A 5 m LONG IMPREGNATED NbTi DIPOLE MAGNET

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Abstract

A 5 m long superconducting dipole designed as an accelerator magnet has been constructed and tested at CERN. A bore field Bo = 4.2 T --an integrated field of 23 Tm-- in a 7 cm aperture has been obtained without training. Description of the magnet and measurements are given.

1. Introduction

A 5 m long dipole magnet has been constructed at CERN as a prototype for a string of 5 dipoles to be installed in the external 350 GeV/c proton beam P_0 at the SPS[1]. The features of these 5 dipoles connected electrically and cryogenically in series and deflecting a proton beam of 560 KJ with background losses which could reach 10^{-4} of the proton beam are similar to the features of the magnets designed for the Tevatron[2] or for the Hera machine[3]. The design and the construction of the P_0 magnet including its tooling and its cryogenics have started in 1979 with a small group of less than 12 people ; first tests have been made in 1984.

The main features of the P_0 magnet compared with the existing magnets of similar style are :
- non-porous coils using a high current density cable;
- magnet mechanically associated with its cryostat which is aligned and stays centered at ± 0.05 mm in the yoke by a suspension system calibrated at room temperature whithout any a-posteriori correction ;
- a liquid helium pump in the cryogenic scheme.

2. Description and characteristics of the magnet

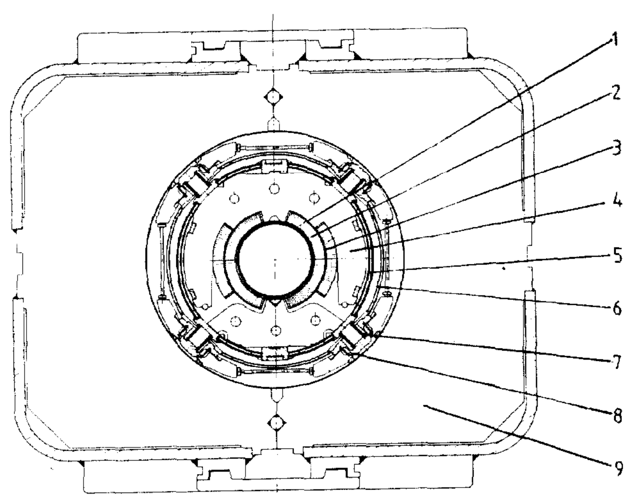

Fig. 1
Cross section of Po magnet

1-Cold bore, 2-Coils, 3-He channels, 4-Collars 5-6-4.2K & 60K cryostat, 7-8-Suspension, 9-Yoke

Fig. 1 shows the cross-section of the P_0 magnet at a radial suspension plane. The coils consist of 2 layers of winding (34 turns and 21 turns) separated by 1 mm thick x 7 mm wide G-10 strips and 1 mm x 3 mm cooling channels. The G-10 strips are covered by a hard, low friction painting and are disposed at 45° angle with respect to the longitudinal axis. The 2 layers are wound in a double pancake mode and successively polymerized under a 70 MPa pressure in the same high-precision tooling. The azimuthal strain curve for the 2 layers is recorded after curing in order to determine the dimensions of the shims located at 71.94° and 35.4° angles and installed together with the 0.25 mm Kapton ground insulation.

The coils are assembled in laminated two-pieces 316LN stainless steel collars (Fig. 2) and compress in a press of 2250 t until the lateral keys can be placed and welded in their groove, meaning that the correct geometrical dimensions and the right value of preloading are obtained. The 1.5 mm thick stainless steel laminations were stamped with an accuracy of ± 0.01 mm, and present no burrs thanks to the use of the fine-blanking technique.

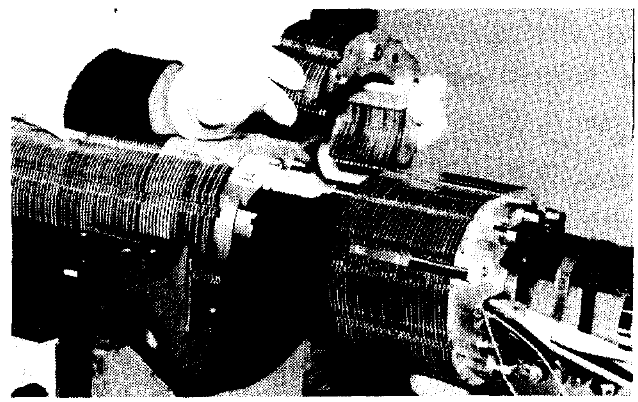

Fig. 2
Assembly of collars around the coils

As it can be seen in Fig. 1, stainless steel sectors are mechanically associated to the collars and provide passages for a helium flow between the coils and the two-phase cryostat. The radial displacement of the collared-coil assembly is 0.1 mm on the horizontal axis under the magnetic forces. Fig. 3 shows the winding machine and the press. Table I gives the main characteristics of the P_0 magnet.

Table I : Main characteristics of the P_0 magnet

Cold bore diameter	66	mm
Inner diameter of the winding	72	mm
Outer diameter of the winding	113.2	mm
Outer diameter of the collared coils	167.0	mm
Inner diameter of the iron yoke	240.0	mm
Overall current density at Bo=4.2T	303	A/mm^2
Self-inductance	37.3	mH
Magnetic lenght	5.60	m
Load line B_0	0.0934	T/A
∫Bodl at 4500 A	23	Tm
Weight of the cold part	1050	kgs

Heaters consisting of a 38 μ thick stainless steel meander have been mounted in close thermal contact with the conductors on one end of the two layers. The time delay for initiating a quench has been measured on the superconducting cable in a zero applied field and varies from 38 msec at I = 3 KA to 27 msec at I = 5 KA when a 5 mF capacitance at 150 V is discharged in the heater (R=2.9Ω). By firing four heaters, after a quench has been detected in the magnet, the maximum calculated temperature in the winding does not exceed 100 K instead of 220 K in the case of a quench without protection.

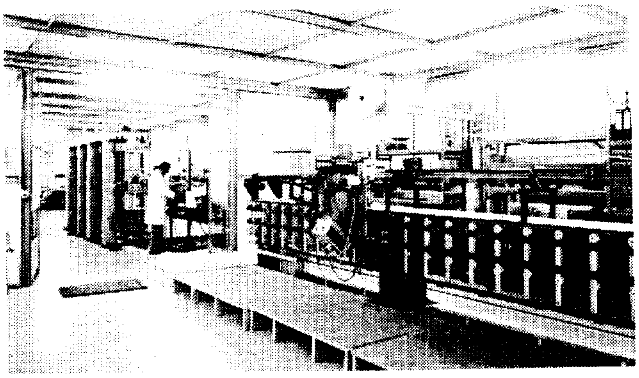

Fig. 3
WindingMachine and the 2250t Press

3. Conductor, insulation, prestress in the coils

The conductor is a soldered (1.2/1.35)x9.3mm² trapezoïdal Rutherford type cable made of 25 strands (0.7 mm diameter) fabricated by BBC Company (CH). The P_0 cable has filaments of different characteristics varying from 17µm to 14µm and current densities from 2.8 to 2.2 kA/mm² (5 T, 4.2 K). The mean current density is 2.45 kA/mm² (5 T, 4.2 K) as shown on Fig. 4. The RRR of the copper is 141 and the Cu/Sc ratio is 1.8.

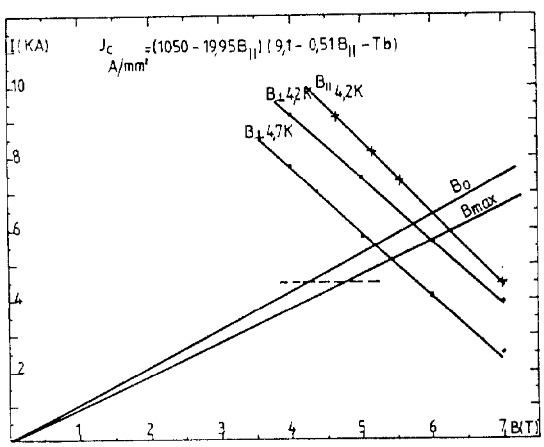

Fig. 4
Critical current and load lines

The cable is wrapped with a 25 µ Kapton ribbon at 50 % overlap and with a 80 µ Bstage fiber-glass ribbon at 0 % overlap. Between the cable and the wrapped Kapton is inserted a (0.02/0.08)x8.5mm² trapezoïdal Kapton shim, which allowed us to accommodate the same conductor to the different theoretical form factors of the inner layer and the outer layer. Measurements have shown that the different conductors are located in the winding with an error of ± 0.03 mm respect to the theoritical placement after having been cured under a pressure of 70 MPa and assembled in the stainless steel laminations at a pressure higher than 50 MPa. It should be mentioned that although the coils are non porous, there is nevertheless no epoxy between the wrapped Kapton and the conductor. Table II shows measured values of the mechanical characteristic of the coils ; ϵ and $\sigma_{\theta,c}$ are respectively the strain and the compressive stress in the azimuthal direction of the coils. The coils were submitted in the press to a compression of 102 MPa to obtain the calculated geometry of the winding.

Table II : Mechanical characteristics of the coils.

$\sigma\theta$,c (MPa)	20	35	65	80	100
$d\sigma/d\epsilon$ (GPa)	8.15	12.50	14.60	17.20	18.10

When the press is removed after insertion of the lateral keys, at least 76 MPa of compressive azimuthal stress remains in the winding as shown in Fig. 5 by the stress distribution obtained by photoelasticity measurements and confirmed by capacitance measurements between conductors on short models. The compressive azimuthal prestress of 76 Ma ensures that the coils remain in mechanical contact with their collars and that a compressive stress higher than 20 MPa exists everywhere in the winding at 4.2 K when the coils are submitted to compressive forces and bending momnents due to the magnetic forces at 5.5 T. The axial magnetic forces are taken by the compressed winding.

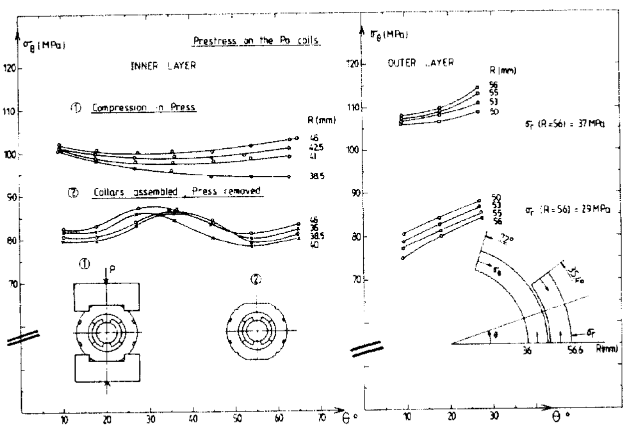

Fig. 5
Distribution of azimuthal compression in the coils

At 4.7 K, the magnet reached 4500 A or 87 % of the critical field without any training, and the measured field distribution agreed within $\pm 2 \times 10^{-4}$ with the calculated one.

4. Suspension and alignement of the collared coils in the yoke

The magnet is centered and supported in the warm iron by six radial suspensions, two angular suspensions and is fixed to the yoke at the mid-point. An improved flexural rigidity of the magnet is obtained by welding supports at 90° and 270° each 47 cm between the collared coils and the double wall helium cryostat.

A radial suspension is composed by 4 supports as it can be seen in Fig. 1. Each consists of 2 concentric G-10 tubes mounted in such a way to increase the path for the thermal conduction. Once the support is loaded, the 2 G-10 tubes are under mechanical compression whereas the intermediate metallic cup is under tension. The supports are calibrated individually before being assembled on the magnet as shown in Fig. 1 and Fig. 6.

This mechanical arrangement is assembled after the 4 supports have been loaded with 27.5 KN (σ in G-10 = 300 MPa) by an external tooling. When the external tooling is removed, the 4 supports stay in place under a load of 12 KN and it can be controlled that the radial dimensions are uniform. The final assembly in the yoke establishes again the initial loading. At helium temperature, after the magnet has contracted radially by 0.25 mm, a load of 8 kN

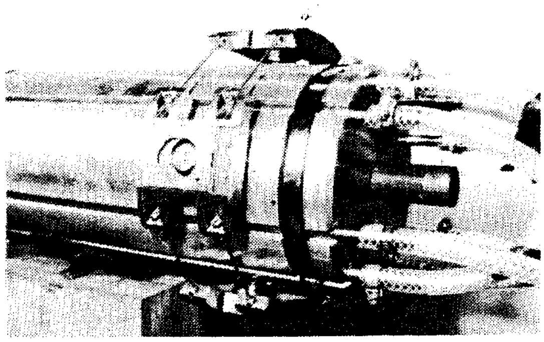

Fig. 6
Radial suspension model

remains on the supports. Sliding surfaces at the outer radius of the suspension are provided for the longitudinal contraction of the magnet. The total losses at 4.2 K for the 6 radial suspensions reaches 2.25 W. Measurements of the quadrupole component inferior to 8.10^{-5} at R = 2.5 cm have shown that the magnet stays aligned within ± 0.05 mm in the yoke for the full excitation range and after several cool-downs.

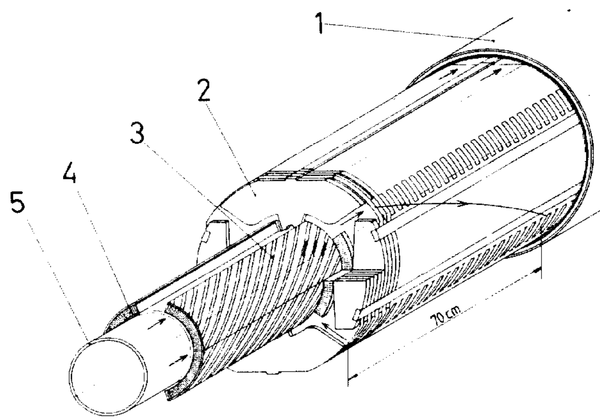

Fig. 7
Helium flow in Po magnet (indicated by arrows)

5. Cryogenics

The magnet is cooled by single-phase liquid helium with 2-phase counterflow heat exchanger. Subcooled helium is forced into the coils by means of a liquid helium pump[5] followed by a sub-cooler. At the end of the magnet, the liquid passes through a Joule-Thomson valve and flows back through the double wall cryostat in thermal contact with the one phase liquid helium. Any heat generated in the coils is transferred to the 1-φ helium and transferred by it to the colder 2-phase reverse flow, which stays at constant temperature. Fig. 7 indicates the distribution of the helium flow in the various passages, which has been observed in an hydraulic analogy with water[6].

The total losses at 4.2 K for the complete installation are 31 W including the dewar with the helium pump and the current leads at 4500 A. The losses to the screens reach 127 W at 60 K. Fig. 8 shows the measured pump losses and the pressure in the magnet for various helium flow rates. It results that the losses of the helium liquid pump reaches 7 W for a mass flow rate of 20 gr/sec at 1.6 bar in the magnet. In the test installation, the helium vapor produced by the pump losses is sent into the screen at 60 K.

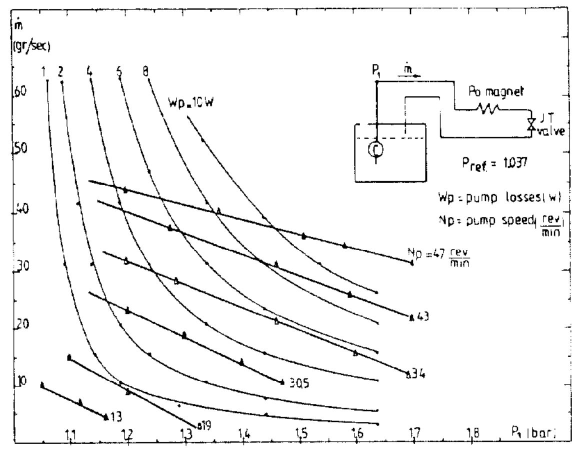

Fig. 8
Pump and He flow characteristics

6. Conclusions

The 5 m long superconducting dipole P_0 has reached 87 % of the critical field at 4.7 K without any training. The integrated field of 23 Tm is 20 % higher than the designed value. The main features of the magnet are :

- The use of a high current density NbTi ; soldered cable (j_c = 2.45 kA/mm² at 5 T, 4.2 K) in non-porous coils.
- Alignement of the collared coils in the warm iron within ± 0.05 mm without any a-posteriori corrections of the supports.
- Magnetic measurements in agreement with the calculated errors within ± $2x10^{-4}$.
- Subcooled liquid helium obtained in a circuit with a liquid helium pump.

7. Acknowledgements

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8. References

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