THERMAL DESIGN MODIFICATION AND OPERATIONAL PERFORMANCE OF INDUS-1 STORAGE RING RF CAVITY

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Abstract

RF cavity of Indus-1 *storage ring*, having an operating frequency of 31.619 MHz, is a normal conducting cavity and is made of stainless steel and has been internally electroplated with copper. Vacuum in the RF Cavity started deteriorating in June 2001 and it came down by three orders [10^{-6} mbar] within a few weeks. The original design of the RF cavity incorporated a double walled construction with a provision of internally brazed copper cooling tubes. After copper plating operation, some corrosive chemicals got trapped in the brazed copper tubes and with time, the tubes started leaking. This corrosive water started getting accumulated in the inter-space of the double walled construction and it led to the corrosion of the drift tubes. After investigations, it was concluded that the cavity would have to be cut to remove the corroded drift tubes and replace them with new ones. It needed a complete change of the basic thermal design of the cavity, which included objectives like avoiding water contact with vacuum weld joints and eliminating a possibility of water leaking and trapping. A lower total thermal detuning (less than 80kHz) and shorter start-up time (less than 20 minutes) were the prime targets in this design modification. Since it was mandatory to complete this work within two months to bring back the Indus-1 into operation, low manufacturing time was also targeted into the design modification. Also, some of the external copper cooling tubes were giving persistent water leaking problems and the new design was expected to eliminate these problems.

After some time of operation of this cavity, the pumping capacity of the chillers unit also came down and it became necessary to revalidate the design for lower flow conditions.

This paper includes the design modification work along with studies for the lower flow conditions. The paper will discuss impact of flow conditions on detuning of the cavity and issues related to its transient behaviour and thermal stability. Finite Element code ANSYS has been used for the *simulation* studies.

Since this cavity is now operational for two years, the paper will compare the calculated frequency detuning, start-up time and total transient time with its *operational performance.*

OBJECTIVES

The objectives of the new thermal design work can be summarized in the following salient points:

- Design for low manufacturing time,
- Keep the thermal detuning to less than 80 kHz,
- Reduce the start-up time from 40 minutes to 20 minutes,
- Restrict the maximum temperature of the cavity structure to 70°C,
- Restrict high temperature zone to the minimum,
- Avoid a contact of water with vacuum weld joint on all areas,
- Eliminate the water leaking problems of copper cooling tubes and
- Keep the thermal stresses within allowable limits.

GEOMETRY AND POWER LOSS ON INTERNAL SURFACES

The internal surfaces of the RF cavity form an axisymmetric structure (barring port holes) with a maximum internal diameter of 840 mm. The total internal length of the cavity is 600 mm. It has got two parallel Capacitor Plates (referred as CP in this paper) with 592 mm diameter each. The cavity is made in two symmetrical halves each having one CP. The nominal gap between the CPs is 20 mm. The cavity has got ports on the shell part for vacuum pumps, RF coupler, tuners and sensors. The end plates have got ports for connecting the cavity to the ring. Each end plate is also equipped with a spider assembly that can perform a coarse tuning of the cavity by controlling its elastic deflection due to external pressure.

The RF power loss data on the internal surfaces of the cavity varies through out its internal geometry. It is maximum on the drift tube external surface (surface no 6) and significantly higher on the backside of the capacitor plate (surface nos. 7,8,9,10,11) as compared to other internal surfaces of the cavity.

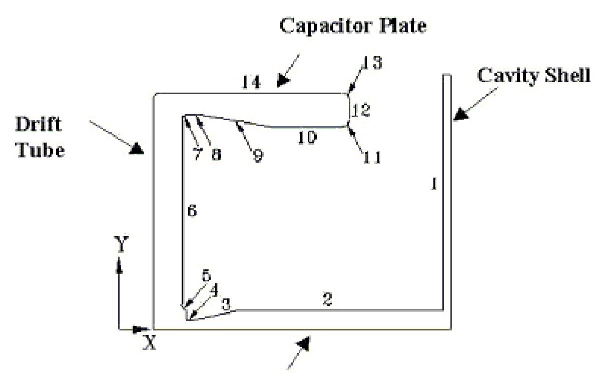

Figure 1: Surface nomenclature of the RF cavity. Y axis shows the electron beam direction and is also the axis of revolution of the RF-structure. X-axis shows the radial direction.

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For a typical case of 22 kV gap voltage, the total power loss is 674 W and out of this, 302 Watt power loss takes place on drift tubes alone.

CONCEPT

The cooling in drift tubes is provided with six circumferentially equally spaced water-cooled longitudinal holes. Six tubes need to be inserted in these annular holes. This provides an annular cooling cross section for each tube-hole pair. Water flows through these cooling tubes towards the CP and at the end of these tubes, it comes out and strikes on the wall of CP and a flow reversal takes place. Then water flows through the annular holes in reverse direction. The diameter and length of the annular holes were selected on the basis of the drill diameter and length readily available in CAT workshop.

The capacitor plates are cooled only by conduction and therefore the major disadvantages of this design were the higher expected temperatures and temperature gradients on CPs. A thorough finite element based thermal analysis was performed to see these effects. The thickness of CP was also adjusted to have minimum thermal gradient.

FINITE ELEMENT MODELING

This RF Cavity loses its axisymmetric nature due to presence of various ports and annular holes. However, the assumption of axisymmetric structure still can be made without sacrificing much on the accuracy of results. The ports on the shell part of the cavity have been ignored for this analysis.

Following correlation has been used for calculation of average heat transfer coefficient in the turbulent region over the cooling slot surface:

$h = 0.023\ (k/d)\ (Re)^{0.8}\ (Pr)^{0.3}$

Following correlation has been used for calculation of average heat transfer coefficient in the laminar region over the cooling slot surface:

$h = 4.364\ (k/d)$

The entrance effect and influence of impinging flow (due to very small area on which water strikes) have been ignored. Since an axisymmetric model has been prepared, a correction factor was used for appropriating the value of applied heat transfer coefficient:

Reference temperature has been taken as 30°C.

Second order quadrilateral axisymmetric elements were used to model the structure. Only one half of the cavity structure was modelled and symmetry boundary conditions were imposed to simulate the other half in thermal strain analysis. No such boundary condition is required in heat transfer analysis.

Sequential coupled field analyses were performed to calculate thermal displacements.

Following properties were used for the stainless steel 304L material:

$K = 0.016$ W/mm.K $\rho = 7.8 \times 10^{-6}$ kg/mm^3
$C_p = 500$ J/kg.K $\alpha = 17.6 \times 10^{-6}$ per K
$E = 190$ GPa

RESULTS

Heat transfer analyses were carried out with two parameters as input variable:

Flow Rate: It was varied from 50 lpm to 10 lpm

CP Gap Voltage: It was varied from 22kV to 30 kV

Since the RF Cavity was successfully working for five years, its operating experience was also used to restrict the design to more realistic specifications. It was observed that the CP gap voltage remains around 20kV. A 10% higher value of 22kV was chosen for design optimization. However, to see the effect of higher gap voltage, the analyses were extended to the situations where this gap voltage goes up to 26 kV and 30 kV.

Maximum Temperature inside the cavity

The results show that the maximum temperature depends on the flow rate but this dependence is negligible unless the flow is taken to laminar region. However, the maximum temperature reached shows a strong dependence on gap voltage. The temperature remains within 56° C for a gap voltage of 22 kV and within 66° C for 26 kV gap voltage for flow rates above 20 lpm. The maximum temperature reached for 30 kV gap voltage case is around 75°C for flow rates above 20 lpm. For 50 lpm case, the maximum temperature reached in case of 30 kV gap voltage remains less that 73°C which is marginally above the design limit.

Temperature variation inside the cavity

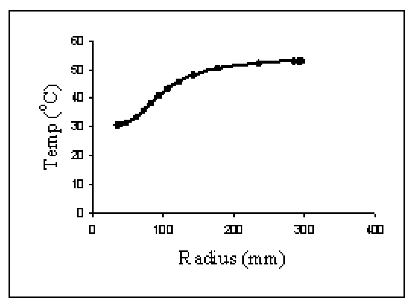

Figure 2: Temperature distribution on the front side of CP for 50 lpm, 22kV case.

The temperature of the whole cavity remains within 32.6°C except for the CP and adjoining part of the drift tube. The geometry of CP has been chosen to decrease the temperature difference across the thickness of the CP. This will help in reducing the longitudinal thermal distortion of the plates towards the median plane of the cavity.

Figure 2 summarizes the temperature distribution on the front side of the CP for 50 lpm, 22kV case.

Thermal deformation of the RF Cavity

Whole cavity structure distorts when subjected to RF power loss. This thermal deformation of the cavity produces change in the fundamental frequency of the cavity. The two online tuners of the cavity with 100 kHz tuning range take care of this change during the operation of the storage ring. The sensitivity towards change in fundamental frequency of the cavity due to thermal displacement of other parts of the cavity structure is significantly less than that due to thermal displacement of CPs in axial direction. A slightly conservative estimate of frequency detuning was made by accounting for longitudinal thermal displacements of the CPs only.

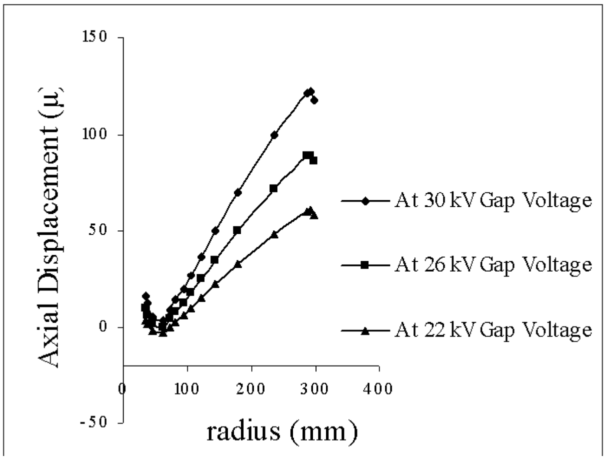

Figure 3: Axial displacement of CP

The thermal displacements increase with reduced flow rate and increased gap voltage. After investigation of all cases of flow rates it was concluded that the longitudinal displacement is primarily due to swelling of CPs as it was found to depend on the temperature and the thickness on a particular radial location.

Frequency detuning of the cavity

It was found that the frequency detuning remains within 55 kHz at nominal operating gap voltage of 22 kV.

Transient behaviour of cavity

The rate of rise of the temperature is initially high but reduces with time. Slow variations in the fundamental frequency of the cavity after elapse of three hours is expected. For a case of 22kV Gap Voltage and 50 lpm flow rate, the total thermal detuning is around 55 kHz and therefore around 35 kHz detuning should take place in 3 to 4 hrs. After this the detuning will increase with extremely slow rate. Since the total frequency detuning itself falls within the tuneable range, this prolonged drifting will not cause any problem. This, in turn, was expected to eliminate the practice of manual tuning at the start-up and hence the start-up time was expected to fall sharply.

Forced air cooling on outside surfaces to replace forced water cooling

A set of calculations was performed to see the effect of cooling by natural convection on the shell and end plates and to facilitate a decision regarding removal of water-cooling through copper cooling tubes brazed on the external surfaces of the cavity. It was found that if we employ forced convection by air, then the maximum temperature may not rise beyond 33°C on the end plate. Consequently, copper cooling tubes were removed and a forced air convection system, that included 12 six-inch fans put over each end plate, was designed and assembled on the cavity. 8 fans were put on the periphery so that they can also cool the shell part.

CONCLUSION OF THE ANALYSIS

This design satisfies all the objectives and therefore no problem is foreseen up to a gap voltage of 26 kV. It was assumed that the laminar to turbulent transition takes place at Re = 2300. However, in practice, this value varies from 2100 to 3000. Hence, it is suggested that the flow rates must be kept above the 20 lpm value. The design may be tested for 30 kV gap voltage.

OPERATIONAL PERFORMANCE

S.N.	Parameter	Original Cavity	Modified Cavity	
			Calculated	Observed
1	Thermal detuning	140 kHz at 25 kV 90 kHz at 15 kV	80 kHz at 26 kV 55 kHz at 22kV	80 kHz at 30 kV 50 kHz at 22 kV
2	Start-up time	40 minutes	No start-up time requirement was observed	5-15 minutes
3	Detuning time	40 minutes	70% of detuning will occur in 240 minutes duration	180 –240 minutes
4	Thermal Stability	Data not available	Stable.	Stable

The cavity was operated at 30kV gap voltage for limited period and no operational difficulty was observed

ACKNOWLEDGEMENTS

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REFERENCES

[1] Restoration of RF Cavity for Synchrotron Storage Ring INDUS-1 –APAC 2004- Jishnu Dwivedi et al.