# Electrical Joints in the CMS Superconducting Magnet

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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. The CMS coil consists of five independent modules each containing four winding layers. Each winding layer is composed of a single length of aluminum stabilized and aluminum alloy reinforced conductor. Each of the four conductor lengths within a module will be electrically joined after winding is completed, and each of the five modules will be connected to the magnet bus bars during module assembly. Due to the large dimensions of the conductor and to the high current it carries, the conductor joints are sources of substantial and nontrivial joule heating during nonsteady state operation of the magnet. In addition to steady-state conditions, three transient conditions have been analyzed. The first is related to the current diffusion during a magnet transient that results in a time dependent joint resistance. The second is the current induced in a joint during a transient. The third is connected to the joint protection in case of quench. A complete analysis of the joint behavior is reported.

Index Terms—Joints, superconducting magnets.

## I. INTRODUCTION

T HE LARGE Hadron Collider, LHC, is the next important project of CERN, the European Laboratory for Particle Physics. The Compact Muon Solenoid (CMS) detector [1] is based on a solenoidal superconducting magnet. The design central field of the CMS magnet is 4 T, with a magnetic length of 12.5 m and a free bore of 6 m.

The technology of high purity aluminum stabilized superconductors is applied for the design and manufacture of the magnet. The dimensions and the proportions of the conductor sub-components were determined taking into account the requested electrical characteristics of the coil, the thermal properties of the coil, the quench protection and stability, and the mechanical strength. The conductor consists of a Rutherford type cable embedded in a high purity aluminum matrix using an extrusion process, joined by dedicated continuous Electron Beam Welding technology to two aluminum alloy profiles acting as mechanical reinforcements.

The design and manufacturing steps of these magnets require electrical joints to be performed, as the magnets will be manufactured from several lengths of co-extruded conductor, which will be wound into 5 distinctive modules, requiring 21 joints to

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Fig. 1. Joint configurations.

be performed. The magnets are operated at a nominal current of 20 kA at liquid helium temperature, so the electrical resistance of the joints shall be kept low enough in order not to alter the enthalpy margin and endanger the magnet stability. Furthermore, the joining techniques must not degrade the superconducting properties of the Rutherford cable.

In order to achieve joint electrical resistance lower than  $10^{-9} \Omega$ , Metal Inert Gas (MIG) welding are performed. MIG welding process was preferred as it has a better versatility of application compared to other welding techniques. Finite element modelization showed that the electrical resistance due to the pure aluminum stabilizer is less than 10% of the total resistance, hence nonfull penetrating processes such MIG is sufficient to get the requested resistance. Also this welding process induces a lower heat input in the base material compared to conventional arc welding. The use of low electrical resistance with appropriate weld geometry.

The retained geometry of the joints is the "praying hands" configuration as shown on Fig. 1. This configuration is preferred to the traditional overlap, as it gives the possibility to have long conductor lengths on the CMS magnet external cylinder. The reinforcement of the conductors must be machined out in the joint area as the weld is performed to join the pure aluminum stabilizing matrix of both conductors. The conductor lengths are welded together side by side on a length of about 2 m. Sufficient space is available on the external cylinder to have longer welds or to cut one extremity of a joint if a weld was unsatisfactory.

The samples have been welded at CERN Central Workshop using the pulsed MIG facilities, with the arc in vertical position. The samples were in horizontal position during welding. The samples are welded on both sides as shown on Fig. 2. The maximum temperature measured in the pure aluminum stabilizer reached 201 °C at 0.75 mm distance from the cable. A chamfer 3.5 mm deep at an angle of 45° is machined. The filler material is aluminum 1050 (99.5% content of aluminum).



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Fig. 2. Cross section of a joint.



Fig. 3. Schematization of the "praying hands" model.

# II. JOINT THEORETICAL MODEL

When joining the CMS aluminum stabilized conductor, two configurations are possible, called "praying hands" (see Fig. 1) and "shaking hands." Generally, the former is used to join the conductor outside the winding, the latter is foreseen, if necessary, for internal connections. In steady state, being the cable in the superconducting state, the two configurations are equivalent, but during a transient their behavior is different: due to the conductor inductance, the current is initially distributed inhomogeneously and takes a finite time to diffuse through the joint, so that the voltage drop reaches an initial value higher than the steady state one. The diffusion time is a function of the conductor inductance, of the joint resistance and of the joint layout, basically related to the mutual inductance. The behavior of both the joint configurations, in steady state and under time-varying current, is extensively analyzed in [2]: they are described by



Fig. 4. Joint input current time dependence.

simple models, as shown in Fig. 3 for the "praying hands" joint, which allow solving analytically the diffusion problem. If L [m] is the joint length,  $\tau$  [s] the decay time, r [ $\Omega$ m] the specific joint resistance,  $\ell$  and m [H/m] respectively the self and mutual inductance per unit length, the basic differential equation for the "praying hands" joint is:

$$\frac{\partial^2 I(x,t)}{\partial x^2} = \frac{\tau}{L^2} \frac{\partial I(x,t)}{\partial t}, \quad 0 \le x \le L$$
(1)

where

$$\frac{1}{\tau} = \frac{r/L}{2(\ell - m) \cdot L}$$

The boundary conditions are: I(0, t) = I(t), I(L, t) = 0, I(x, 0) = 0.

Following the procedures described in [2], it can be demonstrated that the voltage drop across a "praying hands" joint, if the joint current is the one described in Fig. 4, is given by (2) as shown at the bottom of the page. r/L represents the steady state resistance and  $\tau$  can be used as a fit parameter to compare the analytical solution with measurements. Equation (2) can be easily expanded for subsequent current ramp and flat.

It is worth noting that the joint resistance can not be simply obtained by V(t) due to the inhomogeneous distribution of the current inside the joint during a transient. This can be done only

$$V(t) = \begin{cases} \frac{r}{L} \left[ k_1 t + 2k_1 \tau \sum_{n=1}^{\infty} \frac{1}{(n\pi)^2} \left( 1 - e^{-(n\pi)^2 (t/\tau)} \right) \right] & 0 \le t \le t_1 \\ \frac{r}{L} \left[ k_1 t_1 + 2k_1 \tau \sum_{n=1}^{\infty} \frac{1}{(n\pi)^2} e^{-(n\pi)^2 (t-t_1)/\tau} \left( 1 - e^{-(n\pi)^2 (t_1/\tau)} \right) \right] & t_1 \le t \le t_2 \\ \frac{r}{L} \left[ k_1 t_1 + k_2 (t - t_2) + 2\tau \sum_{n=1}^{\infty} \frac{1}{(n\pi)^2} \left( k_1 e^{-(n\pi)^2 (t-t_1)/\tau} \left( 1 - e^{-(n\pi)^2 (t_1/\tau)} \right) \right) + k_2 \left( 1 - e^{-(n\pi)^2 (t-t_2)/\tau} \right) \right] & t_2 \le t \le t_3 \end{cases}$$

$$(2)$$

$$\frac{r}{L} \left[ k_1 t_1 + k_2 (t_3 - t_2) + 2\tau \sum_{n=1}^{\infty} \frac{1}{(n\pi)^2} \left( k_1 e^{-(n\pi)^2 (t-t_1)/\tau} \left( 1 - e^{-(n\pi)^2 (t_1/\tau)} \right) + k_2 e^{-(n\pi)^2 (t-t_3)/\tau} \left( 1 - e^{-(n\pi)^2 (t_3 - t_2)/\tau} \right) \right) \right] & t \ge t_3$$

in steady state, i.e., a constant current and  $t > \tau$ . The correct way to calculate the joint resistance R(t) is:

$$R(t) = P(t)/I_0^2$$
(3)

where the dissipated power P(t) is defined as:

$$P(t) = r \int_0^L \left[\frac{\partial I(x,t)}{\partial x}\right]^2 dx.$$
 (4)

## **III. MEASUREMENTS**

The joint sample resistances have been measured on the CEA-Saclay joint measurement test facility. The samples are cooled down to 4.2 K inside a dedicated cryostat. It is connected through current leads to a 10 kA power supply. This power supply is bipolar and allows ramping the current up and down. The cryogenic power is enough to keep 10 kA in the joint sample for more than one hour. During measurement a step was done at 5 kA. The resistance value is obtained by direct measurement of the voltage drop. Typical values of voltage were 1–10  $\mu$ V, using a nanovoltmeter. Measurement accuracy is typically  $\pm 10\%$ . A magnetic field can be applied perpendicular to the sample to simulate the external field. A dipole is used, the sample being inside the aperture of this dipole. In order to ease the sample change, and to avoid warming up the dipole and its iron, the dipole was inside its own cryostat, while the sample is inside an anti-cryostat. Nevertheless, the dipole used for these tests has a limited length, of 680 mm. Respectively at 0 T and 2 T resistance measured on a 1 m long sample were respectively 0.6 n $\Omega$  and 0.7 n $\Omega$ . The measurement results are given on Fig. 5, together with the fit calculation results, obtained by applying (2).

#### **IV. DISCUSSION**

As obtained by the solution of the diffusion equation and confirmed by the measurement results, the voltage drop and, in turn, the joint resistance show a strong time dependent behavior. With respect to the steady state value, the voltage drop reaches very high values (more than twice with current rates up to 20 A/s), then it decades with a time constant depending on the applied field. In terms of dissipated power that means a peak value, at B = 0 T, of 45 mW with respect to a steady state value of 39 mW.

The fit with the analytical expression is in good agreement with the measurements, excluding the low current regions where oscillations of the power supply occur (the reported current vs. time curves are the imposed ones).

The decay time and the steady state resistance values are respectively 1700 s and 0.39 n $\Omega$  at B = 0 T and B = 1 T, and 1460 s and 0.454 n $\Omega$  at B = 2 T. As expected, the decay time is perfectly proportional to the reverse of the steady state resistance.

A question arises about the consequences on the magnet operation. Considering a steady state joint resistance of 0.39 n $\Omega$ , and the 5 h charging time foreseen for the CMS magnet (up to 20000 A), the voltage peak value is only 3% higher than the



Fig. 5. Measured voltage drop across the joint at the applied fields B = 0 T, B = 1 T, and B = 2 T, compared with the results of the fit with the analytical expression. The joint current is shown as well.

steady state one. Lower values of the joint resistance lead to higher voltage ratios, but the effect on the magnet behavior is negligible.

### REFERENCES

- [1] A. Hervé *et al.*, "Status of the CMS magnet," *IEEE Trans. Appl. Superconduct.*, submitted for publication.
- [2] R. Musenich, S. Farinon, C. Priano, and P. Fabbricatore, "Evolution of the ohmic voltage drop in connections of superconductors under timevarying current," *Cryogenics*, vol. 40, pp. 45–52, 2000.