Design, Installation and Commissioning of new Vacuum chamber for Analysing Magnet of K-130 Cyclotron

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Abstract. In view of up-gradation of K-130 Cyclotron at VECC, Kolkata, we have designed a new Vacuum chamber to modify the existing vacuum chamber system. This new chamber is meant for C-shaped 1T dipole type 159.5⁰ Analysing Magnet of 4710 OD x 2750 ID x 1075 mm tall in the RIB feeder beam-line. The welded type vacuum chamber is made of SS-304. The chamber with trapezoidal cross-section is of 4447 OD x 4057 ID x 61.5 mm average height. Pumping ports and modules are selected accordingly to ensure the required high vacuum for beam transport. The chamber improves the base vacuum and reduces the complicated O-ring replacement mandatory for existing chamber made of aluminium alloy. The new chamber is installed at site along with all the pumping module and beam line components. This paper presents the detailed design, installation and commissioning results.

1. Introduction
Analyzing magnet in the beam transport line (BTS) of K-130 cyclotron is used to bend the extracted beam selectively. It is a C-shaped, dipole magnet made of low carbon steel, with normal entry and exit and can produce 9 KG field maximum in an average pole gap of 63.5 mm. The beam path is confined in the vacuum chamber kept at a vacuum of the order of 2 x 10⁻⁶ mbar. At present, the vacuum chamber of analyzing magnet is nothing but the beam space enclosed by two vertical walls made of aluminium alloy against the upper and lower pole pieces. Both the vertical walls’ ends are vacuum tight against pole cap by a large “O” ring. It is a very critical job to achieve required vacuum tightness of this chamber because of sealing groove configuration and limited accessibility. To assemble or disassemble, a series of laborious, exhaustive steps like removal and re-assembly of RIB laboratory, ECR laboratory, chilling plant as well as nos. of shielding plank weighing ~27 ton each and various power supply terminals etc. are mandatory. As a modification to the present vacuum chamber, a welded type stainless steel vacuum chamber has been designed, fabricated and installed to cut short these huge jobs as well as to reduce the down time coming out of frequent vacuum leaks. This chamber is consists of two vertical and two horizontal plates welded together that forms the 159.5⁰ arc of the magnet. The trapezoidal chamber volume is of ~19 ltr. and weight is about 150 kg.
2. Design aspects and theory
The semi-circular vacuum chamber is trapezoidal shape (see Fig-1.) in cross section due to tapered pole pieces. Thereby, the 200 mm wide section is 59.94 mm and 63.06 mm in height at the ends respectively thus an average 51.5 mm beam space is to be ensured. Being the non-circular cross-section with an arc shape complex vacuum chamber i.e. vessel under external pressure, structural design is limited to carry out by the standard formulas or ASME –Section-VIII, Div-1. Thereby, a Finite element tool like ANSYS Multi-physics is used. Considering the circular length to a equivalent straight length of non circular cross section vacuum chamber , calculation through MathCAD as per ASME code seeks for higher thickness of plate for shorter side to 6.5mm as against 5mm as per FEM calculation.

![Fig. 1. Sectional view of Analysing Magnet](image)

Equation or formulas used for calculation:-

- \[ S_{mA} = \frac{P_A h H}{2(t_1 h + t_2 H)} \]
- \[ S_{mB} = \frac{P_A h}{2(t_1)} \]
- \[ S'_{crA} = \frac{\pi^2 E_2 \left( \frac{t_1}{H} \right)^2}{12(1 - v^2)} K_A \]
- \[ S'_{crB} = \frac{\pi^2 E_2 \left( \frac{t_1}{L_w} \right)^2}{12(1 - v^2)} K_B \]
- \[ S'_{crA} = S_y - \frac{S_y^2}{4S'_{crA}} \]
- \[ S'_{crB} = S_y - \frac{S_y^2}{4S'_{crB}} \]
- \[ S_{crA} = S'_{crA} \text{ if } S'_{crA} \leq \frac{S_y}{2} \]
- \[ S_{crB} = S'_{crB} \text{ if } S'_{crB} \leq \frac{S_y}{2} \]
- \[ S_{crA} = S'_{crA} \text{ otherwise} \]
- \[ S_{crB} = S'_{crB} \text{ otherwise} \]
\[ 2 \frac{S_{ma}}{S_{crd}} + 2 \frac{S_{mb}}{S_{crd}} \leq 1.0 \]

For column stability

\[ S_{ma} = \frac{P_e h_y H_o}{2(t_1 H_a + t_2 h_b)} \]

\[ M = P_e h_y H_o y \]

\[ C_e = \sqrt{\frac{2\pi^2 E_2}{Sy}} \]

\[ S_b = \frac{M c}{I_e} \]

\[ \frac{S_a}{F_a} + \frac{S_b}{\left(1 - \frac{S_a}{F_a}\right)} \leq 1.0 \text{ where,} \]

\[ F_a = 5 + 3 \left(\frac{2}{8C_e} \right) \frac{3}{8C_e} + \frac{3}{8C_e} \]

\[ F'_e = \frac{12\pi^2 E_2}{23 \left(\frac{2}{R1} L_v\right)^2} \]

Where, \( P_e \) - External pressure, \( t_1, t_2 \) - plate thickness for long and short side, \( K_A, K_B \) - plate buckling factor; \( h, H \) - heights respectively, i.e subscript - inner and outer side. \( S \) - allowable stress, \( S_{ma}, S_{mb} \) - compression stress at the short and long edge, \( S_{crA}, S_{crB} \) - plate buckling stress, \( I_e \) - moment of Inertia, \( R_1 \) - least radius of gyration, \( \nu \) - poison ratio, \( L \) - equivalent length, \( c \) - neutral axis to extreme fibre distance.

![Fig.-2: Cross Section of non circular Vacuum chamber](image-url)
3. Materials and fabrication aspects
The chamber material is required to be paramagnetic since they are placed inside the central magnetic field. Moreover, the material should have low out gassing rate and high modulus of elasticity. SS-304 grade stainless steel is used and the quality of the material used for fabrication is ensured through sample testing by induced field measurement method. The flatness and the surface finish, complex geometry as well He leak tightness (better than 1 x 10^-9 mbar ltr/s) are enhanced strictly. The most difficulty in fabricating this chamber of this size was to maintain the required flatness after performing the circumferential TIG welding in all the four sides.

Table 1. "SS-304" Constant Properties

| Name                      | Value                |
|---------------------------|----------------------|
| Density                   | 7.75×10^-6 kg/mm³    |
| Poisson's Ratio           | 0.31                 |
| Tensile Yield Strength    | 172.37 Mpa           |
| Tensile Ultimate Strength | 482.63 Mpa           |
| Young's Modulus           | 193,053.0 Mpa        |
| Compressive Yield Strength| 172.37 Mpa           |

Allowable stress for SS-304, \( S = \min\{\frac{Sy}{1.5}, \frac{Su}{4}\} = 150 \text{ MPa} \)

4. Analysis report
The vacuum chamber may be placed between the spacers and pole tips. In this case, inside width of the cross section of the chamber made of SS-304 will be 210 mm. The thickness of the chamber wall should be as minimum as possible to provide the sufficient space for beam path. Initially, calculation was carried out based on ASME to find out the minimum wall thickness which can withstand the vacuum load for this chamber. It is assumed that the vessel of noncircular cross section is straight (equivalent length) instead of circular nature of the chamber. Wall thickness is required as per ASME / Section-VIII / Appendix-13 for Vessels of Non-circular cross subject to external pressure, to be found as 6.5 mm.

Table-2: Structural calculation results of vacuum chamber for various thicknesses

| Sl. No. | Thickness (mm) | Maximum Deformation (mm) | Maximum Stress (Mpa) | F.O.S |
|---------|----------------|--------------------------|----------------------|-------|
| a)      | 4              | 0.73                     | 181.5                | 0.95  |
| b)      | 5              | 0.38                     | 64.43                | 2.67  |
| c)      | 6              | 0.21                     | 53.73                | 3.20  |
| d)      | 7              | 0.13                     | 52.01                | 3.31  |
To increase the beam path space, 3-D model analysis for external pressure is carried out on ANSYS Multi-physics platform. The bending stress distribution, deformation and buckling stability were checked for various wall thicknesses. The result of the analysis for 4 mm to 6 mm is given in the Table-2. The FEM result shows that the wall thickness 5 mm is safe for this annular vessel as the curvature of the inside and outside walls are imparting more strength than the straight one. Finally, the chamber has been fabricated as per the ANSYS Multi-physics calculation which conforms to structural as well as beam dynamics requirements.

![Fig. 3. Total deformation](image1)
![Fig. 4. Equivalent.(Von-Mises) Stress](image2)

5. **Installation and commissioning report**
The said chamber is installed at site on conforming all quality control as well assembly requirements.

![Figure 5. Evacuation test of chamber prior to upper pole cap placement](image3)
![Figure 6. Re installed AM Magnet with SS vacuum chamber](image4)

6. **Final result:**
Evacuation was carried out with two set of Rotary pump (14 m³/hr) backed Diffusion pump (Diffstak DN 160 flange, 700 l/s N₂) and the system vacuum was achieved to 3.0 x 10⁻⁵ mbar after 24 hrs and 1.0 x 10⁻⁶ mbar after 60 hrs smoothly with leak rate of < 2.0 x 10⁻⁸ mbar l/s.

Beam transport line with this Analysing Magnet (achromatic mode) in the channel-IV i.e. RIB feeder line was commissioned with 40 MeV alpha beam. Presently, the beam line is in use for various experiments.

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