# Conceptual Design and Analysis of Prototype Center Stack for Spherical Tokamak based Technologies Development*)

Aditya Kumar VERMA, Ranjith Kumar SANTHARAM, Prasada Rao PEDADA, Shiju SAM, Yellamraju S.S. SRINIVAS and Rajendra Kumar ELLAPPAN

*Affiliations Institute for Plasma Research, Bhat Gandhinagar Gujarat-382428, India*

(Received 29 December 2021 / Accepted 5 April 2022)

Institute for Plasma Research (IPR) is developing Spherical Tokamak (ST) related technologies to realize a low aspect ratio compact device for plasma experiments. Center Stack is one of the critical components in ST which requires R&D to design, manufacture and assemble in a limited space within required tolerances. A Prototype Center Stack (PCS) is being developed based on reference ST parameters with major radius 0.28 m and minor radius 0.16 m for magnetic field 0.1 T. The main objective of PCS is to design and check its manufacturing feasibility to achieve required tolerances at component and assembly level and maintaining overall accuracy. The PCS assembly consists of two sets of coils, namely Toroidal Field (TF) coils and Ohmic (OH) coil made of Electrolytic Tough Pitch (ETP) Copper. It consists of 6 number of TF coils, with 3 turns per coil, all connected in series. The OH coil has two parallel layers, with 143 turns per layer. The SS 304 support structure consists of tension cylinder and Center Stack Casing (CSC) which are mounted on a pedestal support. Two different capacitor bank based power supplies are considered for TF and OH coils with a maximum operating current of 8.5 kA and 10 kA respectively. This paper discusses the conceptual design, engineering analysis including thermal, electromagnetic and structural analysis using ANSYS Mechanical, Multiphysics and Maxwell modules.



Keywords: Prototype Center Stack, Center Stack, Copper Toroidal field coil, Copper OH coil, Spherical Tokamak, Engineering Analysis

DOI: 10.1585/pfr.17.2405074

## 1. Introduction

Spherical Tokamak (ST) is a special type of magnetic confinement configuration based device which is being pursued to develop fusion energy for commercial power production on a fast track approach [1–3]. The main components of ST are Center Stack (CS), Toroidal Field (TF) outer legs, Vacuum Vessel, auxiliary powers sources and support structures. CS assembly is one of the most critical and challenging system (in magnetic and mechanical aspects) of Spherical Tokamak configuration.

Institute for Plasma Research (IPR) is developing a Small Scale Spherical Tokamak (SSST) in which the TF coils and Ohmic (OH) coil are conventional type similar to large aspect ratio for phase 1 operations. In phase 2, same machine would be modified to a compact ST by replacing the TF and OH coils with centre stack in which the TF coils and OH coil are integrated as a single system. Based on this requirement, a Prototype Centre Stack (PCS) has been planned to design and manufacture as a part of R&D activities considering reference ST parameters as shown in Table 1.

The main objective of PCS is to design and check its manufacturing feasibility to achieve required tolerances at component and assembly level and maintaining overall accuracy. The PCS will be tested for magnetic field at its major radius, coolant temperature, flow parameters and structural integrity. This paper presents the design calculations, 3D modelling, thermal, electromagnetic and structural analysis results of PCS.

Table 1 Reference design parameters for PCS.

| Parameters | units | value |
|---|---|---|
| Major Radius, $R_0$ | mm | 280 |
| Minor radius, a | mm | 160 |
| Aspect ratio | | 1.75 |
| Available bore diameter | mm | 162.6 |
| Magnetic field at $R_0$ | T | 0.1 |
| OH coil magnetic flux | mWb | 25-30 |
| Max. current of TF coil power supply | kA | 8.5 |
| Max. current of OH coil power supply | kA | 10 |

## 2. Major Components of PCS

PCS assembly consists of two sets of coils, namely TF and OH made of Electrolytic Tough Pitch (ETP) Copper. Figure 1 shows PCS assembly which has major components such as TF Coil (inner and outer legs), OH Coil,

author's e-mail: adityakumar@ipr.res.in

*) This article is based on the presentation at the 30th International Toki Conference on Plasma and Fusion Research (ITC30).

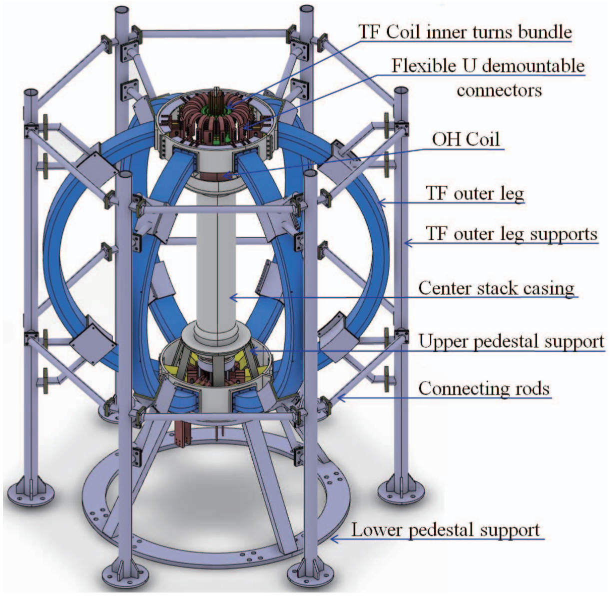


Fig. 1 3D model of PCS assembly.

G10 central rod, tension cylinder, Center Stack Casing (CSC) and support structure. PCS components and assembly models are prepared in CATIA V5 software [4].

**TF Coil:** It is made into two parts - inner and outer legs. TF coil inner turns are tightly nested on G10 central rod, which is a center reference of PCS. It is an electrical insulator made of high pressure fiber glass laminate and is used as the central support to withstand high compressive strength.

TF inner legs are designed in trapezoidal shape in order to achieve high packing factor and maximum cross sectional area. The inner turn sharp edges are chamfered with 1 mm corner radius to prevent insulation damage. All inner turns are insulated with 1 mm of polyester film electrical insulation. The provision of active cooling is provided through copper tubes in the inner turns as shown in Fig. 2 (a). The 18 inner turns of the 6 TF coils are arranged in the periphery of G10 rod and form a TF inner leg bundle as shown in Fig. 2 (b). The estimated bundle height is 1400 mm.

A single complete TF Coil is formed by connecting three inner TF turns with the outer leg. The TF outer leg assembly consists of three TF outer turns, intermediate insulation (G10), turn insulation (polyester film insulation tape) and stainless steel (SS304) envelope. The inner and outer turns are connected through flexible U demountable connectors.

The design calculations have been carried out and the estimated values are listed in Table 2.

A thick layer of electrical insulation is wrapped over TF inner leg bundle and tightly fitted into tension cylinder assembly. The tension cylinder is made of SS304 pipe which is split vertically into two halves. An electrical insulation is sandwiched between the two halves of the tension cylinder to avoid electrical looping.

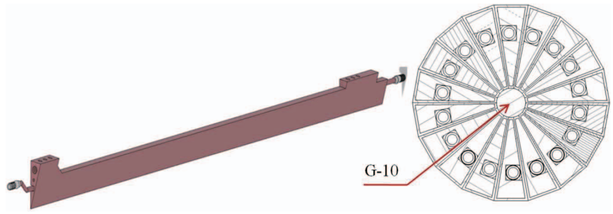


Fig. 2 (a) Trapezoidal shape TF inner turn with cooling tube, (b) Cross section view of TF inner turns bundle.

Table 2 Estimated TF coil design parameters.

| Parameters | Units | Value |
|---|---|---|
| Number of turns per coil | No's | 3 |
| Total number of coils | No's | 6 |
| TF inner turn width | mm | 35.5 |
| TF outer turn width | mm | 50 |
| TF inner turn cooling hole diameter | mm | 4.5 |
| Peak current | kA | 8.5 |
| Peak Voltage in TF coil | V | 3000 |
| Resistance of TF | mΩ | 6 |
| TF coil weight | kg | 45 |

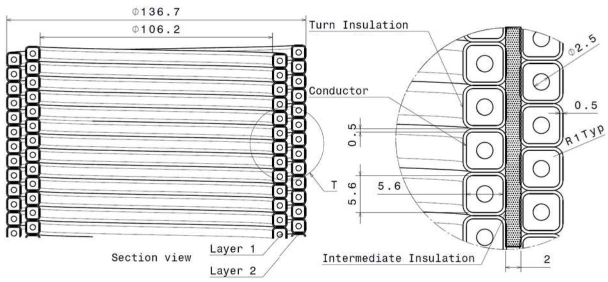


Fig. 3 Cross section view of OH coil.

**OH Coil:** The OH coil conductor is wound over the tension cylinder in 2 layers with an electrical insulation of 2 mm wrapped in between the layers. A square cross section hollow conductor of ETP copper of 5.6 mm with a central cooling channel of Ø2.5 mm has been considered for OH coil [5]. Figure 3 shows the cross section of the OH coil conductor which is insulated with class F polyester film insulation tape of 0.5 mm thickness.

Design calculations have been carried out for the OH coil and the estimated values are listed in Table 3.

Based on TF and OH coil estimations, Fig. 4 shows the radial build up of the PCS components.

The temperature sensors will be mounted on the OH coil and TF coil outer surfaces. The complete TF inner leg assembly with OH coil is enclosed within a CSC made of SS304. The CS is assembled on lower and upper pedestal supports with bolting arrangement.

**Support structure for PCS assembly:** The entire

Table 3 Estimated OH coil design parameters.

| Parameters | Units | Value |
|---|---|---|
| OH number of layers | No's | 2 |
| Number of turns in each layer | No's | 143 |
| OH coil inner radius | mm | 53.3 |
| OH coil outer radius | mm | 68.5 |
| OH coil height | mm | 1000 |
| Peak current in OH | kA | 10 |
| Voltage | V | 8000 |
| Resistance of OH | Ω | 0.07 |
| OH Coil inductance | H | $8.9 \times 10^{-4}$ |
| Peak Magnetic flux density | T | 2.5 |
| OH coil weight (including tension cylinder) | kg | 50 |

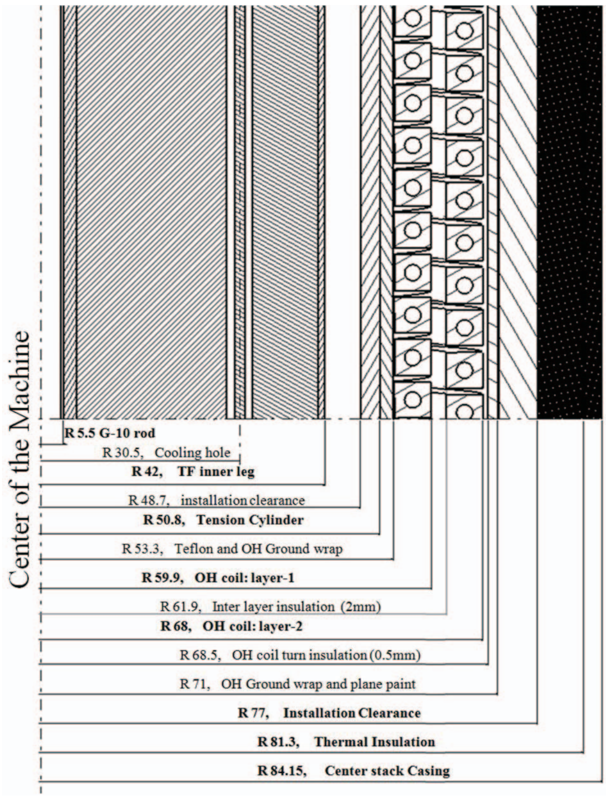


Fig. 4 Radial build up of PCS.

PCS assembly is held and supported using pedestal and pipe support structures made of SS304 as shown in Fig. 1. The TF inner leg assembly and the OH coil assembly are mounted on a lower and upper pedestal support structure respectively. TF outer leg assembly is supported using pipe supports. The pedestal supports are opted to fulfill the space requirements for bus bars & cooling tubes routing and maintenance. Connecting rods are introduced to avoid distortion of TF outer legs during operation. The pipe supports and connecting rods are modular type and connected with fasteners.

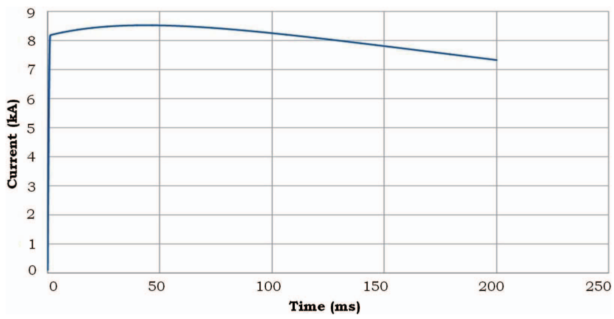


Fig. 5 Current waveform for TF coil.

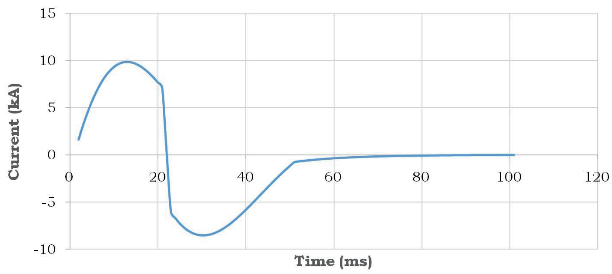


Fig. 6 Current waveform for OH coil.

# 3. Engineering Analysis

The engineering design analysis and structural integrity check of the PCS assembly have been performed using ANSYS modules [6, 7]. This includes thermal, electromagnetic and structural analyses.

## 3.1 Thermal analysis

Thermal analysis is performed to estimate the peak temperature of the coils due to the input coil currents, considering 8 hours of operation in a day, with back to back shots at an interval of 17 minutes. The typical input current waveforms for a shot are shown in Figs. 5 and 6 for TF and OH coil, respectively.

The thermal analysis has been performed in ANSYS Mechanical in 2D models using 4 node element. Trapezoidal cross section of inner turn has been considered for TF coil. Considering the vertical symmetry of OH coil, a vertical cross section with four adjacent conductors has been modeled for the analysis.

As the air flow is restricted at the inner bore, a tentative value of natural convection of 1 W/m$^2$ °C is applied along the radial outer periphery of the coils which is exposed to air.

Apart from this, forced cooling convection (HTC = 12 W/m$^2$ °C) using water is applied on the cooling channels of TF and OH coils corresponding to a velocity of 0.35 mm/s independently. An ambient temperature of 35°C is considered for the analysis. The temperature time plot for TF and OH coil (conductor and insulation) are shown in Figs. 7 and 8, respectively.

The peak temperature of the copper conductor and in-

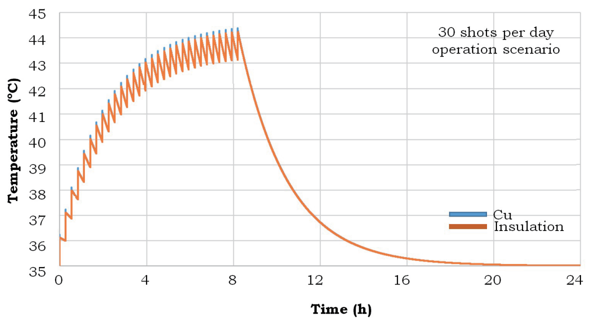


Fig. 7 Temperature time plot for TF inner leg (copper conductor and insulator).

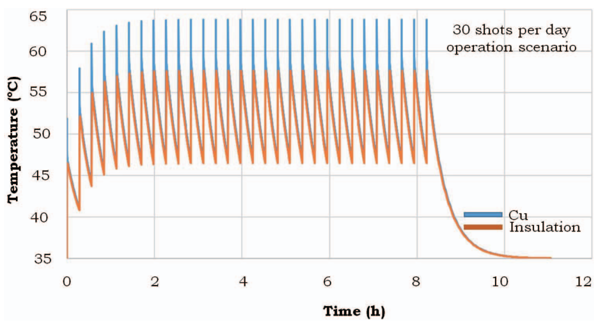


Fig. 8 Temperature time plot for OH coil (copper conductor and insulator).

sulation material for TF coil is nearly 44°C whereas for OH coil, the corresponding temperatures are 64°C and 57°C. The peak temperature experienced by the coils is within the allowable temperature limit of insulation.

## 3.2 Electromagnetic (EM) analysis

Static EM analysis has been performed for the PCS assembly using 8 node 3D elements. A simplified integrated model consisting of TF and OH coils is used for EM analysis for the estimation of forces in the coils. The static value of peak current mentioned in Table 2 and Table 3 has been used as input for the coils.

Figure 9 shows the distribution of forces on individual elements of TF coil. The overall force on the coil has been estimated by integrating the individual element forces. The coil inner turn experience an inward force while the outer turn experiences an outward force. The resultant force experienced is inward with a magnitude of 15 kN, which eventually will be transferred to the center G10 rod.

Similarly, the resultant outward radial force on the OH coil obtained by integrating the individual element forces is 1.5 MN. The elemental force distribution on OH coil is shown in Fig. 10.

Figure 11 shows the element force distribution in overall model. It is observed that the OH coil forces are higher as compared to TF coil. These estimated forces acting on the coils are used as inputs for structural analysis.

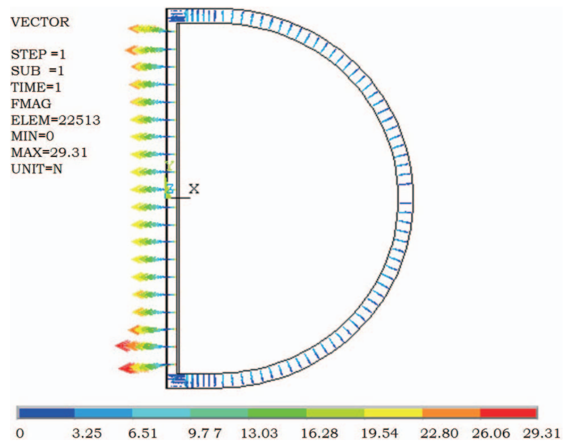


Fig. 9 Magnetic force vector distribution on a TF coil.

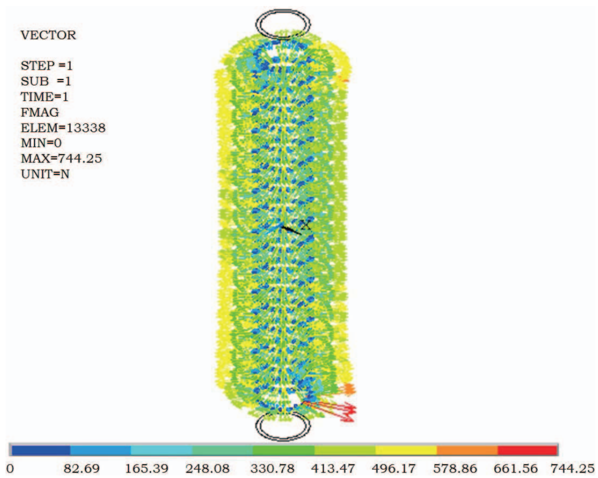


Fig. 10 Magnetic force vector distribution on OH coil.

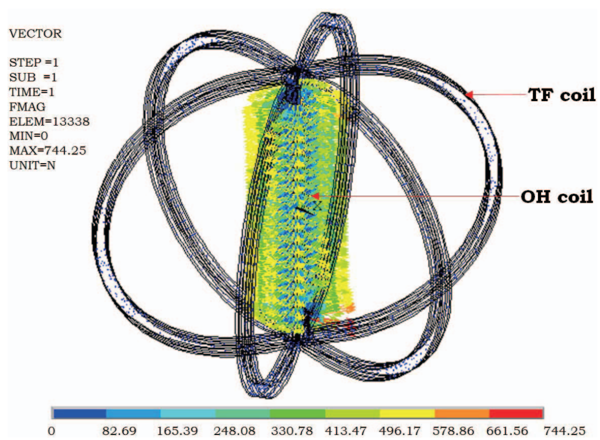


Fig. 11 Magnetic force vector distribution on the integrated TF and OH coil.

## 3.3 Structural analysis

Structural analysis is carried out on the integrated model of PCS assembly. The primary loading condition is the combination of self weight and static electromagnetic forces applied on the coils. The secondary loading

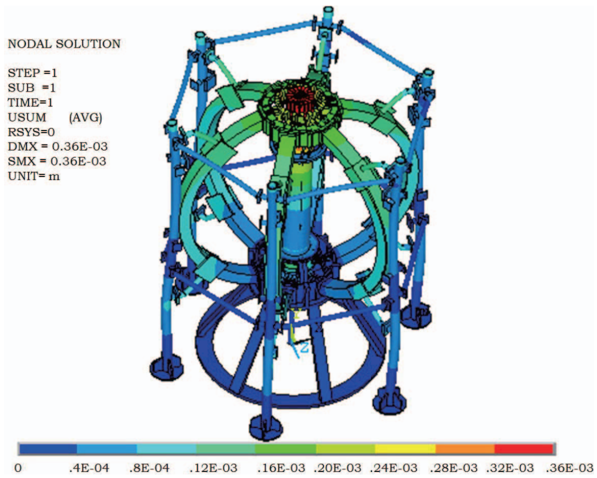


Fig. 12 Deformation plot for secondary loading (peak 0.36 mm).

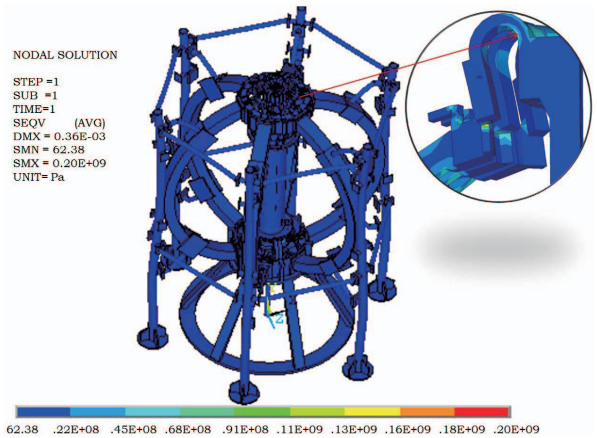


Fig. 13 von Mises stress plot for secondary loading (max 86 MPa on TF coil).

condition is the combination of peak temperature due to input current, along with the primary loads. The base of the support is assumed to be fixed. The structural analysis has been performed in ANSYS Mechanical module using 8 node solid element.

The peak deformation and von Mises stress for the primary loading are 0.115 mm and 35 MPa respectively. The results of the primary loading are within the acceptable limit of the structural material. The allowable stress limits [8] of the materials SS304, G10 and ETP copper considered at operating condition for the qualification of stresses are 144, 87 and 46 MPa, respectively.

For secondary loading, the peak deformation and von Mises stress are 0.36 mm and 206 MPa, respectively. The result plots of the secondary loading condition are shown in Figs. 12 and 13 which mainly indicate the deformation and von Mises stress plot, respectively.

The peak stress observed on the coils due to secondary loading is 86 MPa. The peak stress of 206 MPa is observed on the flanges of the spring support in a localized region at the end of the spring which is modelled as a 1-D spring element. The stresses due to primary loading as well as due to secondary loading are well within the allowable limits of the material.

## 4. Summary

The conceptual design of PCS has been carried out along with engineering analyses. The analytical calculations have been carried out for the TF and OH coils and accordingly the conductor sizes are estimated. Thermal analysis has been performed for the TF and OH coils considering forced cooling scenario. The peak temperature for both the coils during operation are found to be within limit. Electromagnetic and structural analysis are performed in order to verify the structural integrity of the entire PCS assembly. The peak forces experienced by TF and OH coil is 15 kN and 1.5 MN respectively. The peak stress on the structure due to primary and secondary loading conditions are determined using the estimated forces experienced by the coils which are found to be within the limit.

The present design is to be further analyzed for assembly loads such as twisting/misalignments of coils and supports. In addition, a transient electromagnetic analysis will be performed on the integrated model to reassess the forces and torques acting on the coil and its effect on the support structure. These analyses may lead to the optimization of the PCS assembly support structure.

[1] C. Neumeyer *et al.*, Engineering design of the National Spherical Torus, Fusion Eng. Des. **54**, 275 (2001).
[2] Vasily K. Gusev *et al.*, Central Solenoid for Spherical Tokamak Globus-M, ISSN: 0748-1896 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ufst19
[3] G.M. Voss *et al.*, Centre Column Design for the MAST Spherical Tokamak, Fusion Technology 953 (1994).
[4] 3D Modelling Solutions | CATIA$^{TM}$ - Dassault Systems, (2019).
[5] Data Sheet_Luvata_List of tools OF-OK Copper Hollow Conductors.
[6] Ansys Maxwell | Electromechanical Device Analysis Software.
[7] ANSYS 2019 R3Modules, https://www.ansys.com
[8] https://www.matweb.com/