PRESENT DESIGN OF THE HT-7U TOKAMAK DEVICE

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Abstract

The HT-7U superconducting tokamak is an advanced steady-state plasma physics experimental device to be built at the Institute of Plasma Physics, the Chinese Academy of Sciences (CASIPP). The preliminary engineering design incorporates the superconducting toroidal field (TF) and poloidal field (PF) magnets, the vacuum vessel, the radiation shields, the cryostat and the current leads. The general mechanical structure of the HT-7U tokamak device with the detail structure of main parts is in design phase. The stability calculation and analysis of superconductors and coils have been done initially. The maximum field on the TF and PF coils and the maximum stress on the cases of coils, vacuum vessel and cryostat are evaluated. The R&D programs on the HT-7U tokamak device have been planned and in progress, which are focused on the design and development of conductors and model coils both in bath-cooling and force-cooling, test facility, winding machine, prototype of one 1/16 segment of vacuum vessel, and some key technologies.

Introduction

The HT-7U superconducting tokamak, which is approved by Chinese government, is an advanced steady- state plasma physics experimental device to be built at the Institute of Plasma Physics, the Chinese Academy of Sciences (ASIPP). The scientific mission of the HT-7U project is to study physical issues on the sustainment of a non-burning plasma scenario for the steady-state operation of next generation advanced tokamak devices. The engineering mission of the HT-7U project is to establish technology basis of full superconducting tokamaks to support future reactors. HT-7U will have a long pulse (60-1000s) capability, a flexible PF system, and auxiliary heating and current drive systems, and will be able to accommodate divertor heat loads that make it an attractive test for the development of advanced tokamak operating modes [1].

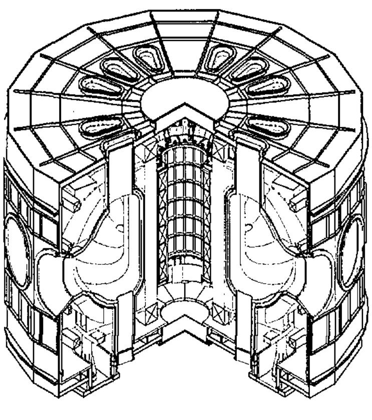

Fig. 1. The HT-7U tokamak device.

The preliminary engineering design incorporates the superconducting toroidal field (TF) and poloidal field (PF) magnets, the vacuum vessel, the radiation shields, the cryostat and the current leads. The general mechanical structure of the HT-7U tokamak device with the detail structure of main parts is in design phase. The overview structure of HT-7U is shown in Fig. 1. The main parameters of the HT-7U device are summarized in Table I.

TABLE I. MAIN PARAMETERS OF HT-7U

Toroidal field, B_o	3.5 T
Plasma current, I_P	1 MA
Major radius, R_o	1.7 m
Minor radius, a	0.4 m
Aspect ratio, R/a	4.25
Elongation, K_x	1.6 - 2
Triangularity, d_x	0.6 - 0.8
Heating and driving:	
ICRH	3-3.5MW
LHCD	3.5 MW
ECRH	0.5 MW
Pulse length	1- 1000 s
Configuration:	double-null divertor
	single null divertor
	pump limiter

The considerations on the choice of the device parameters are:

- Based on the criterion and scaling law of experiment results of tokamaks in the world.
- To ensure the advanced status of the HT-7U device and its physical experiment in the world.
- To reusethe existing HT-7 facilities as possible as we can, including the high power supplies, the cryogenic system, ICRH, LHCD, ECRF, vacuum pumping and gas puffing system, etc..
- To take advantage of the tokamak design experience and fabrication ability accumulated in past years in the world and in ASIPP. The design of HT-7U features sixteen superconducting TF coils and twelve superconducting PF coils, symmetrically located about the plasma mid-plane. Six inner PF coils constitute the CS assembly. A vacuum vessel with race-shaped horizontal ports and bathtub-shaped vertical ports are located in the bore of the TF coil. Two thermal shields of about 80 K cover all of the superconducting magnet system. A cryostat encloses all of the superconducting coils with radiation shields, the vacuum vessel and support structures. The superconducting magnets system, the vacuum vessel and the thermal shields are supported on the cryostat independently [2].

Superconducting Magnet System

Design of the PF System: The PF system consists of twelve coils located symmetrically about the vertical mid-plane and the equatorial plane. Six inner PF coils form a central solenoid assembly. The PF coils will provide about 10 V-s for inducing 1 MA plasma current ohmically and ensure plasma equilibrium by controlling the vertical field amplitude and curvature index. All the PF coils are capable of steady-state operation. The operational current of PF is less than 14 kA. The maximum field on the PF coils is less than 4.2 T and the maximum ramp during plasma startup is about 7 T/s in 60 ms [3].

NbTi cable-in-conduit conductor (CICC) cooled by supercritical helium at 4.5 K is used as superconductor for all of the PF coils. To minimize A.C. losses, all wires in the PF conductor will be

TABLE II. MAIN PARAMETERS OF PF CONDUCTOR

Conductor	NbTi/Cu
Type of conductor	CICC, Forced-flow
Cabling configuration	(2NbTi+1Cu)×3×3×(6+ 1Tube)
No. of NbTi strands	108
No. of Cu strands	54
Conduit:	
Material of conduit	316 L
Wall thickness of conduit	1.5 mm
Conduit outer dimensions	17.4×17.4 mm × mm
Operating current	14 kA
Rated magnetic field	4.5 T
Cooling condition	SHe, 4.5K, 4bar
Temperature margin	2.14 K
Stability margin	700 mJ/cm^3

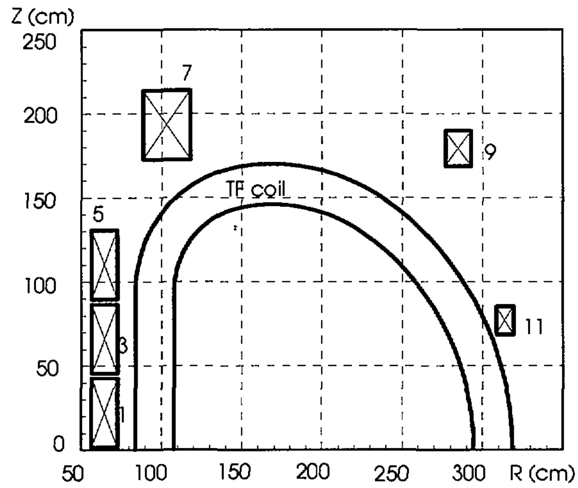

Fig. 2. The HT-7U PF Location and TF coil shape overview.

electroplated with 2 μm chromium (Cr) and the second stage cable will be 80% wrapped with a stainless steel strip of 0.05 mm thickness. The main parameters of the PF conductor are summarized in Table II and the PF location is shown in Fig. 2.

All of the PF coils will be attached to the TF assembly. The CS sub-assembly will be hung and bolted inside the inner bore formed by squeezed cases along the straight legs. The other six PF coils will be cramped and bolted on the TF assembly.

Design of the TF System: The superconducting TF magnet system of HT-7U is consisting of a toroidally arrayed sixteen coils which produce 3.5 T toroidal field at plasma major radius of 1.7 m and about 5.8 T peak field at the TF coils with ripple of less than 1% within the plasma volume. The TF magnets are designed to withstand the magnetic centering force by wedges at their inner legs and to withstand overturning torque by wedges between their outer arc segments. Two TF coils are encased in a TF module case from two sides and assembled in one coil module. Two modules are then jointed into a quadrant. Four quadrants form a TF assembly. Through thermal insulation bearings, the TF assembly with twelve PF coils is mounted on a circular structure supported by eight pillar assemblies.

TABLE III MAIN PARAMETERS OF TF CICC

Dimension (mm×mm)	22.0×22.0
Length of CICC in a double-pancake (m)	174
Thickness of the conduit (mm)	1.7
Dimension of the central channel (mm)	∅7.5×1
Diameter of SC strands (mm)	∅0.85
Number of SC strands	192
Ratio of Cu/NbTi in SC strands	1.38:1
Diameter of copper strands (mm)	∅0.65
Number of copper strands	192
RRR of the copper	100
Fraction of Iop to Ic	0.306
Void fraction in CICC	0.356
Final Cu/NbTi	2.77:1

TABLE IV. PARAMETERS OF TF COIL (Based on CICC)

Central field in major plasma radius	3.5 T
Peak field in the windings	5.8 T
Ampere turns	30 MAt
Operation current of the cables	15.5 kA
Operation system pressure of helium	4.5 bar
Operation temperature of helium Number of turns in a coil	4.5 K 120
Dump resistance	0.1 ohm × 2
Inductance of half of the TF magnets	1.06 henry

TABLE V. MAIN CALCULATION RESULTS OF TF CICC

Stability margin	14.6 kW/m (301 mj/cm^3)
Quench calculation time	20 s
Protection lagging time when quenched detected	1 s
Dump residual time	10.8 s
Peak helium pressure when quenched	10 bar
Peak temperature of the conductor when quenched	75 K
Peak voltage v (v = IR) when quenched	3.4 V
Peak resistance of the conductor when quenched	0.63 mΩ
Operation system pressure of helium	4.5 bar
Pressure drop (Pin-Pout)	0.5 bar

TABLE VI. MAIN PARAMETERS OF TF BCC
(Based on the SSC Inner Cable)

Maximum field	5.8 to 6.6 T
Operation current	5234 A
Operation temperature	4.3 K
RRR of Cu	> 150
Critical current(at 4.3K, 6.6T)	10307 A
Recovery current	5584 A
Conductor dimension	6.9 × 16.7 mm × mm
Solder material	Sn 95% + Ag 5%
Roughened surface:	
Depth of fins	0.9 mm
Angle of fins	62°
Pitch of fins	1.2 mm
Number of fins	10
Wetted perimeter	42 mm
Total length of SSC	64.2 km

TABLE VII. MAIN PARAMETERS OF TF COIL (based on BCC)

Magnet field in the center of plasma	3.5 to 4.0 T
Number of coils	16
Number of turns in a coil	406
Turn-to-turn insulation thickness	0.3 mm
Pancake-to-pancake insulation thickness	2.7 mm
Ground insulation thickness	6 mm
Inductance of ¼ TF coils	8.7 H
Paris of current leads	4
Total Ampere-turns	30 to 34 MAt

Each pillar assembly is cooled by cold helium gas evaporated from a liquid helium container connected to the interface of the TF supports.

NbTi CICC and bath-cooling conductor (BCC) are candidates to be the superconductor of the coils. Up to now, several versions of the TF conductor design have been done. The configuration of 15.5 kA CICC is (2SC + 2Cu) × 4 × 4 × (6 + 1 tube). The stability calculation of the 15.5 kA CICC has been finished. The parameters of CICC, the TF coils and the stability calculation results are shown in Table III, IV, and V respectively. The voltage evolution, temperature distribution, helium pressure and helium velocity during a quench in the middle of one conductor are shown in Fig. 3, 4, 5 and 6 respectively [4]. The main parameters of one of the design of BCC and its coil based on the SSC cable are shown in Table VI and VII.

The maximum stress on the TF cases is less than 350 MPa [5], shown in Fig. 7. Through thermal insulation bearings, the TF assembly with twelve PF coils is mounted on a circular structure supported by eight pillar assemblies.

Preliminary calculation of the heat loads to the TF and PF systems: The radiation from the thermal shields (QES-TF, QIS-TF), the heat flux caused by a residual gas (QP), and that of mechanical supports (QSUP) have been considered in the calculation of the stationary heat load (QTOT) to the TF and PF systems. To reduce QSUP from 310 W to 90 W, the nitrogen cooling pipes on the support pillar assemblies are needed. At $\varepsilon = 0.2$ and $T = 300$ K of the vacuum vessel, the total stationary heat

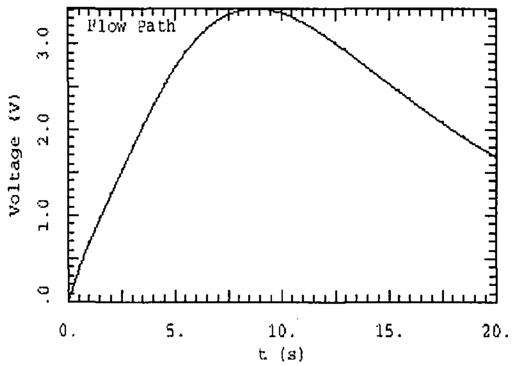

Fig. 3. Voltage (V = IR) Evolution.

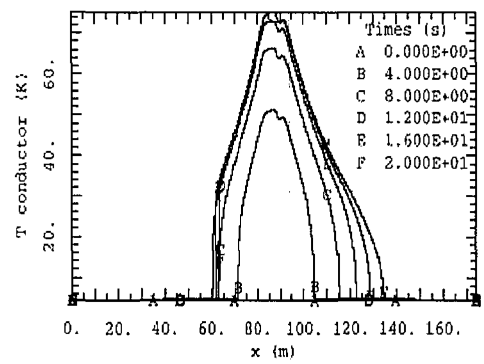

Fig. 4. The conductor temperature distribution along the length at different periods.

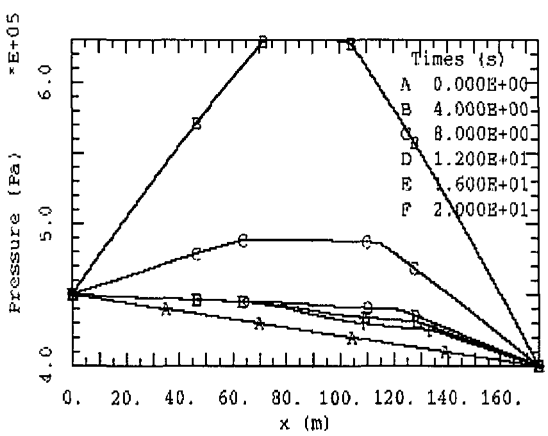

Fig. 5. The helium pressure distributions.

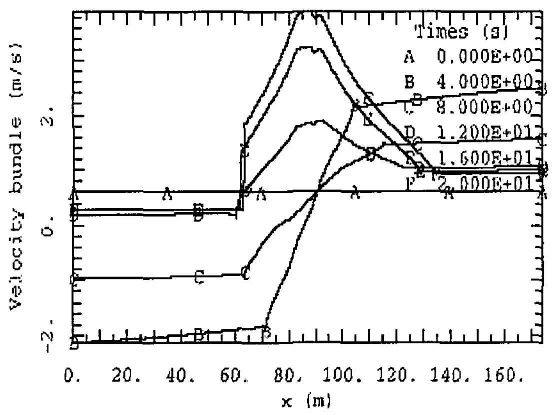

FIG. 6. The distributions of helium velocity along the length at different periods in the bundles along the length at different periods.

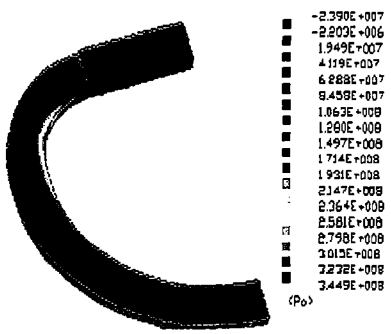

Fig. 7. The result of stress analysis of the TF case.

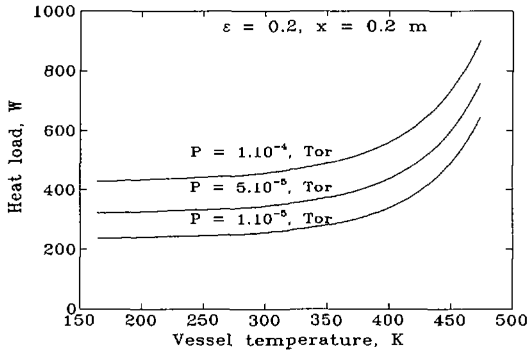

FIG. 8. Total stationary heat load to TF and PF systems at different pressures in cryostat depend on vacuum vessel temperature.

load of TF and PF is changed from 260 W up to 460 W based on the pressure range p = 1 × 10^{-5} to 1 × 10^{-4} torr [6], shown in Fig. 8. The resistive heat loads will be 8 to 40 W based on a joint resistance of 1 to 5 × 10^{-9} ohm. The liquid helium consumption of current leads will be 96.5 l/h at zero currents and 266 l/h at maximal operational currents based on 4 × 10^{-4} W/A at zero current and1.1 × 10^{-3} W/A at the operational current respectively. The total helium consumption for 1000s operation will be about 266 l.

Vacuum vessel and other components

Design of the vacuum vessel: The vacuum vessel of HT-7U is a completely welded toroidal structure with noncircular cross-section nested in the bore of the TF coils. Double-wall configuration design is considered for neutron shield. The preliminary finite element analysis of stress load on the body of the vacuum vessel has been conducted. The loads considered in the analyses were dead weight, atmospheric pressure, electromagnetic force caused by the disruption of a 1.5MA plasma current and a 3.5 T magnetic field and thermal stress caused by bake-out. Fig.9 shows the Von Misses stress distribution on Vacuum Vessel. The Maximum stress is 816 kgf/cm^2 (about 80 MPa). The concept of plasma facing components (PFC) has been considered which includes a divertor, passive plates, feedback control coils and limiter. The draft calculation and design of the vessel baking system has been done, in which heaters disposed on the inner surface of the vacuum vessel are used, as shown in Fig.10. The results of calculation show that required baking power is changed from 60 kW for $\varepsilon = 0.1$ up to 160 kW for $\varepsilon = 0.3$, shown in Fig. 11 [7]. Preliminary calculation of the water cooling system of the vessel has been based on design scheme of PFC. The results show that the total mass flow is about 154 kg/s with the maximum temperature of less than 5000C on the graphite, are depicted in Fig. 12 and Fig. 13 [8].

Design of the thermal shield: An internal shield and an external shield of about 75 to 80 K which are made of sandwich structure with square tubes welded to enclose the whole superconducting magnets of HT-7U. The internal shield is polygon shaped from 16 wedged of noncircular cross-section with sectors of 22.5^0 toroidal angle each. The external shield is polygon shape cylinder consisting of three parts including an upper structure, a polygon ring and a lower structure with four support structures. The internal shield and the external shield are strongly linked by ducts surrounding the ports of the vacuum vessel to form a rigid tour that is supported by four grounded supports down on the cryostat base through insulators. The total heat load to the thermal shields cooled by nitrogen determined by radiation from the cryostat, the vacuum vessel and the heat conduction of mechanical supports is about 40 kW based on $\varepsilon = 0.2$ and the vacuum vessel temperature of 300K, as seen in Fig. 14.

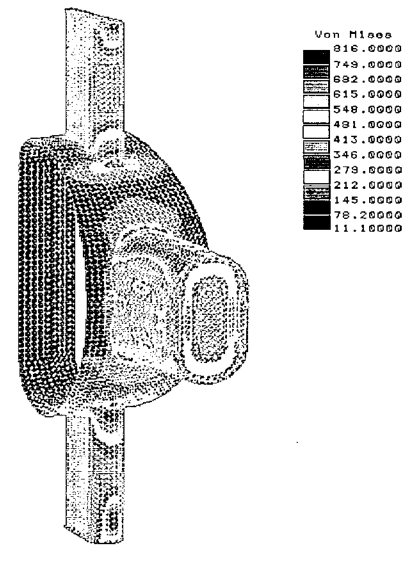

Fig. 9. Von Misses stress distribution on vacuum vessel inside the vacuum vessel.

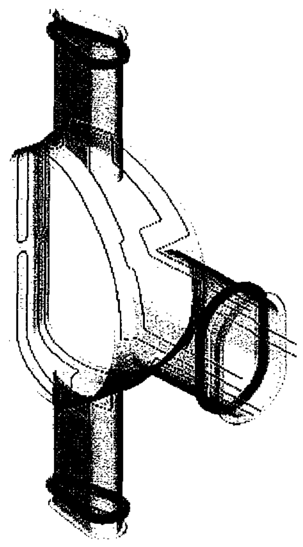

Fig. 10. The heater cables layout.

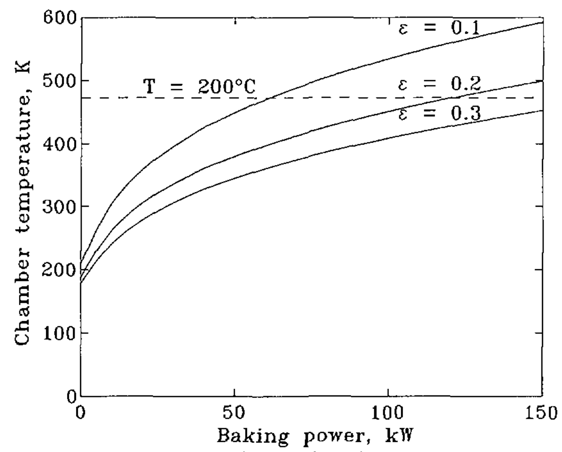

Fig. 11. The chamber temperature dependence for different elements vs. water temperature.

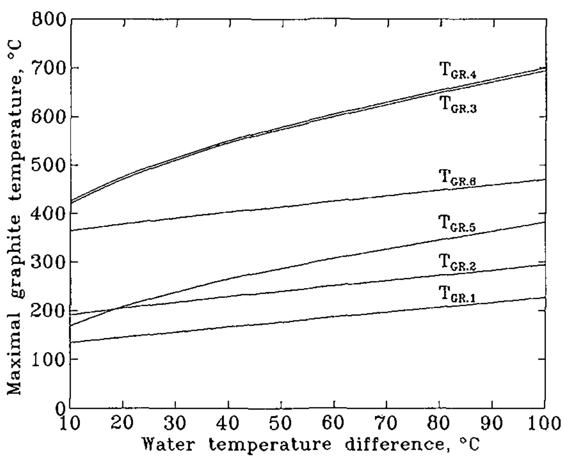

Fig. 12. Maximal graphite temperature dependencies via baking power for different ε values.

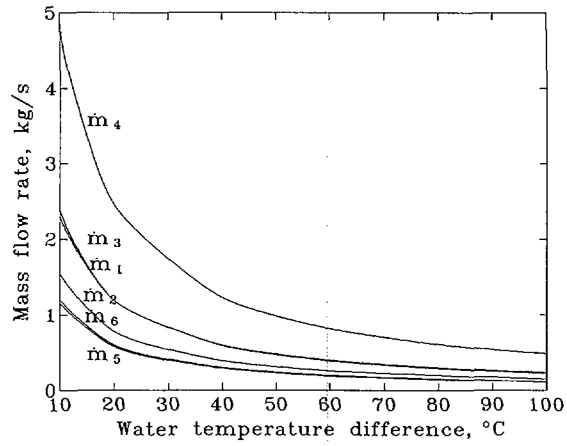

Fig. 13. Mass flow rate dependencies for different PFC elements vs. water temperature shields at different vacuum vessel temperature.

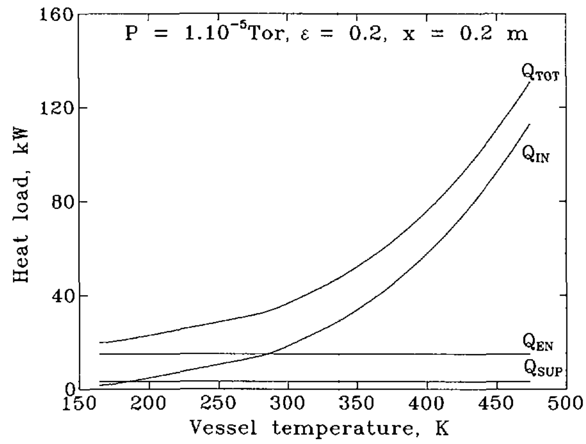

Fig. 14. Total heat load to nitrogen radiation.

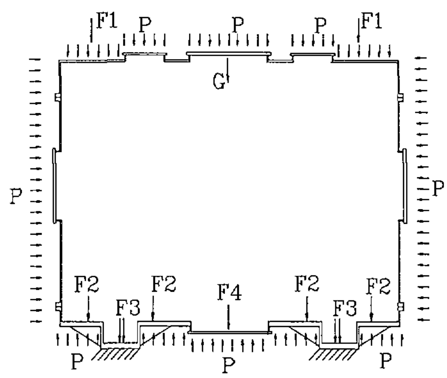

Fig. 15. Loads considered in cryostat analyses.

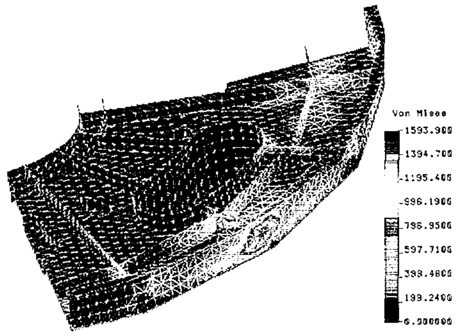

FIG. 16. Von Misses stress distribution on the base of the Cryostat (kgf/cm²): Progress of the R&D programs.

Design of the cryostat: The cryostat of HT-7U is a polygon cylindrical vacuum vessel with ambient operating temperature, which consists of a cap structure, a middle ring and a base structure. The cryostat will house the TF and PF assembly with the vacuum vessel, the radiation shields and will support all loads from them. The preliminary calculations of finite element analysis show that the former structure design should be modified. Fig. 15 shows the load considerations during analysis. The stress distribution on the cryostat is shown in Fig. 16.

Design and fabrication of test conductors: Two types of CICC and one type of BCC were chosen as the test conductors for R&D purposes [9]. With the cooperation of Chinese industries, three pieces of test CICC including one dummy CICC have been fabricated and delivered to ASIPP. The configuration of the test CICC is 3 × 3 × 3 × (6 + 1 tube). In the first stage of the cable, a pure copper strand is added to increase the ratio of copper to superconductor [10]. A spiral tube made of stainless steel strap is in the center of the conductor to relieve the inner pressure of the conductor during quenches. In the test CICC of PF, Cr coating on the surface of every strand is required, and a stainless steel foil of 0.05mm thickness is wrapped on the third stage of the cable to reduce A. C. losses. The final cable is wrapped by a stainless steel strap of 0.1 mm thickness for cable protection during jacketing. The conduit is made by continuous tube milling and seam tungsten-inert-gas (TIG) welding with the cable inside. 316L is selected as the conduit material in the test CICC. 316 LN will be the conduit material in real CICC of HT-7U. The designed cross-section size of the PF test CICC is 17.3 mm × 17.3 mm. In order to gain experience at different steps of test CICC fabrication such as Cr coating, cabling and jacketing, a dummy CICC of 350 m with the same configuration, strand diameter and size as the test CICC, but with all copper strands inside, was fabricated prior to the test CICC fabrication. To test the process of jacketing, several empty tubes had been fabricated and formed to required size. During the jacketing of the dummy CICC, the temperature of TIG welding had been measured and adjusted carefully to a suitable value. The PF test CICC of 375 m and the TF test CICC of 275 m were fabricated following the fabrication of the dummy CICC. In the third stage of cabling for the TF and PF test CICC, a voltage sensor wire of 0.4 mm diameter was added.

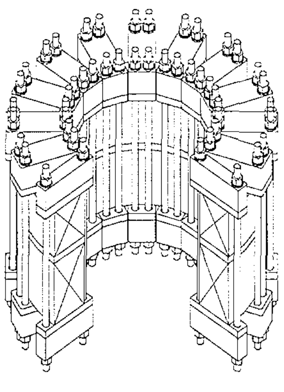

Fig. 17. Overview of central solenoid model coil.

TABLE VIII. MAIN PARAMETERS OF CSMC

Inner diameter	574 mm
Outer diameter	1140 mm
Height	485 mm
Number of turns	216
Operation current	18 kA
Maximum field	6.3 T (with 18 kA)
Total length of CICC	650 m
Inductance	36 mH
Stored energy	5.83 MJ
Test ramping rate	7 T/s

One type of test BCC has been designed. A transposed cable is housed in and soldered with a copper matrix. The surface of the copper matrix is roughened to increase the effect of heat exchange with liquid helium. Now, a 20 m BCC with copper cable has been developed in ASIPP to verify the technical processes. The test BCC of 10 m length using SSC cable is planned to be fabricated.

Design of CSMC and TFDC: To define design criteria and ensure fabrication processes, a central solenoidal model coil (CSMC) is designed and will be fabricated in ASIPP [11], as seen in Fig. 17. The designed maximum field on the coil is 6.3T with the operation current of 18kA. The main parameters of CSMC are shown in Table VIII. The test of mechanical and electrical performances, including stress and strain in the conductor, deformations on the winding, critical current at different temperature and self-fields are planned to be done. To determine the requirements of equipment and processes for D-shape bending and forming using an automated system to support continuous winding, a TF dummy coil (TFDC) of a 2/3 scale of the TF coil is designed and will be fabricated in ASIPP using the dummy CICC. Now, a double pancake of 1/10 scale of the TF coil of HT-7U has been fabricated using a copper conductor of rectangular cross-section of 8 mm × 10 mm to confirm the transition design.

Development of voltage sensors: The consideration of adopting co-winding sensors inside the conduit is based on avoiding compromise of the electrical insulation system of the conductor and obtaining better signal to noise ratio [9]. During cabling of the test CICC, a high-strength enamel-insulated copper wire of 0.4 mm diameter was co-wound inside the third stage of the cables as voltage sensor. Unfortunately, some local insulation had been damaged after jacketing. Now, a type of armored copper cable covered by stainless steel of 0.1 mm thickness and filled with polymer between cable and jacket is being developed successfully.

Development of helium isolators: High-voltage isolators at inlet and outlet of each helium channel of superconducting magnets are required. Two types of isolators made of ceramics and composite are the candidates. The composite one is in priority to be developed for its more secured properties. Labyrinth structure has been adopted in the design of the composite isolators. Six pieces of isolators have been fabricated with different processes and using modified insulation materials. All these isolators have been tested under pressure of 10MPa and electric voltage of 15kV between stubs from room temperature to liquid nitrogen temperature and liquid helium temperature. The test results show that some modifications should be done for the structure, insulation materials and fabrication processes.

Development of cooling stubs: In the manufacture of the HT-7U superconducting magnets of CICC, the method of continuous pancake winding will be adopted to reduce slices inside the coils. To reduce the cooling channel length and cool the coils more effectively, each CICC coil will be divided into several cooling channels. Each channel has an inlet stub and an outlet stub attached to the conductor surface. To avoid the damage of cables and degradation of superconductor performances, following considerations have been taken during installation of helium cooling stubs:

- to avoid the damage of cables during conduit and foil penetration, a special and extreme care processes should be adopted;
- to control the temperature inside cables, TIG welding of intermittent process will be helpful. And the region of the cable immediately under the stub must be cooled in an effective way.

At present the empty conduits are being used for penetration and welding trials in ASIPP. Important examination for stubs should be the leak test after thermal cycling between room temperature and liquid helium temperature.

Separable joint for CICC: A type of separable joint for the CSMC has been designed and is under fabrication in ASIPP. The joint consists of two copper conjunctions and two copper lids. After two terminals of the cable being soldered with the joints, two joints will be soldered and connected by bolts. Because of the requirement of separability, the separable and massive conjunctions are needed. The A.C. losses of the separable joint may be higher, but the resistance may be low. A compact joint used in the TF and PF systems will be developed.

Test of strands and sub-cables: To ensure feasibility, the superconducting strands and sub-cables need to be tested. Up to now, the $I_c(B)$ of strand samples has been tested in different background fields from 5 T to 7 T. The test results indicate that $I_c(B)$ of most strands tally with the values provided by the vendor. In the primary test of the first stage of sub-cables, no significant degradation of the critical current of strands has been shown. The second stage and the third stage of sub-cables are planned to be tested in the future. The test of A. C. losses of strands is in progress. The strands will be wound on a spool and located in a background field of less than 6 T with a verifying field.

Development of winding machine for CICC coils: To fabricate PF or TF coils in pre-bending and continuous pancake winding way, a winding machine has been designed and fabricated in ASIPP. To understand the bending/forming behavior of CICC and formulate the specifications of the machine and manufacturing procedures, principle tests have been demonstrated by bending/forming a short piece of the dummy CICC. Now, trials and tests are being done using the empty conduits and the dummy CICC to determine the elastic range of the conduit and the relationship between deflection and deformation of the conduit after it is removed from the machine.

Development of the test facility: A full size TF coil is planned to be fabricated and tested and essential test on every TF coil and eight PF coils must be done to ensure coil qualification before they are installed in the device. So, a test facility is being designed. The test facility consists of a cryostat with a nitrogen shield, a vacuum pumping system, a power supply system, a quench detection and protection system, support structures and current leads. The support structure for test magnets inside the cryostat is similar to the support designed for the magnets of HT-7U. One section of the nitrogen shield will be designed in a similar structure as the radiation shields of HT-7U to see if it works properly. A pair of 18kA current leads will also be designed for test magnets. The vacuum pumping system, the power supply system and the quench detection and protection system not only will be used in the test facility system, but also may be reused in the HT-7U system after modification and upgrade.

Design of prototype segment of vacuum vessel: A prototype 1/16 segment of the vacuum vessel is required to obtain design and fabrication experience which will benefit final design and subsequent fabrication of the vacuum vessel. A prototype segment of the vacuum vessel is planned to be designed. It consists of two 11.25° segments of the vacuum vessel body, one radial port, two vertical ports and a support assembly. The arrangement of heating elements and cooling channels will be designed, too. The prototype segment of the vacuum vessel will be used to test deformations and stress with the simulation forces on it and test temperature distribution during simulation bake-out. The assembly processes of PFC will also be simulated inside the prototype segment.

Conclusions

The preliminary engineering design has begun, which incorporates superconducting magnet systems of TF and PF, vacuum vessel, thermal shields, cryostat and current leads. The R&D programs on the HT-7U tokamak device are in progress, which focuses on the design and development of conductors and model coils, test facility , winding machine, prototype of one 1/16 segment of the vacuum vessel, and some key technologies. Because the detail physics design related to the device has not finished, some improvements on the engineering design may be required and even significant changes in configuration may be required in the near future. The future thermal and stress analysis for each component of the device shall be performed in detail. The R & D program will also be continued further in the future.

ACKNOWLEDGEMENTS

All works mentioned above are the efforts of the HT-7U Project Team.

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