum systems were conductance limited, and there was limited freedom to install pumps, it is not a very good proposition to pumps with highest available speeds. It was needed to optimize the pumping speed of installed pumps. This also became important to find if adequate pumping speed was installed, as the pumping speeds of SIPS were pressure dependent. Calculations were carried out by varying speed of installed pumps from 20 l/s to 500 l/s. For these calculations the
specific outgassing rate equal to $2 \times 10^{-12}$ mbar.l/s/cm$^2$ was assumed. From the calculations, the pressure values at all the nodes along the beam tube were obtained. By plotting pressure vs. distance, the pressure profiles were obtained along the beam duct of the section under consideration. The average pressures in the segment were obtained by the relation:

$$P_{av} = \frac{1}{l_{max}} \int_0^{l_{max}} p(x) dx$$

Figure 4 shows the pressure profiles and average pressure in one segment of Indus-2, by using different pumping speeds for individual pumps.

![Figure 4: Pressure profiles in a unit cell with different speeds for SIPs](image)

In order to clearly understand the effect of pumping speed on average pressure, average pressure vs. pumping speed plot is given in Figure 5. This plot showed that very significant improvements were not observed for pumps with more than 200 l/s pumping speed. From plot it was also observed that the effective speed near 50 l/s should be maintained even at very low pressures. Since the SIP speeds are pressure dependent, the choice of 140 & 270 l/s SIPs was made for Indus-2, as they had sufficient speed in this range even at $10^{-9}$ mbar.

![Figure 5: Variation of average pressure with pumping speed of each SIP](image)

3.3. Variation of pressure profiles with specific outgassing rate
Since the specific outgassing rates ($q$) reduced with time and also with cleaning effect of beam, an improvement in the ultimate vacuum was expected in the storage ring for static gas load condition.
Using electrical equivalent network, calculations were done at $2 \times 10^{-14}$, $2 \times 10^{-13}$, $2 \times 10^{-12}$, $5 \times 10^{-12}$, $2 \times 10^{-11}$ mbar.l/s/cm² specific outgassing rates. The resulting pressure profiles for different specific outgassing rates are shown in Figure 6. Fixed pumping speed of 200 l/s per SIP was used for these calculations. It was noted that the measured values of pressures were in $10^{-10}$ mbar range for Indus-2 and it corresponded to an outgassing rate in $10^{-12}$ mbar/l/s/cm² range.

**Figure 6:** Pressure profile in a unit cell with varying specific outgassing rates $q$.

### 3.4. Effect of real leaks

In order to understand the behavior of UHV system, it was beneficial to know the influence of real leaks. Therefore, simulations were carried out by deliberately introducing real leaks in the network. The real leaks were introduced at an end of vacuum section and gas flow rates due to leak were varied from $10^{-8}$ to $10^{-3}$ mbar l/s. Figure 7 shows the resulting pressure distributions. It was observed that the leaks in the range of $10^{-6}$ to $10^{-3}$ mbar l/s had resulted in the pressure rise beyond the adjoining dipole chamber and up to more than half of vacuum segment. However, smaller leaks indicated an influence only up to adjoining dipole chamber and this pressure rise was utmost in $10^{-9}$ mbar range. Therefore, the normal operation of vacuum segment may be continued with a leak rate less than $10^{-7}$ mbar l/s. However, it is not advised to compromise with real leaks initially, as the quality of vacuum will deteriorate if there was power shutdown and pumps were OFF.

**Figure 7:** Pressure profile of a unit cell with different orders of leaks.

### 4. Computer analysis for dynamic gas load

In order to take care of dynamical gas load due to synchrotron radiation and also to account for cleaning effect due to SR, computer calculations were done using a finite element program obtained...
from BESSY. The program used finite element method, where the different sections of vacuum system like sector valves, pumps, bending magnet chambers, straight section chambers, photon absorbers etc were chosen as finite elements. Each of these finite elements was described by number of characteristics like volume, conductance, pumping speed, thermal outgassing and the photon induced desorption. Its own vacuum characteristics and the pressure in the two adjoining elements influenced the pressure in each element. The initial values of PID yield $\phi$, thermal outgassing rates and the starting pressure were assumed and values of volume, conductance, thermal outgassing and photon induced desorption were provided as input for each element.

For dynamic gas load calculations, the reduction in $\phi$ value due to cleaning effect of beam was taken into consideration. The $\phi$ value was assumed proportional to an empirical value of $D^{0.63}$, where $D$ is the dose in A.Hrs. For any electron storage ring, there is large momentary pressure rise during the first injection of beam. An initial pressure and specific outgassing rates were assumed to be $10^{-5}$ mbar and $5 \times 10^{-12}$ mbar-l/s/cm$^2$ respectively, for the unit cell of Indus-2. To assess the effect of cleaning, especially glow discharge cleaning, two cases were studied wherein the initial $\phi$ values were assumed to be $10^{-2}$, $10^{-3}$ molecules/photon. The Pressure profiles and their average pressure calculations were carried out for various values of operating periods ranging from 1 Hr to 5000 Hrs at 300 mA beam current. Figure 8 and Figure 9 show these plots for initial $\phi$ values $10^{-2}$, $10^{-3}$ molecules/photon respectively.

Figure 8: Pressure profiles and Average pressures, for $\phi = 10^{-2}$ molecules/photon.

Figure 9: Pressure profiles and Average pressures, for $\phi = 10^{-3}$ molecules/photon.
As expected, the average pressure in the vacuum segment reduced due to cleaning effect of beam. It was observed that it may take nearly 1500 A.Hrs to achieve an average vacuum of $1 \times 10^{-9}$ mbar at the specified operation, if the initial value was taken to be $10^{-2}$ molecules /photon. However, this period may reduce to less than 40 A.Hrs, if the initial value was taken to be $10^{-3}$ molecules /photon.

Taking this fact into account all the chambers of Indus-2 were GDC cleaned to get $\pi = 10^{-3}$ molecule/e by giving an ion dose of $2 \times 10^{19}$ ions/cm$^2$. Figure 10 shows the variation of average pressure with accumulated dose, for different initial PID yields, where this effect of initial cleaning is clearly visible.

**Figure 10:** Variation of average pressure with accumulated dose.

5. Conclusion
The static gas load simulations using electrical equivalent network showed that an adequate pumping speed had been installed on Indus-2. The specific outgassing rate of $2 \times 10^{-12}$ mbar.l/s/cm$^2$ should be targeted to achieve ultimate vacuum of 2 to $3 \times 10^{-10}$ mbar. Based on dynamic gas load calculations, the Al chambers were cleaned by GDC to have low initial value of PID yield and it is expected to reduce the required accumulated beam dose to achieve the specified beam life time. During the commissioning of Indus-2, the initial behavior of vacuum system [4], indicated that the vacuum system will behave as per specifications and beam life-time of 20 hrs will be achieved for 300 mA, 2.5 GeV operation within reasonable time.

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