A compact 4 K cooling system for superconducting nanowire single photon detectors

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Abstract. Compact, low power, robust closed-cycle cooling platforms are a key requirement for emerging low temperature quantum technologies. We have repurposed a 4 K Stirling/Joule-Thomson cooler built for the Planck space mission into a flexible demonstration system. We have verified a cooling power of 4mW at 4.7K. We have installed a fibre-coupled superconducting nanowire single-photon detector in this platform and deployed it for two key advanced infrared photon counting applications: single-photon LIDAR and dosimetry for laser cancer treatment. We discuss proposed improvements to the Stirling cooler design for increased cooling power, manufacturability and turn-key operation.

1. Introduction
Superconducting Nanowire Single Photon Detectors (SNSPDs) can be used for advanced single photon counting systems in the infrared, outperforming alternatives such as semiconductor single photon avalanche diodes and photomultipliers [1]. Fibre optic coupled single pixel SNSPD devices offer near unity single photon detection efficiency [2], low timing jitter [3], and low dark count rate [4]; this makes them the ideal detectors for a wide range of emerging applications, including long range 3D infrared depth imaging [5] and quantum key distribution [6]. However, widespread use is hampered by their requirement to be cooled to around 4 K, or below. Although the need for liquid cryogens has been eliminated by the use of closed cycle cryocoolers, such systems are bulky, power hungry and not truly capable of mobile operation.

Consequently, interest in compact, closed-cycle cooling systems for SNSPDs – and other low temperature detector technologies – is continuing to grow. To achieve the temperature requirements of SNSPDs in a compact system suggests the use of hybrid coolers, such as Joule-Thomson (JT) and pulse tube, or JT and Stirling. Systems of the former type are under development by the National Institute of Standards and Technology (NIST) [7] and by the Chinese Academy of Sciences (CAS) [8]. Both systems employ a pulse-tube–JT architecture, with the NIST pulse tube having three stages compared to the two stage version on the CAS system. The NIST system uses a commercial flexure-bearing linear compressor to provide the pressure wave to drive the pulse tube; the compressor to drive
the JT cooling loop in a closed cycle is currently under development and test [9]. The complete system is projected to consume less than 300 W of input power and, during open-cycle testing of the JT circuit, provided a maximum heat lift of approximately 1.2 mW at ~2.2 K. In contrast, the CAS system drives both the pulse tube and the JT coolers with flexure bearing compressors suitable for space use – offering the potential for deployment in mobile applications. The power consumption of the cooler (excluding ancillary equipment) is reported as 319.8 W to cool the SNSPD to 2.8 K (available cooling power not reported). The cooler has a total mass of 55 kg.

This paper describes an SNSPD cooling system developed by Rutherford Appleton Laboratory (RAL) and the University of Glasgow. It utilises a Stirling–JT architecture, based on compressor technology developed for space applications, into which a fibre coupled SNSPD has been integrated and tested. The Stirling cooler offers the benefits of an inherently more efficient thermodynamic cycle. This results in a compact, long life, maintenance free system that can be used for a variety of applications.

2. Experimental Configuration

2.1. Cooler design

The cryogenic system is based on a 4K cooler developed for the Planck [10] space mission. This comprises a miniature two-stage Stirling cycle cooler that reaches a base temperature of around 18K. This pre-cools a separate Joule-Thomson (JT) cooler that takes the temperature down to 4K. This cooler combination was developed at RAL and further advanced as a demonstrator for the Planck spacecraft. The tests on the demonstrator involved integrating a large dilution refrigerator with the 4K system and vibration testing it. As a result the cooler is mounted in a rather robust 34kg frame.

The two stage pre-cooler has twin opposed linear compressors feeding a small two stage displacer unit. All the cooler compressor mechanisms are based on flexure bearings and have an extremely long life – a unit at RAL was run for ~19 years with no failure. The two stage cooler has a base temperature of below 18K but with loading from the JT system this can vary.

Figure 1. Left: illustration of the cold stages of the cooler and their configuration inside the cryostat, right: photograph of the 20 K and 4 K stages separated by the 3D printed thermal isolator.

The 4K JT system consists of two stages of compression that takes the helium pressure from just above 1 bar to around 10 bar depending on the operating conditions. The gas passes through a getter which removes water and other condensibles. Counter-flow heat exchangers between the pre-cooler stages limit the heat load. A third JT counter-flow heat exchanger then leads to a fixed orifice
which is where the cooling occurs. Liquid is then trapped in a sinter pot. To improve the cool-down time we use two high pressure lines in the heat exchangers between the stages on the pre-cooler. One of these lines then enters the JT heat exchanger. The other line by-passes the heat exchanger and the orifice completely and enters the liquid pot. The flow through this second line is controlled with a room temperature valve. With the valve open, the 4K stage is brought rapidly to the pre-cooler temperature. When the 4 K stage temperature is close to that of the pre-cooler, the valve is closed and the JT effect takes over the cool-down phase. The 4K stage is mounted on a conical low thermal conductance support which is additively manufactured (shown in figure 1).

The reciprocating compressor mechanisms are all computer controlled. The signals from the computer are fed into the compressor drive coils through power amplifiers. The computer also monitors the various transducers on the system; these include temperature, pressure and flow. The total input power to the cooler mechanisms is around 130 W.

2.2. SNSPD
A NbTiN single meander SNSPD in an optical cavity (optimized for 1310 nm wavelength) supplied by Single Quantum, BV, The Netherlands, was housed in the cryostat and attached via self-alignment to 9 µm core single mode optical fibre (entering the cooler through an epoxied feedthrough). The critical current of the device was measured to be 8.5 µA at 3 K, and 6 µA at 4.2 K. Further details of the detector biasing and read-out can be found in [11].

3. Results

3.1. System testing
The cooler temperatures during a typical cool-down are plotted in figure 2, showing the total time from room to base temperature is <30 hrs. Temperature fluctuations of the order 10 mK are observed over a time frame of several hours, and are linked to temperature variations within the laboratory space. With the cryostat configured to accept an SNSPD and with a detector coax cable running to the 4 K stage – but without a detector fitted – a cooling power of 4 mW at approximately 4.7 K was achieved. Further stroke margin on the JT compressors was still available, so it is anticipated that higher cooling powers are possible, offering the possibility to run the system with multiple SNSPDs.

Figure 2: Temperatures of the 3 stages of the cooler during a typical cool down.

Single photon efficiency tests performed at 1310 nm (the peak design wavelength of the SNSPD optical cavity), with the cooler operating at 4.3 K, demonstrate an efficiency of > 20 % at kHz dark
count rate (see figure 3). This corresponds with initial tests performed using conventional cooling methods, which gave detection efficiencies of 21% at 4.2K (liquid $^4$He) and 30% at 3K (commercial closed cycle cooler).

![Figure 3](image)

**Figure 3:** Left: single photon detection efficiency measured from the fibre optic input of our system, as a function of dark count rate, showing a peak efficiency of >20% at 1310 nm wavelength. Right: photograph of fibre-coupled SNSPD device mounted at the 4 K stage in the miniature cooler.

3.2. **LIDAR demonstration**
Infrared single photon measurements allow long range eye safe range-finding and imaging, and therefore have potential applications in driverless cars and high speed terrain mapping from ground or air. These would require a portable cooling technology of the type described in this paper.

A simple Light Detection and Ranging (LIDAR) experiment using a coaxial transmit and return beam path split by a mirror with a hole has been performed using the system described here. A 1.5 mW average power, 50 MHz repetition rate, 1560 nm wavelength fibre laser was used as the illumination source. Laser sync and SNSPD outputs were sent to a time correlated single-photon counting module to time-stamp photon arrival times, relative to the laser rep rate. The results were used to discriminate between two targets, separated by approximately 15 cm at a distance of 1.7 m. Further details are available in [11].

3.3. **Singlet oxygen luminescence demonstration**
A further demonstration of the system has been made with the detection of 1270 nm infrared photons that are the signature of singlet oxygen. This is crucial in direct dose monitoring for photodynamic therapy (PDT) in the treatment of cancer, where the photosensitiser treatment drug (typically a dye molecule) exchanges energy with surrounding oxygen molecules on optical excitation, creating singlet oxygen radicals which kill tumour cells. Further details of the test performed are given in [11].

4. **Engineering future system improvements**
The system described in this paper is inherently compact, efficient and reliable, due to the design heritage it takes from spaceflight coolers. Further reducing the system footprint, power consumption and weight is highly desirable. A key part of this is the pre-cooler, which should provide both a low temperature stage with a heat lift/temperature appropriate for optimum performance of the JT cooler and a higher temperature stage with appropriate heat lift/temperature performance for shielding and heat sinking requirements of the cryostat. Work is currently underway at RAL in the performance modelling and design of such a cooler; assembly of a prototype version will commence shortly. This improved Stirling pre-cooler should also be suitable for mass-manufacture in future commercial products. Additionally, a JT cooler with the potential to operate at 2 K and below is also under construction [12]. This will use helium-3 and achieve a lower pressure on the inlet to the compressors.
such that temperatures below 2 K can be reached. Test results of both coolers will be the subject of future publications.

Other areas that are important in the construction of a next generation system are design of compact drive and control electronics for the cooler, small scale – or passive – pumping of the cryostat vacuum and effective air cooling of the compressors. These will be addressed in future developments of the system described here.

5. Conclusions

A Stirling–Joule-Thomson cooling system has been constructed, based on proven space cooler technology, to provide > 4 mW of cooling at 4.7 K. An SPSPD has been successfully integrated into the system and demonstrations of both LIDAR and singlet oxygen luminescence applications have been performed. The system has the potential to cool multiple detectors. Improvements to achieve lower base temperatures and to reduce the size in power consumption of the system have been outlined. Work to optimize the performance of the Stirling pre-cooler is ongoing.

6. References

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