DEVELOPMENT AND TEST OF A CRYOGENIC PULSATING HEAT PIPE AND A PRE-COOLING SYSTEM

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ABSTRACT

The needs of thermal links in cryogenic applications are increasing, especially because of the use of cryocoolers which offer a reduced size cold finger. The Pulsating Heat Pipe (PHP) is a passive two-phase high performance thermal link. Like the conventional heat pipe, it features a closed tube filled with a two-phase fluid able to transfer heat from its hot part (evaporator) to the cold part (condenser). A general problem for any two-phase cryogenic thermal link is the pre-cooling of the evaporator to ensure the presence of liquid inside the evaporator to start the flow motion. In conventional heat pipes, this problem is by-passed by the wick but in the case of PHPs it has to be specially addressed. We have designed, manufactured and tested a helium PHP associated to a novel pre-cooling system. It allows reducing significantly the cool down time of the PHP evaporator. The maximum transferred power of the PHP is 145mW with a cold source at 4.2K.

KEYWORDS: Pulsating heat pipe, two phase heat transfer.

INTRODUCTION

Efficient thermal links are needed to ease the distribution of the cold power in any cryogenic systems when mechanical cryocoolers are used. When the distance between the object to be cooled and the cryocooler becomes large, typically of the order of one meter or more, the use of copper bar leads to significant temperature gradients. The two phase thermal links become attractive in such a situation and a lot of developments have been made. The pulsating heat pipe (PHP) is considered as the most efficient two-phase thermal link, compared to other systems such as thermo siphons or and loop heat pipes [1]. It is very simple and features a single capillary tube partially filled by liquid and bended in several turns between the cold hot sources. At cryogenic temperature PHP has been already studied using nitrogen [2] and other fluids such as helium [3-4] with a large number of turns. We present the thermal performances of a laboratory prototype of cryogenic closed PHP using helium at around 4.2 K as a working fluid. It is proposed to be coupled with a novel a pre-cooling system to reduce the cool down time which could be a problem in future applications.

DESCRIPTION OF THE PHP AND ITS NOVEL PRE-COOLING SYSTEM

Helium PHP

A laboratory prototype has been designed manufactured and tested at the Service des Basses Températures of Institute of Nanosciences et Cryogenics. It features (FIGURE 1) a thick condenser bloc and an evaporator bloc on which an electrical heater is glued (not represented on the figure). The blocs are made of copper in which parallel grooves are machined. The tube is bended into 5 turns and brazed onto the blocs where grooves have been machined. The inner diameter of the tube is 0.5 mm, which is smaller than the capillary length [1].

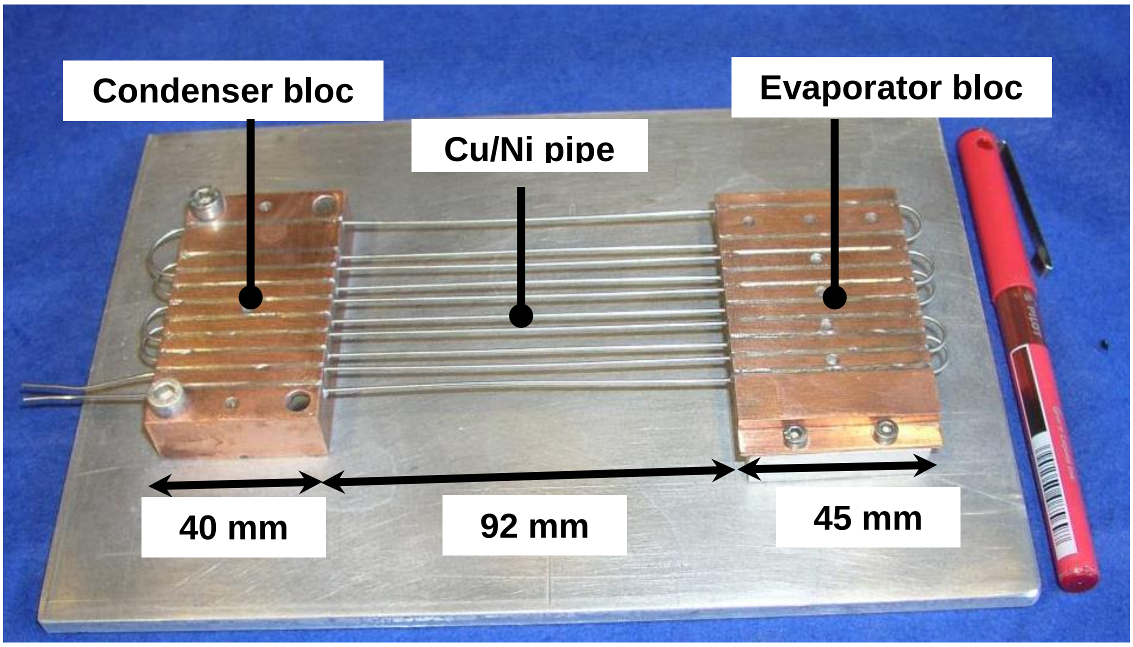

FIGURE 1. PHP setup.

Novel pre-cooling system

If the PHP evaporator is not pre-cooled, its thermalization may take a considerable time because it represents a significant thermal mass together with the hot object to be cooled. To reduce the cool down time, the evaporator is thermally coupled (FIGURE 2) to a novel pre-cooling system explained in FIGURE 3. It is a closed two phase system. It consists of two cold reservoirs, two thermal resistances that may heat the reservoirs, an evaporator and a single pipe that connects it to the reservoirs. Initially, the reservoirs are cold and thus contain the liquid inside. The pre-cooling procedure consists in actuating alternatively the electrical heaters of the reservoirs.

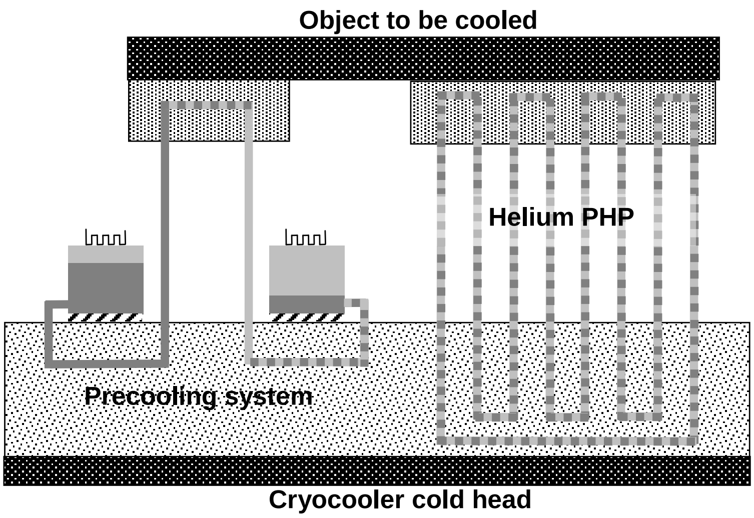

FIGURE 2. Arrangement of the PHP coupled with the novel pre-cooling system.

When applying a small heating power Q_{R1} to the reservoir 1, both its temperature T_{R1} and pressure increase slightly and a pressure difference between the two reservoirs appears. It pushes liquid towards the other reservoir. The cold liquid flows towards the evaporator where it is evaporated. The vapor penetrates into the reservoir 2 where it is condensed and the reservoir 2 is filling up. During this process, a significant cooling power Q can be removed from the object due to the latent heat. When the reservoir 1 empties, its heater is switched off and the heater Q_{R2} of the reservoir 2 is turned on. As a consequence the flow direction changes and a similar process occurs.

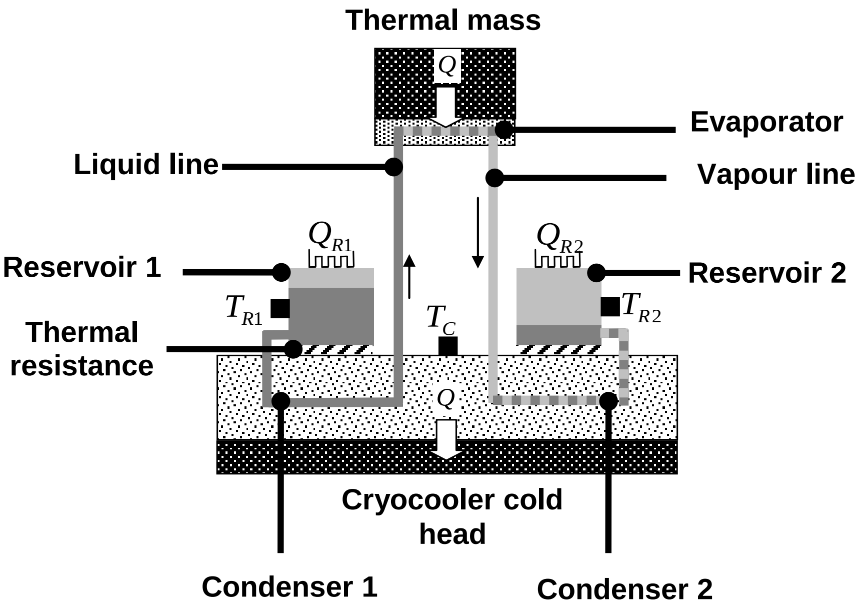

FIGURE 3. Principle of the novel pre-cooling system.

The pre-cooling system setting is presented in FIGURE 4. The reservoirs (5 cc each), the condenser and evaporator blocs are made of copper. The pipe (1 mm outer diameter) is brazed in grooves machined in the copper blocs. The pipe ends are brazed close to the bottom of each reservoir to use their full liquid capacity. The system is equipped with electrical heater on each reservoir and with thermometers (Cernox sensors) mounted on the reservoirs and on the condenser bloc.

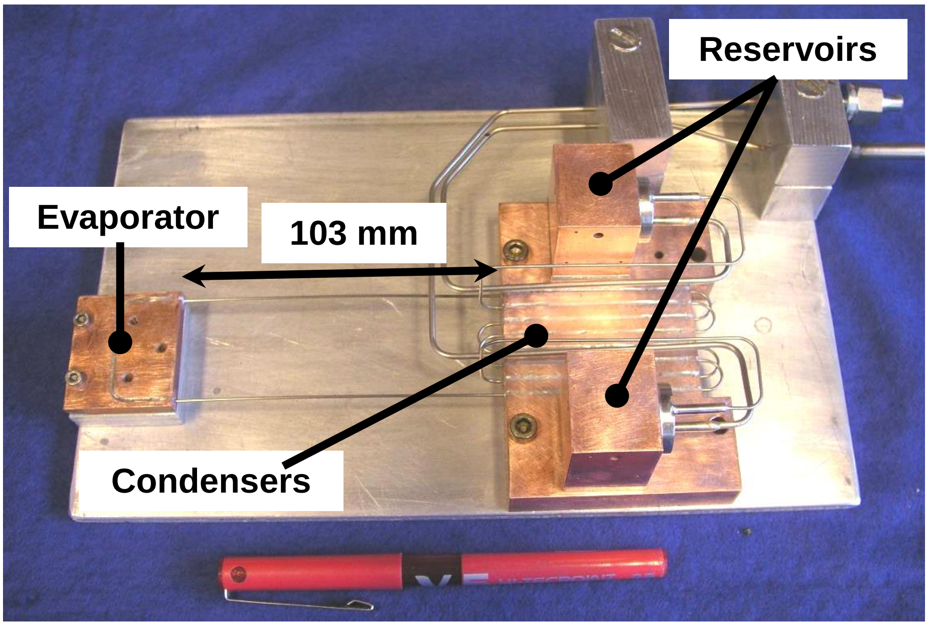

FIGURE 4. The pre-cooling system.

EXPERIMENTAL SET UP

The PHP and the pre-cooling system were tested in a variable tilt angle test cryostat (FIGURE 5). It features a vacuum vessel with a double stage pulse tube cryocooler as a cold source. The first stage is used to cool the first 40K copper thermal shield. The second stage cools the internal 4 K thermal shied and a large, thick and isothermal copper cold plate whose temperature T_{CP} is kept constant at 4.2 K with PID regulation. The condenser bloc of the pre-cooling system and the PHP condenser are mechanically anchored to the cold plate. The evaporator of the pre-cooling system and the PHP evaporator are mechanically and thermally coupled together. They represent the total mass of 0.37kg to be cooled. Both systems can be separately filled with helium using a 1 liter hot reservoir located outside the cryostat and equipped with a pressure sensor. During the cold tests the hot reservoir is isolated from the cold parts with valves. However the PHP, which has a quite low internal volume (~0.4cc) is connected with warm pipes located inside the cryostat. Their total volume is much larger, of the order of 30cc. Thus the PHP is not an ideal closed PHP, but a PHP with a connected warm volume. Two types of tests have been performed:

- Cool down tests starting from 60 K evaporator and 4.2 K condenser in horizontal orientation ($\theta = 0°$); first without pre-cooling system (passive cooling down), then with it (active cooling down). These tests aim at quantifying the efficiency of the pre-cooling system.
- PHP thermal performance at different favorable tilt angle θ (FIGURE 5), from 0° to 40° and different transferred power Q up to 150mW.

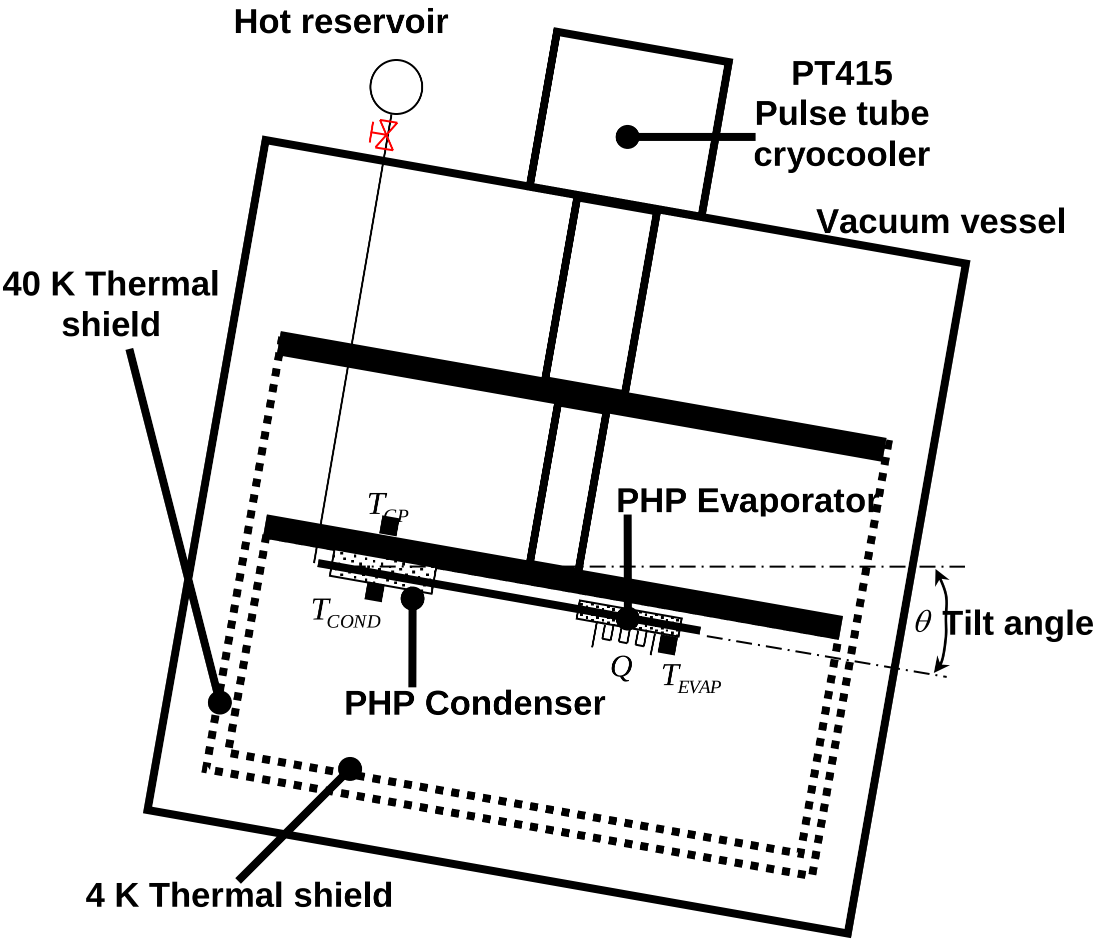

FIGURE 5. Experimental set up.

RESULTS AND DISCUSSION

Cool down test

The time needed to cool down the PHP evaporator from 60 K to 4.2 K is five times smaller when using the pre-cooling system (FIGURE 4). In the case of passive cool down it takes almost 9h to reach 4.2K while only 1.7h is necessary in the case of active cool down.

The passive cool down is dominated by the longitudinal conduction along the tube wall of the PHP and to a lesser extent by the radiative heat exchange with the cold environment. Therefore, the time depends strongly on the geometry of the PHP: number of turns, thickness and length of the adiabatic section of the PHP. It is proportional to this length at constant number of turns and to the tube thickness. On the other hand, it is inversely proportional to the number of turns at constant length and tube thickness. Thus, for a thermal link length close to 1 m, the cooling time may become inacceptable. For the active cooling, the typical time does not depend on these parameters and the PHP can be designed without bothering about the pre-cooling time.

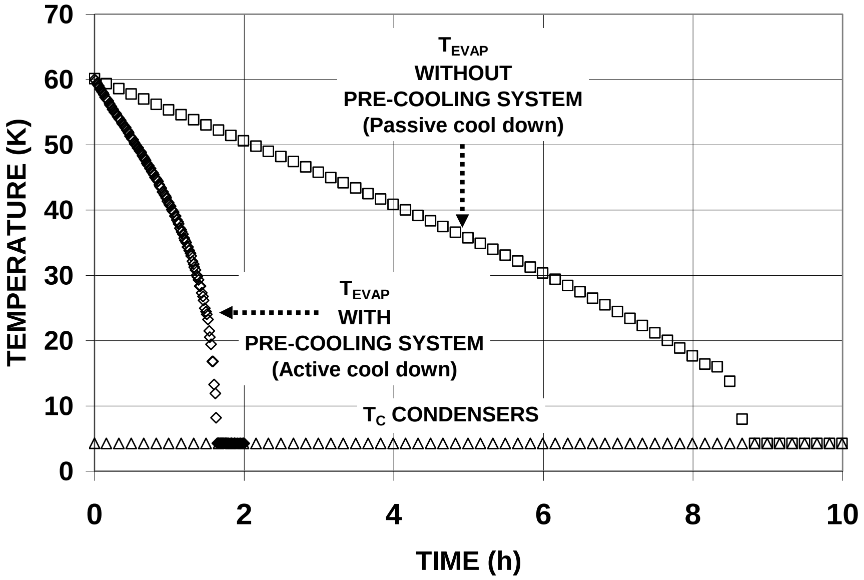

FIGURE 4. Cool down of the PHP evaporator using the pre-cooling system (active cool down) and without if (passive cool down).

During active cool down (FIGURE 5), a small heating power (5 mW) is alternately applied to the two-phase reservoirs. The temperature of the heated reservoir rises (up to 4.9 K) and fixes the pressure of the system. As a consequence, the temperature of the other (not heated) reservoir is close to that of the heated reservoir because of negligible pressure drop in the pipe. When the heated reservoir empties, the vapor starts flowing out of it instead of the liquid. Therefore the reservoir temperature starts to decrease. This phenomenon is used to switch the heating of the reservoirs. In the experiment, the use of such a process allows removing a total energy of 950 J (value calculated using the mass of the two evaporators and the specific enthalpy of copper) from the PHP evaporator. This corresponds to a mean transferred power of 150mW.

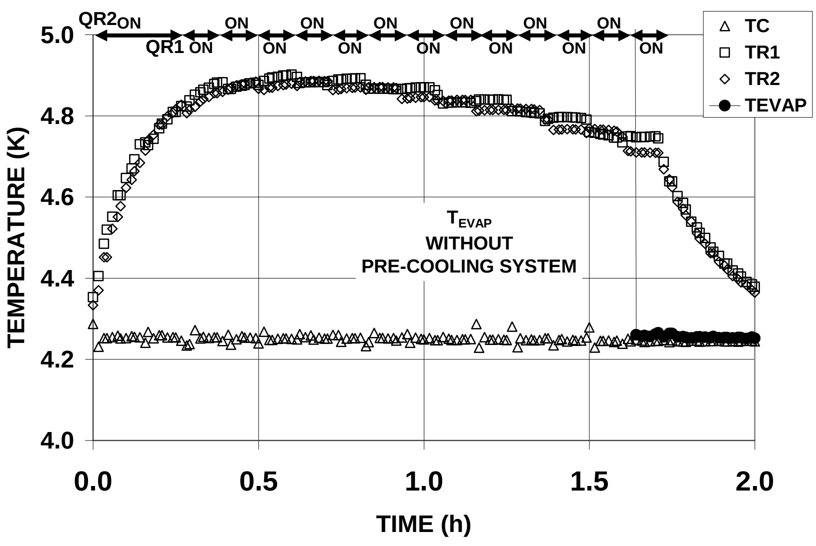

FIGURE 5. Cool down of the PHP evaporator with the pre-cooling system. The temperatures as functions of time are shown.

As a conclusion, the pre-cooling system is capable to remove a significant power (150mW) by using a very small active heating power (5mW). This demonstrates the excellent capability of such a system to cool down any warm object to cryogenic temperature.

Cryogenic PHP

FIGURE 5 presents a typical thermal response of the PHP for a θ=10° favorable tilt. The thermal resistance is constant 2.5 K/W up to the maximum capability (75mW). Above this level the evaporator temperature rises dramatically (about 7 K above the vapor-liquid critical temperature of helium). This thermally stabilized behavior probably corresponds to a heat transfer process similar to that of a thermo siphon. When the tilt angle is increased, the maximum capability increases as shown in FIGURE 6 and 145 mW transferred power is reached. When the PHP is horizontal, a small power (15mW) is transferred.

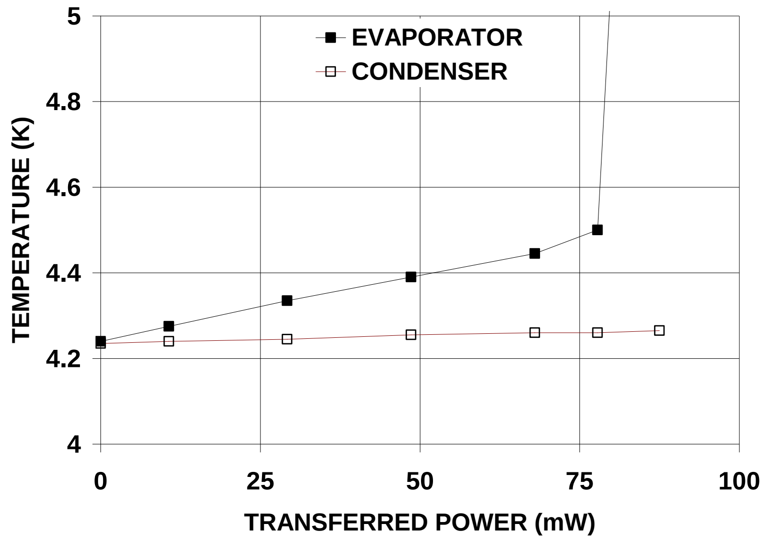

FIGURE 5. Condenser and evaporator temperatures of the PHP as functions of transferred power at θ=10° favorable tilt.

The presented results are close to those obtained with a PHP [4] that had two times more turns.

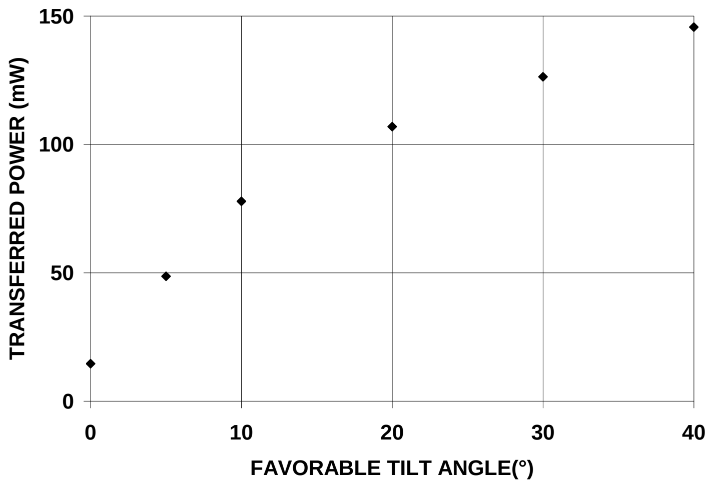

FIGURE 6. Maximum transferred power as a function of favorable tilt angle.

CONCLUSION

A helium PHP associated to a novel pre-cooling system has been designed, manufactured and tested at INAC/SBT. A pre-cooling system, which uses a small heating power (5 mW) applied to one of its two reservoirs, allows reducing dramatically the cool down time of the PHP evaporator. It is capable to remove a mean power of 150mW from any object to be cooled from 60 K to 4.2 K. The maximum power of 145 mW is transferred by the PHP with a cold source at 4.2 K and 2.5 K/W thermal resistance.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the help of D. Garcia, J. Inigo, Y. Poultriniez and all technical support staff of INAC/SBT in manufacturing, commissioning, and testing of the cryogenic system.

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