THEORETICAL ANALYSIS AND FABRICATION OF COUPLING CAPACITOR FOR K500 SUPERCONDUCTING CYCLOTRON AT KOLKATA

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Abstract

K500 SC cyclotron has already been constructed and commissioned after spiralling Ne^{3+} internal beam with 70 nA up to extraction radius (670mm) at variable Energy Cyclotron Centre at Kolkata, India. Several problems have been experienced related to the coupling capacitor of the radio frequency system including its sever burning during commissioning of the cyclotron. Making of the dissimilar joints between alumina ceramic and copper of the coupling capacitor demands the usage of vacuum furnace to avoid the cracking of the ceramic. Therefore exhaustive analysis has been carried out to facilitate the in-house fabrication of the coupling capacitor without using the vacuum furnace in case of emergency. The maximum allowable rate of temperature rise of the ceramic and the optimum thickness ratio of the copper to ceramic have been estimated. Finally, fabrication of the coupling capacitor has been carried out in-house without employing vacuum furnace. At present the coupling capacitor is performing well as maximum 57 KV DEE voltage were been achieved till date. This paper presents the details of the analysis and experiences gained during the fabrication of the coupling capacitor.

INTRODUCTION

K500 Superconducting Cyclotron was installed at VECC last year. After commissioning of all the individual sub-system and having spiralling internal beam up to extraction radius, beam extraction process is going on.

While commissioning of the cavity-C of the Radio Frequency (RF) system was going on, suddenly coupling capacitor of the same cavity was burnt with immediate effect of vacuum degradation to 10^{-1} mbar from $8x10^{-7}$ mbar. Whereas other two cavities were energized satisfactorily up to 15 kW RF power which is equivalent to 40 kV DEE voltage. Several arching marks at some places of the inner conductor of the coupling capacitor were observed. Copper made argon tube was charred and melted copper drop deposition on the ceramic insulator was noticed. The ceramic insulator acts both as electrical insulator between inner to outer conductor of the coupling capacitor and interface between beam space vacuum (around $8x10^{-7}$ mbar) to atmospheres. Subsequent helium leak testing of the burnt coupling capacitor revealed that ceramic to metal joint was leaking. Therefore in-house fabrication of the coupling capacitor was taken up on top priority basis to short cut the delay in commissioning of the K500 Superconducting Cyclotron.

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DESCRIPTION

Coupling capacitor of K500 Superconducting Cyclotron couples the RF power that is to be fed to the DEE of resonating cavity from amplifier. It is connected to the RF amplifier by coaxial transmission line. Inner conductor of the coupling capacitor is insulated by ceramic insulator made of alumina (99.99 % purity) from its outer conductor. It also acts as interface between beam space vacuum and atmosphere. Therefore the ceramic to metal joint of the insulator should have helium leak tightness of the order of 10^{-9} mbar.lit/s.

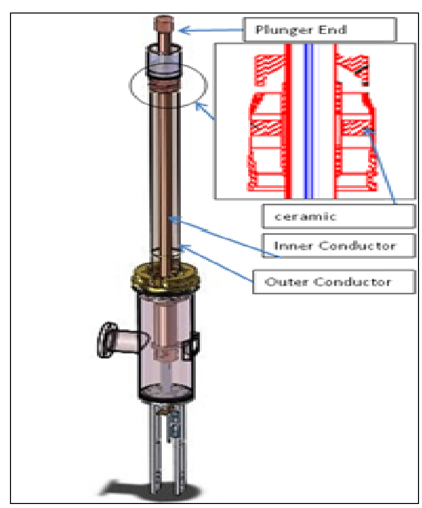

Figure 1: 3D view of the coupling capacitor.

Some part of it is located in the beam chamber vacuum and rest in air. Plunger end of it is positioned within the coupler cup of the DEE after penetrating beam space vacuum from atmosphere. Gap between the plunger and DEE coupler cup is adjusted by moving the inner conductor up and down by hydraulic drive system for the smooth transmission of power. Sliding electrical contact was fabricated by soldering be-cu made contact figure on

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outer conductor surface. Cooling water is circulated within the inner conductor for removing the heat generated in it. Figure 1 shows the 3D view of the coupling capacitor.

THERMOSTRUCTURAL ANALYSIS

Main criticality involve in fabricating the coupling capacitor is successful making of ceramic to metal joint and few neighbouring vacuum tight brazed joint. In the first few trial it has been revealed that ceramic was cracking repeatedly even though provision for maximum cooling was made available. Cracking of the ceramic might be due to the induced thermal tensile stress caused by the excessive heating rate of the ceramic regarding which we were complete ignorant.

Analytical

Therefore a comprehensive analysis to find out the thermal stress developed because of transient temperature gradient and differential thermal expansion coefficient between copper and ceramic was carried out.

A lumped model for the ceramic was considered and temporal variation of temperature (given by equation-1) was found out by solving the equation-2. Lumped modelling of this ceramic material is valid as the value of Biot number is 0.005 which very less than the criteria (i.e. 0.01) below which lump analysis is fairly valid.

$$T = T_a + (T_o - T_a)\exp(-t/\tau) \qquad \text{eq-(1)}$$

$$\rho\, C_p\, V(dT/dt) = h.\, A(T_a - T) \qquad \text{eq-(2)}$$

Where, ρ=Density, Cp=Specific heat, V=Volume, T=Temperature, t=Time, h=Heat transfer coefficient, A= Heat transfer area, Ta =Atmospheric Temp, h= Heat transfer coefficient, To=Initial Temp and τ is time constant given by [(ρ.Cp.V)/(h.A)].

Calculated time constant for our geometry and material is 15 minute. Heat transfer coefficient has been calculated using the empirical formula given by Churchill and chu for natural convection for horizontal plate as given by equation-3.

$$Nu = 0.36 + \frac{0.518\, R_a^{0.5}}{[1 + (0.559/\Pr)^{9/16}]^{4/9}} \qquad \text{eq-(3)}$$

Where, Nu= Nusselt no i.e.$\left(\frac{hL}{K}\right)$, R_a=Rayleigh no i.e. $(G_r.P_r)$, G_r= Grashof no i.e.$\left(\frac{g.\beta.\Delta T.L^3}{\nu^2}\right)$, P_r= Prandtl no i.e $\left(\frac{C_p.\mu}{K}\right)$, μ=Dynamic Viscosity, g= Gravitational Acceleration, β= Volume expansion coefficient and ν= Kinematic Viscosity (μ/ρ), μ = viscosity of liquid, L= Characteristic length, ΔT= Temperature deference, K= Thermal conductivity of copper.

Therefore to have quasi static heating process and to avoid cracking of the ceramic, pre-heating of the ceramic should be done continuously but temperature rise should not go beyond 40 K (calculation shown below) for length of time of duration of time constant i.e. 15 minute.

Now what should be the step of temperature rise for a time interval of each time constant? Maximum possible transient thermal stress is calculated using the formula given by equation-4.

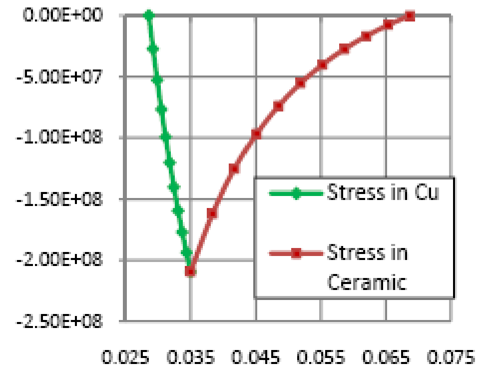
$$\sigma = \frac{E*\alpha*\Delta T}{1-\Omega} \qquad \text{eq-(4)}$$

Where, E= Elastic Modulus, α=Liner Thermal Expansion, ΔT=Temperature gradient, Ω=Poison Ratio.

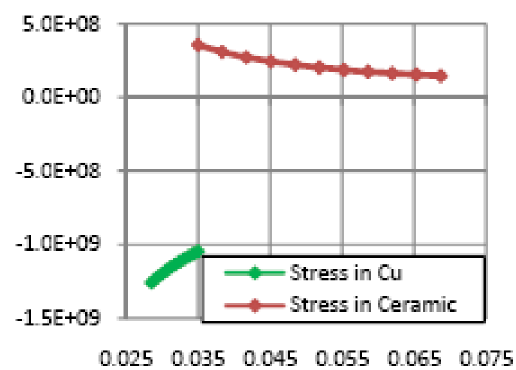
Equation-4 gives out the allowable maximum sudden rise of temperate without cracking the ceramic, i.e.

$\Delta T = \frac{\sigma_{t(1-\mu)}}{E.\alpha.\Delta T.FS}$ (ΔT is calculated putting $\frac{\sigma_t}{FS}$ in place of σ)

Where, σ_t = Ultimate tensile Stress, FS= Factor of Safety



Graph-1: Radial stress in Pa along y-axis and radial distance in meter along x-axis



Graph-2: Tangential stress in Pa along y-axis and radial distance in meter along x-axis

Evaluated ΔT comes out as 40 K for FS=1.5.Therefore allowable rate of temperature rise is ΔT/ τ i.e. 2.66 K/min. And this rate of temperature rise also decreases (i.e as the brazing process goes on) as the stress induce due to the differential liner thermal expansion of the ceramic and copper increases with time. This increase in stress further eat away the available allowable stress.

Thermal Stress induces because of temperature gradient has also been calculated using equation-5, 6 along with the assumption made are infinite long cylinder and shear stress is neglected, All the material properties are isotropic.

$$\sigma_\theta = \frac{E}{1-\Omega^2}\left\{\frac{u}{r} + \Omega\frac{du}{dr}\right\} \qquad \text{eq- (5)}$$

$$\sigma_r = \frac{E}{1-\Omega^2}\left\{\frac{du}{dr} + \Omega\frac{u}{r}\right\} \qquad \text{eq- (6)}$$

Where, u=Radial displacement, r=Radial direction, σ_θ= Tangential (circumferential) stress, σ_r= radial stress

Radial displacement has been find out solving the equation-7 and the plot of the radial stress and circumferential has been presented by graphs-1 and 2

$$\frac{1}{r}\frac{d}{dr}\left\{r\frac{du}{dr}-\frac{u}{r}\right\}=0 \qquad \text{eq-(7)}$$

Maximum tangential stress induced in the ceramic is found to be 120 MPa, Therefore the rate of temperature rise reduced to 1.5 K/min.

Calculation has also been made to find out the minimum current of the TIG welding machine by which TIG brazing could be carried out. When the temp of the welding zone reaches to 600°C, the steady heat loss to the atmosphere due to convection and radiation is 500W. To maintain the temperature of the brazing material minimum 40A current is required to be set in the TIG welding machine at 10 to 12 V. Where ever at the first trial, current at which brazing was done was 100A which in turn resulting to higher rate of temperature rise than the allowable.

Finite Element Analysis

Also 3D finite element analysis has also been carried out using ANSYS software code to evaluate spatial temperature distribution and hence the thermal stress induced due to the temperature gradient. Simulation revealed uniform heating around the copper tube will reduce the induced stress from 100 MPa to 45 MPa. Therefore TIG brazing was preferred with pre-heating along with distributed heating with multiple torch instead of TIG brazing only. Figure-2a shows the model used in FEM analysis and Figure-2b shows the thermal stress induced in case of only TIG brazing is done.

Figure-2a

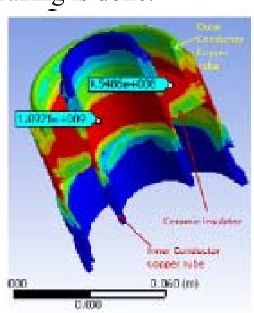


Figure-2b

FABRICATION

During fabrication, arrangements were made for monitoring the temperature of the alumina ceramic as well as copper tube using thermocouple temp. sensor.

Suitable fixture were made and employed to maintain the concentricity between inner and outer conductor of the ceramic as well as to control the brazing distortion. And it has been observed that by heating a copper tube by using one torch could not be sufficient to maintain the rise of temperature within the tolerable limit. Therefore preheating of the copper was carried out up to 200°C by using heater and multiple torch along the circumference and length of the tube. To avoid the contamination of the ceramic reduced atmosphere with argon gas is used.

Finally brazing (see Figure 3) of the copper along with their mating part has been performed. Melting point of the used brazing filler rod (i.e 43% Ag and 57% Cu) is 600°C. To carry out the single circumferential joint of 215 mm length, it took around 6 hours of time. Brazing of the joint was tried to performed with minimum current so that concentrate heating effect could be minimised. It was observed that current could be reduced to 40 A minimum value. After the joint was performed, cooling rate of the joint as well as ceramic was controlled using the heater. After each joint was performed, subsequent vacuum test was carried out and all the joints were pass the helium leak test successfully. Leak found was less than $1\text{x}10^{-9}$ mbar.lit/s.

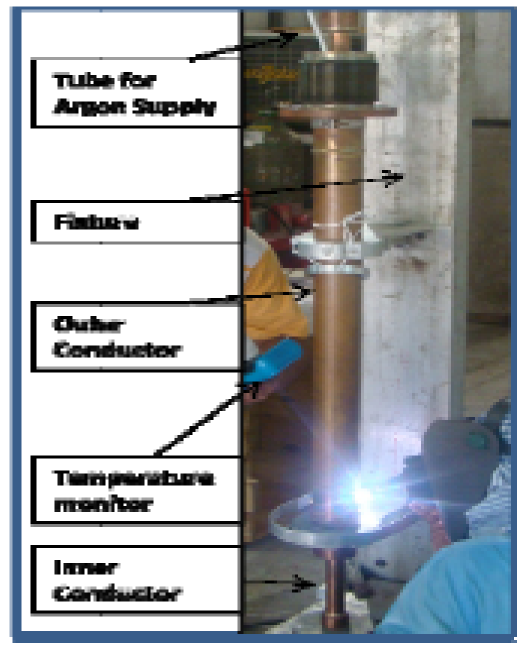


Figure 3: Gas brazing process is under progress

Presently the fabricated coupling capacitor is working satisfactorily with the cyclotron for more than a year and beam extraction using Ne^{3+} is under progress.

REFERENCES

[1] F.P. Incorpera, D.P. Dewitt, “Fundamentals of Heat and Mass Transfer”

[2] J. Kokavec and L. Cesnak, “Mechanical stress in cylindrical superconducting coils”, J. Phys. D: Appl. Phys. 10 NO 11 (1 Aug. 1451-1459).

[3] S. Timoshenko, “Strength of Material Part 2 Advance theory and Problem”, 3rd Edition, CBS Publication & Distributor.

[4] J.F. Harvey, P.E,“ Theory and design of pressure vessel", CBS Publications & Distributor.

[5] S.P. Sukhatme," A textbook on Heat transfer", 4th Edition, University Press.