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The Cryogenic System for the Superconducting Solenoid Magnet of the CMS Experiment

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Abstract **-The design concept of the CMS experiment, foreseen for the Large Hadron Collider (LHC) project at CERN, is based on a superconducting solenoid magnet. The large coil will be made of a four layers winding generating the 4 T uniform magnetic induction required by the detector. The length of the solenoid is 13 m with an inner diameter of 5.9 m. The mass kept at liquid helium temperature totals 220 t and the electromagnetic stored energy is 2.7 GJ. The windings are indirectly cooled with a liquid helium flow driven by a thermosyphon effect. The external cryogenic system consists of a 1.5 kW at 4.5 K (entropy equivalent) cryoplant including an additional liquid nitrogen precooling unit and a 5000 litre liquid helium buffer. The whole magnet and cryogenic system will be tested at the surface by 2003 before final installation in the underground area of LHC.**

I. INTRODUCTION.

The CERN Large Hadron Collider (LHC) has been designed [1] to collide protons with a centre-of-mass energy of 14 TeV (at a luminosity of 10^{34} cm^{-2} s^{-1}) and heavy (Pb) ions with a centre of mass energy of more than 1000 TeV (at a luminosity in excess of $10^{27}cm^{-2}$ s^{-1}).

The Compact Muon Solenoid (CMS) experiment [2], located at one of two (diametrically opposite) high luminosity collision points of LHC, will be built around a single large superconducting solenoid generating a uniform magnetic induction of 4 T. The favourable dimensional ratio of the magnet (L=13 m over D=5.9 m inner free diameter) with the high field allow efficient muon detection in the forward directions leading to a compact design of the muon spectrometer (hence the name CMS) and to a simple overall architecture of the detector.

II. MAGNET CRYOGENICS.

The design of the superconducting coil [3,4] is based on a four layers self supporting winding structure made of an innovative conductor which includes a high purity aluminium component as stabiliser and a high strength aluminium alloy component as mechanical reinforcement. The windings are surrounded by a 12 mm thick aluminium cylinder acting as cooling wall and permitting equal heat dissipation during a fast dump of the stored energy (quench-back mechanism). The corresponding total cold mass kept at liquid helium temperature is 220 t.

The nominal operating magnetic induction at the interaction point is 4.0 T generated by a current of 19.5 kA. The electromagnetic stored energy is 2.7 GJ of which only 20% is dissipated in the cold mass during a fast dump, raising the temperature to an average value of ~55 K. During a slow dump, the current ramp-down is achieved in ~5 hours without quench-back.

A. Internal cooling scheme.

The CMS magnet is a low thermal losses coil and has good thermal heat conduction through the cold mass. Cooling can, then, be achieved by using the indirect method which greatly simplifies the conductor design.

The helium flow in the cooling channels is driven by the hydrostatic pressure difference between the pure liquid supply and the two-phase mixture (of maximum vapour mass content 5 to 10%) in the return channels in a U shaped circuit configuration (thermosyphon). This cooling scheme, successfully operated since many years for the ALEPH solenoid [5,6], simplifies the cryogenic circuits and provides both high reliability (no mechanical moving parts) and the capability of self adapting the helium flow to the heat load distribution and to the thermal transients.

The thermosyphon is made of 8 independent sub-circuits and the cooling pipes (vertically orientated) are attached to the outer side of the external cylinder every 260 mm. The liquid helium is continuously re-cycled and the vapour returns to the refrigerator via a phase separator of 100 litres volume located at the top of the detector. Because of the flow impedance in the return circuit of the heat exchangers of the refrigerator, the separator is operated at a minimum pressure of 1.25 bar corresponding to 4.45 K saturated helium.

The thermal shield has a low flow impedance piping composed of 6 parallel sub-circuits each of them supplying 6 shield panels in series. In normal operation, the shield cooling needs 35 g/s helium flow forced by the refrigerator (60 K inlet to 80 K outlet at 5 bar supply with an expected total pressure drop of less than 100 mbar).

B. Thermal loads.

Because of the large dimensions of the solenoid, the radiative thermal load both at 4.5 K and 70 K levels is the predominant (Table 1). The conductive heat load at 4.5 K is derived from the coil support system composed of 18 axial rods and 12 radial belts made of titanium alloy (Table 2).

TABLE 1
Radiative heat loads

	Surface area m^2	Number of layers of superinsulation	Heat flux W/m^2	Heat load W
Cold mass at 4.5 K	560	5	0.2	120
Thermal shield	560	30	5	2800

TABLE 2
Conductive heat loads at 4.5 K

Support	Section mm^2	Length m	Heat input/rod W	Quantity	Total heat load
Axial tie rod	3600	12.7	0.4	18	7.2
Radial belts	2700	1.6	2.4	12	28.8

There is neither mechanical nor a thermal link between the coil support structure and the radiation shields which have an independent holding system producing a thermal load of 500 watt at 70 K.

The total (including auxiliary equipment's and conductor junctions) isothermal load at 4.5 K in steady operation condition is summarised in Table 3. The helium flow rate for the cooling of the current leads at nominal value amounts to 2.5 g/s.

TABLE 3
Isothermal (4.5 K) and liquefaction loads

Total heat load at nominal current = 192 W		
Radiative heat load	120	W
Holding system	40	W
Phase separator and valves	20	W
Conductor junctions	12	W
Current leads (19.5 kA) He mass flow = 2.5 g/s		

Dynamic heat loads during ramp-up and down the coil current are due to eddy currents and plastic deformation of pure aluminium. At constant dI/dt, eddy current losses are almost constant whilst heat generation because of plastic strain is zero up to the aluminium elastic limit and approximately increases linearly with the magnetic forces (B^2 dependence). For a ramp-up/down time of 5 hours, the mean dynamic heat load is 70 watt and the peak value is 240 watt. During energization of the coil, the maximum temperature gradient across the cold mass might reach 100 mK whilst at constant nominal current it will not exceed 50 mK.

III. THE CRYOGENIC PLANT.

A. The refrigerator and auxiliaries.

Two screw compressors providing a total cycle mass flow of ~180 g/s at a maximum pressure of ~18 bar are installed at the surface. An additional screw compressor (30 to 40 g/s up to 18 bar) powered by an emergency supply will be used for the recovery of helium into two 250 m^3 (20 bar) gas holders in the event of the cycle compressors being shut down, thus eliminating the need of low pressure gas storage with a dedicated purification unit. Also located at surface is a 50000 litre liquid nitrogen dewar.

The cold box will be housed in an underground service area fully accessible during LHC operation and located near the main detector cavern. Based on the thermal loads during normal and transient (ramp-up/down, cool-down 100 K/ 4.5 K, thermal recovery after a fast dump) operating conditions, the refrigerator capacity is estimated to be 1.5 kW at 4.5 K (entropy equivalent) including redundancy. Additional cooling power will be provided by liquid nitrogen/helium heat exchangers used for cooling the cold mass from ambient to 100 K in ~20 days and for boosting the liquefaction capacity of the refrigerator during the filling of the reserve dewar. Expected liquid nitrogen consumption during cool-down is 500 l/hour.

The cold box will be connected (see the principle flow-sheet in figure 1) to the magnet via an intermediate valve box located in the detector cavern and housing a 5000 litre liquid helium dewar. The connecting thermally shielded transfer line (L=~30 m) contains four separated pipes: two for the 4.5 K circuit (feed 50 mm, return 80 mm diameter) and two for shield circuit (both 60 mm diameter).

Finally the intermediate valve box will be connected, via four separated transfer lines performing the same functions, to the valve box housing the thermosyphon phase separator located at top of the detector. This layout configuration (split intermediate valve boxes) was dictated by the need of minimising underground space requirements.

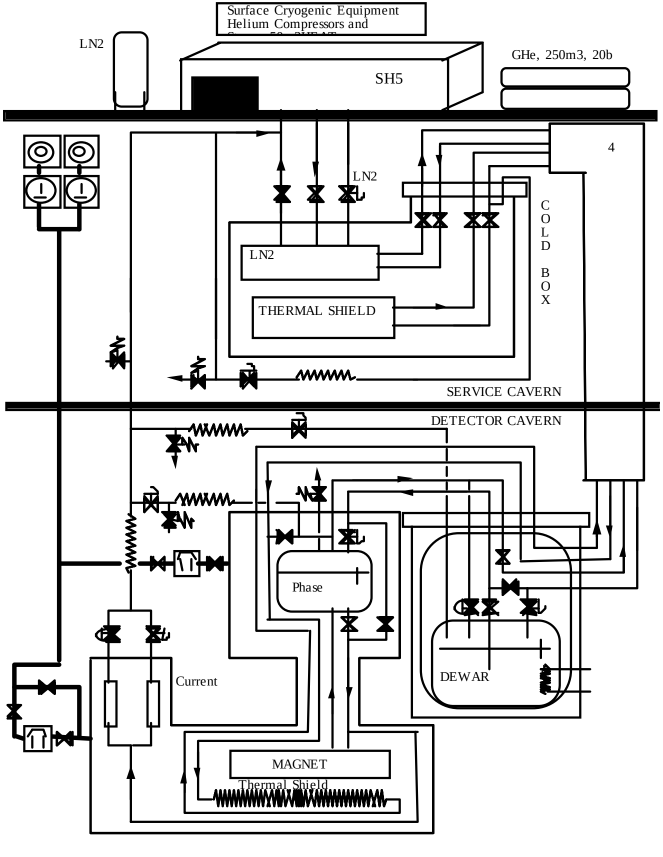

Fig.1. Shematical flow-sheet of the cryogenic equipment

B. Process definition.

The large cold mass will be first cooled-down to 100 K using the liquid nitrogen/helium heat exchangers. Assuming 50 K maximum temperature gradient and a 20 days duration, the required mass flow will be an average of 90 g/s (~50 % of the total cycle flow). During this phase the turbines are switched off and the heat shield cooling not yet started. The intermediate valve boxes will have bypass-valves to avoid large impedance of the circuits designed for low temperature flow operation. Both the dewar and the phase separator will be cooled-down using parallel flows.

Below 100 K cooling is achieved using the turbines. Gas is first circulated only in the shield to cool them down to 100 K via their circuits and then (below 100 K) in parallel to the coils. The return flow from the coil will be channelled to the appropriate cold box heat exchanger depending on temperature levels. At the end of the cool-down process, the refrigerator will deliver supercritical helium (3 bar, 4.5 K) to complete the cool-down and, in parallel after expansion to 1.5 bar, to fill the dewar and the top phase separator. The thermosyphon can then be started bringing the magnet into steady cryogenic operating conditions. The expected total duration of all these steps will be about 2 weeks.

In case of failure of the refrigerator or associated utilities, slow ramp-down of the current can be carried out by using the liquid helium stored in the back-up 5000 litre dewar. The vapour produced can be channelled in the shield circuits to prevent their natural warming-up, therefore shortening the thermal recovery time after the plant restart. After injection at the low pressure suction side, the gas from the shield and from the current leads is recovered in the gas holders either by the cycle compressor or, in case of their failure, by the recovery unit.

During fast ramp-down of the current, both the refrigerator and the dewar will be isolated from the magnet circuit and the helium is vented through the relief valve of the thermosyphon phase separator.

Thermal recovery (from 55 K) after fast energy dump can be achieved either by supplying from the refrigerator high pressure gaseous helium (as for cool-down below 100 K) or 4.5 K supercritical helium directly to the coil circuits. The recovery time is ~3 days.

During warm-up to 300 K, electrical heating of the coil is preferred to gas circulation heating using the piping attached to the external cylinder in order to minimise the mechanical stresses generated in the windings by the thermal expansion of the overall structure.

C. Installation.

The CMS magnet will be fully tested at the surface prior to its final assembling in the underground cavern and the installation of the associated cold box will be accomplished in two steps. First at the surface level and then in the underground service cavern. Furthermore, whilst the intermediate valve box is an integral part of the magnet structure and can be moved with the magnet without modification, the interconnecting transfer lines must be purpose-built for the surface and underground positions. The surface and final underground layouts of the cryogenic infrastructure are shown in figures 2 and 3.

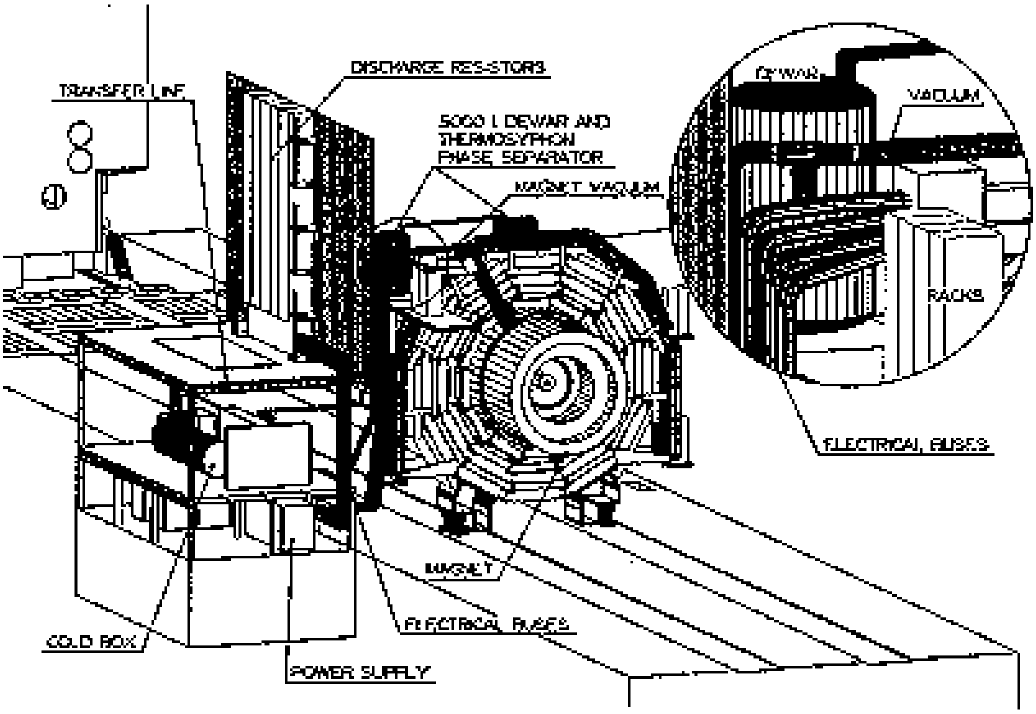

Fig. 2. Surface test layout

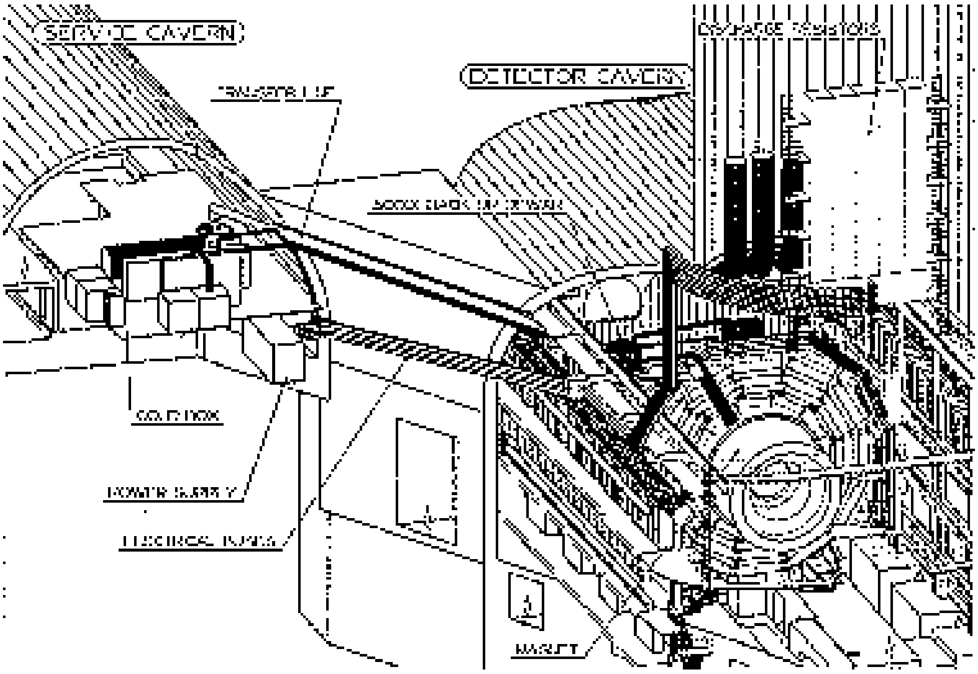

Fig. 3. Integration of the cryogenic system in the underground area

IV. CONCLUDING REMARKS.

The design of the internal cooling scheme and of the external cryogenic system of CMS is largely inspired by the existing ALEPH magnet. However, it will include new features to satisfy both the specific CMS requirements and to implement the modification suggested by the long operational experience of almost 10 years of ALEPH namely: the separated back-up 5000 litre dewar, the bypass between the coils and the thermal shield circuit, the suppression of a dedicated helium purifier since found economically not justified. Furthermore, special effort will be devoted in improving the reliability of the quench detection system, to avoid too frequent triggering by parasitic events of the fast current ramp-down, and in defining a control system architecture with a sufficient degree of compatibility between the various subsystems.

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