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STRUCTRAL DESIGN OF THE NEGATIVE TRIANGULARITY SPHERICAL TOKAMAK (NTST)

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Abstract

The NTST is the world's first originally negative triangularity spherical tokamak. It is designed to in-depth investigate the performance of negative triangularity plasmas and application prospects in fusion reactors. The unique idea of the NTST brings unexpected challenges in structual design, including compact spatial constraints and complex vacuum chamber geometries. Within a 4.5m diameter, and 7 m height overall structure space, we expect to achieve **1.4T@R=0.65m**. Integrating advanced structural schemes and innovative concepts, the NTST has completed critical tasks including overall structural scheme evaluation, detailed structural design, and performance verification of key components. The TU1(and Cr-Zr-Cu) coppers are used in the magnets on 77K temperature for low resistance， and Inconel625 alloys are used in vaccum vessels for high resistance. The design considerations and objectives of the NTST are introduced. The main structural scheme derived from multi-physics optimization encompassing electromagnetics, thermodynamics, materials science, and structural mechanics is highly stressed. Additionally, it details the mechanical design solutions for structures such as magnetic coils and vacuum Dewar . Finally, briefly summary the overall progress of the NTST project.

1. INTRODUCTION

Based on the core parameter indicators (1.4T@R=0.65m, Ip=1.3MA) provided by the physics team, the magnet coil positioning and current-carrying requirements, as well as the plasma operational space requirements within the vacuum chamber, were clarified. The mechanical design team completed the design development/iterative upgrades/finalization of the magnet coils and their mounting structures, vacuum chamber structure, Dewar structure, magnet cooling pipelines, and vacuum chamber baking pipelines. Concurrently, structural strength assessments and optimizations were performed under various loads including electromagnetic forces, high-temperature baking, cryogenic cooling, vacuum, and seismic conditions. Evaluations and optimizations were also conducted for heat generation during current flow and cooling flow/cooling capacity during operation. Additionally, material and critical structural performance verification tests were carried out to better support subsequent manufacturing, assembly, operation, and maintenance of the main machine structure.

The paper is organized as followings. Section 2 gives an overall introduction to the mechanical structure of the entire NTST device. Sections 3 offers the detailed introduction of the NTST structure. Finally, Section 4 concludes with a summary and presents the upgrade plans for future development.

2. NTST HOST STRUCTURE SOLUTION

The host device structure is the core of the entire NTST device, and the goal of structural design is to ensure that the device achieves discharge operation parameters, stable and reliable operation, and easy operation and maintenance. Based on the principles of economic, reliable, and fast device structure design, while taking into account the requirements of compact structure, variable configuration, flexible operation, and engineering feasibility, the structural form of the NTST host device has been determined. That is, the TF coil is formed as a whole in a reverse D-shaped structure, and the vacuum chamber is manufactured in sectors for on-site welding. The center field (CS) coil and the polar field (PF) coil are both located outside the circumferential field (TF) coil; The magnet coil structure is installed as a whole, and the vacuum chamber structure is installed as a whole, both of which are independently installed on the Dewar base and placed in the Dewar vacuum environment. Considering that the magnet operates at a low temperature of around 77K and the vacuum chamber needs to be baked to around 450K, the design fully considers the deformation of the device structure caused by temperature changes, as well as issues such as heat leakage protection of the device.

After repeated iterations and sequence determination, the coil structure form, size, position, installation and fixing structure of the device, vacuum chamber shape, size, wall thickness, window, support and other structures, Dewar size and window, structural form, current lead structure, cooling pipeline and baking pipeline structure were determined. The mutual relationship between each subsystem system was fully considered, and after evaluation and confirmation, a unified and complete NTST host device structural design scheme was finally formed.

3. NTST STRUCTURAL DESIGN SCHEME

The main structure of NTST device mainly includes TF coils and their fixed structures, coil structures of other magnets (CS, PF, CC), current lead, cooling pipelines, vacuum chamber, baking pipelines, Dewar and other structures, as shown in the following figure(*FIG. 1.*); The total weight of the host is about 76.4t (including 19.2t for TF coil and its fixed structure, 7.0t for other magnet coil structures, 2.0t for current leads, 0.7t for cooling pipelines, 6.9t for vacuum chamber, and 40.6t for Dewar). The structural dimensions of the main body (Dewar body, excluding leads and cooling outlet pipelines) are about 7081mm high and 4900mm in diameter.

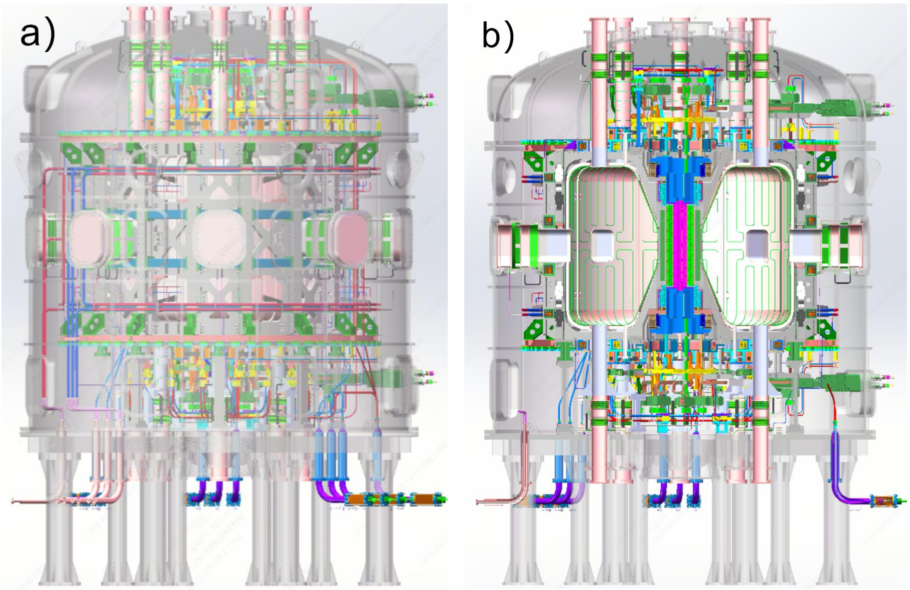

FIG. 1. (a) NTST host structure overview, (b) internal sectional overview

3.1. Magnet coils&structures

There are totally 39 NTST magnet coils, including: ①16 TF coils; ②7 CS coils (1 CS1, 2 CS2/3/4); ③12 PF coils (PF1/2/3/4/5/6, 2coils each); ④4 CC coils (CC1/2, 2coils each). The main parameters of the magnet coil conductor are shown in the table(see Table 1.) below:

TABLE 1. core parameters of magnet coils

	Coils number	Material	per coil				Cross-section h-w-d mm	Current capacity kA
			Turns	Length (m)	Resistance (300K) mΩ	Resistance (77K) mΩ		
TF	16	TU1	12	76	7. 36	0. 90	18x12xØ7	22
CS1	1	Ag-Cu	200	174	13. 81	2. 04	18x17xØ8	40
CS2	2	TU1	26	36	2. 26	0. 28	18x18xØ8	40
CS3	2	TU1	14	27	1. 70	0. 21	18x18xØ8	40
CS4	2	TU1	8	23	1. 45	0. 18	18x18xØ8	40
PF1	2	TU1	20	35	2. 20	0. 27	18x18xØ8	40
PF2	2	TU1	31	72	4. 52	0. 55	18x18xØ8	40
PF3	2	TU1	15	77	4. 84	0. 59	18x18xØ8	40

PF4	2	TU1	16	144	9. 05	1. 11	18x18xØ8	40
PF5	2	TU1	16	194	12. 81	1. 56	18x18xØ9	40
PF6	2	TU1	20	238	15. 72	1. 92	18x18xØ9	40
CC1	2	TU1	2	13	0. 82	0. 10	18x18xØ8	40
CC2	2	TU1	1	14	0. 88	0. 11	18x18xØ8	40

The magnet coil structures (as shown in *FIG. 2.*) mainly consists of four parts: TF coil and its fixed structure, other magnet coil structures, current lead structures, and cooling pipeline structures.

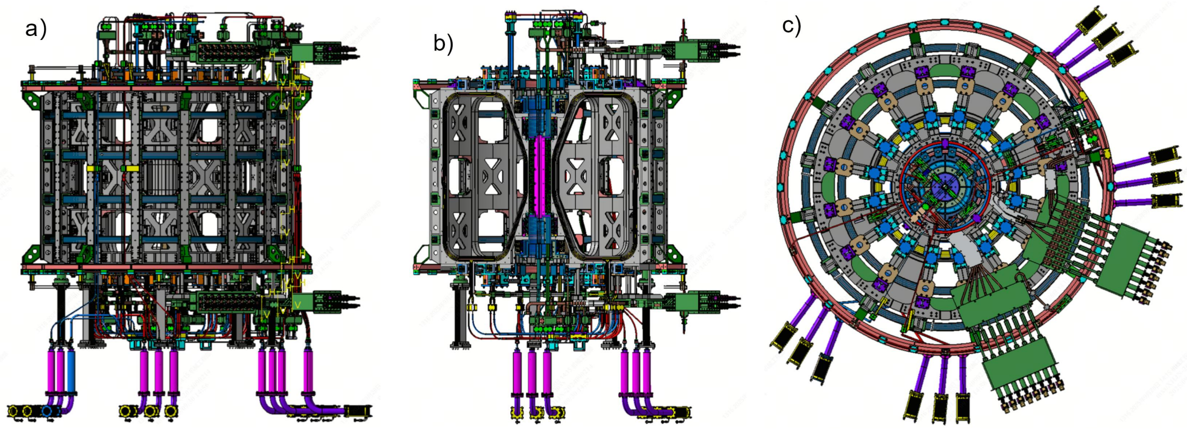

FIG. 2. The magnet coil structures(a) front view, (b)sectional view, (c) vertical view

TF coils and fixing structures

The TF coils and their fixed structure(*FIG. 3. a*) include 16 TF coils and their coil boxes, reinforcement structures (including reinforcement rings, low field side reinforcements, top and bottom reinforcements), support structures, and TF coil series wires. The whole is fixedly connected to the bottom of Dewar through a supporting structure.

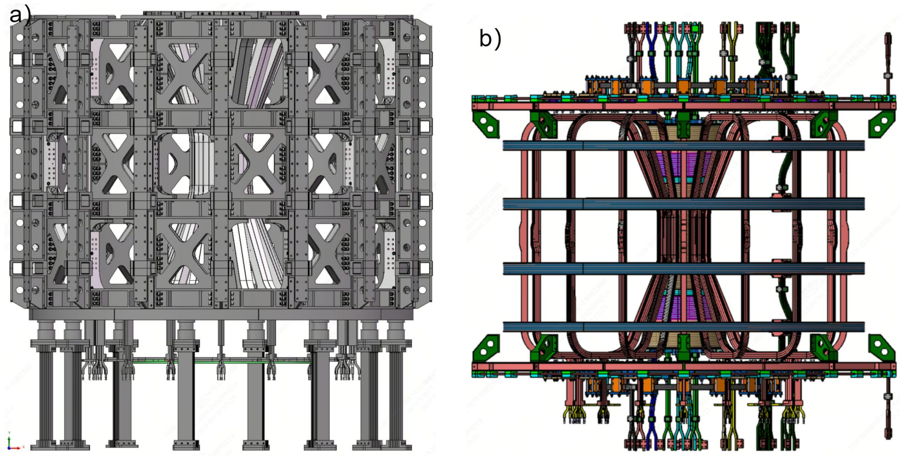

FIG. 3. (a)TF coils and fixing structures, (b)Other magnet coil structures

Other magnet coil structures

Other magnet coil structures(*FIG. 3.b*), including 9 central magnet coils (CS1, upper/lower CS2&PF1, upper/lower CS3&PF2) and installation/fixing structures, and 14 non central magnet coils (upper/lower CS4, upper/lower PF3/4/5/6, upper/lower CC1/2) and installation/fixing structures. All other magnet coil structures are fixedly installed on the TF coil structure.

Current lead structures

The current lead structures(*FIG. 4. a*) include all current lead wires (25 sets) and spare wires (7 sets) for TF/PF/CS/CC coils, totaling 32 sets (1 set with 1 in and 1 out through Dewar). Among them, there is 1 set of TF leads, 2 sets of CS1/2/3/4 leads each, 2 sets of PF1/2/3/4/5/6 leads each, and 2 sets of CC1/2 leads each; Out of the 7 backup lines, 2 lead the lines to the top of the device, 2 lead to the bottom of the device, and 3 only lead into the interior of the Dewar.

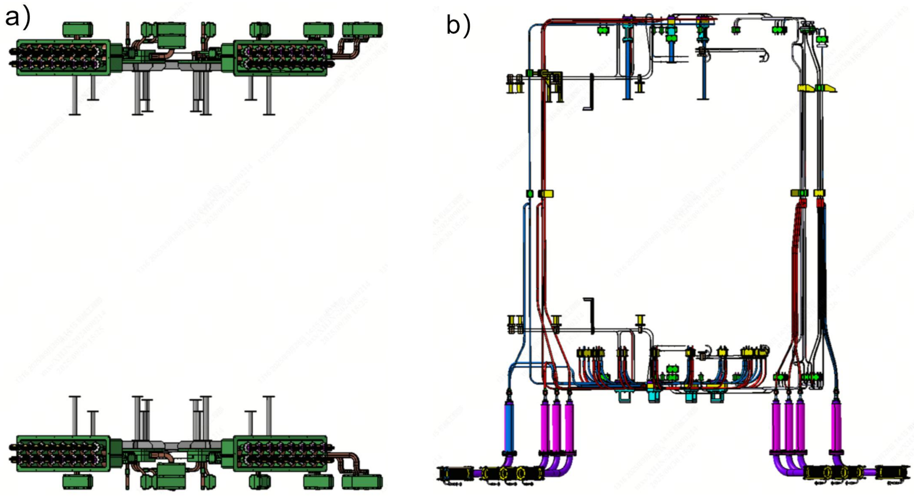

FIG. 4. (a)Current lead structures, (b)Cooling pipeline structures

Cooling pipeline structures

Based on the design requirements of copper conductors for magnet coils, combined with the flow resistance (size), cooling capacity (heat generation) and other requirements of each coil, 39 coils are divided into 6 groups (1 group with 1 inlet and 1 outlet through the Dewar, respectively for cooling circuits 1-6) for low-temperature cooling pipeline structure, all of which are led out from the bottom of the Dewar and connected to the cold source system for cooling. Among them, cooling circuit 1 occupies one group for cooling CS1 coils, cooling circuit 2 occupies one group for cooling upper/lower CS2/3/4, upper/lower PF1/2, upper/lower CC1/2, a total of 14 coils and current lead cold plates, cooling circuit 3 occupies one group for cooling 16 TF coils, cooling circuit 4 occupies one group for cooling upper and lower PF3/4 coils, cooling circuit 5 occupies one group for cooling upper/lower PF5 coils, and cooling circuit 6 occupies one group of cooling pipelines for cooling upper/lower PF6 coils. The main parameter information of the 6 cooling circuits is shown in the table(see Table 2.) below.

TABLE 2. core parameters of Cooling pipelines

Grouping of coil cooling path		Coolant	Flow rate g/s	Backpressure MPa	flow resistance MPa
Line 1	CS1	He（Gas）	52	4	0.27
Line 2	upper/lower (CS2/3/4, PF1/2, CC1/2), current lead cold plates	He（Gas）	108	4	0.09
Line 3	TF1~16	He（Gas）	192	4	0.09
Line 4	upper/lower PF2/3/4	He（Gas）	144	4	0.74
Line 5	upper/lower PF5	He（Gas）	88	4	0.82
Line 6	upper/lower PF6	He（Gas）	112	4	1.52

3.2. Vacuum Vessel & Dewar Structure

The NTST vacuum&Dewar structure mainly consists of three parts: the vacuum vessel body, the vessel heating system, and the Dewar structure, as shown in the following figure(*FIG. 5.*).

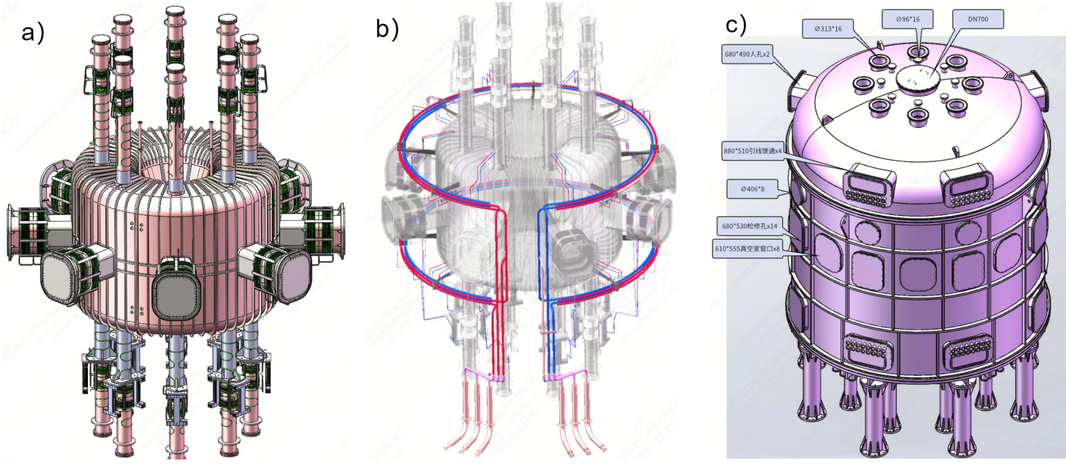

FIG. 5. The VV&Dewar structure(a) the vacuum vessel body, (b) the vessel heating system, (c) the Dewar

Vacuum vessel body

The total height of the vacuum chamber is 5810mm, the maximum diameter is 4576mm, and the total weight is about 6.9t. The designed background vacuum degree is better than 1.3e-5Pa, and the leakage rate is $\leqslant$1.0e-10Pa • m^3 /s. Composed of 8 sectors welded together, fixed to the bottom surface of the Devar through lower pipe supports and 8 sets of flexible supports. There are a total of 42 windows in the up-down and circumferential directions, including 8 rectangular windows 400*395mm in the middle plane circumferential direction, 8 CF200 windows in the up-down direction, and 9 CF35 windows in the up-down direction.

Each 1/8 sector of the vacuum chamber structure is composed of the following parts: ① 1/8 vacuum chamber main chamber structure; ② Medium plane rectangular window structure; ③ Upper window pipeline;

① The main chamber structure of the 1/8 vacuum chamber is made of Inconel625 material, designed to withstand a baking temperature of 200℃. It consists of a contour thin-walled structure (1.5mm on the high field side and 6mm on the low field side), reinforced ribs and sector welded flanges, and baking pipelines.

②Medium plane rectangular window structure, arranged in an 8*45° circumferential direction, with stepped windows. The size inside the neck tube near the vacuum chamber is 400*395mm, and the size inside the neck tube near the Dewar side is 520*465mm. The two sections are connected by corrugated pipe sections, and the local baking temperature is designed to be 100℃.

③Upper window pipeline, 8 vertical CF200 feed through Dewar outlet devices, with a wall thickness of 6mm, evenly distributed along the circumference at 8*45° ; From the vacuum chamber outward, there are Inconel625 pipe section, 316L pipe section, 316L corrugated pipe structure section, 316L pipe and port structure in sequence. The outer wall of the pipeline is welded with baking pipes-the baking temperature is designed to be 100℃.

④ The lower and upper windows of the lower window pipeline are symmetrical about the plane in the vacuum chamber. There are also 8 vertical CF200 windows evenly distributed along the circumference of 8*45° . The difference is that the lower window pipeline supports the vacuum chamber and has a wall thickness of 10mm. From the vacuum chamber outward, they are Inconel625 pipe section, flexible support structure of the vacuum chamber, 316L corrugated pipe structure section, 316L pipe and port structure. The outer wall of the pipeline is welded with baking pipeline - the baking temperature is designed to be 100℃.

Vacuum vessel heating structure

Vacuum chamber baking structure(*FIG. 6.*), the baking main circuit is divided into three paths leading to the outside of the Dewar, as shown in the figure below. ① One path is diverted to the upper window baking pipeline (baking temperature 100℃); ② Divide one path into two, and distribute the upper and lower baking pipes of the vacuum chamber sector (baking temperature 200℃); ③ Separate the series pipeline of baking pipes for the middle and lower windows along the way (baking temperature 100℃).

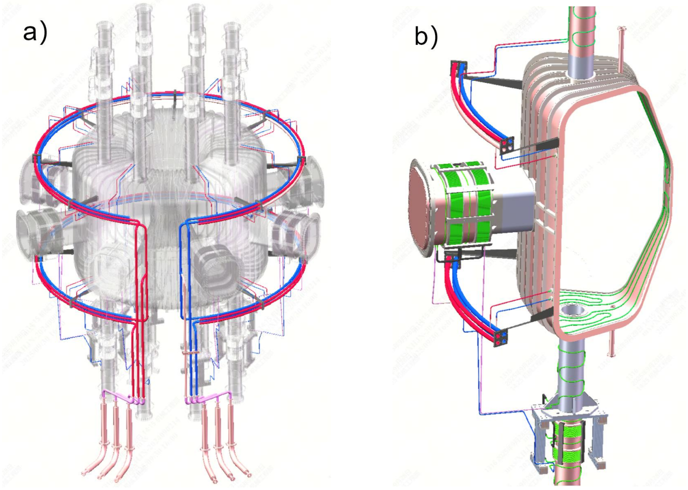

FIG. 6. (a)VV heating system, (b)1/8 VV heating pipelines

Dewar structure

The Dewar structure(*FIG. 7.*) consists of a base, a ring, and an upper cover, with a total weight of approximately 40.6 tons, a main body wall thickness of 20mm, a background vacuum degree better than 3.0e-4Pa, and a leakage rate ≤3.0e-9Pa*m^3 /s. The bottom is fixedly connected to the ground through 16 Dewar support leg structures, with a leg height of 1580mm. The inner surface of the Dewar base is 1879.5mm above the ground where the legs are installed, with an inner diameter of 4608mm and a net height of 4959.2mm inside the Dewar. It is used to accommodate vacuum chambers and magnet coil structures.

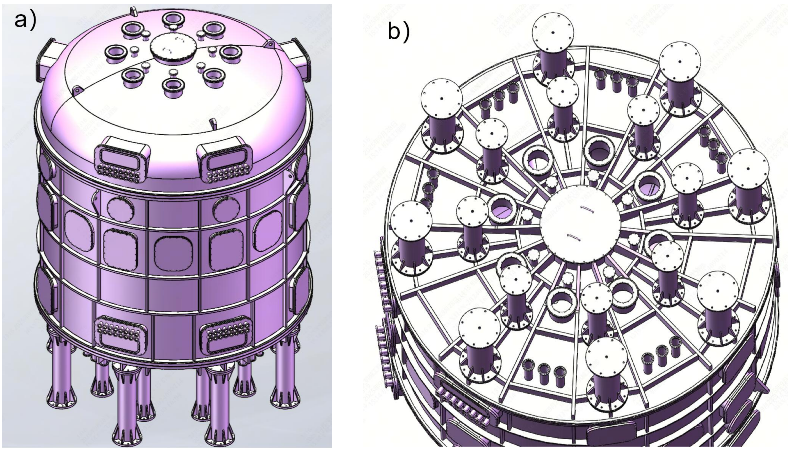

FIG. 7. (a)overall view of the Dewar, (b)bottom view of the Dewar

The main window dimensions and layout statistics of the Dewar are as follows:

TABLE 3. Main Windows of the Dewar

Windows dimension	Count numbers	Location	using
680*490mm	2	Cover	maintenance
880*510mm	4	Cover、Ring body	Current lead feed-through
610*555mm	8	Ring body	Connecting with the mid-tubes on the VV

680*530mm	14	Ring body	Maintenance、Spare hole
DN900mm	1	Base	maintenance
DN700mm	1	Cover	maintenance
⌀ 406mm	8	Ring body	Spare hole、coils monitoring
⌀ 313mm	16	Cover、Base	Connection of upper&lower tubes on the VV
CF100mm	18	Base	Feed through port of cooling&heating system

Base of the Dewar

The thickness of the base body is 59.5mm, and the height of the reinforcing rib is 200mm. The upper surface of the base is welded with lifting ears, TF coil support, and vacuum chamber support installation seat. Bottom opening of the base: 1*DN900 window, 8* Φ 313 windows, 8* Φ 96 windows, 18*CF100 interfaces, used for maintenance and structural extraction of windows, pipelines, etc.

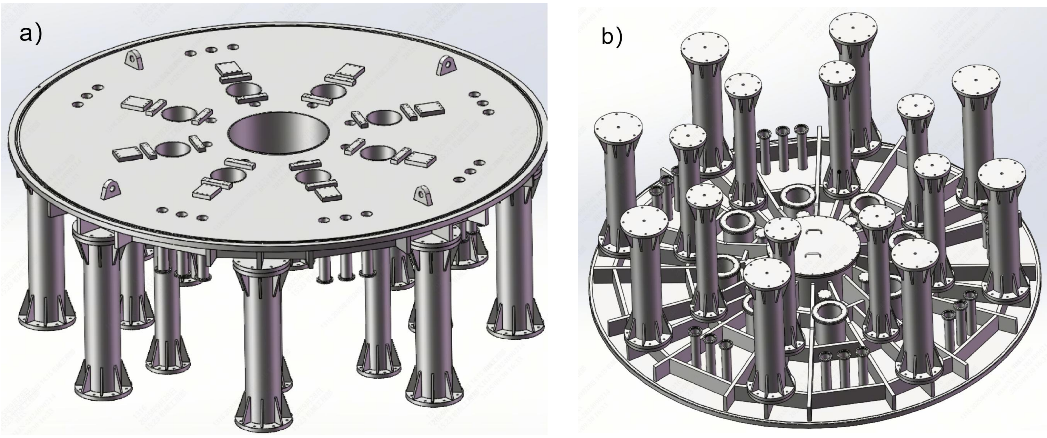

FIG. 8. (a)Base of the Dewar, (b)bottom view of the Base

Ring of the Dewar

The wall thickness of the circular barrel is 20mm, and the thickness of the flange rings on the upper and lower ends is 59.5mm. As shown in the figure below, 3 reinforced ring rib plate structures are arranged from top to bottom, with 16 columns of vertical reinforced rib plate structures distributed in the circumferential direction and 4 evenly distributed hanging ear structures in the circumferential direction. There are 2x880*510mm windows, 8x610*555mm windows, 14x680*530mm windows, and 8x Φ 406mm windows in the ring opening.

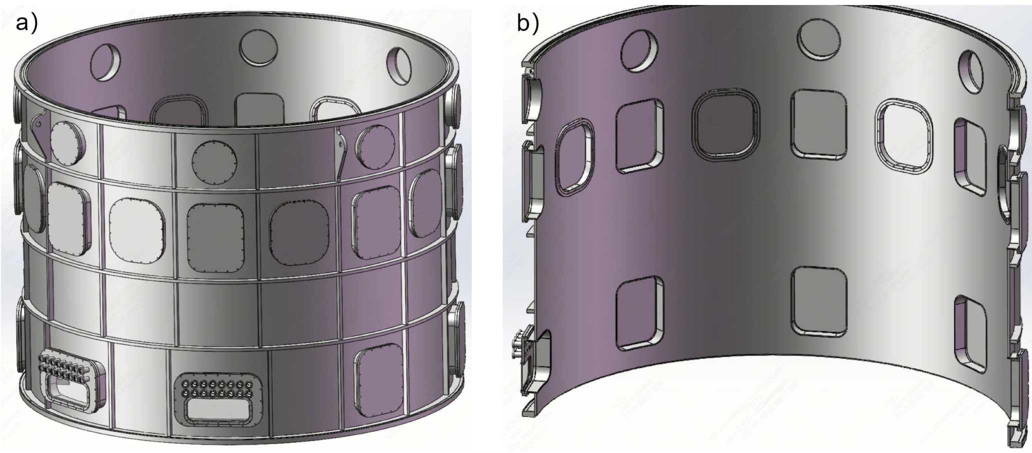

FIG. 9. (a)Ring of the Dewar, (b)internal sectional view of the Ring body

Cover of the Dewar

The upper cover(*FIG. 10.*) is a standard butterfly shaped head DHA4600, with 16 reinforced ribs added inside. Extend the straight section of the head and open a lead feeding window and maintenance port in the extension section. Open a DN700 hole and 8x Φ 313mm windows at the top, and arrange 4 lifting lugs; There are 2x880*510mm windows and 2x680*490mm windows on the side.

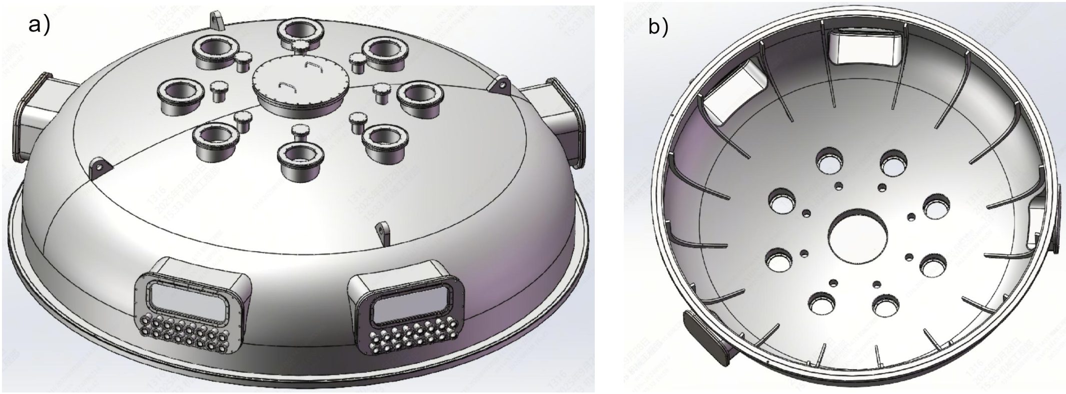

FIG. 10. (a)overall view of the Cover, (b)internal view of the Cover

4. CONCLUSION

After more than a year of design and development investment by the mechanical team, the design and finalization of the NTST host structure has been completed, which can meet the design specifications requirements proposed by the physics department, meet the conditions for production and ordering, and exercise/form the mechanical department's overall structural design and development capabilities.

At present, the design and development of NTST cold source cooling system is underway, and the verification and trial production of various components are being carried out simultaneously. It is expected to complete the installation and commissioning of the whole machine in the second half of 2026.

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REFERENCES