Conceptual & Engineering Design of Plug-in Cryostat Cylinder for Super-Conducting Central Solenoid of SST-1

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Abstract. SST-1, country’s first indigenously built steady state superconducting tokamak is planned to be equipped with a Nb₃Sn based superconducting central solenoid, which will replace the existing copper conductor TR1 coil for the purpose of Ohmic breakdown. This central solenoid (CS) of four layers with each layer having 144 turns with an OD of 573 mm, ID of 423 mm length of 2483 mm will be housed inside a high vacuum, CRYO compatible plug-in cryostat thin shell having formed from SS 304L plate duly rolled and welded to form cylinder along with necessary accessories like LN₂ bubble panel, current lead chamber, coil and cylinder support structure etc. This paper will present the design drivers, material selection, advantages and constraints of the plug-in cryostat concept, sub-systems of plug-in cryostat, its conceptual and engineering design, CAD models, finite element analysis using ANSYS, safety issues and diagnostics, on-going works about fabrication, quality assurance/control and assembly/integration aspects with in the existing SST-1 machine bore.

1. Introduction
SST-1 [1] country’s first indigenously built steady state superconducting tokamak is planned to be equipped with a Nb₃Sn based superconducting central solenoid which will replace the existing copper conductor TR1 coil for the purpose of Ohmic breakdown. The main advantage of the plug-in cryostat is that it acts as an assembled unit containing the CS coil and accessories, which can be integrated with in the SST-1 machine bore of 690 mm without disturbing any sub-systems of machine.

2. Components of Plug-in Cryostat
The plug-in cryostat system figure 1 and figure 2 [2] consists of (a) Cryostat cylinder (CCY), (b) LN₂ shields and copper radiation guards for cryostat cylinder, (c) Current lead chamber (CLC), (d) LN₂ shields and copper radiation guards for current lead chamber, (e) CS Magnet support, (f) Base spacers and (g) CS Vacuum Line Pumping Duct line components.

(a) Cryostat cylinder: CCY of central solenoid is a high vacuum compatible \(\leq 1 \times 10^{-5}\) mbar) CRYO compatible (5 K) thin cylinder component having a wall thickness of 6mm, made of SS 304L material. It acts as housing to superconducting central solenoid and supports CS coil and accessories dead weights. Its dimensions should have the assembly compatibility with SST1 in available cryostat bore space of 690 mm with a radial clearance of 20 mm.
Figure 1. Plug-in Cryostat – General Assembly

Figure 2. 2D View of Plug-in Cryostat

(b) LN₂ shield for CCY: LN₂ shields for CCY are made in two halves (diametrically) in order to minimize the eddy current formations. The material of construction is SS 316L, are of one-sided bubble type with a sheet thickness of 1.6 mm as per ASME Sec VIII – Div –1 appendix – 17 with respect to space restrictions. The advantage of bubble type geometry is the uniformity in temperature distribution along the entire surface area of the thermal shield. The LN₂ shield at 80 K acts as a thermal barrier between 5 K surface of CS coil and ambient surface of CCY so that the coil does not view the cylinder directly in order to reduce the thermal heat load on the coil. The gaps are covered by copper radiation guards, which are passively cooled due to conduction from the shields. The shields are mounted with insulated supports from the bore of the CCY. The radial clearance between shields and CCY is 10 mm, so that there is no interference between them during assembly. There are also three shields mounted on cylinder base in order to reduce the heat load on the coil supports.

(c) Current Lead Chamber: CLC of central solenoid is a high vacuum compatible (≤ 1 × 10⁻⁵ mbar) CRYO compatible (5 K) thin cylinder component having a wall thickness of 6 mm, made of SS304 L material. At the top end it also has a 2:1 semi elliptical head of 6 mm thickness. It acts as housing and exit points of the two current leads of super-conducting central solenoid, man-hole ports for hydraulic connections, diagnostics requirements and opening of the vacuum line pump duct required for evacuation of the plug-in cylinder.

(d) LN₂ shield for CLC: LN₂ shields for CLC are made in two halves (diametrically) in order to minimize the eddy current formations and also with demountable type at port openings. The material of construction is SS316L, are of double-sided bubble type with a sheet thickness of 1.6 mm as per ASME Sec VIII – Div –1 appendix – 17. The advantage of bubble type geometry is the uniformity in temperature distribution along the entire surface area of the thermal shield. The LN₂ shield at 80 K acts as a thermal barrier between 5 K surface of CS coil current leads and ambient surface of CCY so that the current leads does not view the cylinder directly in order to reduce the thermal heat load on the current leads. The gaps are covered by copper radiation guards, which are passively cooled due to conduction from the shields. The shields are mounted with insulated supports from the bore of the CCY. The radial clearance between shields and CLC is 12 mm, so that there is no interference between them during assembly.
(e) CS Magnet support: CS coil is supported at the base with three equally angular spaced SS 304L/G10 supports raised from the cylinder base. SS 304L pipe are welded onto cylinder base and molded G10 pipes inserted on SS 304L pipe to reduce the heat conduction from cylinder base to coil surface. There are SS 304L and G10 pads mounted on the G10 pipe onto which the coil is supported. The SS 304L pipes are circumscribed by LN$_2$ bath to reduce the heat load on the coils due to conduction from ambient surfaces of cylinder base. The annular spaces between supports are used for interlayer joint connections of CS coil and also for hydraulic connections/joints for cryogenics fluids.

(f) Base spacer: The assembled base spacer is situated outside the vacuum environment consists of SS 304L ribbed structure in two halves tightened together with a sandwiched G10 pad in between to reduce the effect of eddy current formation. The cylinder with all its content sits on the base spacer having a G10 pad in between and is tightened with base spacer with nuts and bolts. The base spacer is mounted and assembled with the SST-1 machine frame structure.

(g) CS Vacuum Line Pumping Duct: It is an approximately 5 m long, 274 mm OD, 6mm thick SS 304L pipe connected at the current lead chamber opening, used for evacuating the plug-in cryostat assembly to vacuum level of $\leq 10^{-5}$ mbar. It is a height of 4.35 m from cylinder base and is toroidally oriented between radial port 3 and 4.

3. Assembly plans and sequence for CS coil and its cryostat in SST-1

Assembly sequence of plug-in cryostat is very important; as the system has to be inserted in the SST-1 cryostat bore of 690 mm figure 3 and figure 4 without disturbing any sub-systems. The design, dimensions, tolerances and radial clearances are finalized keeping in mind smooth and interference free insertion of the system in SST-1 machine bore. A tentative assembly sequence is presented here for reference purpose. A detailed assembly sequence/procedure will be worked out before actual integration of plug-in cryostat with SST-1.

- CS Coil mounted with support bases and hydraulic connection.
- LN$_2$ shields in two halves is mounted inside the cylinder bore.
- The cylinder with pre mounted LN$_2$ shields will be lifted to enclose the coil.
- This compound assembly of coil & cylinder will be inserted in SST-1 CS bore upon the base spacer and bolt tightened with the same.
- CLC semi elliptical head with lead connections is welded with the current lead chamber having pre mounted LN$_2$ shields.
- CLC chamber is lifted, mounted with already inserted CCY in proper toroidal orientation
- Hydraulic connections for Helium and LN$_2$ transfer lines and leak testing.
- Finally the vacuum line pump duct is lifted and mounted with respective flange in CLC so that the toroidal orientation of the duct line is between radial port 3 and 4.
- Closing & leak testing of the plug-in assembled system, thermal and electrical isolation checks.

4. Safety and Diagnostics

In case of a pressure build up inside plug-in cryostat due to leak in LN$_2$ and helium circuits, suitable rupture disks/pressure release valves will be installed at the current lead chamber ports to release the buildup of pressure and prevent the systems from any damage. With rupture discs/safety pressure release valves installed, maximum pressure inside the plug-in cylinder in the event of a leak will be limited to about 1.1 atmospheres.

Also the plug-in cryostat will be equipped with temperature sensors to monitor the temperature patterns, Venturi meters to measure the flow parameters, voltage traps, suitable grounding scheme etc.
5. Load acting on the plug-in Cryostat

The main load acting on the plug-in cryostat are the (a) radiation/conduction heat loadings on the shield and coil support maintained at 80 K and 5 K with respect to the cylinder surface and base maintained at ambient temperature of 300 K, (b) the vacuum (external pressure) loading on cylinder and current lead chamber walls and (c) the dead load of coil on support structures, base supports etc.

(a) (i) Radiation heat loads on shields (300 K to 80 K): The total radiation heat loads on LN$_2$ shields $Q_r$ from ambient cylinder and CLC surfaces are calculated analytically with Stefan Boltzmann formula (equation 1) based on concentric cylinder assumption between shields and cylinder/CLC are found to be around 278 watt.

$$Q_r = \frac{\sigma A_{cy} (T_{cy}^4 - T_s^4)}{1 + \frac{A_{cy}}{A_s} \left( \frac{1}{\varepsilon_{cy}} - 1 \right)} \text{ Watt \quad \text{(1)} \quad [3]}$$

where $A_{cy}$, $A_s$ are surface area of cylinder/CLC and shield, $T_{cy}$ and $T_s$ ambient cylinder/CLC temperature of 300 K and 80 K, $\varepsilon_{cy} = 0.2$ emissivity of cylinder/CLC (buffed surfaces), $\varepsilon_s = 0.1$ emissivity of shields (electro-polished surfaces), $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ is Stefan Boltzmann constant.

(ii) Conduction heat load through supports: The conduction heat load onto coil at 5 K from ambient temperature of 300 K through supports/insulators are estimated with FE package ANSYS, [4] using 2D, axis-symmetric thermal analysis with PLANE 55 elements considering temperature dependent thermal conductivity of the support/insulator materials. Figure 5 shows the CAD model and boundary conditions of the analysis. Figure 6 shows the temperature distribution on a support between 300 K to 5 K.
Heat load on coil base support as estimated from ANSYS is $Q = 0.5$ Watt (per support)

For 3 Supports, $Q_{\text{TOTAL}} = 3 \times 0.5 = 1.5$ Watt

(b) Vacuum loading: The principal load acting on it is the vacuum loading i.e. external atmospheric pressure of 1 bar on the wall surfaces. The allowable external pressure is calculated using ASME code (ASME Section II part D, subpart 3) [5] for external loading. The cylinder/CLC being a thin one subjected to external pressure, the critical buckling pressures [6] are also calculated for the same. The allowable loading and stress parameters [7] are analytically estimated and tabulated in Table 1.

| Component Name            | Material   | Pressure Load Acting | Allowable design Pressure (N/mm$^2$) | Critical buckling Pressure (N/mm$^2$) | Remarks          |
|---------------------------|------------|----------------------|--------------------------------------|---------------------------------------|------------------|
| Cryostat Cylinder (CS)    | SS304L     | Vacuum Load: External Pressure $p = 0.1$ N/mm$^2$ | 0.3                                  | 0.35                                  | Safe design      |
| Current Lead Chamber (CLC)| SS304L     | Vacuum Load: External Pressure $p = 0.1$ N/mm$^2$ | 0.48                                 | 0.27                                  | Safe design      |
| Current Lead Chamber top  | SS304L     | Vacuum Load: External Pressure $p = 0.1$ N/mm$^2$ | 9 MPa (Maximum Stress developed)     | ----                                  | Safe design      |
| elliptical Cover          |            |                      |                                      |                                       |                  |

(c) Dead weight of coil: The load acting on the supports are the dead weight of the coil and accessories about 5 tons, we have kept a FOS of 2 to account for dynamic loading condition scenario, hence total acting on three supports is 10 tons. A 3D ANSYS structural analysis with SOLID 45 elements has been done for a single support assuming equal distribution of dynamic loading and support base pipe fixed at all directions on each support to estimate the deformation and stress developed in them. Maximum deflection obtained is 0.14 mm figure 7 while maximum Von Mises stress developed is 35 MPa figure 8 much less than allowable stress of 110 MPa for SS 304L. The
corresponding maximum deflection and Von Misses stress values for base spacer with a total loading of 10 tons is 0.29 mm and 62.5 MPa respectively, as shown in figure 9 and figure 10.

Figure 7. Deflection 0.14 mm (max.) (Support)  
Figure 8. VM stress 35 MPa (max.) (Support)  
Figure 9. Deflection 0.29 mm (max.) (Base spacer)  
Figure 10. VM stress 62.5 MPa (max.) (Base spacer)

6. Present status  
The plug-in cryostat cylinder has been fabricated, successfully inspected/tested at vendors site and has been delivered to IPR in January 2016. The functionality checks of the thermal shields at cryogenic LN$_2$ temperature and integrated vacuum leak testing of assembly system with a leak rate of $1.5 \times 10^{-9}$ mbar l/s, has also been successfully completed. Figure 11(a) shows the thermal shock tests for the CS cylinder thermal shield figure 11(b) shows the thermal shock tests for the CLC thermal shield. Figure 12 shows the integrated leak testing of the plug-in cryostat assembly.

7. Conclusion and future works  
The conceptual and engineering design of plug-in cryostat for superconducting CS is discussed in this paper with the following points

- Conceptual and engineering design for component of plug-in cryostat and both analytical, FEM structural analysis shows that the design is safe and acceptable.
- Thermal analysis shows minimum conductive heat transfer of 1.5 watt through three columnar supports from ambient temperatures, which is acceptable. Also radiation heat loads on shields are with in the design limits.
- The assembly sequence for the installation of plug-in cryostat into SST-1 cryostat bore considering the requirements and constraints involved has been discussed.
• The component has been fabricated, tested and delivered at IPR. Thermal shock tests, ground assembly test mock ups and integrated leak testing has also been successfully completed at IPR.
• The final assembly trials plug-in cryostat along with the superconducting coil and integration with SST-1 will be carried out in near future.

![Figure 11. Thermal Shock test of (a) CCY Shield, (b) CLC shield](image)

![Figure 12. Integrated Vacuum leak testing CCY assembly](image)

References
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