Performances of the Planck-HFI cryogenic thermal control system

Christophe Leroy[a,b*], Antoine Arondel[c], Jean-Philippe Bernard[b], Hervé Carfantan[a], Cydalise Dumesnil[c], Jean-Jacques Fourmond[c], Guy Guyot[c], Jean-Michel Lamarre[d], François Pajot[c], Michel Piat[e], Jean-Loup Puget[c], Jean-François Trouilhet[a], Sylvain Varesi[c] & the Planck-HFI Instrument Team

[a]LATT, Université Paul Sabatier/CNRS - UMR5572, Toulouse, France
[b]CESR, Université Paul Sabatier/CNRS - UMR5187, Toulouse, France
[c]IAS, Université Paris Sud/CNRS - UMR8617, Orsay, France
[d]LERMA, Observatoire de Paris/CNRS - UMR8112, Paris, France
[e]APC Collège de France, Université Paris VII/CNRS - UMR7164, Paris, France

ABSTRACT

The core of the High Frequency Instrument (HFI) on-board the Planck satellite consists of 52 bolometric detectors cooled at 0.1 Kelvin. In order to achieve such a low temperature, the HFI cryogenic architecture consists in several stages cooled using different active coolers. These generate weak thermal fluctuations on the HFI thermal stages. Without a dedicated thermal control system these fluctuations could produce unwanted systematic effects, altering the scientific data. The HFI thermal architecture allows to minimise these systematic effects, thanks to passive and active control systems described in this paper. The passive and active systems are used to damp the high and low frequency fluctuations respectively. The last results regarding the tests of the HFI passive and active thermal control systems are presented here. The thermal transfer functions measurement between active coolers and HFI cryogenic stages will be presented first. Then the stability of the temperatures obtained on the various cryogenic stages with PID regulations systems will be checked through analysis of their power spectrum density.

Keywords: Planck-HFI, Submillimeter, Millimeter, PID thermal control, Thermal transfer function

1. INTRODUCTION

The European Space Agency Planck[1] satellite will be launched in 2008. Planck is a space telescope observing at sub-millimeter and millimeter wavelengths. The main Planck scientific objective is to achieve a complete survey of the Cosmic Microwave Background anisotropy with high angular resolution and sensitivity. In order to achieve this survey Planck will be placed at the L2 Lagrangian point of the Sun-Earth system with an optimal scanning strategy[2] for a full-sky coverage after about half a year of observation. Planck is a 3rd generation CMB anisotropy space experiment after COBE[3] and WMAP.[4] The observations with Planck will put new and important constraints on the various parameters of the cosmological models.

The Planck High Frequency Instrument[5] will observe in six photometric bands between 100 and 857 GHz. Four of these channels will measure simultaneously the polarization of the sky thanks to Polarization Sensitive Bolometers (PSB). The bolometric detectors of this instrument are cooled to 0.1 Kelvin with three cryogenic active coolers allowing a warm launch and thus a system without a window minimizing the background on the detectors. Without a dedicated thermal control system, the weak thermal fluctuations of the active coolers could produce unwanted systematic effects, altering the scientific data. The HFI design has been optimized in order to damp the thermal fluctuations induced by these coolers. The HFI mechanical architecture provides a passive filtering of the high frequency thermal fluctuations

*Christophe Leroy: cleroy@ast.obs-mip.fr, +33 5 61 33 28 85, Laboratoire d'Astrophysique de Toulouse Tarbes, Observatoire Midi-Pyrénées, 14 avenue Edouard Belin, 31400 Toulouse, France

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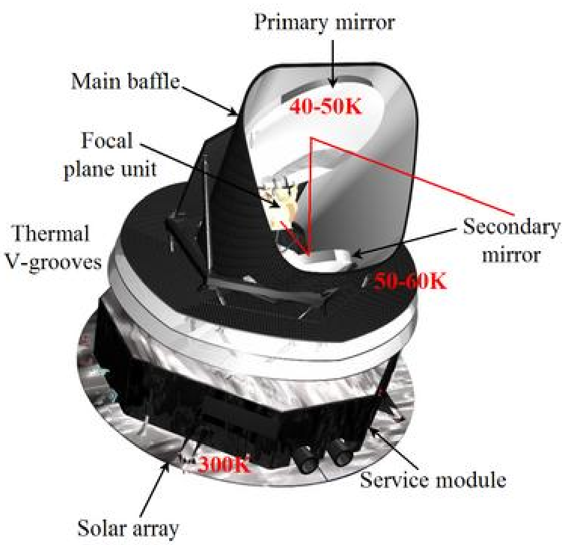
while dedicated PID active control systems have been developed for the control of the low frequency thermal fluctuations. These active systems consists of heaters, located on the various cryogenic stages and controlled through a PID algorithm implemented in the HFI thermometers readout system. The PID regulation parameters are then controlled through the HFI on-board computer.

During HFI ground tests and calibration campaigns at instrument and system levels, several tests of the PID regulation systems have been performed. In the same time, measurements of the passive filtering between HFI stages have been done thanks to HFI ground test setups and dedicated test procedures.

2. HFI THERMAL ARCHITECTURE AND BEHAVIOR

2.1. HFI cryogenic design

The Planck High Frequency Instrument is composed of several cryogenic stages with caracteristic equilibrium temperature (figure 1).



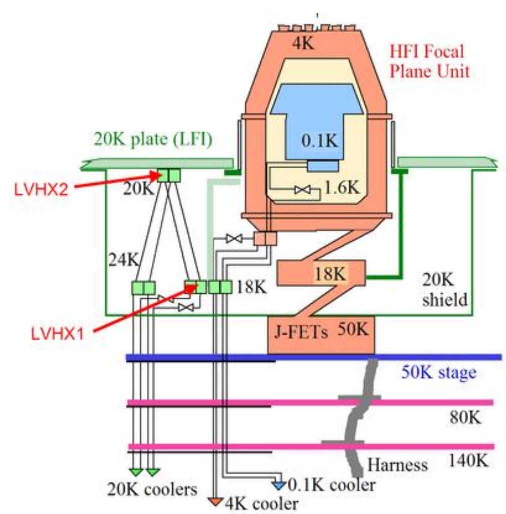


Figure 1. Left: Planck Satellite temperatures. Right: HFI cryogenic architecture. Temperatures given are indicative and for the purpose of identifying the various stages.

The first stage is at 50K, which corresponds to the Planck telescope temperature reached through passive cooling, thanks to the thermal V-grooves system located between the telescope and the warm satellite platform and solar array at 300K. Then two intermediate stages at 18K and 4K are cooled by two dedicated active cryogenic coolers: the JPL 18K Sorption cooler[6] and the RAL 4K cooler.[7] The 18K Sorption Cooler is used for cooling simultaneously the two instrument on-board Planck: HFI and LFI.[8] The last stages are at 0.1K and 1.6K, achieved thanks to the last active cooler: the 0.1K dilution cooler[9] designed by the CRTBT, Grenoble and the IAS, Orsay.

2.2. HFI thermometers location

In order to control and check HFI temperatures during the whole project life, several thermometers have been placed on the various HFI cryogenic stages (figure 2).

Two low sensitivity thermometers Cernox_18K and Cernox_4K are placed on the 18K and the 4K stages respectively. Other thermometers on the figure 2 are sensitive thermometers.[10] The PID4R and PID4N control 4K plate temperature while the 4KL1 and 4KL2 thermometers measure the temperature of the side of the 4K box. Then PID1.6R check the 1.6K stage temperature. Finally PID1R and PID2R probes are used to follow the 0.1K stage temperature changes.

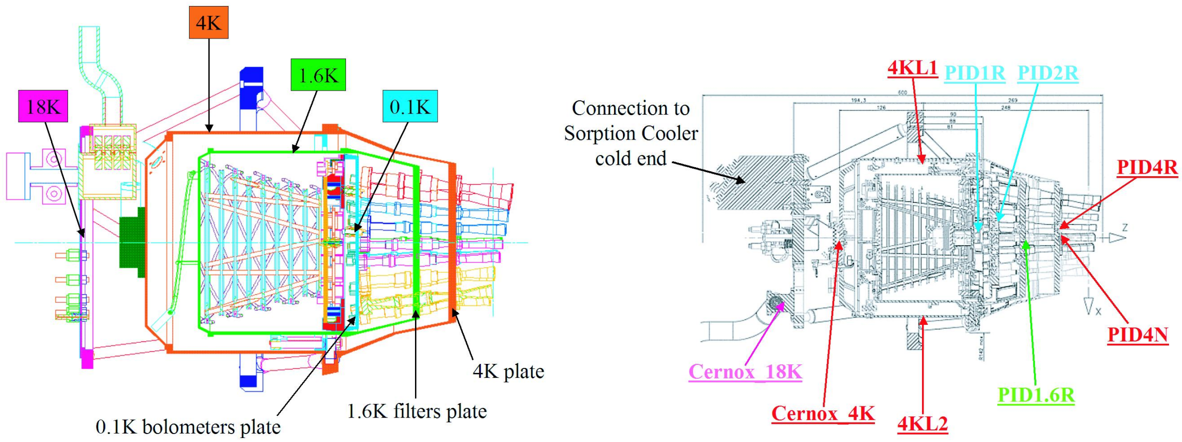


Figure 2. Left: Planck-HFI cryogenic stages. Right: HFI thermometers location.

2.3. HFI temperature stability requirements

In order to reach the Planck final sensitivity performance, the temperature stability of the various HFI cryogenic stages is critical.

The back to back horns fixed on the 4K plate (figure 2) located at the top of the HFI 4 box radiate at horns temperature. This thermal emission is viewed by HFI bolometers in the band defined by the various filters along the HFI cold optic.[11] So thermal fluctuations of HFI 4K horns generate parasitic systematic effects on bolometers signals.

The same kind of parasitic signals are produced by the thermal emission of the filters placed on the 1.6K filters plate (figure 2).

The bolometers equilibrium temperature depends of the cryogenic bath temperature around. Small variations of the 0.1K bath temperature could produce important changes in the bolometers impedance.[12] So temperature fluctuations of the 0.1K stage introduce direct systematic additive signal. Bolometer responsivity changes also occurs when 0.1K temperature change but it is a secondary order effect.

In order to keep these various sources of systematic effects down to acceptable values, the requirements set on the temperature stability of the different HFI stages in the critical frequency range of 10mHz to 100Hz are given below[13]:

- Thermal fluctuations of the HFI-4K back to back horns should be below: 10μK/$\sqrt{Hz}$.
- Thermal fluctuations of the 1.6K HFI filters should be below: 28μK/$\sqrt{Hz}$.
- Thermal fluctuations of the HFI-0.1K bolometers thermal bath should be below: 20nK/$\sqrt{Hz}$.

2.4. Active cooler fluctuation measurements

HFI active coolers have intrinsic temperature fluctuations. The goal of HFI thermal control system is to attenuate these fluctuations. The various fluctuations of these coolers have been measured during various test campaigns of these Planck sub-systems. The results of these different tests are presented bellow:

Sorption Cooler fluctuations measurement The Flight Model of the 18K Sorption Cooler has been tested in March 2006 at the Liege Space Center (CSL) as part of an integrated test on the Planck satellite platform and payload excluding the two instruments (CSL-PFM1 test). The preliminary results indicate that LVHX1 and LVHX2 Sorption Cooler Cold End (see figure 1 for location) have periodic fluctuations of

480 seconds due to the characteristic cycle of the 6 compressor elements of the cooler. Then a complete cycle of the Sorption Cooler and its fluctuations is around 3000 seconds (six times 480 seconds). The peak to peak amplitude of these fluctuations with 480 seconds period is around 400 mK. Since the 18K stage is used for the pre-cooling of the 4K one, these Sorption Cooler fluctuations induced parasitic temperature fluctuations of the 4K stage. These last fluctuations need to be attenuated in order to be in the requirement of 10μK/$\sqrt{Hz}$ for the 4K stage.

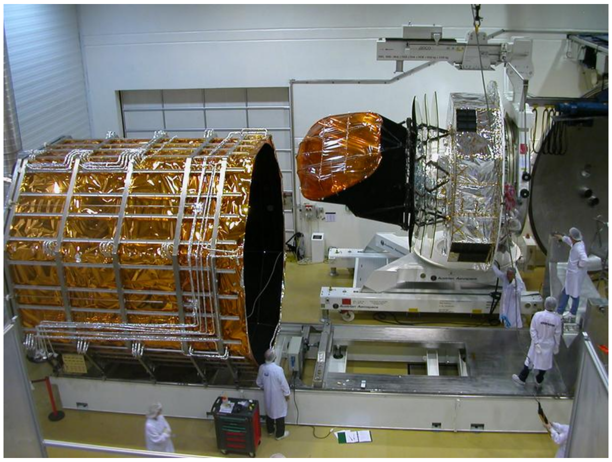


Figure 3. Planck Cryogenic Qualification Model and its test setup at CSL.

4K Cooler fluctuations measurement The Cryogenic Qualification Model (CQM) of the 4K Cooler has been tested at CSL during Qualification Model test of Planck in september 2005 (figure 3). The intrinsic fluctuations of this cooler have been observed by HFI Cernox_4K thermometer during this test (figure 4).

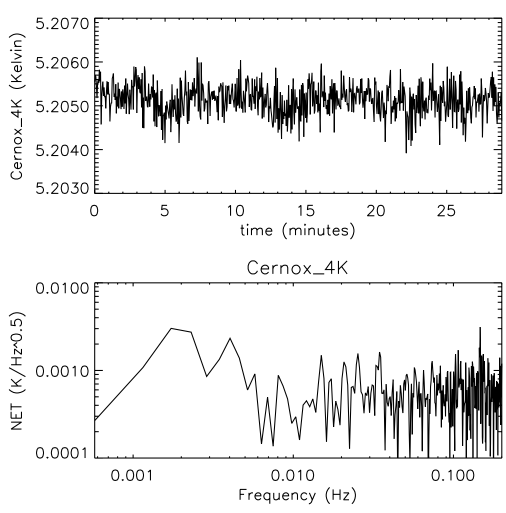


Figure 4. 4K Cooler fluctuations measurement during CSL-CQM test.

Dilution Cooler fluctuations measurement during CSL-CQM test The Cryogenic Qualification Model of the Dilution Cooler has also been tested at CSL during Planck CQM test (figure 5). The temperature fluctuations on figure 5 are as expected much larger than the requirement on bolometers temperature stability.

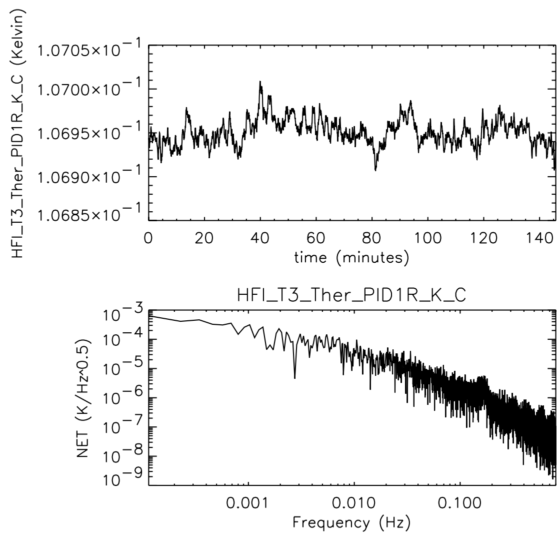


Figure 5. Dilution Cooler fluctuations measurement during CSL-CQM test.

3. THERMAL CONTROL TESTS

3.1. Passive thermal control tests

18K-4K damping measurement The thermal transfer function between Sorption Cooler cold end at 18K and HFI 4K horns has been measured on the Cryogenic Qualification Model (CQM) of Planck during CSL-CQM test. In this test the Sorption cooler compressors were not available. The cold end Joule-Thomson (PACE) was fed by hydrogen bottles.

The measurement principle for the HFI CQM was to generate various thermal stimuli on the 18K cold ends of the PACE by modulating the hydrogen flow in order to quantify the impact of in-flight Sorption Cooler fluctuations on HFI stages stability. Various pressure changes sequences in the PACE allowed to generate different periodic fluctuations of LVHX1 and LVHX2 with various amplitudes. From the result of the various PACE fluctuation tests it is then possible to deduce the thermal transfer function between LVHX1 and the other HFI stages.

A first thermal test consisted in a fast thermal step of 1 Kelvin on the LVHX1 and LVHX2 temperature (figure 6). Others tests with simple thermal step on LFI mechanical support only have allowed us to establish which part of 4K horns fluctuations come from LVHX1 and which one come from LVHX2. From this first measurements, the static gain for the thermal transfer function between LVHX1 and HFI 4K horns appears to be 0.045 with a time constant of 5000 seconds. LVHX2 contribution is around three times lower. So static gain between LVHX2 and 4K horns is 0.015 with a time constant of also around 5000 seconds.

Then two different quasi-periodic fluctuations of the PACE were tested (figure 7 and 8). From these measurements it is possible to deduce the thermal transfer functions between PACE cold ends and 4K horns by computing the peaks ratio in the power spectrum at different stimulus frequencies. A model deduce from thermal fluctuations on LFI support was used for separate LVHX1 and LVHX2 effects. The final thermal transfer function measured in this way on Planck-CQM is presented on the figure 9.

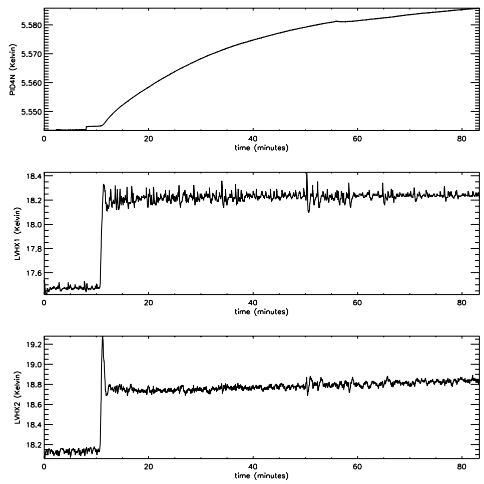


Figure 6. Effect of LVHX1 and LVHX2 temperature step on HFI 4K horns (PID4N).

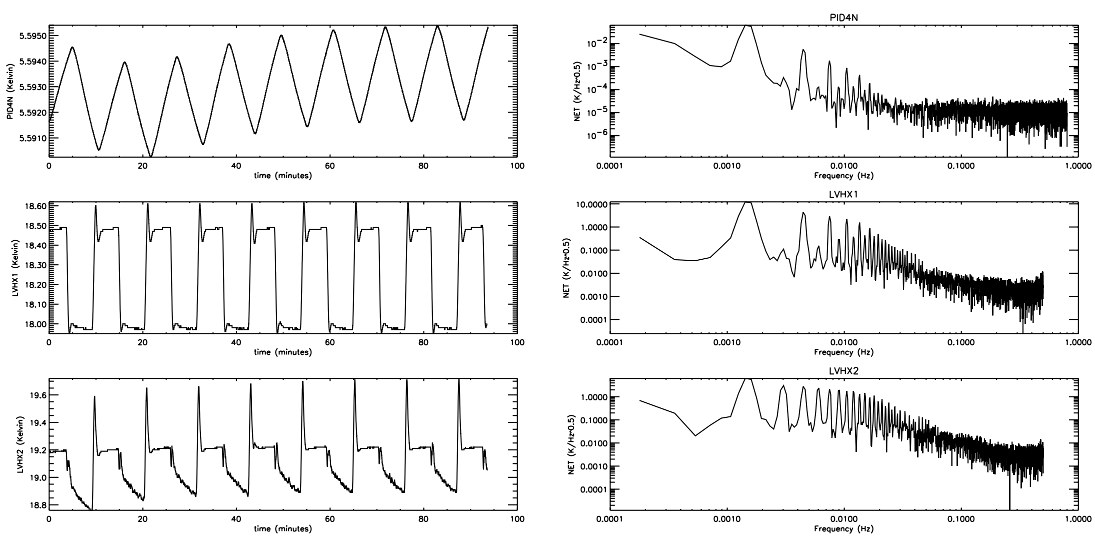


Figure 7. Effect on 4K horns of PACE fluctuations with 666 seconds period. Left: Thermometers measurements. Right: Thermometers signals power spectrum density.

This thermal transfer function can be fit by a low-pass first order filter. By extrapolate this low-pass model, we can deduce that the passive damping of the high frequency fluctuations in the critical frequency range of 10mHz to 100Hz is important enough to kill the sorption cooler induced signal for this frequency range.

Some measurements with the same kind of periodic stimulus at 4000, 666 and 100 seconds were also carried-out with the 4K stage PID regulation ON (figure 9).

4K-1.6K damping measurement In the same way, it is also possible to deduce from the CSL PACE tests the thermal transfer function between Sorption Cooler both 18K cold ends and the 1.6K filters. From this tests it was established that this last effect was negligible and the principal source of thermal fluctuations of the 1.6K stage are the one induced by the dilution cooler intrinsic fluctuations.

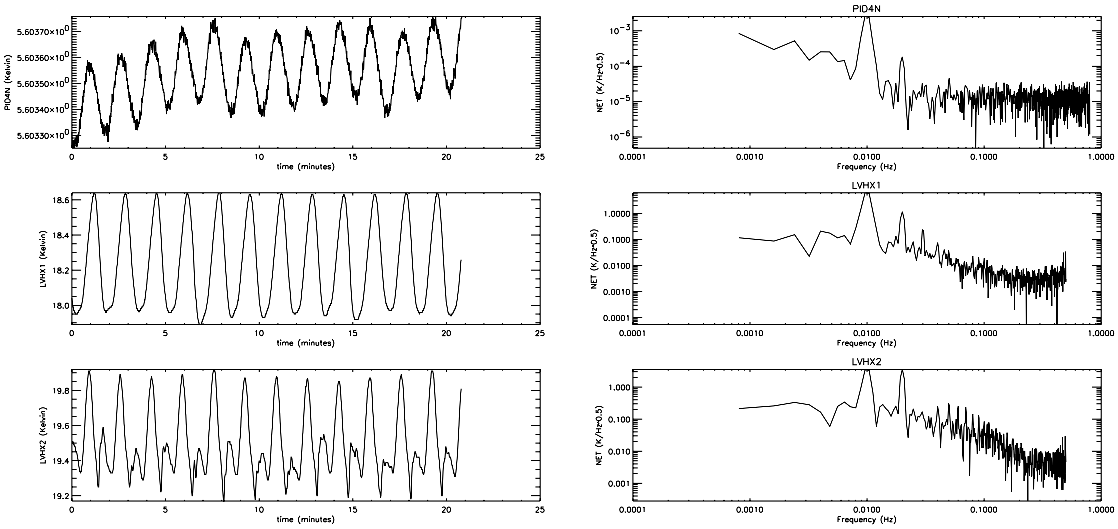


Figure 8. Effect on 4K horns of PACE fluctuations with 100 seconds period. Left: Thermometers measurements. Right: Thermometers signals power spectrum density.

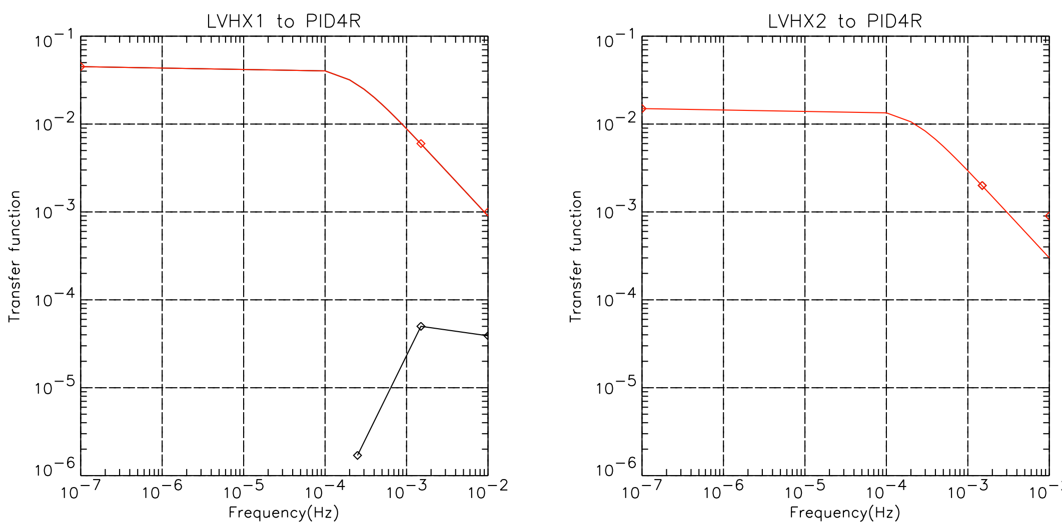


Figure 9. Thermal transfer functions between Sorption Cooler 18K cold ends and HFI 4K horns with (black line) and without (red line) 4K temperature regulation.

0.1K stage internal damping measurement The HFI 0.1K stage is made of two sub-stages: the 0.1K dilution plate and the 0.1K bolometer plate (figure 10). Thanks to the use of an alloy of Holmium Yttrium[13] (HoY) linking the two 0.1K stages it is possible to completely damp the high frequency thermal fluctuations induced on the dilution plate by the 0.1K dilution cooler. HoY alloy shows a huge peak of heat capacity around 0.1 Kelvin which allows this damping effect. The performances of HFI HoY based architecture has been check during HFI characterization campaign (PFM-CAR) in the Saturne cryostat (figure 11) at IAS, Orsay in march 2006

On the figure 10 we see that the fast temperature changes of the dilution plate (PID1R) has nearly no effect on the bolometers plate temperature (PID2R).

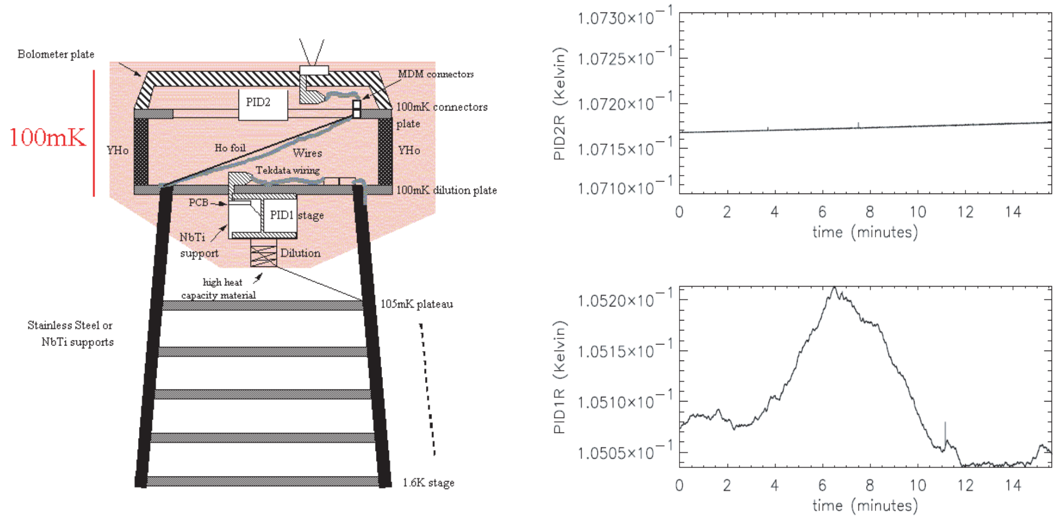


Figure 10. Left: 0.1K stage architecture and PID heater location (PID1 and PID2). Right: HoY damping effect between HFI 0.1K stages.

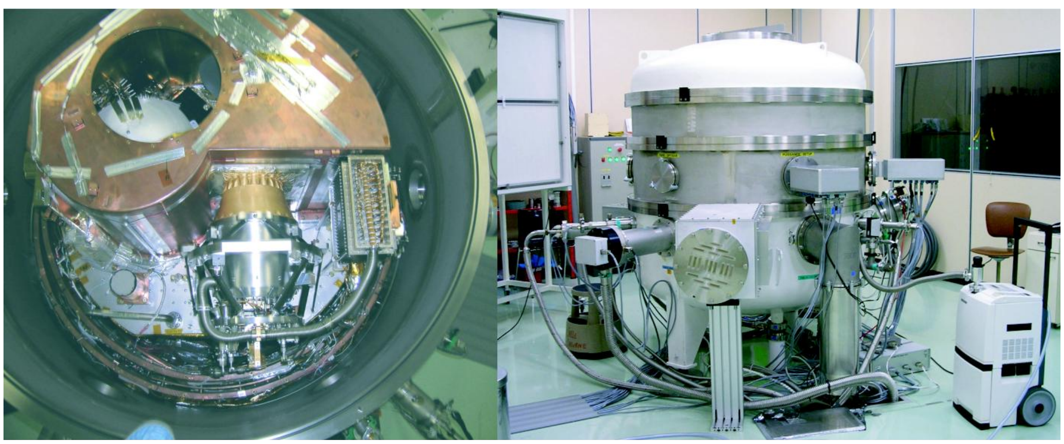


Figure 11. Left: Planck-HFI Flight Model in IAS Saturne cryostat. Right: IAS Saturne cryostat.

3.2. Active thermal control tests

The HFI active thermal control system is made of various heaters located on the HFI cryogenic stages with heating power controled by a PID regulation algorithm implemented in the sensitive thermometers readout system.[14] For the 4K and 1.6K stage, one thermometer and one heating belt placed around each stage (figure 12) are used for the temperature regulation. For the 0.1K stage single heaters are placed at thermometers location (PID1 and PID2 on figure 10). Regulations tests of the HFI cryogenic stages have been performed during HFI PFM-CAR campaign. The results of these regulation tests are presented below:

4K stage PID thermal control test The power spectrum density of the 4K stage temperature during regulation test is presented figure 13. We see that with the regulation ON, the temperature fluctuations of this stage are not far from requirements.

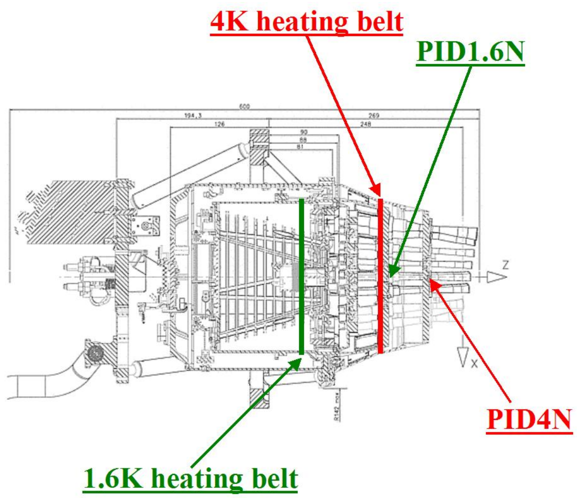


Figure 12. Thermometers and Heaters locations for the PID regulation systems of the 1.6K and 4K stages.

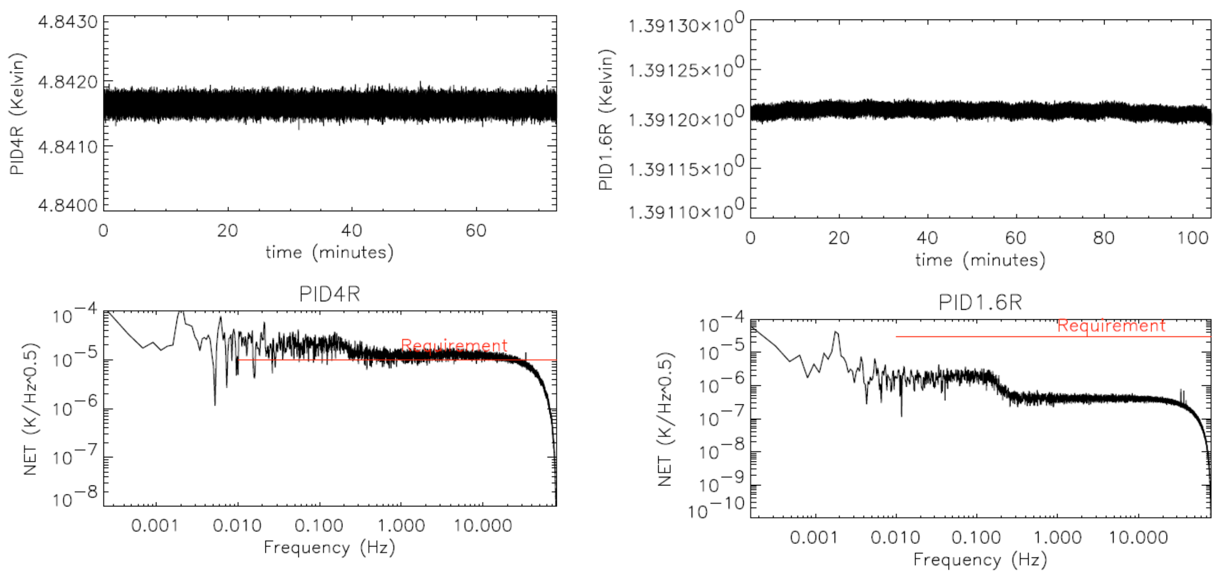


Figure 13. Left: 4K stage temperature stability during PFM regulation tests. Right:1.6K stage temperature stability during PFM regulation tests.

1.6K stage PID thermal control test The power spectrum density of the 1.6K stage temperature during 1.6K regulation test is presented figure 13. We see that for this stage, we are well under the requirements when the regulation is ON.

0.1K stage PID thermal control test Preliminary regulations tests of the HFI 0.1K stage have been performed during HFI PFM-CAR campaign (figure 14). During this test the two HFI 0.1K regulations (PID1 and PID2) were setting on simultaneously.

The 20nK/$\sqrt{Hz}$ temperature stability specification is applied to the temperature of the bolometer plate only. We see on (figure 14) that the temperature stability of the bolometers plate is within specifications if we look at the density power spectrum of the PID2R thermometer.

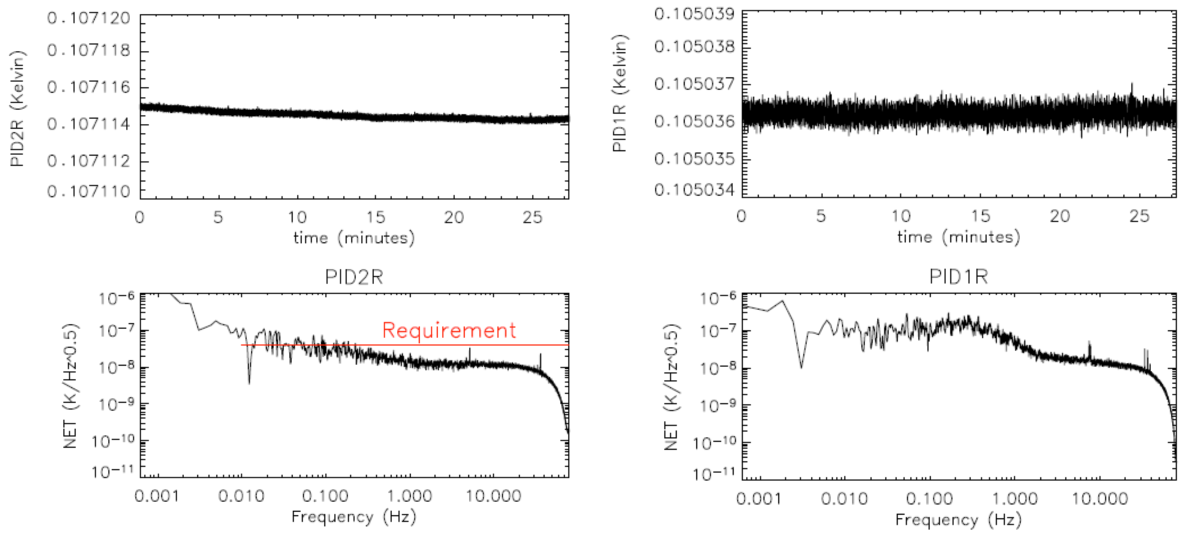


Figure 14. HFI 0.1K stages temperature stability during PFM 0.1K regulation test (06/03/25).

4. CONCLUSION

The expected sources of fluctuations in the Planck High Frequency Instrument are intrinsic fluctuations of the three active coolers on-board the satellite.

The measurements done on the CQM and FM models of the HFI in the Saturne test tank and at system level including the 4K and Sorption coolers have allowed us to establish the relevant transfer functions between coolers cold tips and critical elements of the instrument: HFI 4K horns, 1.6K filters, 0.1K bolometers plate and LFI reference loads.

The Sorption cooler temperature fluctuations affect the 4K box through conduction of several elements (harness, pipes, heat switch and dilution gases) and through the modulation of the pre-cooling of gases of the 4K and dilution coolers.

The 1.6K and 0.1K stages thermal fluctuations are dominated by the intrinsic fluctuations of their coolers cold tips. The 1.6K PID brings these well within requirements. The passive filtering by the HoY link between the dilution cold head and the bolometer plate filters very efficiently periods shorter than a few minutes. The PID takes care of the long term drifts and brings the bolometer plate temperature stability within requirements.

The 4K fluctuations are dominated by the Sorption cooler ones through conduction from the HFI-FPU 18K plate ($\sim$3/4) and conduction through the LFI instrument ($\sim$1/4). These fluctuations have been found to be attenuated at high frequency by passive damping. The 4K PID brings back the longer periods near the requirement.

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