ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Milano

INFN/TC–92/23
1 Ottobre 1992

E. Acerbi, R. Marabotto, E. Perrella, L. Rossi:

SOLEMI-1, A 8 TESLA, 535 mm ROOM TEMPERATURE BORE, SUPERCONDUCTING SOLENOID – PART 1: DESIGN AND CONSTRUCTION

Servizio Documentazione
dei Laboratori Nazionali di Frascati

INFN - Istituto Nazionale di Fisica Nucleare
Sezione di Milano

INFN/TC–92/23
1 Ottobre 1992

SOLEMI-1, A 8 TESLA, 535 mm ROOM TEMPERATURE BORE, SUPERCONDUCTING SOLENOID – PART 1: DESIGN AND CONSTRUCTION

E. Acerbi[1], R. Marabotto[2], E. Perrella[2], L. Rossi[1]

[1] Dipartimento di Fisica dell'Universita' di Milano e INFN – Sezione di Milano, Laboratorio LASA, Via Fratelli Cervi 201, 20090 Segrate
[2] Ansaldo Componenti, Via Nicola Lorenzi 8, 16152 Genova

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 basic design of *SOLEMI-1* , the magnetic, mechanic and thermal design is presented as well as the results of the first excitation.

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 ≤ 8 tesla, the inner Nb_3Sn solenoid can be used alone, too, for experiments where intermediate field level, ≤ 15 tesla, is sufficient [2], [3].

In the paper, after a brief description of the whole facility, the detailed design of the 8 tesla NbTi coils is discussed and compared with the results obtained in the first two runs of the solenoid. The results of a number of quench experiment performed to measure the actual velocity of the quench propagation (problem still open for adiabatic solenoid and very important for high field NMR magnet) will be published in a next report.

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.

Operation at 4.2 K in the LHe bath was chosen for both cryostats at the beginning

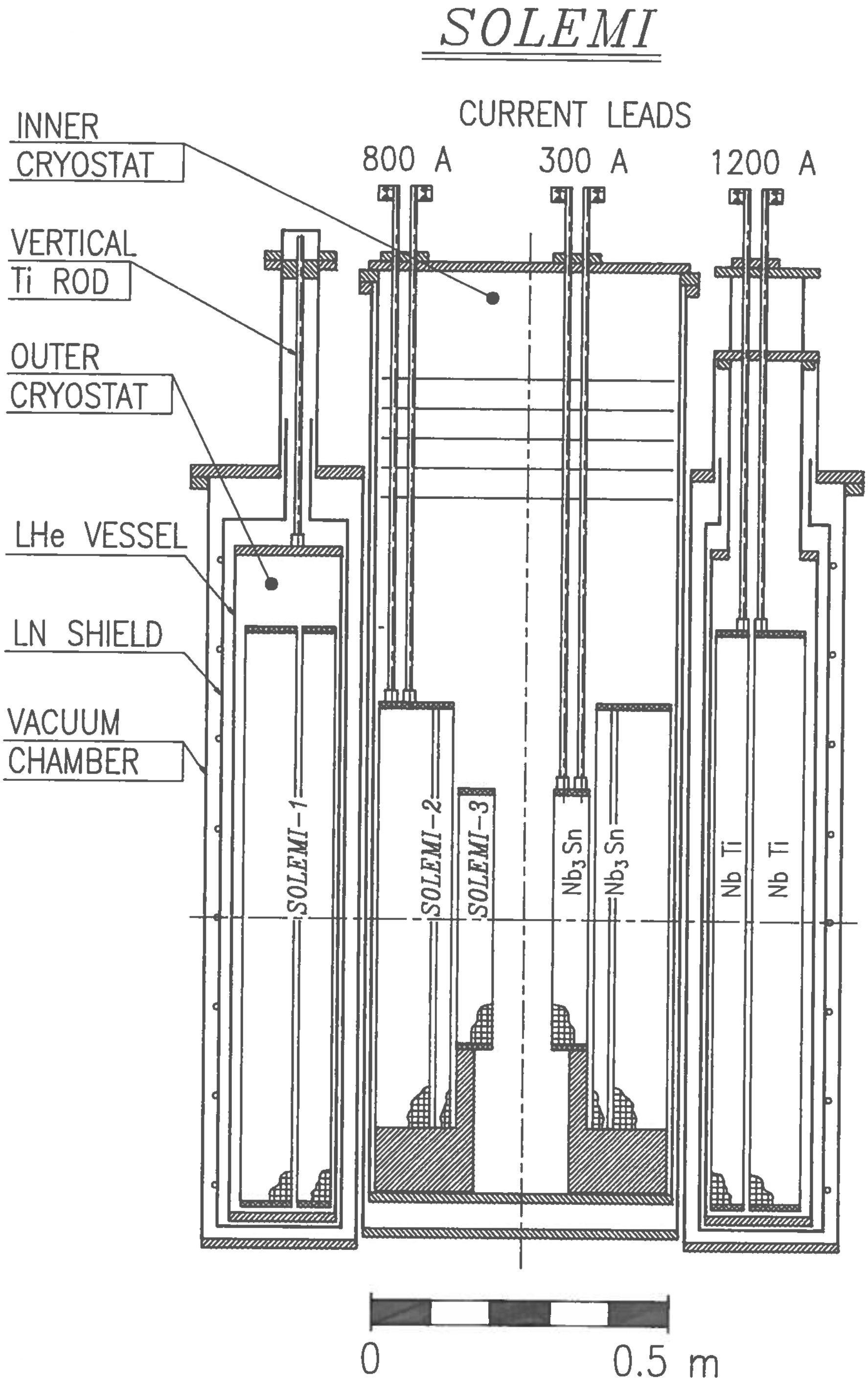

Figure 1: Schematic section of the superconducting multiple solenoid *SOLEMI*

of the design process. A cooling improvement is possible for both cryostat by means of λ-point refrigerator.

The height-to-diameter ratio is sufficiently great 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 ± 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.- NbTi COIL DESIGN

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 and the measured NbTi critical current density is plotted vs magnetic field in the Figure 2, where the requested values are reported.

It must be pointed out that the degradation due to cabling for the inner cable was measured by extracting a wire from the cable and was found 1.5 A (1.1 %). The value given in Table 1, 2.8%, is obtained by measurements on the virgin strands and cable. Degradation of the conductor for the outer coil was not measured, but it should be in the same range (1-3%) of the inner inner, since the structure is very similar.

The insulation was done by wrapping a 0.12 mm thick glass tape around the conductors with a 50% overlap. The nominal thickness is 0.24 mm but experimental test showed that the actual insulation thickness, when the winding pressure is applied to a coil stack, reduces

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)

to 0.2 mm. The glass tape is dressed with SILAN.

3.2 - Mechanical Design

The two sections are wound with a tension on the cable of about 40 MPa. They are both former-free in order to minimise problem of training which can be very severe with such a big solenoid. Every coil section has a bottom and a top flange, made out of epoxy-fibreglass composite (MAT). The two coils are fixed each other at the bottom with a common G11 plate which is free to grow in radius during the energization. At the top the two windings are axially fixed each other by means of G11 clamps. The two coils are almost independent in the radial direction, so that expansion during excitation is not counteracted. The inlet of liquid helium is between the outer coil and the outer cryostat wall, therefore the bottom common flange is grooved, with radial channels, in order to allow the liquid to flow between the coils and between the inner coil and the inner cryostat wall.

Tests were carried out in order to evaluate the bonding strength between the insulated conductor and fibreglass-resin composites: An ultimate shear stress higher than 20 MPa between copper and G11 bonded with an epoxy resin was measured.

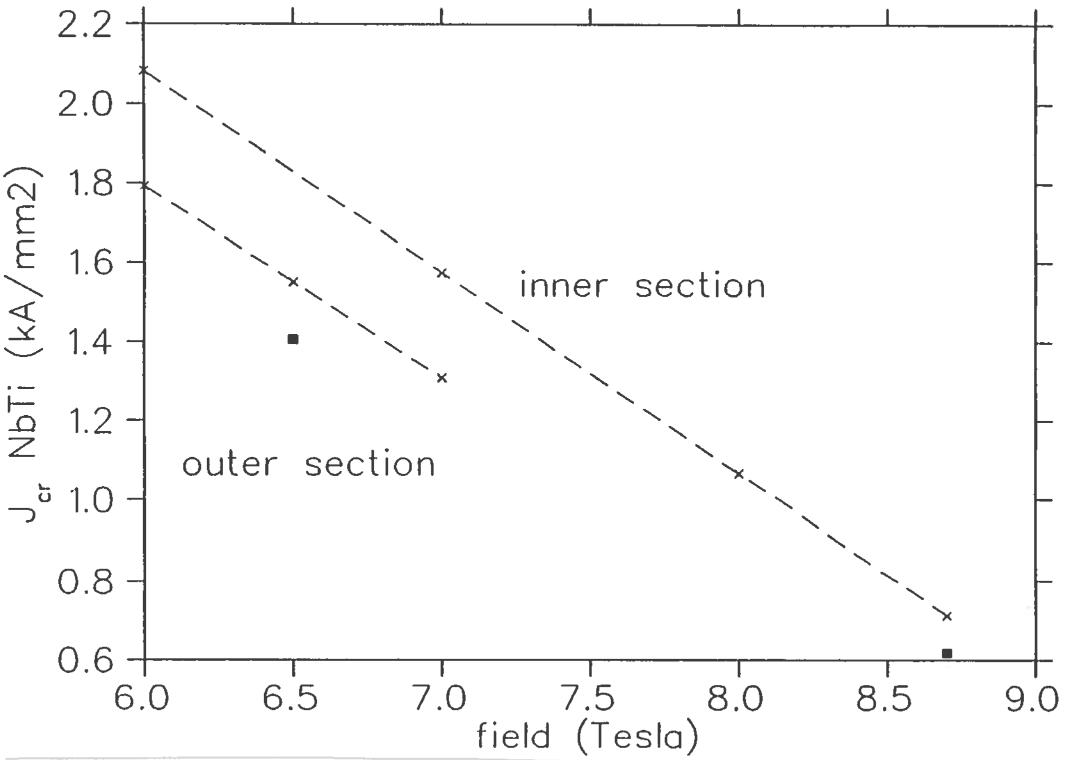

Figure 2: Critical current density of the conductors

The detailed list of the coil characteristics is reported in Table 2, while in Figure 3 the magnet load line is shown. The maximum theoretical performance is obtained by intersection of the maximum field in the coils with the critical current curve. As shown in Figure 3, 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.

Operation of an adiabatic magnet so near to the short sample limit is very ambitious and requires great care in the design and manufacture. Any heat generation, like friction and crack of the resin must be kept very low and reciprocal movement of the coils and of the turns must be avoided.

The magnet is a big one, the free-turn electromagnetic stress is J B R = 210 MPa and 230 MPa for the inner and outer coil, respectively. To cope with such level of stress the inner section has a banding: 15 turns of 316 L stainless steel strip was wound with a tension of 150 MPa onto the inner coil. The outer coil does not need banding: calculation carried out with more realistic model, taking into account each conductor and its insulation and the interaction between adjacent layers, indicates an acceptable stress level. In Figure 4 the coil stress is plotted vs radius.

The banding was wound onto the inner coil after its impregnation and then was cast by means of a resin with lower curing temperature. Care must be taken to avoid a strong shear stress coming from the differential thermal contraction of the stainless steel and the coils, which is very near the copper coefficient. Adjacent turn of the banding were 1 mm spaced, and the gap partially filled with a glass rope, such that the axial contraction of the composite (steel + filler) is almost equal to the coil one.

The terminals of the banding were shorted, mainly to avoid high voltage in case of a fast discharge. Possible use of high strength aluminum alloy instead of steel was discussed:

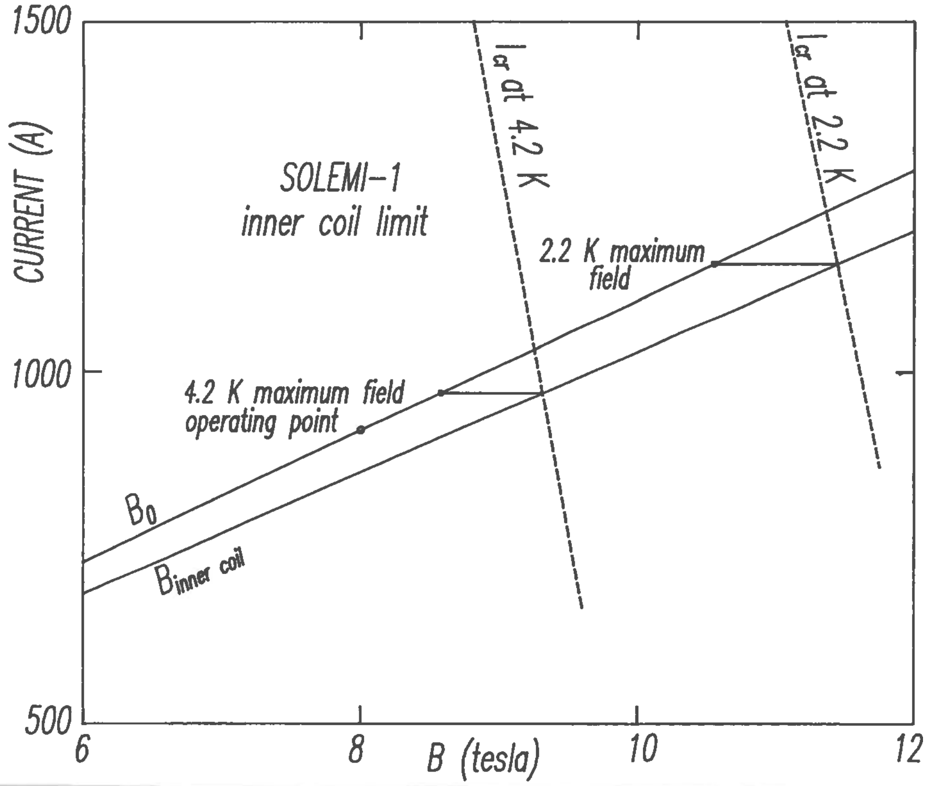

Figure 3: Load line and critical current curves of *SOLEMI-1*

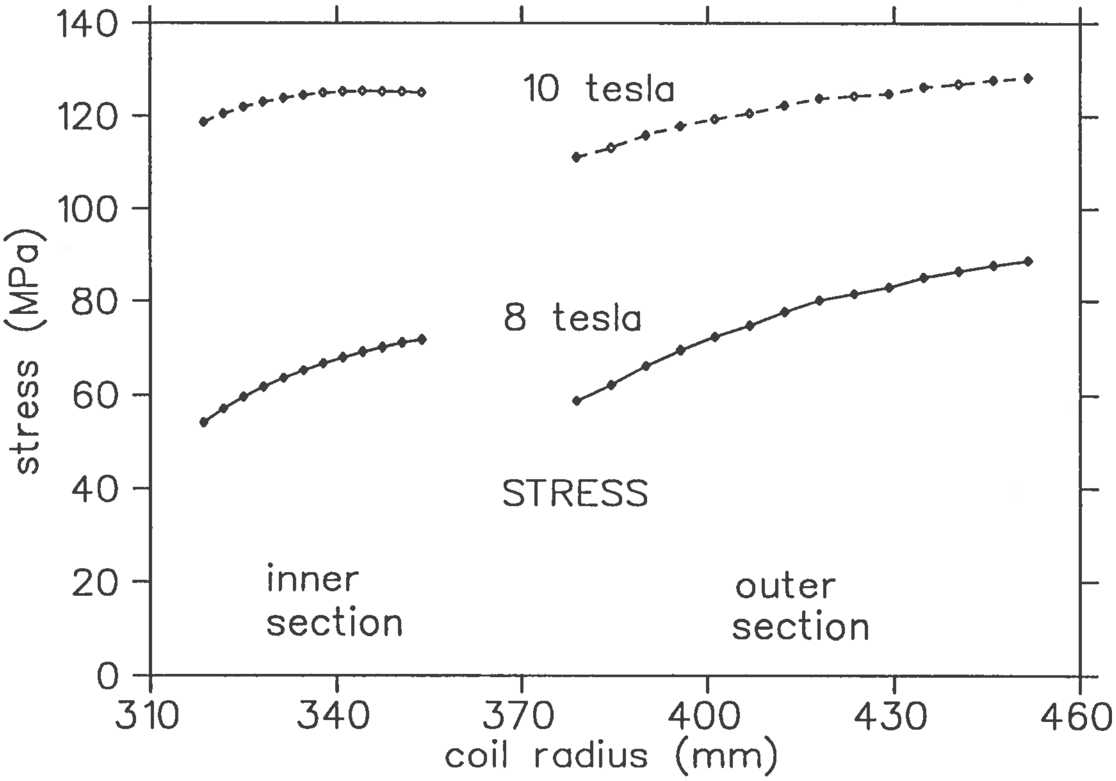

Figure 4: Stress in the two coil sections at B_0= 8 T

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	2266	6227
section inductance (H)	1.82	19.7
total inductance (H)	30.44	
magnet current at 8 T (A)	905	
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	

since the benefit on the magnet safety due to possible back-quench effect in the banding is marginal even with aluminum, the stainless steel was preferred for the higher modulus.

The vapor cooled current leads were supplied by Fuji (J). They are optimized for 1200 A, to accommodate possible improvement of the magnet performance in case of superfluid helium cooling. They were tested against electric breakdown at 1 KV ×1 min. and have a survival time of at least 4 min. in case of flow interruption. The helium flow rate, in self-cooling condition at 1.2 kA, is 0.075×2 g/s, corresponding to 2×2 l/h of liquid helium evaporation.

The layer to layer electric junctions are made by soft soldering two adjacent cables over a length of 150 mm. Since the junctions are inside the bottom or the top G11 flange, a rectangular pure copper block is soldered over the two cables along every junction. This copper block acts both as a stabilizer of the junction (adding an extra 30-50 mm^2 of copper cross section) and as cooling element since one copper face (about 300 mm^2) is exposed to liquid helium. The electric resistance has been measured and was found $1.2\ 10^{-8}\ \Omega$ per junction. Tin-lead (Sn60-Pb40) alloy, which has a resistivity of $2.6\ 10^{-7}\ \Omega\,m$, was used as solder.

The connection to the current leads and between the two coil sections are done with heavy copper bars whose cross section is 570 mm^2 mm^2. The copper bars are shunted with superconducting cables, with the exception of the inner to outer section junction. At the maximum current of 905 A, the total dissipation in the copper should be 5÷6 mW .

3.3 - Stability and Quench Protection

The coils are adiabatic, fully impregnated in epoxy resin under vacuum. The lack of coolant inside the coils makes the stability against a perturbation very small. The minimum

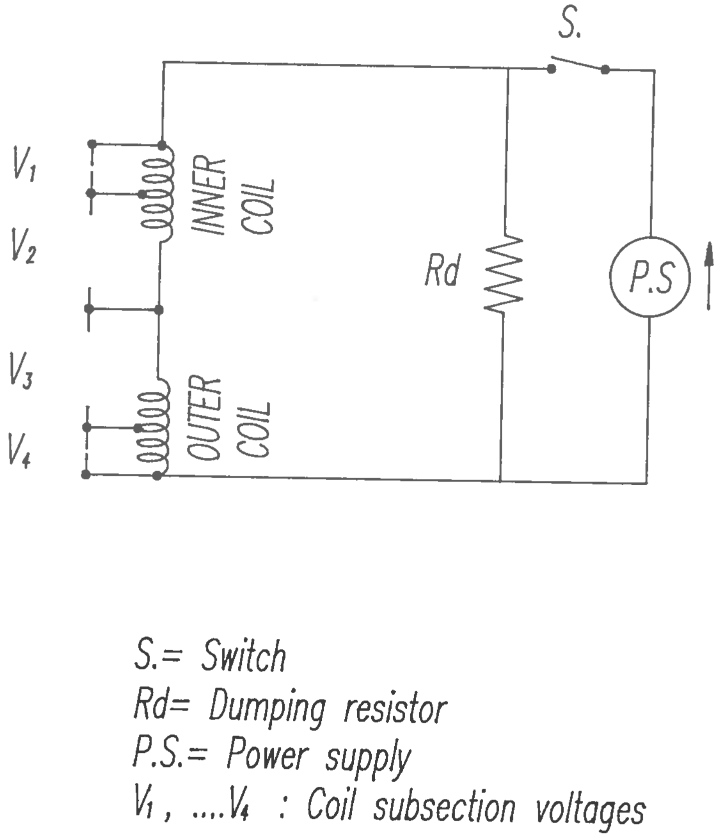

Figure 5: Electric scheme of the solenoid and protection system

quench energy against transient point disturbance, based on the theory developed by M.N.Wilson [4], is in the mJoule range.The stability margin in actual magnet is usually higher than what is predicted by the theory, nevertheless the possibility of severe training and especially of degradation of the magnet performance was one of the major concern in the all design.

In order to find out the best impregnation, i.e. with strong bonding with cable and glass tape and with good mechanical properties together with low fracture energy, many samples were tested. A solution based on glass tape in the virgin state (not pre-impregnated) and 60 % resin was used.

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 5 the scheme of the protection system is shown. Both coil sections are spit 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 with a fine wire, on the banding of the inner coil. Every voltage of the coil subsection is compared with the voltage of the pick-up and with some of the other subsections (1-4, 1-2, 3-4). 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 5) is opened in about 100 ms, disconnecting the power supply and leaving the magnet to discharge through the dumping resistor.

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 × 260 ms. Thermal conductivity λ, quench velocity and Minimum Propagating Zone (MPZ) are calculated when quench starts (at maximum field).

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)	18 ×1	29 ×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	

3.4 - Field Computation

The usefulness of an iron yoke to prevent large stray field in the area surrounding the solenoid was studied by means of the Poisson code. Different solution were investigated, like warm and cold iron, none of them was found really satisfactory, generally because the iron thickness needed to have an effective shield of the stray field is big enough to raise severe complication either in the cryogenic or in the mechanic of the cryostat. Finally we decided for an ironless magnet.

The field profile in the bore and in the outside region is shown in Figure 6 for the maximum current. For field computation at greater distance the usual dipole approximation is very accurate.

4.- CRYOSTAT AND DIAGNOSTIC

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 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. In case of quench the heat transfer to the liquid helium is about 76 kwatt, with a evaporation rate of 29 l/s. The calculated pressure raise in the helium vessel to evacuate the corresponding 3650 g/s of helium gas with a $\phi = 100$ mm line is 0.09 bar per meter length of the line. The pressure increases to 0.27 bar/m if the line is $\phi = 80$ mm. A safety valve of $\phi = 35$ mm, opening to the atmosphere at 0.5 bar of overpressure is installed,

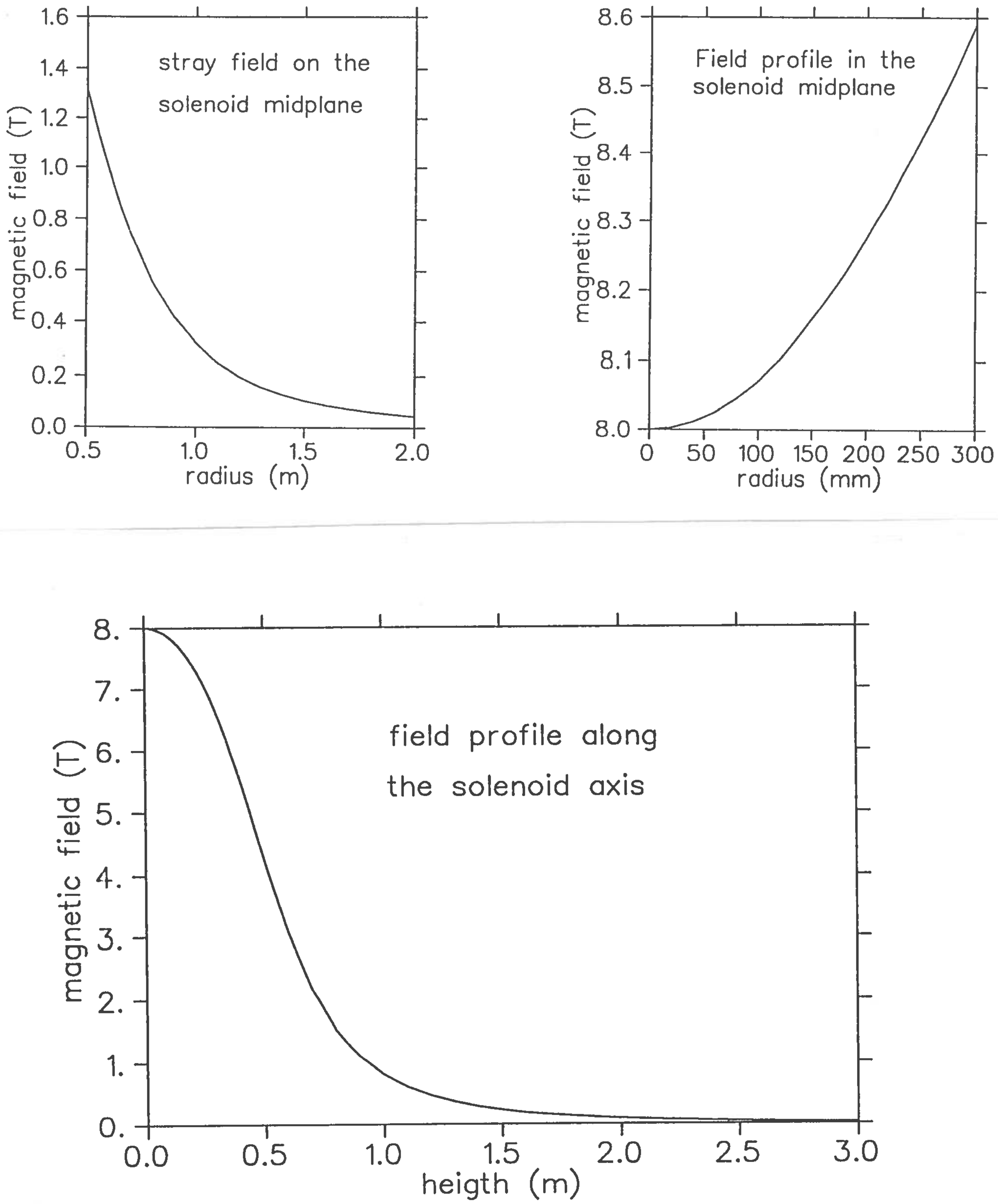

Figure 6: Field profiles inside and outside the bore of *SOLEMI-1*

together with a $\phi = 50$ mm rupture disk breaking at 0.7 bar.

The thermal shield is made out of copper, 2 mm thick, with a longitudinal cut in the walls and in flanges to avoid problem with eddy current (heating during ramping and forces during quench). The shield is cooled with a continuous flow of liquid nitrogen through cooling channels soldered around the vertical walls.

The helium can is suspended by means of three titanium (5 Al-2.5 Sn titanium alloy) rods, 8 mm in diameter. The total weight, included coil is about 2.56 tons (coil: 2.08 tons, cryostat and necks: .25 tons, pressure on necks: .23 tons).

The helium vessel is radially centered inside the vacuum chamber via six (three pairs) titanium (5 Al - 2.5 Sn) rods. These rods are 4 mm in diameter and are attached radially to the helium vessel.

Thermal insulation is assured by a vacuum in the 10^{-6} mbar range and by multilayer superinsulation (NRC-2). With about 30 layers of aluminised polyester films the calculated heat load from 300 K on the 80 K shield is negligible (5 watt).

In between the thermal shield and the helium vessel we decided to avoid multilayer superinsulation. It has been shown [5] that covering the stainless steel with aluminised self-adhesive tape (Scotch No. 425 produced by *3M*) is very effective to shield the helium vessel from radiation heat. This solution was preferred to the usual multilayer one because it's more simple and needs less room between the 4 K and 80 K walls.

The heat load in the helium bath is composed by several terms:

- current leads : 1.44×2 = 2.9 W at 1.2 kA (2 W without current)
- 3 vertical suspension rods: 0.53 W
- 6 horizontal rods: 0.2 W
- three necks :
  - 0.9 W for conduction through the metal
  - 1 W for conduction through the helium gas
  - 0.3 due to radiation from the top flange

  total necks : 2.2 W
- 16 electric junctions :0.15 W
- radiation from the 80 K shield (about 0.015 W/m^2): 0.1 W

The total calculated heat load is 6 watts, which corresponds to 8.5 l/h of helium consumption when the cooling of the vapor coming up the neck top is not taken into account.

5.- FIRST EXCITATION AND CONCLUSIONS

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.

Cool down is done using nitrogen at controlled temperature (maximum acceptable ΔT is 35 K at 300 K and 50 K at 80 K) down to liquid nitrogen temperature. Tranquil

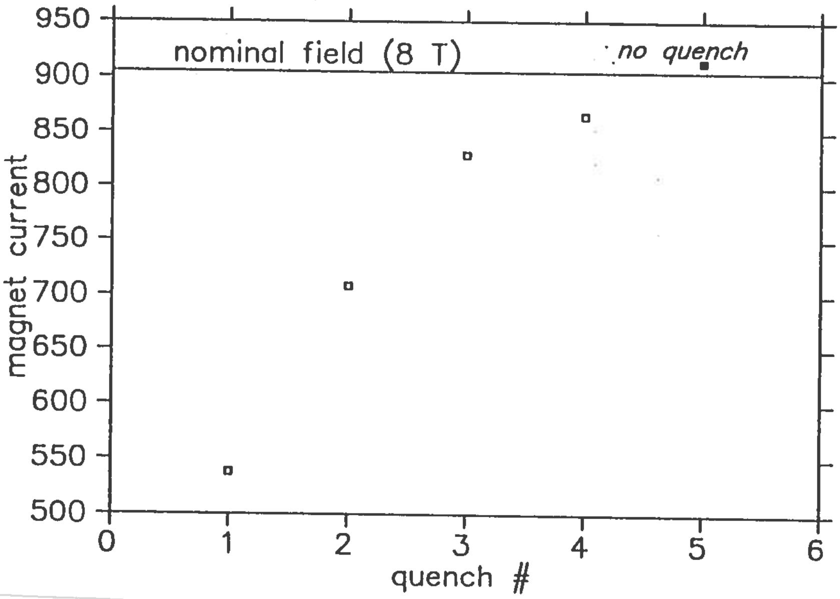

Figure 7: Training history of the magnet

operation takes place if the cooling rate is around 1-1.2 K/h. Many problems, fault of the helium liquifier, 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 discharge 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, because of not sufficient helium recovery line to the low pressure balloon.

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 permitted for entering of the cooling flow into 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.

The Figure 7 shows the training history of the magnet. 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.

Helium consumption is about 13 l/h, which is 50% higher than calculated. When transfer is taken into account the total consumption is around 17 l/h.

The thermal shield is very well cooled, being the temperature measured at different point at 80 K. Anyway we found the solution based on continuous flow not really satisfactory, because its consumption, when the heat loss on a 10 m long LN line is taken into account, is too large compared with the actual needs.

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 [4] still considered the impregnation technique, and consequent "adiabatic" operation of the coils, safe only for small, laboratory size, superconducting magnets.

References

[1] E. Acerbi, F. Alessandria, G. Baccaglioni, C. Birattari, E. Fabrici, L. Rossi, A. Sussetto, "High field superconducting solenoid for the LASA in Milan," *IEEE Trans. on Mag.* , Vol.24, No.2, March 1988, pp. 1417-1420.

[2] E. Acerbi, G. Baccaglioni, C. Barrila' and L. Rossi, " Progress report of the high field superconducting facility at LASA laboratory," *Proceeding of MT-11 Conference,* Elsevier Science Publisher, 1990, pp.1324-1329.

[3] E.Acerbi, G.Baccaglioni, P.Jarvis, J.Mellors, L.Rossi, M.Thoner, G.Volpini "The 18 Tesla - 100 mm 4.2 K Free Bore Solenoid for LASA - Milan" *IEEE Trans. on Magnetics,* Vol.28, N.1, January 1992, p.428

[4] M.N. Wilson *"Superconducting Magnets",* Oxford University Press, Oxford (UK), 1983

[5] T.R. Gathright and P.A. Reeve, "Effect of Multilayer Insulation on Radiation Heat Transfer at Cryogenic Temperatures", *Proc. of MT-10 Conference,* Boston 1987.