Engineering design and integration of in-vessel single turn segmental coil in vacuum vessel of SST-1

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Abstract: SST-1 tokamak is having the error field due to unsymmetrical positioning of Toroidal field coils which push the plasma to inner side from its major radius of 1100 mm. hence it is required to install the In-vessel Coil (PF6) at a location of 1350 mm radius and elevation of 350 mm above and below the mid plane of the toroidal field coils. The In-Vessel coil was decided to make in eight segments for futuristic use, to control the individual localized error field correction by supplying the different current. A single turn, eight segments, copper conductor with 18 mm diameter with GFRP insulation and in housed in SS304 L casing to carry 8000 A current for 10 s was designed and installed in vacuum vessel of SST-1. This paper will present the design drivers, material selection, advantages and constraints of the in-vessel coils, its conceptual and engineering design, CAD models, finite element analysis using ANSYS, its fabrication, quality assurance/control and assembly/integration aspects inside vacuum vessel of SST-1.

1. Introduction

During the refurbishment of the SST-1, the error field was mapped with the help of the hall probe and mirnov’s probe magnetic field mapping methods. Which in turn reveals the shifting of plasma null to one side due error in magnetic field generated due to unsymmetrical positioning of the Toroidal field coils. The unsymmetrical positioning was due to error in TF supporting ring design and partially due to uneven tightening of Toroidal field coils. These error field causes plasma to form inboard side of the vacuum vessel from its major radius of 1100 mm. the simulation of the exact positioning of the TF coil and correcting of this field lead to evolution of the design of the in-vessel coil. To counter the effect of the magnetic field error, it was required to install pair of In-vessel Coil (PF6) at a location of 1300 mm radius and elevation of 350 mm above and below the mid plane of the toroidal field coil (figure 1). The In-Vessel coil was decided to make in eight segments (each segment with 3000 mm and one coil of 6900 mm length) for futuristic use, to control the individual localized error field correction by supplying the different current. The design of the in-vessel coil has many critical aspects for considerations like terminals of two successive copper conductor along with stainless steel casing must be come out from 46 mm diameter nozzle, secondly casing should be welded to radial port such to vacuum integrity of vessel remains intact, thirdly copper conductor can able to withstand maximum current of 8000 A for 10 s with maximum temperature rise of 50° C, there must be close tolerance between copper conductor and SS casing to reduce any movement of copper conductor inside the casing for keeping geometrical stability within vessel. Hence The in-vessel coil was made from single solid ETP copper conductor encased inside the prefabricated SS 304 L piped casing in eight segment.
to form full circle. The In-vessel coil is open to atmosphere and experiencing the vacuum inside the vacuum vessel as shown in figure 2. To maintain the circular shape of the coil copper rod inside the SS casing, very close tolerances are maintained e.g. copper conductor has outer diameter of 18mm and after FRP insulation and Kepton tap wrapping the outer diameter reaches to 19mm (figure 3). This coil is made from solid copper rod which under forces while charging can vibrate and change the shape. Hence it is required to keep in circular shape by encasing in steel pipe casing with close tolerances.

Figure 1. An open view of segmental In-vessel coil

Figure 2. In-vessel coil inside the vessel

Figure 3. Cross section detail of In-vessel coil

2. Design of components

2.1. Design of SS Casing
The Stainless Steel pipe is experiencing internal vacuum pressure of vessel and is open to atmosphere. Though entire casing house the copper conductor along with insulation in tight tolerances, the entire assembly is act as solid rod. Also all pipes has to go through hydraulic testing at 70Psi pressure, there isn’t need to design check for bursting pressure. Even though it has been verified by the following
equation (2.1.1) and value derived for hoop stress is 0.6 MPa much below the yield stress value of SS 304L casing material (170 MPa)

\[
\text{Hoop stress} = \frac{P \times \text{Inner Diameter}(d)}{2 \times \text{Pipe thickness} \times \text{weld efficiency}}
\] (2.1.1)

2.2. Design of In-vessel coil conductor

Design of copper conductor is mainly done with input rating of 8000 A current carrying capacity in 10 seconds and with maximum differential temperature rise to 50° C with following equations (2.2.1,2.2.2,2.2.3) and result is validated with ansys analysis software and is plotted below.

(a) Resistance of the single copper segment

\[
R = \frac{\rho \times l}{A}
\] (2.2.1)

Here \( \rho \) = copper resistivity in \( \Omega/m \), \( L \) = length of the copper conductor, \( A \) = Area of copper conductor

(b) Mass of the conductor

\[
m = V \times \delta
\] (2.2.2)

Here \( V \) = Volume of conductor, \( \delta \) = Density of copper

(c) Maximum current carrying capacity of conductor

\[
I^2 = \frac{m \times C_p \times \Delta T}{R \times t}
\] (2.2.3)

Here \( C_p \) = Specific heat of copper, \( \Delta T \) = Temperature rise difference, \( t \) = Charging time

Figure 4. Thermal Ansys analysis of Rise of temperature during charging of In-vessel coil.

The above analysis plot shows the rise of the temperature of about 79°C from the ambient temperature while charging to maximum current of 8000 A for 10 s. The cool down time for the in-vessel coil after maximum current charging condition is also calculated to find out time lapse required between two successive plasma shots as per equation (2.2.4). The below mentioned formula used to calculate the cooling time and also analysis plot at the end validated the calculation as the cool down time is 10°C for 10 min. of cooling by radiation. The copper conductor duly in contact with ss casing
leaves the heat with casing through conduction which in case dissipated through radiation to vessel in vacuum.

\[
\text{Time of cooling} = \frac{Nk}{2\varepsilon\sigma A} \left( \frac{1}{T_{\text{final}}} - \frac{1}{T_{\text{hot}}} \right)
\]

(2.2.4)

Here N = number of particles of copper = \(\frac{mN_A}{M} = \frac{6.72 \times 10^{23}}{63.54} = 0.636 \times 10^{26}\)

M = molecular mass of copper, m= mass of copper, N\_A = avagrado number, K = thermal conductivity of copper (401 W/m K), \(\varepsilon\) = emissivity of copper (0.65) \(\sigma\) = Stephen Boltzman constant = \(5.67 \times 10^{-8}\) w/m\(^2\) k\(^4\), A= area of radiating surface. \(T_{\text{final}} = 343.18\) K = \(70.03^\circ\)C

![Figure 5. Thermal Ansys analysis of cool down of in-Vessel coil after maximum charge](image)

2.3. Design and Analysis of support structure

The pair of In-vessel coil experiencing the vertical force from each other which is very much negligible, hence design is done from force generated by radial control coils which experience both vertical and radial forces. The support for holding the In-vessel coil and Radial control coil is taken from Outer passive stabilizer support at eight Inter Connecting Ring locations at top and bottom as shown in modelled figure 6 and figure 7.

![Figure 6. Conceptual support with ceramic insulation](image)

![Figure 7. Fixing of support inside the Vacuum vessel](image)

These supports experiences the Radial force of 30000 N and Vertical force = 1300 N with total 8 nos. of support for holding 8 segments of in-vessel coil (Load data provided by simulation group). A simplified free body force diagram is shown in figure 8 below showing the vertical and radial force acting on single support and the stresses and deflection found which are around 49.14 MPa and 0.58...
mm deflection respectively. The same is validated by the ansys analysis software and its image plotted here in figure 9.

![Free Body diagram of the forces and unknown reactions in problem](image.png)

**Figure 8.** Free Body diagram of the forces and unknown reactions in problem

![Bending stress](image.png)

**Figure 9.** Bending stress

### 2.4. Calculation and Analysis of Insulation

The in-vessel coil is clamped with supports along with alumina ceramic as isolation between In-vessel coil and support for stopping the loop of eddy current formation. 99% purity alumina with high compressive strength was used in four pieces to hold the In-vessel coil and Radial control coil together. These ceramics are designed for crushing strength as per equation (2.4.1) and the values are validated with ansys analysis software as shown in figure 10 below.

\[
\text{Crushing stress} = \frac{P}{d \times l} = 4.07 \text{ N/mm}^2
\]  

(2.4.1)

Here \( P \) = Radial force experience by ceramic, \( d \) = Projected diameter of ceramic, \( l \) = Length of ceramic
3. Fabrication and Installation

The In-vessel coil copper conductor is duly insulated with fiberglass tap and kepton inserted within close tolerances to SS casing. These pair of coil is installed on outboard passive stabilizer support mounted in Inner connecting ring at the radius of 1300mm and elevation of 350mm above and below the mid-plane of Toroidal field coil with ECDS system with vary close tolerances as shown in image. The Stainless steel casing are welded from outside with vessel radial port in order to make the coil vacuum proof. The copper conductor leads comes out form the vessel is brazed with successive terminal to form full circle. In future, these terminals can be separated for individual segment operation for localized field error correction (N mode correction). All the weld joint of the radial control coil is tested at the leak rate of $1 \times 10^{-8}$ mbar/l/s. The final megger test is done between In-vessel coil casing and vacuum vessel to find resistance in order of giga-ohms. The installed in-vessel coil inside SST-1 VV is shown in Figure 11 and 12.

4. Characterization of the coils

In vessel coil has been tested with giving 200 A, 500 mHz square signal current and checked the magnetic field effect at the plasma radius of 1100 mm with putting hall probe at plasma radius at different location which measured value of average 3.5 Gauss. This measured value comes to vary close to the theoretical value as well with standard 1st & 2nd order elliptical equations for determining magnetic fields of circular loop. A measured signal wave form is also shown in below image.
5. Conclusions
The In-vessel coil support design, analysis, fabrication aspects and assembly inside SST-1 vacuum vessel are presented in detail. The analytical stress calculations and ANSYS FE results match closely. In-vessel coil and its supports are successfully assembled inside SST-1 vacuum vessel. The initial characterization of the In-vessel coil performance has found satisfactorily and the operation of the coil will commence in short duration.

6. References
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Figure 13. An oscilloscope waveform image