T.2 Experience with RF Cavity for Synchrotron Storage Ring Indus-1

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RF Cavity for Synchrotron Storage Ring, Indus-1, is made of Stainless steel and it is internally electroplated with copper. The cavity is designed for 31.613 MHz operation and has an internal diameter of 840 mm and length of 600 mm. The cavity structure is re-entrant type and there are big "capacitor disks" at 10 mm from the median plane which are attached to the end plates through 290 mm long "drift tubes". This article describes the experience with this cavity touching upon the problems encountered and their solution, including design improvements, Finite element analysis of temperatures & thermal deformations, RF analysis, coarse & fine tuning arrangement, electroplating, assembly, vacuum testing, RF testing and integration in the ring. Some details about the performance of the cavity and its influence on the ring are also given.

Introduction

Indus-1 is a 450 MeV, 100 mA electron storage ring. It has a perimeter of 18.96 meter. The ring requires one radio frequency cavity operating at 31.613 MHz. A length of 900 mm is available for the cavity in the ring. Considering the relatively low frequency of the cavity and the limits suggested by mechanical design, a re-entrant type of structure was designed. The resulting inside diameter of the cavity was 840mm and inside length was 600 mm. The cavity should maintain a vacuum of the order of $\sim 10^{-9}$ mbar. After about five years of operation, the cavity developed a vacuum leak and the vacuum deteriorated to unacceptable level. Considerations of geometry of the structure, location and type of defect and the fact that it is an RF structure, dictated that the solution couldn't be achieved by local repair of the leak. Executing a re-design and fabrication of the defective part of the cavity structure has solved the problem.

Fig. T.2.1 *The original cavity structure*

The original cavity

The cavity is made by internally electro-plating copper on stainless steel Type 304L substrate. The original structure, shown in Fig.T.2.1 worked successfully for five years. This is a reentrant type of construction. The resonating frequency of the structure is very sensitive to the movement of capacitor plates, frequency shift being 1.27 MHz/mm of symmetrical parallel movement of the plates towards median plane. To keep the frequency shift to a minimum during evacuation, the end plates are designed on the basis of stiffness. Fig. T.2.2 shows the photograph of the defect on the drift tube, which led to vacuum leak, on one symmetrical-half of the cavity. The cavity is made in two halves having a large joint at the median plane (normal to the axis) sealed by a Helicoflex® seal. This seal has a sealing lining of aluminum, inner lining of Inconel 600 and elastic core spring of Inconel X750 (HN200 seal).

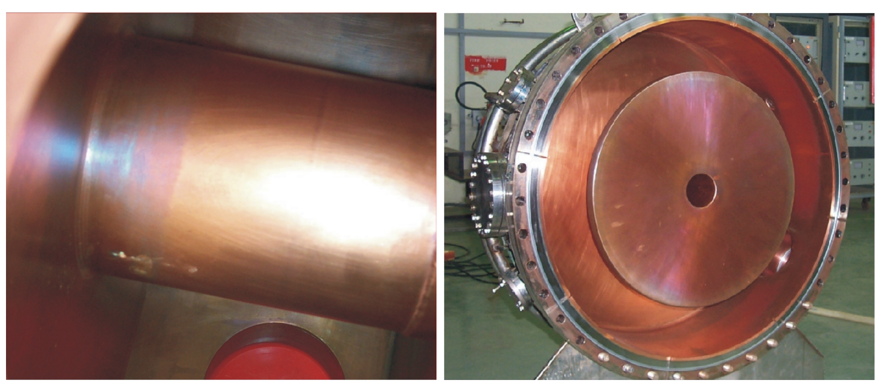

Fig. T.2.2 *The defect on the drift tube can be seen on the left. The original cavity structure after opening, a large Helicoflex seal, in place for many years, can be seen on the flange*

Operational experience and problems encountered

The cavity was assembled outside the ring and then integrated with its vacuum envelope. The cavity achieved a vacuum of $5x10^{-9}$ mbar after its onsite baking using electrical baking oven. The cavity was cooled using a separate chiller with temperature control within 1 ºC. The cavity fulfilled the required RF parameters. However it had a slightly longer start-up time due to initial thermal detuning. Vacuum in the cavity started degrading in the second week of June 2001. During investigations, a longitudinal crack (caused by the corrosion) was found on the drift tube adjacent to a cooling coil, which was attached to the drift tube by torch brazing with Ag-Cu eutectic filler.

Considering that the operation of storage ring depended on this cavity, the cavity had to be restored in a short period. This dictated an important design consideration of short implementation time for the restoration effort. This aspect was taken into account in the design and time consuming operations of Cu plating and welding were minimized.

Design details of modified cavity

Two options were considered to resolve the problem of vacuum leak. The first option was operating the cavity in air. This could be done by isolating the beam pipe using an alumina tube passing through the drift tube. The second option was to replace the capacitor disk-drift tube with such new construction that can be manufactured in a short time.

The first option had to be discarded due to following reasons:

a) There was a significant power loss in the alumina tube and very high air flow velocity, over the tube, was required for cooling the alumina tube

b) Previous adverse experience of arcing/unstable operation of the cavity in air.

Hence the second option was pursued. The modified cavity structure in shown in Fig. T.2.3. Stainless steel grade AISI 304L was chosen for manufacturing RF cavity due to manufacturing constraints in the center. The capacitor disks with inter-space are replaced with solid stainless steel disks, relying on cooling by conduction through solid. The previously existing brazed cooling tubes on the back walls of the capacitor disks were done away with. This became possible due to lower level of actual gap voltage requirement (22 kV as compared to initial estimate of 30 kV), for operation of Indus-1, thus reduced power loss. The typical heat loss on various cavity surfaces, calculated for modified geometry, is shown in Fig. T.2.4. The choice of solid disks removes the multiple machining requirements, brazing of long cooling coils and also reduces the weld length to a very minimum. In addition the four vacuum boundary joints are eliminated. Two coaxial tubes in original design were replaced with a single thick tube with six longitudinal holes drilled in the tube wall each having a smaller tube inside it. The cooling water enters through the smaller inner tubes and returns through the annular space as shown in Fig. T.2.5, thus providing flow directly on internal surfaces of the holes of the drift tube on a large area.

Fig. T.2.3 The modified cavity structure

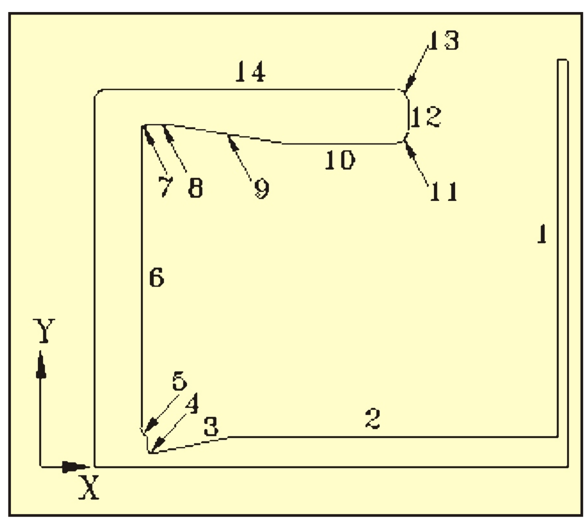

Fig. T.2.4 Power loss in one symmetrical-half of the cavity structure

Table 1

Surface No.	Power Loss (W) @ 22kV Gap Voltage	Surface No.	Power Loss (W) @ 22kV Gap Voltage
1.	30	8.	6
2.	47	9.	32
3.	25	10.	16
4.	4	11.	2
5.	3	12.	3
6.	151	13.	2
7.	9	14.	7
Total power loss			**337**

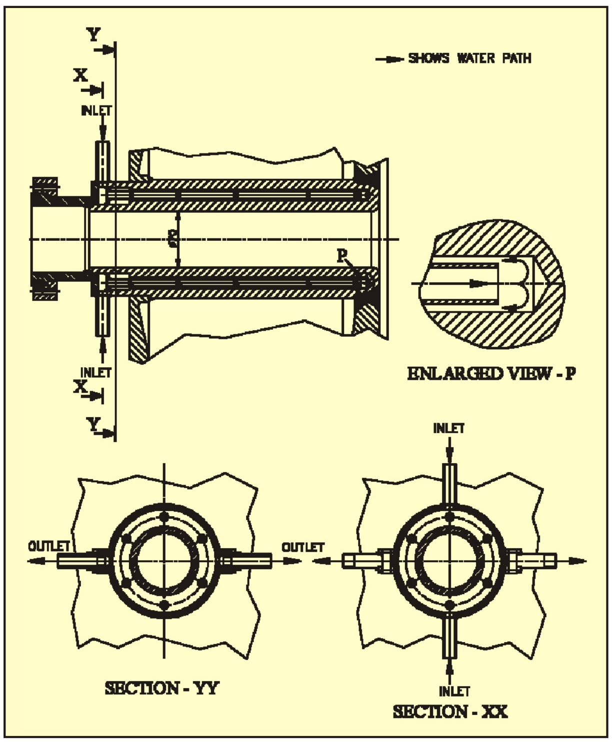

Fig. T.2.5 *Cooling circuit of the modified cavity structure, note that the cooling coils are not welded to the drift tube yet its rigorous cooling is available. There is no joint on water to vacuum boundary*

This concept also provides a high coefficient of heat transfer at the end of the hole, where water impinges on the bottom of the hole. This provides vigorous cooling in the drift tube, reducing the variation of the frequency sensitive capacitor plate gap, which is important for controlling the thermal frequency shift. Such construction of drift tube has inherent advantage of better thermal performance and robust manufacturing compared to brazed and welded coils. The capacitor disks are tapered towards the inner diameter to reduce the welding requirement. Water cooling from the end plates and shell of the cavity were removed, due to frequent leakage problem, and blast air cooling using 16 Nos. of 4.5” instrument cooling fans was provided. Temperature distribution and thermal deformation were calculated using software COSMOS/M and ANSYS (Figures T.2.6 and T.2.7). These values were then used to calculate the frequency shift of the cavity from no power to full power using software SUPERFISH.

Fig. T.2.6 *Temperature distribution for power loss corresponding to 22kV with cooling water flow of 50 lpm in the drift tube cooling circuit*

Fig. T.2.7 *Variation of Axial Displacement of capacitor disk, towards the cavity median plane, is plotted as a function of its radius with cooling water flow of 50 lpm in the drift tube cooling circuit*

Copper plating

As mentioned above, the original plating of the complete cylindrical shell and most of the area of the end plates of cavity was preserved. Plating was stripped selectively from the end plate adjacent to the weld and then new drift tube wad joined. Capacitor-drift tube subassemblies were welded, finish-machined and electroplated separately, leaving a small area adjoining the weld location. The sub-assemblies were welded to the end plates. Cooling headers were also welded at this stage. After completing all the welding operations, the weld and its adjoining area was electro-plated by using the cavity shell itself as the tank for holding the electrolyte.

A series of cleaning steps were followed to remove the surface contaminants (oil, grease, oxides etc.) and for activation of the surface before deposition [2]. Copper was deposited to a thickness of 60 microns based on the skin depth calculations.

Heat treatment

The newly electroplated capacitor-drift tube sub-assemblies were heat treated in vacuum furnace to

- remove the gases generated during the plating
- improve the adhesion of the copper plating
- to stress relieve the structure to prevent deformation due to stress relieving during baking.

The heat treatment was done at a temperature of 200°C and a vacuum level of 1.0E-5 mbar. A large vacuum furnace, equipped with a cryo pump with a pumping speed of 10000 liter per second, with a cylindrical hot zone of diameter 750 mm and a length of 2500 mm was used. The mass of the sub-assembly was about 130 kg.

Each of the copper-plated sub-assembly was treated separately. Job loading was done with care to avoid any scratch on plated surfaces. There was no prior experience of degassing a copper-plated SS plate. Heat treatment cycle lasting about 72 hours was followed.

Vacuum performance

The individual weld on the vacuum boundary were leak tested by MSLD (He) having a sensitivity of $3X10^{-10}$ mbar.lit/sec and no leaks were detected. When the cavity was assembled using Helicoflex®, the joint showed a gross leak rate of 10^{-6} mbar.lit/sec. Initially it was suspected that the flange surface may have scratches, however even after re-machining of the flange surfaces and careful centering of the seal in the groove, the leak persisted at the same level. Due to repeated non-sealing of the joint with Helicoflex®, a VITON gasket was used. The Helicoflex® seals used here were bought in a lot when the cavity was developed in 1992 and it is suspected that during a long storage period their aluminium surface has developed a thick oxide layer, which is hindering a proper sealing. It is to be noted that the previously installed Helicoflex® worked for about five years and when the leak in drift tube was found, the seal was still good. The cavity was baked at 120°C for 24 hours using a special oven around it and the cavity is sustaining a vacuum of $1X10^{-8}$ mbar with two 270 lit/sec SIPs and two 1000 lit/sec TSPs.

Tuning of the cavity

Coarse tuning was done by changing the axial gap between the capacitor disks. A mechanism has been provided on the end plates of the cavity for this purpose. Online fine tuning is done by using three cylindrical tuning plungers, which operate in the cavity volume.

High power testing of Indus 1 modified RF cavity

After baking the cavity, initial resonant frequency was adjusted to 31.770 MHz with β of feed loop adjusted to 1.28. RF conditioning of cavity was started without cooling water circulation. Power was increased slowly in pulsed mode. CW power of 200 watts could be fed on the first day and cavity gap voltage of 29 kV was reached on the second day (with considerable multipactoring). With cooling water flow & forced air-cooling, frequency drift of 2 kHz /°C was observed (due to the change in ambient temperature). With three tuning plungers for taking care of beam loading & thermal detuning, auto start of RF system was possible.

The tuning range of the three tuners is 110 kHz. Resonant frequency of RF cavity was again adjusted to 31.619 MHz (desired Indus-1 RF system frequency) with coarse tuning arrangement mounted at both the end plates of RF cavity. With all these modifications in RF cavity & optimization of feed back loops for amplitude, phase & frequency, smooth operation was achieved. Consequently downtime of Indus-1 RF system has been greatly reduced since October 2001. With maximum of 100 mA and 150 mA of stored current in the storage ring the detuning observed, due to beam loading, was around 9 KHz and 12 KHz respectively, which is well within the available tuning range of the tuning plungers. Table-2 summarizes operating experience of this modified RF cavity.

Failure analysis:

A failure analysis was performed to identify the cause of the failure. There was a possibility that halogen acids used during electro-plating were left in the crevices at braze interface. This brazed interface remained under atmospheric pressure during the operation of the cavity. The cavity was baked about 15 times to 170°C using electrical heating tapes. During the course of operation the cooling water started leaking into the interspace and it is suspected that high temperature combined with the presence of brazing flux & acid residues provided favorable conditions for corrosion. The drift tube was de-brazed and failure analysis was done to know the exact cause of the problem. This revealed intergranular corrosion and extremely coarse grains of the material [3].

References:

1. Thermal design of modified Indus-1 RF cavity - Abhay.Kumar, Jishnu Dwivedi,SG Goswami, RS Sandha & HC Soni, CAT internal report CAT/2002-25

2. Internal Report on failure analysis of drift tube of RF cavity – Rakesh Kaul, P.Ganesh, AK Nath, CAT.

3. Electrodeposition of Coper on Stainless Steel Radio Frequency Cavity of Indus-1 - P.Ram Sankar, B.Q.Khattak, A.P.Singh, S.K.Sharma, M.B.Kadam, C.Manikandan, C.R.Singh and S.N.Vyas, presented at "Indian Particle Accelerator conference 2003".

Table - T.2 : Thermal Detuning and Start-up time of original and modified cavity

S.N.	Parameter	OriginalCavity	Cavity Modified
1	Thermal Detuning	140 kHz at 25 kV 90 kHz at 15 kV	80 kHz at 30 kV 50 kHz at 22 kV Around 70% of the detuning takes place within two hours and rest 30% continues for 3-4 hrs.
2.	Start-uptime	40 minutes	5-10 minutes

The cavity was operated at 30 kV for limited period and did not show any problem of either out of range frequency detuning or vacuum degradation.