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ABSTRACT

Different support posts for the LHC prototype superconducting magnets have been designed and manufactured. They have been evaluated both mechanically and thermally. The posts are made of a tubular section in composite materials, i.e. glass- or carbon-fibre and epoxy resin, with glued metallic heat intercepts and connections. Mechanical tests have been carried out with both radial and axial loads, before and after cooldown to working temperature. The design considerations and future developments concerning dimensions and other materials are also discussed in this paper. Thermal performance has been evaluated at 1.8 K, 5 K and 80 K in a precision heat inleak measuring bench. The measurements have been carried out using calibrated thermal conductances ("heatmeters") and boil-off methods. The measured performances of the posts have been compared with analytical predictions.

INTRODUCTION

The proton beams of the LHC will be guided and focussed respectively by superconducting dipole and quadrupole magnets. These magnets must be operated at a temperature below 2 K and thus must have a closely controlled heat budget. In particular, the supporting system, linking the cold mass (2 K) to the external envelope of the cryostat (300 K) must give a minimum of heat inleaks. At the same time, it must be able to hold the various axial and radial loads occurring during the assembly and the running of the LHC machine. Following good experience with a prototype design¹, it was decided to support the prototype magnets inside their cryostats with two cylindrical support posts.

DESIGN CONSIDERATIONS

Technical Requirements

Each 18 t magnet is supported by two posts. Each post must withstand a permanent axial load of 90 kN. In the case of the quadrupole, the fixed post must withstand an additional radial load of 50 kN induced by the vacuum barrier². The latter load can occur only at room temperature during assembly of the LHC; it is generated by the pressure difference of 1 bar between two adjacent halfcells. This load is applied only on the fixed post, the second post being mobile and sliding on the warm vacuum vessel when the magnet expands or shrinks longitudinally. The budgeted heat inleaks from the posts to the 1.8 K, 5 K and 80 K temperature levels are 0.1 W, 1 W and 10 W respectively.

Design

The post is made of a cylinder in glass-fiber epoxy composite, 6 mm thick, with glued flanges. The lower and upper flanges are made of stainless steel, the intermediate flanges of aluminium alloy. The latter are supporting the thermal shields of the cryostat and are thermally connected to the 80 K and 4 K piping system. The inner cylindrical flanges are supporting thermal insulation inside the post column.

Construction

Based on a CERN functional specification³, prototype posts have been made by two manufacturers (Courtaulds and Stesalit) using the filament-winding process for the tube. The outer diameter of the mandrel is 228 mm, so no machining occurs after winding on this side. The specific gravity of the resin is around $1.2 \times 10^3 \text{ kg/m}^3$ and that of the fiber is $2.55 \times 10^3 \text{ kg/m}^3$.

For post No. 1 the winding provides 8 layers and the outer diameter is machined afterwards, leaving approximately 6 layers for the finished product; the winding angles are $\pm 15^\circ$ and $\pm 88^\circ$, to withstand compression and flexion. The amount of fiber in the composite is 65% in volume, and the polymerisation temperature is 120°C. The inner flanges are made of glass-fiber plates glued to the cylinder. The top and bottom stainless steel flanges are attached with an epoxy glue able to withstand a maximum shear load of 35 MPa at room temperature. The elastic modulus of each component (as quoted from the manufacturer) is:

- 73 GPa for the glass fiber,
- 2.6 GPa for the epoxy resin,
- 32 GPa for the composite (axial)

For post No. 2 (Figure 1), the winding angles are $\pm 54^\circ$ and $\pm 30^\circ$, with 8 layers after winding, and 6 remaining after machining. The amount of fiber in the composite is 60% in volume and the polymerisation temperature is 120°C. The inner flanges are made of stainless steel and glued to the cylinder. The top and bottom flanges are attached with glue (Araldite 136, polymerizing at room temperature) able to withstand 30 MPa in shear. The elastic modulus quoted by the manufacturer is 26 GPa for the composite.

Figure 1. Support post No. 2 made of a cylindrical fiberglass compound column, with glued metallic flanges.

MECHANICAL EVALUATION

Axial Load at Room Temperature

The axial compressive load has been applied to post No. 1 by means of a conventional press going from 0 to 100 kN. At the nominal load of 100 kN, the stress in the composite cylinder was 23 MPa and the total deflexion of the post was 0.20 mm. According to strain gauges, the deflexion of the composite cylinder alone was 0.15 mm, the difference could come from elasticities in the glued joint and the end flanges. The measured modulus in compression was found to be equal to 37 GPa. A test in traction has also been made, to check the resistance of the glued joint and to measure the elastic modulus in traction. The axial traction load in the test went up to 50 kN, and the modulus was found to be 40 GPa, in good agreement with the compression test.

Radial Load at Room Temperature

The lower flange of the post has been fixed to the base of a rigid metallic column. With a hydraulic jack, a load has been applied between the upper flange and the top of the column, through a fiberglass composite bar equipped with calibrated strain gauges (Figure 2). The radial load could go from 0 to 65 kN, i.e. 0 to 130% of the service conditions.

Four posts (two from each firm) have been tested in this condition, and only one failed at 65 kN. The indication on the strain gauges fixed to the cylinder of the post gave a stress of 32 MPa. The failure occurred at the glued joint, at the bottom of the post. This indicates that the weak point of the design is the glued junction. However we could conclude that the design meets the specification.

Figure 2. Mechanical test apparatus : a hydraulic jack pushes radially on the top of the foot, giving a flexion torque on the composite cylinder.

Radial Load after Liquid Nitrogen Cooldown

Post No. 2 has been dipped in liquid nitrogen overnight and tested again a few days later. It withstood the radial load of 65 kN and seemed to be more elastic afterwards.

Radial load after Liquid Helium Cooldown

Post No. 1 has been tested thermally, and put a few days later under the press. During the thermal test, the upper part of the post was cooled down to 1.8 K, and it was interesting to study its mechanical behaviour afterwards. The post after warmup withstood the radial load up to 65 kN and the stress/strain curve was linear.

THERMAL EVALUATION

Both prototype posts have been mounted on the precision thermal test bench⁴ as shown in Figure 3. In order to simulate LHC conditions, the post was thermally bridged, via de-mountable copper plates, to each of the cryogenic reservoirs filled with liquid nitrogen, normal liquid helium and saturated helium II. The base of the post was maintained at a temperature of 293 K using a controlled electrical heater.

To thermally evaluate the posts both heatmeter and boil-off measurements were used^{5,6}. The main instruments used for that purpose were the heatmeters. Six heatmeters were currently used in the cryostat, two at each temperature level (80 K, 5 K and 1.8 K). The amounts of liquid nitrogen and helium boiled off from the cryostat were also used as cross-checks of the heatmeter results at 80 K and 5 K.

All temperature measurements on the post were made using platinum and carbon resistors. Temperature sensors were placed both inside and outside the post at positions shown in Figure 4. On the 1.8 K and 5 K temperature levels, all resistors were Allen-Bradley carbon 100 Ω , and at 80 K Pt1000 Ω and Pt100 Ω resistors were used. A current source has been used to supply precise currents of 10 μA to the carbon resistors and 100 μA to the platinum resistors. The voltages across the resistors were read by a digital multimeter.

It can be seen in Table 1 that the measured values agreed with the calculated heat loads. As the temperatures were different on the inside and on the outside of the post, the calculated heat loads were given for both temperatures⁷.

The thermal behaviour of post No.1 and post No. 2 was very similar, but the temperatures and heat loads on post No. 1 were slightly higher. In addition to the Courtaulds and Stesalit posts, CERN has built a prototype post with a short available cylinder of carbon fiber composite (thickness 3 mm), working at the 2 K and 80 K levels only. Carbon fiber was tested because recent measurements⁸ have shown the extremely low thermal conductivity compared to glass fiber, under 40 K. The small heat load for the carbon fiber-epoxy (~50% less than Courtaulds or post No. 2 at 1.8 K) demonstrates that if this material can be incorporated on the upper part of the post, the thermal performance can be significantly improved.

Figure 3. Experimental Set-up of the Heat Inleak Measuring Bench.

Figure 4. Positions of the thermal sensors (T1-T6).

Table 1. Summary of Results of Post Tests

Prototype Post	Temperature (K)	Measured heat load (W)		
		Heatmeter	Boil-off	Calculated ¹ heat load (W)
	80 K temperature level (T4, T5)			
Post No. 1	89.6-96.0	7.3	7.8	5.6-5.3
Post No. 2	88.3-94.9	6.7	6.5	5.6-5.3
CARBON EPOXY	78.5-80.5	-	-	-
	5 K temperature level (T2, T3)			
Post No. 1	6.8-10.3	1.0	1.2	1.2-1.0
Post No. 2	6.4-9.9	1.0	1.1	1.2-1.0
CARBON EPOXY	5.5-8.5	0.49	0.42	0.66-0.42
	1.8 K temperature level (T1)			
Post No. 1	2.41	0.101		0.15-0.082
Post No. 2	2.17	0.075		0.15-0.079
CARBON EPOXY	1.75	0.019		0.042-0.023 ²

INTERNAL THERMAL RADIATION

The support post is subject to internal radiation and it can be seen from Table 1 that the temperatures are significantly higher in the center of the post than on the outside.

¹ The heat loads are calculated for both temperatures in column 1.

² Extrapolated values.

Calculations using these temperatures show that thermal radiation will significantly affect the heat load only at the 80 K level.

CONCLUSION AND FUTURE DEVELOPMENT

After these mechanical and thermal tests, one can say that the prototype post completely fulfil the requirements of the technical specification³. However, it would be interesting to decrease the thermal budget and the manufacturing cost while keeping the mechanical performance to an acceptable level. In the near future, we will have to build an apparatus simulating the actual working conditions of the post: 2 posts rigidly connected via a heavy cold mass, one post being fixed and one sliding, under vacuum, with a radial load going up to 65 kN.

In parallel a complete study will be made on a compound post, made of carbon composite on the top and glassfiber on the bottom to benefit from the lower thermal conductivity in the range 2 to 40 K of carbon fiber.

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