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# Effect of Chrome Coating on Resistance of Sintered Joint for ITER Central Solenoid

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# Effect of Chrome Coating on Resistance of Sintered Joint for ITER Central Solenoid

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***Abstract*—The ITER Central Solenoid has 36 interpancake joints. The joints are required to have resistance below 4 nOhm at 45 kA at 4.5 K. The US ITER Project Office developed and qualified a sintered joint for the interpancake joints that consistently showed exceptionally low DC resistance of 0.13 nOhm at up to 80 kA in the self-field of about 1.5 T. To provide a good current distribution in the joint, we removed chrome plating from the strands in this area.**

**We built and tested four samples of the sintered joints before 2012. Such a low resistance prompted an investigation of the possibility of leaving the chromium on the strands during the joint preparation and still staying well below allowable resistance. Although removal of the chrome plating is not a very labor-intensive or time-consuming operation, it requires handling of harmful fumes and produces a solution containing hexavalent Cr, which is a hazardous substance. Elimination of the Cr removal step is a simplification of the fabrication process and therefore is a desirable act. We built two identical racetrack samples of the sintered joint and tested them in our joint test apparatus. One sample had Cr removed from the strands, the other had Cr intact.**

**This paper provides a description of the test samples, fabrication steps, and results of the DC resistance measurements.**

***Index Terms*— ITER Central Solenoid, Superconducting Cable in Conduit Conductor, Electrical Joints, Electrical Resistance**

## I. Introduction

The pancake-to-pancake joint was developed [1] and qualified [2] by the US ITER Project Office (USIPO). The brief assembly procedure is as follows: The cable is made of superconducting and copper strands coated with chromium (Cr), about 1.5 μm thick. The two last stages of cabling are undone, and after removal of the Cr, half of the strands are cut in the manner described in [2] and reassembled in the original cabling pattern so the cross section remains the same. Then the cable is compacted inside a copper tube to 20% void fraction. (The original void fraction is 30%.) Finally, the closeout profiles are welded to restore the jacket. During the heat treatment the strands are sintered to create a low-resistance joint.

The fabrication process of the sintered joint is given in detail in [1], [2], and the schematic of the joining subcables is shown in Fig. 1.

The term 6×6 refers to the last-stage cabling in which six subcables (called petals in the cross section) are connected after half of the strands from each side are cut.

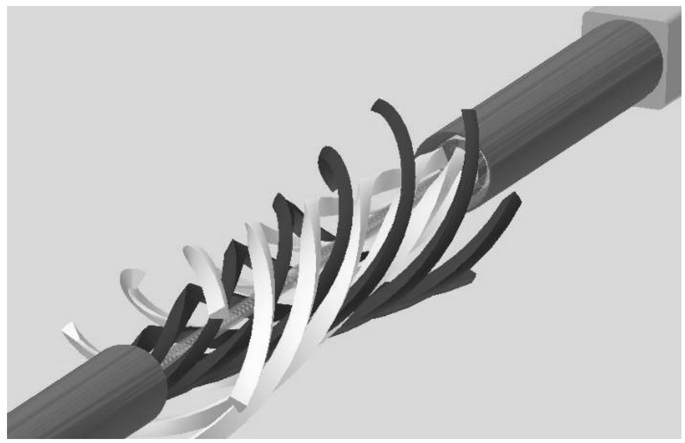

Fig. 1. Sintered joint 6×6 schematic.

Experience gained in operation of the Central Solenoid (CS) Model Coil [3] showed convincingly that AC losses in the joints do not significantly contribute to total cryogenic losses in contrast to the Joule losses. Also, it was demonstrated that cables compacted to 20% void fraction are capable of withstanding relatively high dB/dt, up to 0.5 T/s and 4 T amplitude without stability problems. The CS joints operate at much lower dB/dt and amplitudes.

To provide the lowest possible DC resistance, we removed the Cr not only from the outside layer, but also from the whole surface of all strands. We realized that as a result the AC losses would be slightly higher but decided that was a good price to pay.

The operation of removing Cr is not only low to moderately complex. The traditional method of removing Cr from a copper surface using hydrochloric acid was developed at the University of Tennessee Magnet Development Laboratory (MDL). This method, which was based on a well-accepted practice in industry and in the applied superconductivity community, is described in the code [4]. In mid-2011, however, it was prohibited by the ITER International Organization when a stress-accelerated corrosion in the JK2LB jacket was observed on several samples [5]. The accelerated corrosion was attributed to a miniscule presence of

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halogens on the surface of the steel left from Cr stripping by acid.

We developed an alternative method for Cr removal without using halogens by reverse electroplating in the sodium hydroxide strong solution, as described in [4] to avoid corrosion of the steel. This process has a harmful hexavalent Cr byproduct, though, that requires personal protection, good fumes extraction, and proper waste management procedures.

Several sintered joints were tested in 6×6 configuration in 2008–2010 with Cr removed, and all of them showed a very low resistance in the range of 0.13–0.14 nOhm.

In 2010 Bernard Turck, retired from the Commissariat à l'Energie Atomique, Cadarache, France, proposed investigation of the CS sintered joint in which Cr would not be removed. At this point we had a very good results with Cr removed, and no results with Cr not removed. Given a significant margin in the joint resistance, we decided to study the effect of Cr on the sintered joint resistance.

## II. Sample Preparation

The samples were prepared out of CS cable made with internal tin OST (for Oxford Superconducting Technology) strands that were used for ITER toroidal field (TF) conductors [6] except that the outside diameter of the strands was 0.83 mm instead of 0.82 mm as for the TF strand. The cabling parameters are given in [7]. The cable was produced by New England Wire Technology Company, Lisbon, New Hampshire. The only deviation from the specs was that the copper wires were not Cr plated for economic reasons. Given copper does not carry any significant current until quenched, it is presumed that this deviation is insignificant for current transfer.

We built two identical samples. In one sample we left Cr plating intact. For the other sample we removed Cr by reverse electroplating.

The joint sample represented a racetrack of the CS cable in a thin-walled stainless steel tube that was tested in the joint test apparatus (JTA). The details of the racetrack configuration and test procedure in the JTA are described in detail in [1],[2]. Figure 2 shows a racetrack during fabrication, prior to copper sleeve compaction over the joint.

Fig. 2. The racetrack during fabrication. The joint weaving is complete.

The JTA represents a superconducting transformer, where the current in the racetrack is induced by the primary winding that is actively charged by a power supply [1]. The primary coil is placed inside the racetrack. The assembly of the racetrack and the primary winding in the JTA are schematically shown in Fig. 3. The current in the racetrack is deduced from the Hall probe readings from Ht and Hb sensors as shown in Fig. 3 and explained in [2] and by measuring the current decay in the racetrack when the current in the primary is kept constant.

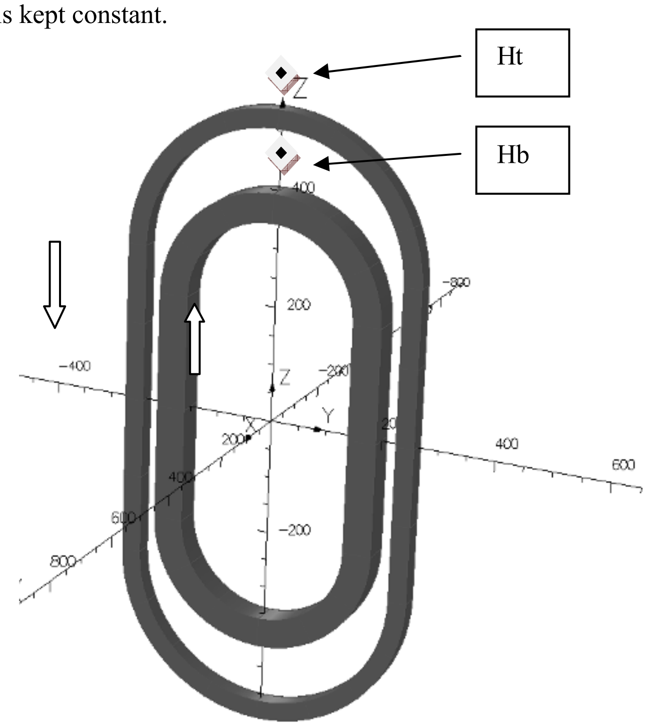


Fig. 3. Schematic of the JTA. The axes are in millimeters.

In the beginning of the joint testing in the JTA, we planned to use a heater to kill the induced current in the racetrack. It turned out that a 50 W short heater was insufficient to drive the conductor normal, and the heater burned before that despite significant thermal insulation installed outside the heater. The racetrack is located in the liquid helium bath, and the helium flow inside the jacket is driven by natural convection, which demonstrates the very high stability and temperature margin of the joint. Even without the heater, multiple tests and calibrations allowed us to deduce the current in the racetrack from the Hall probes with better than 5% accuracy, which is sufficient for the resistance measurement test.

We also had voltage taps across the joint to directly measure the resistance. This method is less reliable, however, as a result of nonuniform current and voltage distribution in the vicinity of the joint.

## III. Test Results and Discussion

Figure 4 shows the current's evolution in the primary coil and racetrack. The current in the primary is controlled by a four-quadrant power supply with maximum current of +/−200 A. Depending on the joint resistance, this configuration allows the racetrack current to charge up to 50–70 kA on the first ramp and up to 100 kA and higher on the reverse ramp because the swing is two times larger from +200 to −200 A.

Usually the racetrack current is not zero at the reverse ramp, however, because the decay time is too long to wait for the complete decay of the current in the racetrack. That is why the peak current in the racetrack at the end of the big swing from +200 A to −200 A in the primary (75 kA, see Fig. 4 at 4800 s) is less than double that of the racetrack current at the end of the ramp-up from 0 to 200 A in the beginning of the test (56 kA at 200 s).

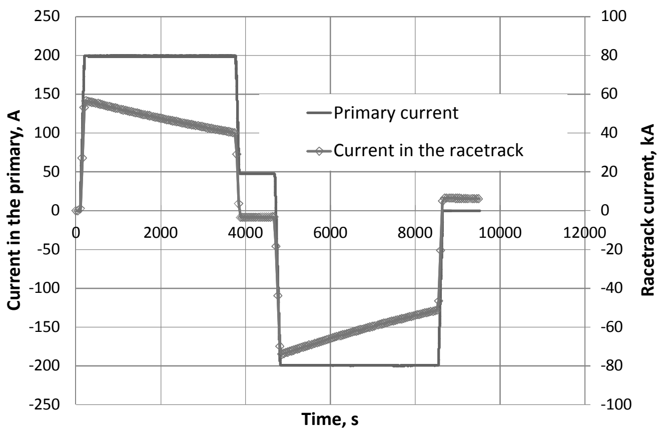


Fig. 4. Typical current profile in the JTA for resistance measurement.

We determined the resistance by measuring the time decay during the flat tops and knowing the inductance of the racetrack. We also measured voltage across the joint when the primary coil current was kept constant.

The results for all the sintered joints with 6×6 configuration tested by USIPO are shown in Fig. 5. Resistances determined by both the inductive and resistive methods are provided. Evidently sample #1, showing an unusually low resistance by microvoltmeter, had issues with location of the voltage taps being too close to the joint. The inductively determined resistances had very little scatter, which emphasizes the maturity of the design and fabrication procedure. The last two joints were assembled for the comparative study of the Cr effect on resistance. For sample #9 Cr was not removed from the superconducting strands. Removal of Cr by reverse electroplating (sample #10) proved to be about as effective as removal by hydrochloric acid (samples #1, #5, and #6). Cr left on the superconducting strands increased resistance by a factor of 1.7 or by roughly 0.1 nOhm in comparison with resistance when the Cr was removed. Taking into account that the specification allows 4 nOhm DC resistance, even with the provision that the joint operate in 3.5 T peak field instead of the 1–1.5 T peak field we have in JTA, it looks as if we have a significant margin of resistance and can afford Cr on the strands. We plan to test one more sample with the sintered joint and Cr not removed in the SULTAN facility [5] to confirm this result. If confirmed, the Cr removal operation may be omitted in sintered joint preparation.

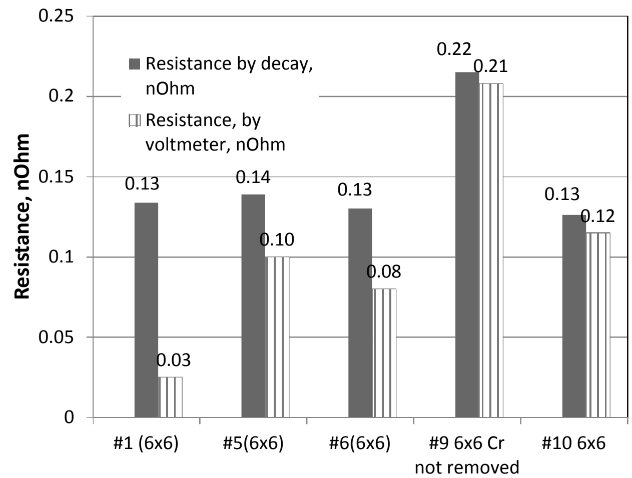


Fig. 5. A summary of the sintered joint test results.

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