Successful Qualification of the First PFM Space Dilution Refrigerator

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ABSTRACT

We report on the successful qualification down to 100 mK of the first space dilution refrigerator. This dilution refrigerator will cool down the bolomoters of the high frequency instrument (HFI) of the Planck Satellite for 18 months. For HFI, the required sensitivity ($\Delta T/T \sim 2.10\text{-}6$) is achieved by using an array of bolometers cooled down to 100 mK by an open-cycle dilution cooler.

To achieve the temperature of 100 mK, the isotopes are pre-cooled with external cryocoolers down to 4.5 K. Further cooling to less than 1.6 K is achieved through an internal Joule Thomson (J-T) expansion process on the mixture return line.

The results obtained on the proto-flight model (PFM) at the J-T and dilution cooler stages are compared to those obtained with the qualification model. The influence of the pre-cooling temperature on the performance of the dilution cooler is also discussed.

Potential applications of this cooler or of an upgraded version for other missions are presented.

INTRODUCTION

A cascade of coolers (see for instance[1]) is needed to reach a temperature of 0.1 K required by HFI. The first cooling stage, down to 50 K, is obtained passively by using thermal shields and radiators. Then, a first closed cycle cooler, based on J-T expansion of H_2, provides intermediate cooling down to 18 K. A second closed cycle cooler, based on J-T expansion of He, provides cooling to about 4.5 K. Finally, the dilution cooler operates down to 100 mK.

The principles of the open cycle dilution cooler as well as its main features have been described together with the results obtained on the CQM model.[2] We here focus on the results obtained for the PFM.

RESULTS OBTAINED WITH THE DILUTION COOLER PFM

The results obtained with the dilution cooler PFM model as compared with the requirements are presented in Table 1. All requirements are fulfilled with margin.

Cryocoolers 14, edited by S.D. Miller and R.G. Ross, Jr.

Table1. Measured values as compared with requirements for the dilution cooler PFM model.

Function	Requirements	Value measured
Autonomy @100mk (survey mode)	≥18 months	**≥24 months**
Cold end unit absolute temperature	100 mK ± 5 mK	**94 +/-2mK**
Cold end unit minimum power	≥100 nW	**180nW**
1.6K stage upper interface temperature	<2.1K (1.6K nom.)	**1.40K**
Cold End Unit Temperature stability at high frequency (0.01…100Hz, unregulated)	<5μK/Hz ½	**<5μK/Hz ½**
1.6K Temperature stability at high frequency (0.01…100Hz at the blocking filter level, unregulated)	≤10mK/Hz ½	**≤1mK/Hz ½**
Minimum cooling power at 1.6K focal plane	150μW	**200 μW**
Cold end unit leak tightness	10^{-9}mBar.l/s	**<10^{-9}mBar.l/s**

As can be seen in Figure 1, the dilution cooler performance was evaluated on a large domain of flows.

This was done to confirm the operating flow domain for the dilution cooler and to compare with the set of flows provided by the dilution cooler control unit (the flows for both ^{4}He and ^{3}He isotopes can be adjusted in a range of 1 to 2 by steps of about 15% of the minimum one). Depending on the actual in flight conditions, it will be possible to adjust the ^{4}He and/or ^{3}He flows in order to:

- Get in the flow domain if the initial operating point is out of specification
- Reduce the flows for a longer survey

Figure 2 shows the power response of both PFM and CQM models. The results are quite similar with a power following the expected T^2 dependence. The fitting parameters can be related to the design of the system.[2]

The results displayed in Figure 2 were reproduced after the focal plane structure underwent vibration testing and also after integration of the complete focal plane unit including bolometers.

SENSITIVITY TO HIGHER PRECOOLING TEMPERATURE

Due to the presence of a J-T stage located on the return line of the mixture, the dilution cooling process is not affected by a modification of the precooling temperature. This is valid until the J-T

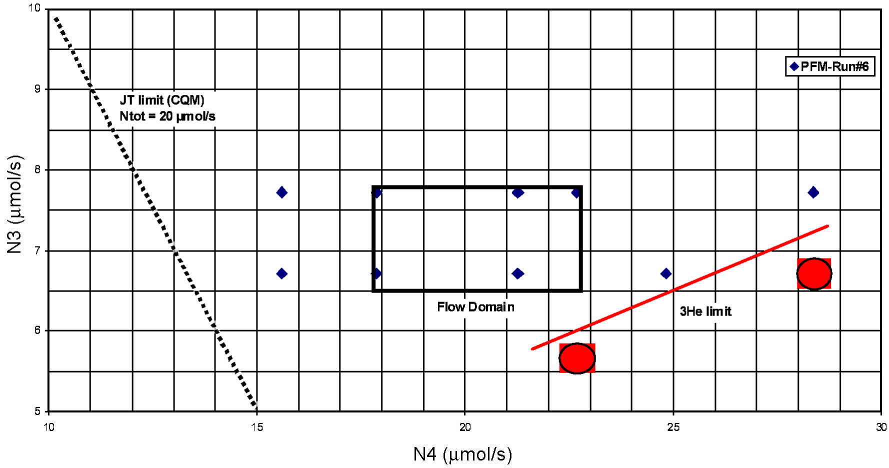

Figure 1. Determination of the flow domain for the dilution cooler. ^{3}He limit corresponds to a lack of ^{3}He in ^{4}He. J-T limit is issued from CQM measurements. It corresponds to a lack of liquid in the J-T box.

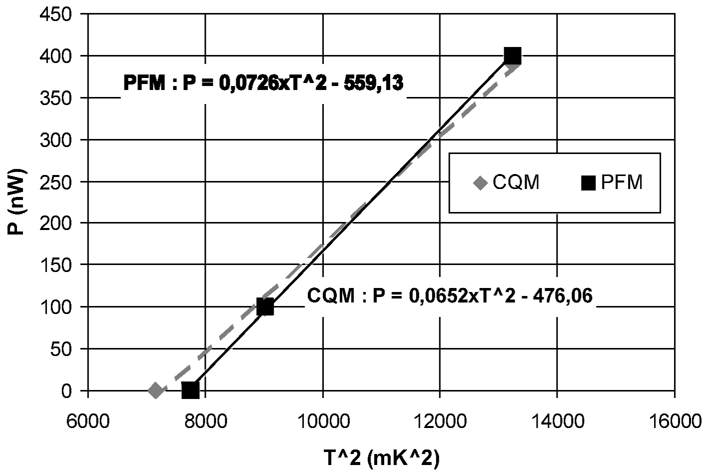

Figure 2. Power response of the dilution cooler. Comparison between CQM and PFM.

has sufficient amount of liquid to compensate the extra heat loads coming from the upper stage (4.5 K nominal temperature in the case of Planck). The typical dependence of available enthalpy as function of J-T inlet pressure and precooling temperature is given in Figure 3.

Using these data, it is possible to compare the required cooling power with the expected one. Yet, the complete J-T system, which includes several thermal links between the fluid and the 1.6 K J-T plate, is more complex and this approach is limited.

The definition of a criterion based on the vapor content in the J-T box (see Fig. 4) gives a more robust condition for the J-T inlet pressure since the vapor content in the fluid is supposed to have a strong influence on the heat transfer coefficient, i.e. on the available power at J-T stage.

For a given precooling temperature, one can then define a minimum required inlet pressure (see Table 2). As far as the manufacturing of the dilution cooler is concerned, it simply means modifying the small capillary forming the J-T impedance.

In principle, such a dilution cooler could use a precooling source up to 8 K.

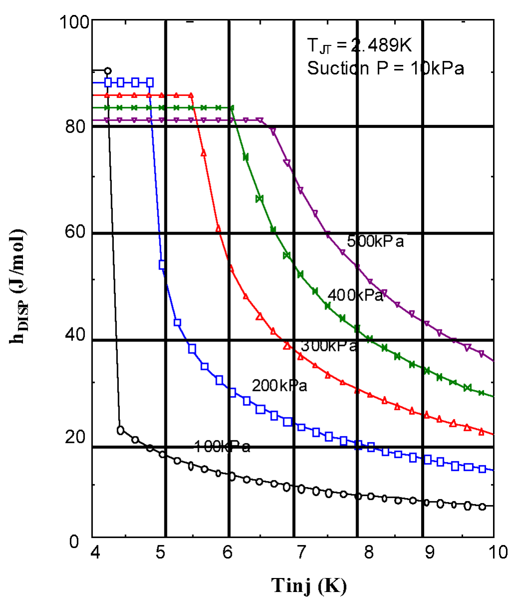

Figure 3. Theoretical enthalpy available on the J-T stage (J/mol ^{4}He)

Table 2. Minimum required inlet pressure

Pre-cooling temperature Tinj (K)	**Minimum inlet pressure (kPa)**
4.5	150
5.0	250
5.5	300
6.0	400

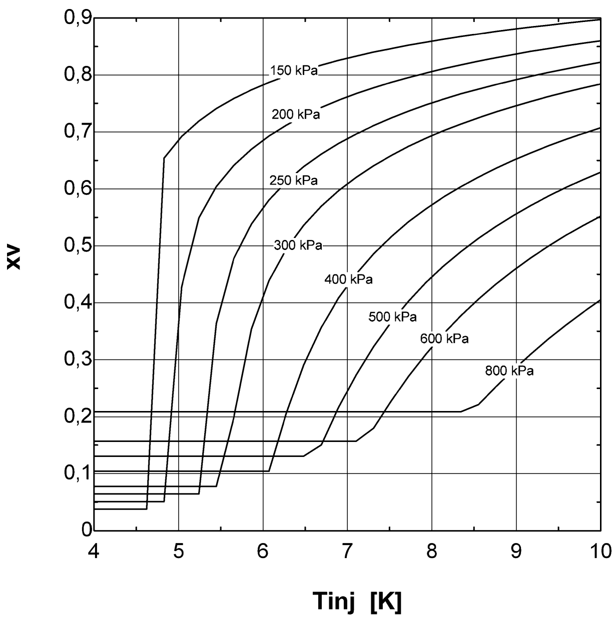

Figure 4. Theoretical vapor fraction at the JT heat exchanger inlet.

POTENTIAL UPGRADES OF THE DILUTION COOLER

As described above, a precooling temperature up to 8 K can be envisaged. As a few tens of mW (typically 20 mW) would be required, this opens the way to a coupling between a Stirling or pulse type mechanical space cooler to a dilution cooler. A test of the dilution with higher inlet temperatures is in process in collaboration with CRTBT under CNES funding.

Another approach under investigation is a closed loop dilution cooler. This would allow its use for missions of more than 5 years duration.

ACKNOWLEDGMENT

The present work and ongoing developments are mainly supported by CNES.

REFERENCES

1. B. Collaudin et al., “Hershel-Planck and the Next Steps in Space-Cryogenics,” Proceedings of the *ICEC 19 Conference,* New York (2002), pp. 493-502.
2. S. Triqueneaux et al., “Design and Performance of the Dilution Cooler System for the Planck Mission”, *Cryogenics*, Vol. 46, Issue: 4 (April 2006), pp. 288-297.