

Design and Test of the Titanium Alloy Tie Rods for the CMS Coil Suspension System

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Abstract-- The Compact Muon Solenoid (CMS) is one of the general-purpose detectors to be provided for the LHC project at CERN. The design field of the CMS superconducting magnet is 4 T, the magnetic length is 12.5 m and the free bore is 6 m.

Thirty titanium alloy tie rods are used to support the 225 tonne weight of the cold mass inside its vacuum vessel and react against the forces generated by potential magnetic misalignment. This paper describes the suspension system and its mechanical analysis in different loading cases corresponding to operating conditions of the magnet. Two grades of titanium alloy are foreseen (Ti 6 Al 4 V ELI and Ti 5 Al 2.5 Sn ELI). Based on mechanical tests at room temperature and at 4.2 K, the safety criteria are analyzed for both materials. Before final installation, all tie rods will be tested at 110% of the maximum load with one end at room temperature and the other one at cryogenic temperature. The test system and the test results of the prototype tie rods are also presented.

Index Terms-- Superconducting coil, Suspension system, Titanium Alloy.

I. INTRODUCTION

The CMS magnet is a superconducting solenoid enclosed in a steel return yoke. A detailed description and the status of the CMS solenoid magnet are presented elsewhere [1]-[2]. Tie rods are used to sustain the cold mass and react against the magnetic forces. The tie rods, which are attached on one side to the vacuum tank and on the other side to the cold mass, are subjected to a thermal gradient from 4.5 K to room temperature. Titanium alloy has been chosen as tie rod material for its low thermal conductivity and high mechanical strength. Its thermal contraction and Young modulus limit also the induced stress during cool-down. This document presents the tie rod mechanical design and safety margins with respect to the qualified material properties. As titanium alloys present potential fragile behavior at cryogenic temperature, each tie rod will be tested in its cryogenic conditions before installation on the magnet. A new test system will be used for this purpose and to check the soundness of the tie rod instrumentation.

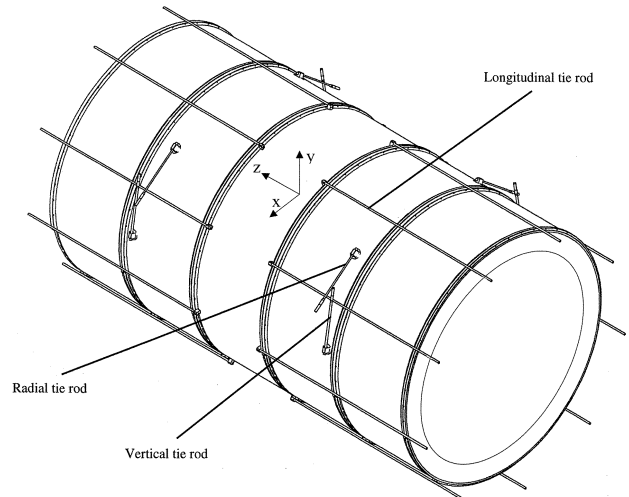


Fig. 1: system Suspension system general overview

II. SUSPENSION SYSTEM DESCRIPTION

A. Suspension principle and dimensions

The suspension system consists of three sets of rods made of titanium alloy (see Fig. 1).

Four vertical tie rods and eight radial tie rods at 120° and 240° contain the coil weight and the radial forces. The longitudinal forces are taken through 2x9 longitudinal tie rods.

The part of the tie rods which is screwed inside the cold mass is called foot and is cooled at 4.5 K. The part of the tie rods which is connected to the vacuum tank is called head and works at room temperature. The connection in-between the vertical or radial tie rod head and the vacuum tank is made through one spherical joint. The main dimensions of the tie rods have been optimized (see §IV) and are given in the TABLE I. One vertical tie rod is presented on Fig. 2.

TABLE I
TIE ROD MAIN DIMENSIONS

Tie rod type	Main diameter (mm)	Length (mm)	Thread
Vertical	60	1871	M72
Radial	35	1853	M42
Longitudinal	45	5500	M64

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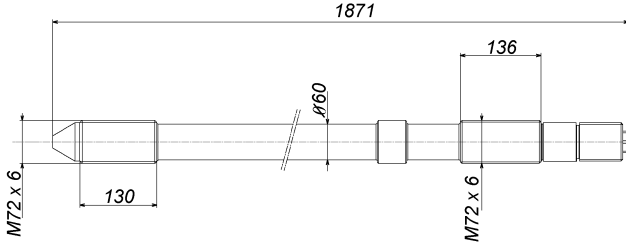


Fig. 2: Vertical tie rod

B. Loading

The CMS coil suspension system has to withstand:

- the 225-tonne weight of the cold mass;
- the magnetic forces applied on the cold mass due to a potential misalignment of the coil with respect to the return yoke [3] (see TABLE II);
- the forces due to a potential earthquake. (a 0.15 g acceleration, applied to the cold mass, in the x, y and z direction is used as safety loading.).

TABLE II
FORCES DUE TO A MAGNETIC MISALIGNMENT

Solenoid Misalignment	Load due to the misalignment
Longitudinal (z direction)	Longitudinal force : 850 kN
Radial (direction perpendicular to z)	Radial force : 80 kN
Tilt (rotation around an axis perpendicular to z)	Momentum : 1650 kN.m

We assume that, after alignment, the solenoid axis will lie within a cylinder of 10 mm radius and 12.5 m length, the axis of which is the return yoke magnetic axis. The forces (or momentum) act in the direction of increasing the coil misalignment.

III. MATERIAL

In order to choose the proper material for the suspension system, a qualification campaign has been performed on bars of diameter similar to the tie rod one. The characterization is detailed in [4]. Two Extra Low Interstitial titanium alloys have been tested:

- Ti 5Al 2.5Sn ELI (reference standard: AMS 4924D)
- Ti 6Al 4V ELI (reference standard: ASTM B 381-97)

The mechanical test results are reported in the TABLE III. As expected, Ti 6Al 4V ELI has higher mechanical strength than Ti 5Al 2.5Sn ELI. Elongation and notch sensitivity are similar for both material at room temperature but not at 4.2 K. At this cryogenic temperature, the notch ratio is below one for Ti 6Al 4V ELI whereas superior to one for Ti 5Al 2.5Sn ELI. Fracture toughness tests confirm the different behavior of the two materials at cryogenic temperature.

TABLE III
TITANIUM ALLOY MECHANICAL PROPERTIES

	Rp _{0.2} (MPa)	Rm (MPa)	A (%)	NTS/TS	K _{IC} (MPa.m ^{1/2})
Material properties at room temperature					
Ti 5Al 2.5Sn ELI	790	875	16.2	1.47	
Ti 6Al 4V ELI	881	957	15.6	1.49	
Material properties at 4.2 K					
Ti 5Al 2.5Sn ELI	1348	1475	9.9	1.12	78
Ti 6Al 4V ELI	1650	1698	4.8	0.94	61

As one of the threads of the tie rods will work at cryogenic temperature, no notch sensitivity can be allowable for the material at 4.2 K. Ti 5Al 2.5Sn ELI is then technically preferred to Ti 6Al 4V ELI even if Ti 6Al 4V ELI tensile properties are better.

IV. MECHANICAL DESIGN

A. General

Four different coil working cases have been studied:

- *coil at room temperature*

In order to have a rigid suspension system, to be sure of the solenoid position after warning-up and to insure that the tie rods are in tension in any case, the suspension system is pre-stressed. After iteration, the pre-stress value has been fixed at 20 MPa for the longitudinal and radial tie rods.

- *coil at 4.5 K, non energized*

The cold mass is at 4.5 K and the tie rods are subjected to a thermal gradient from 4.5 K to room temperature.

- *coil energized, aligned with respect to the barrel yoke*

During energization and due to the magnetic field, the cold mass is bent out of barrel shape. It shrinks of 10 mm in length and expands of 4.1 mm in radius in the tie rod plane.

- *coil misaligned (see TABLE II)*

The tilt misalignment around x-axis is the worst case for the vertical tie rods whereas it is the longitudinal misalignment case for the longitudinal tie rods.

The cold mass is considered as uniformly made of aluminum alloy. The Young modulus and Poisson ratio are considered constant whatever the temperature is (see Table IV).

TABLE IV
MATERIAL PROPERTIES

	Young modulus (GPa)	Poisson ratio	Thermal contraction (K ⁻¹)
Titanium alloy	133	0.33	6x10 ⁻⁶
Aluminium alloy	77	0.3	1.47x10 ⁻⁵

Thermal contraction is the mean integrated value from 4K to 293 K

B. Vertical and radial tie rods

The extensive study of the vertical and radial tie rods would need a coupled magnetic, thermal and mechanical computation. Considering the respective size of the tie rods and of the cold mass, it would lead to a large model difficult to optimize for the 3 types of computations. The aim of this study is to get engineering stress values for the tie rods. It has then been decided to use a partial model. A 3D elastic study has been performed by Finite Element Analysis (FEA) with Cosmosworks V6 software. A 500 mm wide slice of solenoid containing 2 vertical and 4 radial tie rods has been modelled. This model is fully representative of the cold mass and tie rod behaviour in sections perpendicular to the z-axis. To simulate the thermal contractions in the radial direction, a previously

calculated temperature field is applied to the model. For the longitudinal thermal contraction, the coil slice is translated in the longitudinal direction. Adjusting the thermal contraction coefficient simulates the coil deformations under field. The torque due the tilt misalignment is applied as one resultant force on the cold mass slice. The model contains 15613 tetrahedral solid elements (4 corner nodes, 6 mid-side nodes) and 29957 nodes (see Fig. 3).

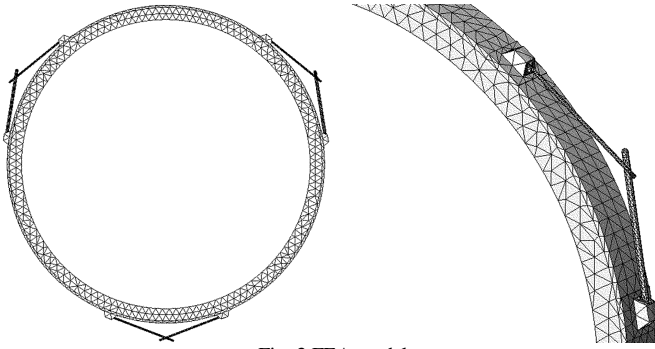


Fig. 3 FEA model

C. Longitudinal tie rods

Considering the length (5500 mm) over diameter (45 mm) ratio, we assume that no meaningful bending occurs on the longitudinal tie rods. The stresses in the longitudinal tie rods have then been calculated with analytic formulae. Pre-stress, thermal and magnetic contractions have been taken into account.

D. Results

The results of these studies are given in the TABLE V. The radial and vertical tie rods are fixed on the cold mass and can rotate with respect to the vacuum tank. Bending stress is then maximal on the tie rod foot. The maximum Von Mises stress occurs on the foot of the vertical tie rod and is equal to 425 MPa. The maximum stress on the head of the tie rods is 335 MPa and occurs also on the vertical tie rods.

TABLE V
MAXIMUM VON MISES STRESS IN THE TIE RODS (MPa)

Type of tie rod		Solenoid at 293K	Solenoid at 4.5 K	Solenoid energized	Solenoid misaligned
Vertical	Head	239	292	296	335
	Foot	254	369	382	425
Radial	Head	64	193	213	293
	Foot	65	229	265	347
Longitudinal		32	189	280	310

E. Safety margin

Safety margins with respect to the yield and rupture strength are presented in TABLE VI. The safety margin is defined as material strength / maximum stress. ASM 4924D requires $R_{p0.2} > 620$ MPa and $R_m > 690$ MPa at room temperature. The maximum stress on the head of the tie rod is compared to the room temperature properties, whereas the maximum stress on the foot of the tie rod is compared to the

material properties at 4.2 K.

The increase of mechanical properties at cryogenic temperature gives a larger margin on the foot of the tie rods with respect to the head even if the stress is higher.

These safety margins are based on a ductile behavior of the material. To prevent any fragile rupture on the final tie rods, each one will be tested in its cryogenic conditions.

TABLE VI
SAFETY MARGIN

	Margin with respect to $R_{p0.2}$		Margin with respect to R_m	
	ASM 4924 D	Measured value	ASM 4924 D	Measured value
Head of the tie rod	1.9	2.3	2.1	2.6
Foot of the tie rod		3.2		3.5

Measured mechanical properties are given in TABLE III. Properties of Ti 5Al 2.5Sn ELI are taken as reference.

V. FULL SCALE TESTS IN CRYOGENIC CONDITIONS

A. Test system description

A special test system has been designed and manufactured to pull every tie rod at 110% of its maximum working load. During the test, the foot of the tie rod is cooled at a temperature below 20 K and the head of the tie rod is at room temperature. This test system is housed in an 8 m deep cryostat (see Fig. 4a). Three radial or vertical tie rods and three longitudinal tie rods can be cooled down at the same time. The tie rods are inserted in thick tubes (see Fig. 4b). The foot of the tie rod is attached to the cooled plate. The head of the tie rod is pulled with the help of a jack, which seats on the cryostat upper plate. The tie rods are tested one by one at a maximum of 1000 kN for the vertical tie rods, 250 kN for the radial tie rods and 540 kN for the longitudinal tie rods. The pulling force is measured with one FGP instrumentation force cell.

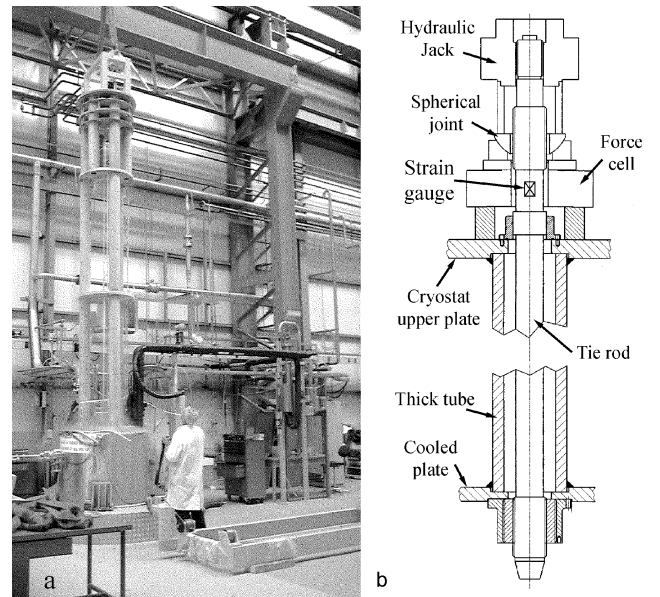


Fig. 4: Test system

a- Being removed from the cryostat

b- Local cross section

B. Tie rod instrumentation

The tie rod stresses are function of the coil alignment with respect to the return yoke (§II.B). During the magnet test, the cold mass will be re-aligned, if necessary, as function of the tie rod measured stresses.

Radial and vertical tie rods

The radial and vertical tie rods are loaded in tension and flexion (§IV.D). To measure the tension and flexion strain, 3 strain gauges are placed on the tie rods at 0° ($\mathbf{e1}$), 90° ($\mathbf{e2}$) and 180° ($\mathbf{e3}$) (see Fig. 5). A fourth one is placed in a perpendicular direction to compensate the potential thermal and magnetic measurement disturbances.

ϵ and ϵ_b are respectively the tension strain and the bending strain. q is the angle of the bending direction with respect to $\mathbf{e1}$. One can write:

$$\left. \begin{aligned} \mathbf{e1} &= \epsilon_t - \epsilon_b \cdot \cos q \\ \mathbf{e2} &= \epsilon_t - \epsilon_b \cdot \sin q \\ \mathbf{e3} &= \epsilon_t + \epsilon_b \cdot \cos q \end{aligned} \right\} (1)$$

$$(1) \Rightarrow \begin{cases} \epsilon_t = \frac{\mathbf{e1} + \mathbf{e3}}{2} \\ \epsilon_b = \frac{1}{\sqrt{2}} \cdot \left[\mathbf{e1}^2 + 2 \cdot \mathbf{e2} \cdot (\mathbf{e2} - \mathbf{e1} - \mathbf{e3}) + \mathbf{e3}^2 \right]^{\frac{1}{2}} \end{cases} (2)$$

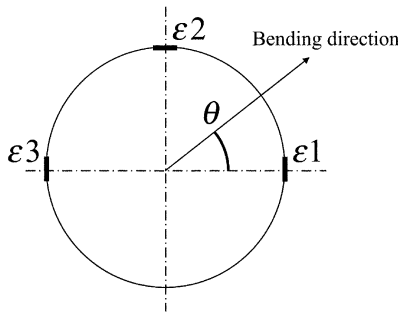


Fig. 5: Tie rod cross section and strain gauges

Longitudinal tie rods

The bending stress being negligible (§IV.C), only one strain gauge and its compensation are placed on the longitudinal tie rods.

C. Test results

One vertical and 2 radial prototype tie rods have been tested with the foot cooled at 40 K. The tie rods have been pulled at 850 kN for the vertical one and 250 kN for the radial one. No damages have been observed.

During the test, force cell signal, $\mathbf{e1}$, $\mathbf{e2}$ and $\mathbf{e3}$ are recorded. ϵ is calculated using (2). We can also define $Ft = A \cdot E \cdot \epsilon$. A is the cross section and E the Young

modulus of the tie rod. On Fig.6, Ft is plotted versus the force measured by the force cell. These 2 independent measurements are in good agreement (6%).

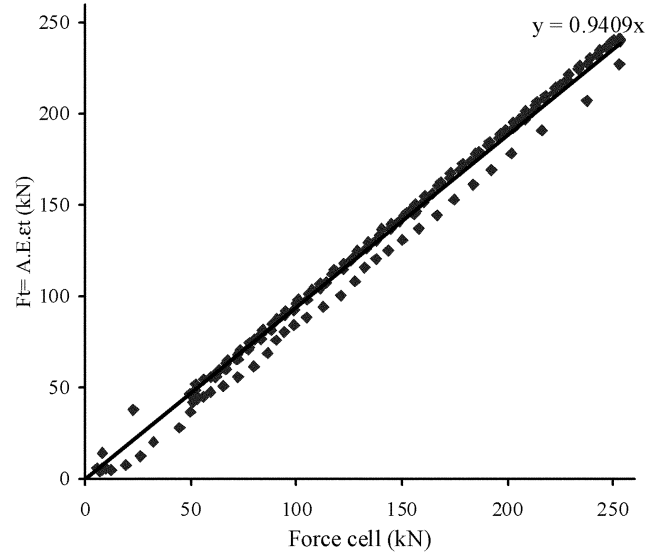


Fig. 6: Force measured by the strain gauges vs force measured by the cell

VI. CONCLUSION

The mechanical design shows significant safety margins with respect to the Ti 5Al 2.5Sn ELI material properties. To prevent any fragile rupture, each tie rod will be tested at 110% of its maximum load in its cryogenic conditions. The prototype tie rods have been successfully tested with the new test system. The tie rod instrumentation is able to measure bending and tension strains, which are useful information during the magnet tests.

VII. ACKNOWLEDGMENT

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