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SOLEMI-1, A 8 TESLA, 535 mm ROOM TEMPERATURE BORE, SUPERCONDUCTING SOLENOID – PART 2: CRYOGENIC, VACUUM, DATA ACQUISITION AND CONTROL SYSTEM

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ABSTRACT

The superconducting solenoid *SOLEMI-1* has a central field of 8 tesla with a room temperature bore of 535 mm. It was assembled and successfully energized in the LASA laboratory in 1991. The coils, with an inner diameter of 640 mm and a length of 900 mm, are wound with NbTi/Cu cable and operate in LHe bath at 4.2 K. While the stored energy is quite large, 12 MJoule, the coils are "adiabatic", fully impregnated with epoxy resin, in order to have more compactness and less cost. This solenoid is the first part of a complex facility, *SOLEMI* , aimed to reach 18 tesla by insertion of two more NbSn coils.

In this report the diagnostic (temperature, pressure, strain and coils displacement gauges), the power supply, the vacuum and the control system of *SOLEMI-1* are presented and their experimental performances are discussed.

1.- INTRODUCTION

In the LASA laboratory (INFN and Physics Department of the University of Milan) a high field superconducting facility is under construction, funded by INFN. The aim is to reach a static magnetic field of 18 tesla in a useful bore of 100 mm at 4.2 K. The facility has been designed to meet two basic requirements:

1. to have available a background field in a large bore for a test station suitable for critical current measurements of high current cables. One aim of this test station is the measurement of the critical current of cables used for the superconducting dipoles for LHC (Large Hadron Collider) under study at CERN.

2. to have a magnetic field in the range 15 - 20 tesla in a smaller bore. This high field, which must be generated with superconducting coils to avoid excessive power consumption, will be used for fundamental studies on superconductive and normal materials as well as for technical development of superconducting cables. In order to test cables in a real situation, i.e. wound in a small but still significant coil, the free bore must be substantially larger than the usual 30 - 40 mm typical of the superconducting magnets working in this field range.

In order to fulfil the above mentioned requirements, we proposed to construct a solenoid with multiple windings and to split the cryogenic equipment into two concentric, independent cryostats [1]. This resulted in a design where the NbTi windings generate a field of 8 tesla in a free, room temperature, bore of 535 mm, the coils having an inner diameter of 640 mm. This first stage, named *SOLEMI-1* can be used either to provide the background field for the inner NbSn coils or to generate the field for the cable test station. Just as *SOLEMI-1* will be used alone for measurements at moderate field level $\leq$ 8 tesla, the inner Nb_3Sn solenoid can be used alone, too, for experiments where intermediate field level, $\leq$ 15 tesla, is sufficient [2], [3].

While the detailed design of *SOLEMI-1* is reported elsewhere [4], in this paper, after a brief description of the whole facility, we recall the main features of the the cables and coils of *SOLEMI-1* and we describe the magnet diagnostic, with particular reference to the Quench Detection System (QDS). Therefore the results obtained in the first year of operation are reported and compared with the design expectation. The data measured during a number of quench, induced to measure the actual velocity of the quench propagation, are discussed and analyzed (hot spot temperature, maximum voltage, current decay, etc.).

2.- GENERAL DESCRIPTION OF *SOLEMI*

The use of only superconducting coils was a prerequisite condition in projecting the high field facility because of the prohibitive (for our lab) power requirements of hybrid magnets. Also we decided to reach the high field by means of concentric solenoids having two independent cryostats. This obviously reduces somewhat the bore as compared with that of a single solenoid but allows us to change easily the configuration from high field (18 T) in a small 4 K bore (100 mm) to intermediate field (8 T) in a large 300 K bore (535 mm). In Figure 1 the sketch of the whole magnet *SOLEMI* is shown.

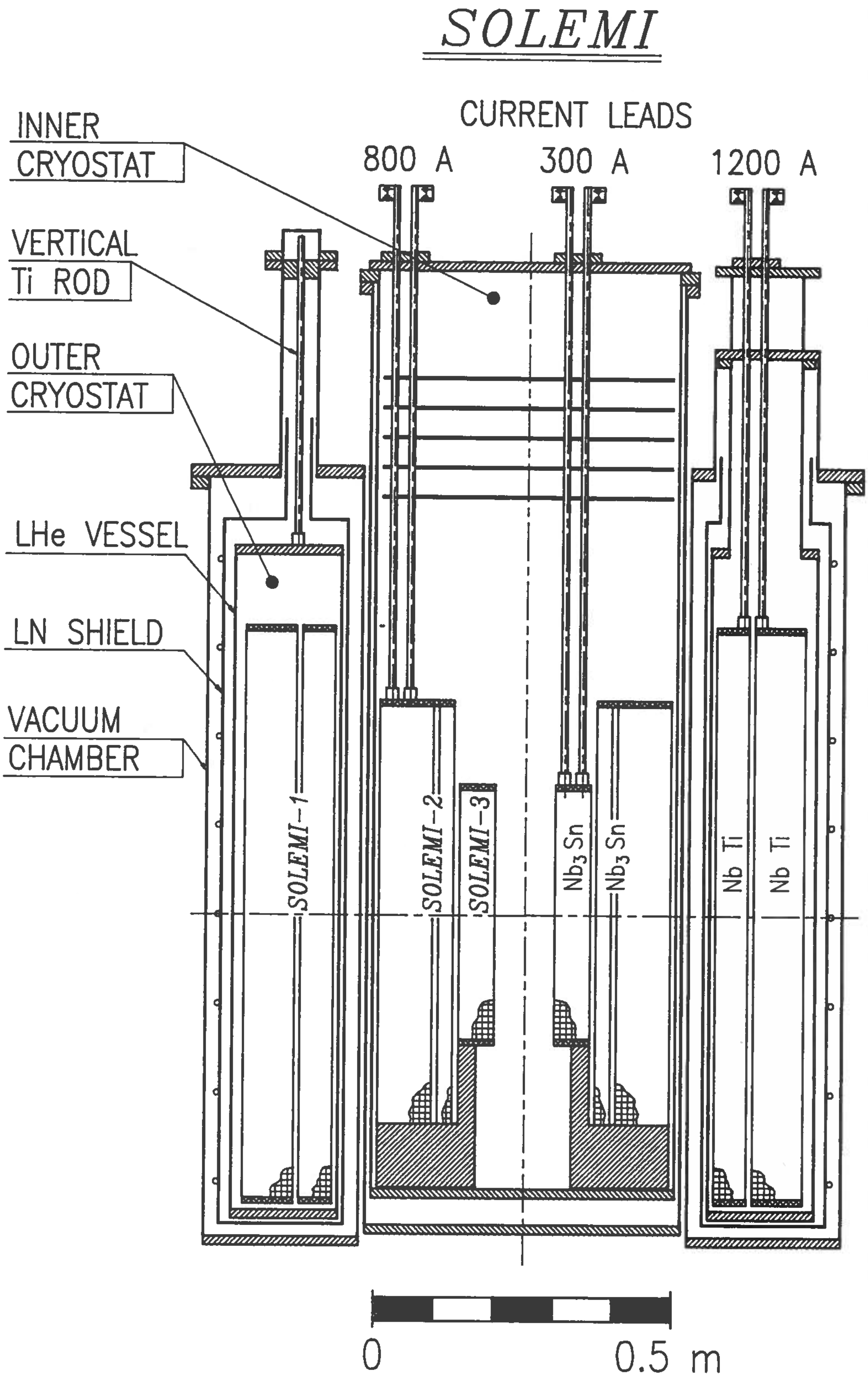

Figure 1: Schematic section of the superconducting multiple solenoid *SOLEMI* .

Operation at 4.2 K in the LHe bath was chosen for both cryostats at the beginning of the design process. A cooling improvement is possible for both cryostat by means of λ-point refrigerator.

The height-to-diameter ratio is great enough to have a sufficiently homogeneous field for physics measurements: in the center of the bore (defined by a 10 mm diameter sphere) the field variation is within $\pm$ 50 ppm. By inserting small trim coils the field homogeneity can easily be improved by an order of magnitude.

The great height-to-diameter ratio also helps to keep the field at the coils quite near to the central field allowing a better exploitation of the current density performances of the superconducting cables. In every solenoid the coils are split into two sections with a small gap in between to improve both the cooling and the superconductor efficiency. Moreover this subdivision makes easier to support the electromagnetic stresses by means of suitable banding.

All the coils are vacuum impregnated with resin. The overall current density is high but still reasonable in the range of 60-80 A/mm^2. The choice of adiabatic, not cryostabilized, coils was mandatory to contain both the total size of the magnet and the cost of the facility. Since the total stored energy in magnet is fairly large, 18 MJ, the stability of the coils has been carefully investigated. The safety system consists of an individual external dumping resistor for each solenoid with a fast discharge triggered by an analog Quench Detection System (QDS) based on the measurement of the voltage across every winding unit (total 9).

3.- CHARACTERISTICS OF THE NbTi COIL

3.1 - Superconducting Cable

The conductor chosen for the magnet was supplied by Vacuumschmelze (Hanau - D) for the inner section and by Europa Metalli - LMI (Florence) for the outer one. The two cables are similar, made of a rectangular copper core on which 13 NbTi/Cu superconducting strands are soldered with tin alloy. The cable for the inner section was guaranteed to have no degradation of critical current up a stress level of 150 MPa.

The characteristics of the cable are listed in Table 1.

3.2 - Windings and Protection System

The detailed list of the coil characteristics is reported in Table 2, while in Figure 2 the magnet load line is shown. The maximum theoretical performance is obtained at the intersection of the line of the maximum field in the coils with the critical current curve. As shown in Figure 2, the maximum nominal operating point, 8 tesla in the centre, is very near to the critical current limit of 8.55 tesla at 4.2 K.

The magnet is not self-protected (stored energy is 12 MJoule) and a solution based on an external dumping resistor activated by a Quench Detection System (QDS) was chosen. In Figure 3 the scheme of the protection system is shown. Both coil sections are split into two subsections by voltage taps, to have four voltage signals from the coils. Another signal is the voltage across a pick-up coil wound on the banding of the inner coil. The pick-up coil is wound with a fine copper wire, 144 turns and 29.3 Ω. Every voltage of the coil subsection

Table 1: characteristics of the NbTi conductors.

	inner coil	*outer coil*
supplier	VAC (Hanau - D)	EM-LMI (Florence)
Core size (mm)	1.3×2.9	1.3 ×2.6
No. of strands	13 NbTi/Cu	7 NbTi/Cu + 7 Cu
strands diameter (mm)	0.84	s/c 0.67 + Cu 0.55
filament diameter (μm)	19	13
twist pitch (mm)	30	25
cable transposition length (mm)	60	60
cable dimensions (mm)	2.8 ×4.4	2.4 ×3.7
Cu cross section (mm^2)	8.378	6.61
NbTi cross section (mm^2)	2.425	0.889
Cu:NbTi	3.5	7.37
solder cross section (mm^2)	1.5	1.38
total Cu : non Cu	2.13	2.92
RRR (at zero field)	118	$\geq$100
requested I_c at 4.2 K	1500 @ 8.7 T	1250 @ 6.5 T
measured cable I_c (A)	1730 @ 8.7 T	1377 @ 6.5 T
criterion	$10^{-14}\Omega$m	0.1μV/cm
n-value	20–25	17
I_c cable degradation	2.8%	$\leq$ 3%
NbTi J_c A/mm^2	713	1404
total length (m)	4900 (2 pieces)	16500 (12 pieces)

is compared with the voltage of the pick-up and with some of the other subsections (1-4, 2-4, 3-4 and 4-1). The inductive voltages are compensated so that the unbalanced voltage is due to resistance of the coil. When a fixed threshold is passed, of the order of 100 mV × 100 ms, the switch (see Figure 3) is opened in about 100 ms, disconnecting the power supply and leaving the magnet to discharge through the dumping resistor.

In principle the comparison of the two main coils voltages with the pick-up voltage is enough to detect a quench also while ramping the magnet. Anyway the safety of such a big adiabatic coil calls for a redundant system, to avoid unwanted long delay in detecting the start of a quench. Splitting each coil section into two subsections by means of voltage taps and comparing also the signals of adjacent subsections improves the QDS sensitivity for two reasons:

1. the noise is somehow proportional to the length of the winding across two voltage taps;

2. the ratios of inductive voltage between sections and pick-up winding and between the two main sections are not exactly constant when current changes. In fact the increase in radius is slightly different for the coils and for the stainless steel banding the pick-up is wound onto. It is likely to be more constant between two halves of the same section, which, being impregnated, moves almost as a solid shell.

The balance of the inductive signals between different subsections is not critical for the QDS: indeed the $\Delta V \times \Delta t = E$ threshold starts to be considered only when $\Delta V \geq V_0$. Both

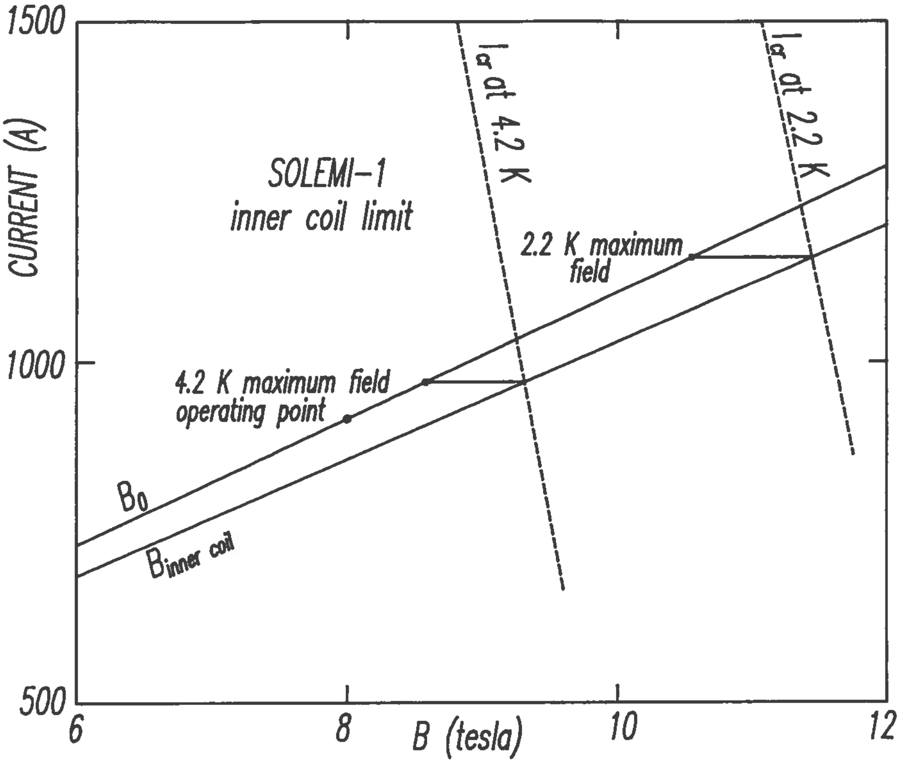

Figure 2: Load line and critical current curves of *SOLEMI-1* .

Table 2: Main parameter of the superconducting coils.

	inner section	*outer section*
inner radius (mm)	317	377.4
outer radius (mm)	355.4	455.8
length (mm)	907.2	910.2
insulation thickness (mm)	0.2	0.2
winding unit cell (mm)	3.2 ×4.8	2.8 ×4.1
cross section (mm^2)	15.36	11.48
layer	12	28
turn number	2268	6227
R.T. coil resistance (Ω)	9.63	44.11
section inductance (H)	1.86	18.9
total inductance (H)	29.4	
magnet current at 8 T (A)	905	
stored energy at 8 T (MJ)	12.3	
non copper J_c A/mm^2	715	1550
overall J_c A/mm^2	58.9	78.8
max. voltage to ground (kV)	2	

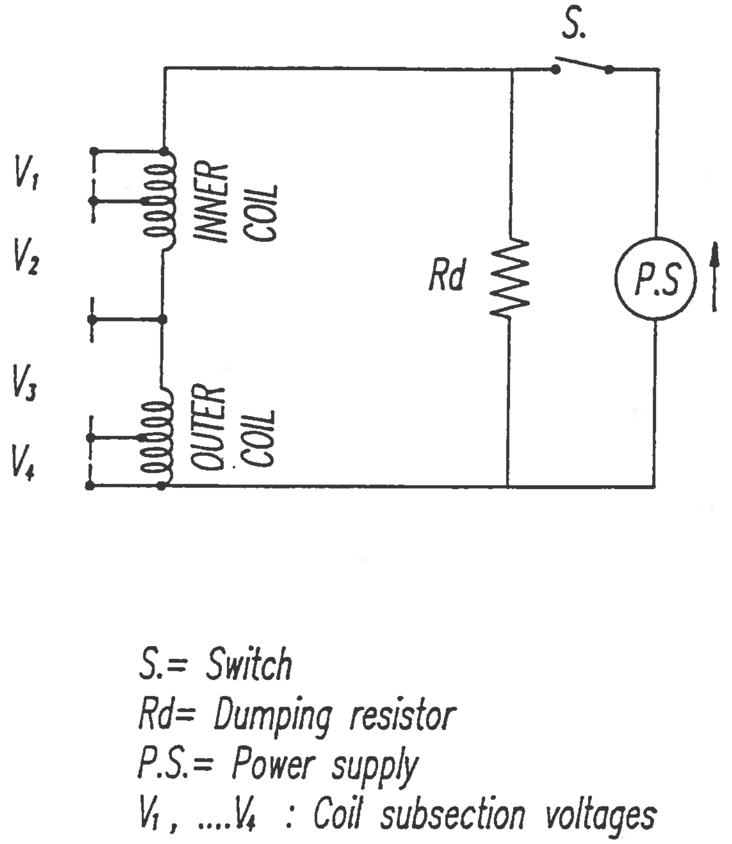

Figure 3: Electric scheme of the solenoid and protection system.

E and V_0 are different for every subsection. In Figure 4 the scheme of the comparator circuit is shown.

The detailed list of parameters concerning stability, quench evolution and protection is shown in Table 3. Parameters are calculated with a dumping resistor of 1.2 Ω and a QDS threshold of 350 mV $\times$ 260 ms for subsection 1 and 2 and a threshold of 500 mV $\times$ 260 ms for subsection 3 and 4. Thermal conductivity λ, quench velocity and Minimum Propagating Zone (MPZ) are calculated when quench starts (at maximum field).

3.3 - Cryostat

The cryostat is annular, to have a warm bore. The vacuum chamber is made out of stainless steel 304 L while the helium vessel and all parts likely to be be cold either in the cool down or during a quench are in 316 L. The inlet of the cooling fluid is done near the bottom of the vessel and outside the outer coil. A copper tube with small holes is bonded with resin to the vessel wall all around the coils to improve temperature homogeneity.

The helium vessel is designed for operation at 3 bar (absolute) and three neck are provided for electric and cryogenics. The maximum free volume in the vessel for the liquid helium is 140 liters, with a maximum of 60 liter over the coil top if the 14 cm are totally filled. A safety valve of $\phi = 35$ mm, opening to the atmosphere at 0.5 bar of overpressure is installed, together with a $\phi = 50$ mm rupture disk breaking to the atmosphere at 0.7 bar.

The thermal shield made out of copper, 2 mm thick, is cooled with a continuous flow of

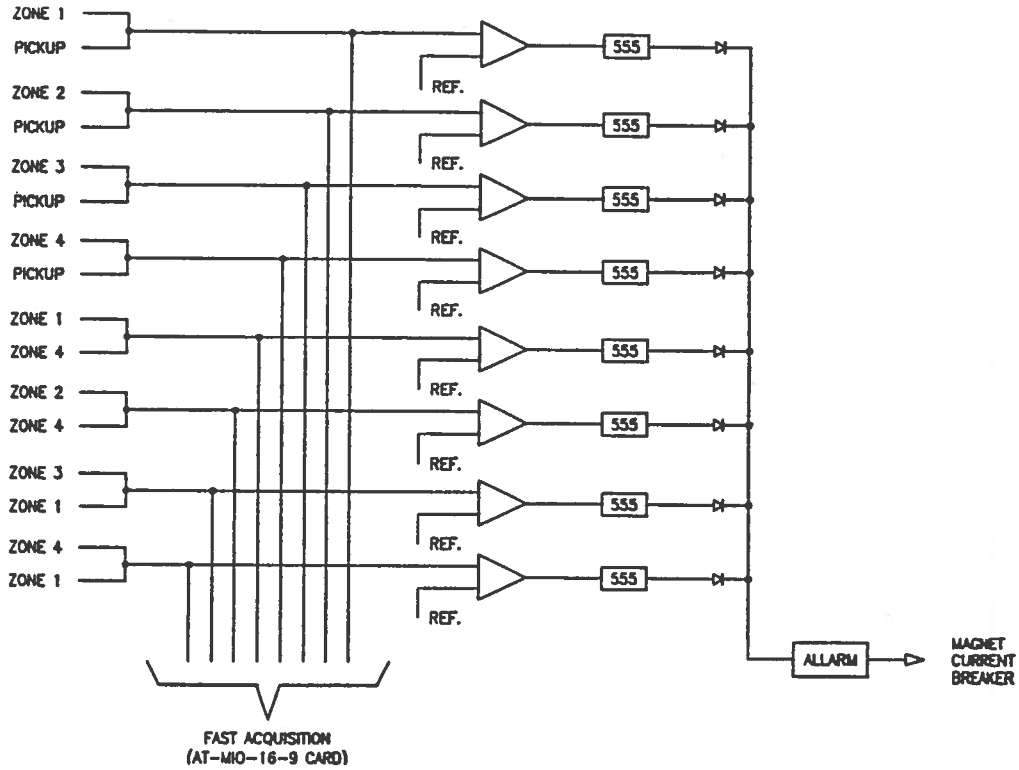

Figure 4: Electric scheme of the circuit comparing voltages across coil subsections.

Table 3: Stability and quench parameters.

	inner section	outer section
maximum coil field (T)	8.7	6.5
λ_l (W/m-K)	167	237
λ_t radial (W/m-K)	0.43	0.53
λ_t axial (W/m-K)	0.48	0.64
MPZ size (mm)	17.9×0.95	28.5 ×1.5
MPZ energy (mJ)	0.15	0.95
long. quench velocity (m/s)	6.83	8.8
v_l / v_r	51.5	54.2
v_l / v_h	40	41.4
Hot spot temperature (K)	100.6	102
max. coil voltage (V)	1080	

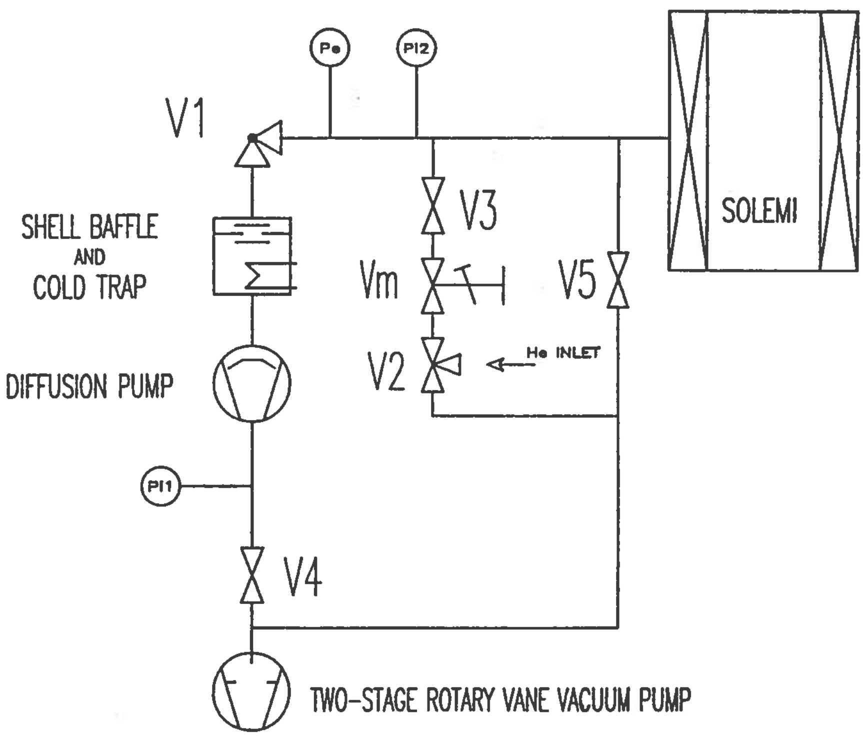

Figure 5: vacuum system of *SOLEMI-1* .

liquid nitrogen through a cooling pipe soldered all around the vertical walls.

3.4 - Vacuum

The vacuum system for the cryostat is basically composed by a rotary pump and a diffusion pump. The choice of this system was based on the large stray field in the region surrounding the solenoid and also based on consideration of less cost and easier maintenance of the diffusion with respect to an equivalent turbomolecular pump. A scheme of the vacuum plant is shown in Figure 5.

The rotary unit is about 5 m far from the magnet, where the field level is 3 mT (when B_0 is 8 T) while the diffusion unit is 2 meter in a maximum field of 23 mT, together with the pirani and penning vacuum gauges. These gauges are shielded form the field with two coaxial soft iron cylinders. Also the box of relais acting on pumps and valves are in the same environment and it's shielded with a 7 layers of 1 mm thick soft iron sheets. We checked the ratio between the vacuum indicated by the permanent gauges, positioned in their shields near the diffusion pump, and the actual vacuum inside the cryostat: the indication is about 3 times better than the actual vacuum when the chamber is at 10^{-7} mbar, and almost correct in the mbar range.

The diffusion pump has a pumping speed of 1010 l/s when $P \leq 10^{-5}$ mbar, while the vapor tension of the oil is 4 10^{-9} mbar. A cold trap is attatched to the diffusion unit, with a cold cup baffle and a shell baffle, this last cooled with fluid at -30 °C by means of a local refrigerator. The cold cap and shell baffles lower the effective pumping to about 500 l/s and the other elements between the diffusion pump and the cryostat — an ISO 160 90 °C valve, a 1.8 m long tube of ϕ=153 mm, bellows, a frame and a final gate ISO 100 — makes the total effective pumping speed in the chamber to be about 90 l/s.

The cryostat is not perfectly vacuum tight and has a total leak of about 1.5 10^{-5} mbar l/s. There is not a unique or major leak point and in spite of some effort it was not possible to reduce the total leak, which actually includes also the outgassing (there are many layers of aluminized mylar). The best vacuum reached inside the chamber is 2-3 10^{-7} mbar, in good agreement with the calculated performances.

The vacuum system has its own local control based on programmable PLC, such that in any case the cryostat is safe and when the normal conditions are restored the system restarts automatically. From start the sequence is:

1. slow pre-vacuum with rotary pump from 1 bar to 10 mbar; it takes 4-6 hours, the reason for such slowness is to avoid damage to the multilayer insulation;

2. fast pre-vacuum, with rotary only down to 7 10^{-3} mbar; 30 minutes;

3. diffusion starts when $P \leq 7\,10^{-3}$; it takes about half a day to reach the steady condition.

While the vacuum system worked well and reliably, the vacuum chamber is less than satisfying : as already mentioned, many elements present a not negligible leak and moreover some O-rings are in position to get frost when the helium consumption is high and the cold gas recovery is consistent. To cope with this problem, heaters were installed on the necks but the problem appears again sometime after a quench, when large cold helium flow are expelled in few seconds from the vessel. In particular one O-ring is strongly affected by frost and four times we had partial lost of vacuum, the first one so unexpected that caused the interruption of the test of the magnet. At present the problem is partially solved by strong local heating near the O-ring after the quench and with additional pumping unit for short time when needed.

3.5 - Temperature Sensors

Following the experience on a big superconducting magnet [6] we decided to have a detailed temperature map of the coil-cryostat system. We mounted CLTS (Cryogenic Linear Temperature Sensor of Micro-Measurements, USA) for their easy use, which allows rough measurements without calibration over the entire 4–300 K temperature range. In fact the first cool down was done without using the proper calibration for every CLTS probes and the results, when compared with a further cool down were individual calibration was used, was sufficiently good. Six CLTS were bonded on the coils and six on the vessel on the side of the vacuum.

Other six CLTS are employed to monitor the temperature of the radiation shield. For these measuring points use of Pt-100 temperature sensors would have been a better and more economic choice since the minimum temperature is around 80 K but CLTS were preferred for uniformity. These sensors are supplied by a 100 μA d.c..

The coil resistance is measured during cool down suppling a d.c. current of 10 mA. When converted in average coil temperature it shows an agreement within few degrees with the mean values of the six CLTS bonded to the coil. This means that although these six CLTS are separated from the nearest copper turn by at least 2 mm thickness of epoxy impregnated glass tape (ground insulation), their reading is quite representative of the actual coil temperature (at least with cooling rate $\leq$ 2 K/h).

Two CLTS bonded on the coils, in the median plane position where the field is maximum, have been employed as heaters (their 4 K resistance is about 220 Ω) in special runs of the magnet were we investigated the quench propagation in the solenoid.

In Figure 6 a scheme with a general view of the position of all the sensors mounted in the cryostat is given.

The CLTS are very easy to use but they are not very accurate and are strongly affected by magnetic field. To measure with good accuracy (within few tens of mK) the temperature of the bath we mounted four CGR (Carbon Glass Resistor of Lake Shore, USA), fixed inside the bottom and top G11 flanges delimiting the coil length. They are calibrated down to 1.8 K, allowing accurate reading also when superfluid helium will be employed to lower the bath temperature.

3.6 - Pressure Gauges, Strain Gauges and Load Cells

First of all let's state that any value of pressure in this report is an absolute value (if not otherwise indicated), i.e. the normal operating pressure of the helium vessel is 1.0–1.2 bar.

The pressure in the helium vessel is measured with three independent gauges. One is an electric pressure transducer based on a strain gauges full bridge encapsulated in a stainless steel jacket. This model, EBM 6043 of Tekkal, is a special type useful for cryogenic gas down to 4 K. The range is from 0 to 4 bar and is linear within 0.15 %. Its output is sent to the computer control for display and recording. This pressure transducer was found quite sensitive to magnetic field (which is not completely surprising, since is based on regular strain gauges). In its initial position, when the magnetic field on the transducer was about 0.25 tesla the measured pressure was about 1.4 bar while the actual pressure was 1.25 bar.

Two manometers are also employed. One with a limited range of 1–2 bar, is for accurate reading having a sensitivity of 2.5 mbar and a total accuracy of 5 mbar. It does not withstand vacuum or high pressure. The reason of this precision manometer is for measurements in case of failure of the transducer (it happened twice: once for freezing of a non cryogenic model and the other time for magnetic field induced reading error). Actually since the computer display is not always active and since its reading is easy and immediate, this manometer is the most frequently used for pressure measurements.

Another manometer is always on line. It is less accurate but allows to exploit a larger range, from vacuum to 3 bar and it has a trailed needle to indicate the maximum pressure reached during a quench. It has a sensitivity of 10 mbar and an accuracy of 20 mbar. Both manometers and pressure transducer are approximately 8 meter far from the magnet center. In this position the magnetic field, when B_0 is 8 T, is less than 1 mT.

The helium vessel is suspended by means of three titanium rods. The rods are 8 mm in diameter and the load is 2.6 tons, which gives a stress of 170 MPa. Additional load can be applied on these rods both due to attraction of iron masses (the floor is steel reinforced and other steel bars and nets are not far from the solenoid) and due to interaction with the Nb_3Sn coils when the facility will be completed. For this reason strain gauges (SG)are bonded to the Ti rods to monitor vertical force or torque acting on the coils. The SG type is WK-06-062AP-350 of Micro-Measurements (USA), suitable from 4 to 500 K. They are arranged in a full bridge configuration, powered with 5 V.

The coils are radially centered by means of three pairs of Ti rods, 4 mm in diameter. Since it's very difficult to bond strain gauges on such a thin rod, the force acting on these suspensions is measured via load cells. The radial position of the coils must be carefully

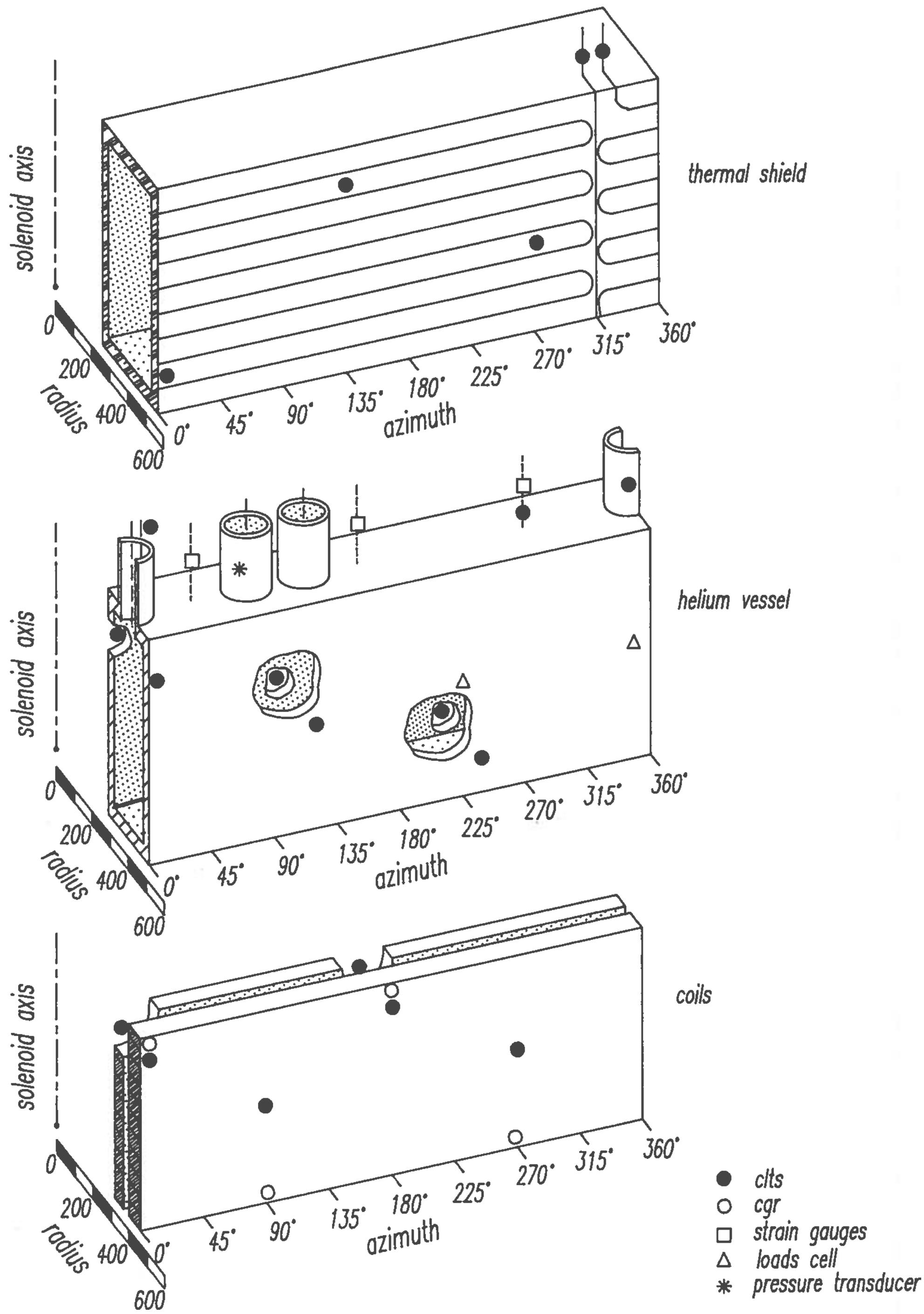

Figure 6: Map of the sensors mounted in the solenoid.

controlled because, when the inner Nb_3Sn coils of *SOLEMI-2-3* will be inserted, an off-center of the vertical axis will raise a decentering force of the order of 8 kN for 1 mm of displacement. We have to control the centering of the coils, acting on the rods of the NbTi cryostat, in order to keep the force below 1.5 kN, which means a centering better than 0.2 mm. Since the high cost of the load cells, made out of stainless steel to avoid effect due to the high stray field (up to 1 T), and since the insertion of the Nb_3Sn coils is foreseen at the end of 1993, we decided to put load cells (model EBM 6203 of Tekkal only on two rods, just to check their reliability. They are based on a full strain gauge bridge with an electric sensitivity of 1 mV/V. Their range is from 0 to 4.9 kN (500 kg-force) and they are powered with 5 V (1 mV reading corresponds to 980 N). Hysteresis is less than 0.05 % and their total accuracy is better than 0.5 %.

3.7 - Power Supply

A water cooled d.c. power supply provides a current up to 1200 A with a maximum of 36 V. Its regulation is base upon SCR and active filter. It was built by Foeldi, Zurich (CH), following our specification: stability of the current output: better than 25 mA peak-to-peak in the current mode with less than 50 mV peak-to-peak in the 0-1 kHz bandwidth both in steady state and during current ramp. It has a local control panel with a 16 bit DAC for current regulation (the bit corresponds to 18 mA) and a 12 bit DAC for voltage regulation (1 bit $\simeq$9 mV) and it can be remote programmed via GPIB. The magnet current is read via a DCCT with a precision better than 10^{-5} (12 mA).

The power supply cabinet includes a fast (50 ms) electro-mechanical switch, to break the current to the magnet in case of QDS alarm, and the dumping resistor. This last is modular, allowing the following values: 0.6, 0.8, 1 and 1.2 Ω. Usually 1.2 Ω value is selected. The resistor, air cooled with natural convection, is designed to dissipate 22 MJ energy in 120 s with a maximum temperature of 200 °C.

3.8 - Control System

A personal computer HP Vectra ES/12 takes care of the control and provides data display and recording. The PC is connected through a GPIB to a data acquisition/control unit HP3852A. This last unit is the core of the control system, being a very powerful scanner with many functions like precision voltage, resistor and strain gauge direct reading. It takes care also of the remote driving of the magnet power supply. Only the vacuum system has its local control unit, see para 3.4.

During cool down and when the cryostat is at 4.2 K but the magnet is off, all the sensor values are displayed, with reading every 3 seconds and recording on diskette every one hour.

During coil excitation all the signals and sensors are scanned and recorded on diskette every 2.26 s but to facilitate the visual control only the most important are displayed. Only the last 199 scans are kept in memory (which means last 450 seconds). When the QDS circuit activates the dumping system, only few important parameters are recorded with a faster scanning rate, 215 ms. After quench detection the fast data acquisition is active for 200 scans, which corresponds to 43 s, and afterwards the normal, slow and complete, data acquisition can be restored. The complete list of signals and sensors recorded is reported below, together with the indication of those actually displayed on the monitor (M) and those recorded during a fast discharge (Q).

1. current in the magnet; M, Q;
2. voltage of pick-up coil;
3. voltage of subsections 1 and 2; M (1+2), Q;
4. voltage of subsections 3 and 4; M (3+4), Q;
5. voltage drops along the current leads; M, Q;
6. helium level; Q;
7. vacuum in the cryostat; Q;
8. CGR 7 (inner coil, top flange, 0°); M, Q;
9. CLTS 5 (outer coil, 20 cm above the bottom of the vessel, 0°);
10. CLTS18 (LN shield, top, 137°); M, Q;
11. CLTS 21 (inlet tube of LN to the shield);
12. CLTS 1 (inner coil, 20 cm below the top flange, 0°);
13. CLTS 11 (inner wall of the helium can, 20 below the top, 0°); M;
14. CLTS 22 (temperature of the current lead neck); M;
15. CLTS 27 (temperature at warm terminal of one current lead);
16. pressure in the helium vessel; M, Q;
17. force on two horizontal suspension rods (load cells); M;
18. force on a vertical suspension rod (strain gauge); M.

The values of liquid helium level and the vacuum in the cryostat are not displayed on the monitor but their values are displayed on the instruments near the operator console.

In Figure 7 is reported a schematic outline of the control system.

The QDS signals, balanced difference between subsection voltages are recorded with an independent system based on the card AT-MIO-16-9 of National Instruments. The 8 signals, see Figure 4, are scanned with a 200 Hz frequency, the scan itself being so fast — 90 kHz of sampling rate — that the measurements of the channels in one scan can be considered simultaneous. In the memory are kept the last 32,000 readings, which corresponds to 30 seconds and are continuously refreshed. When the fast discharge is activated by the QDS, the data acquisition is triggered such that the readings of 10 s before and 20 s after the trigger are kept and later discharged on a diskette for analysis. By means of this acquisition the quench evolution can be investigated in detail.

4 - COOL-DOWN

The cryogenic plant of LASA consists of a 10,000 l dewar for liquid nitrogen storage and a liquid helium refrigerator–liquefier, Sulzer model TCF 100, capable of 80 W–30 l/h without

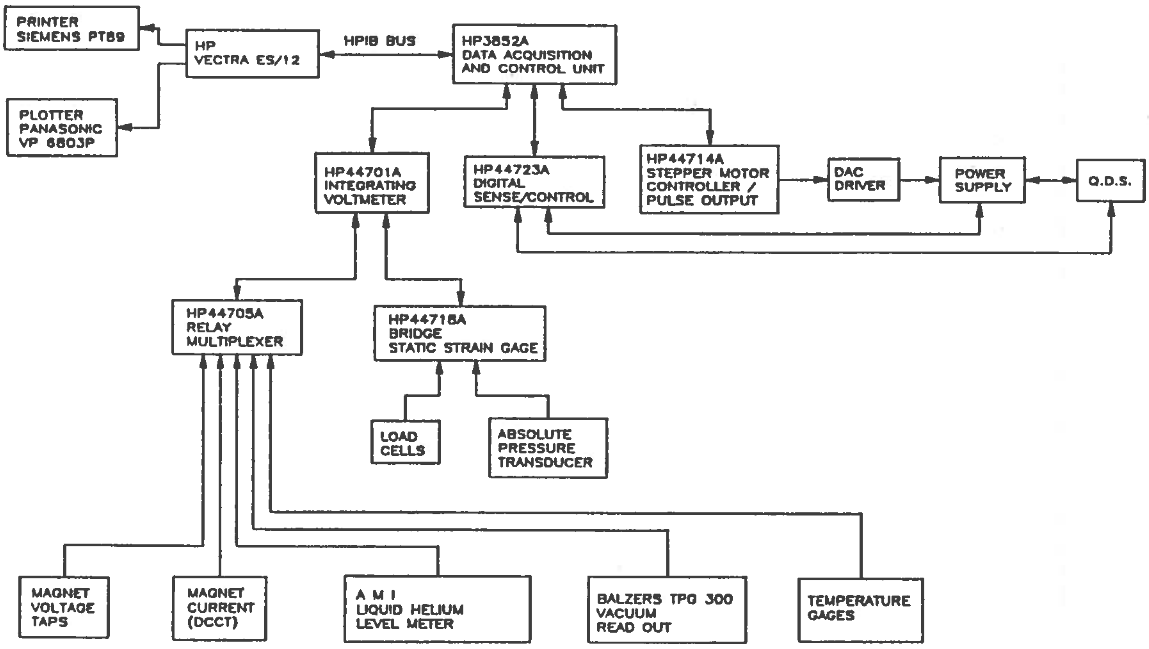

Figure 7: scheme of the acquisition and control system.

LN or 120 W–45 l/h with LN pre-cooling of refrigeration power–liquid helium production. The magnet is not directly connected to the cold box and helium is recovered all at room temperature so the system works in only liquefier mode. A 1000 l dewar is permanently connected to the liquefier as main liquid helium storage. From the 1000 l dewar the helium is transferred into 450 l dewar which are transported with a crane near the cryostat where the helium is then transferred into the magnet vessel cryostat.

4.1 - LN Cooling with Mixer

The cool down is divided into two steps: 1) liquid nitrogen, coming from the 10,000 l reservoir through an insulated fixed line, is used as cooling source down to 80-100 K; 2) further cooling takes place with liquid helium from one 450 l dewar.

Liquid nitrogen coming from the line is mixed with warm nitrogen gas in order to obtain controlled temperature of the inlet gas. In the first cool down the inlet temperature regulation was very rough, performed just balancing the liquid and the warm gas by opening and closing two manual valves. Despite the roughness of the method the cool down was controlled without serious problems, only required an almost continuous presence of an operator for all the cool down (8 days).

Starting from the second cool down we made use of an automatic gas-liquid mixer. The mixing unit has a liquid nitrogen line and a warm gas pipe as input, a small LN vessel, an heater, and a cold gas line as output. The output gas temperature can be programmed via a local control system which allow the selection of many cooling (or warming) rates. A scheme and a photograph of the mixing unit, furnished by SIO–Alpha Gaz, Milan, are shown in Figure 8 and its main parameter are listed as following:

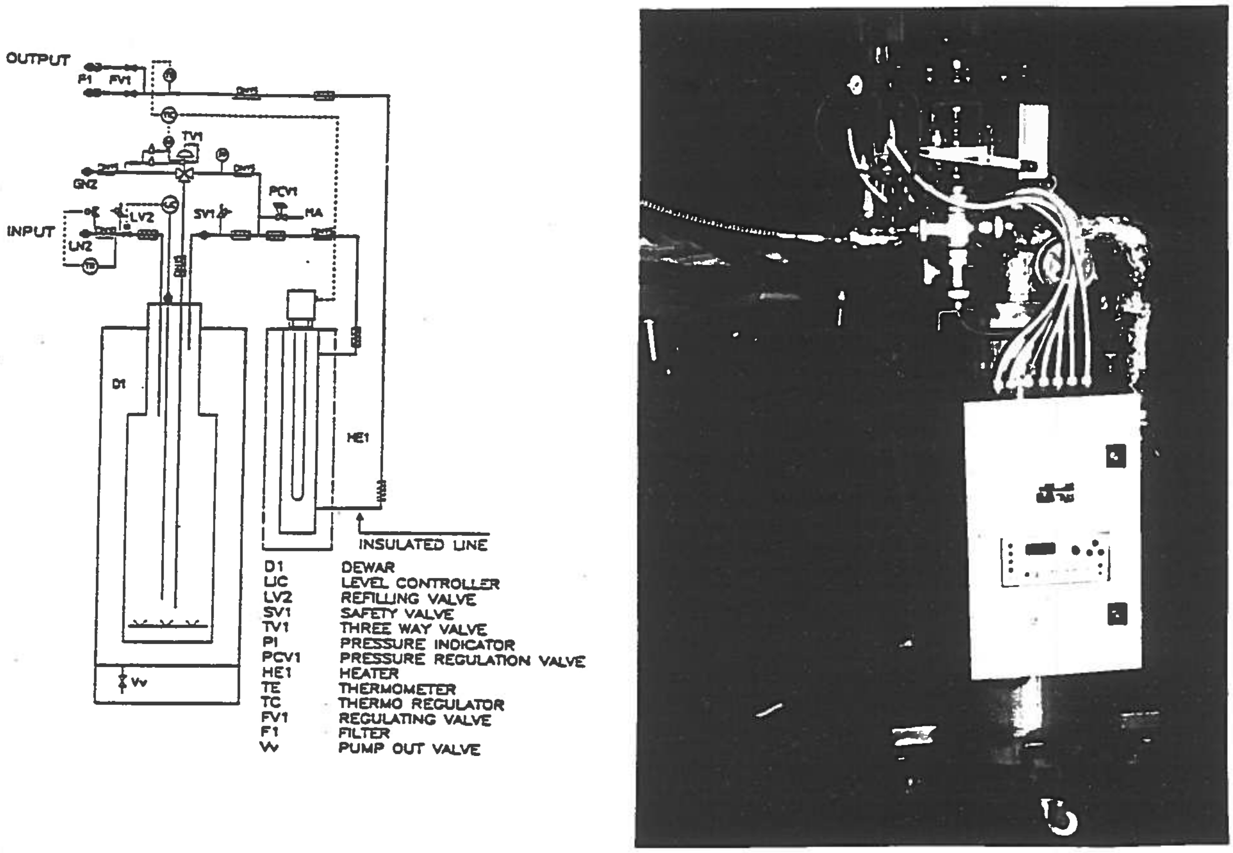

Figure 8: function scheme and picture of the LN–N gas mixer with programmed temperature control.

1. output gas temperature range: 80–300 K (pre-programmed);
2. mass flow range: 3–20 n.m^3/h (manually adjustable);
3. temperature rate: 0.5–10 K/h (pre-programmed);
4. maximum pressure at the output: 2 bar (absolute);
5. maximum inlet–outlet pressure drop : 0.5 bar;

The LN source is the 10,000 l reservoir, usually at 2.8-3 bar absolute connected to the mixer through a vacuum-insulated cryogenic line about 12 m long. The mixer feeds both the helium vessel and the LN shield, so that the two elements cool together.

Cool down of the cryostat starts with the mixer until the cooling gas is about 100 K. The average temperature rate is small, around 1 K/h: for this cooling rate the maximum ΔT is less than 20 K for the coils and less than 30 K for the helium vessel.

After a week, when the cooling gas is at the limit of the mixer capability, around 100-110 K, the mixer is taken away and liquid nitrogen is sent directly into the cryostat through two semi-flexible insulated transfer lines.

One line is permanently connected for all the time of the magnet run and feeds the 80 K thermal shield. The nitrogen flows through the small round channels (6 $\times$8 mm) soldered to the wall of the shield and at the end the cold gas is warmed through a heat exchanger and eventually collected in a pipe which exits to the atmosphere outside the experimental hall. The regulation of the mass flow is done by adjusting a manual valve.

The other nitrogen line goes into the helium vessel and is used to introduce liquid nitrogen and to cool the coil effectively down to 80 K (when the mixer is stopped the minimum temperature in the vessel is 110-120 K, but most of the mass is at 140-150 K). It's not convenient to cover the coils with LN because it would take too much time to evaporate. LN then is introduced up to 200-300 mm of height, and the system is left quiet for 2–3 days (usually a week-end) so that every part of the cryostat is thermalised at around 80–100 K. Therefore starts the nitrogen removal. The liquid is expelled by pressurizing with nitrogen gas the vessel, forcing the liquid to exit through a syphon inserted to the bottom of the reservoir. At the end the vessel is pressurized with helium gas up to 1.2–1.3 bar, to remove any trace of nitrogen.

At this points cooling with liquid helium starts through a flexible transfer line, the helium being in a portable 450 l dewar near the cryostat. Typically one day is enough to cool the coils down to 4.2 K and to fill the vessel with liquid helium. In Figure 9 the temperature behaviour of the magnet during a cool down is plotted.

4.2 - Recovery System and Cryostat Consumption

The helium is recovered as warm gas in a low pressure 10 m^3 balloon from where is stocked into high pressure cylinders. The rate of the balloon evacuation is 43 m^3/h, when the cylinders are at the maximum pressure of 200 bar. We have 5 fixed recovery ports from the cryostat, one for each neck and one for each vapour cooled current leads. There is one more pipe is for recovery of the evaporation of the 450 dewar used for helium transfer.

In Figure 10 a schematic of the recovery plant from *SOLEMI-1* is shown. Every line is controlled by flowmeters which have a manual regulating valve at the entrance. Each flowmeter can be virtually by-passed by opening the manual gate which connect each recovery line (20×22 mm tubes) directly to the collecting pipe (51×54 mmtube). The collecting tube goes to the balloon through a check valve.

Before entering the recovery lines, the cold helium gas coming from the cryostat is warmed through two heat exchangers working with a continuous flow of nitrogen gas. An overpressure of 250–300 mbar in the dewar is enough for the helium transfer, being the pressure in the vessel about 1.1–1.15 bar. The pressure in the vessel is mainly determined by the check valve (about 30 mbar), the flowmeter (about 30 mbar), the balloon pressure itself (about 20 mbar) and the pressure drop required by the line to evacuate the vaporized helium.

The helium consumption has not yet been measured accurately because our present system is not suitable to maintain constant the liquid level inside the vessel. Usually we fill the vessel and afterward we have about two hours of working time while the level lower until the safety limit is approached. Anyway we could evaluate that consumption of the cryostat itself is around 13 l/h of liquid and rise to about 17 l/h when transfer is taken into account. Such consumption is about 50 % higher than calculated.

The LN shield has very low thermal inertia and, since has not reservoir but is cooled by conduction from the LN flowing into the channels, its actual temperature depends on the temperature of the nitrogen entering in the circuit. This last temperature was found not stable because depends on the total nitrogen flow inside the vacuum insulated line. Actually the line serves other utilities, so that when the total LN flow is large then liquid enters inside the shield and the temperature is really 80 K. When *SOLEMI-1* works alone the LN consumption is so low that nitrogen is vaporized through the feeding line and the temperature of the shield rise to 90–100 K.

The shield temperature could go over 100 K (which is considered the safety limit not affecting the helium consumption of the vessel) but we prevent the temperature raise by

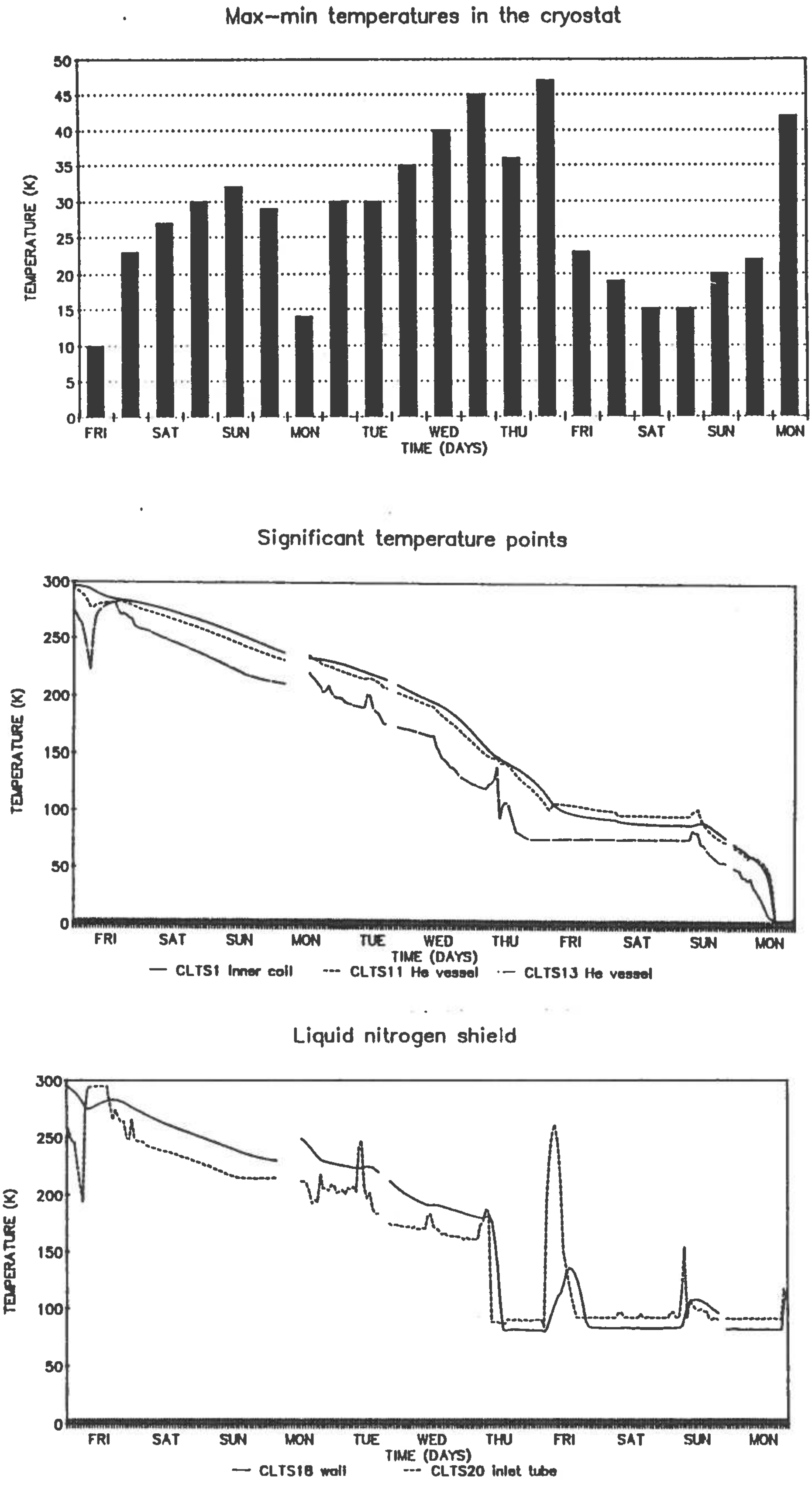

Figure 9: temperature vs time during the third cool down of *SOLEMI-1* . (start 28.5.92, end 7.6.92).

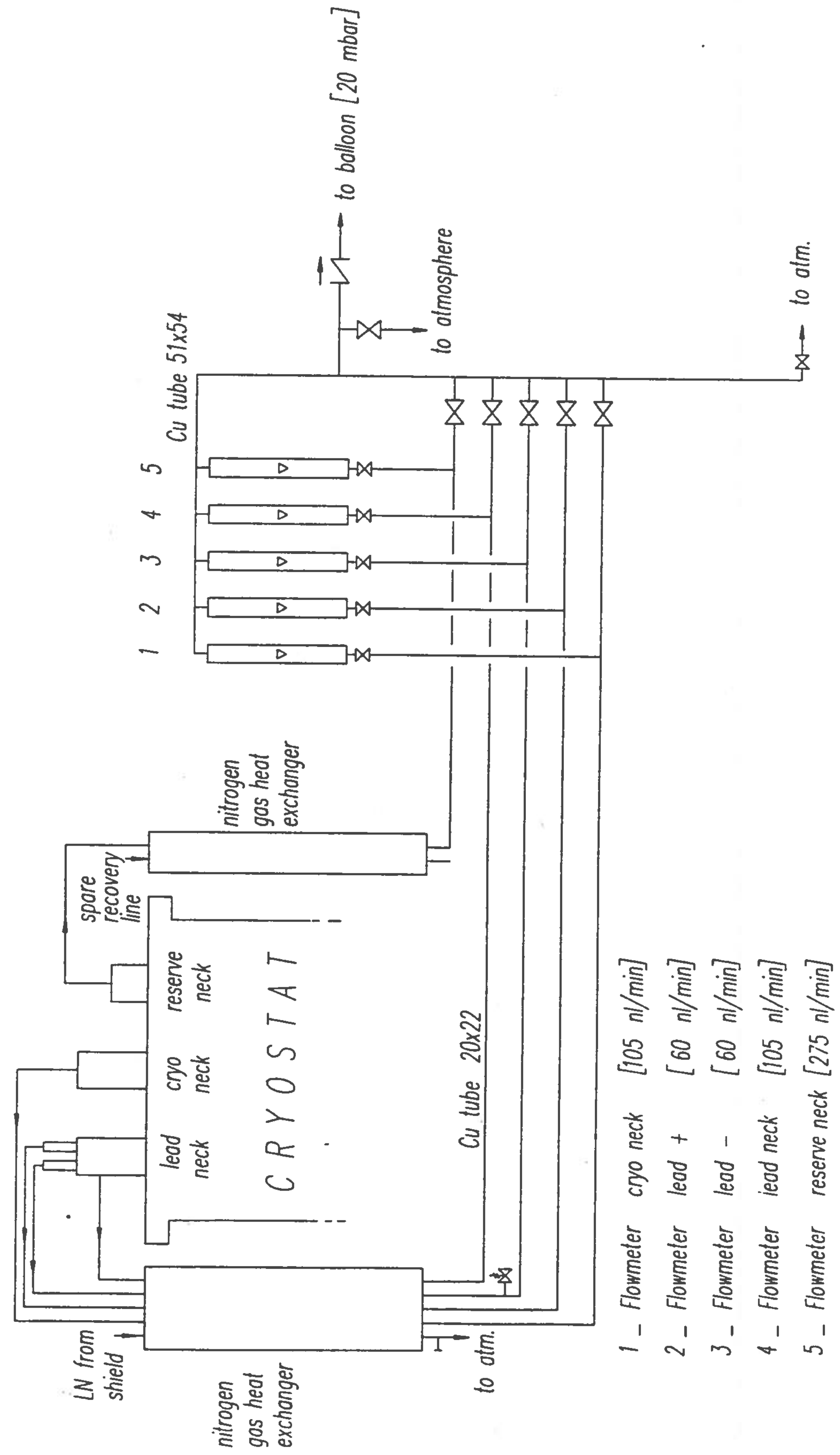

Figure 10: schematic of the helium recovery system.

increasing consistently the flow of cold gas. Actually this has a price: we have a large flow of cold gas at the exit, virtually at same temperature of the inlet, of about 5–10 m^3/h while the need of the cryostat itself is less than 1 m^3/h. Such a consumption is unfair and because the cold gas is warmed in the same heat exchanger used for the helium, see Fig. 9, takes almost all the capacity of the exchanger itself making a lot of frost.

In conclusion the operation of the shield is less easy than expected, with a lot of minor troubles. The thermal design of the shield is good, being the temperature of three sensors bonded in different point of the shield within few degrees. Anyway, probably, a shield based on 20-30 l reservoir of LN inside the cryostat, cooling the shield walls via conduction, would have been preferable.

5 - ENERGIZATION AND QUENCH BEHAVIOUR

The solenoid was delivered by Ansaldo to INFN–LASA lab in April 1991. The cool down and first energization started in May after a few weeks to connect the cryogenic plant as well as the electric controls. Many problems, fault of the helium liquefier, frost on the cryostat necks and consequently lost of vacuum due to freezing of the O-rings, were encountered in this first test. Also the power supply stability and the QDS needed to be improved. In spite of these problem we were able to run the magnet up to 4 tesla, half the nominal field.

Based on the experience gained in the first run, in November 1991 another run of the magnet started and the nominal value of 8 tesla was reached. We had several fast discharges on the dumping resistor, triggered by the QDS system. Some of them were recognized as "false", i.e. due to noise in circuitry. Some other fast discharges were triggered by reaching the danger threshold of parameters like vacuum of the chamber or pressure inside the helium vessel. Especially this last parameter was disappointingly high, 1.25 bar, because of not sufficient helium recovery line to the low pressure balloon. When the present recovery system, described in para 4.2, was installed and the pressure went down satisfactory to 1.1 bar when operating without helium transfer (100 mbar of overpressure is just needed for the operation of the main coil electric feedthrough).

We recorded at least six quenches of the coils. We believe that four of them were caused by a low level of LHe: one at the beginning of operation for bad calibration of the level meter while the other were unexpected. We realized that the way the electric connections between coil sections and to the current leads are done requires higher LHe level than we thought. This last point makes the cryostat working only when the liquid level is very near the maximum allowed for the cooling of the current leads. This problem is the one more limiting the functionality of the system and makes it not easy to be run, since the useful range of liquid level is of the order of fews cm.

In Figure 11 the training history of the magnet is reported. Only the quenches clearly due to training are shown. The nominal field was reached with an overpressure of about 200 mbar in the bath, (because of the small recovery line) which corresponds to a temperature of about 4.4 K. The current was 1% higher than the nominal and the field was checked by measuring with a 1% precision Gaussmeter in the stray field region.

In Figure 12 is reported a photograph of the magnet and the area while the He gas is violently expelled during a quench at 4 tesla. The long tail of the outpouring gas is well visible, it lasts for about half a minute. In the right corner at the bottom is visible the 450 l LHe dewar used for refilling. In the forefront of the right one can be seen of the two N-gas heat exchangers, with many recovery lines covered with insulating black foam (Armaflex).

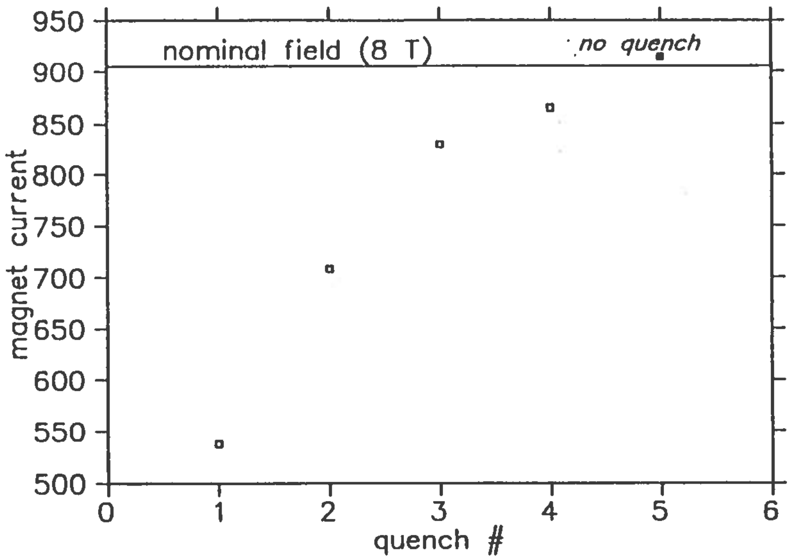

Figure 11: training history of the magnet.

Near the center the current leads are all frost at the "warm" end and, coming from the left part there is the curved flexible cryogenic line which feeds the LN shield's pipe.

Despite a number of imperfections of the cryogenic system, the magnet itself worked very well and proves the reliability of large not cryostabilised windings, near the limit of the NbTi performance. Such a concept is certainly a major step gained in these last years in the superconducting application, since only few years ago M.N. Wilson in his textbook [5] still considered the impregnation technique, and consequent "adiabatic" operation of the coils, safe only for small, laboratory size, superconducting magnets.

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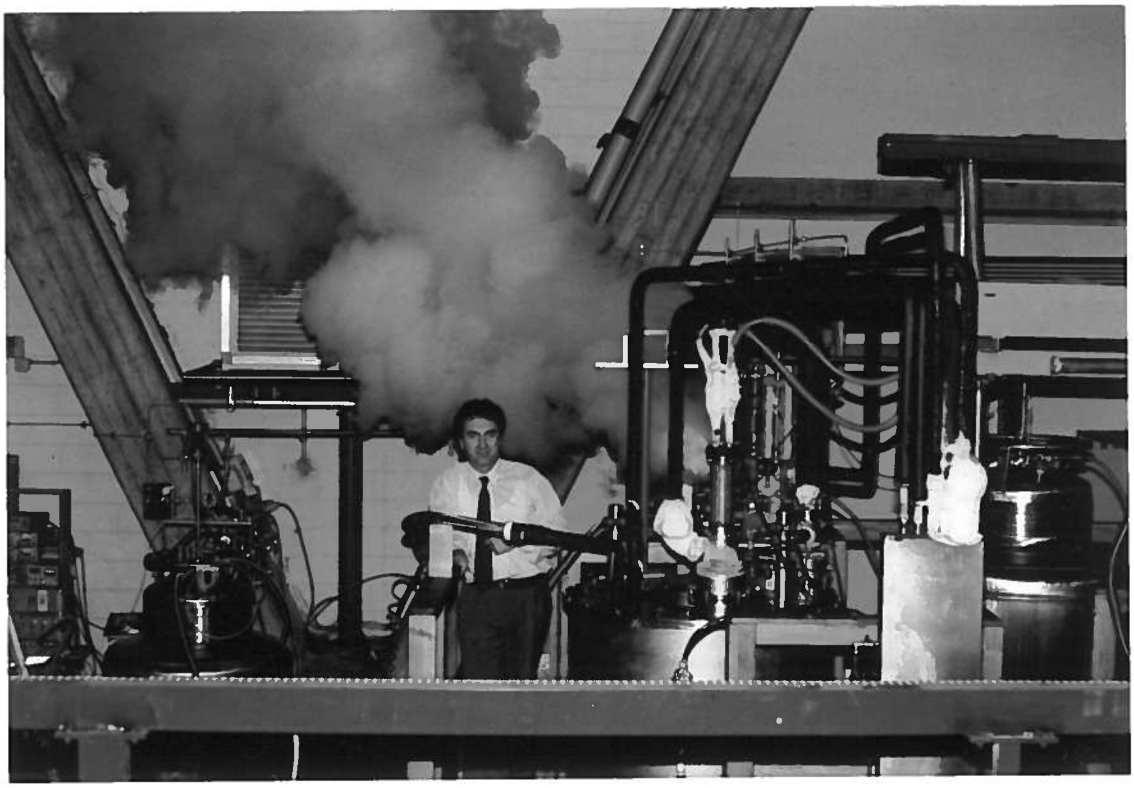

Figure 12: picture of *SOLEMI-1* during a quench (see text for details).

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