Heliyon 6 (2020) e03609

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Design, qualification & manufacture of ITER gravity supports

P.Y. Lee [a,*], B.L. Hou [a], Z.C. Sun [a], D.A. Kang [a], S.L. Han [a], T. Zhang [a], D. Xu [a], T.F. Yan [a], B. Zhang [b]

[a] *Southwestern Institute of Physics (SWIP), P. O. Box 432, Chengdu, China*
[b] *China International Nuclear Fusion Energy Program Executive Center (CNDA), Fuxing Road, Beijing, China*

ARTICLE INFO

Keywords:
Energy
Nuclear engineering
Structural engineering
Energy economics
Energy sustainability
Gravity support
Engineering test
FEM analysis
Leakage test

ABSTRACT

As one of the key components to support all the magnet coils, the GS faces engineering challenge to its operational safety throughout the design, qualification and manufacturing process as a result of extreme loading condition. The structural safety of GS was confirmed by both the FEM analysis and the semi-prototype engineering test after a long time of design, qualification, manufacture and assembly. Welding the cooling pipe to the flexible plate without obvious deformation as well as tightening uniformly and precisely all the tie rods to clamp the plates were carried out successfully during manufacturing. The result of final vacuum leakage test indicates that the GS can not only meet the ITER vacuum requirement but also have no slow out-gassing. The first set of GS which has passed the ITER acceptance test is to be delivered to ITER construction site soon.

1. Introduction

The International Thermonuclear Experiment Reactor (ITER), a deuterium and tritium burning tokamak facility under an international collaboration, is designed to operate for 20 years, discharging over 30,000 times. The gravity supports (GS)are one of the key components to sustain about 10000 tonnes of magnet coils. Extremely powerful electro-magnets will be used to generate the high magnetic fields for stabilizing the deuterium-tritium plasma operation in the ITER Tokamak. These electro-magnets will be operated in the superconducting state at a cryogenic temperature of 4K. Due to these high magnetic fields, electromagnetic forces (Lorentz forces) will be acting on all the coils of the ITER Tokamak. Therefore, the GS must withstand the extreme loads, including deadweight (10000 tonnes), huge electromagnetic force (normal/abnormal operation) and thermal stress (during cooling down). It is estimated that the temperature difference during cooling down can trigger a shrink of the top of the support towards the centre of the machine up to 31mm while the bottom remains stable. Considering the different operational conditions, such as disruption, vertical displacement event (VDE)and seismic load (SL), totally up to 32 loading combinations might occur, therefore, high requirements for design, qualification and manufacturing of GS are indispensable.

2. Design & qualification test

2.1. Alternative design

In the conceptual design, each flexible plate of GS was jointed to the top and bottom flanges by welding, leaving a 19mm gap between two adjacent flexible plates. The 150mm thick top flange was connected to the Toroidal field coil (TF) leg flange by insulation shims with electrically insulated keys and bolts. The 200mm thick bottom flange was connected to the top surface of the cryostat support ring by keys and bolts. Cooling pipes for helium gas at 80K (thermal anchor) were welded on the side of the flexible plates, whereas welding the flange to flexible plate is very difficult due to the space limitation, shown in Figure 1(a).

An alternative design was proposed without changing the material property and the boundary dimension of the GS. The scheme of the new design is shown in Figure 1(b). The original upper and lower flanges were seperately cut into 20 pieces of 19mm thick spacer plates, two clamping bars and two pressing bars. The 21 flexible plates were lengthened but their thickness remains unchanged. The 20 upper and lower spacer plates were inserted into the gap between two flexible plates. The upper and lower pressing bars were installed outside the flexible plates. All the flexible plates, spacer plates and pressing bars were clamped by tie rods in the horizontal direction, and there was no change in dimension,

---

* Corresponding author.
E-mail address: lipy@swip.ac.cn (P.Y. Lee).

https://doi.org/10.1016/j.heliyon.2020.e03609
Received 11 July 2019; Received in revised form 4 November 2019; Accepted 12 March 2020

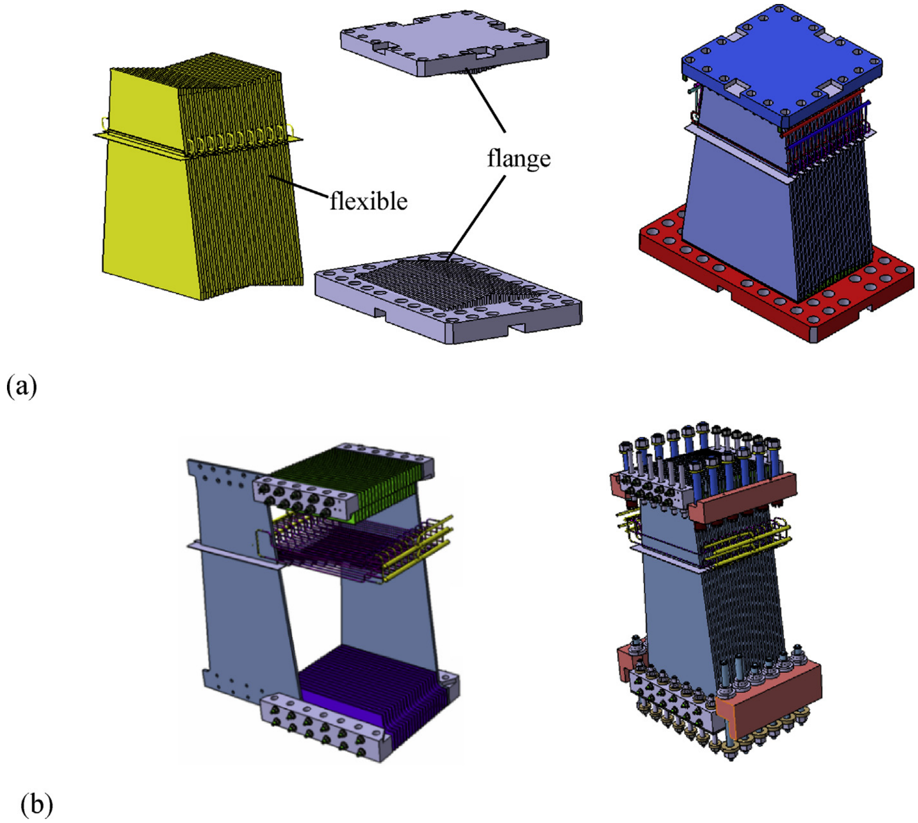

Figure 1. (a)Old design and (b) new design of GS

materials and main structure. The frictional contact areas, i.e., among plates and two upper pressing bars, were applied to increase the friction and resist the separate sliding tendency during operation. The detailed structure design is reported elsewhere [1, 2].

The most important merit of the new GS structure is the exemption from welding, which can considerably simplify the manufacture. The reliability of this structure was investigated by FEM analysis, including the static analysis, fatigue analysis and buckling analysis. The GS not only withstands the dead weight (DW) of the whole magnet system, but also carries the forces such as the thermal stress from the relative thermal motion of the magnet system during cooling down (CD) and warming up, the electromagnetic loads (EOB: end of burning, VDE, DIS: disruption of plasma) during the different operation steps of the ITER device, and the possible seismic loads (SL) in vertical and horizontal directions. Totally more than 32 kinds of load cases/combinations were carried out. The detailed FEM analysis is reported elsewhere [1, 2, 3]. The results reveal that the maximum stress intensities of the ITER magnet GS structure are below the allowable stress limit of the materials, and the components of the gravity support have also enough fatigue strength against the cyclic loads of the overturning electromagnetic forces on the TF coils with 30000 cycles, and the GS structure is safe enough.

2.2. Engineering test

In order to further confirm the reliability of this new design, the multi-dimensional mechanical loading tests were performed. A GS mock-up and a special multi-dimensional test platform were designed and constructed, as shown in Figure 2. To reduce the test difficulty, the GS mock-up was designed to consist of only 5 prototype flexible plates of the same thickness and size, and 4 spacer blocks that were used to replace the rest 16 prototype flexible plates on the full-size GS. Materials, assembly configuration, fasteners, bolt preloads and dimension of the GS mock-up were the same as the GS. The actuators were arranged on the mock-up: one in the X-direction, two in the Y-direction, and four in the Z-direction. The loading forces acting on the GS mock-up were scaled down by a factor of 5/21, as shown in Figure 2(a) and Table 1. The test platform comprised four sub-systems which were the actuator system, structure system, control system and measurement system, as shown in Figure 2(b). The GS mock-up was mounted on the multidimensional loading test platform. During the test, the forces were applied on the GS mock-up by the seven actuators. The strain rosettes for measuring the stress on flexible plate of the loaded mock-up were stuck on the surfaces of each flexible plate where the stress concentration was suspected via FEM analysis. The grating displacement sensors and pulled wire optical code readers were placed on each corner of GS mock-up to measure the displacement, while the ultrasonic bolt stress meter was employed to measure the bolt preload.

The test result [4] elucidates that the GS can maintain its structural integrity under the testing loads; the maximum static stress intensity of all the flexible plates is below the allowable stress limit of 316LN material. All the qualification results prove that the GS structure is safe enough to be used in ITER construction. The processes of machining, assembly and inspection of the GS that were qualified during the qualification phase are applicable to GS production.

3. Manufacturing & assembly test

3.1. Cooling system

The 21 flexible plates and 40 top and bottom spacers were machined firstly with an allowance for the final machining after assembly. Cooling pipes were then attached to flexible plates by TIG welding and connected to each other with manifolds. The welding deformation, leakage and cooling performance shall be taken into account during manufacturing.

The flatness requirement of each flexible plate is 0.8mm after pipe attachment. The welding deformation of the flexible plate by two

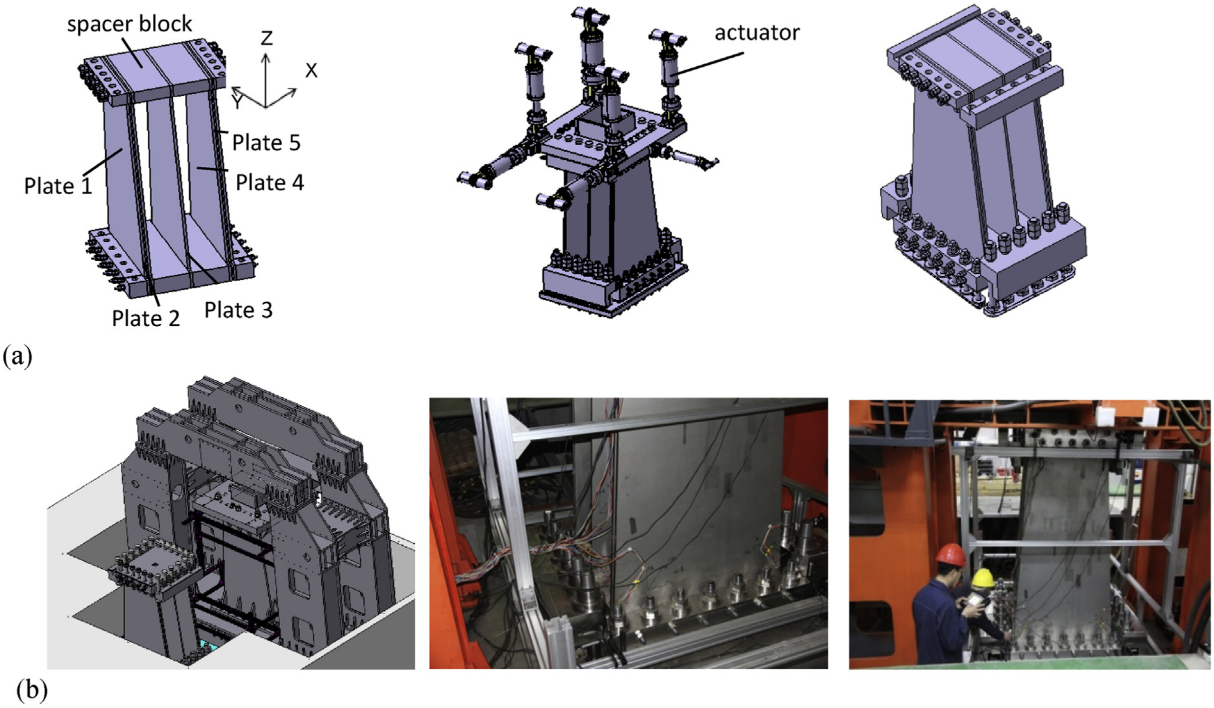

Figure 2. Schematic illustration of (a)GS mock-up and (b)multidimensional loading test.

continuous fillet welds was assessed to be about 0.9mm according to the FEM simulation, which failed to meet the dimensional requirement. Hence, staggered intermittent welding [5] was applied to deformation control. A 3D coordinate measuring machine was adopted to measure the dimension of the plate before and after welding. The deformation was well controlled owing to the less heat input of the staggered intermittent welding.

Because of the staggered intermittent welding, the length of the welds for pipe attachment was only half of the original design. The cooling performance of these cooling pipes were tested. A single flexible plate with one cooling pipe injected with liquid nitrogen was placed in a vacuum chamber to represent the whole GS assembly. The temperature distribution of the flexible plate was recorded by the attached thermocouples when the temperature variation was not obvious, as shown in Figure 3(a). Thermocouples TA-2, TA-6, TA-10, TB-3 and TB-7 on center line of flexible plate were chosen to demonstrate the temperature distribution on the plate. The temperature at the top of the plate dropped to about 130K in 24 h, while the bottom almost stayed at room temperature. Approximately 600 L of liquid nitrogen were consumed during the process. A finite element model for the cooling performance test was built and corrected by the results of the cooling test. The cooling of the GS flexible plates with 80K helium gas was calculated by this model. The simulation results imply that the plate attached with the pipe can be cooled to around 100K after 80 h with only one pipe, as shown in Figure 3(b).

3.2. Assembly

These flexible plates attached with cooling pipes and spacers were pre-assembled and clamped together at bottom and top with pre-stressing bars and tie rods, as shown in Figure 4(b). After finish machining the whole GS sub-assembly, four manifolds were welded to cooling pipes on GS to form twocooling loops.

In order to ensure the accuracy of the dimensions, the following steps were carried out. Firstly, 21 flexible plates and 40 spacers (top and bottom) for one set of GS were chosen carefully to make sure the accumulated thickness can meet the drawing requirements. Secondly, an assembly platform with fixtures and special locating pins was designed for stacking flexible plates accurately. Finally, finish machining without cutting fluid as well as the protection of non-machined part were performed since the assurance of the dimensional accuracy rejects disassembling for internal cleaning. And the finished sub-assembly was cleaned by deionized water at a pressure of 15MPa.

The 21 flexible plates and 40 spacers were fastened together with 12 pieces of M33 and 10 pieces of M42 alloy 718 studs tighten by a hydraulic tensioner with 48MN and 78MN preloads for M33 and M42

Table 1. Load values for load combination cases.

Load cases	Ux (mm)	Fy (kN)	Fz (kN)	Mx (kN.m)	My (kN.m)	Mz (kN.m)
CLD01	-31	34.63	-1741.72	-1264.50	-1467.84	540.54
CLD02	-31	1132.38	-2824.38	-94.11	-911.92	467.01
CLD03	-31	223.74	740.76	-864.29	-1056.69	355.32
CLD07	-31	231.80	1281.37	-661.70	-791.73	271.24
CLD010	-31	0	2800	0	0	0

Notice: Ux is the displacement along the X direction; Fy and Fz are the forces applied along the Y direction and Z direction respectively; Mx, My and Mz are the moments applied along the X direction, Y direction and Z direction respectively.

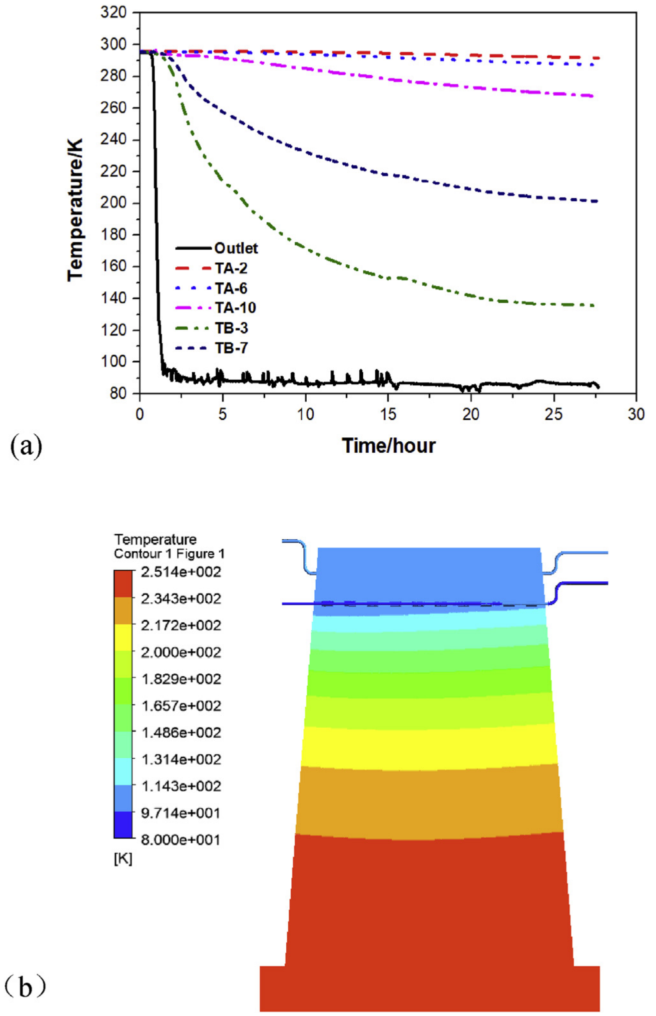

Figure 3. (a) Cooling performance test results and(b) simulation results [6].

studs respectively. To ensure the reliability of the GS during ITER operation, the deviation of the preload on the studs shall be controlled within 5%, which, however, is difficult as the deviation of the effective sectional area(A) of the studs is large than 2%, the deviation of the effective length of the studs is large than 1%(C), and during the installation the preload of the studs will be cross-impacted by each other.

A high precision hydraulic tensioner whose systematic error is less than 2% at the same oil pressure was utilized to preload the studs, as shown in Figure 4(a). The precision was guaranteed by repeating synchronous preloading in groups. Take M33 bolt for example. Three M33 studs per GS were randomly taken and calibrated by 0.5 grade accuracy tensile test device. The calibrated elongations were used to adjust the oil pressure of the hydraulic tensioner and to verify the preloading accuracy after tightening. All M33 studs were tightened by the hydraulic tensioner three times following the sequence of Group A –Group B- Group C with calibrated oil pressure. The deviation of the preload was demonstrated within ±3% by comparing the calibrated elongation with the tightening elongation of the three calibrated M33 studs.

3.3. Leakage test

Installed within the cryostat vacuum boundary in ITER, the GS requires the leakage test. According to the ITER project requirement, the cooling system of each GS shall not present any leak $>10^{-9}$Pam^{3}s^{-1}at a

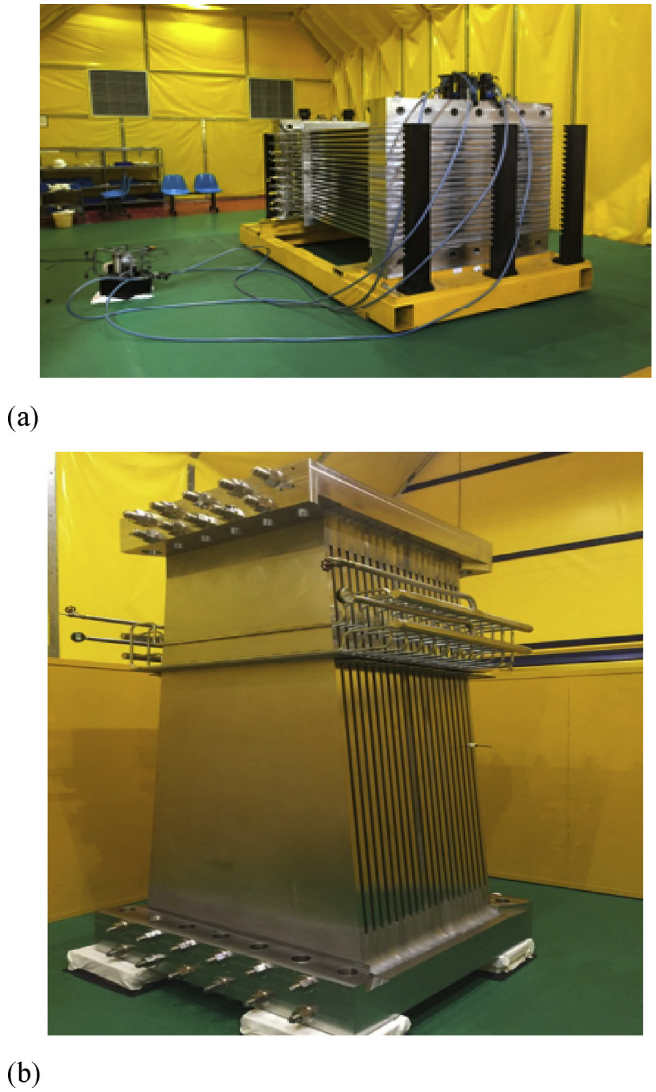

Figure 4. (a) Oil pressure calibration of the tensioner for GS preloading and (b) assembled GS.

helium pressure of 3MPa as measured by the application of the tracer gas method according to ISO 20485. Figure 5(a) shows the schematic diagram of leakage test.

Each GS consists of over 240 parts and hundreds of contact surfaces. The total surface of the GS is over 200m^2, most of which is non-machined. According to the ITER require-ment, a special vacuum chamber (Φ2800 mm × 3000 mm) made of SS304 was constructed. Outgassing issue was taken into consideration for the test results and test efficiency. Firstly, multiple molecular pumps were equipped and run simultaneously to ensure an adequate pumping rate. Secondly, a nitrogen cleaning system was designed to flush the GS surface to accelerate outgassing. Finally, a liquid nitrogen cold trap was established inside of the vacuum chamber to promptly obtain a required background of leakage test.

Prior to installing the GS into the vacuum chamber, both the GS and the chamber were cleaned to reduce the background noise as much as possible. The vacuum degree reached 5.5×10^{-4}Pa in 24 h. Thanks to the nitrogen cleaning system and cold trap, the system background signal was up to 1.05×10^{-10}Pam^{3}s^{-1} which is sufficient for the leakage test. The leak detector was calibrated firstly by a standard leak. No obvious leak signal was detected after the high-pressure helium (3.14 MPa) had

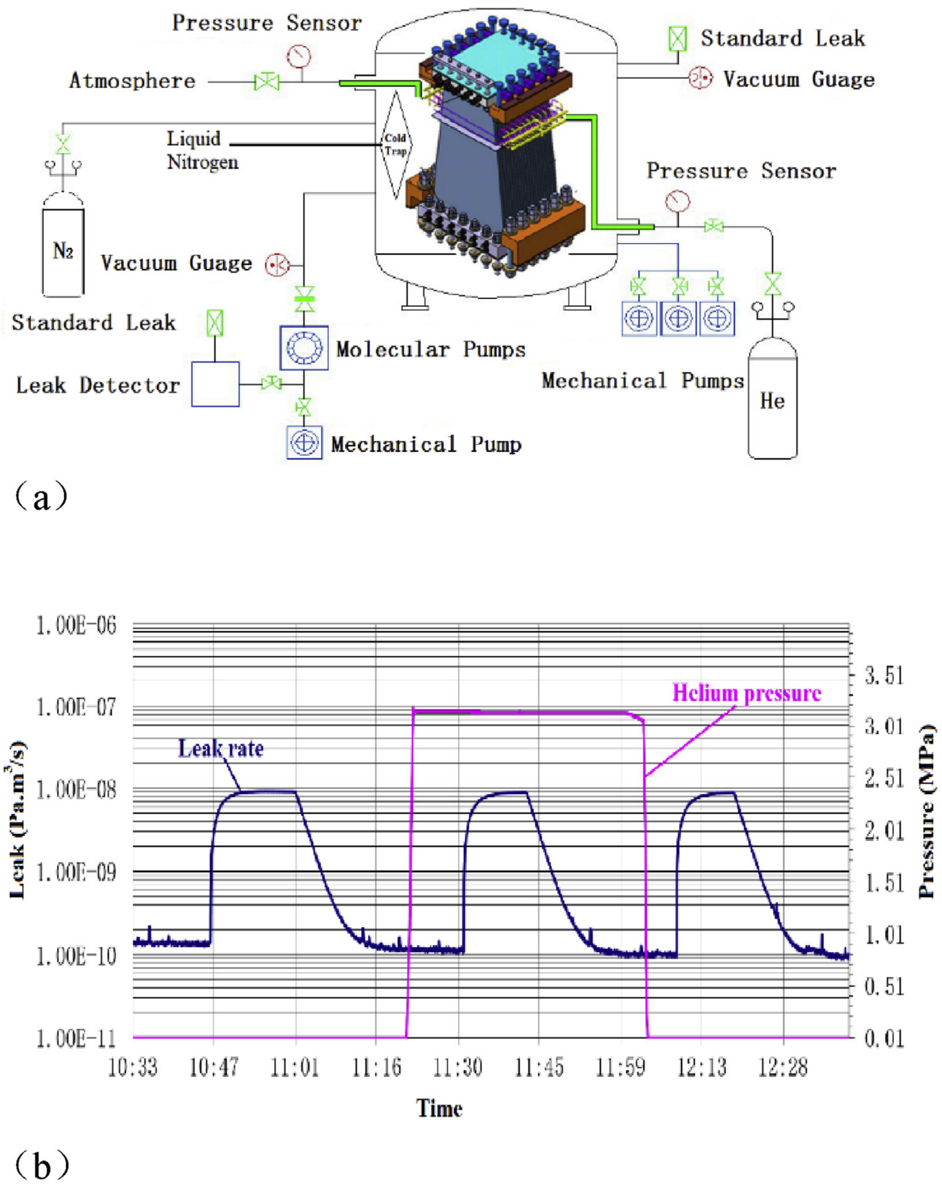

Figure 5. (a) Sketch of leakage test and (b) test results.

been introduced into the cooling system of the GS. Figure 5(b) displays that the background signal reaches 9.80×10^{-11} Pam^{3}s^{-1} when the pipes are filled with helium and the leakage rate is 5.10×10^{-12}Pam^{3}s^{-1}, which is lower and better than the required 1.0×10^{-9}Pam^{3}s^{-1} at 3MPa helium pressure.

4. Summary

An alternative design of GS was proposed because of its better manufacturability. The structural safety of the new design under the extreme loading condition was confirmed by both the FEM analysis and the semi-prototype engineering test. The cooling system, which was fabricated by optimzed TIG welding to control the deformation, indicates a cooling performance which is good enough for the normal operation of superconducting magnet. All the tie rods for clamping GS were tightened uniformly and precisely by tensioners, justifying the successful qualification of assembly process. And the result of final leakage test in a special vacuum chamber proves that the GS can fulfill the ITER vacuum requirement. Having passed the ITER acceptance test, the first set of GS will be delivered to ITER construction site soon.

Declarations

Author contribution statement

P.Y. LEE & B.L. HOU: Conceived and designed the experiments; Wrote the paper.

Z.C. SUN: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

D.A. KANG: Performed the experiments.

S.L. HAN: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

T. ZHANG: Conceived and designed the experiments; Performed the experiments.

D. XU: Analyzed and interpreted the data; Wrote the paper.

T.F. YAN & B. ZHANG: Analyzed and interpreted the data.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The work was sponsored by ITER Major Project of the Ministry of Science and Technology of China, to which the sincere gratitude shall be extended. Besides, special thanks shall go to the ITER International Fusion Energy Organization for their generous help and constant cooperation duiring the exection of the project task.

References

[1] P.Y. Lee, B.L. Hou, g.d. jian, Redesign of gravity support system for ITER construction, Fusion Eng. Des. (2010) 33–38.

[2] B.L. Hou, P.Y. Lee, r. gallix, The conceptual alternative design for ITER gravity support using clamp bolt, Fusion Eng. Des. (2010) 1919–1923.

[3] Youkun Fu, Remy Gallix, Cornelis Jong, Frederic Savary, Structural assessment of the ITER magnet system gravity supports, Fusion Eng. Des. (2011) 1389–1392.

[4] ITER document: ITER_D_NQ5JH8 v1.4, SWIP.IT-MS-FR.GST7-V1.2 Final Report - GS Task 7: Assembly Mechanical Qualification (SWIP).

[5] ISO 2553. Welding and Allied Processes-Symbolic Representation on Drawings-Welded Joints.

[6] Z.C. Sun, P.Y. Lee, H.H. Wei, Study on the Heat Exchange Efficiency of ITER GS thermal Anchor, Fusion Eng. Des. (2018) 13696–13699.