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MAGNET FOR THE CERN LHC PROJECT

D. Hagedorn, Ph. Lebrun, D. Leroy, R. Perin, J. Vlogaert,
A. McInturff (FERMILAB., Batavia, USA)

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DESIGN AND CONSTRUCTION OF A TWIN-APERTURE PROTOTYPE MAGNET FOR THE CERN LHC PROJECT

D. Hagedorn, Ph. Lebrun, D. Leroy, R. Perin, J. Vlogaert
European Organization for Nuclear Research (CERN),
CH-1211 Geneva 23 (Switzerland)
A. McInturff, FERMI National Accelerator Laboratory,
P.O. Box 500, Batavia IL 60510 (USA)

ABSTRACT

A twin-aperture, 10 m long, prototype magnet was designed by CERN and built by industry in order to gain experience in the construction of full-scale, twin-aperture, high-field magnets and with the superfluid helium operation of such magnets. In order to gain time and reduce the cost of development and tooling, the superconducting windings were chosen to be the same type and geometry as those of the dipoles of the HERA proton ring but operated at the lower temperature of 1.8 K.

The active part of the magnet consists of two dipole coils wound from a keystone NbTi cable, clamped with aluminium collars. The collar/coil assembly is surrounded by a split low carbon steel yoke enclosed by an aluminium alloy shrinking cylinder.

The cryostat consists of a stainless steel liquid helium container, a radiation screen at 4.5 K, a liquid nitrogen screen, and a steel vacuum vessel.

A central bore field of 7.5 tesla is predicted for an operational temperature of 1.8 K.

INTRODUCTION

CERN is studying the possibility of a Large Hadron Collider (LHC) [1] being installed in the LEP tunnel. A development programme [2,3] has therefore been started for the required high-field superconducting magnets which guide the two counter-rotating proton beams in the quasi-circular tunnel.

In parallel with the 1 m long model magnet programme, which produces both single and dual aperture dipoles (8 to 10 tesla field range), it was decided to design and order from industry a twin-aperture 9 m long prototype magnet. The primary objective of which 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.

In order to gain time and save in the tooling costs, superconducting coils of the same type and geometry as those of the DESY HERA proton ring dipoles were used. The geometry of yoke and shrinking cylinder is the same as in the twin-aperture 10 T dipole.

MAGNET AND CRYOSTAT ASSEMBLY

The main features of the TAP magnet and cryostat are shown in Figure 1 (transverse cross-section) and Figure 2 (longitudinal cross-section). The major parameters are given in Table 1.

ACTIVE PART

Fig 1 - Transverse cross-section

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

The excitation coils used in the TAP magnet are of the same type and geometry as those used in the dipoles of the DESY-HERA proton ring [4], but operated at 1.8 K. They are wound from a key-stoned Rutherford type cable with 24 strands, each coated with a 0.005 mm thick silver-tin layer [5]. The cable is insulated first by a layer of 12 mm wide 0.025 mm thick Kapton tape wrapped with a 60 % overlap and then a 9 mm wide 0.12 mm thick glass fiber tape impregnated with 21 % (weight) of "B" stage epoxy is wrapped over the first. The latter tape has 3 mm gaps between wraps to allow free helium passage between adjacent turns. The excitation coil of a beam channel is composed of two identical half coils, having each a two shell structure. The inner shell has 32 turns per coil half, the outer 20 turns. The current density is uniform in both shells. The approximation of the cosine θ current distribution by the angular length and radial thickness of the shells is further improved with the insertion of an insulated copper wedge in each quadrant and shell after the 4th turn.

Two excitation coils are clamped with pairs of 3 mm thick collars of

Fig2 - Longitudinal cross-section (Test lay-out).

1. Liquid helium vessel
2. Radiation screen
3. Liquid nitrogen screen
4. Vacuum vessel
5. Support post

TABLE 1

Main parameters of the TAP magnet and cryostat

Cable Parameters

Cable width	10.0 ± 0.03 mm
Thin edge thickness	1.28 ± 0.02 mm
Thick edge thickness	1.67 ± 0.02 mm
Twist pitch	75.0 to 95.0 ± 2.0 mm
Superconductor	NbTi alloy
Copper to superconductor volume ratio	1.8
Number of strands	24
Diameter of strand before cabling	0.84 ± 0.01 mm
Number of filaments per strand	1230
Diameter of the filaments	0.014 ± 0.002 mm
Filament twist pitch	25 ± 3 mm
Minimum critical current measured with a magnetic field perpendicular to the large surface of the cable at 5.5 T and 4.6 K ($\rho(\text{eff}) = 10^{-14} \Omega\text{-m}$)	8610 A
Residual resistivity ratio of copper at zero field	73
Current density in SC at 7.5 T central field and 1.8 K	1859 A/mm ²

Magnet Parameters

Expected central field at 1.8 K	7.5 T
Excitation current at 7.5 T	8625 A
Stored energy at 7.5 T	4.06 MJ
Maximum field in winding at 7.5 T central field	8.05 T
Coil inner diameter	75 mm
Distance between aperture axes	180 mm
Resultant magnetic forces per quadrant	
horizontal component (inner and outer layer)	1.78 MN/m
vertical component (inner layer)	0.51 MN/m
(outside layer)	0.49 MN/m
Longitudinal magnetic force (total at either extremity)	0.55 MN
Overall length of magnet	9.15 m
Outer diameter of magnet	580 mm

Cryostat Parameters

Overall length	10.1 m
External diameter	1.0 m
Cold mass (magnet and helium vessel)	15000 kg
Mass of vacuum vessel	5000 kg
Number of support posts	3
Spacing of support posts	3.16 m
Liquid helium capacity	260 l
Liquid nitrogen capacity	40 l
Nominal temperature levels	80 K, 5 K, 2 K

AlMg 4.5 Mn G35 material. A pair of collars consists of two different types of mating collars, the difference being that the central part of the first type has a protruding tongue that fits into a groove of the second. Pairs of collars are reversed with respect to their neighbours and locked with stainless steel rods in three horizontal axial holes. Stainless steel shims are in-

serted at the poles in order to obtain the required prestress on the coils. A short press of 0.5 m length that can generate a force of over 5 MN is used to compress the collars around the coils in 20 successive steps. The continuity of the collar/coil assembly is obtained by longitudinally screwing the rods together. The magnet yoke is of the split iron type [6] with an about 1 mm average

non-parallel vertical gap between halves at room temperature. The yoke halves are assembled from precision punched low carbon steel laminations, which have been phosphatised to prevent oxidation. The laminations are preassembled into 0.6 m long stacks. "B"stage epoxy impregnated 0.28 mm thick polyamide sheets are inserted between the laminations of the stack. The whole stack is then cured in an oven for two hours at 160°C. The purpose of the polyamide sheet is to obtain the same longitudinal shrinkage for the yoke as for the coil and to make it impervious to liquid helium. The pre-assembled and cured stacks are aligned and 9 m long stainless steel rods are then inserted. Tapered cutouts are planned for the outer surface of the stack into which are fitted wedge-shaped stainless steel keys. These maintain the relative position of adjacent blocks.

The 0.6 m long stacks are terminated by special laminations with machined grooves allowing radial flow of the helium. The first and last stacks of the half yokes contain a number of austenitic stainless steel laminations to avoid magnetic field enhancement in the coil ends.

Low friction sheets are inserted between the coil/collar assembly and the half yokes and between the half yokes and the outer shrinkage cylinder to allow for relative tangential and longitudinal movements of the structure during thermal cycling.

The outer aluminium cylinder is composed of two preformed half shells made from AlMg 4.5 Mn alloy. The half shells are obtained by the successive bending of a 20 mm thick rolled plate. They are tightly fitted to the yoke, collar and coil assemblies. They are then welded together on both sides simultaneously by automatic MIG welding machines.

The azimuthal stresses introduced by weld shrinkage contribute to the required prestress of the assembly. The aluminium cylinder is terminated by two welded aluminium rings which retain the two aluminium end plates. At room temperature the aluminium cylinder is slightly longer than the yoke to permit free longitudinal shrinkage during cool down.

The combination of aluminium collars and shrinking cylinder was chosen in order to obtain the required prestress on the coils and sufficient contact

pressure on the mating faces of the half yokes at operating temperature, while minimizing those stresses at room temperature.

THE CRYOSTAT

Although the main purpose of the cryostat is to contain the TAP magnet and permit its cryogenic operation and testing, it will also be used as a full-scale test bed to assess the preliminary design of future LHC cryostats. This will permit to study some of the mechanical and thermal problems associated with large-scale superfluid helium cryogenics, therefore establish an early technological reference (materials, components, manufacturing techniques, quality control) for the implementation of the industrial series production.

In order to be compatible with the magnet string configuration [1] and its associated cryogenic distribution scheme [7] in the LHC tunnel, the TAP cryostat has been designed for serial connection with similar units. As a consequence, its stand-alone operation requires the use of feed and end boxes to connect to the cryogenic test station.

The TAP magnet is contained in an integrally-welded austenitic stainless steel (X2 CrNi 19-11) helium vessel and operates in a static bath of "pressurized" 0.11 MPa (1.1 bar) superfluid helium at about 2 K. The magnet and helium vessel are cooled by longitudinal conduction in the static superfluid bath from a "cold source" (saturated superfluid helium) located in the test station. In order to safely sustain the pressure rise, due to the rapid energy release into the liquid helium from a resistive transition of the magnet, the design minimum pressure of the helium vessel was chosen to be 2 MPa (20 bar).

The magnet and helium vessel assembly rest inside the cylindrical vacuum vessel on three low-heat conduction support posts positioned longitudinally for equal loading. The vacuum vessel is made of construction steel (DIN 17102) for reasons of cost and magnetic shielding of stray flux. It has austenitic stainless steel flanges and connecting sleeve equipped with large diameter bellows. The vessel also serves as the vacuum insulation jacket for the

four cryogenic distribution lines which, in the LHC, will provide the refrigeration power at 2 K and 5 K along the magnet string [7]. In the TAP cryostat, the 5 K lines provide an intermediate temperature shield to intercept heat leaks in steady state operation.

The magnet and cryogenic lines are surrounded by a low-emissivity screen made of aluminium alloy (Peraluman 250) and bridged thermally to the 5 K pipes. This geometry minimizes the residual heat leak into the 2 K zone. A second almost concentric screen is cooled by liquid nitrogen and covered with multi-layer reflective insulation. This screen is made of industrial grade aluminium and is also bridged thermally to the support posts. It intercepts the largest fraction of the heat leak at a temperature level of 80 K. The designs of both screens ensure quasi-isothermal conditions in a selfsupporting mechanical structure. These screens must resist deformation when submitted to electromagnetic forces generated by induced eddy currents during a magnet quench.

The support posts subjected to a compressive load consist of epoxy-glass-fiber tubular columns with metallic base, top, and two intercept plates. The intercept plates are connected to the two thermal screens. Mechanical and thermal performance of the support posts require efficient and reliable joining techniques between the non-metallic columns and the metallic plates. This is achieved by epoxy glueing and proper choice of materials ensuring compatible shrinkage during cool down. The support posts fixed to the cold mass can allow for differential contractions between helium vessel, screens, and vacuum vessel by means of sliding supports and rollers, respectively. The roller-equipped base-plates also permit insertion of the cold assembly into the vessel during the assembly of the cryostat. In operation, the central support post is the fixed point between the cold mass and the external vessel. Inertial forces resulting from accelerations encountered during transport are contained by demountable shipping restraints.

INSTRUMENTATION AND PROTECTION

The magnet and cryostat assembly is

extensively instrumented. This is in order to assess the device's performance and to facilitate its operation. The instrumentation monitors voltages, temperatures, flow rates, pressures, stresses, and displacements. Thermal measurements of interest include cool down and steady state heat loads, heat intercept efficiencies, etc. The ability to monitor rapid pressure changes as a function of position along the length can help in the location of quenches. Stress measurements of interest include those of the collars, shrinking cylinder, helium vessel walls, and the helium vessel support posts. The displacements of concern are closure of the iron yoke and the cross checking of stresses in support posts and differential shrinkage coefficients of the materials used in the design.

The TAP magnet presents a particularly challenging problem in coil protection. The original HERA design parameters were 5 kA at 4.6 K. The lower temperature operation of the TAP magnet and the subsequent increase of operational current, magnetic field and stored energy necessitated a redesign of the protection heater contained in the insulation to ground. The heater must be able to warm up a sufficiently large coil volume rapidly enough above transition temperature to avoid a catastrophic overheating of the quenched volume. There are also other constraints, i.e. acceptable voltage and temperature distributions after and during a quench. The largest convenient heater that can be placed in the ground insulation is a factor of two larger than the standard HERA heater. The number of turns however that are heated by it are more than doubled with respect to the HERA dipoles due to a wedge in the outer winding. The maximum computed quenching coil temperature at the expected central field (7.5 T, 8625 A, 1.8 K), if the external current opening switch fails, is 255 K. If the switch works, it will be 203 K. If the heater fails, the calculated temperatures are twice as large and the possibility of damage or destruction of the coil is present. The maximum coil temperatures calculated at the intersection of the magnet load line and the best short sample current curve are 310 K when the switch fails and 240 K when the switch works.

These calculated temperatures indi-

cate that it is advisable to ascertain the performance characteristics of the double heater first at a lower magnet current (3000 to 5000 A) where the external switch can protect the quenching coil from overheating. The procedure is to initiate a quench using the protection heaters and delay the external switch to a later but still conservatively safe time (less than $12 \times 10^6 \text{ A}^2 \text{ s}$). This approach enables the determination of the energy input necessary to the protection heater to conservatively insure its timely operation later on at higher magnet currents where the external switch alone cannot protect the windings in all circumstances.

STATE

Following competitive tendering, CERN has awarded ABB MANNHEIM (Germany) the contract for construction of the active part and F.B.M.-HUDSON Italiana

of Milano (Italy) with the manufacturing and assembly of the cryostat. The superconducting cables were supplied by ABB, Switzerland.

The active part is presently being assembled and tested at room temperature and at liquid nitrogen temperature at ABB MANNHEIM. The active part will then be transported to F.B.M., where it will be assembled in the cryostat. The completed cryostat and magnet assembly will then be transported to CERN SACLAY (France) for cryogenic performance measurements and tests.

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