EXPERIMENT AND ANALYSIS: PARTIAL LOSS OF INSULATION VACUUM IN K-500 SUPERCONDUCTING CYCLOTRON CRYOSTAT

P. Bhattacharyya, A. Dutta Gupta, S. Saha, M. Ahammed, A. Mukherjee, U. Panda, U. Bhunia, A. De, S.Bandopadhaya, C. Nandi, C. Malik , R. De, S. Saha, J. Chaudhuri, R.K. Bhandari, VECC, Kolkata, India

Abstract

At higher currents in superconducting coil of the K500 superconducting cyclotron, it was found that the insulation vacuum surrounding the LHe vessel deteriorate with increasing current in the coil and finally leading to slow dump of the coil. This is a limitation for further increasing current value in the magnet coil. On the other hand, once the current value was returned to zero, vacuum reading reaches to its initial value. Experiment and analysis have been done to quantify the contribution of molecular gas conduction (FMGC) on heat load because of this partial loss of insulation vacuum. Experiment was also performed to find out how much betterment in terms of heat load is possible by incorporating an additional vacuum pump.

The cryostat safety analysis because of the loss of insulation vacuum has become very important at this new scenario. An analysis has been done to know what could be the maximum pressure rise with time in case of loss of vacuum. This data has been used to know what should be the relieving mass flow rate to avoid any pressure burst accident. Finally this data has been compared with the existing relief valve. It is found that the existing safety system can take care of total loss of insulation vacuum scenario.

INTRODUCTION

The K500 superconducting cyclotron [Figure 1] at the Variable Energy Cyclotron Centre has got its internal beam circulating up to the extraction radius of the cyclotron. The cyclotron has an 80 Ton superconducting magnet operating at about 5 T magnetic fields. The NbTi superconducting coil carries about 800 A maximum current to produce the desired magnetic field. The superconducting coils are placed in a liquid helium chamber surrounded by a vacuum insulating chamber called outer vacuum chamber (OVC).

At higher currents (>600 A) in the coils, the outer vacuum chamber (OVC) insulation vacuum reading shows deterioration, which finally leads to slow dump of the coil. The deterioration of OVC vacuum with the current in the coil is plotted in Figure 2. It is seen that at about 600 A, the slope of the pressure rise is too high to increase any amount of current. This in result increases heat load to the liquid helium chamber, thus depleting the liquid level in it and slow dump triggers as the liquid level goes below the coil top surface. This has given a tight limitation for further increasing current value in the coil. It was therefore required to determine that how much is the increase in heat load because of this phenomenon and to find out what capacity of additional vacuum pumping could make the situation better.

Figure 1: The K500 superconducting cyclotron

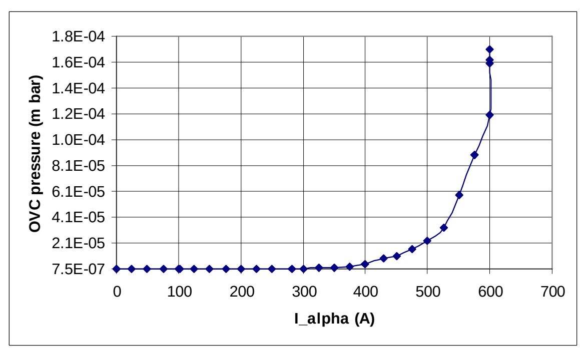

Figure 2: Vacuum reading during increase in coil current

EXPERIMENTS AND THEORETICAL EVALUATION

An experiment was done to find out the dynamic heat load which is coming only with energization of superconducting magnet. Another experiment was done to degrade the vacuum to one order by a control leak without the magnetic field on and heat load was measured. In the first experiment, heat load due to magnet energisation is found to be 100W. In the second experiment, heat load because of worsened insulation vacuum is 90 W. As is seen, the contribution of heat load as a result of degradation of vacuum is almost equal to the contribution of heat load due to magnet energisation. It can therefore be concluded that the reason for limit in the magnet coil energisation is coming from the degradation of vacuum only and an introduction of additional pumping port to improve the vacuum by nearly one order will save a lot of heat load to the coil. A detail calculation says that the saving of heat load will be of about 70W. Details of the experiments done are given below.

Experiment to Find Out the Dynamic Heat Load

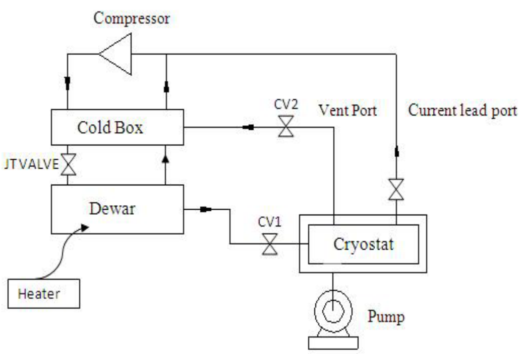

Figure 3: Experimental scheme to find out heat load due to energisation of magnet

Figure 3 shows the scheme to find out dynamic Heat load during energisation. At first, no current was given in the superconducting coil. The additional heater power of 100 W could be given to the plant dewar maintaining stable plant operation. After that, increase in the dewar heater power results in liquid level fall in both cryostat and dewar. During operating condition,when the coil current is increased above 600 A, the cryostat level starts decreasing leading to slow dump. It can therefore be concluded that a dynamic heat load of about 100W is coming at coil current 600A.

The dynamic heat load measured here comprises of free molecular gas conduction (FMGC) as a result of vacuum degradation, coil heat dissipation, current lead heat dissipation & Eddy current heating.

Experiment to Find Out the FMGC Heat Load and Comparison with Theoretical Value

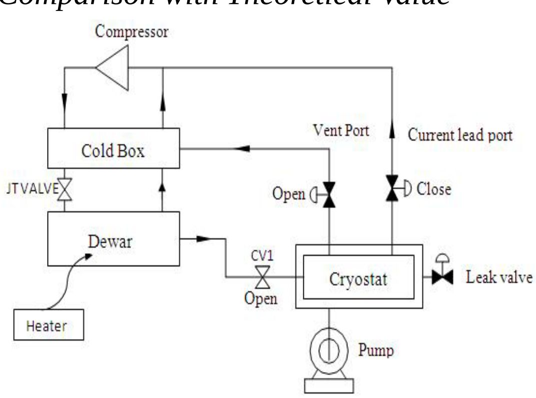

Figure 4: Experimental scheme to find out heat load due to FMGC

Figure 4 shows the experimental set up to simulate helium leak in OVC space. Different vacuum conditions have been established by means of a calibrated leak valve and corresponding maximum possible heater power was noted. Figure 5 shows the calibration graph of the leak valve.

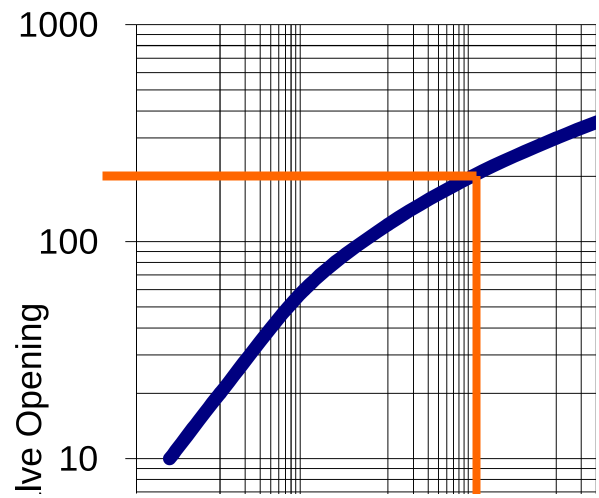

Figure 5: Leak valve calibration graph

Figure 6 shows a theoretical graph where it gives the insulation vacuum and heat load value due to FMGC. The experimental values of heat load at two vacuum values are also plotted. It can be seen that the theoretical calculation matches very well with the experimental result.

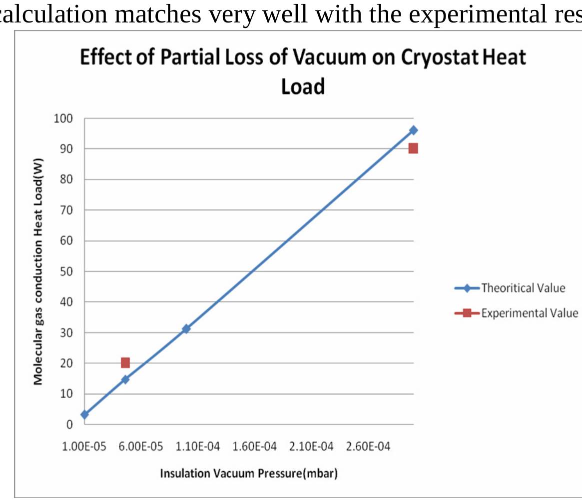

Figure 6: Comparison of theoretical and practical value of heat load.

Theoretical Evaluation of Additional Pumping

A theoretical evaluation was made to find out the vacuum value could be achieved if a standard 300 l/s turbo pump added to the OVC. The result is plotted in Figure 8. The estimated leak rate assumed at 600 A current in the coil is 0.01 mbar-l/s. At 5E-05 mbar vacuum, the estimated saving in the heat load is about 70 W at 600 A current. This saving is expected to improve the performance of the OVC and coil current can be raised to further higher value.

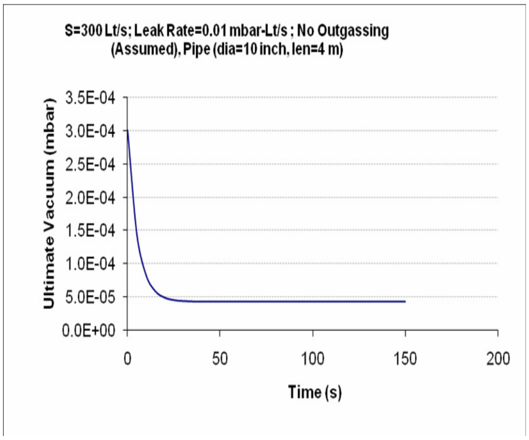

Figure 8: Calculated vacuum with additional pump

Safety Analysis for Complete Loss of Insulation Vacuum

The phenomena of increasing pressure with current in OVC raises the question about adequacy of safety system in case of accidental complete loss of insulation vacuum. The vessel was modelled as closed system. As the total mass of helium and the volume of helium chamber both are constant in case of closed system, the process is isochoric heating [1]. The pressure rise curve is dependent on initial fill up.

The loss of vacuum was assumed for air ingression into the vacuum chamber, which is the most severe case contributing to 0.6 W/cm^2 [2] heat load to the cryostat cold surface.

Below is the pressure rise curve for different initial ullage space.

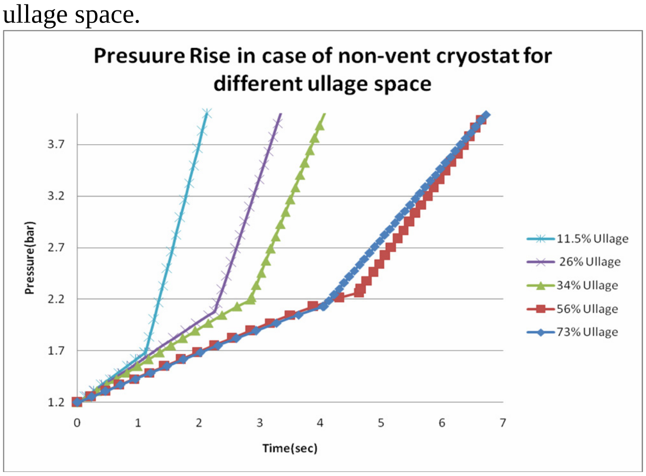

Figure 9: Pressure rise in the helium chamber in case of a total loss of insulation vacuum

The graph shows two different slopes. Initial slope is for two phase pressure rise, this line finally reaches either the saturation liquid line or saturated vapour line of two-phase dome depending upon initial fill up. The next slopes are out of the two-phase dome and describe the single phase pressure rise.

Interesting observation is that, for high liquid volume fraction(i.e. low ullage space), the liquid volume expands with the heat transferring into the liquid, and it causes the liquid to increasingly occupy more and more volume in the vessel and the gas to condense on the surface between the two phases. For low liquid volume fraction, the evaporation of the liquid is more than the volume expansion, and it causes the volume of the liquid to reduce until it vaporises completely.

To find out the relieving mass requirement, the venting process was intentionally assumed to be isobaric (at 3bar$_a$). In spite of heat addition, how much mass should be taken out to maintain the cryostat pressure at 3 bar$_a$ is calculated. For isobaric process the heat addition will be manifested as increase in enthalpy. Helium density corresponding to 3 bar$_a$ pressure and instantaneous enthalpy is found out and helium mass in the vessel is determined. By comparing this to the mass determined in the previous time step, the mass that must be removed to keep the pressure constant as the internal enthalpy is increased has been calculated. Maximum value for this particular case appears to be approximately 3 Kg/s considering normal operating condition (i.e. 11.5 % ullage). Existing rupture disc of K-500 superconducting cyclotron has maximum discharge capacity through it is 11.6 Kg/s.

CONCLUSIONS

Molecular gas conduction contributes to significant amount of heat load at current scenario where the insulation vacuum degrades with current in coil. Experiment and subsequent theoretical evaluations reveal that the reason of slow dump of the magnet is due to high heat load by molecular gas conduction. It also concludes the utility of additional pumping to reduce the heat load to cryostat. Safety analysis considering complete loss of insulation vacuum because of ingression of air reveals that present safety system can take care well of such situation.

ACKNOWLEDGEMENTS

The authors acknowledge all the people involved in the performance of the experiments and in discussion thorough out these studies.

REFERENCES

[1] Dr. Philippe Lebrun ,CERN,Lecture on “Engineering Science for cryogenic Safety” 26th DAE Safety and Occupational Health Professsional Meet.November 16-18,2009.

[2] W. Lehman and G. Zahn, “Safety Aspects for LHe Cryostats and LHe Transport Containers,” ICEC7, London, 1978.