IOP Conf. Series: Materials Science and Engineering **1327** (2025) 012197 doi:10.1088/1757-899X/1327/1/012197

A High-Powered Cryogenic System for Sub Kelvin Electronic Applications

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Abstract. We have developed a powerful table-top cryogenic platform for Quantum computing applications below 1 Kelvin. The system offers a cold plate optimized for the CMOS-spin qubits technology developed by CEA/LETI. The first step is to demonstrate a 100 qubits system. The cryogenic system is designed for 100 mW cooling power at 500 mK, required by this R&D activity. The solution chosen is a high-flow helium-3 Joule-Thomson cycle pre-cooled by a two-stage 4 Kelvin Pulse-Tube (PT420-RM). The table-top architecture is preferred in order to keep an easy access to the quantum processor and the control cryoelectronics components. The pulse-tube and the high flow Joule-Thomson recuperative heat exchangers are mounted into a separate coldbox. The remote cryostat offers three temperature stages: a 50 K stage, coupled to the pulse-tube first stage by a pressurized helium cooling loop; a 5 K stage, coupled to the second pulse-tube stage by a conductive copper link; and a 500 mK stage coupled to the Joule-Thomson cycle evaporator. The pumping speed required (~1000 L/s) is achieved by several dry compact turbopumps in order to reach the required helium-3 flow of 4 mmol/s at 10 Pa. We report the performances achieved with helium-4 and helium-3 on the prototype system.

1. System architecture and design

1.1 Mechanical arrangement

The system is composed of three main parts:

1. The table-top cryostat (a cubic shape with a side length of ~500 mm) (Fig.1);
2. The Gas Handling System (GHS), with the cold box, the pumping components and the control electronics;
3. A short cryogenic line (0.5 m) that couples the cryostat to the coldbox.

The cryostat architecture aims to separate as much as possible the cryogenics and cryolectronics parts, allowing an easy access to the quantum chip. In Fig.1, the inner part (orange in the center) corresponds to the 500 mK stage, i.e. the evaporator. The 'motherboard', containing the quantum processor elements and the control electronics is directly mounted on the 'cold plate', which is the evaporator upper face. Above it, an oval shaped coil creates a magnetic stray field of ~1 T around the quantum-processor volume, required by the CMOS-spin qubits [1].

To minimize the radiative heat load on the cold plate, we have installed a 5 K shield (green) and a 50 K shield (orange). Each stage is supported on the upper stage by 4 struts having a cross section small enough to minimize the conductive heat load. In the cryostat, there is no

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superinsulation mounted on the 50 K shield due to the small space available in-between the screens and to the large footprint of the cryoelectronics wires connectors.

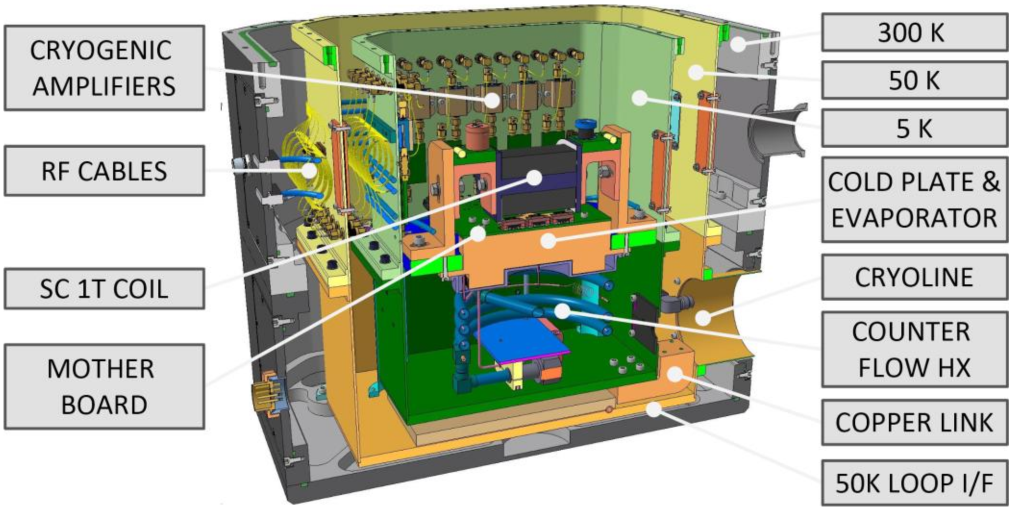

Figure 1. Cryostat 3D view (the external cubic side length is 500 mm).

1.2. Thermal architecture

1.2.1. The CMOS-spin qubits requirements

The motherboard dissipation is ~100 mW for 100 qubits, due to the CMOS control chip integrated within the same holder as the quantum processor unit. The temperature has an impact on the qubit fidelity and should be kept below 0.5 K – 1.0 K [1]. The superconductive coil used to generate a magnetic field of ~1 T needs to install two 15 A current leads. A thermal intercept on the cryostat 50 K stage dissipates the heat load from a resistive part (copper or brass). Below 50 K, we use HTS current leads to keep the heat load below 20 mW on the 5 K stage.

The qubit control and the readout system requires to mount ~10 cryogenic amplifiers on the cryostat 5 K stage (~20 mW/amplifier). Two RF cables are needed per amplifier.

1.2.2. JT cooler and pumping speed

The JT helium flow is pre-cooled on the PT stages with two low pressure recuperative heat exchangers in order to keep the heat load within the PT capabilities (HX1 & HX2 in Fig.2). In order to reach the cooling power of 100 mW, supposing a liquid evaporation of ^{3}He (L_v ~30 J/mol @ 0.5 K), we need a minimal flow of ~3.3 mmol/s (100 mW/ 30 J/mol). To keep a margin, we have considered a flow of 4 mmol/s to design the pumping system. Considering the temperature needed on the cold plate (0.5 K), the pressure on the evaporator has to be lower than 20 Pa (saturation pressure of ^{3}He at 0.5 K). Taking into account a thermal resistance on the evaporatpor and a pressure loss in the low pressure line, we need ~10 Pa at the pump inlet. This is compatible with a pumping speed of ~1000 L/s. We have chosen a compact and dry solution based on 4 turbopumps HiPACE400 (Pfeiffer) with an active water cooling, 4 dry-multiroot ACP40 pumps (Pfeiffer) and a 20 L/MIN membrane compressor to manage the inlet pressure up to 3 bar (0.3 MPa). The JT gas handling system (GHS) is built in order to keep the expensive ^{3}He gas in a low pressure volume (p < 1 bar) to avoid any loss during operation. This principle is similar to any dilution refrigerator system. The developed system could be easily upgraded with a DR system to achieve lower temperatures with a high cooling power (> 2 mW @ 100 mK).

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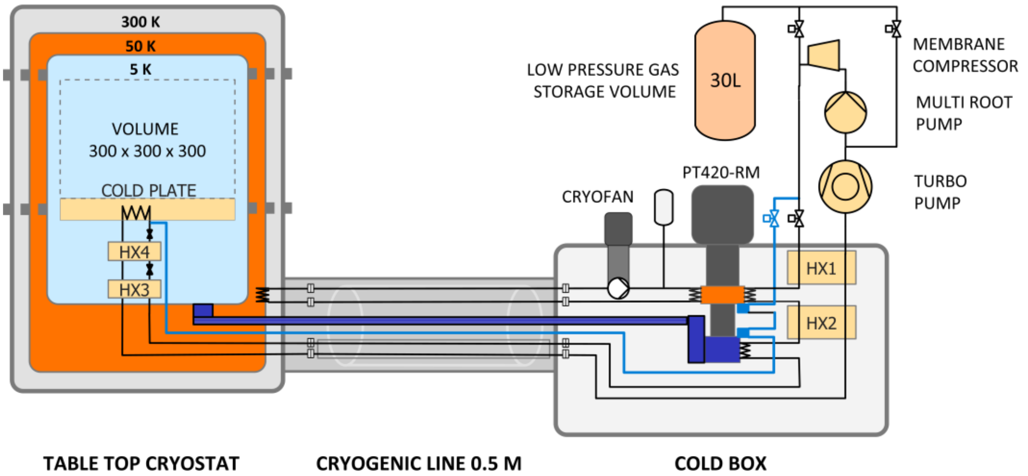


The cryostat is on the left and the cold box with the pulse tube is on the right. Both are connected by the cryogenic line in-between. Inside this short line, we have: the 50 K cooling loop pipes, the 5 K conductive copper link, the JT pre-cooling injection line and the JT 'normal' injection line.

Figure 2. Simplified cryogenic system P&ID.

1.2.3. PT thermal balance

The thermal balance on the PT is summarized in (Table.1). We have separated the contributions of: 1) the cryostat, with the cryogenic system, the CMOS-spin qubits electronics and the SC coil current leads; 2) the cold box with the JT-Cooler heat exchangers loads and the 50 K cooling loop cryofan. The estimated total loads required on the 1st stage drives the choice of a PT420RM (48.3 W @ 40 K) [3]. The load on the PT2nd stage (~1.4 W) is dominated by the JT cooler flow (882 mW), the supporting struts (200 mW) and the cryogenic amplifiers mounted on the cryostat 5 K stage (200 mW).

Table 1: Thermal balance estimation with a JT helium flow of 4 mmol/s.

Element	Heat Source	PT 1st Stage	PT 2nd Stage	Evaporator
Cryostat	Radiation (w/o MLI)	~30 W	4 mW	< 1 μW
	Conduction (struts)	1 W	200 mW	0.2 mW
	Total system	**31 W**	**204 mW**	**0.2 mW**
Cryostat-	SC coil leads (2 x 15 A) (resistive leads + HTC)	1.4 W	< 20 mW	< 0.1 mW
Cryoelectronics	RF Cables (20) + DC lines (200)	2.4 W	75 mW	
	Cryogenic amplifiers (10 x 20 mW)	-	200 mW	-
	SPIN-CMOS control chip (100 qubits)	-	-	100 mW
	Total cryoelectronics	**3.8 W**	**295 mW**	**100 mW**
Cold Box	Radiation (MLI protection)	3 W	~ 1 mW	-
	Cryofan (500 mg/s – 12 kRPM)	~4 W	-	-
	JT cooler flow 4 mmol/s (HX1 & 2, ε = 70 %)	6.5 W	882 mW	-
	Total Coldbox	**13.5 W**	**883 mW**	**-**
Total system		**48.3 W**	**1382 mW**	**100 mW**

2. Experimental results

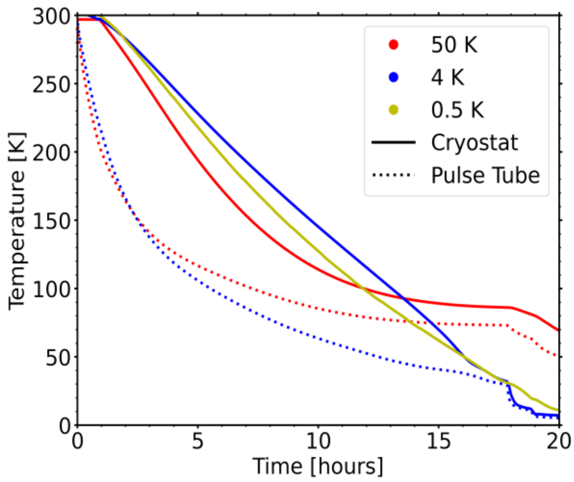
2.1. Test configuration

In a first phase, without the cyroelectronics installed, we have used ^4He in order to validate the system leakage and to measure the JT flow impact on the PT stages (heat exchanger efficiency).

The main differences between the two helium isotopes are [2]: 1) the critical point value for ^4He (T_c = 5.2 K, P_c = 228 kPa) and for ^3He (T_c = 3.3 K, P_c = 116 kPa); 2) the latent heat at the design evaporator pressure (P_{sat} = 20 Pa - L_v ~30 J/mol for ^3He @ 0.5 K and L_v ~80 J/mol for ^4He @ 1.0 K); 3) the molar mass, which has an impact on the turbopumps performances (mean thermal velocity). Because both isotopes obey to the ideal gas law at high temperature ($T >> T_c$, c_p = 21 J/mol-K), the heat loads on the PT stages due to the molar flows are supposed to be identical.

2.2. Cooldown time

The cooldown procedure is similar both with ^4He or ^3He. The pre-cooling flow used to cool the cryostat cold plate can be adjusted to optimize the cooldown time. In Fig.3, we illustrate the main phases (the results have been obtained without any electronics mounted on the cryostat).



The temperatures evolution of the pulse tube stages (dotted lines) and the cryostat (solid lines) are indicated. The cryostat 4 K stage cooling time is limitated by the copper link conductance. The cryostat cold plate is cooled by a 'pre-cooling' flow of ~15 mmol/s. After 18 hours, that flow has been reduced to ~3 mmol/s in order to limit the thermal load on to PT and reach in temperature below 10 K before starting the condensation of the gas within the evaporator. The quantity needed is ~20 LSTP (both ^3He or ^4He) which is stored in a low pressure storage volume (30 L).

Figure 3. Example of cooldown time (^4He test with 15 mmol/s in the precooling line).

2.3. Stationary state

The stationary state reached is exploited to estimate the effective loads applied on the PT stages. The Table.2 indicates the temperatures achieved with and without a JT flow. The thermal loads have been estimated from the manufacture's data [3], adjusted to the performances measured on the model installed. The values obtained are consistent with the expected loads from Table.1.

2.4. Thermal links performances

2.4.1. Cooling loop on the cryostat 50 K stage

To measure the 50 K loop conductance, we have applied an electrical power on the cryostat 50 K stage (0 – 10 W). Supposing a perfect thermal link on the PT 2nd stage, the temperature of the cryostat 50 K should follow a linear response : $P_{HEATER} + P_0 = G.(T_{50K} - T_{2nd})$. The measurements are well fitted with that linear law and the parameters obtained are G ~2.5 W/K and P_0 ~31 W. This is compatible with the estimated heat load on the cryostat and a cooling loop mass flow rate of ~480 mg/s realized with a small cryofan and pressurized helium at ~10 bar [5].

2.4.2. Copper conductive link

A similar method has been applied on the cryostat 5 K stage in order to estimate the copper link conductance. Because of the metal conductivity dependance at low temperature is linear (k = a.T), the fitted law is $P_{HEATER} + P_0 = A_k.(T_{5K}^2 - T_{1st}^2)$. The result is $A_k \sim 13$ mW/K² and $P_0 \sim 200$ mW; this is in accordance with the estimated heat load from the cryostat (Table.1). For an applied power of 300 mW (simulating the cryoelectronics), the cryostat 5 K stage temperature reaches a temperature of ~7.2 K with a PT2nd stage at 3.6 K, which is compatible with the cryogenic amplifiers (T<10 K).

Element	**Stage**	**Temperature**	**Estimated heat Load**
Pulse Tube	1st stage	40 K (39 K)	43 W (42 W)
	2nd stage	3.6 K (2.9 K)	1.15 W (0.5 W)
Cryostat	50 K shield	52 K (51 K)	31 W
	5 K shield	5.2 K (4.8 K)	0.2 W

Table 2: Thermal balance measurement with a JT flow of 3 mmol/s (^{4}He). The values in bracket correspond to measurements with the minimum flow (~0.1 mmol/s), i.e. when no heat is applied on the evaporator)

2.5. Cooling capacity

We have applied an electricial power on the cold stage in order to measure the response of the system. The instrumentation allows to measure the molarflow, the temperature of the stages (PT and cryostat), the injection pressure and the pressure at the inlet of the turbopumps.

The first effect is to increase the molarflow (Fig.4. Left). The maximum flow achieved is limited by the turbopump power limit, respectively 3.7 mmol/s (250 mW) for ^{4}He and 2.9 mmol/s (55 mW) for ^{3}He. That reflects the difference between the helium isotopes: the light ^{3}He isotope is more demanding for the turbopumps due to the higher thermal velocity.

The quantity P_{HEATER} / molarflow (J/mol) is called the specific cooling power and should be comparable to the latent heat in case of a 100% liquid flow. In (Fig.4. Right). We observe a maximum at ~90 mW for ^{4}He and ~47 mW for ^{3}He, where the value approaches the latent heat. The change observed is due to the heat transfer in HX3 and HX4 (i.e. the 'pinch point') and the condensation location which is not discussed here, but quite essential for the system design.

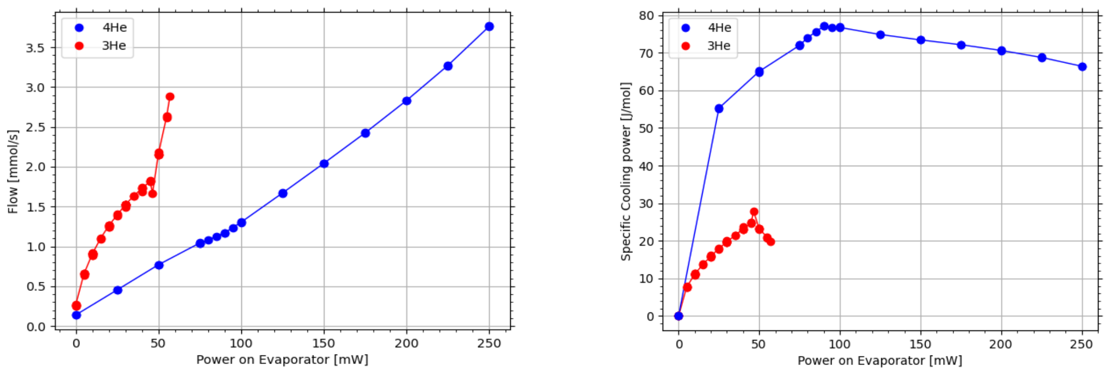


Figure 4. (Right) Molarflow response to an applied power on the cold plate; (Left) Specific cooling power (P_{HEATER} / molarflow).

The temperature response is an indication of the pressure within the evaporator. In Fig.5., we observe an evolution of the temperature, increasing with the power applied. We are clearly well above the expected value of 10 Pa for 4 mmol/s (i.e. T_{sat} = 0.45 K with ^{3}He and T_{sat} = 0.95 K with ^{4}He). The turbopumps inlet pressure was not an issue: P_{inlet} < 10 Pa for both isotopes at the maximum flow reached. The reason identified is an excessive pressure loss in the HX1 & HX2 on the low pressure side (~200 Pa !). In (Fig.5. Left), we have indicated the temperature calculated with the present pumping system (dotted lines), which is consistent with both ^{3}He and ^{4}He measurements, and the expected temperature with a modified design of the recuperative low pressure heat exchangers to be implemented in an improved version of the system in order to reach the temperature requirement (solid lines).

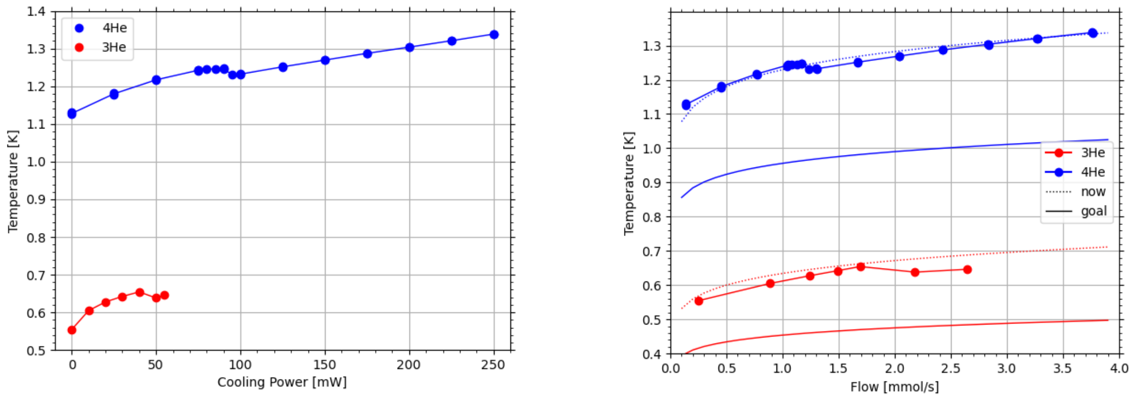


Figure 5. (Left) Temperature response to the applied power; (Right) Pressure loss model of the pumping line with the present situation (now) and the improved version (goal).

3. Conclusions

While the objective performances are not fully achieved, our first measurements using a two-stages PT420RM to precool of high powered ^{3}He JT cycle are very promising. We have a consistent picture of the measurements both using ^{3}He and ^{4}He. With ^{3}He, we have achieved a cooling power of 55 mW at 650 mK with up to 2.9 mmol/s. The reduction of the pressure loss in the pumping line should improve the temperature to below 500 mK. On the prototype, a better adaptation of the JT impedances and an improvement of the pumping speed limit is planned in order to increase the cooling power to ~70 mW. Even in the ^{4}He configuration, we expect to lower the temperature to below 1.0 K with ~ 200 mW cooling power without any modification of the pumping system.

Acknowledgments

This work has been financed by ERC Synergy Grant QuCube (ID#810504) [3].

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