

## Pulse Tube Cryocooler at 4 K: Customization for Sensitive Cryoelectronic Applications in “Dry” Low Noise Cryostats

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**Abstract** – Pulse Tube Cryocooler (PTC) providing temperatures of 4 K by “dry” cooling represents a reliable alternative to conventional bath cryostats with liquid helium. Wherever liquid helium is not available or the increasingly long measurement times of state-of-the-art experiments exceeds the refill interval of liquid helium cryostats, “dry” cryocoolers are utilized. Within the family of regenerative cooling systems, PTCs distinguish themselves by the absence of moving parts inside the cold head. This makes them the preferred choice for sensitive and low noise applications. Unfortunately, PTCs and conventional Gifford-McMahon coolers, exhibit periodic variations in displacement by some microns and in temperature by some hundreds of mK due to the compression/decompression of the working fluid (helium) inside the cold head. This intrinsic effect has to be accounted for in the adaptation of the pulse tube cooler to the individual application. Here, we present successful solutions for dry cooling of sensitive experiments with pulse tube coolers. Since the intrinsic disturbance effects scale with the size of the cold head, the pulse tubes have been minimized to run with low input powers but still providing sufficient cooling power for cooling cryoelectronic devices such as JJ-voltage standards. Customized stages can additionally reduce the residual mechanical vibration amplitude to below 1 nm [4] and dampen the temperature oscillation by more than an order of magnitude [5, 6]. The advanced combination of these adaptations meets the highest requirements the dry cooling of the airborne THz bolometer-telescope of the SOFIA observatory airplane.

**Keywords (Index Terms)** – Cryocooler, pulse tube, cold head, regenerative cooling, cryocooler vibration, cryocooler temperature stability, THz bolometer telescope, SOFIA stratospheric observatory.

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), April 2017.

Received March 6, 2017; Selected March 25, 2017. Reference No. STP570; Category 11.

Pulse Tube Cryocoolers (PTC) providing temperatures of 4 K by “dry” cooling [1, 2] represent a reliable alternative to conventional bath cryostats with liquid helium. Wherever liquid helium is not readily available or the increasingly long measurement times of state-of-the-art experiments exceed the refill interval of liquid helium cryostats, “dry” cryocoolers offer a preferred alternative and are ever more in use.

The main component of a PTC 4 K cryocooler system is the two-stage cold head. In the case of the TransMIT PTD 406C (see the poster, upper panel left side) it provides simultaneously cooling powers of 20 W @ 55 K at the first stage cold flange and 0.75 W @ 4.2 K at the second. In the remote configuration, where the rotary valve is not integrated in the cold head, the cold head itself contains no moving parts thus reducing vibrations to very low levels. The cooling is achieved by the cyclic expansion and compression of helium gas as the working fluid inside the cold head’s pulse tubes. Via a main inlet flexible line, the rotary valve switches into the cold head the high and low gas pressure levels generated by a helium compressor. Since the compressor and the rotary valve are the only moving parts driven by electric motors, the electromagnetic interference (EMI) can be reduced by integrating a galvanic insulation into the main inlet line and thus interrupting the electric conductance

between the cold head and the periphery devices. These two advantages, low mechanical vibrations and low EMI make PTCs the preferable choice for sensitive and low noise applications.

However, PTCs as well as conventional Gifford-McMahon coolers, exhibit a small periodic variation in displacement [3] and in temperature as consequence of the periodic compression/ decompression of the working fluid (helium) inside the cold head (poster, 2<sup>nd</sup> panel down, left side). The cold stages of cryocoolers are built from thin-walled metal tubes to prevent a high parasitic heat conductance from the warm end toward the cold stages at cryogenic temperatures. Thereby, these tubes “breathe” with the amplitude of the two pressure levels of compression and expansion. Likewise, the temperature of the helium gas is direct proportional to the current pressure inside the tubes. This causes a variation of temperature with the pressure at the frequency of the rotary valve.

These two effects, mechanical “breathing” and temperature variation, are of intrinsic nature and cannot, therefore, be eliminated. However, by scaling the cryogenic system to the minimum required pressure supply, they can be minimized to the lowest level. This can be achieved by adaptation of the pulse tube cooler to the individual application.

The cold part of the cold head is built from regenerator- and pulse tubes fabricated from stainless steel. The first stage consists of relatively large tube diameter for pulse tube and regenerator. The second stage regenerator is the extension of the 1<sup>st</sup> stage regenerator where the second stage pulse tube has a small diameter. Due to this arrangement, the deformation of the cold part has a vertical as well as a horizontal component. The direction of lowest and highest displacements can be analyzed by a finite element computational study (poster, 3<sup>rd</sup> panel down, left). The amplitude of the displacements also decreases with smaller operation pressures, which can be used to limit the vibrations to the attainable minimum.

The measurement of the cold flange movement with a sensitive vibration sensor attached shows the dynamic displacement in vertical and horizontal direction. The vibration spectra show the amplitude of the vibration in good agreement with the simulation and also reveal the higher harmonics of the operation frequency.

Small-sized pulse tube cold heads (e.g., TransMIT PTD 4200), which run on input powers as low as 2 kW, already provide a stable platform with cooling powers of 0.25 W @ 4.2 K, adequate for the operation of voltage standards based on Josephson junction (JJ) chips. The variation in temperature can be dampened by an order of magnitude using of a simple steel plate of sufficient thickness. While this method results in an additional temperature gradient, it is suitable for applications with low requirements in cooling power. Separating the cooler from the experiment by placing these inside two different chambers [4] or integration of the cooler into a tailor-made cryostat [5] can reduce the mechanical vibration down to a 1 nm level (poster, lowest panel, left). In most applications, a decent compromise can be found between loss in cooling power and increase in performance stability.

An airplane, such as the stratospheric observatory for infrared radio astronomy (SOFIA), is a unique environment with very demanding requirements for a pulse tube cooler (poster, upper panel, right). The new detector “upGREAT” [6] for the telescope has a high consumption in cooling power, where cooling with liquid helium for the duration of full flight without refilling is not feasible. Therefore, there is no alternative to a cryocooler, which provides temperatures of 4 Kelvin with sufficient cooling power of up to 0.5 W @ 4.2 K. While most high-power helium compressors are water cooled, the compressor onboard the SOFIA should be air-cooled but still provide the necessary 7 kW of input power. The telescope itself also demands a tilting angle of 90 degrees which requires the pulse tube to work under +/- 45 deg tilting angles, while pulse tubes are commonly restricted to vertical

operation. Nevertheless, the “upGREAT” detector also requires very stable temperature levels for the precise measurements of the infrared radiation of less than 20 mK.

To provide low and stable temperatures for the “upGREAT” detector with at the same time high cooling power, a special temperature stabilization unit must be integrated into the cold flange of a cold head (poster, 2<sup>nd</sup> panel down, right). This unit consists of a reservoir with a certain amount of liquid helium. Liquid helium has a high heat capacity at low temperatures (up to 2 orders of magnitude higher as copper at 4 K). This can be used to dampen the intrinsic temperature variations originating from the pulse tube cooler. At the same time, the two-phase mixture of helium (liquid and gaseous) around the boiling temperature of 4.2 K can be used to transfer a large heat flow through the unit working as a so called “thermosyphon”. Depending on the anticipated heat load, this dampening effect sets in at different helium filling levels of the unit, but then provides temperatures of 4.2 K with less than 15 mK amplitude of temperature variation. This performance is stable, even when up to 0.5 W of cooling power is transduced through the unit. In addition, the helium reservoir is automatically filled by an external gas buffer during cool down of the cryostat and after the initial filling does not need any further maintenance.

Pulse tube cold heads are in general restricted to vertical operation. While in Gifford McMahon or Stirling cryocooler a displacer governs the movement of the gas flow inside the cold head, in a pulse tube the gas is prone to normal convection. When a pulse tube is tilted, this convection can be started when the cold gas from the bottom get mixed with warmer gas from the top. However, telescopes usually need a tilting angle of up to 90 degree to be pointed to the object of interest. Consequently, one must be able to tilt the cooler in the “upGREAT” cryostat by  $\pm 45^\circ$  to cover the 90-degree angle (poster, 3<sup>rd</sup> panel down, right). Since both stages of the cooler react differently to tilting, an optimum tilting axis can be found for the telescope. The loss in cooling power due to the tilting can be evaluated by recording a load map. The comparison of the tilted curve with the points of the load map reveals that losses in the first stage are about 5 W @ 45 K and about 50 mW @ 2.4 K at the second stage and thus are acceptable for successful use on board of the SOFIA airplane [6]. Commissioning flights of the new “upGREAT” detector were successfully performed in May 2015 and it is now in regular use.

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