Istituto Nazionale
di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI
SIS-Pubblicazioni

LNF–07/04(IR)
January 29, 2007

THE RAP CRYOGENICS

Carlo Ligi, Sam Maša Vinko
INFN, Laboratori Nazionali di Frascati, P.O. Box 13, I-00044 Frascati, Italy

Abstract

The cryogenic setup of the RAP (Rivelazione Acustica di Particelle) experiment is described. The liquid helium cryostat operation, together with the commissioning of the dilution refrigerator, is reported.

PACS: 07.20.Mc

1 Introduction

The RAP experiment is dedicated to the study of the acoustic effects arising from the passage of high energy charged particles on bulk materials. The impinging particles release energy in the material, producing a local heating and consequentially a local pressure pulse. The latter gives rise to an excitation of the oscillation modes of the material that can be detected by a transducer. This kind of effect becomes important especially in gravitational wave resonant antenna measurements, where cosmic ray showers produce unwanted signals that must be recognized and properly subtracted to get the correct background.

The process is described theoretically by the so-called *Thermo-Acoustic Model* (TAM), that accounts for the thermo-mechanical interaction between particle and material. The TAM has been found to be generally in good agreement with the measurements, but recent detection of high-energy cosmic ray coincidences in the gravitational wave detector NAUTILUS showed a higher rate then expected when the antenna was in the superconducting state. In order to verify the correctness of the TAM at ultralow temperatures, and in particular with superconductive detectors, the RAP experiment has been proposed.

Two cylinders have been used as detectors, one made of the 5056 aluminum alloy (the same material of the NAUTILUS antenna) and the other of almost pure niobium. In both bars two piezoelectrics are placed, to reveal the oscillation signal. The bars are placed in a cryostat (one at a time), in order to study the behavior of the materials at different temperatures.

To perform the measurement, the experimental setup is placed in the Beam Test Facility (BTF) of the DAΦNE electron-positron collider ring in INFN-LNF, Frascati (Italy), that can deliver pulses of up to 10^{10} electrons in the energy range 25-750 MeV [1]. So far, RAP ran three times in the BTF. In the first run the Al5056 bar was operated at room temperature, to test the detector setup and verify the consistency with both the theoretical model and other known experimental results. In the second and third runs, prior to the dilution refrigerator installation, both bars have been cooled down to liquid helium temperature.

With the Al5056 bar, the TAM has been verified down to 4.5 K within a 10% accuracy [2]. The niobium bar, which transition temperature is $\approx$ 9 K, has been used to study the behaviour of a bulk material in the superconducting state simply cooling the bar to LHe temperature. The measurements showed discontinuity in the signal response at the transition temperature and a disagreement with the TAM at lower temperatures [3]. Niobium behavior cannot however be directy compared with Al5056, because the first is a pure element and is a type II superconductor while the latter is an alloy and a type I superconductor. As the final step of the experiment, the effect of the passage of high energy electrons in the superconductive state of the Al5056 cylinder is to be measured. To achieve this, the bar has to be cooled below its transition temperature (about 0.9 K), and this is to be accomplished by means of a dilution refrigerator in the cryostat. During the year 2006 the refrigerator has been mounted and at the moment its operation is being tested.

2 The cryogenic setup

The RAP cryogenic setup consists of a KADEL commercial liquid helium cryostat, 3.2m high and 1m in diameter, suspended on a vertically movable structure. The cryostat contains a dilution refrigerator made by Leiden Cryogenics, with a theoretical base temperature of about 100 mK and a cooling power of about 1 mW @ 120 mK. The entire experimental setup is shown in fig.1 and fig. 2.

2.1 The cryostat

A schematic view of the cryostat together with the cold side of the dilution refrigerator is depicted in fig. 3. The liquid helium (LHe) and liquid nitrogen (LN_2) dewars, with a capacity of 340 lt and 200 lt respectively, are placed in the upper half. 3 stainless steel cables are suspended from the top flange to support the experimental apparatus. To avoid the radiation input from the top flange into the experimental chamber, 8 aluminum radiation shields are mounted between the top room temperature flange, the 77 K OFHC copper flange and the 4.2 K OFHC copper flange. The two latter flanges are thermalized via direct contact with the LN_2 and LHe dewars respectively. The experimental chamber is positioned on the lower half of the cryostat and is surrounded by 1 OFHC copper and 2 aluminum radiation shields. These are attached to the cryostat and maintained at 0.6, 4.2 and 77 K via direct contact with the Still flange, the LHe dewar and the LN_2 dewar respectively. The LHe shield is indium sealed to separate the experimental chamber from the insulation zone. The outer container is an aluminum made vacuum shield.

Almost all connections are located on top of the cryostat (see fig. 2), such as the LHe and LN_2 dewars inlet/outlet ports, the electrical wire port to the experimental chamber, the connection for the experimental chamber vacuum turbo pump, a tube for the filling of gaseous helium in the experimental chamber, the pumping line for the 1K Pot and the feedthrough for the ^{3}He pumping line of the dilution refrigerator. Inside the experimental chamber, just below the ground plate of the LHe dewar, an OFHC copper flange houses the 1K Pot. This is a small container filled with a fraction of the LHe from the dewar, where by pumping on the bath with an Edwards XDS 35 scroll pump, the LHe is cooled to a temperature between 1 and 2 K. The 1K Pot filling is done through 3 small tubes, two of which can be independently opened or closed by means of needle valves. The third tube is directly connected to the dewar and is always open. To avoid transmission of mechanical vibrations to the bar, no strong thermal contact between the cryostat and the detector has been foreseen. Therefore, the heat exchange during the cool-down from 300 K to 4.2 K is provided by gas conduction, inserting a few mbar of gaseous helium in the experimental chamber.

So far, several cool-downs to LHe temperature have been done. The system is very reliable, and the behavior of the cryostat, with the exception of a time in which a failure in the LN_2 dewar occurred [4], is good. The cool-down procedure starts by putting LN_2 both in the LN_2 and in the LHe dewars to pre-cool all the system. After the temperature in the experimental chamber drops down about 80 K, the residual LN_2 in the LHe dewar is removed and all the gas is pumped out from the dewar, to avoid that during the LHe cool-down residual nitrogen freezes, plugging the connection tubes with the 1K Pot. After that, the LHe transfer begins. As the temperature in the experimental chamber drops down to about 6 K, the exchange gas is removed to avoid the helium liquefaction, the liquid vapour pressure of which would provide a lower limit to the vacuum.

Cooling the cryostat to 80 K and filling the LN_2 dewar takes about 3 days and about 1000 lt of LN_2. About 800 lt of LHe and 12 hours are sufficient to cool the system from 80 K to 4.2 K and leave about 150 lt of liquid in the dewar. The bar temperature during the last cool-down is shown in fig. 4. The cryostat liquid consumption, once thermalized, is about 1 lt/hour of LN_2 and about 1.5 lt/hour of LHe, that raises to about 2 lt/hour when the 1K Pot is in operation.

2.2 The dilution refrigerator

To reach the low experimental temperatures required by the experiment, the RAP cryostat has been equipped with a continuous flow, closed cycle ^{3}He-^{4}He dilution refrigerator. Apart from some small adaptation changes, it closely resembles the early version of that used in the MINIGRAIL experiment [5].

The dilution refrigerator is composed of:

- a cold part, consisting of the Mixing Chamber, the 50 mK Plate, the Still and a continuous heat exchanger in between of the latter two;
- a gas pumping system located outside the cryostat, composed of two Varian TV 551 NAV turbo-molecular pumps and an Edwards XDS 35 scroll pump;

- a ^{3}He pumping line that connects the cold part inside the cryostat to the pumping system located outside. This line is a continuous heat exchanger between the incoming and outgoing helium gas and additionally provides for three cooling steps, achieved through thermal contacts between the gas and the LN_2 dewar, the LHe dewar and the 1 K Pot respectively.
- a gas handling system (GHS) control panel, a picture of which is shown in fig. 5. The GHS is a circuit line where the mixture flow is controlled, either manually or automatically, by a number of solenoidal valves. In automatic operation, a CPU manages the valves based on a software program driven by several Pirani pressure gauges and a flow meter placed in the circuit line. The GHS also controls the cryostat helium dewar and the 1K Pot circuit flow, as also the vacuum pumps operation of both the refrigerator and the 1K Pot lines.

A schematic view of the dilution refrigerator is shown in fig. 6. Two separate containers are used to contain the gaseous ^{3}He and ^{4}He isotopes when the fridge is not in operation. The cleansing of the incoming helium gas is achieved through a couple of LN_2 cryo-traps placed in parallel, the second being a spare line in case the first one gets plugged or is saturated by impurities. By passing in the cryo-traps, the risk of plugs in the various impedances in the refrigerator by eventual impurities is depressed. From the cryo-traps the mixture enters the cryostat through the helium pumping line, where it is thermalized first to 77 K and then to 4.2 K through thermal links connected to the LN_2 and LHe dewars respectively. The gas is then brought into thermal contact with the 1 K Pot, so that it is condensed, after which it fills the Mixing Chamber and, partly, the Still. By pumping on the mixture bath, its temperature drops down and once low enough (i.e., below 0.87 K, but depending of the relative ratio of ^{3}He and ^{4}He), the mixture spontaneously separates into a ^{3}He rich and a ^{3}He poor phase. The rich phase, ^{3}He being lighter than ^{4}He, forms the top layer, while the poor phase forms the lower layer of the bath in the Mixing Chamber and also fills the Still. When the Still temperature reaches about 0.5 K, the natural evaporation of the mixture (basically composed by pure ^{3}He, due to the lower vapour pressure) is forced to increase switching on a heater placed inside the Still, which is user-controlled by means of a adjustable current source. This forced evaporation leads the ^{3}He atoms to migrate from the ^{3}He rich phase across the phase separation into the ^{3}He poor phase by osmosis. The migration process is endothermic and provides the refrigerator cooling power. The evaporation rate can be controlled by adjusting the current in the heater, allowing for a temperature control in the Mixing Chamber. The gas is then pumped out of the refrigerator by the pumping system and is returned into the condenser so that the cycle may start again. Three cool-downs have been done so far,

Table 1: RAP thermometers.

type	positioned on	working range
Pt1000	77 K flange	20 – 300 K
Pt1000	experimental chamber	20 – 300 K
FeRh	4.2 K flange	4 – 300 K
RuO_2	bar	0.1 – 20 K
RuO_2	suspension (bottom)	0.1 – 20 K
RuO_2	suspension (top)	0.1 – 20 K
RuO_2	Mixing Chamber	0.1 – 20 K
RuO_2	0.6 K flange	0.1 – 20 K
RuO_2	Still	0.1 – 20 K
RuO_2	1K Pot	0.1 – 20 K

but the temperature of the Al5056 bar never reached the transition temperature (about 0.9 K). The problems were, in all three runs, leaks between the dilution refrigerator mixture circuit and the experimental chamber. In particular, a bellows located above the Still must be changed due to leaks. At the moment part of the cold side of the fridge has been dismounted to be machined for the new bellows. In fig. 7 some of the relevant temperatures and pressures of the system during the last cool-down with the dilution refrigerator are shown.

2.3 Diagnostics

In addition to the GHS diagnostics, the cryostat is equipped by 10 thermometers, 2 vacuum gauges and a LHe level gauge. Capacitance liquid level gauges are also placed in the 1K Pot and in the Still, read by a capacitance meter.

The thermometers are all resistances of three different types, platinum (Pt1000), rhodium-iron (FeRh) and ruthenium dioxide (RuO_2). They cover different temperature ranges and are controlled by an AVS-45 and an AVS-47 Picowatt Resistance Bridges. A complete list of the thermometers in RAP is shown on tab. 1. The resolution of the RuO_2 resistances at low temperatures ($T < 4$ K) is better than 10 mK.

The vacuum sensors are 2 Alcatel ACC 1009 cold cathode/Pirani gauges driven by 2 Alcatel ACS 1000 controllers. They are combined-gauge sensors able to measure in the range 10^3–10^{-9} mbars, and are positioned in the insulation space and in the experimental chamber. The thermometers, pressure and LHe level readings are taken from the controllers via serial and GPIB ports and are stored in a PC running an in-house developed LabView program, which is displayed in fig. 8.

3 Acknowledgements

We warmly acknowledge Mauro Iannarelli for his tireless and invaluable work. We are also grateful to Franco Campolungo, Ennio Turri, Fabio Tabacchioni and the DAΦNE Cryogenic staff for their support, Giorgio Cavallari for the stimulating discussions, Giorgio Frossati and Arlette DeWaard for the assistance provided during the refrigerator commissioning.

References

[1] S. Bertolucci *et al*, Classical Quantum Gravity **21**, S1197 (2004)

[2] B. Buonomo *et al*, AstroParticle Physics **24**, 65 (2005)

[3] M. Bassan *et al*, Europhys. Lett. **76** (6), 987 (2006)

[4] G. Delle Monache and C. Ligi, RAP Technical Note 005 (2005)

[5] A. de Waard *et al*, Classical Quantum Gravity **21**, S465 (2004)

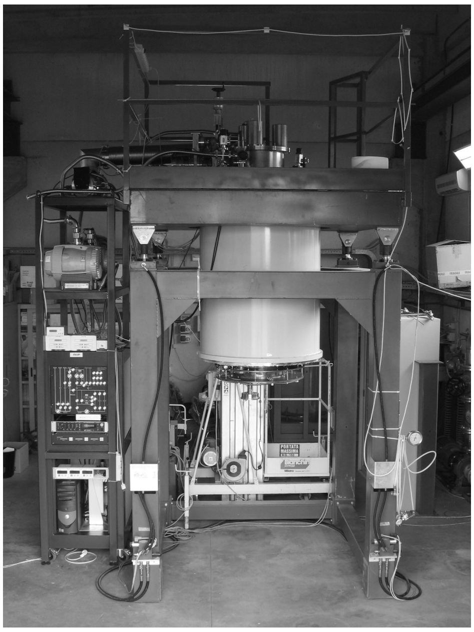


Figure 1: *The RAP cryostat, with the experimental chamber opened. On the left the gas handling panel with the diagnostic electronics and the PC are shown. Above the panel stands the pumping system.*

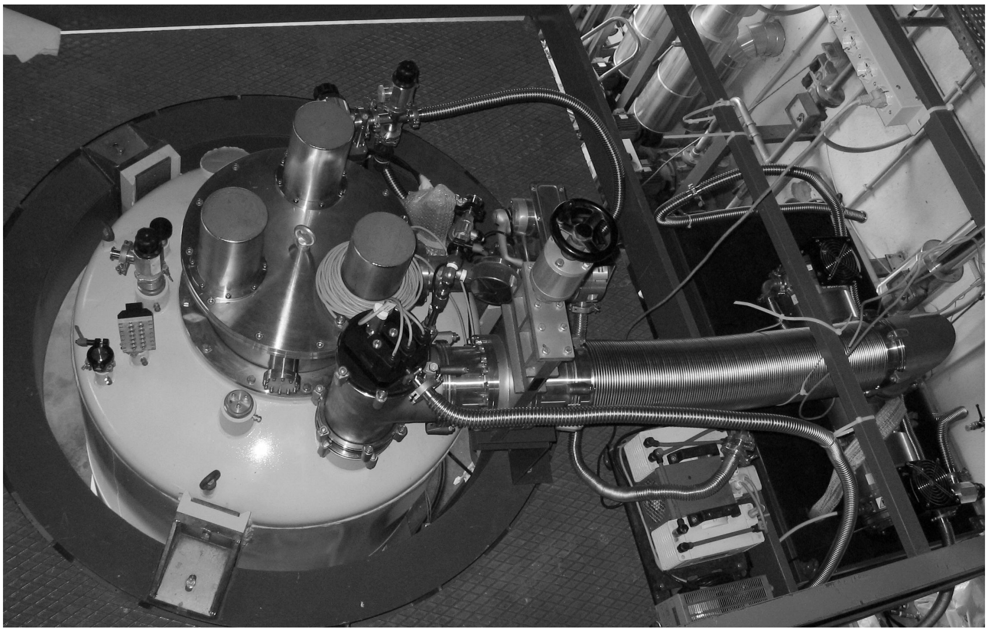


Figure 2: *Top view of the cryostat.*

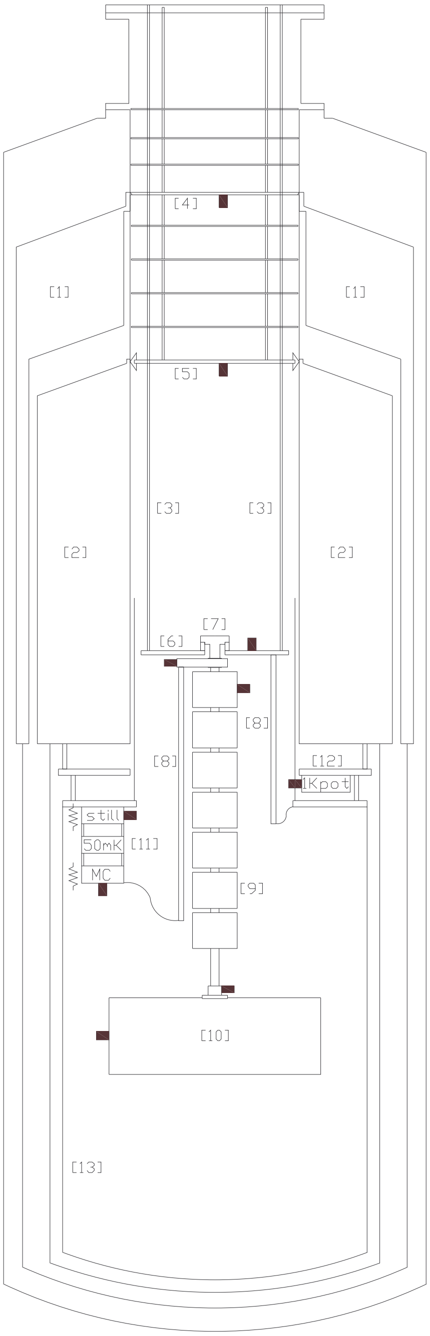


Figure 3: *The RAP cryostat:* [1] *LN_2 dewar,* [2] *LHe dewar,* [3] *SS cables,* [4] *77 K flange,* [5] *4.2 K flange,* [6] *0.6 K flange,* [7] *SS screw with Teflon ring,* [8] *OFHC copper thermal contacts,* [9] *OFHC copper suspension,* [10] *bar,* [11] *dilution refrigerator cold part (from top: the Still, the 50 mK plate and the Mixing Chamber),* [12] *1K Pot,* [13] *radiation shields. On black the thermometers.*

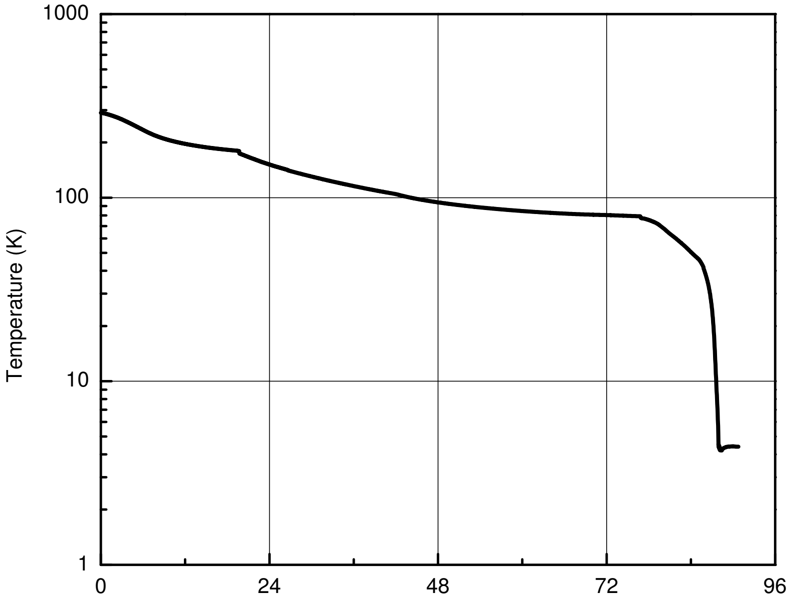


Figure 4: *Bar temperature versus time during the cool-down from room temperature to 4.2 K.*

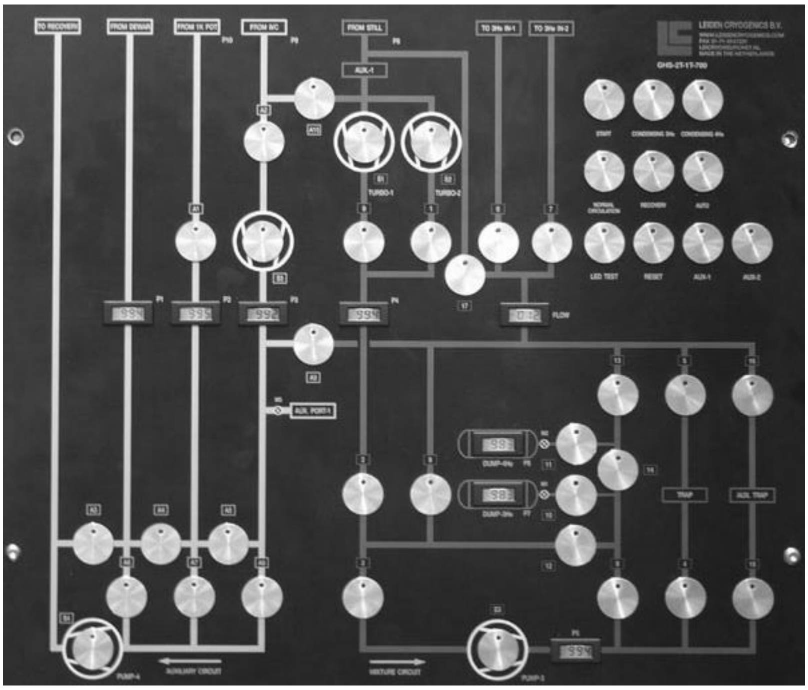


Figure 5: *The gas handling system control panel of the RAP dilution refrigerator.*

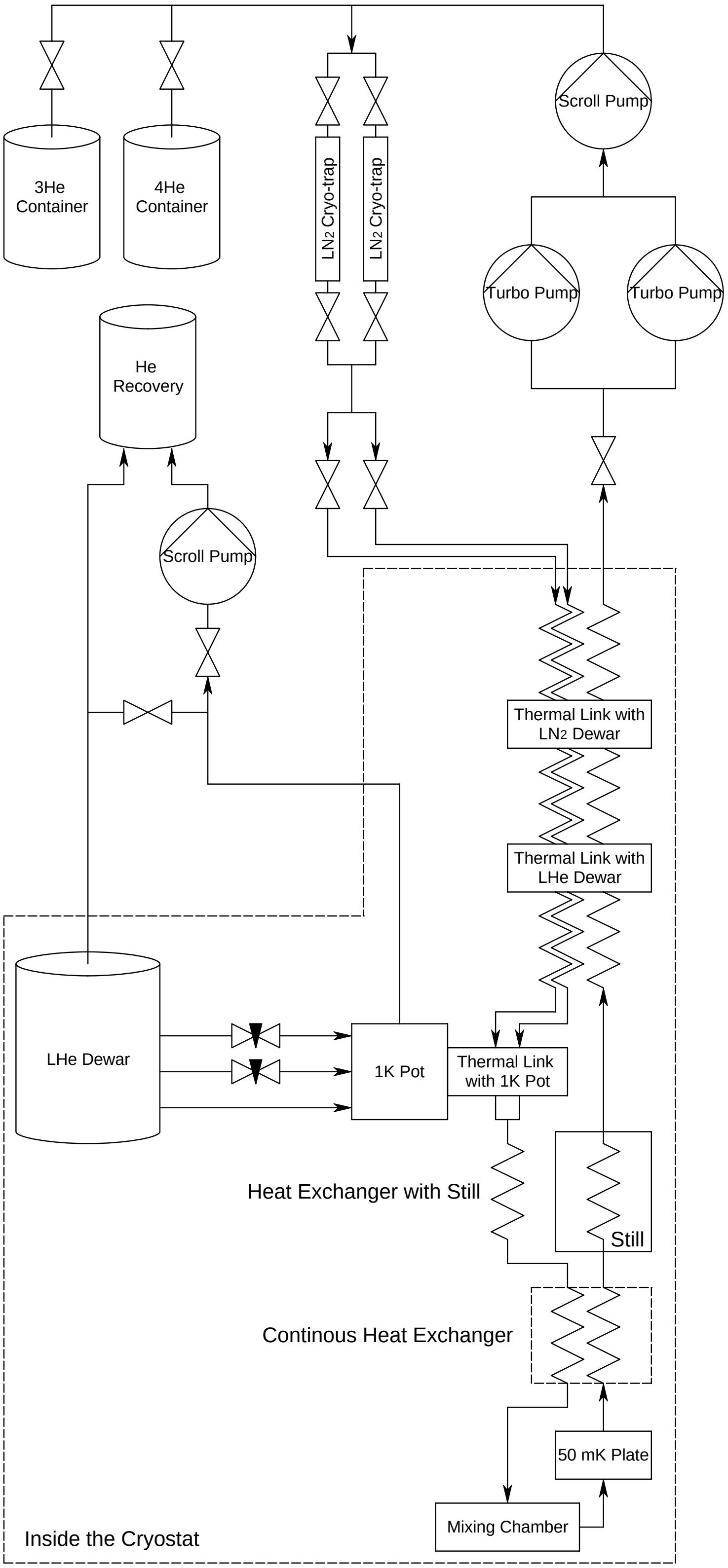


Figure 6: *Schematic view of the dilution refrigerator.*

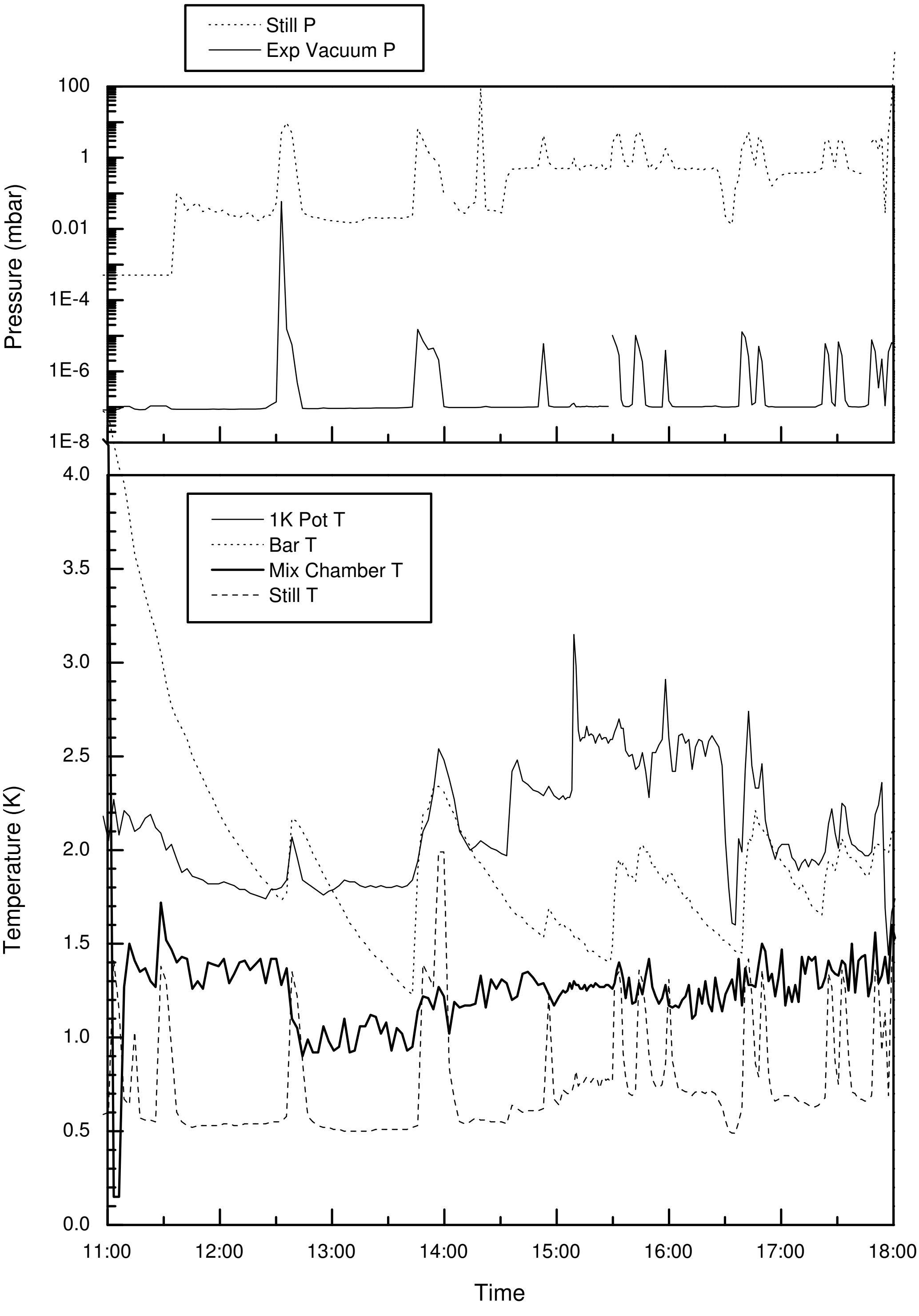
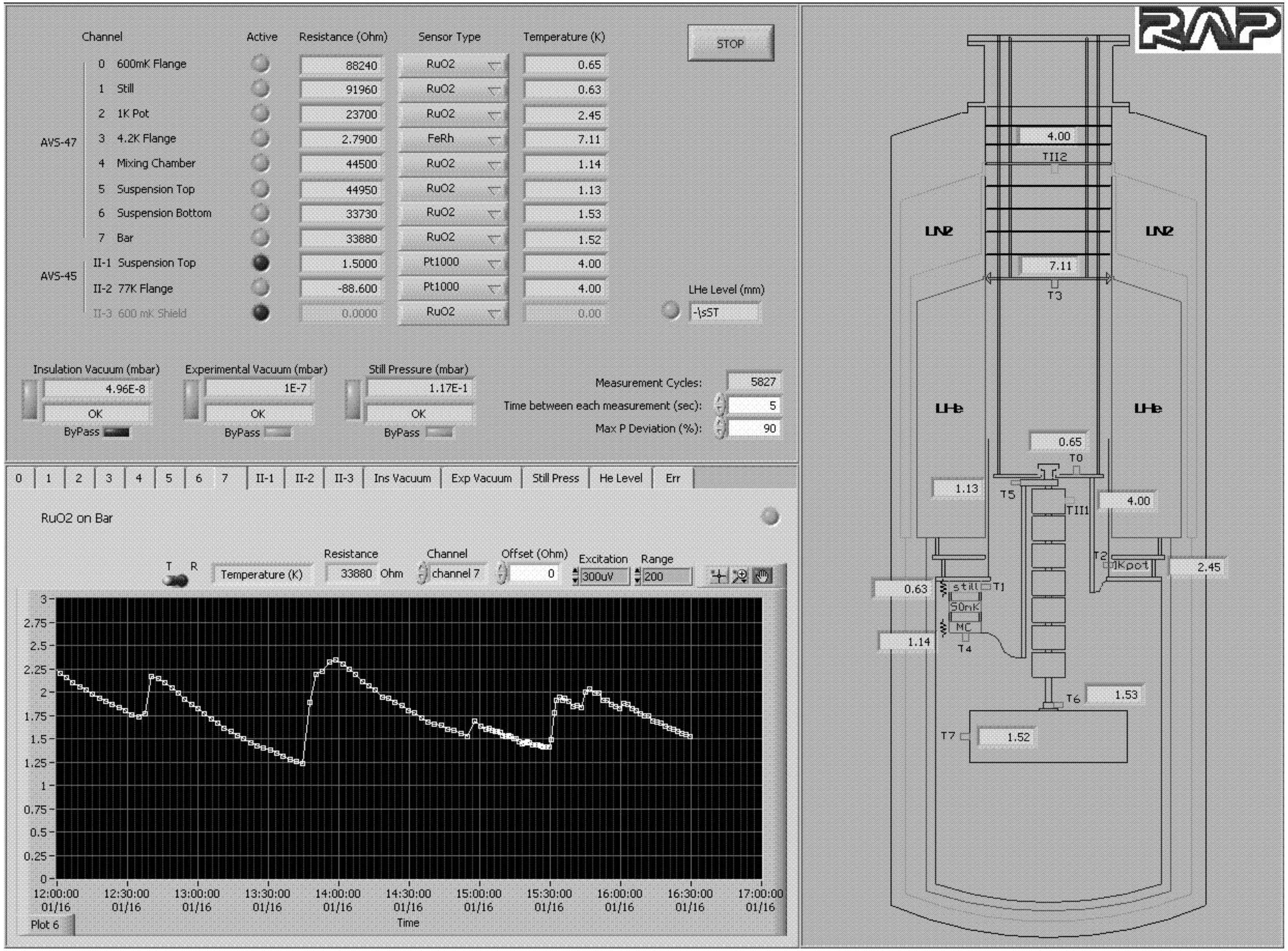


Figure 7: *Temperatures and pressures during the dilution refrigerator test (16/1/2007).*



	Channel	Active	Resistance (Ohm)	Sensor Type	Temperature (K)
AVS-47	0 600mK Flange	○	88240	RuO2	0.65
	1 Still	○	91960	RuO2	0.63
	2 1K Pot	○	23700	RuO2	2.45
	3 4.2K Flange	○	2.7900	FeRh	7.11
	4 Mixing Chamber	○	44500	RuO2	1.14
	5 Suspension Top	○	44950	RuO2	1.13
	6 Suspension Bottom	○	33730	RuO2	1.53
	7 Bar	○	33880	RuO2	1.52
AVS-45	II-1 Suspension Top	●	1.5000	Pt1000	4.00
	II-2 77K Flange	○	-88.600	Pt1000	4.00
	II-3 600 mK Shield	●	0.0000	RuO2	0.00

STOP

LHe Level (mm): -\sST

Insulation Vacuum (mbar): 4.96E-8 OK ByPass

Experimental Vacuum (mbar): 1E-7 OK ByPass

Still Pressure (mbar): 1.17E-1 OK ByPass

Measurement Cycles: 5827

Time between each measurement (sec): 5

Max P Deviation (%): 90

0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | II-1 | II-2 | II-3 | Ins Vacuum | Exp Vacuum | Still Press | He Level | Err

RuO2 on Bar

T R: Temperature (K)

Resistance: 33880 Ohm

Channel: channel 7

Offset (Ohm): 0

Excitation: 300uV

Range: 200

Figure 8: *Display view of the PC Program.*