SUPERCONDUCTING MAGNETS AND CRYOGENICS FOR THE STEADY STATE SUPERCONDUCTING TOKAMAK SST-1

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Abstract

SST-1 is a steady state superconducting tokamak for studying the physics of the plasma processes in tokamak under steady state conditions and to learn technologies related to the steady state operation of the tokamak. SST-1 will have superconducting magnets made from NbTi based conductors operating at 4.5 K temperature. The design of the superconducting magnets and the cryogenic system of SST-1 tokamak are described.

1. Introduction

A steady state superconducting tokamak SST-1 is being designed at the Institute for Plasma Research, with the objectives of studying the physics of the plasma processes in tokamak under steady state conditions and to learn technologies related to the steady state operation of the tokamak. These studies are expected to contribute to the tokamak physics database for very long pulse operations. SST-1 [1] is a large aspect ratio tokamak, configured to run double null diverted plasmas with significant elongation (κ) and triangularity (δ). Superconducting magnets will be used for both the toroidal field (TF) and the poloidal field (PF) coils of SST-1. These coils will operate at 4.5 K. In the following we give a brief description of SST-1 tokamak and discuss the design of the superconducting (SC) coils followed by the description of cryogenic system requirements for these coils.

2. SST-1 Machine

The SST-1 tokamak comprises of superconducting TF coils, a UHV compatible vacuum vessel in the bore of the TF coils and having plasma facing components inside, the superconducting PF coils placed around the TF coils, the support structure for the PF and TF coils, the cryostat enclosing the TF, the PF coils and the vacuum vessel. A liquid nitrogen cooled radiation shield is provided between the SC coils and the vacuum vessel, as well as between the cryostat and the SC coils. A resistive Ohmic transformer system is provided to initiate the plasma and sustain the current for initial period. The overall support system of the machine is derived from 8 pillars grouted to the ground and a central support having four pillars. The vacuum vessel is supported on the cryostat while the TF and PF coils are supported on a cold mass support that transfers the load to the main machine support. Other subsystems include RF systems for pre-ionization, auxiliary current drive and heating, neutral beam injection (NBI) system for supplementary heating, cryogenic systems at LHe and LN_2 temperatures, chilled water system for heat removal from various subsystems. A 3-d view of the SST-1 tokamak is shown in Figure 1. The machine has a major radius of 1.1 m, minor radius of 0.20 m, a toroidal field of 3.0 T at plasma center and a plasma current of 220 kA. Elongated plasma with elongation in the range of 1.7 to 1.9 and triangularity in the range of 0.4 to 0.7 can be produced. Hydrogen gas will be used and plasma discharge duration will be 1000 s. Auxiliary current drive will be based on 1.0 MW of Lower Hybrid current drive (LHCD) at 3.7 GHz. Auxiliary heating systems include 1 MW of Ion Cyclotron Resonance Heating (ICRH) at 22 MHz to 91 MHz, 0.2 MW of Electron Cyclotron Resonance heating (ECRH) at 84 GHz and a Neutral Beam Injection (NBI) with peak power of 0.8 MW with variable beam energy in range of 10-80 keV. A large number of diagnostics for plasma and machine monitoring will be deployed along with a distributed data acquisition and control system. The power for operating various subsystems will be derived from 132 kV grid. A cross-section of SST-1 is shown in Figure 1. In the following the magnet system and cryogenic system for SST-1 tokamak are described in detail.

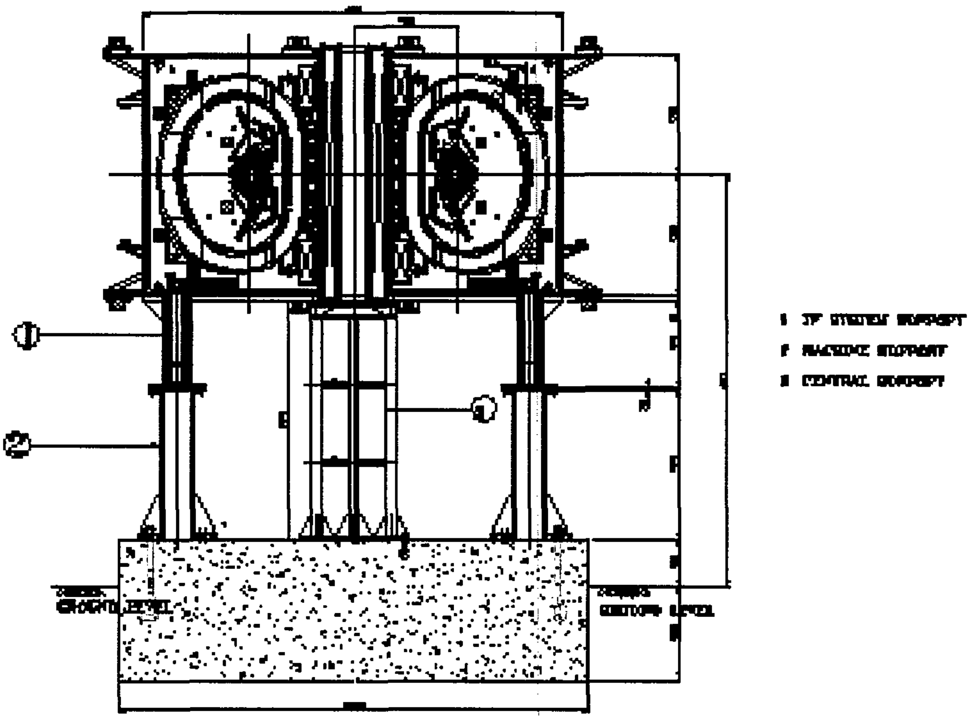

FIG. 1: A cross-section of SST-1 Tokamak.

3. Magnet system

The magnet system comprises of TF system, PF system, Ohmic and vertical field coils, & vertical position control coils.

3.1. Toroidal field system

The TF system design requirements include the production of 3.0 T magnetic field at plasma axis with ripple < 2% within plasma volume. The TF assembly should be capable of providing steady state operation and should withstand the plasma disruptions and vertical displacement events (VDE) without quenching. The assembly shall be capable of being cooled down and warmed up in less than 15 days.

The TF system consists of 16 numbers of modified D shaped TF coils arranged symmetrically around the major axis spaced 22.5° apart. Each of the TF coils will be made up of six double pancakes, each pancake having nine turns. There are 108 turns in each of the coils. A total of 17.28 MAT at a peak current of 10 kA per turn will produce a field of 3.0 T at plasma center and a maximum field of 5.1 T at the TF conductor. The winding pack of 6 double pancakes will be shrunk fitted into a stainless steel (SS316L) casing which supports most of the electromagnetic loads. The contour of D-shaped TF coil consists of a straight leg and 5 arcs. The overall dimensions of the TF coils are dictated by the need to have ≤ 2% field ripple at plasma edge, large enough radial ports on the vacuum vessel so as to allow radial access for NBI, human access inside the vacuum vessel for assembly of in-vessel components.

All coils are connected in series and are protected against the quench by suitable dump resistance, switching and sensing system. The main parameters of TF coils are summarized in Table I.

3.2. The poloidal field system

The SST-1 PF system [2] comprises of nine superconducting coils and two resistive coils. These coils allow for a wide range of elongation and triangularity and support a large range of plasma equilibria.

TABLE I. TOROIDAL FIELD SYSTEM

Number of Coils	16
Shape	Modified D
Turn per Coil	108
Double Pancakes per Coil	6
Rated current	10 kA
Field at Plasma axis	3.0 T
Maximum Field	5.1 T
Maximum Field Ripple	< 0.35%
Bore Dimensions (Radial)	1190 mm
Bore Dimensions (Vertical)	1746 mm
Outer Dimensions (Radial)	1560 mm
Outer Dimensions (Vertical)	2120 mm
Average turn length	5500 mm
Weight of One Coil with casing	1100 Kg
Total weight of TF system	1920 Kg
Centering force per coil	2.73 MN
Tension in the coil	90 – 110 MPa
Total inductance	1.12 H
Total stored energy	56 MJ
Dump time constant	12 s
Peak dump voltage	± 600 V

Feasibility of limiter operation during plasma current ramp-up, double and single null operation at plasma current of 220 kA, double null operation at plasma current of 330 kA and various start-up scenario are the design drivers for PF system. A free boundary, axisymmetric, ideal MHD equilibrium model based code has been used for designing and optimizing the PF system. Table II summarizes the characteristics of the PF coils. The designed PF system allows flexibility in elongation of the plasma in range of 1.7-1.9, triangularity in range of 0.4-0.7, plasma inductance in range of 0.75-1.4, poloidal β in range of 0.01-0.85 and slot divertor configuration.

TABLE II. POLOIDAL FIELD COILS

Coil type	Number of coils	Coil Radius (m)	Vertical Location (m)	Winding Cross-section (mm^2)	Number of turns
PF1	1	0.45	0.0	71x320	80
PF2	2	0.45	±0.43	71x163	40
PF3	2	0.50	±0.93	136x380	192
PF4	2	1.72	±1.03	85x136	40
PF5	2	2.01	±0.65	85x136	40
PF6	2	1.35	±0.35	100x100	16

3.3. Conductor for superconducting coils

All superconducting coils will be made using a cable-in-conduit conductor (CICC) based on NbTi+Copper. The choice of the NbTi is based on the fact that the operating fields in TF and PF coils are moderate. The CICC will be made up of 135 strands cabled in a 3x3x3x5 cabling pattern and conduited inside a SS304L conduit. The characteristics of the CICC are summarized in table III. The CICC is designed for an operational current of 10 kA at 5 T and 4.5 K with a critical current of 36 kA. The nominal critical current for each strand at 5T and 4.5K is 272 A.

The CICC design has been carried out by Institute for Plasma Research in consultation with National High Magnetic Field Laboratory, Florida State University, Tallahassee, USA. In the design and optimization of the CICC various operational constraints have been met. The optimum design was finalized in March 1997 and M/S Hitachi Cables Ltd. were awarded the contract for manufacturing of the cable. Results on pre-qualification trials on virgin strands and strands extracted from sample CICC are summarized in table IV. The tests carried out include critical current measurements at 5T and 4.2K, determination of superconductor to normal state transition index 'n' & RRR, measurement of hysteresis losses, Cu to Sc ratio, sharp bend tests and spring back tests. One strand each from the first stage triplets were taken for the test on extracted strands. Void fraction and conduit thickness measurements were carried out on CICC. The results indicate that degradation in strands due to cabling and jacketing is less than 5% and critical current ≥35 kA at 5T, 4.2K is ensured. A 600m test piece has been fabricated and detailed tests on model coil fabricated from the test piece are in progress at Kurchatov Institute, Moscow. Preliminary results indicate that CICC is able to carry ≥40 kA current at 1.5 T, 4.5k without quenching.

3.4. Support system for superconducting magnets [3]

The straight legs of TF coils are wedged to form the inner vault. The outer vault is formed by connecting inter coil structures between the TF coils. These vaults resist the centering force and overturning torque experienced by the TF system. There is insulation break between each of the TF coils.

TABLE III. CHARACTERISTICS OF CICC

SC material	NbTi + Copper
Filament diameter	≅10 μm
Strand Diameter	0.86 mm
# of filaments per strand	≅1272
Cabling pattern	3×3×3×5
Copper area per strand	≥ 0.482 mm^2
Copper RRR	≥100
CICC Dimensions	14.8 x 14.8 mm^2
Conduit Material	SS304L
Conduit thickness	1.5 mm
Copper Cross-section A_{cu}	0.6769 cm^2
Superconductor Cross-section A_{sc}	0.1386 cm^2
Helium Cross-section A_{He}	0.5484 cm^2
Conductor Cross-section A_{cs}	1.40 cm^2
Void fraction	≥ 36%
Hydraulic diameter	≅0.62 mm
Hysteresis losses	< 100 mJ cm^{-3}

TABLE IV. RESULTS OF CONDUCTOR PRE-QUALIFICATION TESTS

Parameter	Virgin strands	Extracted strands
I_c @ 5T, 4.2K	273 A	262 A
'n' at 5T	46	45
Hysteresis loss (mJ/cm^3)	36.5	32.7
RRR of Cu	108	92
Cu: Sc Ratio	4.98	4.98
Filament breakage %	0	0

The superconducting PF coils are supported on the TF coils' casings and the inter-coil structures, with the coils and structures forming a rigid cold mass of about 30 tons at 4.5 K. The TF coils are further supported on a base support system consisting of a ring with 16 cantilevered beams. The ring rests on eight columns that are inside the cryostat and have liquid nitrogen intercepts to minimize the conduction loss at 4.5 K as the cold mass load is transferred from these columns to main machine support. The main machine support comprises of 16 columns, supporting the base frame of the cryostat and the cold mass, which are firmly grouted to ground.

3.5. Ohmic transformer, vertical field coils and control coils

The SC PF coils cannot be ramped at a very fast rate required for plasma breakdown and initial current rampup. An Ohmic transformer [4], comprising of a central solenoid and two pairs of compensation coils, and made from hollow copper conductor, will, therefore, be used for this purpose in a pulsed mode. The transformer has a storage capacity of 1.4 Vs and can be used for producing circular plasma with current up to 100 kA for almost one second. A pair of vertical field coils will keep this circular plasma in equilibrium during the initial phase till the current drive is taken over by the LHCD and the PF coils are ramped up at slow rate to provide the divertor configuration for elongated triangular plasma. The PF coils' currents will be ramped up to their respective current values in about 2-3 s in pre-programmed way so as to achieve the desired plasma equilibrium.

Passive stabilizer plates are provided inside the vacuum vessel to slow down the vertical instability and a pair of control coils is provided inside the vacuum vessel for active control of plasma position. The coils are made of copper conductor.

3.6. Present status of the superconducting magnets

The engineering design of the SST-1 superconducting magnets has been completed. The cable-in-conduit-conductors for the TF and PF magnets are also presently being manufactured. A 600m long test piece is being used for full scale testing of CICC in form of a model solenoid. Efforts on identifying a suitable vendor from amongst Indian industry for manufacturing the magnets are on. The actual winding activities are expected to begin by mid 1999.

4. Cryogenic system for SST-1

The superconducting magnet system (SCMS), consisting of TF and PF coils, in SST-1 has to be maintained at 4.5 K in presence of steady state heat loads. In addition the pulsed heat loads during the plasma operation have to be taken care of by the cooling system so as to maintain the magnets in superconducting state. The magnets will be cooled using forced flow of supercritical helium (SHe) through the void space in the CICC. Further the magnets have to be energized from power supplies at room temperature using vapor cooled current leads, which evaporate liquid He at cold end to gas He at $\cong$ 300 K at the warm end of the lead. A Helium refrigerator/liquifier with cold circulation system for SHe is, therefore, required for this purpose. In order to minimize the heat loads on magnets and support system at 4.5 K, liquid nitrogen (LN_2) shields are provided between the cold mass at 4.5 K and warmer surfaces, e.g. vacuum vessel and cryostat, at $\geq$ 300 K. A LN_2 storage and distribution system is provided for this purpose.

The different heat loads experienced by the SCMS can be classified into the steady state heat loads (including radiation losses from LN2 shields and residual gas conduction) and the losses during operation, which include the joule heating and ac losses in the joints, and the ac losses in CICC due to the current ramp up/down in the coils and current changes in the feedback coils. In addition to these loads from the SCMS there are heat loads arising from the conduction from supports, eddy currents induced in the magnets casings and structures, losses in the transfer lines and bus ducts, heat loads from cryogenic valves, bayonets and diagnostics inserts. Table V shows the estimates of these heat loads. A total steady state heat load $\cong$ 180W is expected. In addition the SCMS is subjected to pulsed loads during the plasma operation. Typical energy deposited in the SCMS during a plasma pulse is given in table VI. Most of the contribution to these pulsed loads comes from the ac losses in the CICC, which strongly depend on the coupling time constant of the cable. The coupling time constant cannot be estimated accurately and have to be measured experimentally.

The numbers given in the table are based on a time constant of 200 ms for the cable, though the expected time constant is of the order of few tens of ms. The pulsed loads are, therefore, expected to be smaller than those shown in the table. A total pulsed load of ≅ 125 kJ is expected during one plasma pulse. Such pulses will be repeated every 5000 sec with a total of six pulses per day. The exact time constant, and hence the more accurate estimates of the ac losses, will be available from the results of the experiments which are planned to be conducted on a test solenoid using the actual CICC. The magnets will be energized using 20 pairs of current leads. The TF coils will be energized for about 10 h per day, while PF coils will carry current on the average of about two hours per day. This load would on the average evaporate ≅ 150L/h of LHe to He gas at ≅ 300K, in the current leads of the magnets.

4.1. Flow requirements for she

The heat in the SCMS is to be removed by forced flow of SHe through the void space in CICC. For this purpose the entire magnet system is divided in several parallel paths. The flow requirements for each of the paths is estimated based on the requirement of stability of the SC in presence of pulsed loads ac losses superimposed on the steady state heat loads. The details of the flow paths and flow rates are given in table VII. A total flow ≅ 0.3kg/s is required to keep the SC temperature well below the current sharing temperature in presence of peak pulsed loads.

TABLE V. STEADY STATE HEAT LOADS

Radiation losses	40 W
Residual gas conduction	6 W
Conduction from Support	34 W
Transfer line Losses	20 W
Losses in bus duct	10 W
Losses through Valves	30 W
Losses through Diagnostics Inserts	20 W
Joint Losses in TF coils	20 W

TABLE VI. TRANSIENT HEAT LOADS IN SCMS IN ONE PLASMA PULSE (1006 s)

Coil type	Ramp up/down 3s (kJ)	flat top (kJ)	Joints (kJ)	Total (kJ)
TF	2.11	10.3	48.3	62.82
PF1	0.41	0.70	0.25	1.77
PF2	0.52	1.00	0.50	2.54
PF3	21.4	4.16	0.50	47.46
PF4	0.19	0.72	5.03	6.05
PF5	0.16	0.46	5.03	5.81
Total heat load per pulse			126.45	

4.2. The liquid helium plant

A closed cycle LHe plant is required to cater to both the steady state and transient heat loads in SCMS. Taking into account the steady and transient loads and considering the uncertainties in the estimates a LHe plant with a capacity of 400 W refrigeration at 4.5 K and 200L/h liquefaction at the pressure

1.2 bar(a) is to be installed. The plant will, in additional, also provide the refrigeration capacity of around 250W for the heat dissipation in the cold circulation pump. The above total capacity will be achieved with liquid nitrogen pre-cooling. The total capacity of the plant, (both, refrigeration as well as liquefaction) would be variable from 50-100%. It will also be possible to operate the plant without LN_2 pre-cooling at the reduced capacity.

A cold circulation system, for the flow of SHe through the SCMS in a closed cycle, forms part of the LHe plant. The system will comprise of a cold pump, heat exchangers and valves. The system will be designed for a nominal flow rate of 0.3kg/s with a variability of 50-120% of the nominal value. The heat exchangers of the pump circuit will ensure the maximum supply temperature of SHe to the SCMS to be ≅ 4.5K. The heat exchanger located on the return side will dissipate the steady state as well as transient heat loads into a buffer dewier.

TABLE VII. FLOW PATHS AND FLOW RATES FOR SCMS

Coil type	Number of coils	Flow paths/coil	Path length (m)	Flow per path (g/s)	Total flow (g/s)
TF	16	12	48	1.45	278.4
PF1	1	2	109	0.90	1.75
			117	0.85	
PF2	2	1	113	0.85	1.70
PF3	2	4	136	0.70	5.20
			146	0.65	
			155	0.65	
			164	0.60	
PF4	2	4	98	1.00	8.00
PF5	2	4	117	0.85	6.80

An external dual bed, full flow, on-line purifier with automatic regeneration is provided to remove impurities such as water vapor, N2 and hydrocarbons to <1 ppm level. In order to confirm the purity of the processed He gas, the purifier will be equipped with the impurity monitor to detect the above impurities at <1 ppm level. A buffer dewar (MCD) is provided in the plant. The purpose of the buffer dewar is to absorb the heat loads generated within the SCMS and return cold helium vapors to the cold box at a constant temperature and pressure. The SHe coming from the SCMS delivers heat to the buffer dewar through a suitably designed heat exchanger before returning to the cold pump. The buffer dewar also serves as a reservoir for supplying LHe to the current leads. The capacity of the Dewar will be 2500L with maximum operating pressure ≅ 1.2 bar(a).

The refrigerator will be fully automatic with necessary instrumentation and controls. A provision will be made to interface the monitoring and controls to main control system for the remote monitoring, exchange of data and emergency signals. The control system would be capable of handling the variations in the application load. A suitable heater of wattage equivalent to the total capacity of the plant shall be incorporated in the plant. This will ensure an independent testing of the plant before connecting to the SCMS.

4.3. LN_2 distribution system

As mentioned above, liquid nitrogen cooled radiation shields (LN_2 shields) are provided between the SC coils and vacuum vessel as well as between the cryostat and SC coils. While the cryostat walls will be at room temperature, the vacuum vessel walls will have different temperatures under different operating conditions. During baking the walls will be at 525K, during wall conditioning the temperature will be 425K while during plasma operation the temperature will be 325K. The LN_2 consumption during these three phases will be ≅1200L/h , ≅600L/h and ≅300L/h respectively. In addition, LN_2 @150L/h is required for pre-cooler and purifier of the LHe plant and @200L/h for NBI system. LN_2 storage tanks of 105 m^3 has been provided for with a flow rate of 1500L/h . The LN_2 will be purchased commercially and filled in these tanks to replenish the consumed liquid. The gas/vapors from the applications will be released to atmosphere. Appropriate distribution systems with valves, transfer lines and phase separators are being provided.

5. Summary

The Superconducting Magnet System design meets the SST-1 objectives. The engineering design of the magnet system has been completed. The CICC to be used in the magnet windings are presently being manufactured. The winding of the magnets will begin by mid 1999. The cryogenic system requirements have been detailed out and liquid Helium plant and other cryogenic systems are being procured. The SST-1 tokamak is expected to be operational by year 2002.

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