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ADS Injector-I 2 K superfluid helium cryogenic system

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Abstract The Accelerator Driven Sub-critical (ADS) system is a strategic plan to solve the nuclear waste problem for nuclear power plants in China. High-energy particle accelerators and colliders contain long strings of superconducting devices, superconducting radio frequency cavities, and magnets, which may require cooling by 2 K superfluid helium (Helium II). 2 K superfluid helium cryogenic system has become a research hot spot in the field of superconducting accelerators. In this study, the ADS Injector-I 2 K cryogenic system is examined in detail. The cryogenic system scheme design, key equipment, and technology design, such as the 2 K Joule–Thomson (J–T) heat exchanger and cryomodules CM1 + CM2 design, are examined, in addition to the commissioning and operation of the cryogenic system. The ADS Injector-I 2 K cryogenic system is the first 100 W superfluid helium system designed and built independently in China. The ADS proton beam reached 10 MeV at 10 mA in July 2016 and 10 MeV at 2 mA in continuous mode in January 2017 and has been operated reliably for over 15,000 h, proving that the design of ADS Injector-I 2 K cryogenic system, the key equipment, and technology research are reasonable, reliable, and meet the requirements. The research into key technologies provides valuable engineering experience that can be helpful for future projects such as CI-ADS (China Initiative Accelerator-Driven System), SHINE (Shanghai High Repetition Rate XFEL and Extreme Light Facility), PAPS (Platform of Advanced Photon Source Technology), and CEPC (Circular Electron-Positron Collider), thereby developing national expertise in the field of superfluid helium cryogenic systems.

Keywords ADS · Superfluid helium · Cryogenic system · Cryomodule · J–T heat exchanger

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1 Introduction

Nuclear energy is a type of clean energy that will be widely used in the Chinese energy program in the future. However, a serious problem with nuclear energy is the handling of radioactive waste produced by nuclear plants. The ADS is an effective tool for transmuting long-lived transuranic radionuclides into shorter-lived radionuclides and therefore has the potential to mitigate the nuclear waste problem [1]. The ADS project was launched in 2011 in China with the industrial development of a 1.5 GeV high-intensity superconducting (SC) linac. The ADS project is divided into four phases, as shown in Fig. 1. The first phase is called the "Strategic Technology Pilot Project." It has been independently fabricated and commissioned in two different institutes [2]. The Institute of High-Energy Physics of the Chinese Academy of Sciences (IHEP, CAS) is responsible for Scheme I (Injector-I), which is based on a 325 MHz room-temperature radio frequency quadrupole (RFQ) and SC spoke cavities operating at the same frequency. The Institute of Modern Physics (IMP, CAS) is responsible for Scheme II (Injector-II), which is based on a

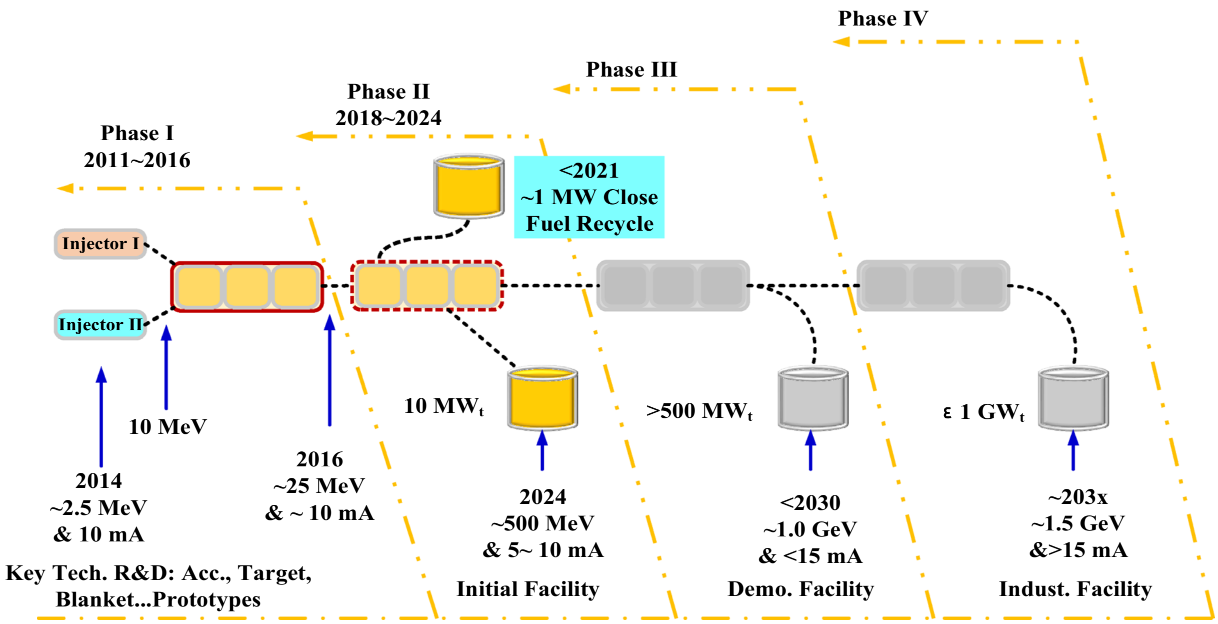


Fig. 1 (Color online) Four phases of the ADS project

162.5 MHz room-temperature RFQ and half-wave resonator (HWR) technology of the same frequency.

The general layout of the ADS Injector-I is shown in Fig. 2. It is composed of an electron cyclotron resonance (ECR) ion source, a low energy beam transport (LEBT) line, an RFQ, a medium energy beam transport (MEBT) line, and the accelerator superconducting section. The ADS Injector-I is a proton accelerator with a proton beam energy of 10 MeV.

The accelerator superconducting section in the ADS Injector-I mainly consists of two cryomodules CM1 and CM2, each of which contains seven spoke-type superconducting cavities and seven superconducting solenoid magnets. The SRF cavities and magnets in the cryomodules are cooled by a 2 K superfluid helium (Helium II) bath, which is a technically safe and economically reasonable choice because of its large effective thermal conductivity and heat capacity as well as its low viscosity. The international and domestic development of the cryogenic system is summarized below.

The Large Hadron Collider (LHC) was built with the refrigeration capacity of 8 × 18 kW@ 4.5 K cryogenic system in by CERN (European Organization for Nuclear Research). It is the largest scale helium cryogenic system in the world [3–5]. The European X-ray Free Electron Laser (XFEL) project has been successfully operated by DESY (Deutsches Elektronen-Synchrotron) with a refrigeration capacity of 2.5 kW@ 2 K cryogenic system. TESLA (Tera eV Energy Superconducting Linear Accelerator) with a 500 GeV energy incorporated XFEL facility has been proposed [6–8]. KEK (Japanese High-Energy Accelerator Research Organization) has built the STF (Superconducting RF Test Facility) cryogenic system with a capacity of 100 W@ 2 K for the ILC (International Linear Collider) and cERL (compact Energy Recovery Linac) [9–11]. The USA has built many acceleration facilities, including the operating CEBAF (Continuous Electron Beam Accelerator Facility) and its associated upgraded projects with a capacity of 4.2 kW@ 2.1 K cryogenic system at JLAB (Thomas Jefferson National Accelerator Laboratory) [12], SNS (Spallation Neutron Source) with a capacity of 2.4 kW@ 2.1 K cryogenic system at ORNL (Oak Ridge National Laboratory) [13], and the Heavy-Ion Linac ATLAS with a capacity of 1.2 kW@ 4.7 K cryogenic system at ANL (Argonne National Laboratory) [14]. In addition, LCLS II (Linear

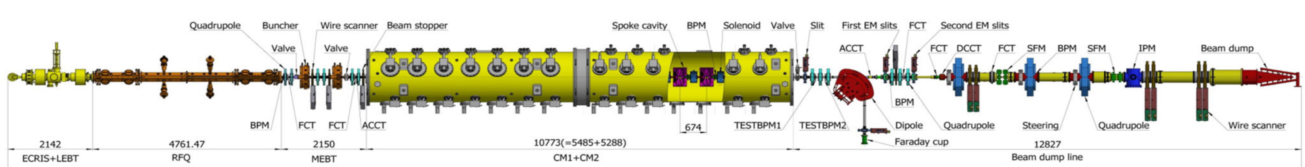


Fig. 2 (Color online) General layout of ADS Injector-I

Coherent Light Source upgrade) with a capacity of 4 kW@ 2 K cryogenic system at SLAC (National Accelerator Laboratory in USA) [15], the ERL (Energy Recovery Linac) with a capacity of 7.5 kW@ 1.8 K cryogenic system at Cornell University's Laboratory for Accelerator [16], and the FRIB (Facility for Rare Isotope Beams) with a capacity of 3.6 kW@ 2.1 K cryogenic system at MSU (Michigan State University) [17] will use Helium II operation.

China has gradually invested in large-scale scientific facilities in recent years. IHEP, CAS built and ran two 500 W@ 4.5 K cryogenic systems in the Beijing Electron-Positron Collider (BEPC) and its upgrade BEPCII [18, 19]. The ADS Injector-I 2 K superfluid helium cryogenic system, which had a capacity of 1000 W@4.5 K or 100 W@ 2 K, was built and tested successfully [20]. An experimental study on the failure compensation of the superconducting cavity in a C-ADS Injector-I was performed [21], and the beam phase and energy measurement system of the ADS Injector-I was designed successfully [22]. A supercritical cryogenic hydrogen loop running at 18 $\sim$ 21 K and 15 bar has been operated at the China Spallation Neutron Source (CSNS) [23, 24]. Further operation and testing facilities also include the ADS Injector-II cryogenic system with a capacity of 1000 W@ 4.5 K by IMP, CAS [25]; SSRF (Shanghai Synchrotron Radiation Facility) cryogenic system with a capacity of 600 W@ 4.5 K by SINAP, CAS (Shanghai Institute of Applied Physics, CAS) [26]; and EAST (Experimental Advanced Superconducting Tokamak) cryogenic system with a capacity of 2 kW@ 4.5 K the by IPP, CAS (Institute of Plasma Physics, CAS) [27]. In addition, the PAPS cryogenic system with a capacity of 2.5 kW@ 4.5 K or 300 W@ 2 K, CI-ADS cryogenic system with a capacity of 18 kW@ 4.5 K or 4.8 kW@ 2 K, SSRF II cryogenic system with a capacity of 60 W@ 2 K [28], SHINE cryogenic system with a capacity of 13 kW@ 2 K, HEPS (High-Energy Photon Source) cryogenic system with a capacity of 2 kW@ 4.5 K, and HIAF (High Intensity Heavy-Ion Accelerator Facility) cryogenic system with a capacity of 10 kW@ 4.5 K or 2 kW@ 2 K [29] are under construction. In addition, technical design studies have begun for the CEPC cryogenic system with a capacity of 4 $\times$ 18 kW@ 4.5 K in the SRF cavity side [30], and planning has begun for CSNS II with a capacity of 1000 W@ 2 K.

The ADS Injector-I cryogenic system is described in this paper, which focuses on the design of the cryogenic system scheme, key equipment, and technology, as well as the process of commissioning and operation. This paper presents the layout of the cryogenic system, overall heat load, process calculation, 2 K superfluid helium scheme, study of the 2 K J–T heat exchanger, and design of cryomodules CM1 and CM2.

2 Design of ADS Injector-I cryogenic system

2.1 Layout of cryogenic system

The ADS cryogenic system is composed of a helium refrigerator, 4.5 K main distribution valve box (MDVB) and 2 K valve boxes (2 K VB), cryomodules, 2 K pump system, control system, liquid nitrogen tanks, helium storage tanks, helium recovery, and purification system. It consists of a vertical test station, a horizontal test station, and two cryomodules CM1 and CM2. The process flow diagram (PFD) of the ADS Inject I cryogenic system is shown in Fig. 3, and the three-dimensional diagram is shown in Fig. 4. The helium refrigerator generates liquid helium and stores it in a 3000 L Dewar. Then, the helium flows from the MDVB to the vertical and horizontal test stations and the cryomodules CM1 + CM2 station, passing through 50 m of cryogenic multi-channel transfer lines. The cryomodules have two thermal shields to reduce heat loss, namely an 80 K liquid nitrogen shield and a 5 K–8 K supercritical helium shield.

2.2 Cryogenic system overall heat load

The primary purpose of the heat load analysis is to size the refrigerator and to define the configuration of the pump station and other large-scale standard equipment. In this paper, the measured heat leakage of the cryogenic joint and valve was 1 W/piece and that of the cryogenic transfer line was 0.5 W/m. The heat load of the cryomodules is shown in Table 1. The static heat load and dynamic heat load of test stations are listed in Tables 2 and 3, respectively.

Based on the heat loads of the cryogenic system, a 1000 W@ 4.5 K refrigerator was selected to provide a liquid helium environment for the cryomodules.

2.3 Process calculation of the cryogenic system

The process calculation is based on the layout and heat load of the cryogenic system. It permits the state parameters of each key node to be determined and provides a theoretical basis for the design of cryogenic equipment. The vertical test station, horizontal test station, cryomodule operation station are operated individually. The process calculation model is shown in Fig. 5. The state parameters of each key node in the vertical test station and cryomodule operation station are shown in Tables 4 and 5, respectively. The state parameters of the horizontal station are similar to those of the vertical test station, which are not listed here.

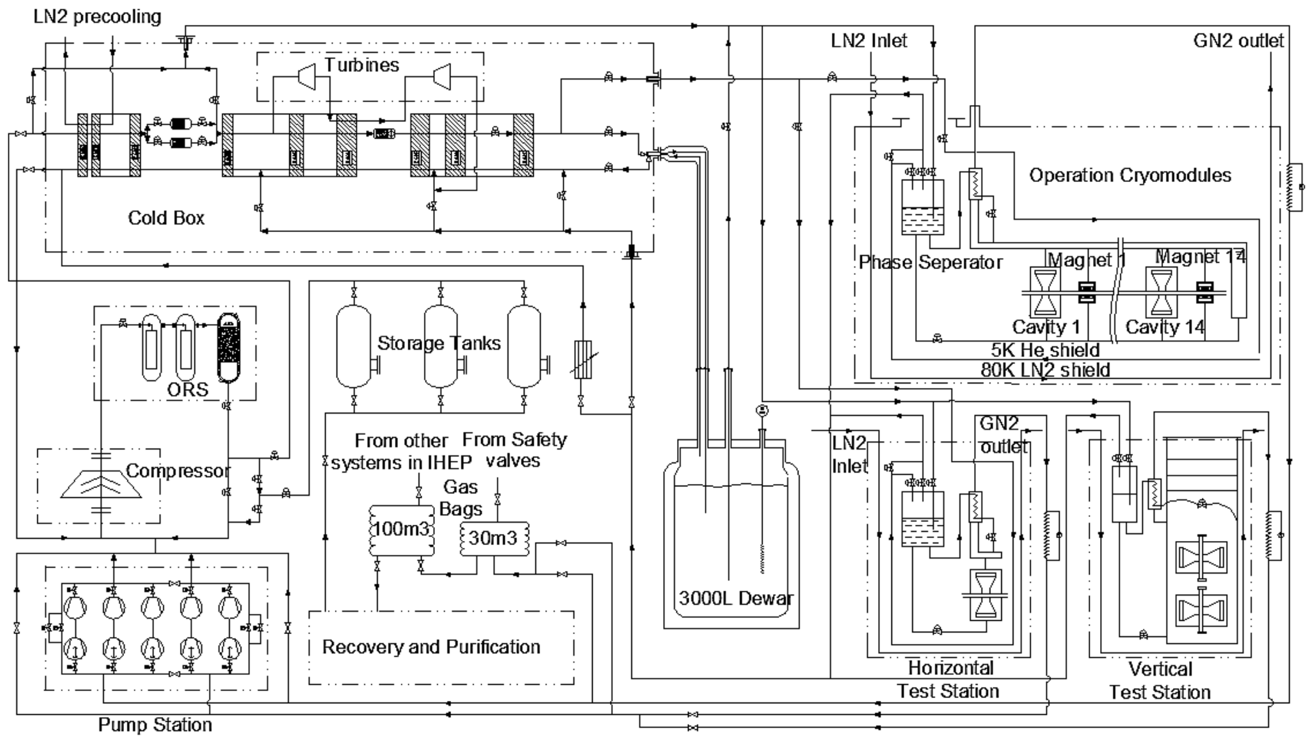


Fig. 3 PFD diagram of the ADS Injector-I cryogenic system

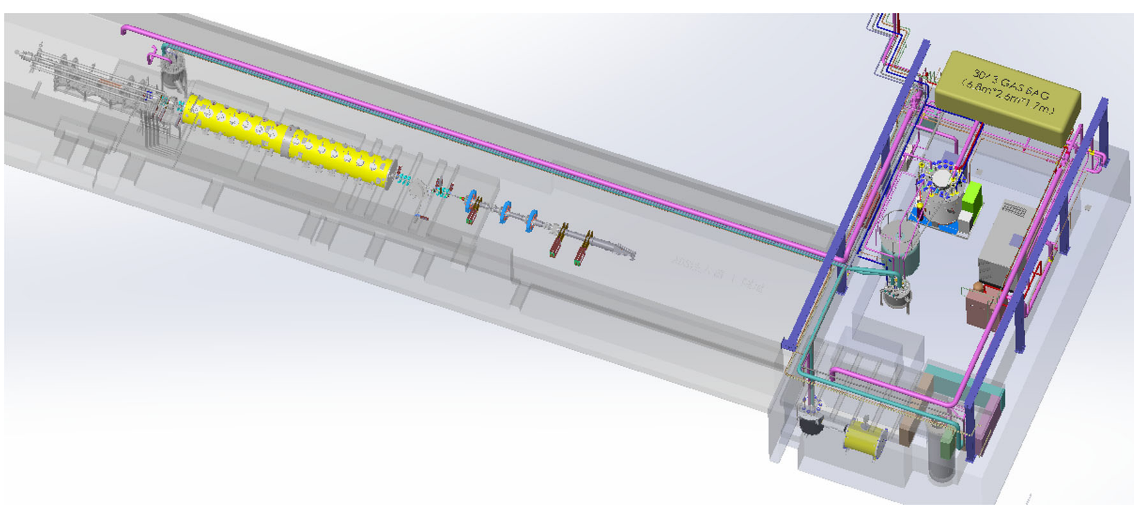


Fig. 4 (Color online) Three-dimensional diagram of the ADS Inject I cryogenic system

2.4 Key equipment and technology

2.4.1 2 K superfluid helium and pump group

The corresponding pressure of 2 K superfluid helium is 31 mbar. As for the 100 W and smaller 2 K superfluid helium cryogenic system, a room-temperature vacuum pump group is generally used to pump down the helium vapor and to reduce the helium bath pressure. In the ADS Injector-I cryogenic system, the total mass flow through the pump is 10 g/s according to the system heat loads. The brand of pump is LEYBOLD, which was produced in Germany, and the specifications for one set are WS2001FU (WS2001 with frequency inverter) and SV750BF/A (SV630BF @ 60 Hz). Five sets of pumps were operated with a total pumping capacity of at least 8000 m^3/h @ 31 mbar, including three sets for the cryomodules and another two sets for the vertical/horizontal test stations. Figure 6 shows the five sets of vacuum pumps' performance curve of the suction speed versus pressure with the

Table 1 The heat load of cryomodules in the cryogenic system

	Number	80 K heat load (W)	5 K heat load (W)	2 K heat load (W)
3000 L Dewar	1	–	8.00	–
Single channel helium return transfer line	54 m	–	27.10	–
Single channel helium supply transfer line	62 m	28.02	–	–
Multi-channel transfer line	72 m	72.00	36.00	–
4.5 K main distribution valve box	1	15.10	25.03	–
Cryomodules	2	571.10	165.65	84
2 K valve box	1	15.33	9.64	0.90
Overall heat load of the whole cryogenic system		701.55	271.42	84.90

Table 2 Static heat load in test stations

	Number	80 K heat load (W)	5 K heat load (W)	2 K heat load (W)
2 K horizontal test valve box	1	15.82	9.64	0.90
2 K horizontal test cryomodule	1	37.57	3.03	0.33
2 K vertical test valve box	1	10.34	6.45	0.00
2 K vertical test cryomodule	1	172.62	12.07	0.49
Test stations total static heat load (W)		236.35	31.19	1.72

Table 3 Dynamic heat load in test stations

Frequency, f (MHz)	Characteristic impedance, R/Q (Ω)	Temperature, T (K)	Test station	Intracavity voltage, V_c (MV)	Quality factor, Q_0	Dynamic heat load (W)
325	142	2	Vertical test station	1.5	2×10^8	79.5
			Horizontal test station	1.3	2×10^8	60

helium fluid test. In February 2015, the pump station was successfully put into joint commission. A diagram of the pump station and photograph showing the set of pumps after installation are shown in Figs. 7 and 8, respectively. The pump group pressure fluctuation is less than ± 10 Pa thanks to the frequency conversion and PID parameters regulation. Figure 9 shows that the vacuum pump group operates stably with limited fluctuation.

2.4.2 *Study on the 2 K J–T heat exchanger*

4.45 K@1.25 bar liquid helium is cooled to about 2.37 K after entering a 2 K Joule–Thomson (J–T) heat exchanger. Then, the pressure is reduced to 31 mbar after passing through a J–T valve due to its throttling effect, hence producing the superfluid helium, as shown in Fig. 10a. The 2 K J–T heat exchanger can improve the liquefaction rate of the J–T valve. As seen from Fig. 10b, if there is no J–T heat exchanger, the liquefaction rate is limited to 57.3%. If a J–T heat exchanger is added, the liquefaction rate can be increased to 88.6%. Therefore, the performance of the J–T heat exchanger is important for the efficiency, economy, and reliability of the entire cryogenic system.

The J–T heat exchanger is a small Hampson-type heat exchanger, which is made of copper fin tubes by spiral winding, as shown in Fig. 11. It is widely used in the fields of air liquefaction, natural gas liquefaction, and helium cryogenic system because it exhibits advantages such as high heat transfer efficiency, compact structure, and small pressure drop.

A detailed description of the design of the J–T heat exchanger has been provided in the literature [31]. The relationship between the liquid and vapor pressure drop

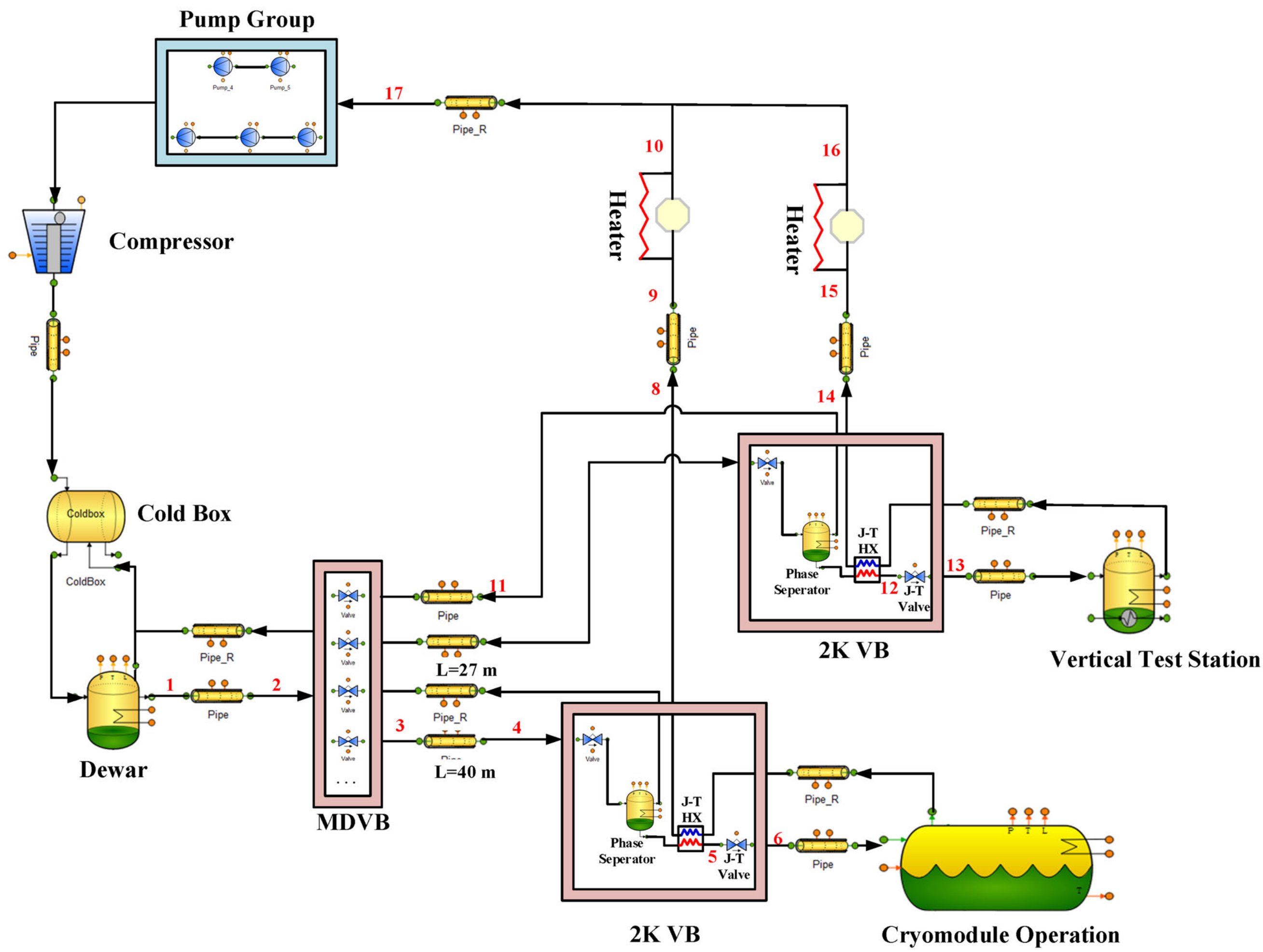


Fig. 5 (Color online) Process calculation model

Table 4 State parameters of each key node of the cryomodule operation station

Key node	T (K)	P (Pa)	M (g/s)
1	4.498	130,000	6.532
2	4.498	129,990	
3	4.498	129,980	
4	4.495	129,713	
5	2.8	124,700	5.143
6	2	3100	
8	3.145	3000	
9	3.238	2998	
10	300	2948	
17	301.9	2923	

Table 5 State parameters of each key node of the vertical test station

Key node	T (K)	P (Pa)	M (g/s)
1	4.498	130,000	6.139
2	4.498	129,991	
3	4.498	129,981	
11	4.496	129,810	
12	2.8	124,700	5.143
13	2	3100	
14	3.145	3000	
15	3.237	2998	
16	300	2948	
17	301.9	2923	

and the mass flow rate is shown in Fig. 12, and the relationship between the liquid and vapor outlet temperature and the mass flow rate is shown in Fig. 13.

It can be seen from Figs. 12 and 13 that when the heat exchanger works at a mass flow rate of 3–5 g/s, its performance and characteristics such as pressure drop, outlet temperature, and other parameters are more reasonable.

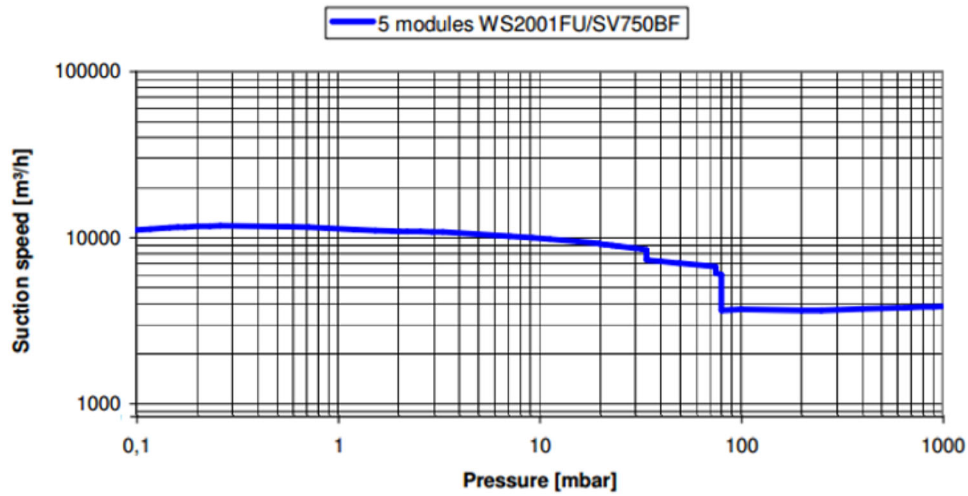


Fig. 6 Performance curve of the suction speed versus pressure with helium fluid test

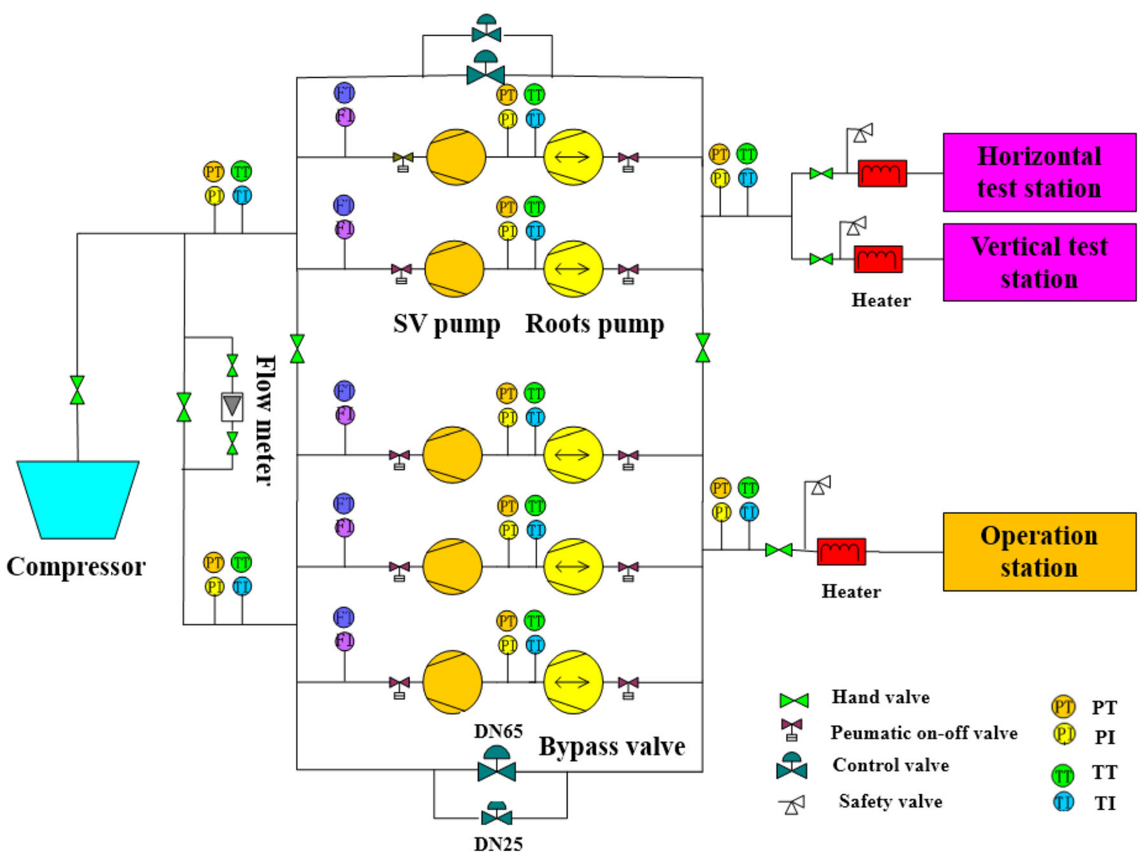


Fig. 7 (Color online) Diagram of the pump station

While operating at a mass flow rate of 10 g/s, the liquid outlet temperature (hot fluid) T_{liquid} is 2.71 K, and the pressure drop ΔP_{h} is 608 Pa. As shown in Fig. 8b, the 2 K liquefaction efficiency is less than 85%. Therefore, it is not recommended that the heat exchanger be allowed to operate at mass flow rates at or above 10 g/s or larger mass flow for a long period of time. Preliminary research indicates that this type of heat exchanger is generally suitable for a 2 K cryogenic system with a refrigeration capacity of 60–100 W.

2.4.3 Design of cryomodules

Cryomodules are used as superconducting accelerating components that have a stable beam current (including energy, current intensity). A cryomodule is composed of a

Fig. 8 (Color online) Photograph of the pump station after installation

superconducting cavity, high-power coupler, superconducting magnet, current lead, and cryostat. The ADS Injector-I cryogenic system contains two cryomodules, CM1 and CM2, each of which contains seven spoke-type SRF cavities and seven SC solenoid magnets. Cryomodule design requirements include keeping the SRF cavities operating at Helium II temperature and providing connections for RF power, cryogenic fluids, a particle beam pipe, a mechanism for adjusting the cavity resonant frequency, and instrumentation. Designing a cryomodule that meets these requirements while being cost-effective is challenging. Therefore, a reliable cryomodule design is critical to the ADS Injector-I cryogenic system.

The TCM cryomodule is the transition equipment of the whole ADS Injector-I system. Its main function is to verify whether the superconducting equipment, beam diagnosis, and cryogenic system required by the ADS Injector-I are able to work together reliably. Moreover, the design and structural framework of the TCM cryomodule are similar to those of the CM1 and CM2. Therefore, the TCM cryomodule is the key component necessary to ensure the success of the ADS Injector-I cryogenic system. A diagram of the design of the TCM cryomodule is shown in Fig. 14. Two layers of heat insulating thermal shields are included in the TCM design to minimize radiation heat leakage, namely a 5 K/8 K cold helium shield and 80 K liquid nitrogen shield. A supporting plate known as the G10 POST support is the main supporting structure.

The finite-element model ANSYS is used to analyze the stress and displacement of the external vacuum vessel (Fig. 15a, b), the stress and temperature of the POST (Fig. 15c), the stress and displacement of the room-temperature support plate (Fig. 15d, e), and the temperature distribution of the 5 K and 80 K thermal shields (Fig. 15f). The pressure stability is ± 10 Pa. The J–T valve, pressure, and liquid level can be automatic adjusted as heat loads fluctuate. The cryogenic system was able to operate in a stable configuration at 2 K, hence validating the test and commissioning of the TCM.

The ADS Injector-I has two 2 K cryomodules, CM1 and CM2. The overall structure of CM1 and CM2 is similar to that of TCM, but CM1 and CM2 added the tuner

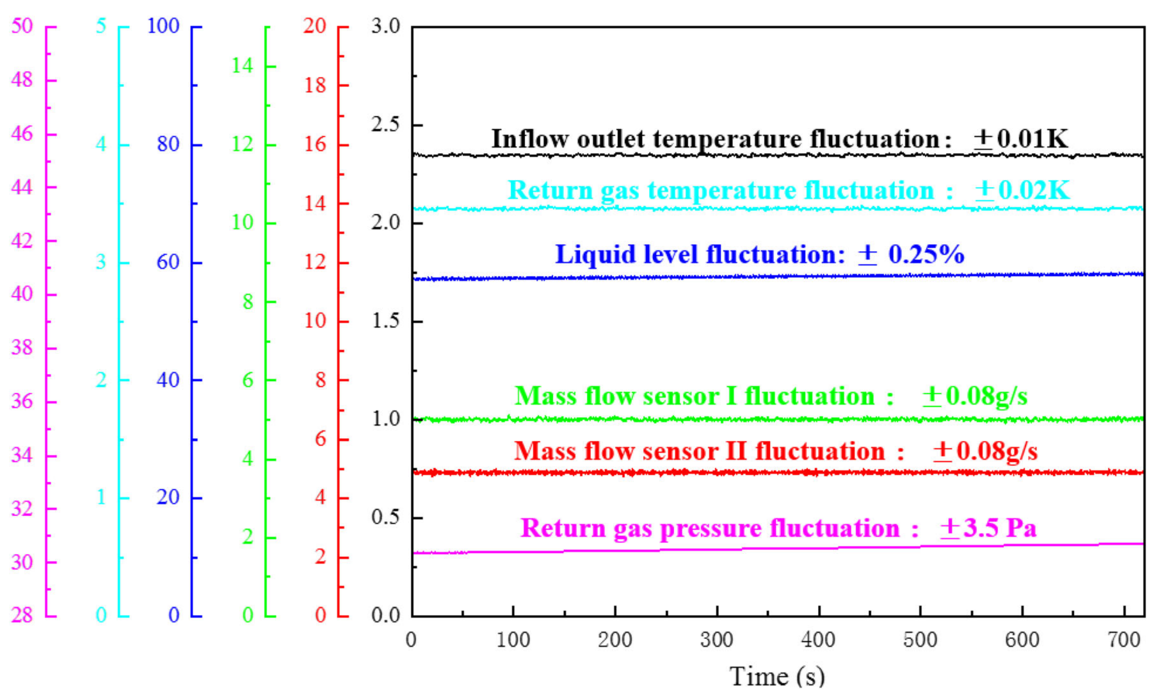


Fig. 9 (Color online) Stability of pump group operation

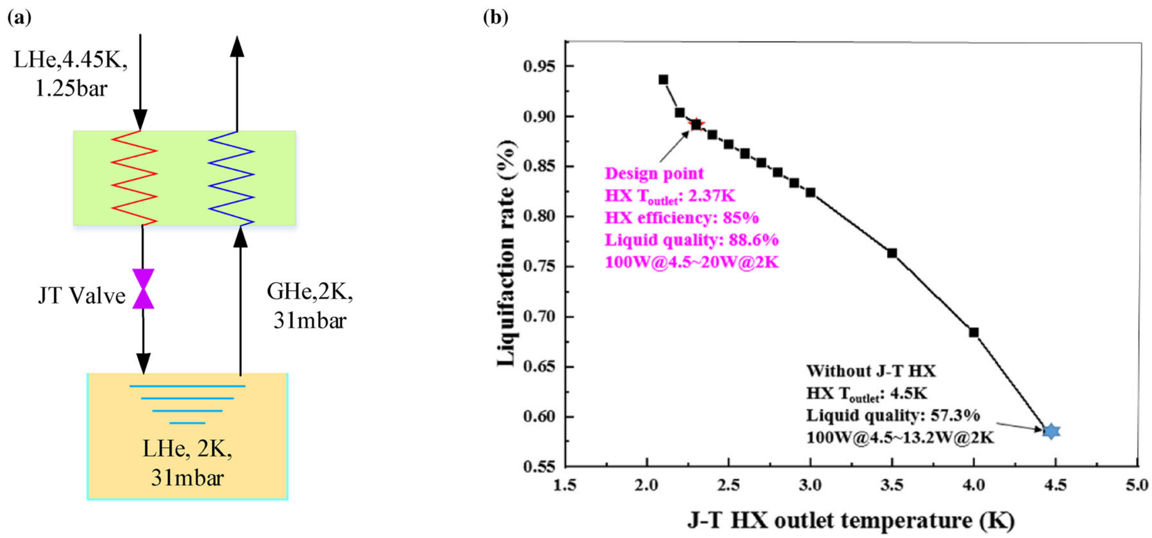


Fig. 10 (Color online) Obtaining 2 K through a J–T heat exchanger and J–T valve

Fig. 11 (Color online) Structural diagram of the Hampson-type heat exchanger

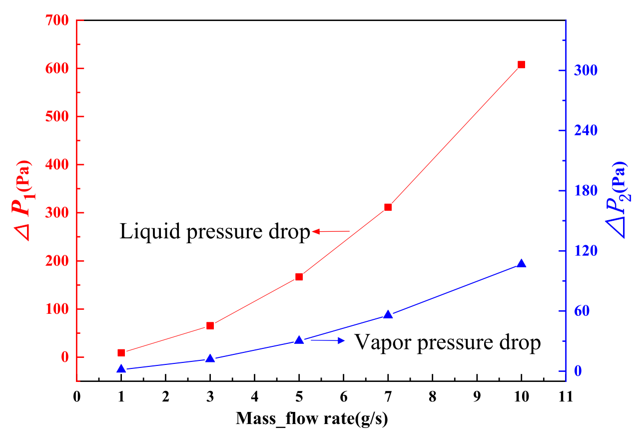


Fig. 12 Relationship between the liquid and vapor pressure drop and the mass flow rate

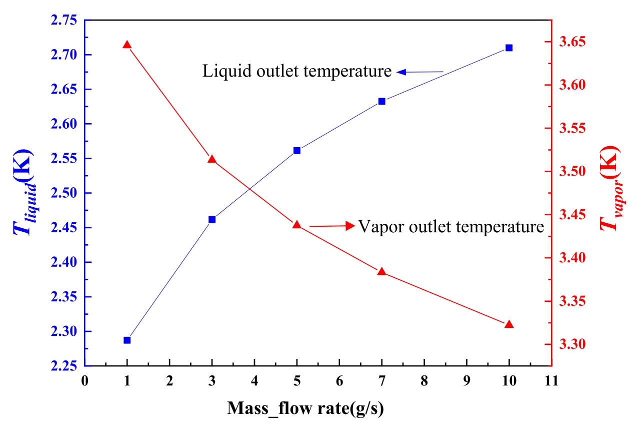


Fig. 13 Relationship between the liquid and vapor outlet temperature and the mass flow rate

maintenance ports, which are not present in TCM. CM1 and CM2 are currently the first large spoke cavity cryomodules in China. The layout of CM1 + CM2 in the ADS Inject I cryogenic system is shown in Fig. 16. The assembly drawing of CM1 + CM2 is shown in Fig. 17.

3 Commissioning and operation of cryogenic system

The cryogenic system was commissioned to operate the refrigerator, 4.5 K main distribution valve box, multichannel transfer lines, 2 K valve boxes, CM1 + CM2 cryomodules, pump group station, and other equipment. In order to represent the cooling process of the cryomodule, a

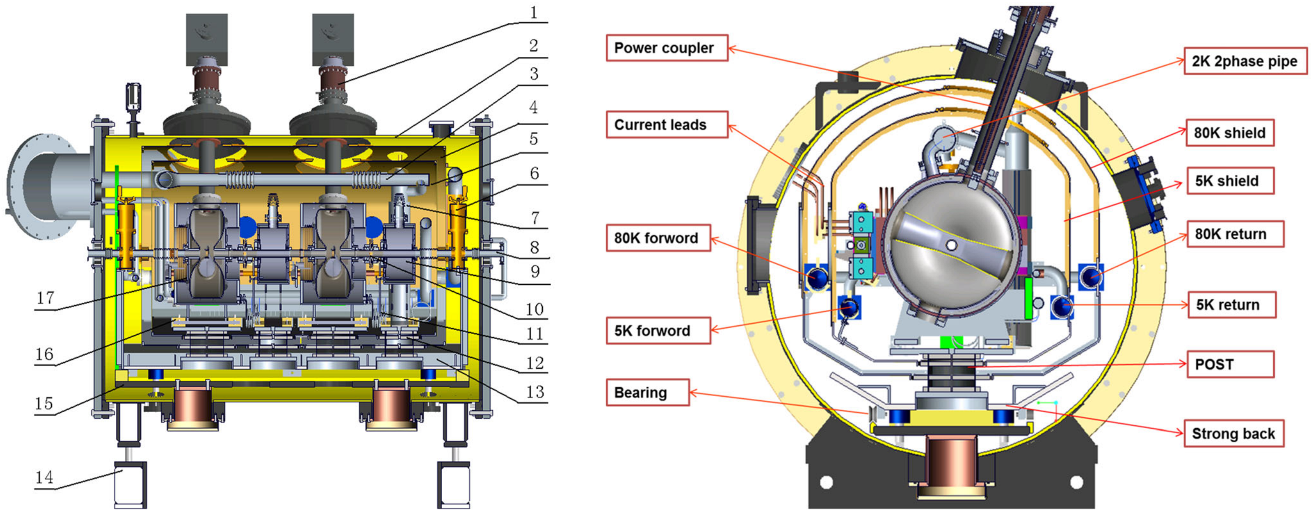
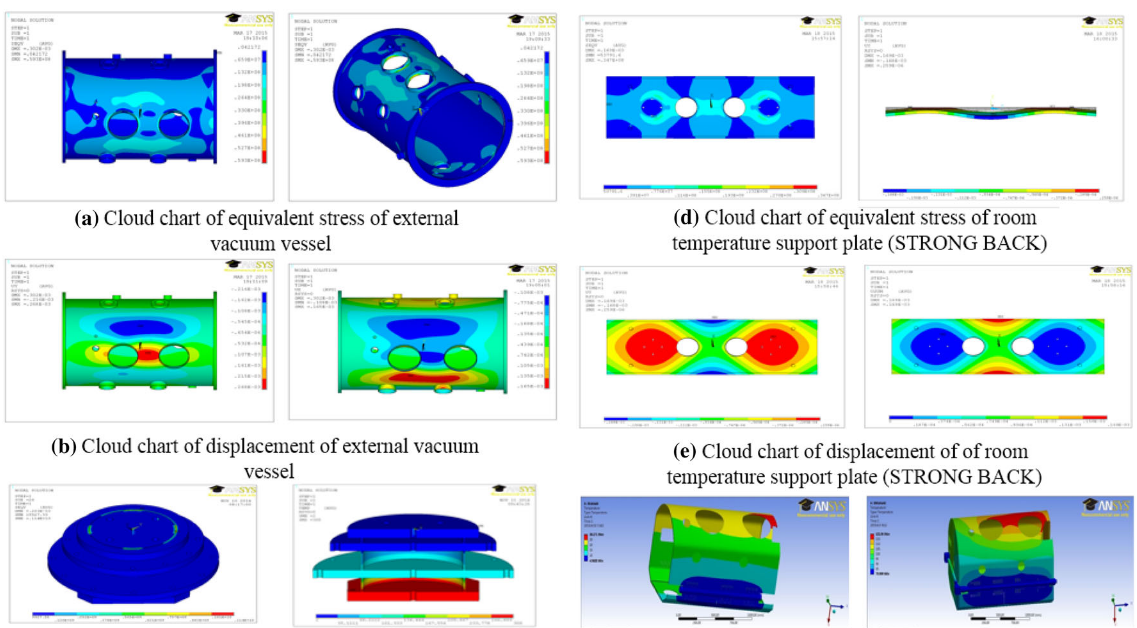


Fig. 14 (Color online) TCM cryomodule diagram. 1—coupler; 2—vacuum cylinder; 3—two-phase pipe of 2 K pump group; 4—80 K liquid nitrogen shield; 5—5 K helium shield; 6—vacuum gate valve; 7—level gauge pipe assembly; 8—beam tube; 9—superconducting magnet + current lead; 10—low temperature BPM; 11—cool-down/rewarming pipe; 12—POST (thermal insulation support); 13—room-temperature support plate (STRONG BACK); 14—saddle and regulating mechanism; 15—base plate + track; 16—three-dimensional adjusting mechanism; 17—SPOKE – 012 superconducting cavity assembly



(a) Cloud chart of equivalent stress of external vacuum vessel

(d) Cloud chart of equivalent stress of room temperature support plate (STRONG BACK)

(b) Cloud chart of displacement of external vacuum vessel

(e) Cloud chart of displacement of of room temperature support plate (STRONG BACK)

(c) Cloud chart of equivalent stress (left) and temperature (right) of POST insulation support

(f) Cloud chart of temperature distribution of 5K (left) and 80K (right) thermal sheilds

Fig. 15 (Color online) Finite-element analysis of key components with ANSYS

Fig. 16 (Color online) Layout of CM1 + CM2 cryomodules in the ADS Inject I cryogenic system

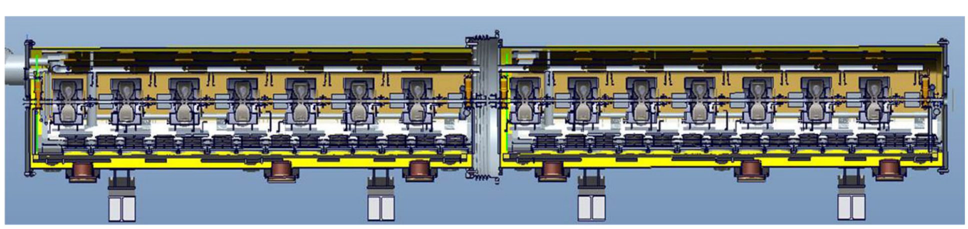


Fig. 17 (Color online) Assembly drawing of CM1 + CM2 cryomodules in the ADS Inject I cryogenic system

diagram of the cryomodule and the 2 K valve boxes is shown in Fig. 18.

First, a static heat leakage test was outperformed on CM1. Two different methods were used to test the CM1 static heat load, namely measuring the liquid level and the mass flow rate, respectively. The measurement was repeated twice using each of these two methods, and the results are shown in Table 6 and Fig. 19.

The test results demonstrated that the static heat loads of CM1 were less than 32 W. The relative difference between the two measurement methods was less than 8%. Furthermore, the liquid level measurement method exhibited good repeatability, and the deviation between the two measurement results was less than 1%, which was a smaller deviation than that of the mass flow measurement method.

Next, CM1 + CM2 were combined to cool the system down from 300 to 4 K. The cooling scheme of the cryomodule CM1 + CM2 was carried out using step-by-step temperature mixing. The refrigerator provided the 300 K and 60 K temperature mixing function. The temperature of the superconducting cavities was first reduced by the mixture of 300 K and 60 K helium gas. The rate of cooling was controlled at 5–10 K/h. When the temperature of the superconducting cavities reached 80–100 K, the liquid helium in the 3000 L Dewar and the 60 K cold helium gas were mixed to cool down the superconducting cavities until the helium vessels were full of liquid helium. The CM1 + CM2 cool-down curve from 300 to 4 K is shown in Fig. 20.

Figure 20 shows that it took 72 h (3 days) for the CM1 + CM2 to cool down from 300 to 4 K. The cool-down process of the superconducting cavity has unique requirements: The release of residual stress requires a certain cooling rate, and the maximum temperature difference of thermal stress should not exceed a given threshold. (In engineering experience, the maximum

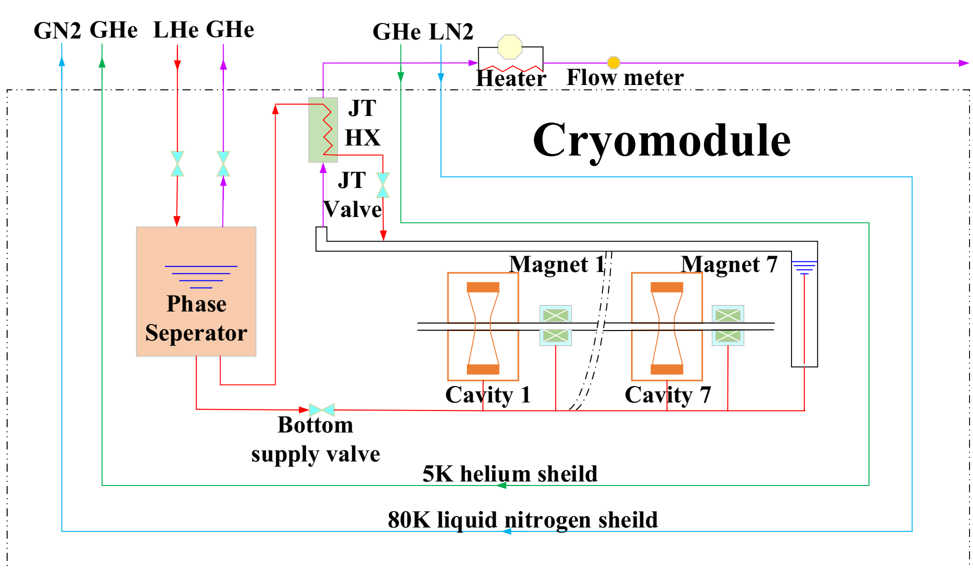


Fig. 18 (Color online) Diagram of the cryomodule CM1 and the 4 K/2 K valve box

Table 6 The results of static heat load tests that were repeated twice using two methods

	Liquid level (W)	Mass flow rate (W)	Relative difference (%)
1st test	31.2	30.4	2.56
2nd test	31	28.5	8.06
%	0.64	6.25	–

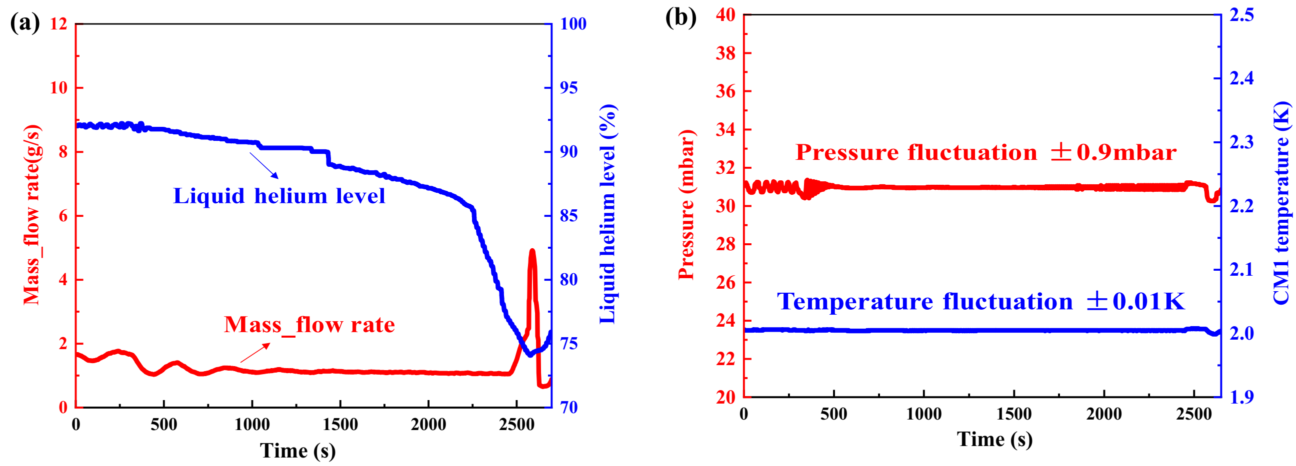


Fig. 19 (Color online) CM1 static heat leakage measurement curve; **a** the relationship between the liquid helium level and mass flow rate versus time; **b** CM1 temperature and pressure curve

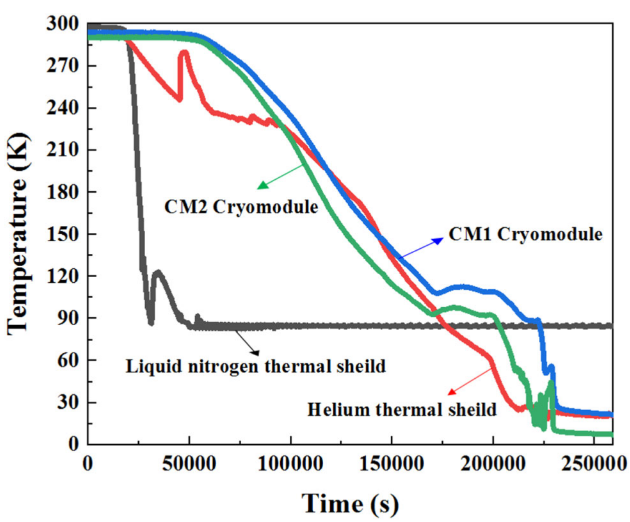


Fig. 20 (Color online) CM1 + CM2 cool down from 300 to 4 K

temperature difference of the superconducting cavity is less than 40 K.) Therefore, the cool-down process should be smooth and gentle.

Then, CM1 + CM2 were combined to perform a cool down from 4.5 to 2 K. When the CM1 + CM2 helium vessels were full of liquid helium, the bottom liquid supply valve was closed, the J–T valve at the outlet of J–T heat exchanger was opened, and the room-temperature vacuum pumps were turned on to reduce the pressure to 31 mbar (negative pressure). The temperature of the cryomodule was reduced from 4.5 to 2 K gradually, as shown in Fig. 21.

As shown in Fig. 21, the time for the CM1 to cool down from 4.5 to 2 K was less than 75 min (except for the stationary section line), and the cool-down rate was very fast. Indeed, a slow cool-down rate leads to almost complete flux trapping and higher residual resistance, while a fast cool-down rate leads to flux expulsion and lower residual resistance [32]. In addition, during the cooling process, the relevant parameters such as temperature, pressure, liquid level were stable, as shown in Fig. 22. The fluctuation in the liquid level was ± 0.5%, the fluctuation in the temperature was ± 0.01 K, and the fluctuation in the pressure was ± 10 Pa, which proves that the design of the ADS Injector-I 2 K cryogenic system and the research related to the key equipment and technology are reasonable, reliable, and fully meet the requirements.

The ADS Injector-I 2 K cryogenic system has been operated reliably over 15,000 h so far. Nevertheless, a few problems have occurred, including (1) a turbine shutdown due to excessive return gas flow during the rewarming period, (2) a safety valve jump due to high pressure in the helium bath, and (3) the liquid level in the Dewar cannot rise excessively due to an insufficient cooling capacity of the refrigerator during the cool-down period. Hence, further projects with a similar cooling capacity could be enhanced by replacing the electric heater with a cold recovery heat exchanger and automating the cooling and

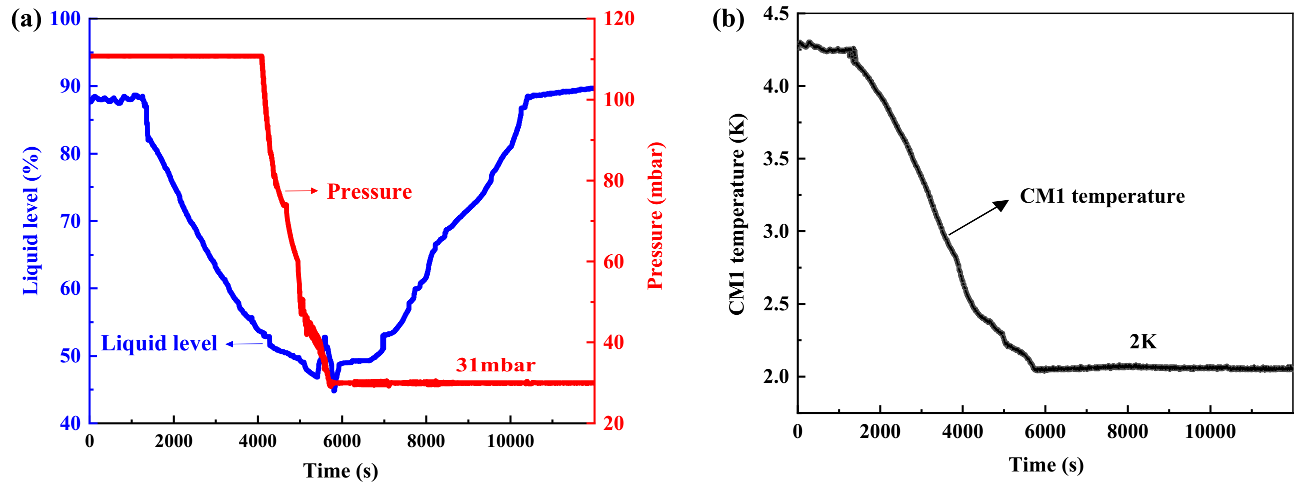


Fig. 21 (Color online) **a** Relationship between the liquid helium level and pressure over time when the CM1 cooled down from 4 to 2 K; **b** CM1 temperature cool-down curve

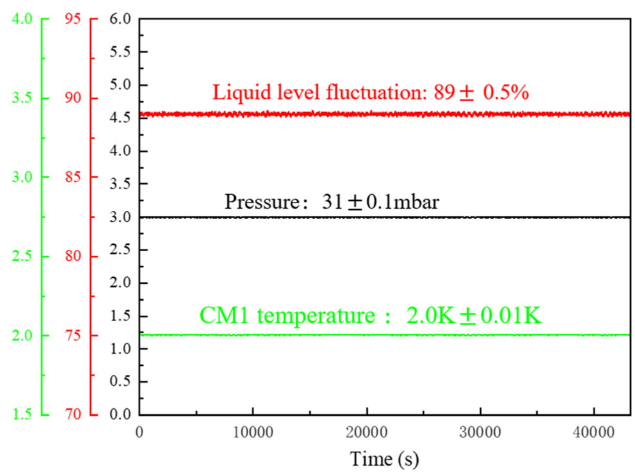


Fig. 22 (Color online) CM1 + CM2 operated stably at 2 K

warming-up procedures, which could improve the efficiency of cold operation as well as the entire system.

4 Conclusion

In this paper, the ADS Injector-I cryogenic system was described with a focus on the 2 K cryogenic system scheme design, key equipment, and technology design. In addition, the commissioning and operation of the cryogenic system was described. The ADS Injector-I 2 K cryogenic system is the first 100 W superfluid helium system designed and built independently in China. The ADS proton beam reached 10 MeV at 10 mA in pulse beam mode in July 2016 and 10 MeV at 2 mA in continuous mode in January 2017, and it has been operated reliably over 15,000 h, which proved that the design of the ADS Injector-I 2 K cryogenic system, key equipment, and technology research are reasonable, reliable, and fully meet the requirements. The resulting selected refrigeration capacity is 1000 W@ 4.5 K or 100 W@ 2 K. Superfluid helium conditions are obtained using the room-temperature pump group. The static heat load of CM1 is less than 32 W. IHEP has also built a 2 K vertical test station for Peking University based on the valuable experiences of the ADS project, and it has also been successfully commissioned. This research provides valuable theoretical and engineering experience that can be used in future projects such as CI-ADS, SHINE, PAPS, CEPC, hence creating new national expertise in the field of superfluid helium cryogenic systems.

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