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Pulse-tube dilution refrigeration below 10 mK for Astrophysics

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Abstract Astroparticle bolometric detectors often rely on the use of dilution refrigerators providing a large cooling power at millikelvin temperatures. Conventional machines, however, need a systematic supply of cryogenic fluids, complicating and making more expensive their operation, particularly in underground laboratories. We describe here novel cryogen-free dilution units, able to cool down large detectors to millikelvin temperatures, and where cooling and warming times have been optimised.

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1 Introduction

Particle and astroparticle physics require very high energy resolution and sensitivity in order to detect very small energy depositions. This is most conveniently achieved by placing at very low-temperatures a suitable material which acts as an absorber medium. The deposition of energy by an incident particle produces an increase in temperature, which is larger for low specific heat materials. High purity insulators at temperatures well below the Debye temperature and superconductors or superfluids well below their critical temperature are currently used for this purpose. In practice, millikelvin temperatures are needed in different experiments related to the detection of low-energy neutrinos, the search for dark-matter, β and γ spectroscopy and X-ray astronomy. Since the detection probability scales with

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the absorber mass, modern low temperature detectors can have masses as large as several tons. This places stringent conditions on the cooling power of the dilution refrigerators used in these experiments.

2 Evolution of pulse-tube precooled dilution refrigerators

Classical dilution units available today are based on a Grenoble design incorporating sintered silver heat exchangers and large pumping systems.[1,2,3,4]. They can achieve large ^{3}He flow rates (a few mmol/s), thus providing the large cooling power needed by massive astroparticle detectors. Unfortunately, their operation requires a constant supply of cryogenic fluids, typically 15 liters of liquid helium daily. This is clearly a major inconvenient for experiments located in deep underground laboratories, for safety reasons, but also for economical and practical considerations. In addition, the liquid helium dewar makes the systems very large, and also complicates the design of the detector environment.

Pionnering cryogen-free dilution refrigerators were buit several years ago, using Gifford-Mac Mahon coolers[5,6], with encouraging results. The main incovenient of these systems was the level of vibrations of the Gifford-Mac Mahon machines. Pulse-tube (PT) coolers, which appeared on the market several years ago, are relatively quiet systems, but their minimum temperature was high. Koike et al.[7] designed a hybrid refrigerator, incorporating a PT and a Gifford-MacMahon cooler used in their appropiate temperature range.

In the late nineties pulse-tube (PT) coolers reached temperatures of a few kelvins with nearly one watt of cooling power. This motivated us to undertake the development of pulse-tube pre-cooled dilution refrigerators (PT-DR) in the framework of a scientific-industrial collaboration (CNRS-L'Air Liquide). Two models (PT-DR1 and PT-DR2) have been built since 2000. PT-DR1 was commercialized in 2001, and PT-DR2 has been developed since then. Technical details have been given in a recent publication[8].

Several groups worked along these lines during this period. In particular, an excellent work has been performed by Uhlig and coworkers, and published in great detail[9,10], while commercial units started appearing on the market. These machines have a similar aspect, dictated to some extent by the PT cooler geometry, but there exist however substantial differences in their cryogenic design, and also in their performance. Our PT-based dilution refrigerator (PT-DR) was specifically designed for astroparticle detectors, with a high cooling power, a very low base temperature ($T < 10$ mK), a large experimental volume, and a short cool-down cycle. We describe in the following the technical aspects directly related to these stringent requirements.

3 The large cooling-power cryogen-free dilution refrigerator

The excellent characteristics of the refrigerator PT-DR2 described here are associated to an important modification of the pulse-tube cooler and to a global optimisation of the system. The latter includes several components. First, a classical low temperature dilution unit, based on a refrigerator developed in Grenoble and commercialised since 1994 by L'Air Liquide as "Maxidil". Several step sintered silver

Fig. 1 (Color online) Cryogen-free dilution refrigerator . The main parts of the dilution unit, i.e. the mixing chamber, a continuous heat exchanger, the still and the Joule-Thomson exchanger are clearly visible, as well as the 4K and 60K plates connected to the pulse-tube cooler. The thermal shields and the 4K vacuum enclosure have been removed.

heat exchangers of large surface area designed with channel dimensions adapted to the nominal flow rate ensure reaching the desired temperature, from 20 mK down to less than 5 mK, depending on the number of step exchangers. PT-DR2, in the version described here, had only two small sintered silver heat exchangers; its design was optimised for flow rates in the range 0.1 - 0.3 millimoles/second.

The second component to be considered is the pumping system of the dilution unit. PT-DR2 was initially equipped with a 300 l/sec turbo-molecular pump and a 18 m^3/h rotary pump. The minimum temperature was 8.5 mK, at flow rates of 45 and 75 micromoles/s. With a 600 l/sec turbomolecular pump and a 40 m^3/h rotary pump we obtained 11 mK at flow rates of 130 and 240 micromoles/s. The power measured at 120 mK was 0.360 mW, and the measured minimum temperature was 8mK at a circulation rate of about 150 micromoles/s.

The third element to be considered is the Joule-Thomson exchanger. This component (Uhlig and collaborators [11]) is needed because temperatures well below 4 K are not available in a standard PT cooler. The condensation of the ^{3}He gas circulating in the dilution unit is achieved here by Joule-Thomson expansion, starting

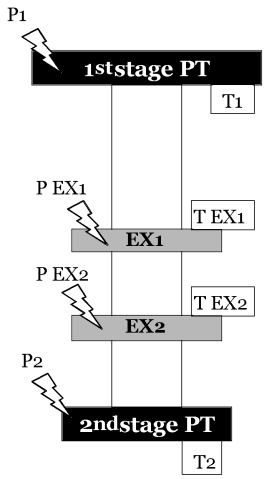

Fig. 2 An important modification ot the pulse-tube cooler (patented) allows us to extract a significant additional cooling power at low temperatures. The picture shows two intermediate heat sinks in addition to the usual two cold ends of the pulse-tube. The additional cooling power is particularly interesting since it allows reducing the precooling time and increasing the dilution refrigerator stage cooling power.

from pressures of a fraction of a MPascal. The cooling power of the cold gas pumped from the still is used to precool the incoming ^{3}He. An analysis of the thermodynamics of the condensation precess readily shows that the heat load on the still is higher than in classical dilution refrigerators, and varies substantially with the flow rate: the absence of the usual "1K pot" to remove a large fraction of the enthalpy of the incoming gas renders the dilution system dynamics rather critical and less flexible that in conventional dilution units, but this has been successfully dealt with in our system.

The fourth item of interest is the pulse-tube cooler itself. Up to this point we have implicitly assumed that the PT could provide the cooling power needed by a large power dilution refrigerator. The pulse-tube used here (Cryomech PT405), is a small cooler delivering relatively high power at high temperatures, but only 0.5 Watts at 4 Kelvin. These figures mean on one hand that long precooling times are necessary, and on the other hand that the circulation rate of the dilution unit is severely limited. Indeed, the temperature of the PT 4 K stage raises substantially with the incident power, as shown in the specifications of the PT405.

However, we have found a method that allows obtaining additional cooling power from the PT cooler[14]. The method exploits the thermophysical properties of the ^{4}He gas as well as the imperfect thermal exchange in the 4 Kelvin stage of the pulse-tube cooler. Several intermediate heat sinks are placed along the low temperature pulse-tube section at convenient locations. We show here an example with two heat sinks. A complete investigation of the cooling power at these heat sinks and at the pulse-tube stages has been performed[15]. The system is complex, since different powers can be applied at four points in the modified PT cooler, and the temperature of these four points depend on these four variables. We have

measured an additional power of one Watt at the 20 K heat sink and 0.7 Watts at the 5 K heat sink, while keeping the nominal power at the 4 K stage. This additional ("free") cooling power is therefore substantial, and achieved without impairing the performance of the pulse-tube usual stages.

This additional power is used for several purposes. In normal operation, the heat sinks, and particularly the 5 K one, alleviate substantially the task of the 4 K stage for the condensation of the ^{3}He gas. The "'4 K"' stage can thus take a much larger flow rate than that handled by other pulse-tube based dilution refrigerators or, for the same flow rate, work at a lower temperature. This is particularly convenient, since the relevant thermodynamic processes (condensation efficiency and ^{3}He/^{3}He concentration ratio) depend strongly on temperature, and a lower stage temperature results ultimately in an improved power and base temperature of the dilution unit. This improved condensation capacity is also important during the initial condensation of the helium mixture. The condensation time has been reduced by a factor of three, for the same amount of mixture, by using the additional cooling power. Last but not least, the time for precooling the system from ambient to Kelvin temperatures is reduced by a similar factor. This is essential when dealing with massive samples and large volume cryostats. This is the case of PT-DR2 (the dimensions and mass are given in [8]), which has a cool-down time of 12 hours.

4 Conclusions

We have developed a dilution unit which does not require liquid helium or liquid nitrogen supply. Temperatures above 4K are provided by a commercial pulse-tube cooler, Cryomech model PT405 [12]. However the latter has been modified for the purpose of providing additional cooling power at intermediate temperatures. This novel feature allows the design of an optimised pulse-tube pre-cooled system. A small PT cooler can therefore be used even for large power dilution units. It has the advantage of allowing short cool down time from room temperature, as well as rapid condensation of the dilution refrigerator ^{3}He-^{4}He mixture. The dilution unit reaches very low temperatures: less than 20 mK with a continuous counter-flow heat exchanger, and less than 10 mK with sintered silver heat exchangers. It provides high cooling power, since continuous circulation rates larger than 0.3 millimoles/sec can be used. A large experimental volume is available, and it can be very simply tailored to the experimental requirements. The new dilution units are therefore particularly adapted to experiments in underground laboratories, for cooling large cryogenic detectors of cosmic particles.

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