DESIGN OF THE MAIN COILS FOR THE MILAN SUPERCONDUCTING CYCLOTRON

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Abstract. - In this paper are described the main design features of the superconducting coils, the cryostat, the power supply and the dumping circuit of the Milan Superconducting Cyclotron. Are also discussed the problems of the stresses in the coils, the cryogenic stability and the quench effects.

1. Introduction.- The overall characteristics of the coils for the Milan Superconducting Cyclotron are already described in another paper at this Conference [1]. Here we will present the guidelines followed in designing both the coils and the cryostat together with the solutions envisaged for the mechanical and cryogenic stability of the coils. We shall also discuss the coils behaviour in the case of a quench, as far as coils temperature and cryostat pressure are concerned. Conservative solutions have been generally adopted in view of the novel problems presented by the coils.

2. Coils and cryostat design features.- The shape, size, position and overall current density of the coils are largely determined by the field isochronism requirements [2]. On this ground three basic choices have been made for the coils and cryostat design:

a) the coils are wound with the double pancake technique;
b) the maximum current is about 2000 A;
c) the coils are in a liquid helium bath at atmospheric pressure (T = 4.21 °K).

The double pancake technique enables us to start the coils construction indipendently of the cryostat and to change only the damaged pancakes in the case of an accident. The maximum current value is determined by the necessity to limit the helium consumption in the current feedthroughs and at the same time to have a cable size useful for the pancake winding. The helium bath solution is the most economic one and is consistent with the previous choices.

On this ground we have defined the coils geometry (splitted into two sections labelled in the following α and β) and the superconducting cable parameters. Their characteristics are listed in the Tables I and II.

The pancake structure is shown in Fig. 1. The turn to turn insulation is made with a mylar ribbon (11 x 0.15 mm^2) with sticked mylar strips (11x4x0.35 mm^3) spaced 6 mm apart. The insulation between the layers and different pancakes is obtained with fiberglass strips (G10, 180x22x1 mm^3) spaced 25 mm apart.

The superconducting cable, prestressed at 3.5 kg/mm^2, is wound on a mandrel 200 mm thick. In the last eight turns a stainless steel tape (12x1.5 mm^2) prestressed at 15 kg/mm^2, is inserted as a banding. The conductor ends are blocked by the U-shaped clamps.

The pancakes will be assembled and centered in the cryostat and compressed to appoximately 700 tons by copper beryllium (2%) tie-rods (144 inside rods, 10 mm diameter - 72 outside rods, 14 mm diameter) in order

Table I - Coil parameters

	Section α	Section β
Internal radius (293 K)	1.000 m	
External radius (293 K)	1.168 m	
Height	0.364 m	0.252 m
Layers	2 x 13	2 x 9
Turns/pancake	2 x 38	
Minimum distance from M.P.	0.062 m	0.463 m
Maximum overall density	3500 A/cm^2	
Maximum nominal current	1944 A	
Maximum F.M.M.	6.5 10^6 At	
Self inductance (NI=6 10^6 At)	8.7 H	3.7 H
Mutual inductance (NI=6 10^6 At)	3.7 H	
Maximum energy stored	38 MJ	
Total conductor length	22600 m	
Total weigth	9700 kg	

Table II - Superconducting coil parameters

Matrix and dimensions	Cu (ETP) 13 x 3.5 mm^2
Overall Cu/Sc	18 : 1
Proof strength (0.2%)	12 kg/mm^2
Copper cold work	5%
Superconducting insert *	monolitic NbTi (46%)
Insert dimensions	1.8 x 3.6 mm^2 (Cu/Sc 2:1)
Filaments number (diameter)	540 (70 m)
Twisting pitch	25 mm
Critical current (B=5T, T=4.2 °K)	2700 A

* The superconducting cable is fabricated by La Metalli Industriale (LMI) - Florence, Italy.

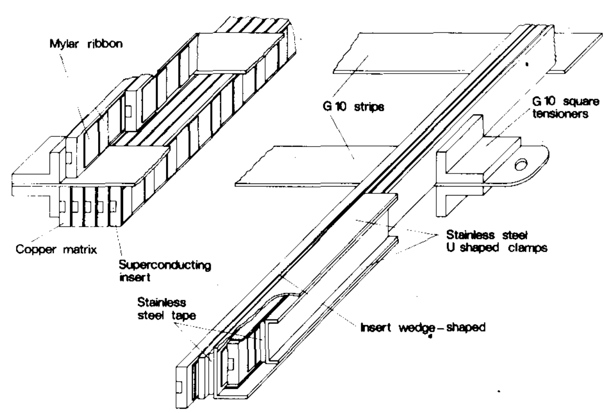

Fig. 1. A sketch of the double pancake structure.

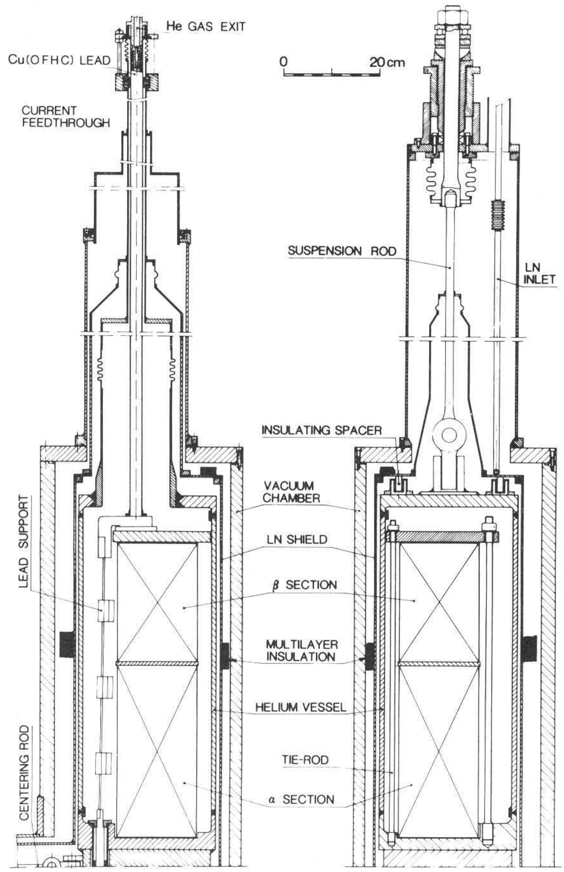

Fig. 2. Coil and cryostat sections.

to prevent the axial lifting of the β section when the latter is excited with a negative current with respect to the α section. The resulting lifting force is about 600 tons.

Two cryostat sections are shown in Fig. 2. The one on the left shows also the current feedthroughs, while on the right the coils suspension rods are shown.

The cylindrical helium vessel is manufactured with stainless steel (AISI - 316 L), has a weight of 4 tons and will hold about 1200 liters of LHe. The vessel is designed to withstand a maximum relative pressure of 6 bar, it has 10 mm thick inner and outer walls and 25 mm thick base plates.

The axial suspension is made with three pairs (upper-lower) of 16 mm diameter Ti-alloy rods, of about 1 m length. We expect to be able to center the coils axially within $\pm$ 0.1 mm.

Three pairs of horizontal Ti-alloy rods, 10 mm in diameter will allow the radial centering of the coils. The rods of each pair make an angle of 12^0. The rationale of this choice (instead of purely radial rods) is to dispose of possible momenta which may induce a coil rotation. We expect to be able to center the coils radially within $\pm$ 0.1 mm.

The LN shield is manufactured with 3 mm thick ETP copper, suspended to the helium vessel as shown in Fig. 2. It will be cut in several sections to prevent damage by eddy currents. Multilayer superinsulation of crinkled aluminized mylar is wrapped around the screen, with a minimum thickness of 15 mm (45 layers).

The anticipated cool down time is 150 hours and the LHe consumption at full current is 15 l/hour + 15 W.

The sections α and β will be excited independently by two power supplies (2500 A - 20 V) with a current stability of $\pm$ 20 mA over the entire operating range. The current control is achieved by water cooled transistor bank, the current sensing is made by a DCCT device. The power supplies will be equipped with all devices needed for computer control. The dumping circuit diagram is shown in Fig. 3.

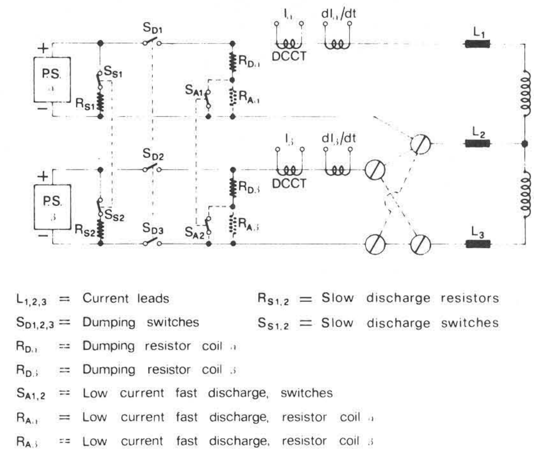

Fig. 3. Dumping circuit diagram.

3. Mechanical and cryogenic stability. - All the results are referred to the two limiting cases in the cyclotron operating diagram[1], i.e. :

(a) $I_\alpha = I_\beta = 1944$ A

(b) $I_\alpha = 1666$ A $\quad I_\beta = -833$ A

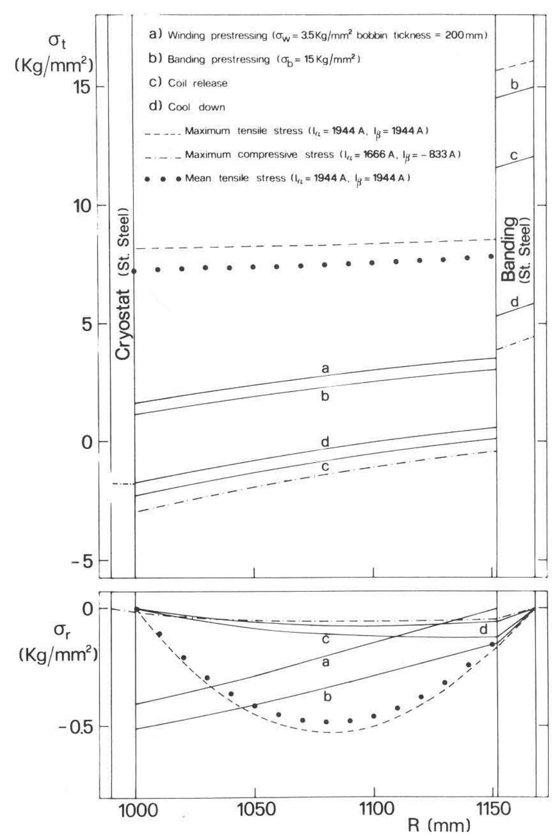

Fig. 4. Hoop and radial stresses in the coils and the banding.

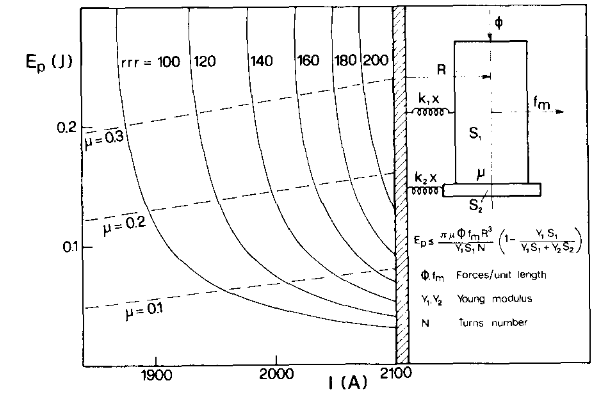

Fig. 5. Maximum energy perturbation supported by the coils.

The maximum compressive force in the coils occurs at a distance of about 25 cm from the median plane in the α section. Its value is approximately 2700 tons, including the precompression of 700 tons, and translates into an axial compressive stress of about 6.5 kg/mm^2.

The stresses (hoop stress σ_t and radial stress σ_r) in the coils and banding during the different phases (winding, mandrel release, cool down, field on) are calculated with a simple code [3] and the results are shown in Fig. 4.

Whereas the maximum radial stress is only $\sigma_r = -0.5$ kg/mm^2, the maximum hoop stress in the pancake is σ_t = 8.4 kg/mm^2. Since the copper must work in the elastic regime, it is necessary to have at least a 12 kg/mm^2 proof strength (0.2%).

In the case (b) the hoop stress in the β section is negative but far away from the buckling condition.

The maximum radial displacement of the coils (case (a)) is nearly 0.8 mm. Since it is impossible to avoid the slipping between the coils and the cryostat plates, we will introduce between them a teflon sheet 0.1 mm thick.

For the cryogenic stability the most restrictive condition is given by the case (a). At this operating condition the superconducting cable works very near to the limit given by the Stekly rule [4]. In our case it would be necessary to have a residual resistivity ratio for the copper matrix greater than 200, very difficult to obtain with the cable mechanical properties (5% cold work). If one use an approach to the heat diffusion

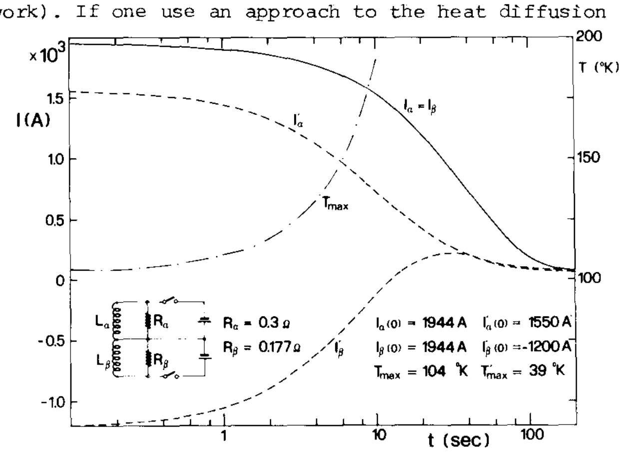

Fig. 6. Current discharge in the α and β sections and the coil maximum temperature during a quench.

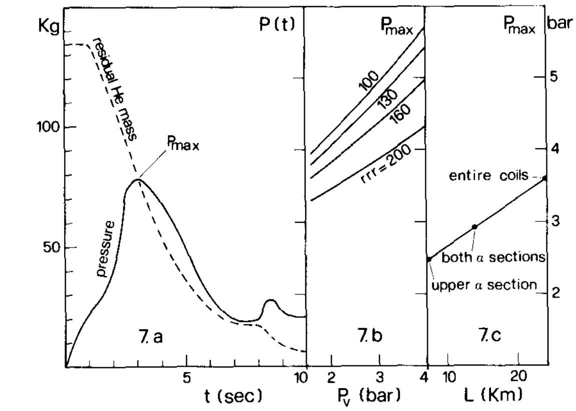

Fig. 7a. Pressure and He residual mass vs time during a fast discharge. The safety valve diameter is 100 mm, its opening pressure 1.6 bar and entire cable is normal.
Fig. 7b. Maximum pressure vs opening safety valve pressure P_V at different copper rrr values.
Fig. 7c. The same vs the length L of the normal zone.

which considers also the matrix thermal conductivity [5], it is possible to evaluate the maximum energy perturbation for which the normal zone is reabsorbed.

In the Fig. 5 are shown the maximum energy perturbations supported by the cable without quench for different rrr. Also, as an example, the maximum energy released in a single turn by a slipping of the coils with respect to the cryostat plates for different friction coefficients is plotted (dashed curves). From these data appears that there is some marge for the cryogenic stability also with rrr = 160 .

4. Quench effects. - The behaviour of the current in the α and β sections (case (a) and (b)) is shown in Fig. 6 when a fast discharge have been initiated by the quench detection system. It is remarkable that the current in the β section is reversed after about ten seconds (case (b)) because of the large mutual inductance.

In the same figure the maximum temperature in the coils (no exchange with the helium bath) is plotted as a function of the delay time in the switch opening. The maximum allowed delay time is 4 seconds.

The pressure and helium residual mass in the cryostat during a fast discharge [6] are plotted as a function of time in Fig. 7a. The maximum pressure reached in the cryostat for different parameters of normal cable and safety valve characteristics is plotted in Fig. 7b and 7c.

References.

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