

Performance of the Twin-Aperture Dipole for the CERN LHC

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Abstract

The paper reports about the measurements performed on the Twin-Aperture Prototype Dipole (TAP) for the CERN Large Hadron Collider. This dipole was designed by CERN and built by European industry. A comprehensive programme for magnetic and cryogenic measurements is in progress at CEN, Saclay, in France. The measurement campaign includes studies of time dependent field effects and detailed measurements of the influence of excitation history on the remanent field.

1. INTRODUCTION

Within the framework of the LHC[1] development programme for high-field magnets it was decided to design and order from industry a twin-aperture 9 m long prototype magnet making use of superconducting coils of the same type and geometry as those of the DESY HERA proton ring dipoles[2]. The geometry of the yoke and the shrinking cylinder is similar to those of the twin aperture 10 T dipoles[3].

The primary objective of the TAP magnet is to gain experience both in the construction of long two-in-one "mechanically hybrid" structures and with superfluid helium operation in a long horizontal cryostat. Following competitive tendering, ABB, Mannheim (D) was awarded the contract for construction of the active part and FBM-Hudson Italiana, Milano (I), for manufacturing and assembly of the cryostat. The superconducting cables were supplied by ABB Switzerland[4].

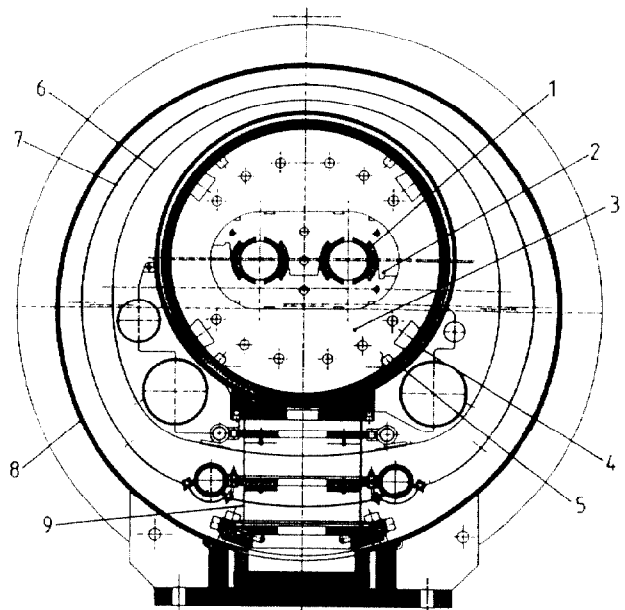
The cryomagnet is installed in a test facility developed at CEN, Saclay (F)[5] and cryogenic and magnetic measurements have been performed successfully.

2. THE CRYOMAGNET

The active part and the cryostat of the TAP magnet have been described in earlier papers[6][7]. The main features are shown in Fig. 1 (transverse cross-section) and Fig. 3. Fig. 2 is a view of the electrical connections and cold protection resistors.

3. QUENCH HISTORY

A first test and measurement campaign was performed at a bath temperature of about 4.5 K. The first quench occurred at 6603 A, corresponding to a central field of 5.8 T. On the basis of BNL measurements on the cables used for the TAP coils at 4.6 K, we estimate this value to be within 2% of the short sample limit.



1. Excitation coil of the HERA type
2. Pair of collars
3. Split iron yoke
4. Shrinking cylinder
5. Helium vessel
6. Radiation screen
7. Liquid nitrogen screen
8. Vacuum vessel
9. Support post

Fig. 1. Transverse cross-section.

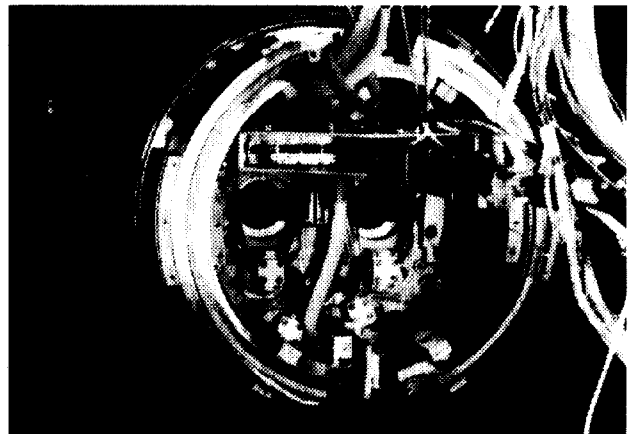


Fig. 2: View of TAP magnet connections and cold resistors.

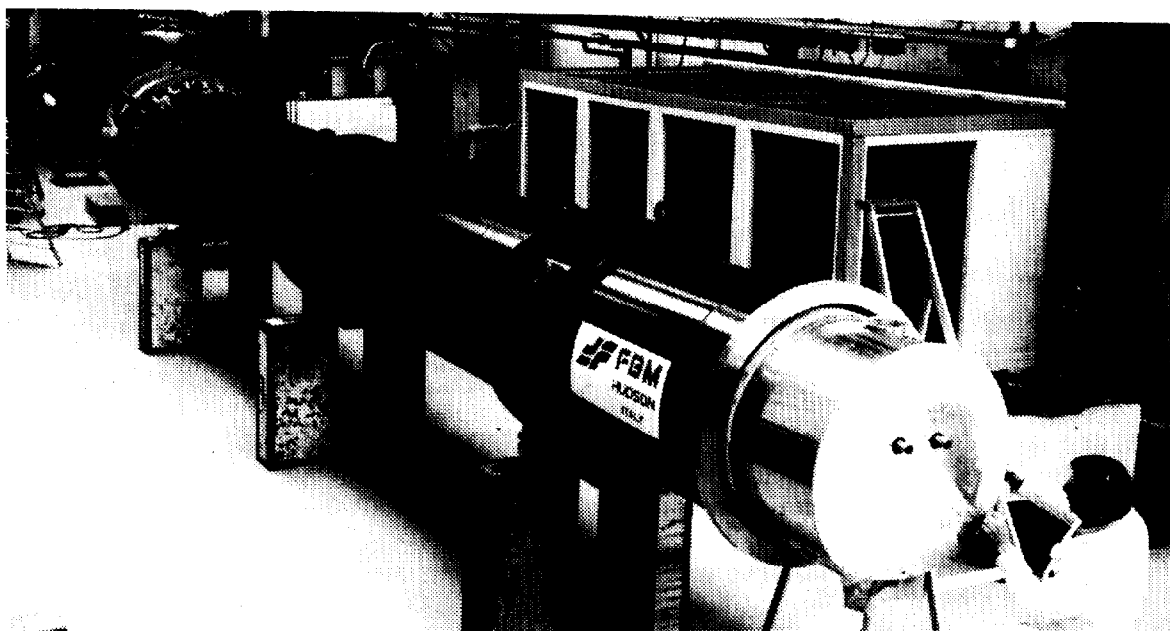


Fig. 3: TAP being prepared for installation in the CEN test facility.

During the following campaign, the bath temperature was lowered to 1.8 K. The quench history is shown in Table 1 (TAP Quench History). Fig. 4 (TAP load line and critical currents) shows the computed load lines for the central field and for the maximum field in the winding and the computed critical currents at 1.8 and 2 K and at 4.2 and 4.6 K.

At the maximum quench current of 9505 A, the horizontal component of the electromagnetic force per quadrant is 1.84 MNm^{-1} , the longitudinal magnetic force at either side is 57 MN, the stored energy is 4.98 MJ and the current density in the superconductor is 2050 A mm^{-2} .

4. CRYOGENIC PERFORMANCE

Cooldown from ambient, performed by forced flow of gaseous helium at progressively decreasing temperature, was slow enough to avoid generating temperature gradients in the magnet and cryostat structures, and took over 100 hours. Final sub-lambda cooling was achieved by conductive heat transport to the cold source in the test station, over 6 hours. Throughout cryogenic tests, the insulation vacuum remained below $5 \times 10^{-5} \text{ Pa}$ ($5 \times 10^{-7} \text{ mbar}$) and helium-free. In spite of some doubts on proper thermalization of the heat intercepts on radiation screen and support posts, the cryostat performed well, with measured heat loads below 1 W at 1.8 K and about 4.6 W at 4.5 K, in accordance with calculated values[7]. Maintaining the apertures at ambient temperature for performing magnetic measurements added another 9 W to the 1.8 K heat leak.

Magnet quenches induce fast pressure rise in the annular helium spaces between coils and bore tubes, up to 3 MPa (30 bar) in 0.1 s. The bulk helium in the ends of the cryostat sees its pressure rise more slowly, up to about 1 MPa (10 bar) in 0.5 s, before being discharged at rates of up to 10 kg/s through a fast-opening, DN 50 cold valve.

5. MAGNETIC CHARACTERISTICS OF TAP MAGNET

An extensive programme of magnetic measurements has been performed on the TAP magnet at several field levels in both apertures. The programme includes the following measurements:

- Analysis of the harmonic content of the magnetic field in several positions along the magnet aperture with a $\sim 1 \text{ m}$ long coil, compensated for the dipole component.
- Measurement of the field integral along the magnet axes using the uncompensated 1 m long coil and a Nuclear Magnetic Resonance device.
- Measurements of the orientation of the vector B along the magnet axes, using a magnetic disc and two orthogonal Hall probes.

Table 1
TAP Quench History

Quench number	Quench current	Central Field	Integral $\int^2 dt$
	(A)	(T)	MA^2s
at 4.5 K			
1	6603	5.8	12.1
at 1.8 K			
1	8354	7.33	13.9
2	8820	7.74	13.3
3	8864	7.78	13.2
4	9198	8.07	13.0
5	9426	8.24	12.5
6	9505	8.31	12.3
7	9440	8.25	12.5

At the time of publishing, the magnetic measurements have been done at 250 A, 650 A, 1000 A, 3000 A, and 5000 A and the evaluation of results is under way.

Table 2 summarises the sextupole component of the magnetic field along the magnet axis in function of the excitation current for one aperture.

6. CONCLUSION

We estimate to have reached successfully the main goals of the TAP project:

- to assess the two-in-one structure for a length of ~ 10 m,
- to evaluate the difference in behaviour of single and double aperture magnets,
- to test the cryogenics with superfluid helium at 2 K of a 10 m long horizontal cryostat.

The detailed analysis of the different electrical, hydraulic and magnetic phenomena when quenching is under way as is the evaluation of the results of magnet measurements.

7. ACKNOWLEDGEMENTS

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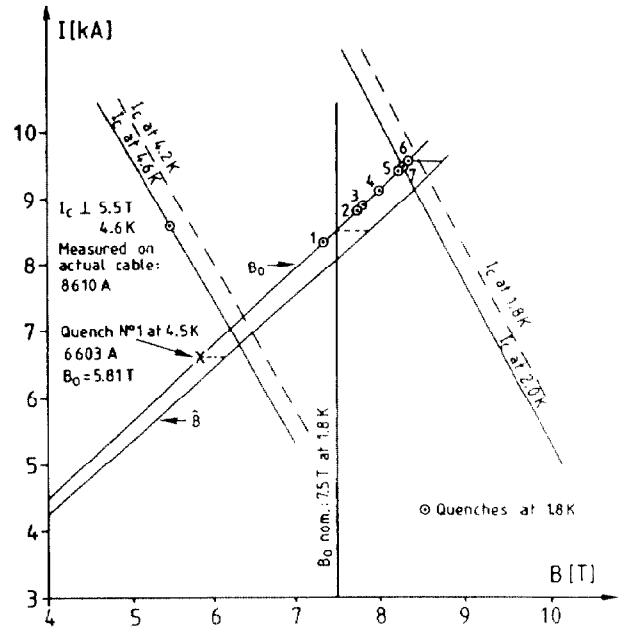


Fig. 4: TAP load line and critical currents with stacking factor 95%.

Table 2
Sextupole component of TAP magnet in 10^{-4} of fundamental at $R = 1$ cm

Excitation current (A)	250	650	1000	3000	5000
Position along magnet axis					
0 (front)	2.56	0.64	1.52	1.88	1.80
1	5.29	2.62	1.28		1.37
2	5.40	2.39		1.59	
3	5.36	2.54	1.02		1.71
4 (middle)	5.56	2.38		1.36	1.51
5	4.54	2.03	1.12		1.56
6	5.52	3.10		0.73	1.37
7	5.21	2.53	1.34		1.70
8 (rear)	4.99	0.90		0.81	0.81

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