Development of a Cryogen-Free Dilution Refrigerator for Superconducting Quantum Computing

Yujia Zhai, Shiguang Wu, Dong Ma, Dirui Wu, Jun Tan, Han Tan, Renjun Xue, and Haizheng Dang

***Abstract*—The superconducting quantum computer with strong data storage capability and fast execution speed has attracted a lot of attention in recent years and is finding practical applications in fields such as finance, military, biomedicine, and artificial intelligence. To suppress the thermal noise and to achieve high coherence, the quantum chips require millikelvin temperature, which poses a significant challenge for the suitable cryogenic system. The dilution refrigerator (DR) with ultra-low vibration and electromagnetic interference becomes an appropriate candidate for this purpose. To achieve the aimed millikelvin temperature, a cryogen-free DR composed of a Gifford-McMahon type pulse tube refrigerator (GM-type PTR), Joule-Thompson refrigerator (JTR), and dilution unit is investigated. This article presents the structural design of the DR and the coupling system with superconducting quantum chips. The cooling performance of the designed DR is estimated based on the developed cryogenic system. The minimum deduced temperature of 0.76 K in the still is achieved and the next steps to obtain the final temperature of 5 mK are underway.**

***Index Terms*—Coupling mechanism, dilution refrigerator, millikelvin temperature region, superconducting quantum computing.**

I. Introduction

THE recent decade has witnessed the rapid development of quantum information technology, leading to increasing demands for the millikelvin temperature region. Quantum computing eliminates the limitations of classical computing due to its strong data storage capability and ultra-fast execution speed. Superconducting quantum computing, as one of the most promising candidates to realize scalable quantum computing, aims at simultaneously increasing the number of integrated qubits and improving its performance so that can exponentially accelerate the processing speed. The quantum chip normally operates below 20 mK [1] in order to suppress the thermal noise at the energy level of GHz [2].

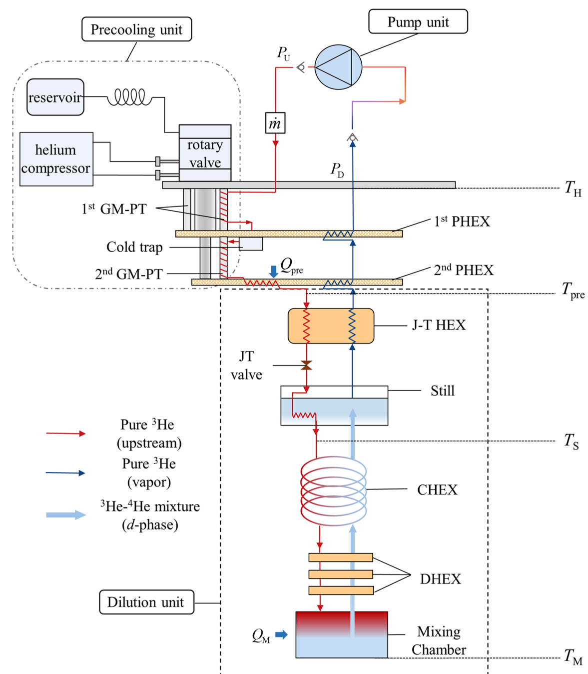

Fig. 1. Simplified schematic diagram of the DR.

Compared with other millikelvin refrigerators such as the adiabatic demagnetization refrigerator (ADR) and the adsorption refrigerator (AR), the dilution refrigerator (DR) can not only operate continuously and stably but also features the merits of low vibration and electromagnetic interference. It provides not only the millikelvin environment for quantum chips but sufficient cooling capacity to accommodate more qubits as well, becoming an irreplaceable key technology in quantum computing.

The DR develops from the "wet" type precooled by liquid helium to the "dry" type by mechanical refrigerators which also known as the cryogen-free DR. The precooling stage of "dry" DR is firstly Gifford-Mcmahon (GM) refrigerator and then is replaced by the GM-type pulse tube refrigerator (GM-PTR) with much lower vibration. So far, there have been some commercial

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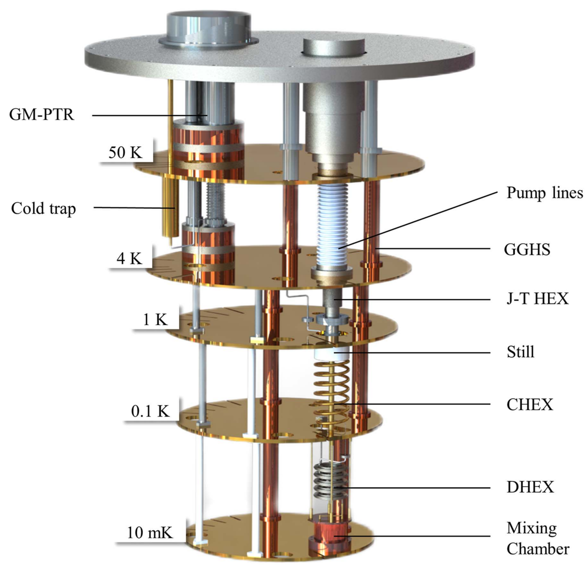

Fig. 2. Designed prototype model of the DR.

products and relative research on the DRs. K. Uhlig et al. [3], [4], [5] designed a DR precooled by GM-PTR and a minimum temperature of 4.3 mK was obtained utilizing the double mixing chambers. R. L. Fagaly et al. [6] optimized the performance of DR to 2.9 mK. T. Prouvé et al. [7] obtained 8.5 mK by optimizing the pump unit and heat exchangers. D. J. Cousins et al. [8] utilized a continuous heat exchanger and fifteen discrete heat exchangers to achieve a minimum temperature of 1.75 mK.

A cryogen-free DR is composed of a GM-PTR, a Joule-Thompson refrigerator (JTR) and a dilution unit. For the past few years, the State Key Laboratory of Infrared Science and Technology, Shanghai Institute of Technical Physics, Chinese Academy of Sciences (SKLIST/SITP/CAS) has developed a JTR reaching the minimum temperature of 1.36 K [9]. To meet the requirements of superconducting quantum computing, a DR that can reach lower millikelvin temperature is under development based on our 1 K cryogenic technology.

In this article, the structural design of the DR and coupling system with superconducting quantum computing are presented. Then the cooling performance of the designed DR is discussed and analyzed based on the developed cryogenic system.

II. System Structure Design

A. Overall Design of the Dilution Refrigerator

Fig. 1 shows a simplified schematic of the dilution refrigerator. The DR is composed of a precooling GM-PTR driven by the helium compressor and a dilution unit driven by the external pumping unit. The precooling unit includes a rotary valve, a helium compressor, a reservoir, two-stage cold fingers, and regenerators. The dilution unit mainly consists of two precooling heat exchangers (PHEXs), a J-T heat exchanger (J-T HEX), a J-T valve, a still, a continuous heat exchanger (CHEX), several discrete heat exchangers (DHEX), and a mixing chamber (MC).

As shown in Fig. 2, except for the above main cooling components, there are five gold-plated cold plates in this system to provide space for the installation of different cables and form the temperature gradient. Besides, the designed gas gap heat switches (GGHSs) are fixed in each stage of the cold plates so that the cooling process can be accelerated. As is shown in Fig. 3, the GGHS consists of a cold block, a hot block, and a supporting shell. The end of the cold block and the hot block are respectively a hollow cylinder and a cylinder which are maintained centered and contactless forming the gas gap. A sorption pump containing activated carbon is connected to the GGHS as the driving source. A cold trap is set under the 50 K cold plate to remove some organic matter from the inlet gas. There is another liquid nitrogen cold trap in the outer system to purify the working fluid after it goes through the pump unit composed of a vacuum pump from Agilent Technology, a rotary pump from Pfeiffer Vacuum, and a diaphragm pump from KNF. In addition, some copper braided tapes that connect each stage of the cold finger of GM-PTR and the corresponding cold plate are used to minimize the vibration of the whole system.

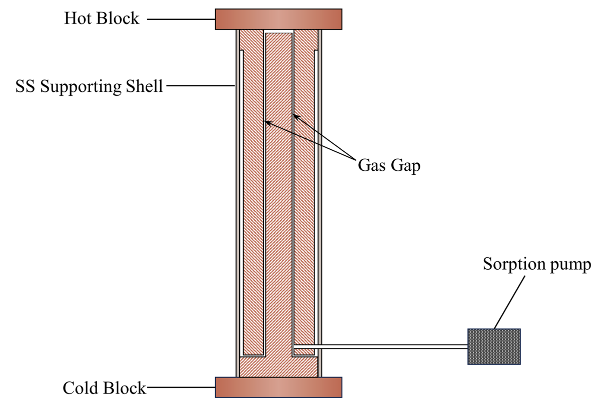

Fig. 3. Section drawing of the GGHS.

In our design, the total amount of ^{3}He and ^{4}He used in the designed dilution refrigerator is 150 liters, in which there are 40 liters of ^{3}He and 90 liters of ^{4}He. The pressure of the ^{3}He working fluid is lifted by the pump unit stage by stage and the fluid enters the system. Then it is precooled by the GM-PTR utilizing both the PHEXs in the cold plates and the tube coiled on the regenerator. After that, the inlet ^{3}He flow exchanges heat with the ^{3}He vapor evaporated from the still in the J-T heat exchanger and passes through the J-T valve. In this process, the temperature together with pressure decreases, which is similar to the cooling process of the JTR and quite crucial to the DR. Then it is further cooled and liquefied in the coil immersed in the ^{3}He-^{4}He liquid mixture in the still. Simultaneously, the liquid mixture is heated by both the inlet flow and the external heater to get ^{3}He vapor. When the liquid working fluid passes through two types of heat exchangers (CHEX and DHEXs), it finally enters the MC where the minimum temperature occurs. In the MC, due to the phase separation characteristic of the ^{3}He-^{4}He mixture at 0.86 K, there exists the ^{3}He concentrated phase (*c*-phase) and dilute phase (*d*-phase) with a phase interface between them. When the ^{3}He in the *d*-phase goes to the still driven by osmotic pressure, the ^{3}He in the *c*-phase passes the interface to offset the loss in the *d*-phase. This produces a corresponding temperature drop

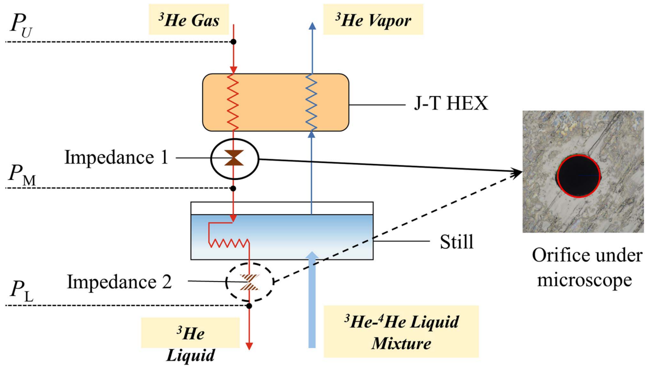

Fig. 4. Flow impedance setting in the system.

due to the increasing entropy, providing cooling temperature and capacity to the quantum chips.

B. Design of Components in the System

After being precooled by the GM-PTR to about 4 K, the working fluid passes through main components including the J-T HEX, J-T valve, still, CHEX, DHEXs, and MC. The design of them is quite crucial to the cooling performance of the DR so it is discussed as follows.

To achieve both the pressure and temperature drop, the J-T HEX is composed of an SS flexible corrugated pipe as the outer tube (25 mm i.d.) and the spiral SS capillary tube (0.8 mm o.d., 0.5 mm i.d.) with a total length of 10 m as the inner tube. The inner spiral tube is supported by adding solder joints to some parts of the outer tube walls. The heat exchanging and part of the throttling occur in this HEX. Actually, the majority of the throttling effect is produced by the J-T valve. As shown in Fig. 4, the valve is set between the J-T HEX and the still and is designed as the format of the orifice. The diameter of the orifice is about 20 μm and the corresponding flow impedance is 1.1×10^{11} cm^{-3}. After passing through the impedance, the working fluid is partially liquefied. Under some practical conditions, another flow impedance is put before the CHEX to avoid the appearance of vapor which seriously deteriorates the heat exchange.

Fig. 5 shows the inner design and outside view of the still. In the still, the inlet gas-liquid mixture is further cooled by the ^{3}He-^{4}He liquid mixture in the Cu-Ni tube (1 mm o.d., 0.6 mm i.d., 1.2 m) immersed in the liquid. Some concentric narrow passages are reserved at the bottom of the still to hold the Mn-Cu heating wire, which aims to maintain the still temperature and control the ^{3}He evaporation. In addition, the purification is also quite significant in that there exists some ^{4}He in the outlet gas. To suppress the superfluid climb of it, a baffle is set in the still chamber and a film heater is installed in the neck of it. In this way, the purity of the evaporated gas can be increased to 97% although the existence of ^{4}He is inevitable.

Then it comes to the heat exchangers at millikelvin temperature. The Kapitza resistance gradually becomes the main factor affecting the heat transfer, especially below 100 mK so there are two types of heat exchangers in the DR. Apart from the traditional continuous heat exchanger as shown in Fig. 6, the discrete heat exchanger shown in Fig. 7 is adopted to increase the heat exchange area by sintered-Ag blocks. In the CHEX, the inner Cu-Ni tube (1 mm o.d. 0.6 mm o.d., 8 m) is firstly bent into a spiral and then inserted into the outer Cu-Ni tube (5 mm o.d., 4 mm i.d., 1 m) which is also set as a helical tube. The c-phase flows in the inner tube while the d-phase is in the annular space between the inner and outer tube. They are separated with a T-joint at the inlet and outlet of CHEX. There are 4–6 stages of DHEXs in the system and each stage is composed of a quite thin Cu-Ni plate, two sinter-Ag blocks, and two SS shields. To reduce the risk of leakage, the flow of both the c-phase and d-phase is achieved by the welding-fixed cubic connections in Fig. 7. The sintered-Ag block is made of Ag powder with a particle of

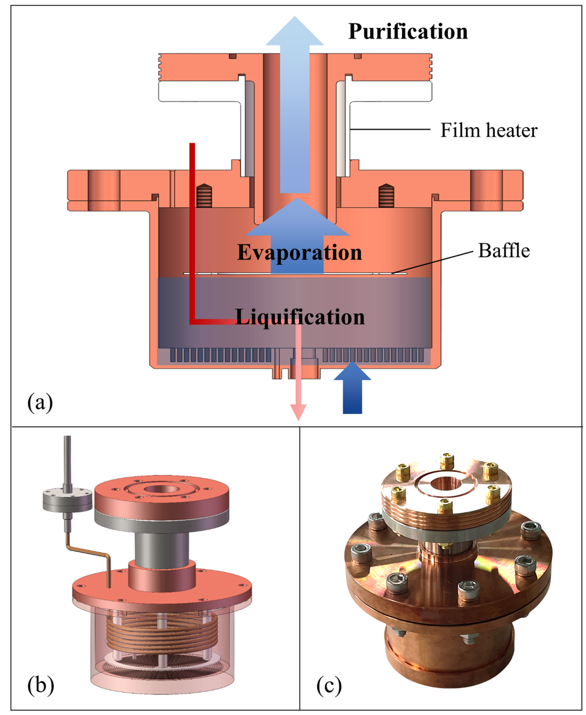

Fig. 5. Inner design and outside view of the still.

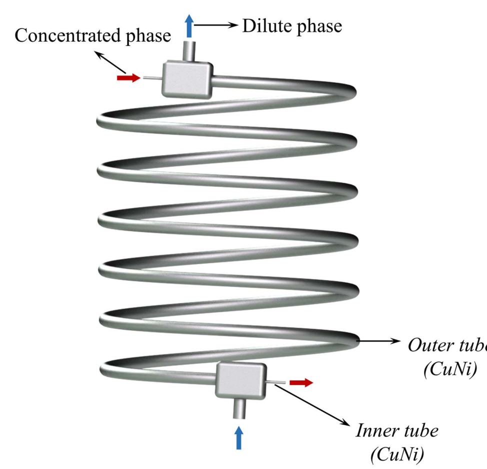

Fig. 6. Depiction of the continuous heat exchanger (tube-in-tube).

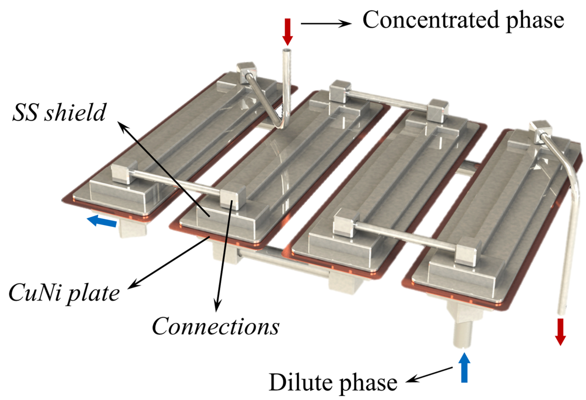

Fig. 7. Depiction of the discrete heat exchangers.

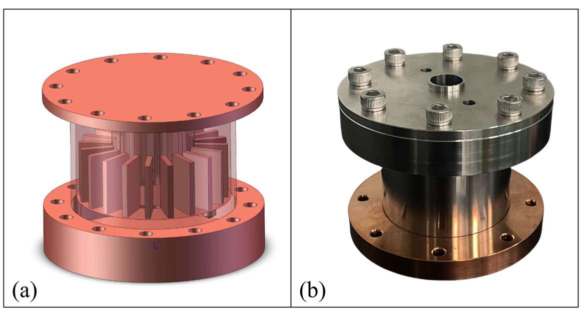

Fig. 8. Inner and outside view of the mixing chamber.

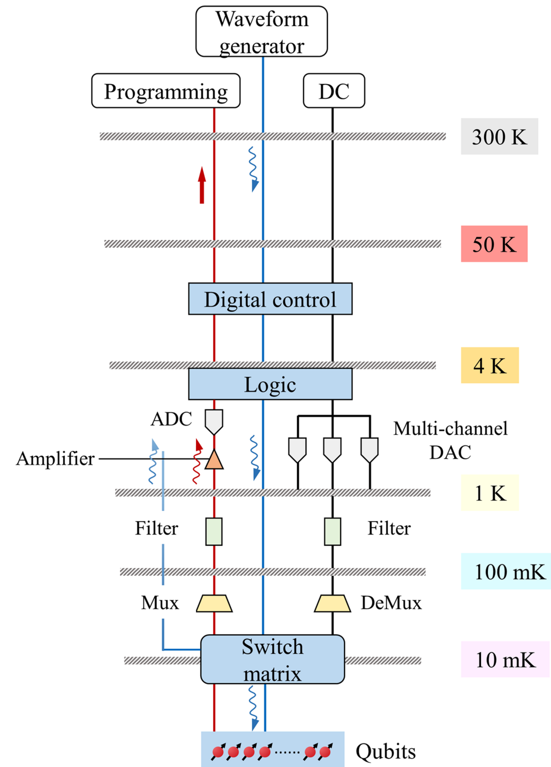

Fig. 9. Coupling structure of the DR with superconducting quantum computing.

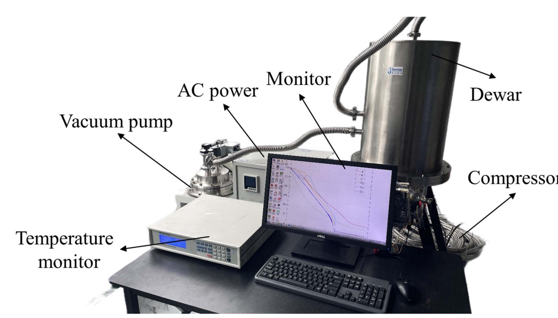

Fig. 10. Experimental setup of the cryogenic system.

50 nm. The Ag powder is first pressed at room temperature with a pressure of about 15 MPa and then heated in an inert atmosphere at 250 °C. There exists an optimal pressure and temperature for the sintered-Ag block to achieve maximum specific surface area and a certain porosity so relevant tests are underway.

The last component is the mixing chamber where the lowest temperature happens and the structure of it is quite clear. As shown in Fig. 8, the main part is a cavity with a volume of about 137 cm^3, and the fins with sintered silver powder attached to them are put in it to enhance the inner heat exchange. The whole MC is made of copper and fixed to the 10 mK cold plate so that the cooling power can be utilized to the maximum extent.

C. Coupling System

The coupling structure of the DR with superconducting quantum computing is shown in Fig. 9. The quantum chip integrated with the switch matrix at the front end is fixed under the 10 mK cold plate in a copper radiation shield and operates at about 20 mK. The logic box is set with the 4 K cold plate and the digital control operates between 4 K and 50 K. There is a large quantity of transmission cables between each stage of cold plates functioning as the carriers of transmitting current signal, microwave signal, and read-out signal, respectively. Thus, some LOS accesses like ISO100 and KF40 are reserved in our system to accommodate as many cables as possible. Besides, it should be noticed that the cables at higher temperatures are SS coaxial lines while that below 4 K should be Ni-Ti superconducting wires.

III. Performance Tests and Simulations

As is displayed in the above section, the construction of DR is quite complicated technically, especially in the discrete heat exchangers. Therefore, the performance of the current cryogenic system is tested without the component below the still. ^{4}He is used as the coolant in the precooling stage while ^{3}He is used as the coolant in the main cycle. The thermometers set in the 4 K and 50 K plates are thin film resistance sensors while that set in the 1 K plate is the ruthenium oxide sensor.

The experimental setup of the cryogenic system is shown in Fig. 10. In view of that the DR is not ready yet, the J-T refrigerator precooled by the GM-PTR is measured first. The driving helium compressor operates at the frequency of 50 Hz and the cold cycle is driven by a multi-stage rotary pump. The inlet and outlet pressures of the GM-PTR precooling stage are 2.3 MPa and 0.5 MPa, respectively. By varying the inflation pressure,

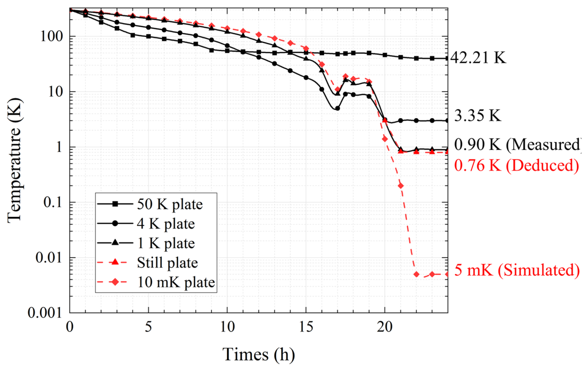

Fig. 11. Cool-down curves of each stage of the DR.

we observe that when the inlet pressure is 0.228 MPa, the cold head of this system can achieve a cooling temperature of 0.9 K (corresponding to a measured still pressure of 0.7 kPa [10]), as shown in Fig. 11. Taking the pressure drop of the downstream pipe into consideration, the cooling temperature of this system can be lower than 0.8 K. It is an excellent performance for a J-T refrigerator and satisfy the still temperature of the DR. Although it is still not low enough to provide the necessary cooling environment for the superconducting quantum chips, a numerical model based on the enthalpy analysis is developed to simulate the flow and heat transfer processes in the designed HEXs at millikelvin temperature and the MC. It is deduced that, if the two types of HEXs are put into practice, the DR would cool to the minimum temperature of 5 mK. Currently, construction of the sintered-Ag HEXs is underway.

IV. Conclusion

A dilution refrigerator precooled by the GM-type PTR has been developed in the authors' laboratory to provide the millikelvin cryogenic environment for superconducting quantum computing. The structural design of the DR and the coupling system with superconducting quantum chips are described in detail. In the preliminary experiments, a cooling temperature of 0.76 K in the still is achieved, which meets the requirement of the DR. The results also indicate that the developed DR is a promising candidate for cooling the quantum chips. The next steps to obtain the aimed temperature of 5 mK are underway.

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