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Theoretical and experimental investigation of magnetic field related helium leak in helium vessel of a large superconducting magnet

Pranab Bhattachryya [a,b,*], Anjan Dutta Gupta [a,b], S. Dhar [c], P.R. Sarma [b], Paramita Mukherjee [a,b]

[a] Variable Energy Cyclotron Centre, 1/AF, Bidhannagar, Kolkata 700064, India
[b] Homi Bhabha National Institute, Anushaktinagar, Mumbai 400094, India
[c] Jadavpur University, Kolkata 700032, India

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ABSTRACT

The helium vessel of the superconducting cyclotron (SCC) at the Variable Energy Cyclotron centre (VECC), Kolkata shows a gradual loss of insulation vacuum from 10^{-7} mbar to 10^{-4} mbar with increasing coil current in the magnet. The insulation vacuum restores back to its initial value with the withdrawal of current. The origin of such behavior has been thought to be related to the electromagnetic stress in the magnet. The electromagnetic stress distribution in the median plane of the helium vessel was studied to figure out the possible location of the helium leak. The stress field from the possible location was transferred to a simplified 2D model with different leak geometries to study the changes in conductance with coil current. The leak rate calculated from the changes in the leak geometry was compared with the leak rate calculated from the experimental insulation vacuum degradation behavior to estimate the initial leak shape and size.

1. Introduction

Superconducting cyclotrons at high energy cyclotron facilities at Michigan State University [1], Texas A&M University [2], Milano [3] and VECC [4] use large superconducting magnets for producing high magnetic fields. These magnets operate at bath-cooled mode with LHe at 4 K. An insulation vacuum ($\sim 10^{-7}$ mbar) jacket encompasses the cold mass of these magnets to minimize heat load to the LHe.

At 4 K temperature, most of the gases in the insulation vacuum jacket space are effectively cryopumped by the cold mass of the magnet. Any rise in pressure in the vacuum jacket is generally due to helium leak from the LHe vessel [5]. These internal helium leaks may originate from the propagation of small cracks due to thermal stress during cool down of the coil to cryogenic temperature. The thermal stress can introduce a crack in the weld or more likely open a leak which was plugged by contamination (e.g. dirt, weld impurities, or water) [6].

During the first LHe filling of the VECC magnet, a small but significant deterioration of insulation vacuum was observed. This degradation occurred when the LHe level reached near the median plane (i.e. the horizontal symmetry plane of the magnet) [7]. It confirmed the opening of some cold leaks in the median plane near the weld zone. Moreover, it was observed, during operation, that the insulation vacuum further degraded significantly with the increase of coil current. However, the insulation vacuum improved and reverted to its initial value (i.e. the insulation vacuum value with filled up LHe) once the magnet was de-energized. The magnet could be operated up to 550 A (about 70% of the maximum value of 800 A), as the existing refrigeration plant could not handle increased heat load due to degraded insulation vacuum. The magnet of SCC at VECC has two coils, viz., α-coil and β-coil (Fig. 1). It was further observed that the effect of the α-coil on the degradation of vacuum is much higher than the β-coil.

It is very difficult to locate and repair any leak of the inner helium vessel after constructing the vacuum jacket around it. It requires a major disassembly of the cryostat to access to the leak location.

Previous studies were carried out for addressing several aspects of the problem. Dutta et al. [8] mentioned the existence of unapproachable critical leaks which were related to the magnetic field. Bhunia et al. [9] discussed their operational experience about the satisfactory performance of the magnet cryostat coupled with the liquid helium refrigerator with moderate currents (550 A) in both the coils and subsequent slow dump at higher current. Naser et al. [10] concluded that the electro-magnetic stress due to Lorentz force increased with current but did not report any detailed stress analysis of the helium vessel. Bhattacharyya et al. [7,11] quantified the amount of excess heat load arising due to degraded insulation vacuum through experiments and theoretical analysis.

* Corresponding author at: Variable Energy Cyclotron Centre, 1/AF, Bidhannagar, Kolkata 700064, India.
E-mail address: pbhatt@vecc.gov.in (P. Bhattachryya).

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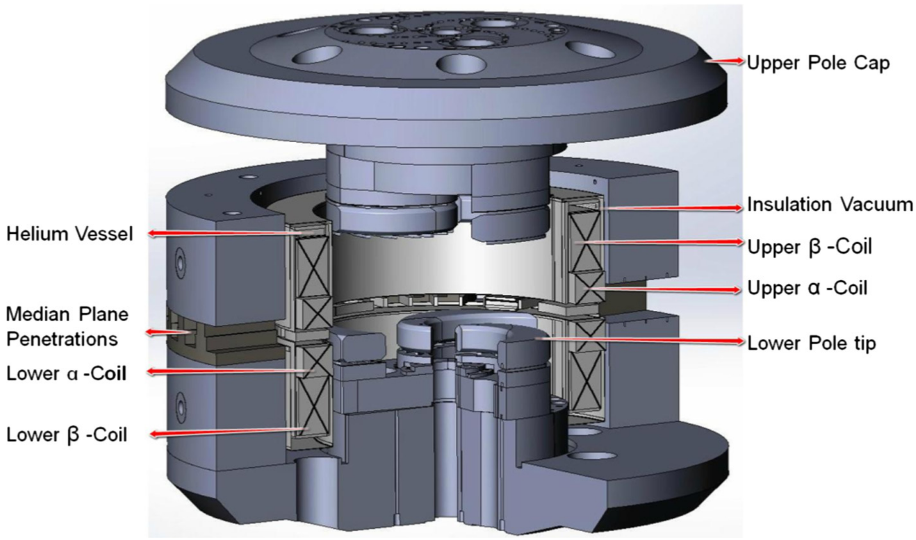

Fig. 1. Schematic view of K500 superconducting cyclotron (SCC) magnet.

In the present work, a coupled electromagnetic and structural analysis has been made for finding out the magnetic field distribution and the stress pattern at the inner and outer wall weld joints near the median plane of the helium vessel at several different combinations of coil current. It is seen that near median plane, there exists a tensile stress pattern which may open up any existing crack. The stress field from the possible location was transferred to a simplified 2D model with different leak geometries to study the change in conductance. The leak rate calculated from the change in the leak geometry was compared with the leak rate that was calculated from experimental insulation vacuum degradation behavior to estimate the initial leak shape and size. The maximum allowable coil current was determined based on the estimated initial leak size and crack tip stress.

2. Effect of coil current on degradation of insulation vacuum

The superconducting magnet of K500 SCC at VECC uses Nb-Ti superconducting coils. The coil consists of two halves (upper and lower sides of the median plane), and each half is again split into a large (β-coil) and a short (α-coil) coil as shown in Fig. 1.

The superconducting coil is housed in an annular liquid helium vessel made of SS 316L material. It is surrounded by a copper thermal shield at 80 K, cooled by liquid nitrogen. The shield and the helium vessel is wrapped with multiple layers of superinsulation and is placed inside an outer vacuum enclosure (AISI 1020) to insulate it from the ambient heat. A high insulation vacuum ($\sim 10^{-7}$ mbar) is maintained in the vessel by continuous pumping via. a turbo-molecular pump backed by a scroll pump. The pump is located 2.5 m away from the magnet to keep the pump away from the high magnetic field.

During operation, it is observed that the insulation vacuum deteriorates with increase in coil current. A similar turbo-molecular pump with a small experimental vacuum chamber was placed separately there (i.e. adjacent to the actual insulation vacuum turbo-molecular pump), and the pumping speed was found to be uninfluenced by the local magnetic field present there due to energization of the superconducting magnet. Thereby reconfirms that a leak was present in the helium chamber, and it is not that the pumping speed is getting reduced due to the magnetic field.

This degradation of insulation vacuum finally limits the operation of the magnet well below the rated operating current. Operational experience further shows that the effect of the β-coil on the deterioration of vacuum is much less than that of the α-coil [7]. The operational data has been analyzed, and it has been found that 0.4 A current in α-coil (I_α) produces the same insulation vacuum degradation as 1 A current in β-coil (I_β) does.

Around 250 operational data points of loss of insulation vacuum with different current combination have been further studied, and an empirical relation (Eq. (1)) is proposed to fit with the experimental data within ±10% error.

$$Log(P) = a + by^2 + cy^4 + dy^6 \quad (1)$$

where P = insulation vacuum (mbar), a = -5.587, b = -7.21×10^{-7}, c = 1.609×10^{-11}, d = -1.26×10^{-17} and $y = I_\alpha + 0.4 \cdot I_\beta$.

Using Eq. (1), the full surface (Fig. 2) has been generated for predicting vacuum degradation at different current combinations.

Fig. 2 clearly shows that the effect of α-coil is more dominant on insulation vacuum degradation than that of the β-coil. In the earlier work [7], we made an attempt to correlate the coil current with the extent of vacuum degradation. We surmised that an increase in the coil current raises the stress in the weld zone which, in turn, opens up the cold-leak and thus degrades the vacuum.

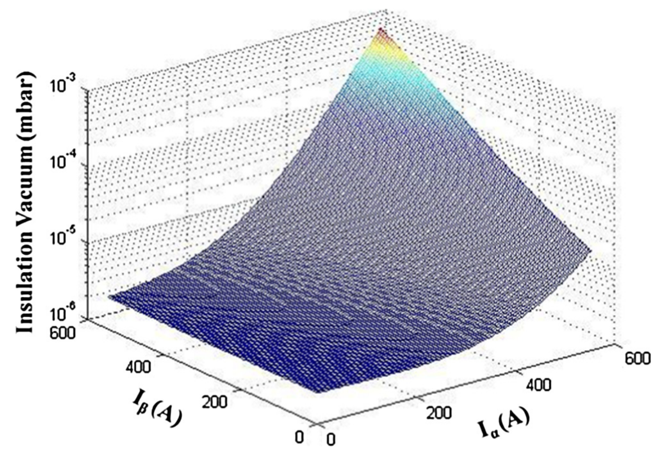

Fig. 2. Degradation of insulation vacuum at different coil currents in α- and β-coils.