17. COIL CRYOGENIC SYSTEM

17.1 INTRODUCTION

The CMS solenoid cryogenic system is composed of two sub systems: the cryogenic plant and the coil cryogenic system these are defined as located outside and inside the coil vacuum vessel.

The cryogenic plant is presented in Chapt. 21. It is a dedicated helium refrigerator which produces and delivers the cryogenic power to the coil cryogenic system through an intermediate 5000 l LHe vessel installed on the side of the CMS magnet yoke, (see Fig. 26.8, p. C-58).

The CMS coil cryogenic system is composed of the 220-tonne superconducting coil working at liquid helium temperature, the thermal shield system cooled by a flow of helium at 60 K to 80 K, and the vacuum vessel. It also includes two chimneys crossing the iron yoke, one for the 20 kA helium cooled current leads, the control wiring and the pumping, and the other one for the cryogenic lines. The latter one ends at the top of the magnet, above the yoke, in an ancillary cryogenic vessel which houses the helium phase separator and the helium manifolds.

The main features of the coil which characterise the CMS cryogenics are:
- the cold mass of 220 tonnes,
- the magnetic stored energy of 2.7 GJ,
- the coil indirect cooling mode using a thermosiphon process.

Another specific aspect is the quench back mechanism: fast dumping the magnetic field spontaneously quenches the coil. This sensitivity to fast field variation brings certain advantages for the quench protection but must not be used for normal operation because 20% of the stored energy is released as heat in the coil, raising its temperature up to 50 K; a period of about 3 days is then necessary for re-cooling. So fast dumping must only be used in emergency cases such as a quench.

The slow dumping sequence, which does not quench the coil, lasts about 5 hours. The main function of the 5000 l vessel is to secure the cryogenic power supply so that the field can always be dumped slowly.

17.2 CRYOGENIC LOADS

17.2.1 Radiation heat flux

The heat radiation is the predominant component of the cryogenic loads because of the large dimension of the solenoid. Multilayer superinsulation is inserted on both sides of the thermal shields and the radiation heat loads are calculated as shown in Table 17.1.

Table 17.1
Multilayer insulation parameters.

	Surface area m^2	Number of layers	Heat flux W/m^2	Heat load Watt
Cold mass at 4.4 K	560	5	0.2	120
Thermal shield	560	30	5	2800

17.2.2 Cryogenic coil Supports

The 18 axial tie rods and the 12 radial belts of the solenoid are made of titanium alloy (Chapt. 18). Their temperature profiles must be independent of the refrigerator availability so there is no thermal or mechanical link between them and the shield system. Table 17.2 gives the dimension and heat input of the axial and radial cold mass tie rods.

Table 17.2
Cold mass tie rod parameters.

Rod	Section (mm^2)	Length (m)	Heat input per rod (W)	Quantity	Total heat load (W)
Axial tie rod	3612	12.70	0.4	18	7.2
Radial tie rod	2700	1.60	2.4	12	28.8

The system holding the shield consists of a set of rods made of low conductivity material, connecting the shield panels to the vacuum vessel. One end of each panel is rigidly fixed and the other allowed to move in the panel plane to accommodate the thermal contractions. Total heat input to the shield is 500 W.

17.3 CRYOGENIC LOAD AT LIQUID HELIUM TEMPERATURE

The saturated helium pressure of the coil cooling circuit is controlled by the refrigerator at a constant value of 1.25 bar providing a boiling temperature of 4.45 K. The losses at this temperature level are given in Table 17.3 at the nominal coil current of 20 kA.

Table 17.3
Steady state heat input at nominal coil current.

Total static heat losses at nominal current = 185 W		
Radiation heat load	120	W
Holding system	40	W
Phase separator and valves	20	W
Conductor junctions	5	W
Current lead LHe mass flow rate	2.5	g/s

When ramping up or down the coil current, eddy current in the coil structure and pure aluminium plastic strain build up additional losses summarised in Table 17.4.

Table 17.4
Dynamic heat loads due to field ramping.

Dynamic heat loads during ramping up and slow discharge of current		
Mean dynamic power dissipated in the coil	70	W
Peak value of dynamic heat load	240	W

17.3.1 Thermal shield cryogenic load

Table 17.5 indicates the heat load on the thermal shield system.

Table 17.5
Thermal shied heat load.

Radiation heat load at 60-80 K	2800	W
Supports	500	W

17.4 INTERNAL COOLING CIRCUITS

The flow chart of the solenoid cooling system is pictured in Fig. 17.1. It consists essentially of two independent cryogenic circuits.

- The coil cooling circuit using saturated liquid helium circulated in a thermosiphon mode. It is a closed loop including the phase separator vessel in elevated location, the cooling tubes attached on the coil external cylinder, the connecting manifolds and one feeding valve. This circuit also supplies the current leads with LHe.
- The thermal shield cooling circuit using forced flow helium gas.

These circuits, including the separator vessel and the current leads, are designed to support a pressure of 18 bars.

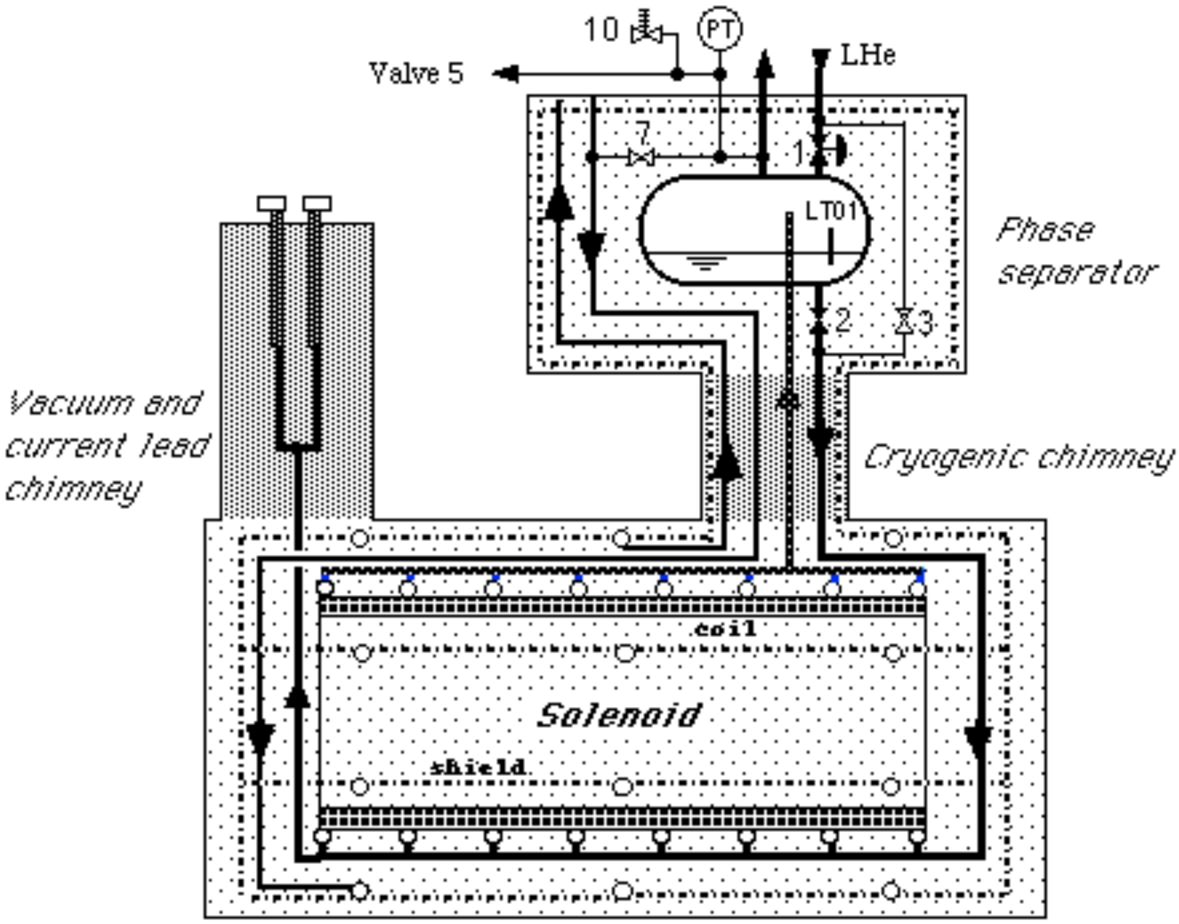

Fig. 17.1: CMS coil cooling circuit.

17.4.1 Thermal shield system

The thermal shield system is composed of 36 independent panels attached to the inner and outer vacuum vessel walls and closing plates at both ends of the coil. This system is designed to accommodate thermal contraction. Each shield panel is made of 5 mm thick aluminium plate with a cooling pipe welded on it.

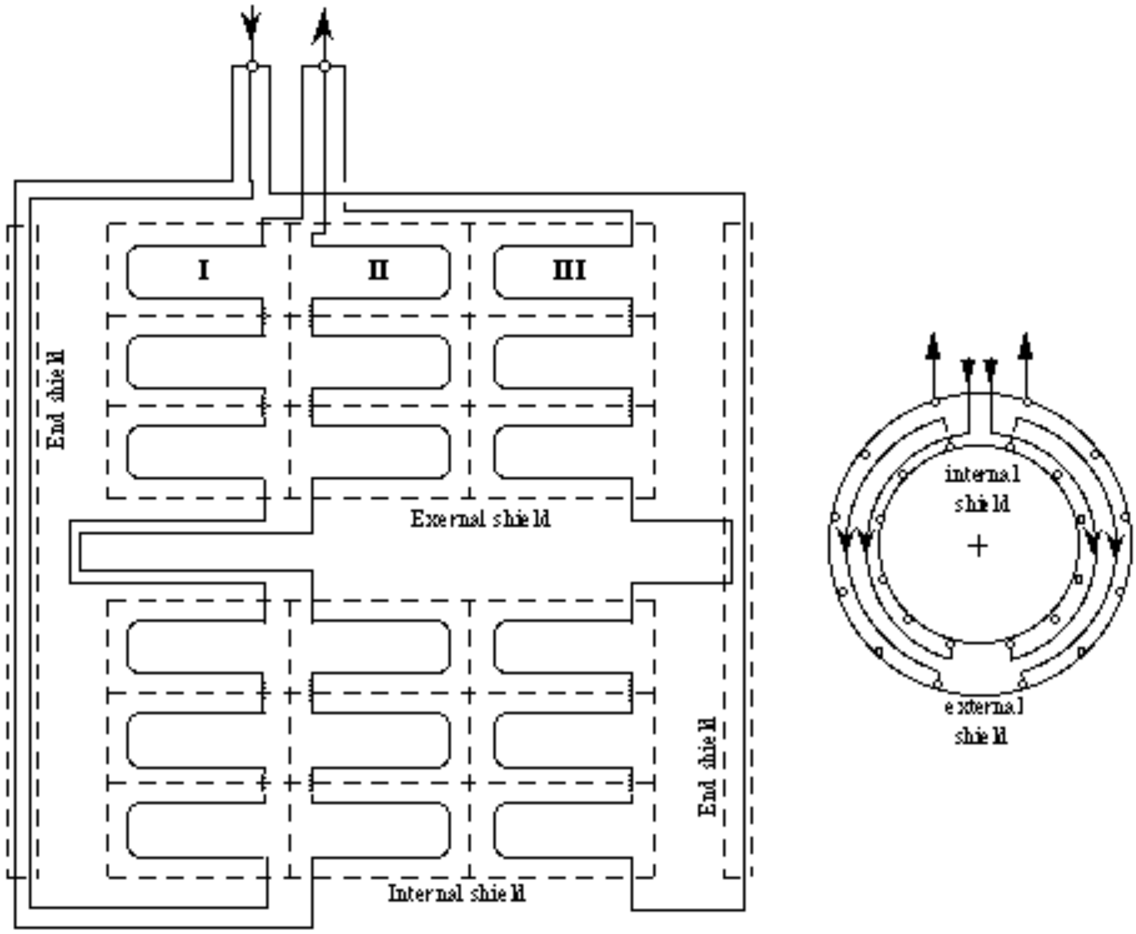

Fig. 17.2: Thermal shield helium circuit.

In normal conditions the thermal shield is cooled by forced flow helium gas provided by the helium refrigerator. In case of a momentary refrigerator stop, it is supplied by the coil circuit helium boil off (valve 7 opened). The cooling power in this second configuration is actually larger than in the normal operation configuration one, resulting in a lower shield temperature.

Table 17.6 and Table 17.7 gives the operating parameters respectively in normal operation and when the shield circuit is supplied with the boil off from the phase separator vessel.

The helium circuit is a low pressure drop network [17-1]. It consists of 6 parallel branches, each of them supplying 6 shield panels in series, as pictured in Fig. 17.2. The inlet and outlet of each branch connections to the main helium lines are installed in the separator vacuum vessel, this allows for a possible adjustment of the parallel flow distribution. Temperature sensors are installed on all the return lines.

Table 17.6
Thermal shield working parameters in normal operation.

Inlet temperature	60	K
Outlet temperature	80	K
Operating pressure	5	bar
Mass flow rate	35	g/s
Cooling power 60K to 80K	3300	W
DT (hot point - helium)	10	K
Length of a branch	110	m
Inner diameter	20	mm
Total shield pressure drop	80	mb

Table 17.7
Thermal shield working parameters when supplied from the phase separator boil off.

Inlet temperature	5	K
Return temperature	80	K
Operating pressure	1.1	bar
Mass flow rate	20	g/s
Total shield pressure drop	60	mb

17.4.2 Thermosiphon circuit

The so-called indirect cooling method is defined by the local heat sinks situated on the outer side of the coil. It is opposed to the hollow conductor or LHe bath cooling method. The indirect cooling can be used for low loss superconducting coils and requires a good thermal conduction throughout the cold mass. It also requires that helium is circulated through the cooling pipes.

The thermosiphon process is a method which provides the required helium circulation. The principle is to use the density difference, between the pure liquid and a two phase mixture made up of liquid and vapour, as driving head in a U shaped circuit configuration as sketched in Fig. 17.3. A vessel, located in an elevated position, allows the helium phase separation. The pure liquid is re-cycled to the cooling circuit while the vapour returns to the refrigerator which continuously supplies the boiled liquid fraction.

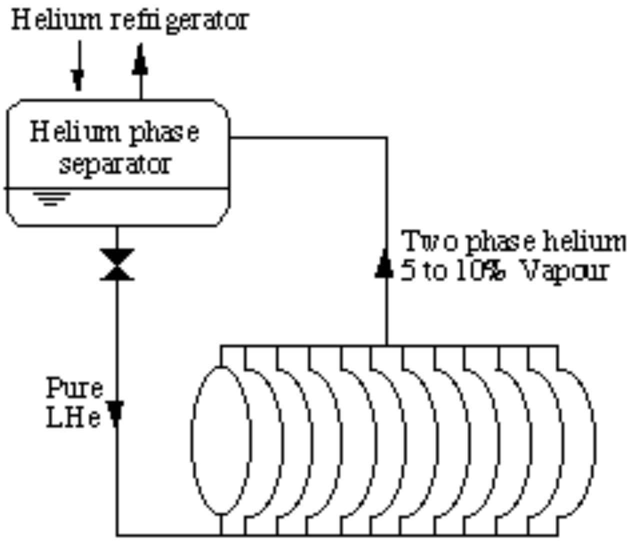

Fig. 17.3: Thermosiphon circulating principle.

This type of system has already been used successfully on the ALEPH solenoid [17-2]. It has the advantage of reliability because it does not have any moving parts such as cold pumps. It is also efficient as the temperature is uniform, due to the fact that the cooling helium flow spontaneously adapts to the heat load distribution. This process also allows the use of short cooling pipes supplied in parallel.

This arrangement also limits the quench pressure. When a quench is detected, the supply valve (V2) is closed and the helium in the cooling tubes is rapidly evacuated to the phase separator vessel due to the fast temperature rise. This surge process limits the pressure rise to few bars without venting any helium to atmosphere.

As the thermosiphon is essentially driven by gravity, the cooling tubes must be vertically orientated. They are semi-circular segments connected at the bottom and top to the supply and return manifolds. These cooling tubes are attached to the outer side of the external cylinder every 260 mm.

The thermosiphon circuit is made up of 8 independent sub-circuits. Fig. 17.4 represents the schema of half of the helium distribution for the thermosiphon cooling circuit. Each sub-circuit can be manufactured and leak tested before assembly on the coil.

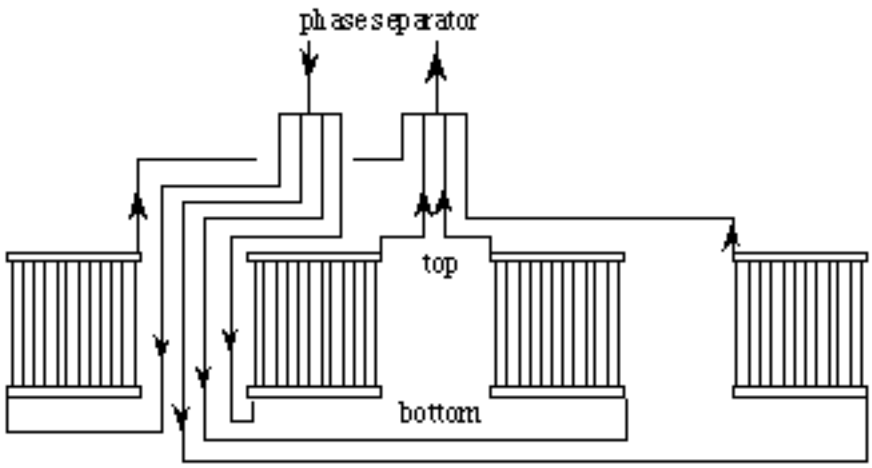

Fig. 17.4: Cooling circuit configuration (half of the thermosiphon circuit).

The piping lengths and diameters are given in Table 17.8. This system is calculated in order to keep the quantity of vapour in the return line lower than 10%.

Table 17.8
Thermosiphon piping parameters.

	Inner diameter mm	Length m
Inlet line	23.7	22
Feeding manifold	23.7	3
Return manifold	23.7	3
Cooling tubes	14	11
Return line	23.7	8

17.5 COIL TEMPERATURE DISTRIBUTION

At constant current the cold mass is subjected to heat radiation (0.2 W/m^2), conduction from the supports and localised internal sources due to the conductor junctions at each layer end and inside the winding (0.4 W per junction).

In varying current regime there are additional transient losses:
- eddy currents in the quench back cylinder,
- eddy currents in the pure aluminium,
- plastic strain of pure aluminium.

AC losses in the strands or filaments are negligible, as are eddy currents in the aluminium alloy.

Computations on the temperature distribution in the cold mass show that the temperature difference is lower than 50 mK at constant nominal current.

The dynamic losses due to eddy currents and aluminium plastic strain are both function of the current intensity and the rate of current variation [17-3]. When ramping up the current at constant dI / dt eddy current losses are almost constant but the heat generated by plastic strain is zero up to the aluminium elastic limit and then roughly increases as B^2 per unit time.

It is at a maximum when it reaches the nominal current. There are some uncertainties when estimating the temperature rise because the metallurgical state of the aluminium is not well defined. Calculations show that temperature differences can be of the order of 0.1 K. This winding temperature has to be monitored during the energising of the coil and the power supply voltage must be adaptable to reduce the energising speed if needed.

17.6 CRYOGENIC SEQUENCES

The operation of the CMS solenoid includes 5 cryogenic sequences [17-4], (see also Chapt. 21):

- cool down,
- normal operation,
- slow discharge in case of main’s failure,
- post quench re cooling,
- warming up.

During cooling down the coil cooling tubes are supplied with forced flow helium. The cooling down speed is controlled in order to limit the temperature difference to 50 K maximum over the winding.

The helium refrigerator is dimensioned for the normal operational cryogenic loads. Additional power is required to cool down the 220 tonne cold mass in about 3 weeks. This is done by supplying LN2 to the refrigerator cold box. The total helium flow delivered by the cycle compressor is used to transfer the cooling power to the coil. The thermal shields are not supplied until the temperature is lower than 120 K. At this temperature level the cold box expansion engines are started and the shields are also cooled down. The cool down curve is shown in Fig. 17.5.

Table 17.9
Cool-down helium flow parameters.

Outlet pressure	bar	7
Mass flow	g/s	150
DP on internal circuit at 300 K	bar	3.5

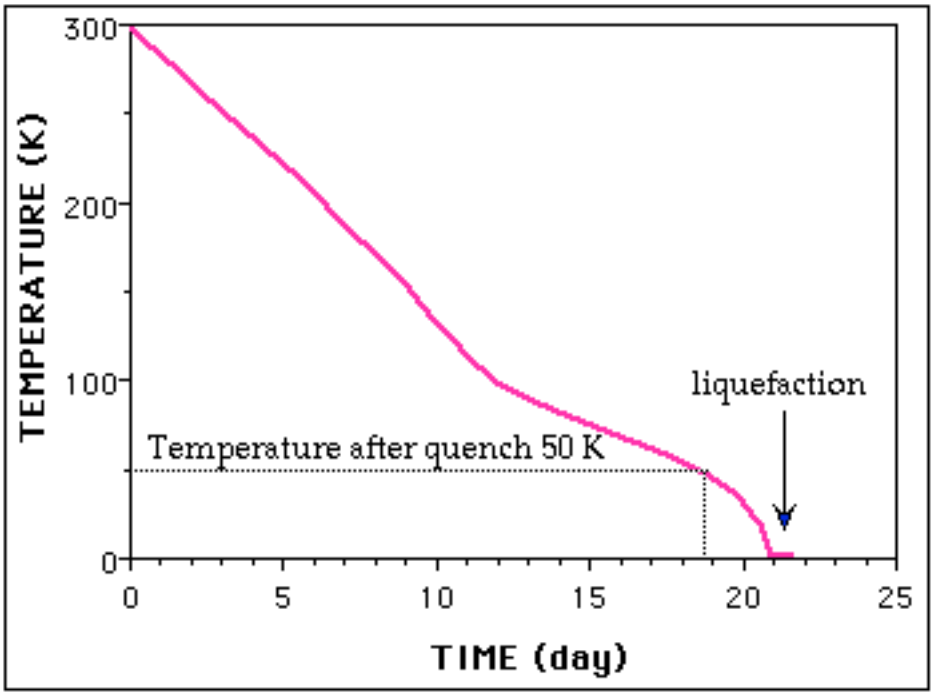

Fig. 17.5: Cooling down of the CMS coil.