ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Milano

INFN/TC-87/3
22 Aprile 1987

F. Alessandria, M. Cafici, G. Rivoltella, L. Rossi and M. Todero:

LIQUID NITROGEN COOL DOWN OF THE CRYOSTAT OF THE MILAN SUPERCONDUCTING CYCLOTRON

Servizio Documentazione
dei Laboratori Nazionali di Frascati

INFN - Istituto Nazionale di Fisica Nucleare
Sezione di Milano

INFN/TC-87/3
22 Aprile 1987

LIQUID NITROGEN COOL DOWN OF THE CRYOSTAT OF THE MILAN SUPERCONDUCTING CYCLOTRON

F.Alessandria, M.Cafici[*], G.Rivoltella, L. Rossi, M.Todero

- Universita' di Milano - Dipartimento di Fisica and INFN - sezione di Milano, Via Celoria 16, 20133 Milano

- [*]INFN - Laboratorio Nazionale del Sud, Viale A.Doria ang. Via S.Sofia, 95100 Catania

ABSTRACT

In this report the cool down to liquid nitrogen temperature of the cryostat of the Milan Superconducting Cyclotron (5 Tesla, 40 MJ) is described.

The LN cool down has been performed to check the cryostat stainless steel weldings against possible failures due to thermal stresses and to take experience in handling so large cryostat and to test the control system. Temperatures and stresses of some components have been continously monitored by means of a personal computer, that provided also a preliminary on-line analysis.

Eight days have been required to carry out the cool down and only four days for the warm up, with a total liquid nitrogen consumption of 27,000 liters. No damages to cryostat weldings or to other components of the superconducting coils have been found.

1. - INTRODUCTION

At the Milan University a heavy ions superconducting cyclotron is under construction (1,2,3). This accelerator, whose a vertical section is shown in fig. 1, is a three sector compact machine which can accelerate up to 100 Mev/nucleon the fully stripped ions and up to 20 Mev/n the uranium ions. One of the main component of the cyclotron is represented by the superconducting coils and cryostat. In particular the design and construction of the cryostat for the cyclotron is a very complicated task which requires a lot of tests to assure a good reability of the cryostat. Some tests, like the cool down of the superconducting coils vessel, could be made after the final assembly of the cryostat but the delay time produced by failures can be very large with heavy consequences on the accelerator time schedule.

For this reason a cool down of the coils vessel to liquid nitrogen temperature has been carried out before the assembly of the cryostat; so to make easy and quick an eventual repair the vessel has not been insulated by vacuum but by means of foam.

The test at LN temperature has allowed to measure the temperature map in the vessel and in the coils during their cooling. These measurements are essentially for the safety of the system because the refrigerant inlet in the vessel is not uniform and large thermal stresses, causing leaks in the weldings or failures in the coils components, may be induced if the cooling is not well controlled. Moreover the cool down has been useful to check the diagnostic system, constituted by a large number of gauges for temperature and stress measurements.

2. - COILS AND CRYOSTAT DESCRIPTION

The superconducting coils (4) are wound with double pancake technique and are immersed in a liquid helium bath at nearly atmospheric pressure. The cable is a copper matrix (13 x 3.5 mm^2) in which a Cu-NbTi insert is soldered. Turn to turn insulation is assured by a mylar ribbon (11 x 0.2 mm^2) on which are mylar glued strips (11 x 0.35 mm^2) 4 mm large and every 5 mm regularly spaced, whereas the layer to layer insulation is obtained by G11 strips 1 mm thick.

The coils, as shown in fig. 2, are splitted in two sections (α and β sections) which, indipendently supplied, can be oppositely excited so that they are pushed away by about a 600 tons force. In order to compensate this force and avoid displacements, the coils

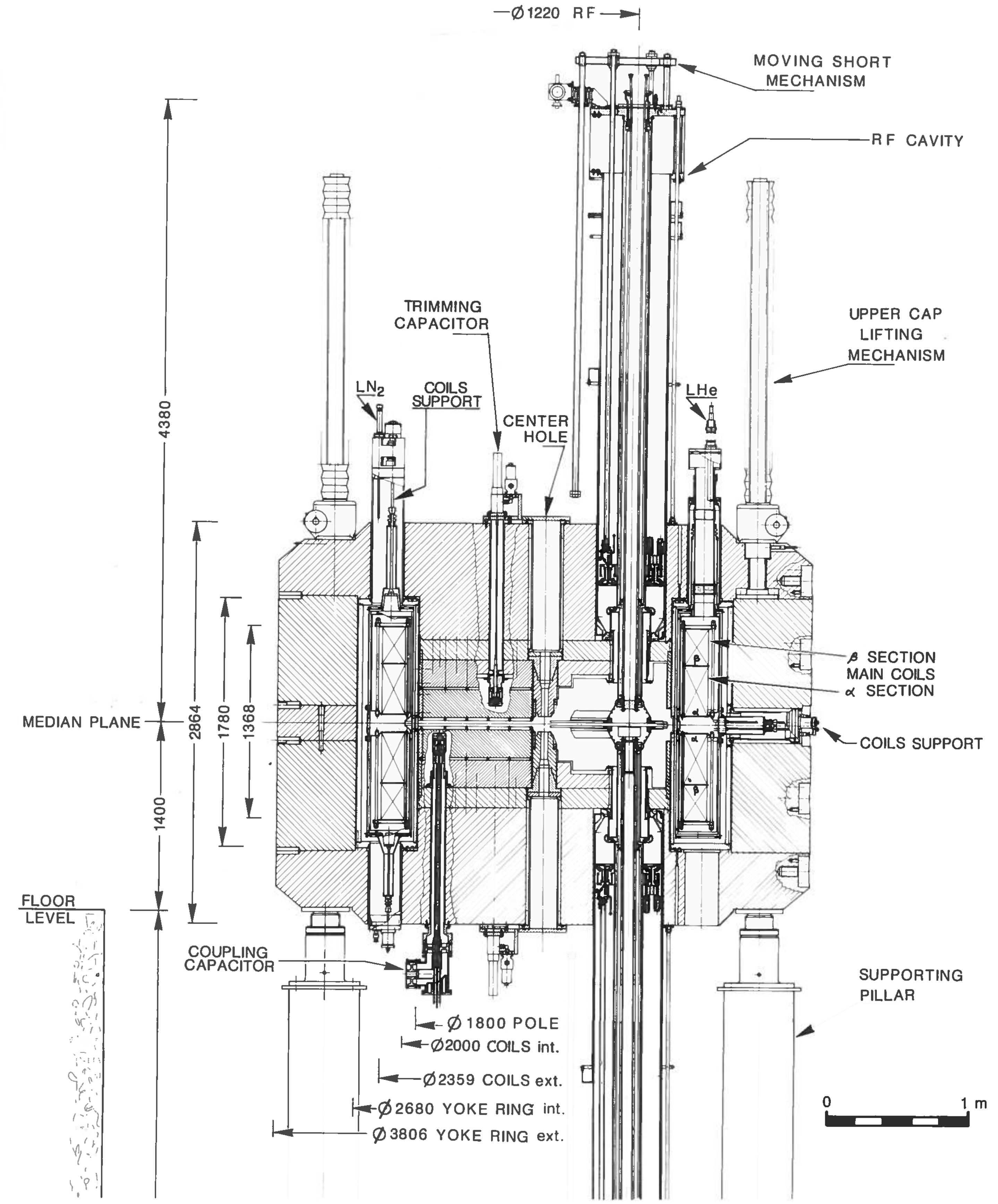

Fig. 1 Vertical section of the cyclotron

are axially prestressed by means of 210 x 2 berillium-copper (CuBe) rods. This prestressing system reduces the accessibility between the coils and the internal wall of the helium vessel and makes difficult the refrigerant distribution in this zone. The weight is 15 tons and the free volume for the refrigerant is about 1200 liters.

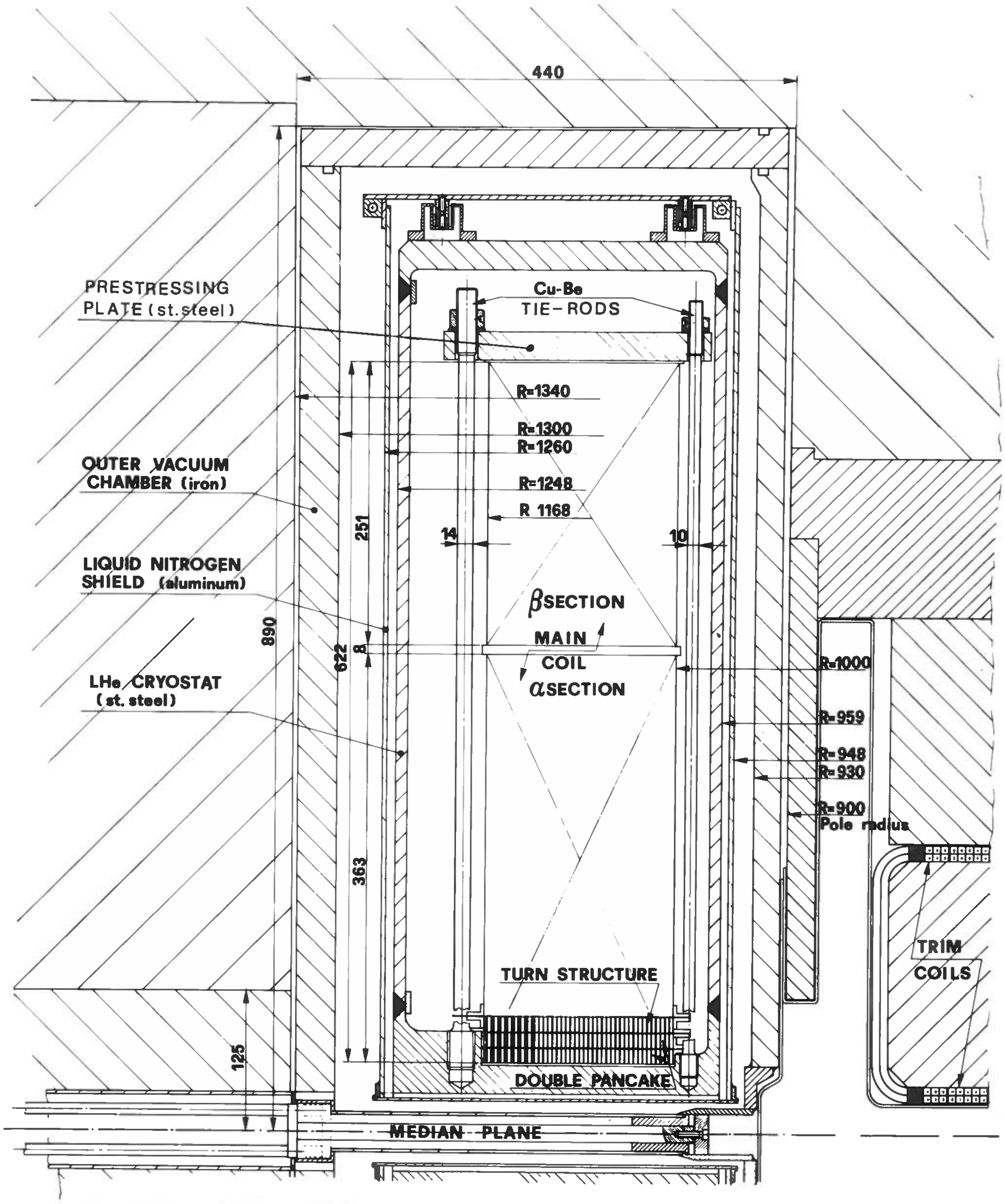

Fig. 2 - Vertical section of the superconducting coils

The helium vessel (AISI 316 L) has a thick plate in the median plane (120 mm height) which separates and supports the upper and the lower coils. The connection between the upper and lower chambers is assured by several holes (total cross section is 135 cm^2) drilled in the midplate near the external wall of the vessel. Helium vessel (about 6 tons) has been designed to support axial and radial magnetic forces and a maximum pressure of 6.34 kg/cm^2 which can be reached during a quench (5).

One of the most critical parts of the vessel is represented by the circumferential weldings with which the vessel has been sealed. The cool down at LN temperature has been carried out also to check that these weldings were free of cracks or other failures, before the complete assembly of the cryostat (helium vessel + LN radiation shield + vacuum chamber + a lot of vacuum tigth channels for beam injection and extraction systems).

The refrigerant distribution is realized only at the external side of the coils, because of the lack of space between the coils and the internal wall of the vessel. The refrigerant distribution system (with 6 exit points) is sketched in fig.3.

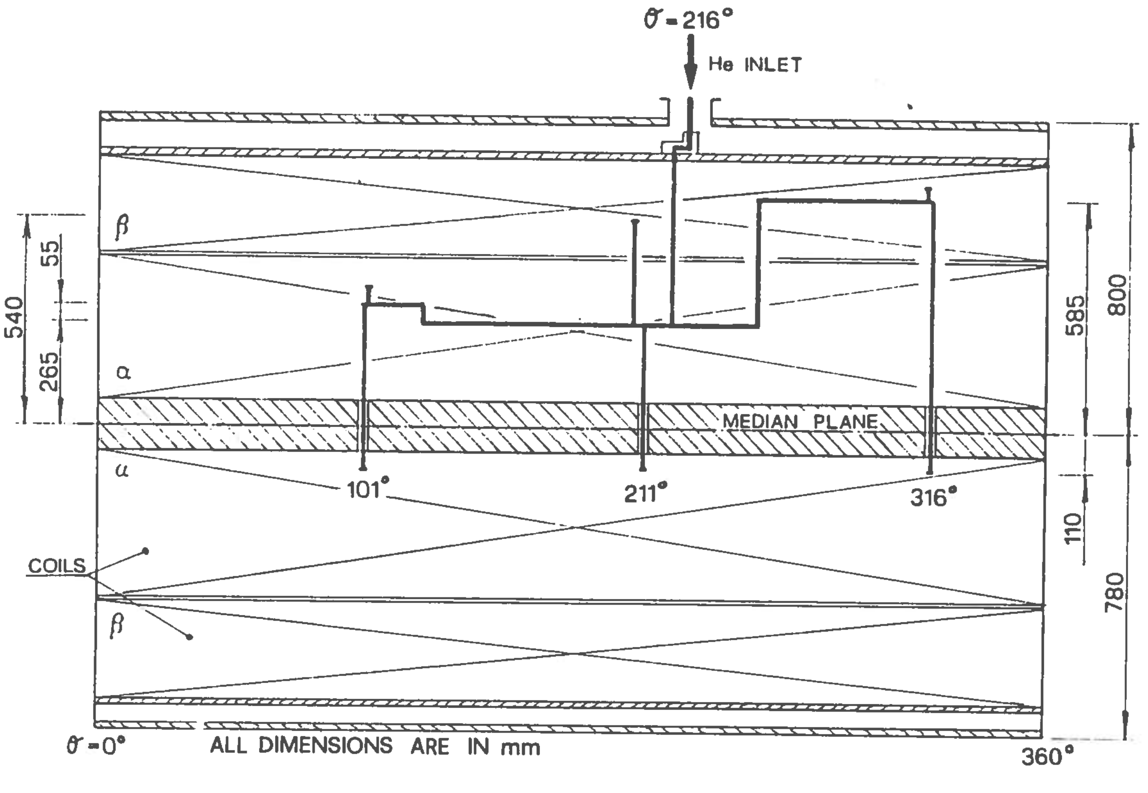

Fig. 3 - Distribution system of the refrigerant in the vessel

3. - CRYOGENIC AND CONTROL SYSTEM

3.1 - Thermal insulation

To avoid an excessive thermal load the vessel has been insulated by various layers of closed cell foam. In particular Armaflex, a well known low temperature insulator, and Coldflex has been chosen (Coldflex is a bit bad than Armaflex but quite inexpensive).

After some calculations with different layers and different thickness of thermal insulation a 92 mm total insulation, one layer of 32 mm of Armaflex and three layers of 20 mm of Coldflex, were chosen. Thermal load, at 77 K has been guessed to be 1650 W (≃ 37 l/h of liquid nitrogen). Total cost of thermal insulators for the vessel was 2700$.

The vessel has been supported by G11 blocks, to avoid a too large thermal load; between each block and the AISI columns, fixed to the ground, a teflon sheet is inserted to make easy the thermal contraction of the vessel (about 6 mm in diameter at 77 K).

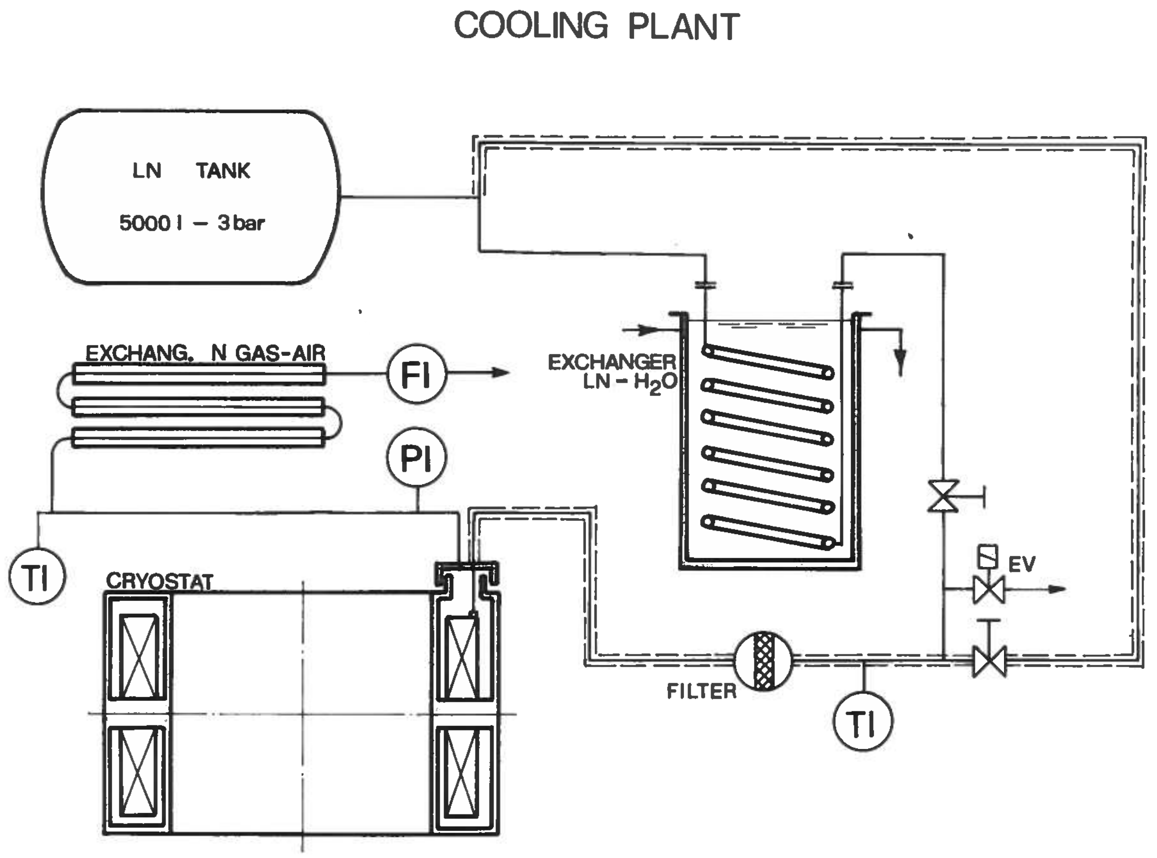

Fig.4 - Outline of the cryogenic plant for the LN cooldown; **EV** safety electrovalve; **TI** temperature gauges; **PI** manometer; **FI** flowmeter.

3.2 - Cooling plant

The cryogenic plant, see fig.4, consists of:

- a 5000 liters LN tank. The pressure in the tank was kept at 3 bar;
- an heat exchanger LN-H_2O to warm part of the liquid nitrogen;
- a mixer to blend the LN coming from the tank and the gas coming from the exchanger;
- a safety electrovalve (EV)to cut nitrogen flux;
- two platinum thermoresistors (TI) to measure the input and output temperatures of nitrogen;
- an heat exchanger N gas - air to warm the gas coming out the vessel till the room temperature.

The LN-H_2O heat exchanger and the mixer enable us to control the cooling fluid temperature, the N gas- air heat exchanger allows to measure the mass rate.

The minimum required quantity of liquid nitrogen for the cooling, taking in account only the latent heat of the liquid and neglecting the thermal losses is about 5000 liters (being about 9 tons the coils weight and 6 tons the vessel one).

3.3 - Temperature and strain gauges

The coils and the vessel temperatures and the stresses on the CuBe rods were monitored during the cool down by means of the following gauges:

- 8 Carbon Glass Resistors (CGR), six placed on the plates prestressing the coils and two on the median plane plate. CGR are mainly intended to measure, with an accuracy of 0.02 K, the temperature between 10 K and 4.2 K where they experiment 90% of their resistance variation between 300 K and 4.2 K. Indeed they are not very accurate in the range 300 - 77 K, and their response are fitted by straight line. CGR power supplies, made in house, have two level of current supply, 10 and 100 μA ($\pm 10^{-4}$ stabilized), to avoid self heating, with automatic selection of the current level in function of the resistance range.
- 2 Strain Gauges (SG) bonded on two CuBe rods. CuBe rods are expected to release about 10% of their tension at LN temperature because the coils thermal contraction coefficient is larger than the CuBe one. SG will be mainly used to control the axial force on β section coils when they will be excited at negative current.
- 5 Cryogenic Linear Temperature Sensors (CLTS) used to monitor the temperature of the CuBe rods (and to clean the SG response from the temperature apparent strain); they have $dR/dT \simeq 0.24\ \Omega/K$ nearly

constant between room and helium temperatures with a maximum deviation from linearity of ±1.5 K;

- 10 measures of voltage drop across the coils. By suppling the coils a 1 mA current ($\pm 10^{-3}$) we are able to read the average temperature of ten coil blocks.

The previous gauges are inside the vessel; other gauges had been put just for the cool down:

- 36 platinum resistors (Pt100) bonded outerside of the walls of the vessel. The grid of the Pt100 positions are reported in the following table, where are indicated also the points of the nitrogen input.

TABLE I

	Θ(°) →	28	101	156	211	263	316
inner wall	top	Pt12	Pt13	Pt14	Pt15	Pt16	Pt17
	midplane	Pt6	Pt7	Pt8	Pt9	Pt10	Pt11
	bottom	Pt0	Pt1	Pt2	Pt3	Pt4	Pt5
outer wall	top	Pt30	Pt31*	Pt32	Pt33*	Pt34	Pt35*
	midplane	Pt24	Pt25	Pt26	Pt27	Pt28	Pt29
	bottom	Pt18	Pt19*	Pt20	Pt21*	Pt22	Pt23*

* this gauges are near the LN inlet points

The temperature coefficient of the platinum resistors, R = 100 Ω at 273.15 K, is 0.3925 Ω/K at room temperature; this gauges have a total accuracy of ±1.5 K .

The resistance measure of CGR, CLTS and Pt100 has been made with four wire technique.

3.4 - Instrumentation and data acquisition

The supply and conditioning modules for SG and CLTS are of the ANALOG DEVICES, with the output in the range 0 - 10 V $(\pm 5\ 10^{-3})$. Multiplexer HP3497A, 5.5 digits, is used to read and store 67 gauge signals and to supply 1 mA to the Pt100 resistors (that are series connected). Multiplexer are guided by a personal computer COMPAQ, providing data acquisition, display of the present temperature situation, storage of the data and preliminary analysis on line. Operation sequence is:

1) opening of operation via PC, imposing the allowed maximum temperature difference and excluding some gauges (if needed) in the maximum-minimum computation;
2) every 5′ a measure of all gauges begins. Data are transferred from multiplexer to PC that displays the values in K or kg/mm^2. At the same time PC searches for the minimum and maximum temperatures, informing the operator if the difference is larger than the fixed value and cutting the cooling flux. Further the maximum and the minimum values and the average temperatures over each component is showed;
3) every 15′ data are printed and once an hour are recorded on floppy disk.

A photograph of electronic system is showed in fig. 5.

Fig.5 - Photograph of the control system

4. - COOL DOWN

4.1 Maximum thermal gradient

Possible dangerous effects of the thermal contractions during the cool down are listed below:

- differences in longitudinal contractions between the inner and the outer turns of the coils. Indeed the cable has been pretensioned during the winding so under thermal strain it can reach the yield strenght. This problem limits to 30 K the temperature difference between inner and outer wall of the vessel (nitrogen distribution is only on the external side of the coils);
- difference between the average coils temperature and CuBe rods temperature. CuBe rods are cooled better and faster than the coils so the coils could be axially stressed with possible danger for layer to layer strip insulators. To avoid this stress overcome 7 kg/mm^2, 30 K is the maximum allowed temperature difference;
- too high temperature gradient in the vessel walls. Indeed 11 kg/mm^2 is the maximum allowed stress to avoid welding damages. Because of the cryostat structure the temperature difference between the higher part and the lower part (respect to the median plane) does not cause stresses; so only the difference between point of the same part of the walls are taken in account. Maximum allowed temperature difference is 40 K at T = 300 K and 60 K at T = 100 K.

For sake of protection,during cool-down, we fixed also a maximum allowed temperature difference between the warmest and the coldest point regardless of their position. We decided to accept a maximum ΔT = 35 K at the beginning of the cool down and to increase ΔT till 50 K near the liquid nitrogen temperature.

4.2 - Data analysis

Eight days were required for cooling and four days to come back at room temperature, as it is shown in fig.6. The time for cooling was doubled than the warming time because the cooling power, the nitrogen enthalpy, was point distributed; therefore the cryostat is essentially cooled by heat conduction so the increasing of the refrigeration power makes increasing the cooling speed of the only parts near to input points and the temperature difference ΔT grows. On the contrary the warm up was performed not only by sending warm gas but also by warming the coils with 5÷50 A current.

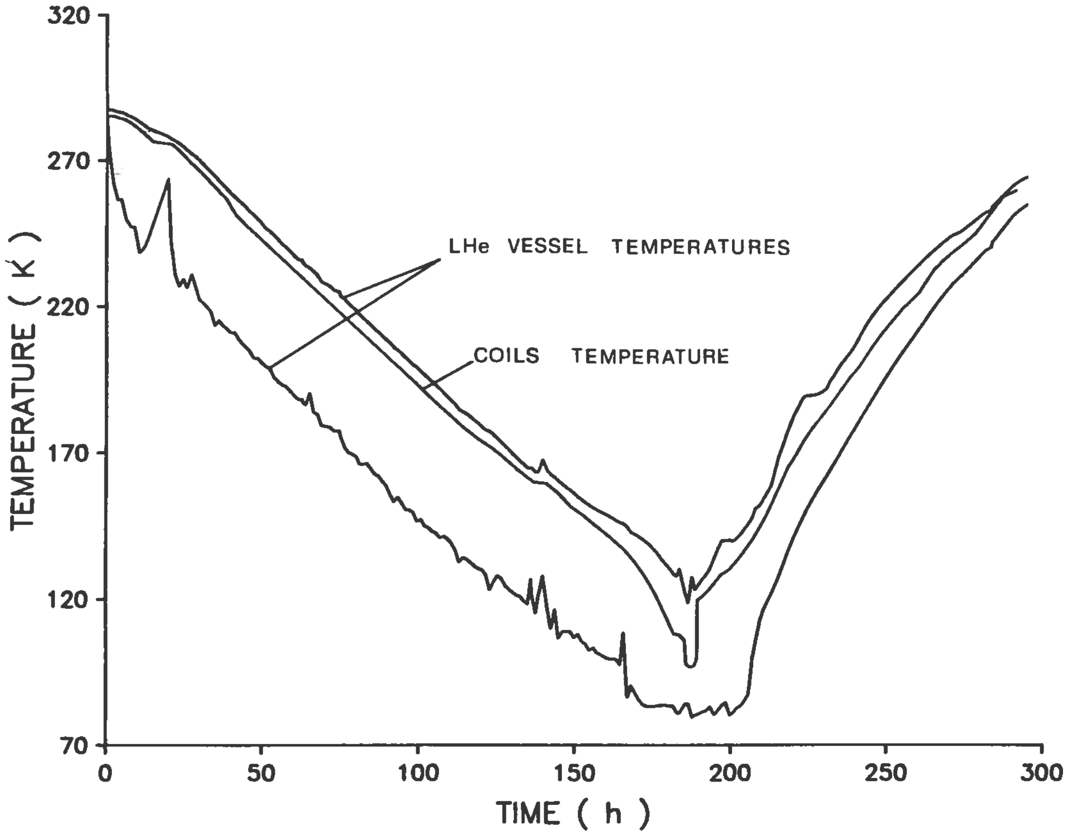

Fig.6 – Maximum and minimum helium vessel temperatures and average temperature of the coils during cool down and warm up; peaks are caused by cutting of cooling

So the power input in this case was uniform and the limit was only the voltage limitation of the power supplies (60 V), that makes the available power decreasing from 2 kW at the beginning of the warm up to about 0.4 kW near room temperature.

For the nitrogen circuit the most remarkable data are:
- entering temperature was 80 K at the beginning and 85 K in the following (except the brief time when liquid nitrogen was transferred);
- vessel pressure was about 0.5 bar ;
- nitrogen flux (measured at 300 K and atmopheric pressure) was increased from 30,000 l/h in the first day till 100,000 l/h;
- total liquid nitrogen consumption (included warm-up) was about 27,000 l.

Such a large nitrogen consumption was caused by impossibility of using all the nitrogen enthalpy. Process is not dominated by available power but by heat conduction. The heat conducibility, k, decreases together the temperature, so untill we kept constant the product k ΔT by increasing ΔT, as we did in the first 30 hours of the cooling, the velocity of the temperature decreasing was constant. When maximum permitted ΔT was not longer increased the

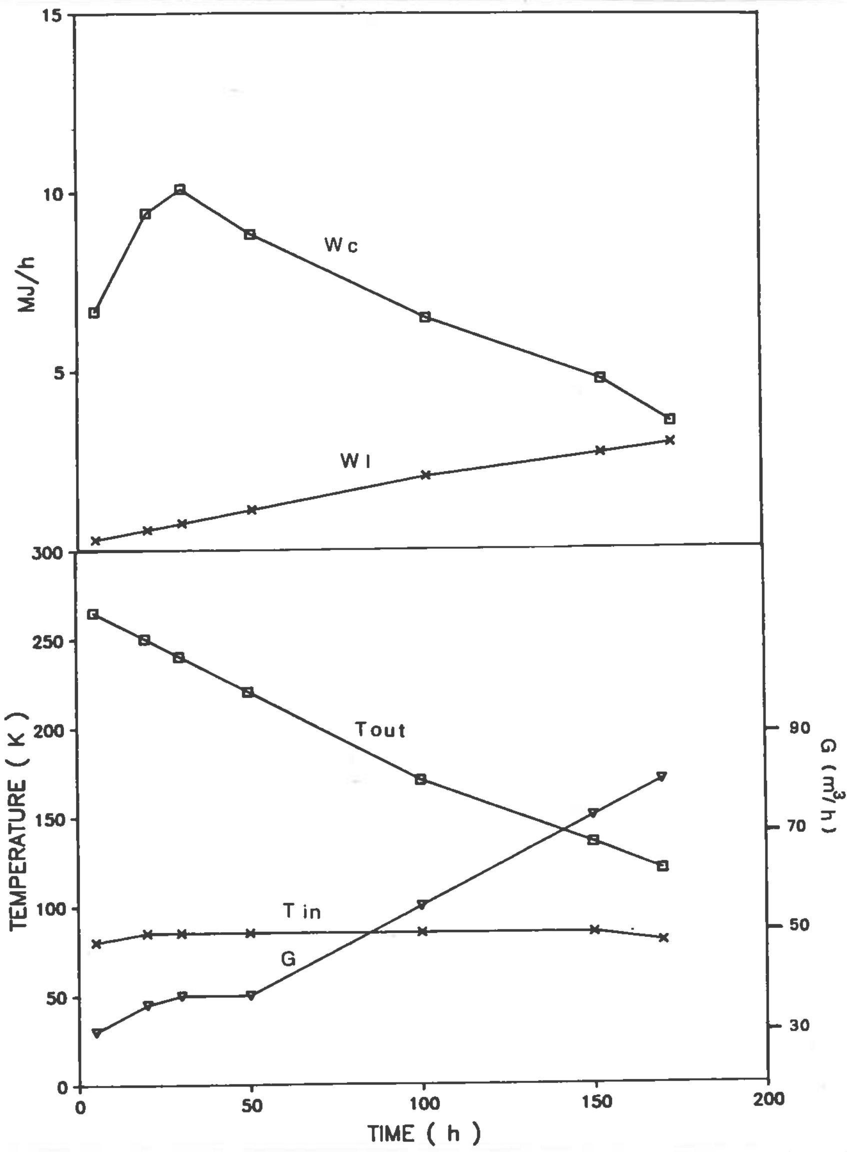

Fig.7 - Inlet and outlet temperatures (T_{in},T_{out}), flow rate (G) of the nitrogen, cooling power (W_c) and the calculated power lost via heat insulator (W_1)

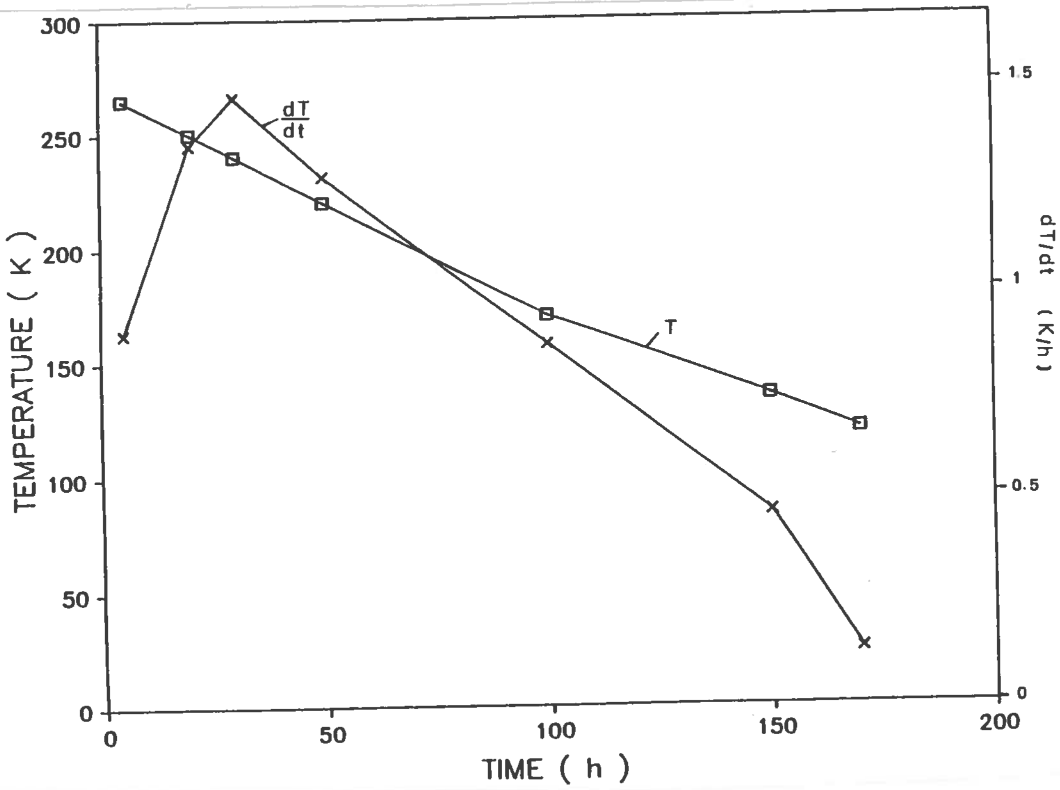

Fig.8 - Average temperature of the helium vessel (measured) and cooling velocity as calculated from energy balance

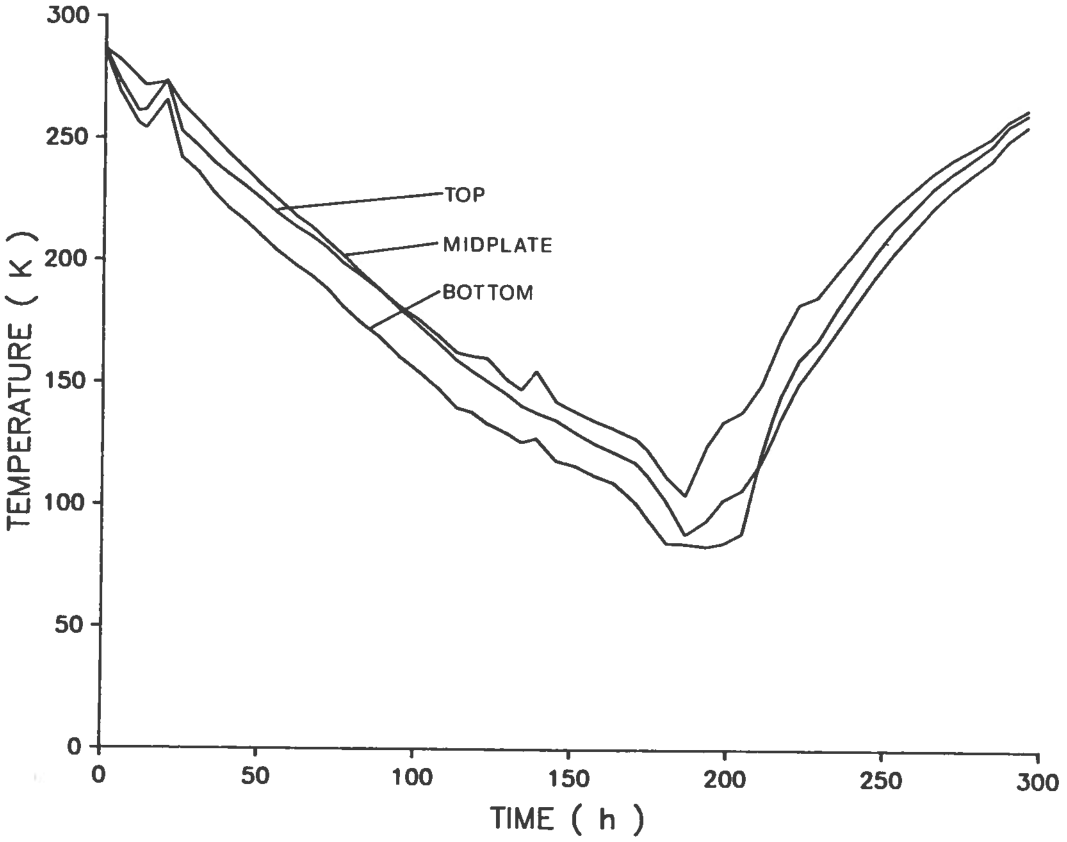

Fig.9 - Azimuthal average temperature at bottom, median plane and top of the external wall of the helium vessel

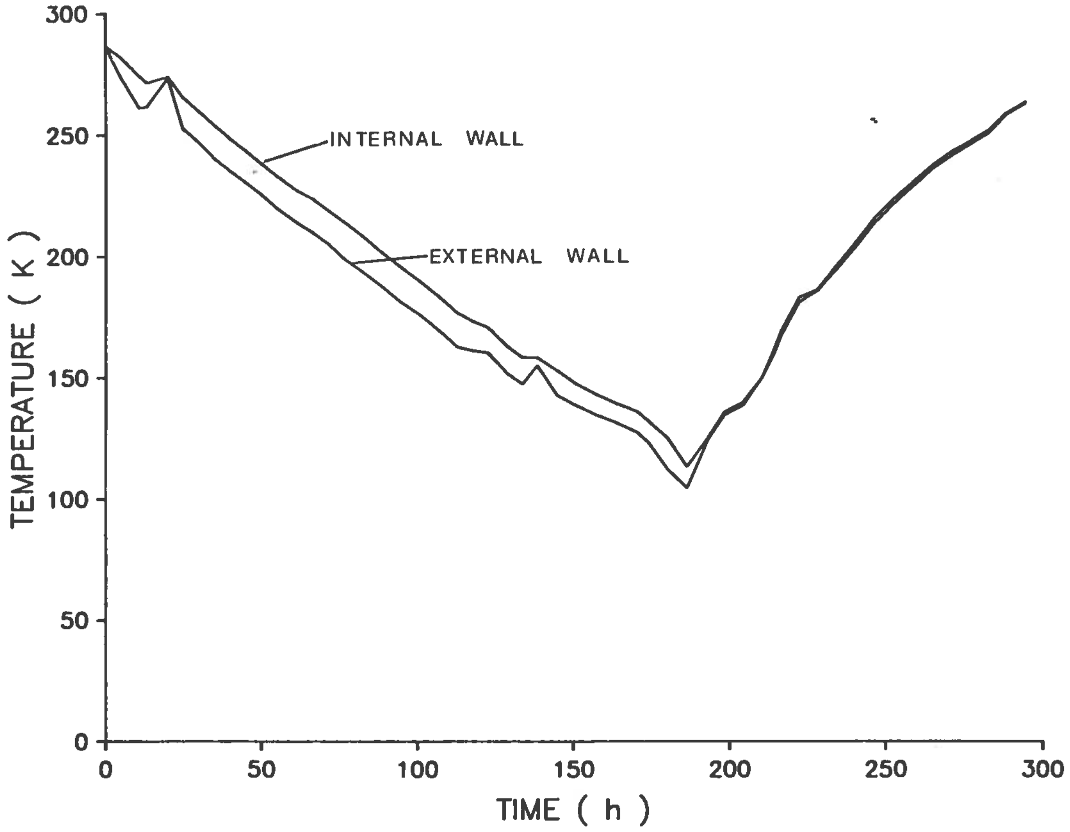

Fig.10 - Azimuthal average temperature of the internal and external wall top

decrease of k lessened the velocity of the cooling.

Pointing attention at energy balance of the process, must be marked that we used only 23 % of the nitrogen enthalpy, mainly because of having not made use of the latent heat. By eliminating the constraint of using a constant source temperature the cool down efficiency might be doubled.

In figs.6 and 7 are plotted versus time the most important parameters determining the energy balance. The cause of slow down of the cooling power input is not only due to the decreasing of the temperature difference between entering and outflowing nitrogen (this could have been compensated by increasing the nitrogen flux), but is a consequence of the limitation in the maximum allowed ΔT.

The rate of the temperature lowering, dT/dt, has been agreed with the rate computed from the energy balance:

$$W_c = W_1 + C(T)\ dT/dt$$

where W_c is the cooling power, W_1 is the power lost via thermal insulation and C(T) is the coils and cryostat heat capacity.

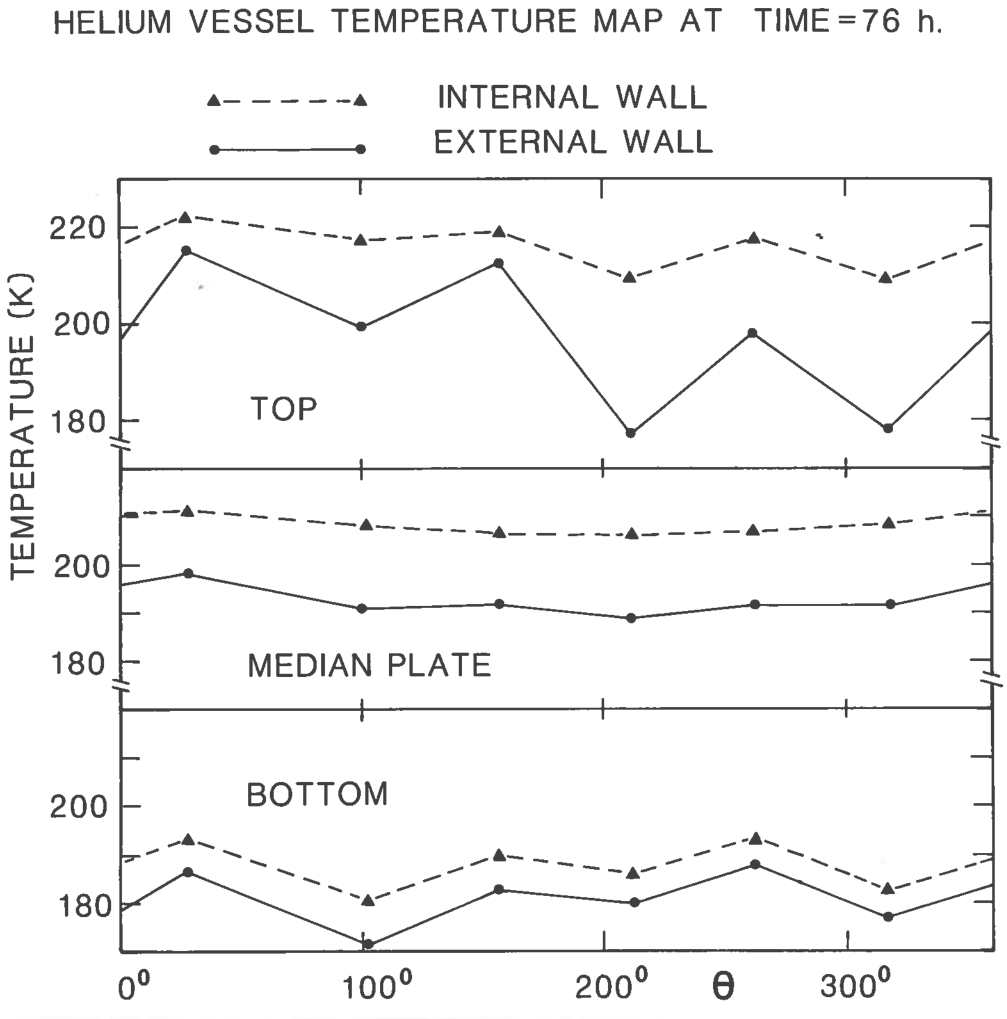

Fig.11 - Azimuthal profile of the walls temperatures three days after the beginning of the cool down

Observing the temperature monitored by every Pt100 resistors it has been found that the whole temperature grid is well fitted by a small number of Pt100, i.e. the maximum and minimum temperatures of the vessel walls are marked by only six sensors. This is a quite important result to limit the number of Pt100 in the final cryostat assembly without losing informations on thermal stresses.

In fig.9 the average (on azimuth) temperature of the external wall of the vessel, at variuos heights, is plotted versus time; in fig.10 the average temperatures of the two walls are compared. It may be noted the quite small ΔT, well within the fixed limits, and that midplane plate temperature is nearly uniform.

On the contrary the azimuthal variation of the wall temperature is very high as it is shown in fig. 11. Thermal gradients are very strong and must be marked that they refers to very near points each other constrained. In the tables II - IV the cryostat temperature map and other meaningful temperature are showed at different time.

Superconducting coils temperature, see fig.6, follows the average temperature of the vessel. Axial thermal gradient is very low, well within safety limits, see fig. 12. The strains of CuBe rods are plotted versus time in fig.13 together their average temperatures. At the beginning the stresses has raised because the CuBe rods are cooled quicker than coils and in the following are lowered to about 90% of their initial level, as expected because the thermal contraction coefficient of CuBe is bit lower than the coils one (due to layer to layer G11 insulators). The peak of stress shown at the beginning is caused by a sudden temperature variation of the rods; the peaks at the end of cool-down are probably related with sudden temperature changes in the coils, as shown in fig.6. At the end of warm-up the signal of strain gauges didn't exactly come back to initial value, showing an hysteresis of about one kg/mm^2.

5. - CONCLUSIONS

This LN cool-down took place in spring '85 and it should have been followed by the vacuum leak test. Actually, after cool down, the Charpy impact test values on samples of the vessel circumferential weldings were found lower than the required one at LHe temperature and the ferrite content was too high. Several analysis on the welding samples indicated that the defect was produced by the bare electrode used in the last welding passes.

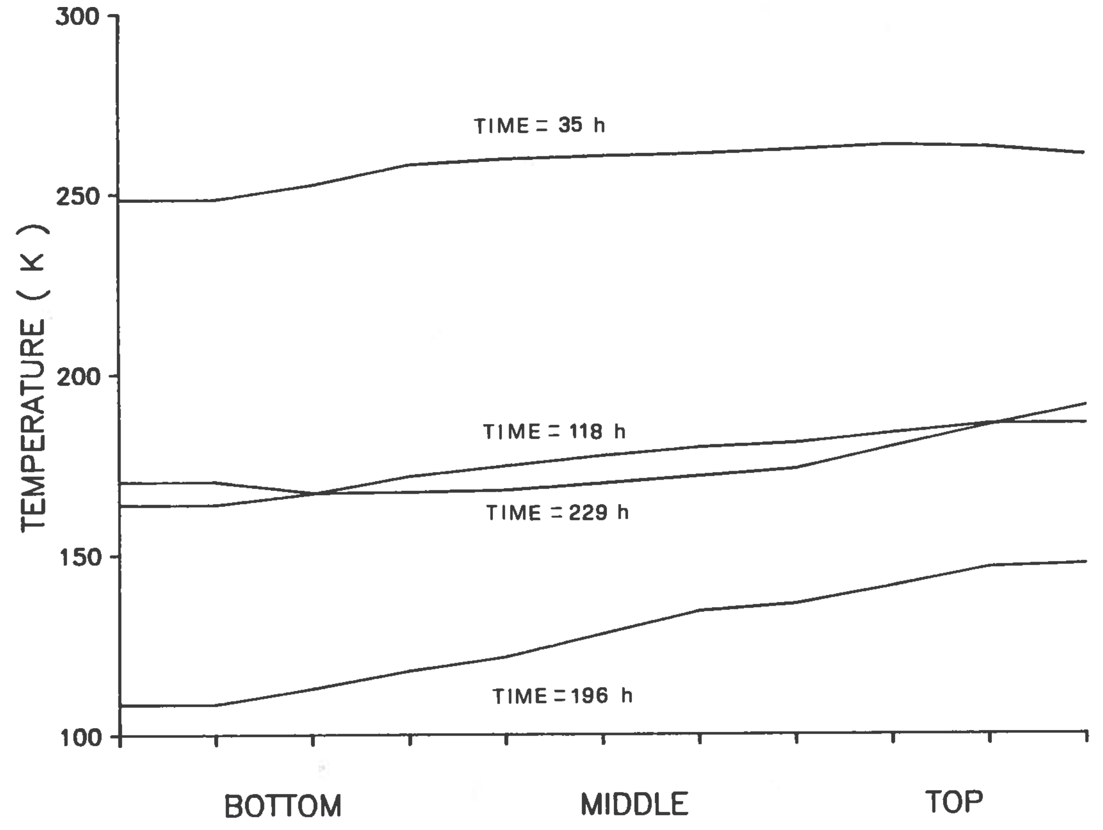

Fig.12 - Axial profile of the coils temperature versus time

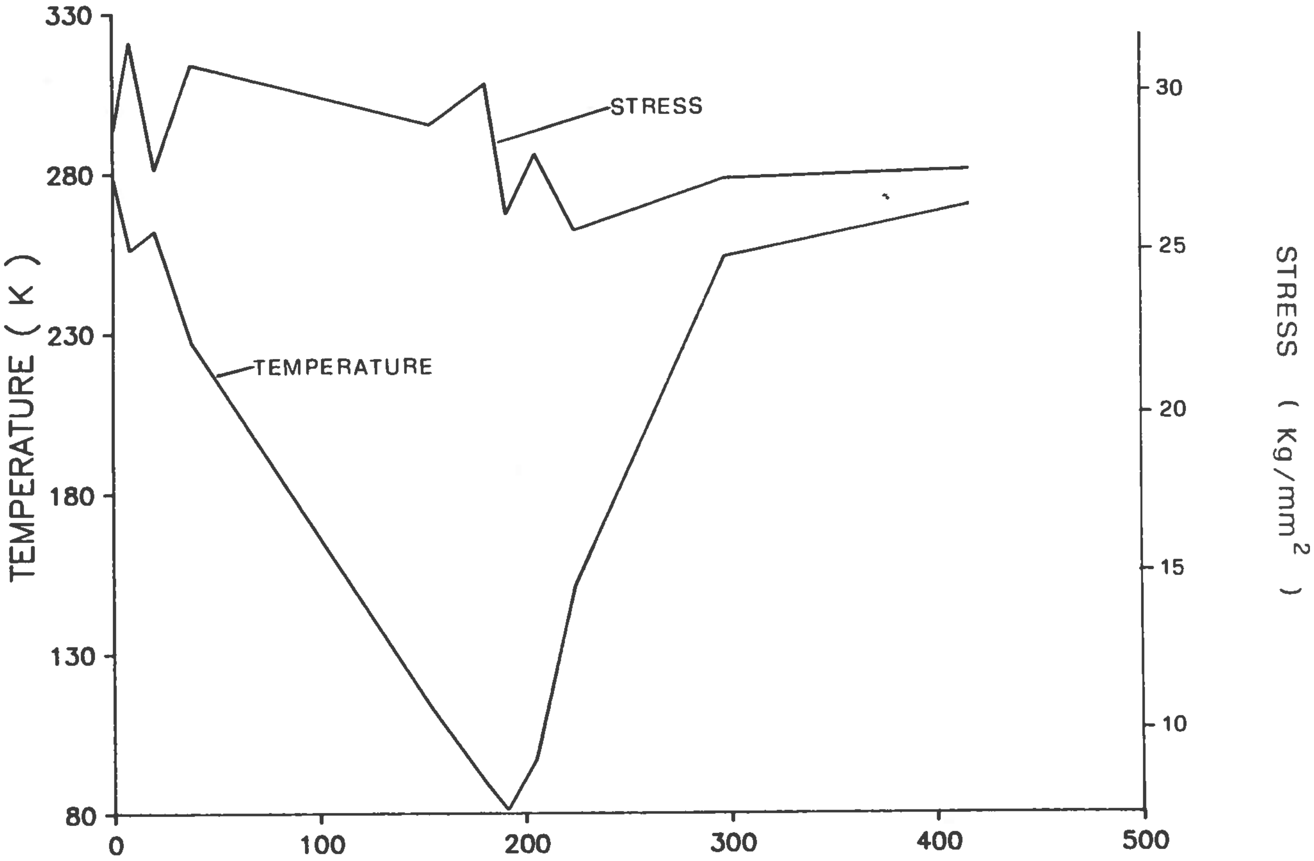

Fig.13 - Stresses and temperatures (measured at about 300 mm from the median plane) of the CuBe rods (at azimuth 208) versus time

Therefore the cryostat was repaired by removing the welding for about 8 mm (the thickness of the vessel walls being 10 mm) to keep selead the vessel and to avoid damages to the superconducting coils.

After repair we decided to proceed with the pneumatic test (at 8 bar) and with vacuum leak test, without further LN cool-down. This tests were successful and the vessel was delivered in our laboratory in july '86 and we are now assembling the complete cryostat for the operation of the superconducting coils.

6. - ACKNOWLEDGEDEMENTS

Authors are gratefully to prof. E. Acerbi and dr. F. Aghion for helpful discussions for the design of the control system and to Mr.A. Amato for his contribute in prepearing the electronic system.

VESSEL TEMPERATURE MAPS (K)

TABLE II (time = 76 h)

	$\Theta(°)$ →	28	101	156	211	263	316
inner wall	top	222	217	219	210	218	199
	midplane	211	208	206	207	207	208
	bottom	193	181	190	186	193	182
outer wall	top	217	200	213	177	209	178
	midplane	204	201	202	199	202	202
	bottom	186	171	183	180	188	178

CGR5 (on upper AISI plate) : 226
lower half of upper β section : 224
CLTS : 182 ÷ 224
ΔT max : 39

TABLE III (time = 171 h)

	Θ(°) →	28	101	156	211	263	316
inner wall	top	145	139	141	135	139	132
	midplane	125	123	121	122	123	124
	bottom	115	108	115	111	113	106
outer wall	top	143	132	139	117	138	112
	midplane	120	115	120	119	121	122
	bottom	113	86	114	107	112	94

CGR5 : 145
upper half of upper β section : 154
CLTS : 105 ÷ 120

TABLE IV (time = 242 h)

	Θ(°) →	28	101	156	211	263	316
inner wall	top	198	198	197	198	200	199
	midplane	176	176	174	174	174	175
	bottom	180	190	182	182	181	183
outer wall	top	201	198	199	200	203	198
	midplane	177	181	178	176	176	175
	bottom	184	194	186	184	184	183

upper half of upper β section : 206
CLTS : 178 ÷ 183

REFERENCES

(1) E.Acerbi et al., "The Milan Superconducting Cyclotron Project", Proc. IX Int. Conf. on Cyclotrons and their Applications, Caen (Fr) 1981, Les Editions de Physique, p.169 .

(2) E.Acerbi et al., "The Milan Superconducting Cyclotron Project", Proc. X Int. Conf. on Cyclotrons and their Applications, East Lansing (Mi - USA) April 1984, IEEE catalog n. 84ch1996-3,p.251

(3) E.Acerbi et al., "Progress report on the Milan Superconducting Cyclotron", presented at XI Int. Conf. on Cyclotrons and their Applications, Tokyo october 1986, and to be published in the proceeding.

(4) E.Acerbi, F.Alessandria, G.Baccaglioni and L.Rossi, "Design of the main coil for the Milan Superconducting Cyclotron", Proc. IX Int. Conf. on Cyclotron and Their Applications, p.399.

(5) E.Acerbi, F.Alessandria and L.Rossi, "Pressure calculations for the cryostat of the Milan Superconducting Cyclotron", Report INFN/TC-83/21.