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Improved Seal for a 4 K Gifford-McMahon Cryocooler

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ABSTRACT

Gifford-McMahon refrigerators operating at ~ 4 K are currently used to cool SIS mixers on radio telescopes at the Berkeley-Illinois-Maryland array. The refrigerators are constructed by adding third stages onto standard 2-stage GM cryocoolers; Er_3Ni spheres are used as the low temperature regenerators. The refrigeration capacity is 50 mW at 3.5 K.

Two refrigerators have been installed on telescopes thus far. The first has operated for 10000 hours. Its temperature fluctuates between 3.5 and 5.7 K, sometimes on time scales of minutes, because helium leaks intermittently past the seal on the third stage displacer. The temperature stability of the second refrigerator is much better. It uses a spring-energized lip seal (Bal Seal) which is mounted on the third stage cylinder, rather than on the displacer. This refrigerator has now operated on a telescope for 3000 hours. It maintains the SIS mixer at 3.0 K, stable to ± 0.07 K over periods of days, even as it is tipped over an elevation angle range of 150 degrees.

The improved reproducibility afforded by the Bal Seal allows one to more reliably compare different regenerator materials. The refrigerator performance is almost identical with Er_3Ni or neodymium spheres.

INTRODUCTION

In the past 5 years several groups have demonstrated[1–4] that Gifford-McMahon cryocoolers utilizing Nd, Er_3Ni, or other rare earth compounds as regenerators can achieve refrigeration capacities of hundreds of milliwatts at temperatures ≤ 4 K. These refrigerators are simpler, more compact, and less prone to clogging by contaminants than the hybrid Joule-Thomson/Gifford-McMahon cryocoolers conventionally used to reach 4 K. However, their long term reliability and stability at low temperature are not yet well established.

Ordinary Gifford-McMahon refrigerators have long been used in radio astronomy to cool amplifiers and Schottky diode mixers to ~ 10 K. Currently, however, the most sensitive heterodyne receivers for millimeter wavelengths utilize SIS (superconductor-insulator-superconductor) tunnel junction mixers which must be operated at about 4 K. Radio astronomers are therefore keenly interested in extending the working range of GM refrigerators to lower temperatures. Takahashi *et al.*[5] were the first to install a 4 K GM refrigerator on a radio telescope.

Three-stage GM refrigerators are now used to cool SIS mixers on the Berkeley-Illinois-Maryland array (BIMA), an aperture synthesis instrument consisting of 6 (soon to be expanded to 10) radio telescopes. Extensive lab tests of a prototype BIMA cryocooler were reported previously.[6] This paper discusses the long-term performance of these refrigerators on the telescopes, and describes a modified seal design which greatly improves the third stage temperature stability.

CRYOCOOLER DESIGN REQUIREMENTS

Each BIMA dewar accommodates 4 SIS mixers, cooled by a single refrigerator. Niobium SIS junctions are used. Although these junctions do function at temperatures as high as 7 K, one obtains the best sensitivity at the lowest possible temperature. Relative to the performance at 3 K, the receiver noise temperature is typically higher (worse) by 3–4% at 3.5 K, 10% at 4.2 K, 25% at 5 K, and 70% at 6 K.

In order to keep the mixer temperatures as low as possible, preferably below 3.5 K, we decided to build 3-stage refrigerators. I.F. amplifiers are mounted to the refrigerator's second stage, so the heat load on the third stage is kept to < 50 mW. Microwave signals are coupled to the mixers quasi-optically, through Teflon windows on the first and second stage radiation shields. The dominant heat load on the third stage is due to infrared radiation which penetrates these windows. The loads on the first and second refrigerator stages are estimated to be 6 watts (from the outer radiation shield) and 0.5 W (from the inner radiation shield and I.F. amplifiers) respectively.

The dewar is mounted at the Cassegrain focus of the telescope, where it is tipped over an elevation angle range of 0–150 degrees. Thus, it is crucial that the refrigerator operate in any orientation. For some experiments it is desirable to stabilize the temperature of the SIS mixer to a few milliKelvin for periods of an hour or so; the refrigerator temperature should be sufficiently stable that this can be done with an active control circuit. Finally, the refrigerator is expected to operate continuously for periods of at least 6 months to 1 year.

A drawing of the BIMA cryocooler is shown in Figure 1. It is based on a standard CTI model 1020 refrigerator. The end of the second stage cylinder is machined off, and a third

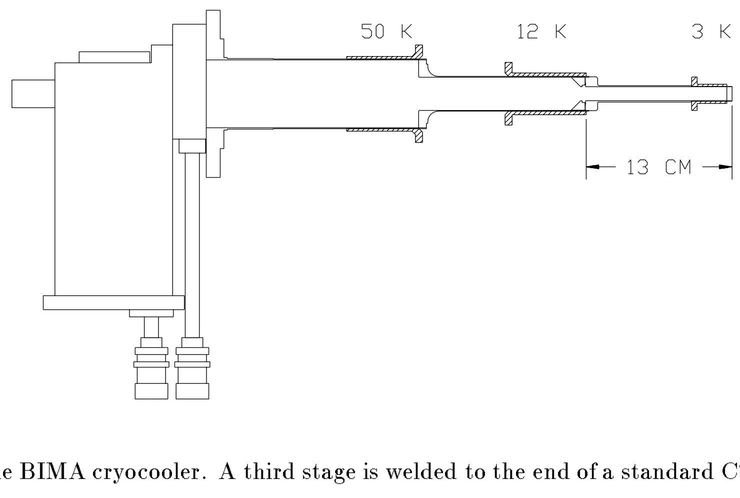

Figure 1. The BIMA cryocooler. A third stage is welded to the end of a standard CTI model 1020 refrigerator.

stage cylinder (1.27 cm ID × 13 cm long) is welded in place. The third stage displacer is fabricated from a stainless steel tube; an 0.5 mm thick plastic[7] sleeve epoxied to the outside of the tube serves as a bearing surface. Spheres of Er_3Ni, diameter range 180–450 μm, are used as the third stage regenerator. Initially a split piston-ring seal was used on the displacer.

The end of the second stage displacer is machined to accommodate the third stage linkage pin, and is chamfered to fit the cone-shaped opening of the third stage cylinder. The chamfer and cone guide the second and third stage displacers into their cylinders, so it is easy to install the displacers even when the refrigerator is mounted horizontally, as it is on the telescope. No other modifications are made to the first or second stage displacers. A digital power inverter is used to control the refrigerator's cycle frequency, which must be reduced below the normal value of 72 rpm in order to get to 3 K. On the telescopes the refrigerators are operated at 30–42 rpm.

Extensive lab tests of 3 prototype refrigerators were reported in an earlier paper.[6] Using 50 grams of Er_3Ni as the third stage regenerator, it was possible to reach temperatures as low as 2.2 K, and to operate at 3.5 K with loads of 10 W, 1 W, and 50 mW applied to the first, second, and third stages. The third stage temperature sometimes fluctuated erratically, however, as shown in Figures 10 and 11 of reference 6; these fluctuations were attributed to intermittent helium leakage past the third stage seal. The refrigerator cools a receiver from room temperature to 4 K in less than 5 hours.

One of the prototype refrigerators was installed on a telescope in February 1993 and has been in nearly continuous operation since. Generally this refrigerator maintains the SIS mixer temperature between 4.0 and 5.5 K, with occasional excursions down to 3.5 K and up to 5.7 K. The mixer operates tolerably well even at 5.5 K, so these fluctuations have not proved to be fatal, but they lead to undesirable variations in the receiver gain and sensitivity.

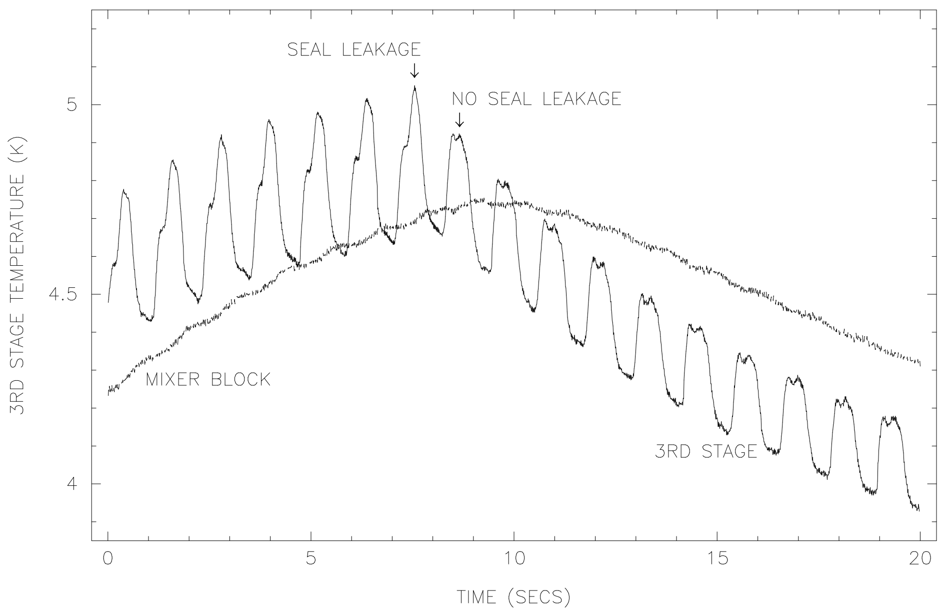

Figure 2. Third stage and mixer block temperatures sampled every 0.01 secs for a span of 20 secs. The cyclical temperature profile changes abruptly at about 8 seconds, probably because the third stage seal suddenly seats.

TEMPERATURE FLUCTUATIONS: CAUSE AND CURE

An example of the erratic temperature behavior exhibited by the prototype refrigerator is shown in Figure 2. Here the refrigerator was operating at 50 rpm. Each refrigerator cycle causes a temperature swing of about 0.3 K on the third stage. The temperature increases as the inlet valve opens and helium in the cold finger is pressurized; it decreases as the exhaust valve opens and the cold finger is depressurized. Owing to the thermal resistance of the connecting straps and the heat capacity of the mixer block, these cyclical temperature swings are almost completely damped out at the SIS mixer, and hence are of little concern. The troublesome temperature fluctuations are the drifts which occur on time scales of tens of seconds.

For the first 7 cycles in Figure 2 the third stage temperature spikes upward about midway through the inlet stroke. On the 8th cycle this temperature spike disappears abruptly, and the third stage cools rapidly. The extra temperature spike almost certainly is caused by warm gas leaking past the third stage seal; presumably the leakage is greatest as the displacer travels fastest, about midway through the inlet stroke.

A piston-ring seal with C-shaped expansion spring is used on this refrigerator; the seal is identical to the one used on the second stage of a CTI model 22 refrigerator. Although the performance of this seal probably could be improved by better controlling the dimensions and surface finish of the seal groove and cylinder, a potential leakage path always exists along the joint where the two ends of the seal overlap. We decided, therefore, to abandon the split seal completely and to convert over to a continuous, spring-energized lip seal. A model manufactured by Bal Seal Engineering[8] was chosen. We first tried to mount a lip seal on the displacer, but found that this approach was hopeless – even with a very stiff spring, thermal contraction of the plastic jacket caused the seal to shrink away from the cylinder wall at low temperatures. Accordingly, following the manufacturer's recommendation, we redesigned the refrigerator to use a flanged seal mounted on the cylinder; in this way thermal contraction increases the sealing force.

The seal mounting arrangement is shown in Figure 3. A clamp ring and six 4-40 screws hold the seal in place at the top of the third stage cylinder. Installing the seal is not difficult. It is pressed into the clamp ring, then lowered into the cold finger with a special insertion tool; a long wrench is used to tighten the mounting screws. The radial clearance between the stainless steel displacer and the cylinder wall is approximately 50 microns.

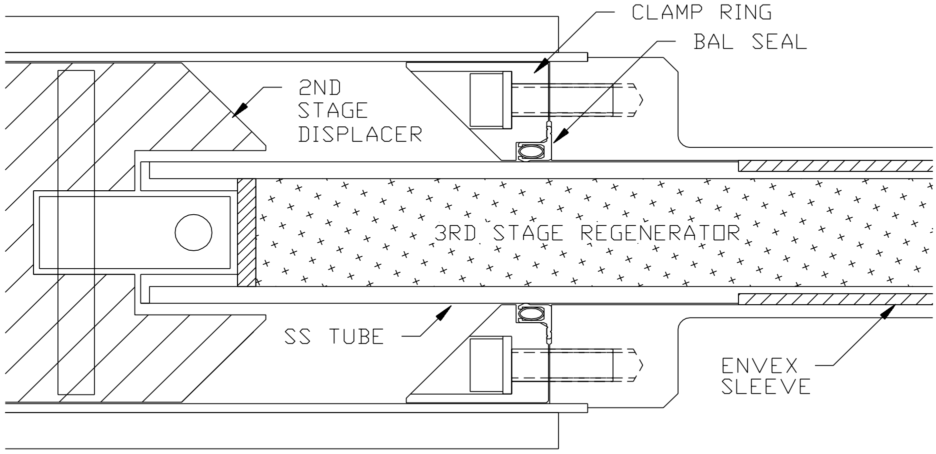

Figure 3. Seal mounting arrangement.

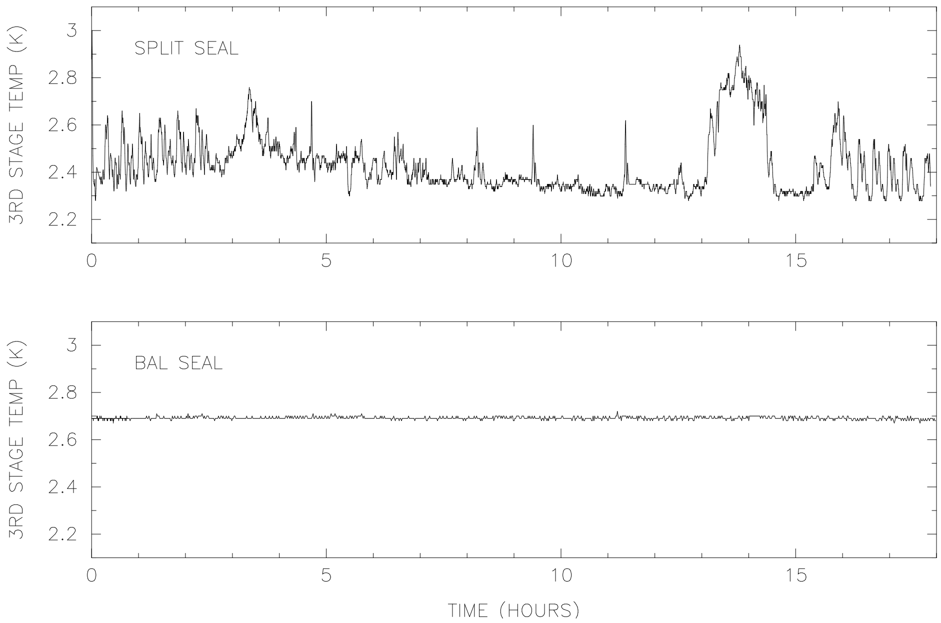

Figure 4. Temperature stability of refrigerators using a standard split seal on the third stage displacer and a Bal Seal mounted at the top of the third stage cylinder. Temperatures were measured every 15 seconds for 18 hours.

RESULTS

Figure 4 compares the temperature stability of the old and new refrigerator designs. Although the no-load temperature of the Bal Seal refrigerator is a bit higher, probably due to greater seal friction, its temperature stability is dramatically better, typically ± 0.05 K over periods of a day. With a computer-controlled heater on the refrigerator's third stage, it was possible to regulate the mixer temperature within ± 10 mK over periods of many hours.

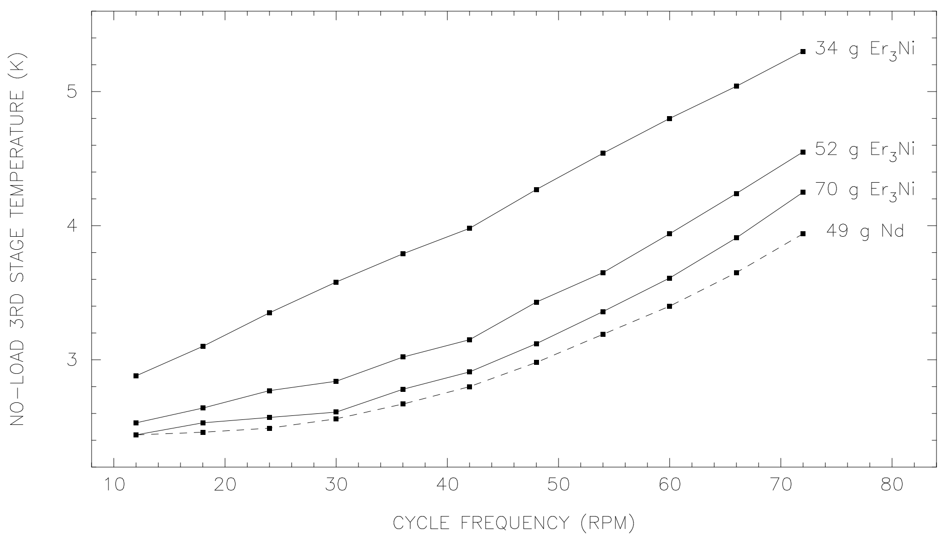

Figure 5. No-load third stage temperature as a function of cycle frequency for different regenerator fillings. The working volume was 4.0 cm^3 and the third stage regenerator volume was 11.8 cm^3. A nylon plug was used to fill up the extra space when the regenerator was partially filled with Er_3Ni.

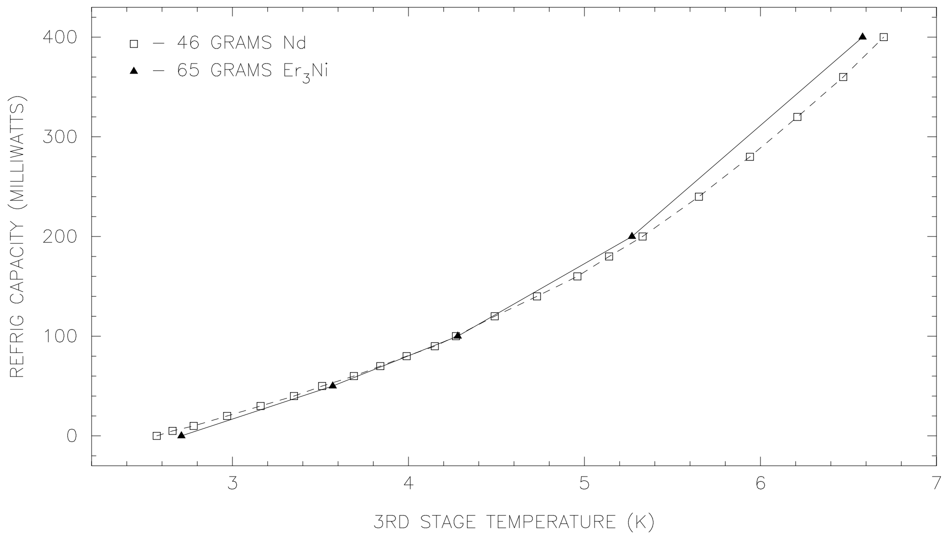

Figure 6. Refrigeration capacity as a function of temperature, for regenerators filled with spheres of neodymium (diameter range 230-500 μm) or Er_3Ni (diameter range 180-450 μm). The cycle frequency was 30 rpm.

The refrigerator performance is considerably more reproducible from cooldown to cooldown with the redesigned seal, allowing more reliable comparisons of different regenerator materials. Figure 5 displays the no-load temperature vs. cycle frequency, and Figure 6 displays the refrigeration capacity vs. temperature, for different regenerators. The performance is almost identical with neodymium or Er_3Ni spheres.

The Bal Seal refrigerator was installed on a telescope in February 1994. The SIS mixer temperature monitored over the subsequent 4 months is shown in Figure 7. Typically it is stable to ± 0.07 K over periods of days, even as the refrigerator is tipped repeatedly over a 150 degree range in elevation angle. Sometimes the temperature jumps to a slightly different value following a brief power outage. This behavior, noted in lab tests as well,

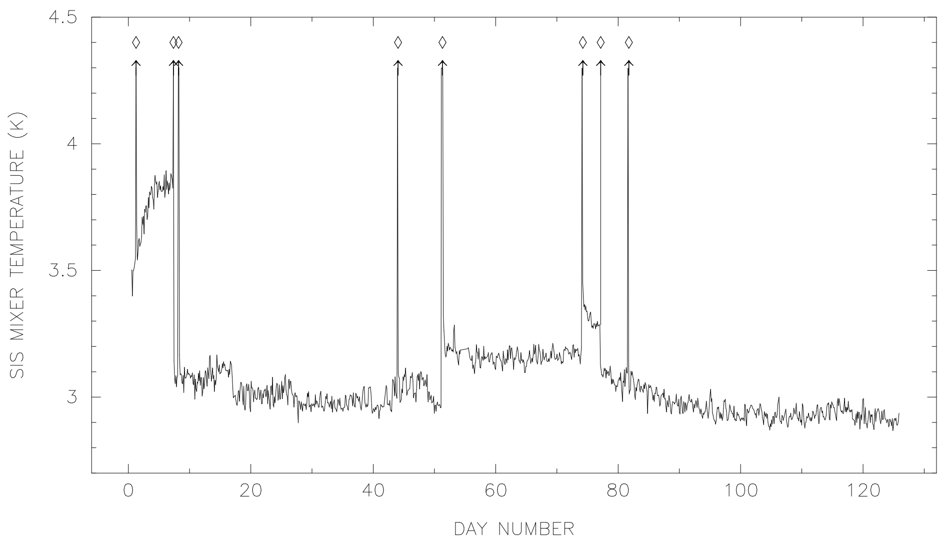

Figure 7. Refrigerator performance over a 4 month period on the telescope. The temperature of the SIS mixer block was measured every 1 minute over this period; the maximum temperature recorded during each 0.1 day interval is plotted here. Diamonds mark brief power outages.

apparently can occur when the third stage temperature rises above 5 or 6 K; possibly it is caused by migration of contaminants within the cold finger.

CONCLUSIONS

Low temperature Gifford McMahon cryocoolers have been used successfully to cool SIS mixers on the BIMA radio telescopes. Switching from a conventional piston ring seal mounted on the displacer to a Bal Seal mounted on the cylinder greatly improves the temperature stability, which can be ± 0.07 K for periods of days. Refrigerators of this type will be installed on all of the BIMA telescopes in the near future, providing a rigorous test of their long-term reliability.

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