LABORATORI NAZIONALI DI FRASCATI
SIS – Pubblicazioni

LNF–97/046 (IR)
19 Dicembre 1997

The DAΦNE Cryogenic System

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Abstract

The DAΦNE Project utilises superconductivity technology for a total of six superconducting magnets: the two Experiment magnets (KLOE and FINUDA) and the four Compensator Solenoid magnets needed to compensate the magnetic effect of the Experiment magnets on the electron and positron beams. This effect, on beams of 510 MeV (nominal DAΦNE Energy), is expected to be relevant, especially with the aim of achieving a very high luminosity, which is the main target of the Project. The KLOE superconducting magnet has two possible working positions: the first in the DAΦNE Hall, when the Experiment will be in operation, and the second one in the KLOE Assembly Hall. This second position is the first to be utilised for the KLOE magnet Acceptance Test and magnetic field mapping, prior to the mounting of all the experimental apparatus inside the magnet.This note intends to present the DAΦNE Cryogenic System and how we have converged to the definition of a common Cryogenic System compatible with all the six superconducting magnets.

1. THE DEFINITION OF THE CRYOGENIC SYSTEM

The Accelerator Division started to study the problem of the Cryogenic System of DAΦNE in 1994. At that time the magnetic characterisation of the full machine (DAΦNE Accelerator, KLOE and FINUDA Experiments [Refs. 1, 2, 3] and the four Superconducting Compensator magnets) was completely defined, and it was possible to begin the study of the cryogenic aspects. Until that moment, the situation of the Accelerator and of the two Experiments had been of a relative independence as regarding the project, design and status of the cryogenic aspect. The magnets manufacturers (Elin and later Oxford Instruments A.T.G. for KLOE, and Ansaldo Energia for FINUDA) were developing two similar system as to thermodynamic solutions (a big solenoid magnet cooled indirectly through a liquid Helium thermosiphon cycle), but rather different in their cryogenic requests (temperature and pressure of the cooling Helium) and in the circuitry and control aspects. In the meantime the project of the Compensator magnets was developing in the direction of magnets cooled by a "Helium pool boiling".

The main activity in 1994 and 1995 was to find a common technical solution in order to arrive at the definition and purchase of single cryogenic plant able to serve and to operate the six magnets at the same time but in different operating modes. This last point was felt as very important for the following reasons. In principle is possible to foresee the simpler cooling scenario for the six magnets as following: the six magnet are cooled down from room temperature (~300 K) to liquid Helium temperature (~4.2 K) simultaneously. This solution, the easier from the operational and thermodynamic point of view, will take probably between four and five weeks, and is a reasonable scenario to cool down the whole system of magnets and cryogenic transfer lines after, for example, a general accelerator shut down for maintenance.

But another scenario is also possible: the idea of cooling down one or more magnets (such in the case of the "small" Compensator magnets) while the other magnets are already cooled and operational at liquid helium temperature. This is requested for example, when one experiment has to be cooled down after a temporary shut down for any reason (a failure, upgrading of some sub-system, etc.). In this case the other magnets are not obliged to stop their operation to allow the cooling down of the warm magnet, and precious time for everybody (accelerator and experiments) can be saved.

In the first study phase (prior to the cryoplant call for tender phase), several meetings were organised between INFN, the magnets manufacturer (the above mentioned Oxford Inst. A.T.G., Ansaldo, and Oxford Inst. S.R.D. manufacturer of the Solenoid Compensator magnets) and the two companies Air Liquide and Linde. These two companies are the only companies in the world (apart some Japanese companies not present on the European market) that have cryo-turbine technology. This technology (i.e. the Helium gas is cooled mainly through an expansion done by very sophisticated small gas turbines running at the frequency of more than 3000 r.p.s.) is the only one that can guarantee a long term cryoplant operation (nominally one year) without any maintenance. It is obvious that a very reliable continuous operation of the cryoplant without interruptions is the first condition in order to permit reliable and continuous Experiments operation. Due to this particular commercial scenario (only two possible competitors) and to the complexity of the cryogenic system layout (six superconducting magnets functioning in parallel involving several manufacturers and different INFN Groups and Collaborations), the solution of a series of general meetings before the call for tender, was chosen, in order to find a technical solution acceptable to all the subjects involved in the Cryogenic System.

The contract of the Cryogenic Plant System (including the Cryogenic Transfer Lines) was finally awarded at the end of December 1995 to Linde Kryotechnik AG (Switzerland). The project started in the January 1996 and a tight time schedule was planned with Linde in order to match the cryoplant erection completion with the request advanced by KLOE Collaboration, of cryogenics availability for the KLOE magnet Acceptance Test and its magnetic field mapping, foreseen for the Summer 1997.

2. THE DAΦNE CRYOGENIC SYSTEM

In Fig. 1 the layout of the DAΦNE Cryogenic system is shown. It is described, in its main aspects, in the following part.

There is a total of six superconducting magnets which are served by the cryogenic plant. There are seven delivery points for the cryogenic fluids. KLOE Experiment has two possible delivery points, one in the DAΦNE Hall, like the FINUDA Experiment, and another in the KLOE Assembly Hall. This second delivery point is the first to be utilised for the KLOE Magnet Acceptance Test and prior to the mounting the entire experiment. In order to simplify the transport of the cooling capacity to the magnets, the cryoplant is providing all the magnets with the following stream of Helium gas:

- *Helium gas at 5.2 K and at appropriate pressure (3 absolute bar).* Inside each magnet, after the final expansion from 3 to ~1.2 bara, the liquid helium necessary to the operation of the superconducting magnet is collected.
- *Helium gas at intermediate temperature (~70 K).* It is necessary for the cooling down of the magnet from room temperature to cold state and to run the thermal radiation shields of the magnets.
- *Helium gas at room temperature (~300 K).* It is necessary for the cooling down of the magnets from room temperature to cold state.

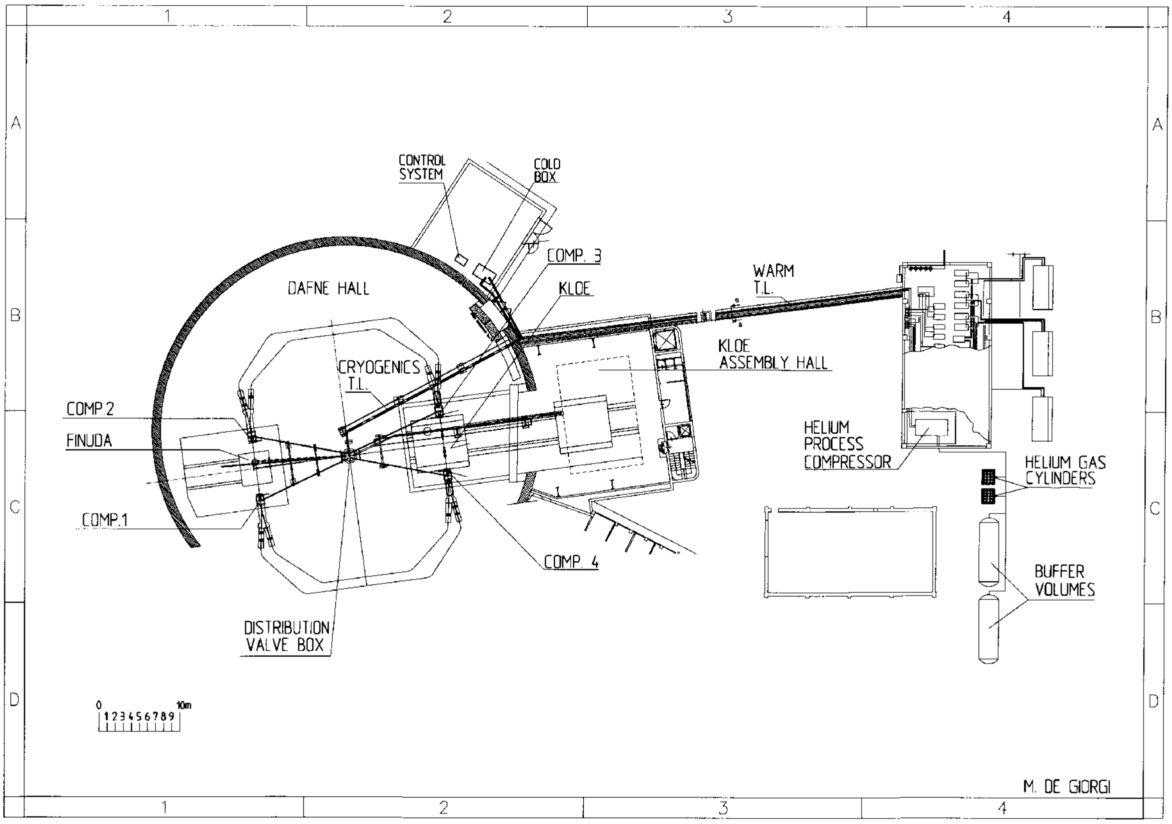

Figure 1 : The DAΦNE Cryogenic System.

2.1. KLOE Superconducting Magnet

The KLOE Magnet [Ref. 4] is an iron shielded superconducting solenoid coil with a thermo-siphoning cooling method (made by Oxford Instruments A.T.G. - England). The cryostat possesses its own valve box, JT valve and LHe reservoir of ~150 liters. The total liquid volume in the system is in the order of 200 liters. All the controls associated with magnet functioning (including cool down and warm up) are an integral part of the magnet system.

- Coil cooling : Thermo-siphoning cycle. 5.2 K GHe @ 3 bara from the cryogenic plant and liquefied through JT valve into LHe reservoir for cooling the coil.
- Radiation shield: cooled with 70K GHe from the cryogenic plant.
- Current leads: cooled with LHe from reservoir; 300K GHe returns to the cryogenic plant.
- The magnet is under "continuous cooling".

Magnet Coil Main Parameters:

- Nominal Magnetic Field: 0.6 Tesla
- Stored Energy: 14.32 MJ
- Nominal Current: 2902 A

- Cold Mass: ~8500 kg

Cryostat Main Dimensions:

- Outer Diameter: 5.76 m
- Inner Diameter: 4.86 m
- Overall length: 4.40 m

Nominal Steady State Heat Loads:

- 55 W @ 4.4 K (for the magnet coil)
- 0.6 g/s LHe (for the current leads)
- 530 W @ 70 K (for the thermal radiation shields).

In the Fig. 2 is shown a view of the KLOE Magnet inside the Assembly Hall and during the cryogenic test. The incoming transfer line from the cryoplant is also visible.

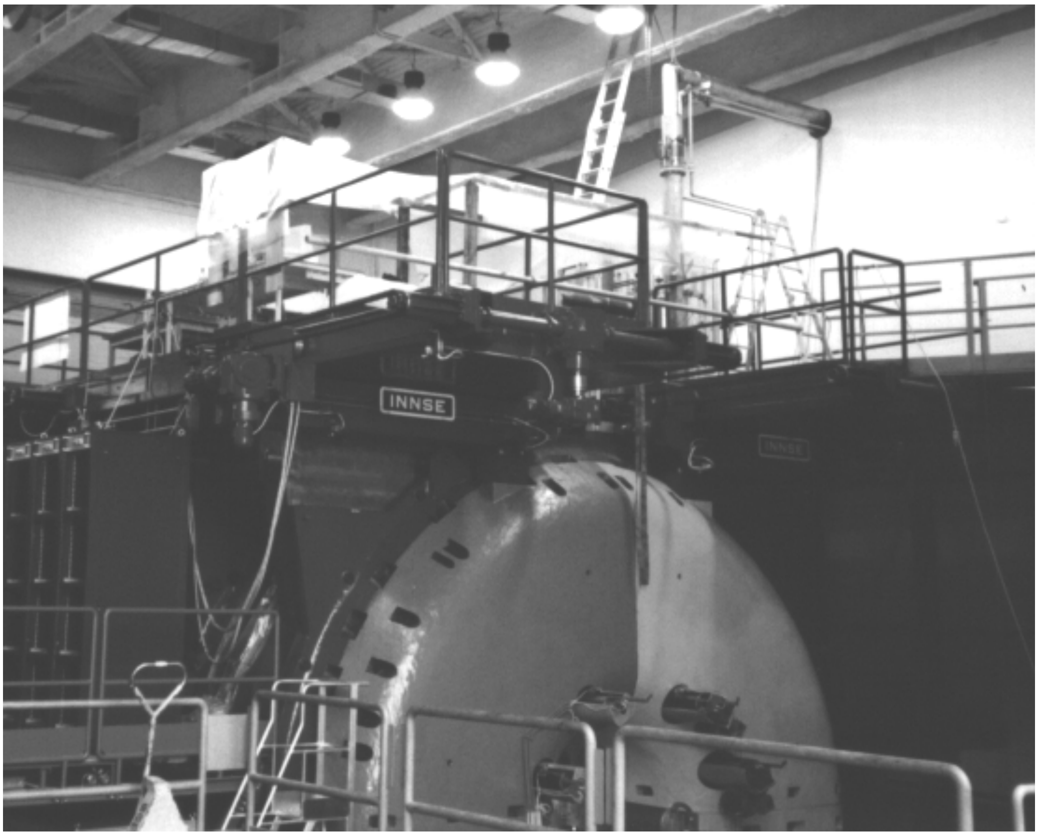

Figure 2 : A view of KLOE Magnet.

2.2. FINUDA Superconducting Magnet

The FINUDA Magnet [Ref. 5] is an iron shielded superconducting solenoid coil with thermo-siphoning cooling method (made by Ansaldo Energia - Italy). The cryostat possesses its own valve box, JT valve and LHe reservoir of ~25 liters. The total liquid volume in the system is in the order of 40 liters.

All the controls associated with magnet functioning (including cool down and warm up) are an integral part of the magnet system.

- Coil cooling : Thermo-siphoning cycle. 5.2 K GHe @ 3 bara from the cryogenic plant and liquefied through JT valve into LHe reservoir for cooling the coil.
- Radiation shield: cooled with 70K GHe from the cryogenic plant.
- Current leads: cooled with LHe from reservoir; 300K GHe returns to the cryogenic plant.
- The magnet is under "continuous cooling".

Magnet Coil Main Parameters:

- Nominal Magnetic Field: 1.1 Tesla
- Stored Energy: 10.34 MJ
- Nominal Current: 2796 A
- Cold Mass: ~4000 kg

Cryostat Main Dimensions:

- Outer Diameter: 3.40 m
- Inner Diameter: 2.77 m
- Overall length: 2.52 m

Nominal Steady State Heat Loads:

- 44 W @ 4.4 K (for the magnet coil)
- 0.4 g/s LHe (for the current leads)
- 270 W @ 70 K (for the thermal radiation shields)

2.3. The Solenoid Compensator Magnets (4 Magnets)

A picture of one of the Compensator magnets installed in the DAΦNE Hall is shown in Fig. 3. The Compensator magnets are iron shielded superconducting solenoid coils, working in pool boiling condition. Each cryostat possesses its own JT valve and phase separator. LHe reservoir is of 25 liters. The total liquid volume in each Compensator is in the order of 50 liters. The controls associated with magnet functions (including cool down and warm-up and refilling) is an integral part of the magnet system.

- Coil cooling: Pool boiling. 5.2K GHe @ 3 bara from the cryogenic plant and liquefied through JT valve into LHe reservoir where coil resides.
- Radiation shield: Cold GHe from LHe reservoir. Warm GHe will go back to the cryogenic plant at 300 K.
- Current leads: Cold GHe from reservoir, warm GHe return to the cryogenic plant at 300 K.
- The magnets are not under continuous cooling. The foreseen refilling of the magnets is approximately once per day.

Magnet Coil Main Parameters:

- Nominal Magnetic Field: 1.45 Tesla
- Stored Energy: 57 KJ
- Nominal Current: ~ 105 A

Cryostat Main Dimensions:

- Outer Diameter: 0.660 m
- Inner Diameter: 0.255 m
- Overall length: 0.935 m

Nominal Steady State Heat Loads:

- Gas He @ 5.2 K, 3 bara, and an adequate flow to refill the 25 litre reservoir, compensating a Liquid Helium evaporation rate of 1 L/h.

Figure 3 : A Solenoid Compensator Magnet installed in the DAΦNE Hall.

2.4. Cryogenic Transfer Lines & Connections

For the main experimental magnets KLOE and FINUDA a total of six lines are necessary, four cryogenic lines and two room temperature lines. Nominally they are:

Cryogenic Transfer Lines

- 5.2 K Helium gas supply

- 4.4 K Helium gas return
- 70 K Helium gas supply
- 80 K Helium gas return

Room temperature Transfer Lines

- 300 K Helium gas supply
- 300 K Helium gas return.

For the Compensator Solenoid Magnets, due to the simpler operation mode, one cryogenic (5.2 K Helium gas supply) and one at 300 K (Helium gas return) lines are necessary.

2.5. Operation Modes for the Cryogenic Plant

Due to the presence of six different magnets, under principle in completely different operating situations, the cryoplant has to face different Operating Modes. In any superconducting magnet the "quench" is an event that must be taken into account, and so one or more quenched magnet is another possible status (undesired but possible) which the cryoplant has to manage. The "quench" phenomenon is the sudden return to a condition of normal conductivity of a superconducting conductor. In this event the joule effect (i.e. the heating of the conductor caused by its electrical resistance) and the discharge in the magnet of the energy stored in the magnetic field generated by the magnet itself, causes a very fast and impressive overheating of the superconducting winding in the magnet. In this situation a dramatic and sudden (few seconds) evaporation of all the Helium contained in the magnet occurs, the magnet stops operating, must be set in a safe situation, and reaches a thermal status that requires a partial re-cooling and the full re-energisation. So the expected Operating Modes for the cryoplant are the following:

- All the six magnets are operating at the full capacity. This is the Normal Operating Mode.
- One or more of the devices are being cooled down or during scheduled warm up while all the others devices are operating at full capacity.
- Recovery to Normal Operating Mode after quenches or fast discharge of one or more devices.
- One or more of Compensator magnets are in refilling while all the other devices are operating at full capacity.

2.6. The Cryogenic Plant

The nominal cryogenic capacities of the Linde Cryoplant at the delivery points to the magnets (so not taking into account the Cryogenic Transfer Lines Heat Loads) are:

- Refrigeration Capacity @4.2 K : 99 W
- Refrigeration Capacity @ 70 K : 800 W

- Liquefaction Capacity @ 4.2 K : 35 L/h

The cryogenic plant consists of the following main elements:

1. Helium Process Compressor
2. Helium Buffer Volumes
3. Warm Transfer Lines
4. Cold Box
5. Cryogenic Transfer Lines
6. Distribution Valve Box
7. Control System.

2.6.1. The Helium Compressor

This element is the first that the Helium gas meets along its process from room temperature (300 K) to the liquid working point in the cold magnet. This compressor is a "screw-type" compressor that compress the Helium gas from ambient pressure of 1 bara to ~14 bara. Beyond the compressor, a system of coalescer filters and charcoal beds is filtering out all the oil (necessary for the compressor functioning but incompatible with the cryogenic functioning) from the Helium gas that will be cooled downstream.

2.6.2. The Helium Buffer Volumes

Two steel cylinders of 34 m^3 each, and working at max. ~13 bara are part of the system. A buffer volume is always necessary for the correct functioning of a cryoplant. In our case a total volume of this size was chosen to limit the shut down time of the cryogenic system in case of troubles (quenches, leaks, etc.) which can generate a major loss of the Helium in the system. The total volume of the buffers contains a complete Helium refilling of the full system.

2.6.3. The Warm Transfer Lines

From the Compressor and the Buffer Volumes a system of warm Transfer Lines (Stainless Steel seamless pipes), takes the compressed Helium gas to the Cold Box and the low pressure Helium gas back from the Cold Box to the low side of the Compressor. The piping mainly located in a pre-existing tunnel, was installed by VICMA (Italy) and was checked by X-rays in order to guarantee the adequate installation quality necessary to avoid any possible leaking of the lines.

2.6.4. The Cold Box

The Cold Box is the real "heart" of the cryoplant. In this high-technology element the incoming Helium gas at ~14 bara is processed in order to be gradually cooled to ~5 K. This process involves two expansions of the gas (in two very sophisticated small gas turbines running at the frequency of ~3500 r.p.s.) several trips through counterflow heat exchangers, and some Joule-Thompson expansion. Another Helium gas stream is extracted at the middle of the cooling process to provide the gas at 70 K necessary for the cooling down of the magnets from room temperature and to the radiation shield cooling. In the Cold Box are also collected (at different points) the different gas streams coming back from the magnets. A picture of the Cold Box is shown in Fig. 4.

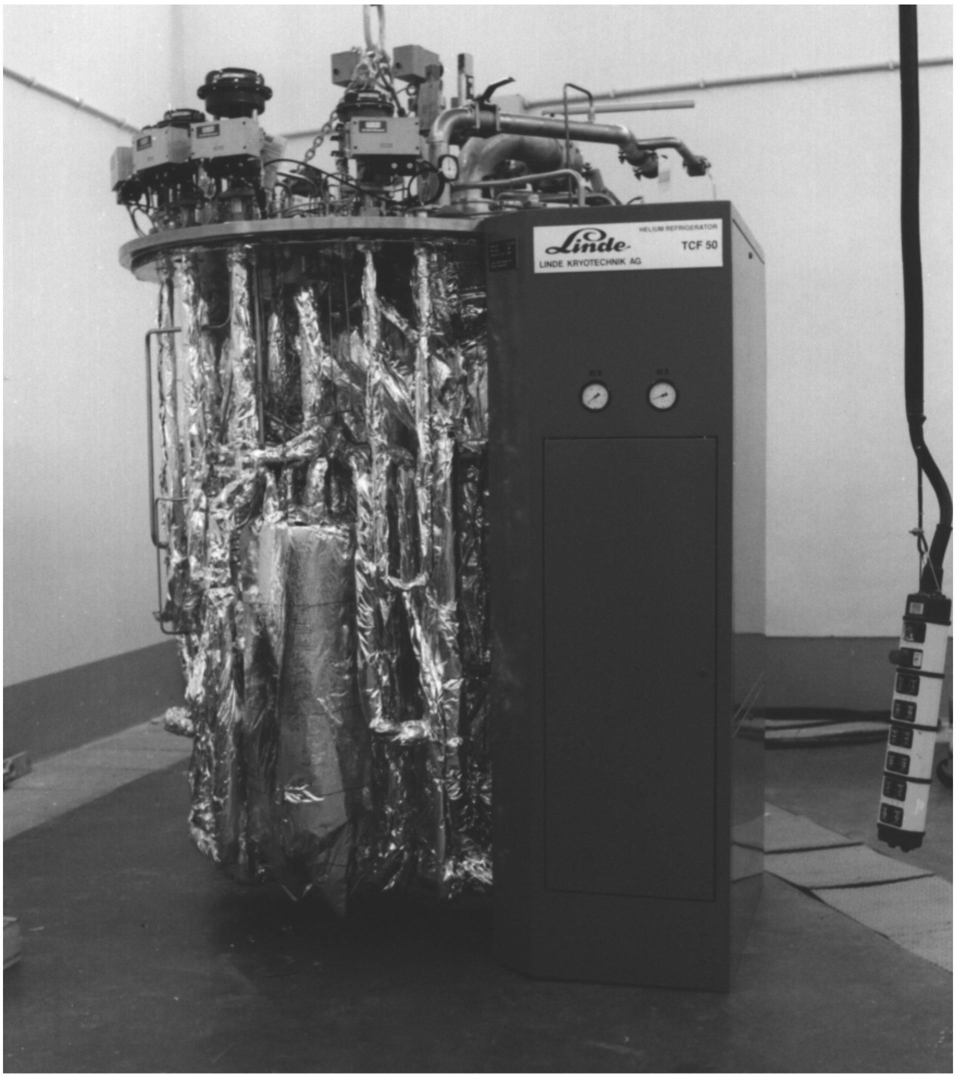

Figure 4 : The Linde Cold Box (open) during the plant installation.

2.6.5. Cryogenic Transfer Lines

As is shown in the Fig. 1, the DAΦNE Cryogenic System consists of different elements that are sometimes quite distant, one from the other. For this reason the Cryogenic

Transfer Lines are an essential part of the full system, and their performance is quite important in order to limit their heat loads that can play a relevant role in the total thermal balance of the plant.

The Transfer Lines for the DAΦNE Cryogenic System were manufactured by Leybold BV (NL) following the well known technique of vacuum shielded lines. The main lines connecting the cryoplant with the magnets is assembled with a "four in one" layout (a vacuum insulated line containing the four cryogenic lines) where the warmer of the four cryogenic lines (the 80 K return) is used to create a thermal shield for the other, colder, lines.

The design values of the Transfer Lines Heat Loads are:

- 0.22 W/m for the 5.2 K & 4.4 K lines
- 1.5 W/m for the 70 K & 80 K lines

2.6.6 Distribution The Valve Box

The Distribution Valve Box is a cryogenic distribution system placed along the cryogenic transfer lines path between the Cold Box and the magnets. Its function is to provide the distribution of the different gas streams to the different magnets. It has 13 cryogenic valves necessary to operate the system in its all operating modes. Several of these valves are operated by the control system through remote control, due to the fact that the Valve Box is placed in the centre of the DAΦNE Hall and during the normal operation of the accelerator, this area is not accessible. The Valve Box is also the place were most of the safety valves necessary to the protection of the distribution system are located.

In Fig. 5 is shown the Valve Box installed in the center of the DAΦNE Hall with part of the Cryogenic Transfer Lines System.

2.6.7. The Control System

A quite complex and reliable control system is necessary to run the Cryogenic System. It shall be considered that the presence of four different manufacturers with their own standard of control systems to drive the different functions of the cryoplant and of the magnets, is a complicated aspect of the system. With several technical meetings, an equilibrium was found between the necessary communication and interconnection of the different control systems and the request of safe and reliable operation of the whole system.

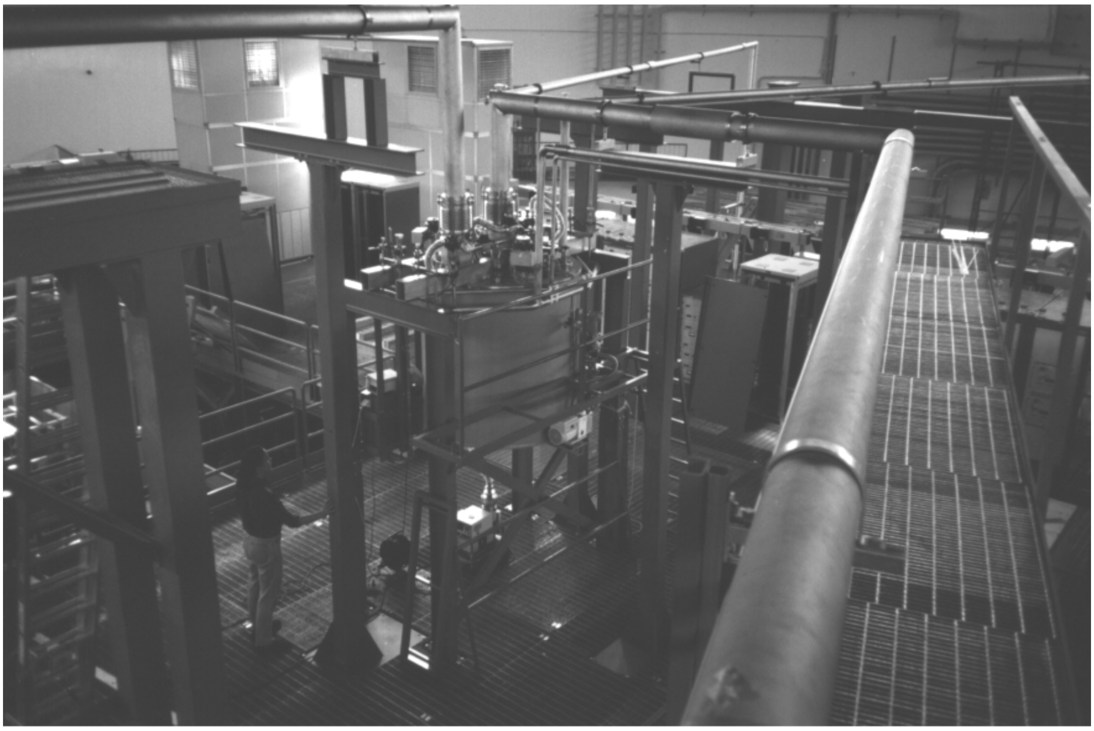

Figure 5 : A view of the Valve Box with the Cryogenic Transfer Lines
installed in the center of the DAΦNE Hall.

3. STATUS OF THE DAΦNE CRYOGENIC SYSTEM

Following the tight scheduling, the Linde cryogenic plant was installed in Spring 1997 and successfully commissioned during the starting of the Summer 1997 [Ref. 6].

The tight scheduling has permitted to match in sequence the commissioning of the cryoplant with the first cooling down of the KLOE magnet. This very important milestone was reached in August 1997 and was followed by the acceptance test and field mapping of the magnet. At the actual date (October 1997) the Linde cryoplant has been functioning for over 3 months continuously, the KLOE magnet has passed through its Acceptance Test and is completing its magnetic measurement phase.

The FINUDA magnet was successfully cooled and cryogenically tested at Ansaldo during the Winter 1996, and its installation in the DAΦNE Hall, is foreseen in 1998.

The Solenoid Compensator magnets were tested at LNF in June 1996. Because at that time the cryogenic plant was not yet installed, the Compensator magnets were cooled in an alternatively way (i.e. cooling and refilling the magnets by a liquid Helium transfer from dewars).

The Compensator magnets are now completely installed on the accelerator and they will be put in operation with the two main Experiments magnets KLOE and FINUDA during 1998.

Acknowledgment

We would like to thank Dr. Giorgio Passardi of CERN for the suggestions, supporting, and specifications revision during the phase of the DAΦNE Cryogenic Plant definition.

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