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Abstract –**Joints for the ITER superconducting Central Solenoid should perform in rapidly varying magnetic field with low losses and low DC resistance. This paper describes the design of the ITER joint and presents its assembly process. Two joints were built and tested at the PTF facility at MIT Test results are presented; losses in transverse and parallel field and the DC performance are discussed. The developed joint demonstrates sufficient margin for baseline ITER operating scenarios**

I INTRODUCTION

The ITER magnets will have joints due to limitations on conductor piece length Because of discontinuity of the superconductor in the joint and the resulting heat generation, the properties of the joint are naturally inferior to those of the conductor In most superconducting magnets, the joints are placed in a low field area, which gives the joint enough margin to perform successfully With the development of Cable-In-Conduit Conductors (CICC), fully superconducting tokamak became possible However, because of the tokamaks' large dimensions, it is nearly impossible to bring the joints to a low field area Therefore, the development of superconducting coils for the ITER project requires the simultaneous development of a high current superconducting joint, capable of working in a variable magnetic field

The requirements, which the ITER joint has to meet, are

a) Low resistivity (less than 4 7 nOhm for the Central Solenoid) at currents up to 50 kA and in the magnetic field up to 7-8T
b) Low losses (less than 15 W in steady state equivalent and less than 400 J per event, like plasma initiation)
c) Structural strength to support the electromagnetic forces generated in the joint and coming from inside the coil into the joint
d) Compact size, the overlapped length is about 450-500 mm
e) Leak tight and capable of withstanding a pressure of 30 bar

The task to develop an adequate joint in ITER Program was identified early in the program and an extensive R&D has been carried out on subscale and full-scale joints of different types

This paper summarizes the efforts of the ITER US Home Team in development of a joint for ITER CS Model Coil (CSMC), which after CSMC testing will be a basis for the ITER joints

II JOINT DESIGN DEVELOPMENT

Two full-scale joints were built and tested – the US Preprototype (USPP) and the US Prototype (USP) joint Close in concept, these joints have some differences, which are discussed below

A Layer-to-layer joint features

The main features of the joint include

- Twisted compacted cables inside Glidcop sleeves
- Chrome plated strands in the cable, chrome removed only from strands at the cable surface
- Insulating Inconel tape maintained between last stage subcables
- Insulating CuNi barrier between the cable and the Glidcop sleeve on the surface opposite to the one facing the copper block
- Resistive breaks in the Glidcop sleeve and copper saddle block
- One twist pitch length
- 20% cable void fraction, with central hole in the cable maintained for cooling
- Enclosure in a stainless steel box

A layer to layer joint is shown in Fig 1 (the joint box is removed from the foreground for clarity)

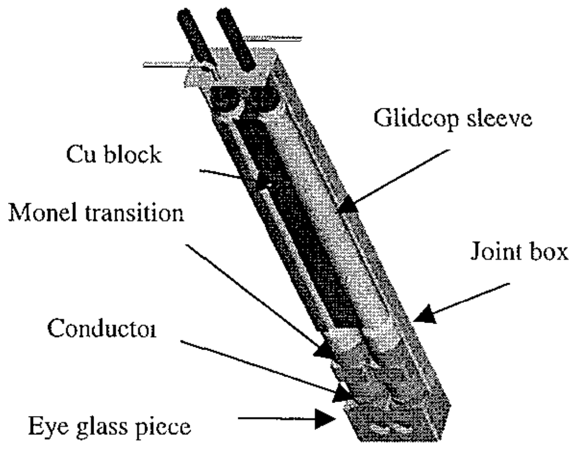

Fig 1 ITER CSMC praying hands joint

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The box around the joint provides the following functions

- secondary helium containment to improve the reliability of the joint
- clamping of the Glidcop sleeves to the copper block
- a load path to transfer forces originated in the joint to the conductors
- protection of the relatively weak joints between the Glidcop and the Monel (brazed joint) and between the Monel and the Incoloy conductor (fillet weld joint)

Prior to assembly, the Glidcop sleeves are brazed to a Monel transition piece This terminal assembly is then slid over the prepared cable and the Monel piece is welded to the Incoloy conductor A cap with cooling holes installed at the top of the Glidcop sleeve allows the joint to be cooled by helium entering or exiting the conductor The details of the joint terminal construction are given in [1]

The interface between the cable and the Glidcop sleeve is the least predictable and is the major contributor to the joint resistance Preliminary R&D for the joint showed that sintering between the cable and the Glidcop occurs at a void fraction of about 20%[1] Thus, in spite of known penalties to the AC performance we decided to proceed with 20% void fraction to assure reliable DC joint resistance

To minimize losses in the cable, the Cr coating on the strands was removed only at the surface of the cable Also, the Inconel tape, wrapped around the subcables was left intact between the subcables, effectively decoupling them

B USPP joint

The US Preprototype (USPP) is described in details in [1] The intent of the USPP joint was to demonstrate that ITER relevant joints can simultaneously achieve dc resistance and pulsed field losses low enough to satisfy ITER criteria

Although the USPP joint failed to achieve some of its performance objectives, it provided valuable manufacturing experience for subsequent joint development while the analysis of its test results provided key insights for joint optimization Analytical models showed that it was possible to markedly reduce these interaction losses by selectively introducing resistive barriers in the Glidcop sleeves and especially in the copper block This loss mechanism is discussed in [3]

C USP joint

The USP joint was built and tested to not only improve upon the USPP performance by incorporating the gained experience, but also to address manufacturing and operational issues of assembly, structural integrity, alignment, quality assurance, etc In other words, a key objective of the USP joint project was to simulate the field assembly of the joint as much as possible

The cross section of the USP joint is shown in Fig 2

From the performance stand point, the USP joint had several changes in comparison with the USPP joint

a) copper block lamination pattern was improved, as a result of analysis performed after the USPP construction, b) for manufacturing and cost reasons, the radial breaks in the Glidcop sleeves were eliminated, c) the soldering technique between the Glidcop and the copper block was improved, providing better interface contact, d) QC of the joint fabrication was improved, especially Cr coating removal and Glidcop compaction, both steps are critical for reducing the cable to Glidcop resistance

The structural support for the USP joint was quite different from the USPP Stress analysis [4] showed that to support the forces originated in the joint, as well as those transmitted from the coil to the joint, the joint box has to be relatively massive The combined electromagnetic and cooldown Van Mises stress can reach 630 MPa Additionally, the wedge clamps need to be strong enough to maintain a guaranteed pressure at the level of several MPa at the interface between the copper block and the Glidcop sleeves [5]

Fig 2 shows NILO inserts between the Glidcop sleeves and the box wedges The low coefficient of thermal expansion (CTE) of the NILO wedges compared with the joint box provides an additional assurance that the joints always stay under compression during cooldown

III RESULTS OF THE PTF TESTS

Testing of the full-scale joints occurred at the Pulsed Test Facility (PTF) at MIT – a specially build facility for joints and conductors testing [6] The details of the tests are given in another paper at this conference

A DC resistance

The DC resistance of the joint was measured by sets of voltage taps and by calorimetric measurements

For the USPP joint we observed that most of the voltage taps attached to the Glidcop sleeves showed a DC resistance of 5 4-5 6 nOhm at 50 kA and 4 T The voltage taps readings indicated an intensive redistribution of the current in the joint and adjacent conductor

The calorimetric method showed, however, that the DC

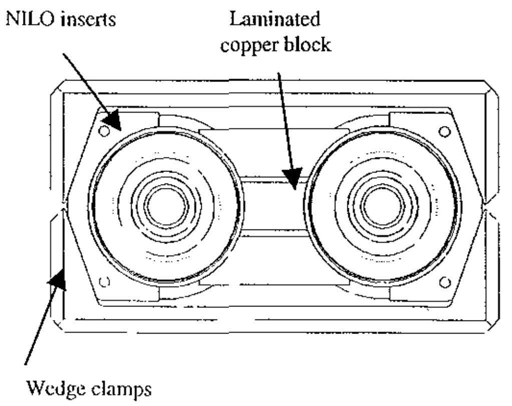

Fig 2 Cross section of the US Prototype Joint

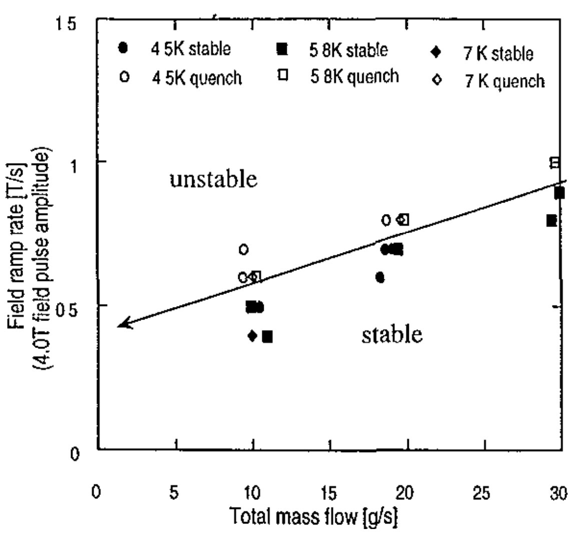

Fig 3 Stability of the USP joint in the transverse pulse field

resistance was about 10 nOhm A detailed study was carried out to explain the difference between the electrical and calorimetric measurement [7]

It was discovered, that the electrical method of the resistance measurement gives always lower reading than the real resistance, however it was difficult to determine how much lower The calorimetry accuracy (about 20 % for USPP) prevented a more accurate determination for the USPP joint resistance

The DC resistance of the USP joint measured with the voltage taps was in the range of 1 7-2 2 nOhm in the field of 4 T at 50 kA, but some voltage taps showed much lower values Inner voltage taps indicated that the effect of the current redistribution between the subcables is strong and obtaining the resistance of the "sintered layer" between the cable and the Glidcop is not possible

The calorimetry calibration proved that the calorimetric method on USP joint is accurate within better than 10% Calorimetric measurement of the heat generation showed that the DC resistance of the joint is below 2 5 nOhm, which is in good agreement with the electrical measurements

The significant improvement in the joint's dc resistance can be attributed to the experience gained on the USPP joint, improvement in the joint fabrication technology and more stringent quality control

B Joint stability in varying magnetic field

The ability of the joint to withstand pulsed field disturbances is a part of the ITER requirements We simulated conditions of the CSMC and ITER operation and found that the joint remained superconducting during these shots

Fig 3 presents the joint stability at 50 kA transport current against the transverse field pulses with 4 T amplitude The stability of the joint has a large, safe margin

The USPP joint had similar trends but was about 30-50% worse than USP joint in terms of ramp rate stability This can be attributed to a lower loss in the USP sample's copper block, which is not cooled directly and therefore can have noticeable impact on overheating

C Loss measurements

Losses in the joint were measured by calorimetric method in three field orientations

- Parallel field
- Transverse field, when the field is parallel to the plane containing both cable axes (we refer to this orientation as "ITER" transverse field)
- Transverse field, when field is perpendicular to the plane containing both cable axes (we refer to this orientation as "non-ITER" transverse field)

1 Joint losses in parallel field

The details of the loss analysis are given in [3]

Fig 4 compares the parallel field losses in USP and USPP joints at large amplitudes It is seen that the losses are slightly lower in the USP joint In general, losses in parallel field turned out to be about 1 5-2 times higher than anticipated originally because of unexpectedly high losses in the cable The earlier measurements on the subcables in parallel field suggested much lower losses [8] in the cable The additional

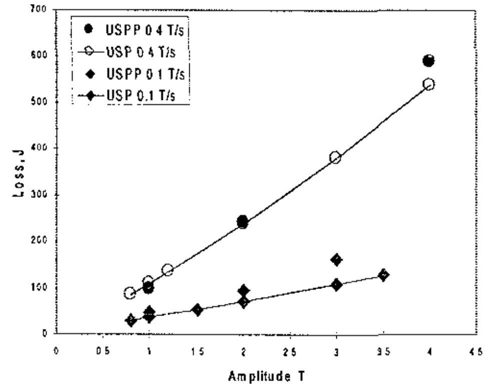

Fig 4 Comparison of losses in USPP and USP joints in parallel field Large amplitude shots

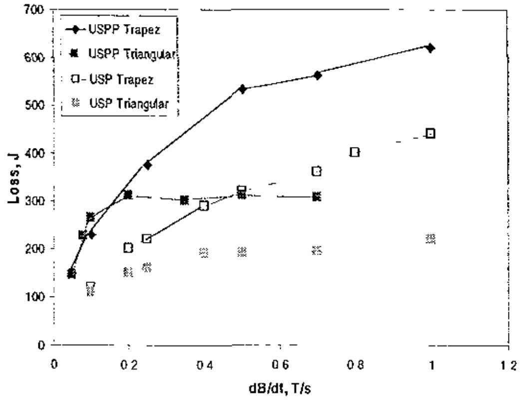

Fig 5 Losses in USPP and USP joints in 1 T amplitude triangular and trapezoidal transverse field pulses

losses are thought to be associated with the coupling of the cables through the copper block Since the cables have some angle to the vertical axis, some of the strands create loops, which trap some magnetic flux This flux variation in the loops drives coupling currents through the copper block The current path in copper coincides with the transport current path Therefore, this component of losses can not be eliminated

2 Joint losses in "ITER" transverse field

Losses in the transverse field orientation were measured for a large variety of field amplitudes and ramp rates, for both triangular and trapezoidal pulses In general, the value of losses in the joint in perpendicular field turned out to be close to expectation [2] More details on losses are presented at this conference

Fig 5 represents the losses in both joints From the analysis, about 50 % of the losses come from the cable, and a large contribution comes from the copper block [3]

Introducing optimized copper barriers in the USP joint, we suppressed almost completely the eddy current losses and significantly reduce the coupling cable losses (see Fig 4)

It is seen from Fig 5 that joint losses during a 2T, 1 2 T/s initiation drop in the ITER Central Solenoid bore, which translates into 0 66 T, 0 4 T/s for the joint region, can be held within 400 J dissipation, as required At the nominal regime of operation of the CSMC, the joints will see about 0 1 T/s transverse field with the amplitude about 3 5 T The ITER requirements on the joint are less strict than those for the CS model coil Therefore, the losses in the USP joint are within both CSMC and ITER requirements

IV ASSEMBLY ISSUES

The ITER joint must be assembled after the layers assembly The alignment of the joints is critical to provide uniform gap between the Glidcop sleeve and the copper block (0 002-0 004") Thus it is very important to maintain high accuracy of the coil winding and location of the leads relative to the coil

This is a very difficult technical task The conductor is very stiff, the coil is heavy and the joint is not strong enough to be "forced" into the proper position Also, Nb_3Sn is a very brittle superconductor with a very low tolerance to a strain The first turn of the layer has to be manipulated to bring the joint into the required spatial position and aligned within a fraction of a millimeter

The joint soldering operation needs to be conducted after the coil impregnation We developed a promising ultrasonic NDE method, which should help us to monitor the quality of the soldered interfaces

The welding of the joint required extensive effort on certification of the welds and welders, which involved testing of the samples, metallographic studies, tensile strength tests, etc During this effort a method and procedures for welding dissimilar metals like Incoloy and 316 LN SST has been developed

V SUMMARY

The result of the joint R&D showed that it is possible to build a joint that has sufficient operating margin to work in fusion machines like ITER

To what extent we may improve this concept in the future? Analysis suggests that we can reduce the losses by 10-20% in both field orientations by introducing optimized barriers in the sleeve The DC resistance is close to the theoretically predicted 2 nOhm The concept of the joint, the optimization effort and the test results suggest that this concept is unlikely to be significantly improved

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