Interlayer Joint for Toroidal Field Coil of EUROfusion DEMO Tokamak

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Abstract

The Swiss Plasma Center (SPC) has developed a layout of Toroidal Field (TF) coil for EUROfusion DEMO tokamak, based on the reference tokamak baseline of 2015. Each TF coil winding pack is wound with graded Nb3Sn conductors and consists of 12 single layers, connected in series by means of inter-layer graded joints.

The design of inter-layer joints takes into account the react-and-wind (R&W) manufacturing technique for fabrication of TF coil winding pack, i.e. the inter-layer joint is prepared with use of two already heat treated Nb3Sn conductors. The development, preparation and test of inter-layer joint at SPC is performed in frame of R&D program for TF coil of EUROfusion DEMO tokamak.

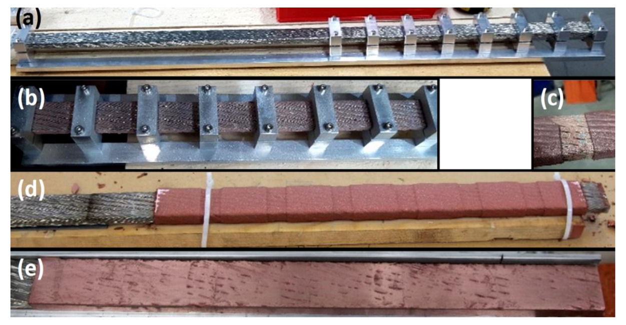
The high-grade Nb3Sn TF conductor, operating at 63.3kA and 12.2T (Tcs>6.5K) was tested at SPC, and afterwards was used for fabrication of inter-layer joint. The developed TF inter-layer joint is an "overlap-type" joint, which can be fit within the dimensions of TF winding pack. Each end of two conductors is copper cladded by a thermal-spraying technique and then bonded together along the surfaces of cladded copper with use of a high-frequency inductor.

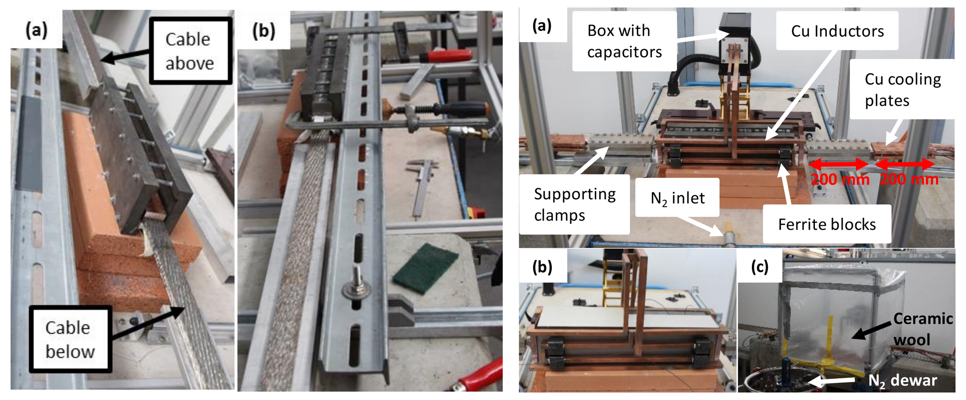
Introduction

The Swiss Plasma Center (SPC) has developed, manufactured and successfully tested the full-scale interlayer joint to demonstrate the feasibility of such a joint. This joint was fabricated using a heat-treated high-grade Nb_3Sn conductor named RW2 (63.3 kA, 12.2 T, Tcs >6.5 K), which has a full-profile (FP) Cu-Ni stabilizer. This conductor was successfully tested in the SULTAN test facility. The developed fabrication technique of such a joint does not imply the use of chemically aggressive flux and mechanically weak solder. The developed technique for this joint fabrication is the diffusion-bonding of two overlapped high-grade Nb3Sn conductors at high ≈650°C temperature with applied pressure of ≈30MPa.

The inter-layer joint with a high-grade conductor operates at 63.3kA current in 8T magnetic field. The requirement of joint resistance is ≤1nΩ, which has been demonstrated during the test of joint.

Fabrication of Joint





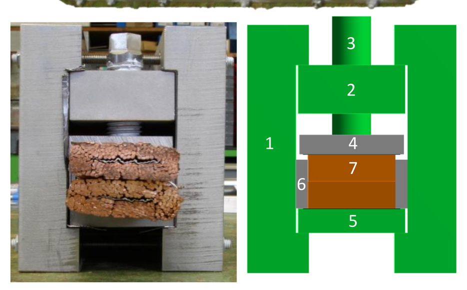
Two Conductor Ends:

- Aluminum clamps
- Sandblasting
- Arc-spray cladding of Cu, 1 mm
- Removal of aluminum clamps
- Sandblasting
- Arc-spray cladding of Cu, 2 mm
- Milling: contact side – 1 mm
  narrow sides – 0.5 mm
  back side ≈0 mm

DB Process (SPC):

Overlapping of two prepared ends in the DB fixture, DB fixture is anchored to the H-profile aluminum beam

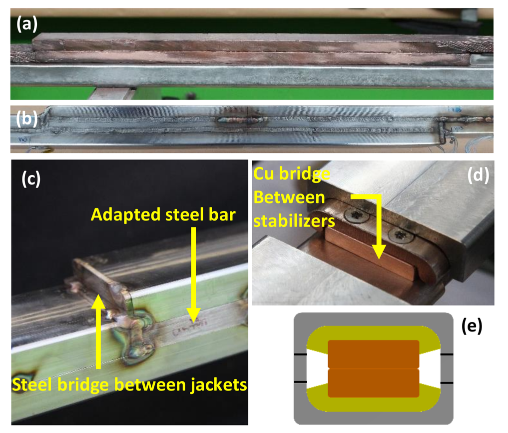
- Ceramic blanket, plastic tent
- Outside the DB fixture – cooling by Cu plates with water (5 l/s), 20°C temperature of conductors
- DB parameters: 52.3 kHz, 4.6 kW, overpressure of Argon
- In 1 hour: 690°C in the center and 690°C at the edge of fixture
- 2 hours to complete DB process (trials with dummy conductors)
- Natural cooling to room temperature



DB Fixture (SPC):

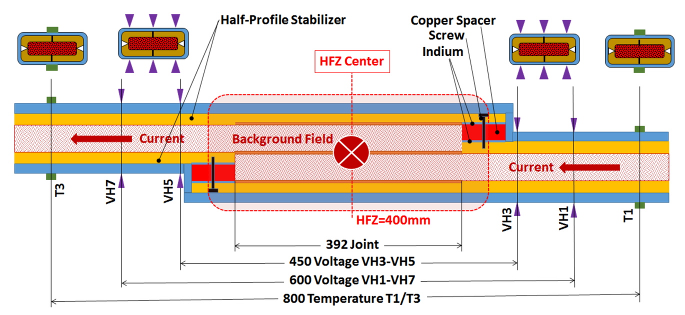
- 1,2,5 – Inconel-600 parts
- 2 – Inconel-600 bolts
- 4,6 – Stainless steel
- 24.6 MPa at RT
- ≈30 MPa at 650°C

Fabrication of Sample



Assembly of Joint in the Sample:

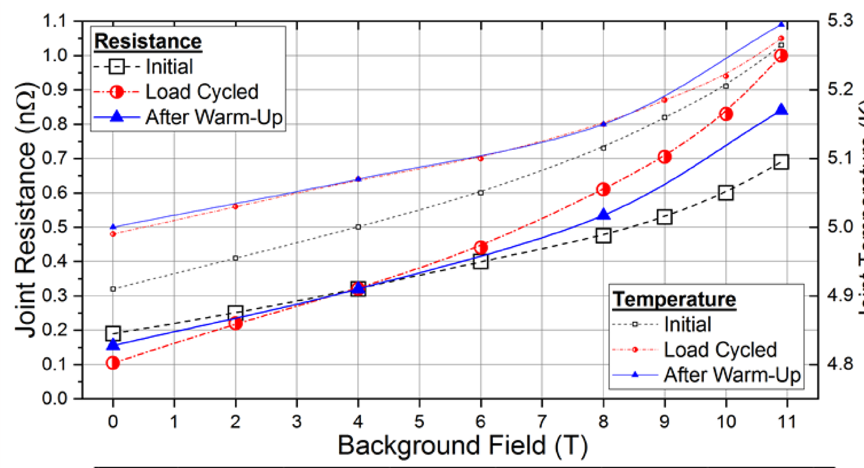
- The sample with the joint is assembled with terminations similarly as usual SULTAN sample
- The stabilizer protrudes with respect to the conductor butt to ensure the electrical continuity of stabilizer at two joined conductors. Such a connection is done by a copper bridge and indium
- The joint is pre-compressed using a 0.2mm thick stainless steel tape inserted between the outer jacket and the stabilizer, analogous to RW2 conductor
- The rest jacket sections are TIG welded around the joint
- The conductor containing the joint is connected to the already tested conductor RW2 by bottom joint



Instrumentation

The joint resistance is measured with use of applied array of voltage taps at a distance of 450 mm (VH3-VH5) and of 600 mm (VH1-VH7). Both distances include the portions of conductor at the sides of joint either 58 mm or 208 mm long. The thermometers T1/T3, placed upstream and downstream the helium flow in respect to the joint, allow the control and monitoring of joint temperature.

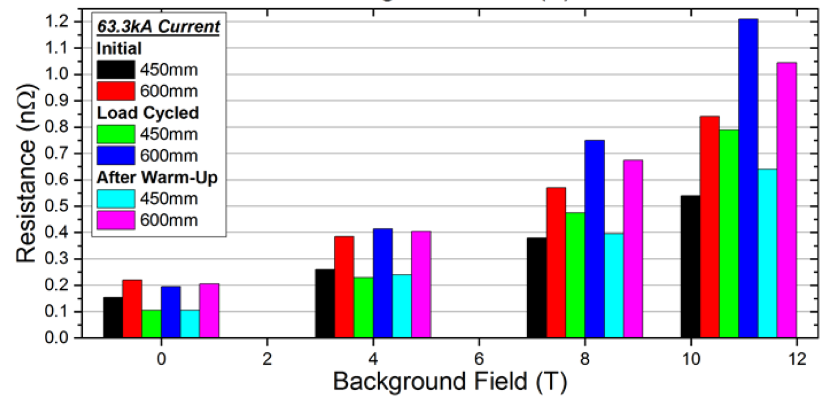
Resistance of Joint



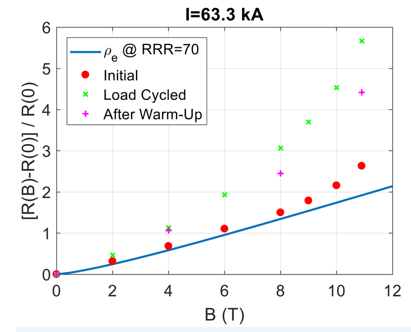
Assessment: $R_{joint}=(R_{450}+R_{600})/2$, includes the portions of conductor leaving the joint 450 mm and 600 mm

Measurements: Initial, after cyclic loading (8 T x 63.3 kA, 1000 cycles) and after intermediate warm-up

The initial resistance of joint at operating condition of 8 T field and of 63.3 kA current is 0.48 nΩ; the resistance increases to 0.61 nΩ after applied 1000 cycle loads and becomes 0.54 nΩ after thermal cycle to room temperature. At operating 8T field and 63.3kA current the temperature of joint increases by 0.04 K after cyclic loading and after thermal cycle as well. At maximal 10.9T background field: the resistance varies from initial 0.69 nΩ to 1 nΩ after cyclic loading and to 0.84 nΩ after thermal cycle.



The curve of resistance vs. background field changes from initial practically linear shape in the fields up to 8T (well in agreement with the computed magnetoresistance of copper, RRR=70) to practically exponential one at full range of fields after cyclic loading and after thermal cycle.

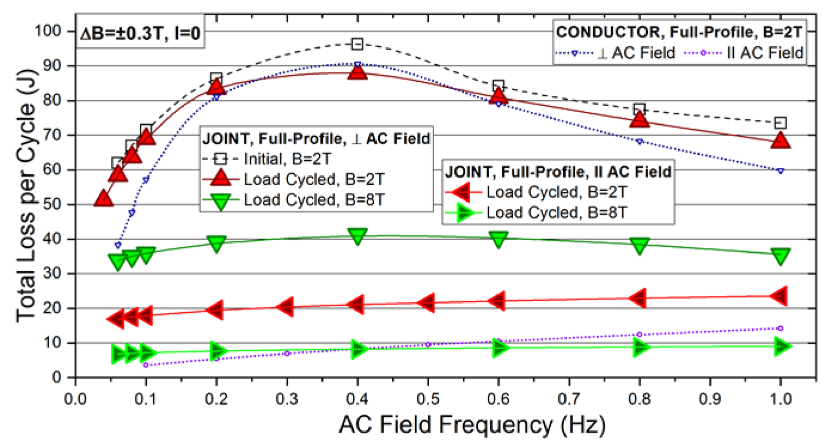


Comparison of R_{450} and R_{600} at 0 T: The change of resistances is insignificant, but the temperature of joint becomes ≈0.1 K bigger at 63.3 kA after cyclic loading (average temperature at T1/T3, 800mm distance). These facts are a sign that there is a small improvement of interfaces in the joint architecture after cyclic loading, but there is a drop of DC performance at those portions of conductor, which are at the sides of joint.

Quench temperature changes from initial value to cyclic loading and to thermal cycle (2.2 g/s) : 8.57K, 8.47K and 8.5K at 8 T, 63.3 kA

The proper mechanical transition/support is required for those portions of conductor, which are at the sides of joint

Joint AC Loss and Stability



Assessment: Gas-flow calorimetry
Measurements: Initial, after 1000 cycles, after warm-up – 2 T and 8 T background field, ±0.3 T AC field, I=0

The change of AC loss in the joint at 2T field is insignificant after cyclic loading, and AC loss of joint is comparable to AC loss of conductor at frequency >0.3 Hz, when eddy current loss is dominating. The loss at <0.3 Hz frequency is almost doubled in the joint in comparison to conductor due to the two overlapped conductors in the joint, when coupling loss is dominating and eddy current loss is a secondary factor.

The significant reduction of AC loss is observed at 8 T background field. **The big AC loss at 2T field and the significant reduction of AC loss at 8T field can be explained by increase of magnetoresistance of copper parts in the joint.**

Stability: The bipolar pulse battery, maximal 60T/s in 128ms.
The transient AC field is applied ⊥ to the broad side of joint.
Test: 8 T, 63.3 kA and 9 g/s helium mass flow rate. This mass flow rate corresponds to 1/2 of the real one in the DEMO TF coil. Voltage take-off happened in the RW2 conductor, not in the joint. The transient AC pulse corresponds to 17.6 T/s and deposited energy in the joint is of 65 J.

Conclusion

- **The successful technique on preparation of high-current inter-layer joint, working at high magnetic field and suitable for TF coil winding process has been developed at SPC for TF coils of EUROfusion DEMO Tokamak**
- **The resistance of developed and tested joint at operating 8T field and 63.3 kA current is about 0.5 nΩ, less than required 1nΩ**
- **The measured joint AC loss is comparable to conductor AC loss at frequency >8Hz and almost doubled at frequency <0.3Hz, but the joint AC loss are reduced by a factor of two at operating 8 T field**
- **The transient stability test for joint was performed at operating conditions up to 17.6 T/s applied in 128ms, with a deposited energy of 264 J. No voltage take-off happened in the joint, RW2 conductor was quenched**
- **The design of joint should be improved at the conductors leaving the joint, providing the proper mechanical transition/support for those portions of conductor, which are at the sides of joint**
- **SPC plans to investigate the mechanical strength of this joint, including a cyclic tensile mechanical loading**

EUROfusion

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