# Design consideration validation of cryo-components for current feeder system of SST-1 using flexibility analysis


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The current feeder system (CFS) of steady state superconducting tokamak (SST-1) has been designed for its normal, cool down/ warm up as well as for emergency operations. The system will transit in a temperature range of 300K to 4.5K during the operation. Components with different materials of construction will experience the differential thermal contraction and thermal stress. Therefore an optimized route for the superconducting (SC) bus bars and layout for piping has been designed to feed cryogen to respective current leads and SC bus bars. The design consideration, salient features and analysis of cold piping network are discussed .


## INTRODUCTION

The Current Feeder System (CFS) [1,2] of SST-1 consists of 10 pairs of 10 kA vapour cooled current leads and 20 no.s of SC busbars. Forced flow supercritical helium (SHe) at 4 bar and 4.5K will be used as a coolant for bus bars and liquid helium (LHe) at 1.3 bar and 4.5K will used as a coolant for current leads. Under such low temperature condition, the pipings are subjected to induce thermal stress due to the prevention of free contraction as CFS being an integrated system. Therefore, an optimized hydraulic network for LHe and SHe with in the current lead assembly chamber (CLAC) has been designed and analyzed. The analysis includes hydraulic and thermal stress considering different loops for the cryogen carrying hydraulic network as well as interconnections details. Design of such a complex system needs many iteration and ANSYS [3] has been used for this purpose. The input for this analysis is the modeling of piping layout, material properties and the temperature loading.

## SYSTEM DESCRIPTION

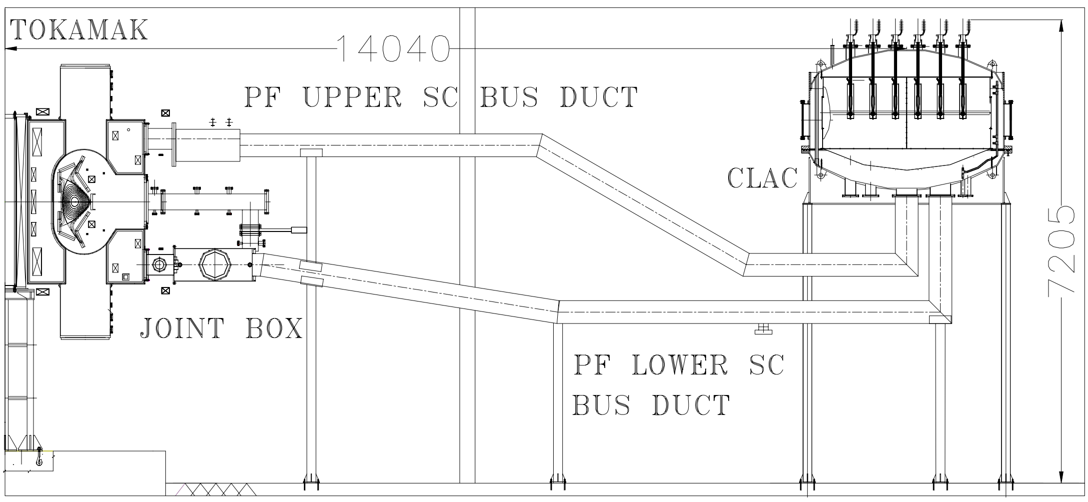



Figure 1 Elevation view of CLAC and SC bus ducts with SST-1

The CLAC of diameter 3 meter and of height ~2.2 meter houses 20 Nos of vapour cooled current leads, joints between current leads and SC bus bars, helium feed lines and isolators along with their supply headers. 20 nos of bus bars are divided in 3 segments and assembled inside 3 individual vacuum ducts. All bus bars are assembled inside three vacuum ducts. The bus ducts are designated as TF, PF upper and PF lower as shown in figure 1. The flow direction of coolant in the bus line will be from bottom end of current lead to SCMS. Therefore, at lower end of current leads SHe will be fed. The SHe & LHe are supplied by individual transfer lines to their respective headers in CLAC. TF and PF bus bars have their separate hydraulic headers for SHe to avoid any instability caused by PF in TF but all the current leads have a common header for LHe. Hydraulic analysis shows that TF bus bars require approximately 1.2 g/s flow and PF bus bars require approximately a total of 11 g/s of SHe. The consumption of LHe for per pair current lead varies from 15 l/h for I=0 to 35 l/h for I = 10 kA. Thus a hydraulic network of cryogen distribution pipes and tubes, with bends is required to distribute equal mass flow rate of SHe and LHe in each SC bus bar and current lead respectively without inducing higher thermal stresses in the piping.

## DESIGN DRIVERS

Cryogen carrying process tubes/piping shall be capable to withstand high-pressure (~40bar) and should have enough flexibility (low thermal contraction coefficient, 3-mm/m upto 4.5 K) to withstand transient events. The designed process line should have acceptable level of pressure drop (1 mbar/m) and piping material shall be high vacuum ($10^{-5}$ mbar) compatible.

## THE THERMAL ANALYSIS

The stress analysis is often made synonym to flexibility analysis, since the thermal stress can be reduced by making the system as flexible as possible. This is done by providing a number of U, O and L bends, which allow more deflections in the lines and make it less rigid. In order to design piping layout with loops, for SHe and LHe network we have used ANSYS software. In ANSYS software we employ the 'pipe 16' element for bends and 'pipe 18' for straight part. Both elements were used for modeling. The boundary conditions are fixed end of a pipe with U bend and load of temperature difference is 295.5 K. The stresses calculated from empirical formula [4] were compared with ANSYS result. The empirical relation for maximum stress is given as

for $\propto$ >1/2

$$\frac{\sigma_{\max} L}{E\varepsilon_t D_0} = \frac{1.5\beta^2(1+\beta)}{\alpha^2(1-3\beta^2)+\alpha\beta(2+3\beta)}$$

and for $\propto$<1/2

$$\frac{\sigma_{\max} L}{E\varepsilon_t D_0} = \frac{1.5\beta^2\left[(\beta/\alpha)(1-\alpha)+1\right]}{\alpha^2(1-3\beta^2)+\alpha\beta(2+3\beta)}$$

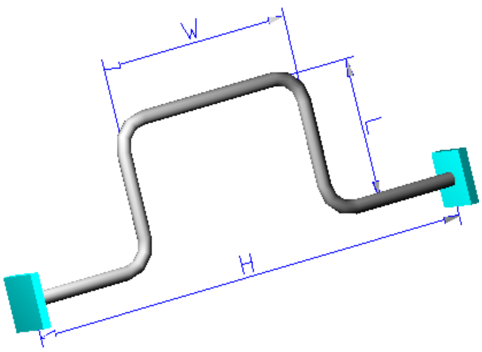


Figure 2 3D view of a U bend

$\varepsilon_t$ :unit thermal strain, Do: diameter, $\propto$: W/L and β: W/H. In our calculation we have taken $\propto$=1/2 for minimum thermal stress. For W = 200 mm, L = 400mm and considering maximum allowable stress as 60Mpa, calculated H is 153.8mm. The same geometry was modeled in ANSYS with identical boundary conditions and loads by using pipe16 and pipe 18 elements. Maximum stress σ is estimated as 68 MPa, which is in agreement with emperical estimation validating the modelling.

## HYDRAULIC ANALYSIS

Hydraulic analysis decides the flow diameter, velocity, and pressure drop. When a single phase fluid flows through a tube, then there will be pressure drop along the length of the line. The mjor contributions are from pressure drop at entry & exit, friction and bends along the line. Pressure drop in turbulence flow due to friction can be estimated by

$$\Delta P_{fric+bend} = \left[\frac{fl}{D} + nK\right]\left[\frac{8m^2}{\pi^2 \rho D^4}\right] \quad (1)$$

$K = 13f + 1.85(r/R)^{0.35}(\alpha/180)^{0.5}$ , $f = 1.325/[\ln\{(e/3.7D) + (5.74/R_e^{0.9})\}]^2$ for turbulent flow in rough tubes/ pipes, with $l$: total length of pipe, D: hydraulic diameter, n: total number of bends, K: loss coefficient in the bend, Re: Reynold number, e: surface roughness of pipe, $\alpha$: bend angle and R: bend radius.

## DESIGN OF SUPER-CRITICAL HELIUM HEADER

In CLAC, SHe will be fed to PF and TF bus bars from individual transfer lines. The TF supply transfer line is connected to 2 nos of bus bars for TF magnet and PF supply transfer line is connected to supply header of 18nos of bus bars for PF magnet. Header connected with PF bus bars has been designed for equal mass distribution of SHe to each current lead, acceptable pressure drop and minimum thermal stress. After each tapping points from SHe header the size of reduced diameter can be estimated by

$$D_2 = D_1 \times (m_2 / m_1)^{0.5} \quad (2)$$

The estimated diameters of the header changes slightly after each distribution and we have divided the header in to four parts. Table 1 shows the change in diameter of header after each tapping of SHe for SC bus bars.

Table 1 Diameter variation of SHe header

| | D1 | D2 | D3 | D4 |
|---|---|---|---|---|
| Flow Diameter (mm) | 23.37 | 18.04 | 15.8 | 10.42 |
| Velocity (m/s) | 0.210 | 0.235 | 0.210 | 0.235 |

## DESIGN OF LOOPS FOR SHe HEADER USING FLEXIBILITY ANALYSIS (FINITE ELEMENT ANALYSIS AND RESULTS)

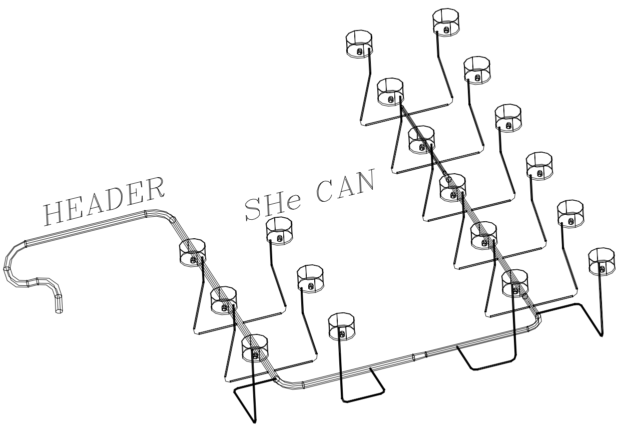



Figure 3 3D view of SHe header with feeding tubes in CLAC

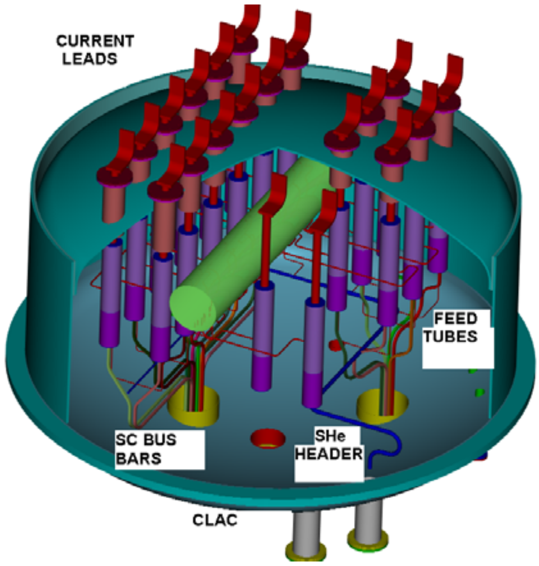
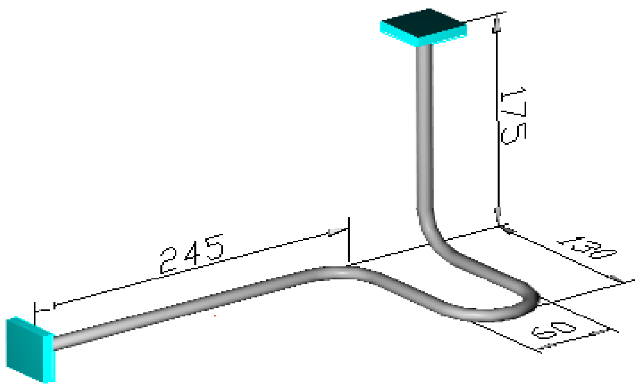



Figure 4. 3D cut view of CLAC

The flexibility of a system is nothing but the ability to resist the loads experienced by it with the help of its meticulous way of construction. Adding more number of bends increases the flexibility of a hydraulic network and allows the thermal contractions. The SHe header with bends is located in between the current leads as shown in figure 3. The weight of the header is ~ 4.5 Kg and can be supported from its taping points connected to 18 current leads, therefore total 19 points, including supply end can be considered as fixed end to design the feed tubes. The main supply end is considered as a fix end, and a loop has been provided for the required flexibility. With this configuration header is free to contract and will move up due to thermal contraction of feeding tubes. In order to feed the SHe to PF bus bar system with one main supply of maximum 12 g/s from the main SHe header, total 18 numbers of tapping are required to feed in lower end of current leads. Hydraulic analysis shows that the required flow diameter of each feeding tube is ~6mm. An optimized layout was modeled in ANSYS with identical boundary conditions and loads by using pipe16 and pipe 18 elements. The result with maximum stress σ is 100 MPa, and is acceptable.

## DESIGN OF LOOPS FOR CURRENT LEADS

The LHe header which supply liquid helium to all the current leads, supported from the top dish end inside the CLAC and all the LHe feeding tubes with their loops (as shown in figure 5) are connected to their respective current leads. The bottom edge of liquid helium header is ~175mm above the supply current lead can and inter-space in between two loops is more then 30 mm from each other to avoid any electrical break down of insulation. LHe feeding loop has been designed keeping a considering simple design, identical, easy to form, easy to assemble and induced thermal stress in the loop is less then 120 MPa. Moreover the axial loading on fixed point connected to current lead shall be less than 40N to avoid bending of current lead. Therefore an optimized loop was modeled in ANSYS. The result with maximum stress σ is 42 MPa, which is acceptable.




tapping of

Figure 5 3D view of LHe feeding tube.

## SUMMARY

This paper describes the thermal stress, flexibility analysis and layout design of cryogen carrying piping/ tubing and their distribution network inside CLAC for CFS of SST-1. At low temperature conditions, the pipelines contracted and thermal stress induces due to prevention limit of thermal contraction. The layout, which is an optimized and aesthetic layout, has been designed by considering the space limitation and restriction, which may rises during the fabrication & assembly. The whole distribution network has been designed using ANSYS software.

## REFERENCES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