JDry-100-ASTRA, a cryogen-free 3He- 4He dilution refrigerator for ground-based Cosmic Microwave Background astronomy

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Abstract. A new custom cryogen-free dilution refrigerator with base temperature of 17 mK and cooling power of 120 μW@100mK was developed in collaboration with the University of Roma (Italy) and Janis Research Company, Inc. (USA). The design is specifically geared for integrating with an existing telescope on alt-azimuth mount. The first lab-based test results show that the system is maintaining its design specifications in its tilted position up to as much as -20 degree and +50 degree from the cryostat vertical axis.

1. Introduction

Cryogenic detectors have been a subject of intense interest to the scientific community for many years. In cosmology, ultra-sensitive cryogenic detectors such as bolometers have been used to study the Cosmic Microwave Background (CMB), allowing a deeper exploration and understanding of the cosmos. However, a further gain in sensitivity is needed to probe the very early Universe, as when studying the polarization signal of the CMB. Such a gain has to arise from the use of larger focal planes, with arrays of thousands of independent detectors providing unprecedented mapping speed. Microwave Kinetic Inductance Detectors (MKIDs) are superconducting detectors whose concept was proposed by Caltech and JPL in 2002 [1]. Radiation detection is achieved by measuring small changes caused by photon absorption in the surface impedance of a superconducting strip metal incorporated in a high Q resonant circuit. Electromagnetic radiation of energy great enough to break Cooper Pairs induces an excess in quasi-particle density which results in a change of the kinetic inductance and, in turn, of the surface impedance.

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The extremely low loss characteristic of superconductors makes these detectors extremely sensitive and, as a consequence of the high Q value, intrinsically “multiplexable” in the frequency domain, so they can be easily implemented into large format arrays. Bruno Kessler Foundation (FBK) in collaboration with University of Rome Sapienza is currently working on the development of MKIDs detectors for CMB applications. These devices will be first designed and optimized with the help of analytical models and software simulations, then fabricated in FBK facilities and finally fully electrically and optically characterized in a cryogenic experimental setup based on a new custom cryogen-free dilution refrigerator JDry-100-ASTRA developed by Janis Research Company.

The final goal is the fabrication of a large format ultra-low temperature camera to be mounted at MITO telescope on Mount Cervino [2], which is optimized for ground observations at millimeter and sub-millimeter wavelengths. The telescope operation will be also an ideal test to check the camera performance and the optical coupling to radiation, before a possible implementation on balloon-borne or satellite missions.

2. System description
The refrigerator includes three main components: a cryostat with a dilution stage, a manually operated gas handling system (GHS1) and a pulse-tube refrigerator (PT) with a dedicated compressor. The cryostat is attached to the telescope’s view-field de-rotating stage and fit into a tight space inside its fork mount below the main mirror. It is designed for easy access to internal components since its vacuum jacket and 60 K shield are made half-split. Per its initial specifications, the refrigerator must continuously maintain its base temperature of 20 mK at all inclinations of the main mirror from vertical to 35 degree South with. A set of windows with 200 mm aperture along the optical path is incorporated into the cryostat, where few narrow-band filters and some optical components would be installed at different temperature levels after initial cryogenic tests with those windows blanked.

At the start of this project, there was no commercially available cryogen-free DR to our knowledge which would allow for such a significant tilting from vertical axis with proven performance stability. The latter requirement put a special burden on the design. On top of the fact that conventional DR’s with 3He close loop circulation need gravity to stabilize the 3He-4He phase boundary in the mixing chamber (MC)[3], there are some geometrical considerations of the actual design such as Still, MC, heat-exchangers geometry and orientation with regards to the tilting plane to be taken into account. Also the PT head used to pre-cool the shields and condense the incoming mixture should maintain its base temperature within acceptable limits in tilted position.

Prior to the design, Janis Research made a special test to measure PT [4] performance at different inclination angles. We found no significant 2nd stage (3K) performance change at angles less than ±45 degrees from its main axis. The Cryostat was then designed with both the PT cold head and the Janis JDR-100 dilution stage core installed pre-tilted at 17.5 degree from the vertical axis. This arrangement kept liquid in the Still and the phase boundary inside MC at all inclination angles required. Lastly the mixing chamber exit pipe was placed off the tilting plane at 90 degree.

Figure 1 shows the JDry-100-ASTRA internal components with vacuum can (VC) and all the shields removed for clarity. The top plate was designed to be directly attached to the telescope, while holding the remote distribution valve (1) of the PT head (2). The 1st and 2nd stages of the PT head were connected correspondingly to lightweight aluminum 60 K (13) and 3 K shields (14) via flexible OFHC copper braids. The Still chamber (8) of the JDR-100 stage core was rigidly attached to the copper 1 K shield plate via a custom-made wedged adapter part. The Intermediate Cold Plate (ICP) and MC were connected to the copper 100 mK (16) and 20 mK (17) plates correspondingly via welded copper links. The 3He-4He mixture is circulated by a hermetic pump [5], installed inside the manually operated gas handling system. The 3He-4He mixture enters the Cryostat at pressures below atmospheric through a bellows sealed valve with VCR fittings (3) and goes directly into demountable charcoal trap (5) attached to the 60 K plate (13). After pre-cooling to 60 K in 1st stage heat-exchanger and to about 4 K inside a spiral heat exchanger wound around second stage regenerator, the mixture condenses in the 2nd stage heat-exchanger at approximately 2.8 K and the Joule-Thomson stage (7) before reaching the
primary flow impedance of $Z = 1E11$ 1/cc (6). The Still chamber is equipped with a diaphragm-type superfluid film suppressor, and is pumped via 2.5 inch diameter Still pipe, isolated with a butterfly valve (4). The pipe exits downwards to allow some Cryostat rotation inside fork mount.

![Figure 1. Cryostat schematic view (see text for details).](image)

The Cryostat is equipped with a mechanical pre-cooling heat switch (HS) operated by manual bellows valve and a stainless steel string (10). The switch has flexible copper braids permanently connected to the 3 K plate (not shown). When actuated, its spring-loaded contacts and a bottom conical contact connect Still, ICP and MC plate to the 3 K plate for initial precooling.

Stainless steel and carbon fiber tubes (not all shown) are used for the system mechanical supports to produce a rigid design, capable of maintaining an alignment of the detector with optical axis in all tilted positions. Two stainless steel semi-rigid cables and two bundles of shielded flexible superconducting wires in twisted pairs are installed for thermometry and customer experiments.

The 60 K and the 3 K plate temperatures were measured with two calibrated Cernox™ sensors [6] Commercial ruthenium oxide [7] thermometers were used to monitor the temperature of the Still and the ICP. The MC temperature was measured with Janis-packaged ruthenium oxide sensor (JRS), germanium sensor and a Cerium Magnesium Nitrate paramagnetic salt sensor (CMN), calibrated against superconducting fixed point device (FPD) [8]. A model LSCI 370S automatic AC Resistance Bridge was used as RTD read-out, while a model Agilent 4263B LCR meter as the CMN and FPD read-out. After CMN calibration it was used to calibrate the JRS.

The optical window (12) and corresponding ports below it were covered with flanges during the tests described below. Multi-layer super-insulation was installed only on the 60 K shield.

3. Performance

After all the shields are installed, the VC was pumped out through the evacuation valve (11) and then leak-checked. The cool-down process began with engaging the (HS) and starting the PT compressor. It typically takes 40 hours to precool the DR stage to below 3 K, where mixture circulation takes over the cooling process. The HS was then dis-engaged and mixture condensed within 5 hours. At the end of the condensing process, the DR reached its base temperature of 17 mK as measured with CMN thermometer.
The DR cooling power measurements at different circulation rates with the Cryostat in its vertical position (PT and DR stage tilted 17.5 degree to vertical) are shown on figure 2. This type of performance is typical for any JDR-100 or JDry-100 system equipped with single Alcatel 2063H mechanical pump. The base temperature of 17 mK was found to be insensitive, within few percent, to slow tilting in the range -20 (left, or North) to +50 (right, or South) degrees. Slow moving and some gentle Cryostat shaking during the motion also did not produce significant warming.

4. Conclusion
Typical additional cooling power available for the filter cooling is estimated as 1000 mW at 60 K plate and 100 mW at 3 K plate. Actual measured power up to 10 mW can be released at Still, or 1 K plate. These results, along with the performance of the dilution refrigerator described above, make us confident of the success of the MKIDs detector-based telescope for CMB applications.

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[6] Models CX-1050 and CX-1070, Lake Shore Cryotronics, Inc. (LSCI), 575 McCorkle Blvd, Westerville, OH 43082, USA
[7] Model RO-600A, Scientific Instruments, 4400 West Tiffany Drve, West Palm Beach, FL 33407, USA
[8] JRS, CMN and FPD are available from Janis Research on special order.