Compact 2.2 K Cooling System for Superconducting Nanowire Single Photon Detectors

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***Abstract*— We are developing a compact, low power, closed cycle cooling system for Superconducting Nanowire Single Photon Detectors. The base temperature of the present prototype, which uses a helium-4 Joule-Thomson stage, is 2.2 K with over 1.2 mW of cooling. This stage is precooled to 10 K using a 3-stage linear compressor pulse tube cooler. A fully optimized system is projected to consume less than 250 W of wall power, and fit within a standard fan-cooled equipment rack enclosure. To-date, the pulse tube coldhead, pulse tube compressor, Joule-Thomson expansion stage, and Joule-Thomson counterflow heat exchangers have been developed, and performance tests show that design goals have been met. Substituting helium-3 for helium-4 should result in temperatures approaching 1 K. Future work includes development of the Joule-Thomson compressor, drive and control electronics, and further optimization of the pulse tube and Joule-Thomson coldheads.**

***Index Terms*— Cryocoolers, Cryogenics, Joule-Thomson, Pulse Tube.**

I. Introduction

Recently, superconducting nanowire single photon detectors have demonstrated performance that enables breakthrough measurement capability in a number of applications[1]. Particularly, WSi detectors have achieved efficiencies, speeds, jitter, and dark count rates that enable detectors for 1550 nm wavelength fiber-optic systems[1].

Widespread acceptance of these detectors will be greatly facilitated by a compact, low power, user-friendly cooling system. Required temperatures are in the 1 – 2 K range, with heat loads as low as a few hundred microwatts, arising primarily from bias/readout lead conduction. These extremely low heat loads enable a compact, low power cooling system.

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Presently, no such system exists. The smallest capacity, commercially available closed cycle cooler is a Gifford-McMahon cycle with 100 mW of cooling at 4 K, and drawing about 1.5 kW wall power. This unit is considerably larger and consumes substantially more power than necessary for this application. Its minimum temperature is about 2.5 K, so that lower temperatures require a second stage of cooling such as helium-4 sorption refrigerator. This lack of an appropriate cooler motivated this development effort.

II. Description of the Cryocooler

A. Architecture

The cryocooler consists of a ^{4}He Joule-Thomson[2] (JT) cooler operating at 2.2 K, precooled to 10 K using a 3-stage linear compressor pulse tube operating at 35 Hz. Although a ^{3}He JT would reach temperatures approaching 1 K, ^{4}He was selected for the initial development because of the relative high cost and rarity of ^{3}He.

Linear compressor pulse tube coolers have demonstrated efficient cooling below 10 K, with high reliability and greater than 10 year lifetimes. These traits have made this type of cooler the choice for satellite applications[3]. However, below 10 K, the helium working fluid approaches criticality, which substantially degrades thermodynamic performance and limits the minimum temperature to about 4 K[4], such that the JT cycle is necessary to reach 2 K.

The hybrid pulse tube/JT cooler is shown schematically in

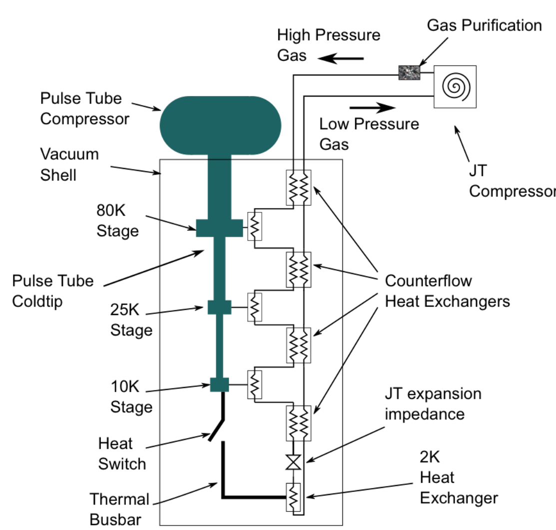

Fig. 1. Schematic of the cryocooler. Radiation shields on the 80 K and 25K stages.

Figure 1. The JT cooler has a room temperature compressor followed by particulate and condensable gas filtration. Within the cryostat, four counterflow heat exchangers precool the incoming high-pressure gas using the outflowing low-pressure gas. The three warmest heat exchangers are successively heat sunk to the three stages of the pulse tube to absorb residual heat from the slight ineffectiveness of the heat exchangers. The pulse tube cold head also absorbs loads from instrumentation leads and radiation loads. The pulse tube stages operate nominally at 80 K, 25 K, and 10K. The entire system- cryocooler, drive and control electronics, and detector instrumentation, will fit in a 7U (0.31 m) tall standard electronics rack mount enclosure approximately 0.61 m long, and will not require water cooling.

B. Estimated Heat Loads and Power Consumption

Prior to designing the cooler, heat loads were estimated for each stage to provide design goals. A four-channel detector system using four 0.86 mm OD, 0.1 m long CuNi coaxial cables was assumed. Table I summarizes these estimates. The largest uncertainty is radiation loads, as they are very sensitive to both radiation shield surface quality and environmental temperature.

The JT stage steady state capacity requirement at 2 K was estimated to be 280 uW. However, because the JT uses a fixed expansion impedance, at high temperatures, low gas densities result in very low mass flow rates, and very little cooling. Therefore, the expansion impedance is sized to allow sufficient mass flow to cool down to the liquid-vapor transition near 5.5 K. Once through the transition, the mass flow rate, and hence cooling, increases dramatically. This results in significant excess cooling capacity at base temperature.

TABLE I
ESTIMATED LOADS FOR EACH STAGE

Stage Temperature (K)	Radiation Load (mW)	JT Heat Exchanger Load (mW)	Conducted Load (mW)	Total Load (mW)
80	1000-2350	400	150	1500-2900
25	5-12	28	7	40-47
10	0.2	2	1	3.2
2	0	N/A	0.28	0.28

Table II summarizes the projected power consumption for the major subsystems. The total is about 250 W, about 6 times lower than the commercial Gifford-McMahon described in the introduction. During cooldown the pulse tube can be driven at significantly higher power to expedite cooldown.

TABLE II
POWER CONSUMPTION BUDGET FOR EACH SUBSYSTEM

Subsystem	Budgeted Power (W)
Pulse Tube Compressor	150
Electronics Power Conversion Loss	35
JT Compressor Including Drive Electronics	35
Cooling Fans	20
Control Logic Circuit	10
Total	250

While the superfluid transition limits the base temperature to just above 2 K, temperatures approaching 1K can be reached using helium-3. The only hardware change required will be resizing of the expansion impedance.

C. Design and Fabrication

The cooler design was a compromise between thermodynamic efficiency, production costs, and risk. We avoided complex, costly components and fabrication processes typically used in spaceflight coolers, resulting in thermodynamic efficiencies lower than those coolers.

The pulse tube coldhead uses the U-tube configuration where regenerators and buffer tubes[5] are arranged side-by-side to simplify integration into the cryostat. All stages use inertance tubes, and the 2nd and 3rd stage inertance tubes are cold[6], thermally anchored to the stage immediately above it. A thermodynamic model was developed using a commercial regenerative engine software package[7], and the design, including impedance matching to the compressor, was finalized using the software's built-in numerical optimizer. Modeling results were checked against a thermoacoustic modeling package[8], and both agreed to within 10%. This process produces a highly optimized and reasonably accurate thermodynamic design.

Regenerators used standard materials. The 1st stage used die-punched stainless steel screens, with #150 mesh, 66 µm wire diameter in the warm side and #400 mesh, 25.4 µm wire diameter in the cold side. The 2nd stage used #400 mesh, 25.4 µm wire diameter stainless steel screens in the warm side and #400 mesh, 25.4 µm wire diameter phosphor bronzes screens, flattened to produce 0.55 porosity, in the cold end. The third stage used the recently developed rare earth Erbium Praesodyminum 50-50 alloy in 100 µm diameter spheres[9]. This alloy has large volumetric heat capacity down to 10 K, plus the spheres are not brittle and will not powderize after extended operation.

We used a commercial flexure-bearing linear piston compressor specifically developed for pulse tubes[10]. This consists of two linear motor driven pistons, mounted head-to-head for vibration cancellation. The pistons and associated moving components are suspended on flexures, which highly constrain their lateral motion such that the pistons have minimal contact to the cylinder walls. This minimizes piston-seal wear without lubrication, resulting in multi-year lifetimes. The piston diameters, moving masses, and compression space volumes were modified to impedance match to the coldhead.

For the JT system, the very low cooling capacity requirement results in a design driven more by fabrication constraints than by thermodynamics. The stage operates between a high pressure of 0.2 MPa and a low pressure of 1.3 kPa, with a flow rate of 0.6 mg/sec. The thermodynamic power required to recompress the gas is only a few watts, which is such a small fraction of the total power budget that a highly thermodynamically efficient design is not required.

All four JT counterflow heat exchangers were simple tube-in-tube designs, with high-pressure gas flowing in the annular space between the two tubes and the low-pressure gas flowing through the inner tube. This configuration simplifies the manifold designs at the ends of the heat exchangers, and has a large internal surface area to allow condensibles to freeze out without plugging the flow passage.

The expansion impedance was a 2 m long, 50 µm ID stainless steel tube, which was the longest, smallest diameter commercially available metallic tube.

At the cold ends of the warmer three heat exchangers, a small heat exchanger consisting of fine mesh copper screens diffusion bonded to a copper body was used to heat sink the incoming gas to the pulse tube. The 2 K coldstage also had a small copper screen mesh heat exchanger.

To mitigate particulate contamination, sintered stainless steel filter discs were inserted in the high pressure line at room temperature prior to entering the cryostat, at the end of the heat exchanger at 80 K and just upstream of the JT expansion impedance. In addition, a small capsule of activated charcoal was placed in the high pressure stream at 80 K to adsorb any condensible contaminants.

The initial cooldown of the 2 K stage from room temperature can be unacceptably slow since the low gas density results in very low mass flows and therefore low cooling. To expedite cooldown, a heat switch, consisting of a small bar that clamps down on a small copper tab attached to the JT coldhead, was used. The clamp was heat sunk to the coldest stage of the pulse tube, and actuated by pulling on a fine stainless steel wire attached to the bar. The far end of the wire was fed through a hermetic seal through the room temperature vacuum flange to allow manual actuation of the wire.

Radiation shields made from rolled and welded Aluminum 1100 electropolished to a mirror finish, were used on the 25 K and 80 K stages. No multi-layer-insulation was used, since an additional goal is to minimize outgassing from polymers in the vacuum space. This design decision was made with the eventual goal of operation without active pumping on the vacuum space.

III. Test Results

A. *Pulse Tube Performance*

The pulse tube stage was first tested separately from the JT stage. The coldhead was installed in a laboratory test dewar, and the warm end was heat sunk to circulating water from a temperature controlled bath. Typically, the water temperature was regulated to maintain the warm end at 310 K to simulate the expected higher temperature environment when the cooler is installed within a fan-cooled equipment rack. The dewar was not temperature controlled and its temperature varied considerably since the laboratory temperature was unregulated. As a result, there was significant run-to-run variability in the radiation load on the 80 K stage. The compressor and 1st stage inertance tube were also not temperature regulated, which also led to some 1st stage performance variability.

TABLE III
Measured Pulse Tube Cooling Capacities

Stage	Temperature (K)	Cooling Capacity (mW)
1	80	2050
2	25	80
3	10	5.0

Simultaneous cooling powers measured with 150 W compressor drive power at 35Hz

Table III summarizes the applied heat loads required to temperature regulate at the design point of 80 K, 25 K, and 10 K at the three stages. The charge pressure was 1.5 MPa and the operating frequency was 35 Hz. Total compressor power was 150 W. The coldhead was in the convectively stable orientation with the coldtip down. Since these are loads in addition to radiative loads, the first stage has considerable excess capacity in comparison to the estimated requirement in Table I. This excess capacity is likely due to a combination radiation shield emissivities and dewar temperatures lower than assumed in the initial requirement estimates.

Figure 2 is the load curve for the 3rd stage, also with 1.5 MPa charge pressure and 35 Hz operating frequency. No loads

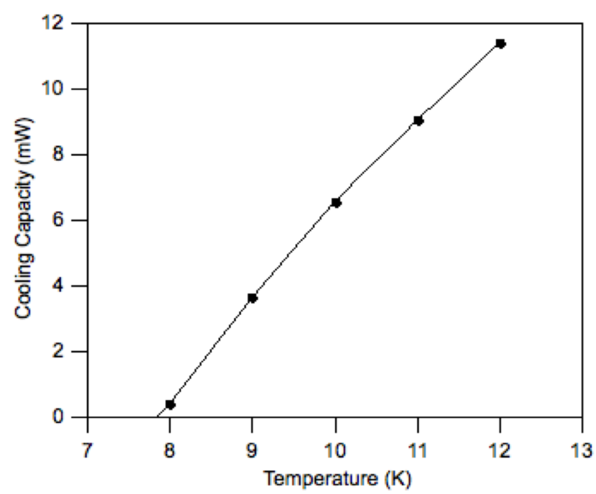

Fig. 2. Load Curve for the 3rd Stage with 150 W compressor power 35Hz, no loads applied to upper stages.

were applied to the upper two stages, so the 1st stage ran at 68 K and the 2nd stage ran at 22 K. The cooler reached a no-load temperature just below 8 K, and at 10 K had a capacity of about 6.5 mW.

Pulse tubes are susceptible to significant losses if not oriented with the cold end down because of gravitationally induced convection in the buffer tube. However, sufficiently high oscillation amplitudes in the buffer tube can suppress convection, and Los Alamos National Laboratory has previously developed a stability criteria[11] for convection suppression. This pulse tube was designed to operate horizontally in the stable regime based on this criteria. To test this, the coldhead was operated at various tilt angles with respect to horizontal. The measured cooling capacities at the 80 K stage and 25 K stage are plotted in Figure 3. These results show that convective losses were not suppressed, and

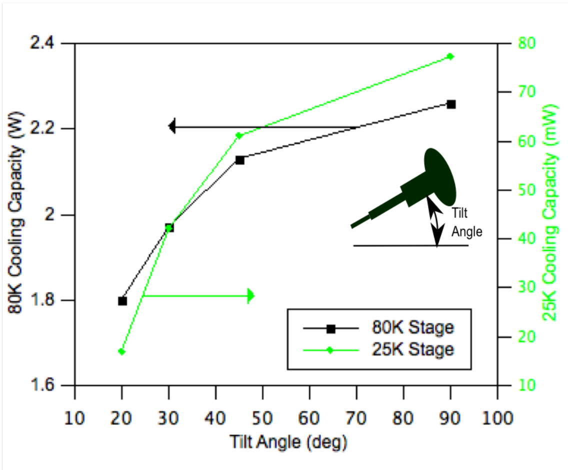

Fig. 3. Cooling capacities of the 80K and 25K stages as a function of tilt angle from horizontal.

tip angles less than about 30 or 40 degrees from horizontal result in significant degradation of 2nd stage cooling capacity. The first stage show a larger absolute loss in cooling capacity, but the effect in the 2nd stage is more significant because of the lower cooling capacity of that stage. The third stage showed no loss in cooling in these tests. It is possible that the 3rd stage may lose some capacity at lower tilt angles, but this could not be verified since the 2nd stage lost cooling capacity and rose in temperature at low tip angles before any 3rd stage loss was observed. Other researchers have also observed discrepancies with the Los Alamos stability criteria[12], indicating that this is an open area of research.

B. JT Test Results

Final tests were performed on the integrated JT-pulse tube coldhead. Because a suitable JT compressor was not available, the JT cooler was tested open loop using a compressed gas storage bottle as a supply and a vacuum pump on the exit side. The high side pressure was controlled with a gas regulator, and the low side pressure controlled by adjusting a valve in front of the vacuum pump. Tests were run with high side pressures of 0.1 MPa, 0.125 MPa, 0.15 MPa, and 0.175 MPa, and low side pressures from 1.3 kPa and higher. A minimum temperature of about 2.2 K was reached. Close to the minimum temperature, a hydrodynamic instability occurred which produced significant flow fluctuations along with temperature fluctuations on the order of 50 mK. The instability was greatly reduced if the return side pressure was below 1.3 kPa.

Figure 4 shows load curves for the four high side pressures with a low side pressure of 1.3 kPa. At temperatures greater that about 5.5 K, helium is in the gaseous phase so there is very little mass flow through the expansion impedance, resulting in very little cooling. However, once the helium liquefied, the mass flow, and hence cooling capacity, increased. These tests suggest that a high side pressure greater than 0.175 MPa is desirable to be able to cool the stage down when additional loads from detector wiring are added.

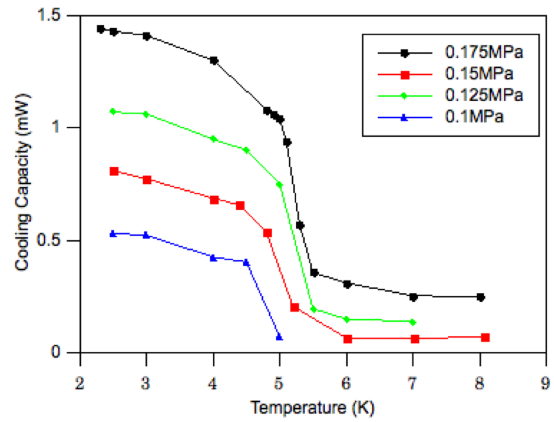

Fig. 4. JT stage load curves for different high side pressures.

Total cooldown time from room temperature was roughly 21 hours, with 2nd and 3rd stages of the pulse tube taking the longest times.

C. JT Compressor Feasibility Demonstration

Although the appropriate compressor for the JT cycle has yet to be developed, we tested an existing off-the-shelf scroll compressor[13] for thermodynamic performance and contaminant generation. This compressor demonstrated the ability to deliver the required flow rate and suction pressures with about 35 W of power including the drive electronics. Unfortunately, since this compressor is a vacuum pump meant to exhaust to atmospheric pressures, it could not reliably generate the required high pressure. We ran this compressor continuously for 42 days and measured condensable gas contamination generation and particulate gas contamination, and both were measured to be at levels that we believe can be mitigated by proper filtration. We tested a second larger compressor, originally designed for CO_2 compression[14] and this compressor achieved the 1.3 kPa inlet pressure, 0.2 MPa, but with 4 times the required mass flow rate and 120W of power. A version of the second compressor, scaled down by a factor of 4, should meet the mass flow requirement with power consumption in the 30-40 W range.

IV. Conclusion

We have demonstrated most of the major subsystems of a compact 2 K closed cycle cryocooler appropriate for superconducting nanowire single photon detectors. Specifically, we have demonstrated the pulse tube precooling stages, the JT coldhead, and radiation shielding. We demonstrated feasibility JT compressor by testing units that approach, but do not meet, all of the requirements. Test results indicate that the system will be able to provide more than 1.2 mW of cooling at 2.2 K with less than 250W total wall power draw.

We are presently refining the JT coldstage to achieve temperatures below 1.9 K with helium-4. We are also refining the 3rd stage of the pulse tube to produce lower 3rd stage temperatures, which will allow the use of NbTi leads for the detectors.

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