ICEC25/ICMC214 Identifier 255

High-Temperature Superconducting (HTS) Coils for a Compact Spherical Tokamak

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Abstract – High temperature superconductors (HTS) have the potential to impact the future development of superconducting applications for research magnets in physical sciences and industrial products. A promising technique to obtain energy from fusion is reliant on high magnetic fields to confine the hot plasma during the fusion reaction. To generate these high magnetic fields very high currents are required which can be obtained by using superconducting magnets. We are constructing the world's first Tokamak using coils made entirely from 2nd generation YBCO tapes. The Tokamak has six D shaped toroidal field coils, and two poloidal field coils which will be operated between 20K and 50K, well above the operating temperature of conventional LTS superconducting magnets.

The use of the HTS tape brings new challenges due to their ceramic nature and sensitivity to mechanical handling. We developed a new process for the formation of the joints for the Tokamak construction which resulted in joints that showed low joule heating. Results will be presented on the development of a process to form metallic joints without the use of flux or external heaters. One of the advantages of this technique is that the joints can be formed *in situ* in complex assemblies while resulting in minimum thermal stress. The results include lap joints between HTS tape / HTS tape which may be used for repair or extension of coils and joints between HTS-tape and copper terminals.

Background - A promising scheme to obtain energy from the fusion of deuterium and tritium is to confine the hot plasma using intense magnetic fields. To produce these fields requires currents in the magnets of order tens of mega-amperes; and to avoid severe losses due to resistive dissipation, superconducting magnets are used in recent Tokamak devices, including the ITER project now under construction in Cadarache, which uses established low-temperature superconductor technology. ITER is a huge device and smaller alternatives - mostly based on compact 'spherical' Tokamaks' - are under investigation. But here the space for the central toroidal field magnet is both very restricted, and also experiences very high fields, of order 20T or more; and it is for this application that High Temperature Superconductors could be especially valuable.

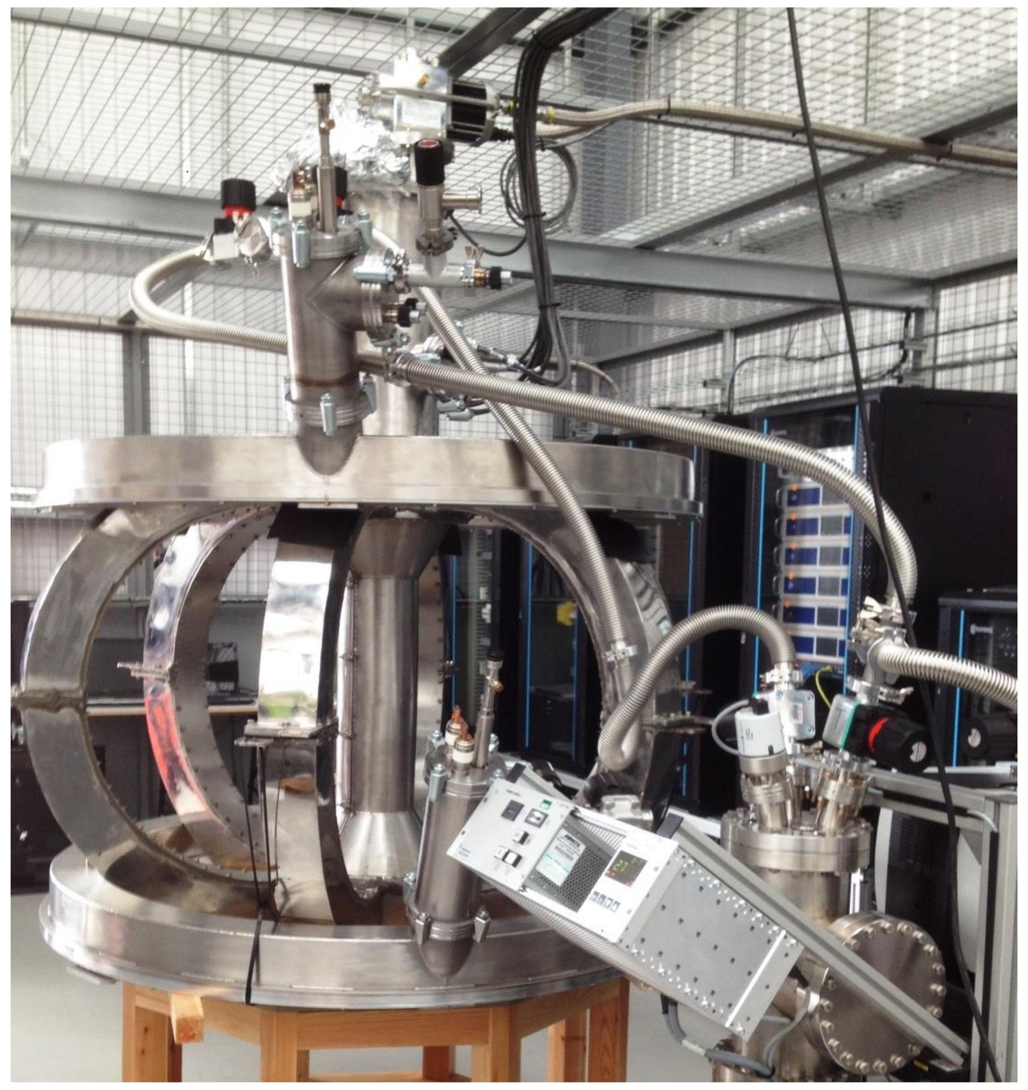

Fig.1: ST25-HTS Tokamak under construction

In recent years significant progress has been made on the development of HTS wires, they offer a combination of high current density, and high performance under extreme fields, combined with reduced cost for the cryogenic environment and operating costs.

ST25-HTS will be the world's first Tokamak operating exclusively with HTS PF and TF coils. The ST25-HTS program is part of a roadmap to developing and testing HTS magnet technology for use in Tokamak systems. The 2G HTS wire used in our application is manufactured by SuperPower and consist of a 12mm wide hastelloy substrate with a stack of buffer layers, a rare earth superconductor material ($YBa_2Cu_3O_{7-\delta}$) and protective over layers incl. silver and a surround copper stabilizer.

Parameter	TF coil	PF coil	Units
Number of coils	6	2	#
Coil OD	0.63	1.21	m
Coil thickness	14.4	6.9	mm
No of layers	48	23	#
Winding type	Pancake	Pancake	
Tape length of 1 coil	117	86	m
Operating current	431	378	A
Maximum operating temperature	50	50	K
Peak field to tape plane	0.99	0.68	T
Peak field perpendicular to tape plane	0.39	0.67	T
Calculated critical current	713	653	A
Characteristic field	0.1 (at major radius 25cm)	0.002 (at centre of PF coil pair)	T

Table 1: HTS coil parameters

Joint Manufacture - In order to minimize the contact resistance at the joints and improve ease of manufacturing we have developed a process (patent applied for) which uses a perform NanoFoil which is inserted in between the two surfaces to be jointed. When activated, the foil creates a self sustaining exothermal reaction that acts as a rapid and controllable localized heat source melting adjoining solder layers, bonding components together without the need of flux, hot plates, soldering irons or heaters. Peak reaction temperatures inside the joint are in excess of 1300° C for a few milliseconds.

We found no evidence that this process deteriorates the properties of the HTS wire. Activation can be achieved with different techniques, the simplest being a 9V battery. During the jointing process the surfaces are pressed together. The simplicity and ease of this process has major advantages during the manufacture of the joints and opens up the possibility to make repairs *'in-situ'* should this be necessary. We have carried out extensive experiments to confirm the suitability of this process for joints operating below 20K and being subject to repeated thermal cycling.

Sample preparation - The copper terminals 'A' and 'B' were treated differently: 'A' was electroplated with 2-3µm tin, 'B' with 8-10µm tin. The HTS tapes were 'hand tinned' using a hotplate. The contact resistance will be a combination of the interface resistance of the tin joint including any voids and the sandwich of copper / silver layers and their interface resistance incl. the HTS/Ag interface.

The layout of the joints was always in a 'face-to-face' orientation, meaning that the HTS sides of both tapes were facing each other. This configuration yields the minimum contact resistance compared to other configurations (e.g. HTS side facing hastelloy side).

To characterize the properties of the joint, we have made lap joints of HTS tape to HTS tape crossing at 90 degree (see Fig.:3; contact area 12x12mm) and lap joints between HTS tape to copper terminals 'A' and 'B' (contact area 12x24mm). The contact resistance of these joints was measured in LN2 in zero field up to 400A, past their onset of non linear behavior.

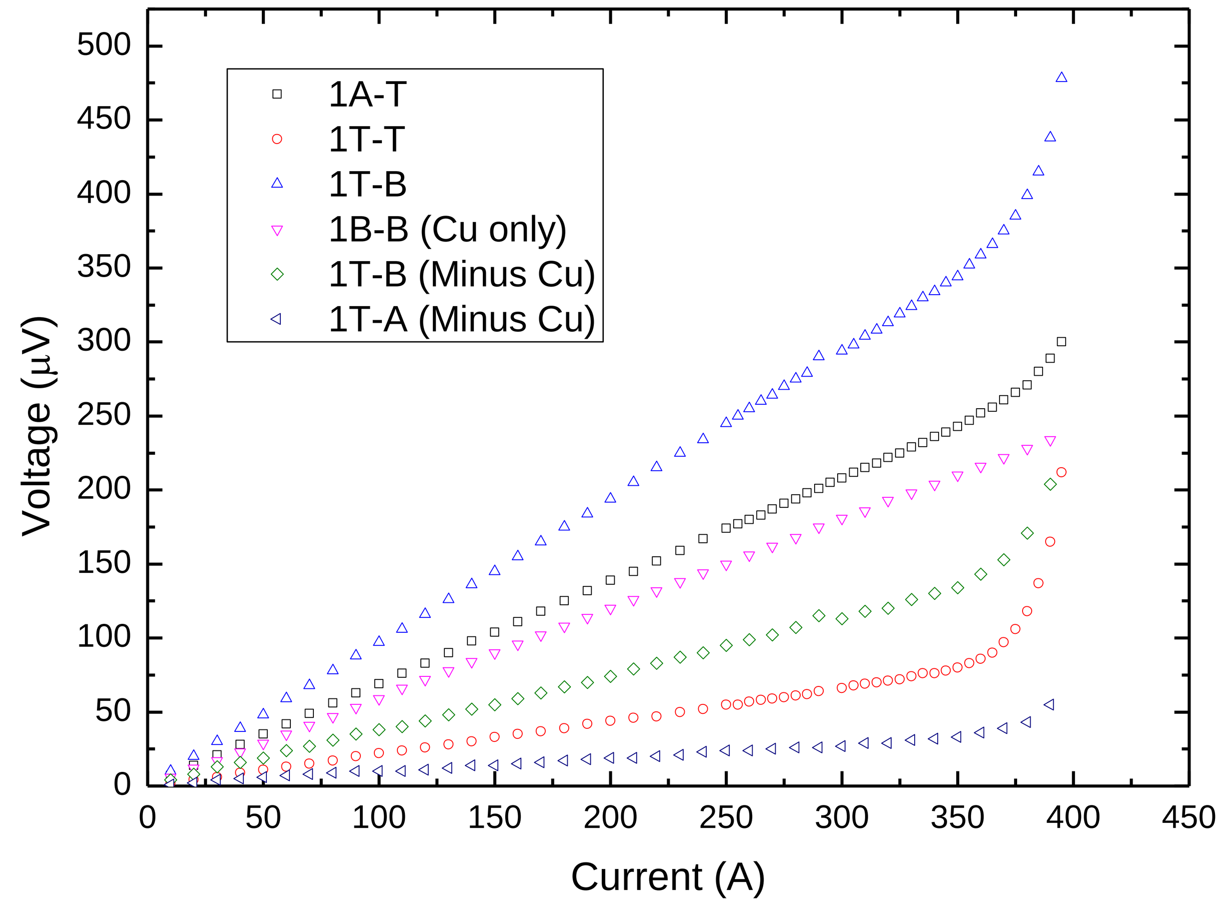

Fig. 1: Plots of sample no1 – 'A' & 'B' = copper terminals; T= HTS-tape. Voltage taps (see Fig.: 3) were positioned at both ends of copper terminal B to measure the I-V plot for 1B-B (linear up to 400A), this value was then subtracted from the 1T-A and 1T-B values and then plotted as 1T-B minus Cu and 1T-A minus Cu. The HTS tape to HTS tape joint is labeled as 1T-T and the joints between the HTS tape and copper terminals are labeled as 1T-A and 1T-B.

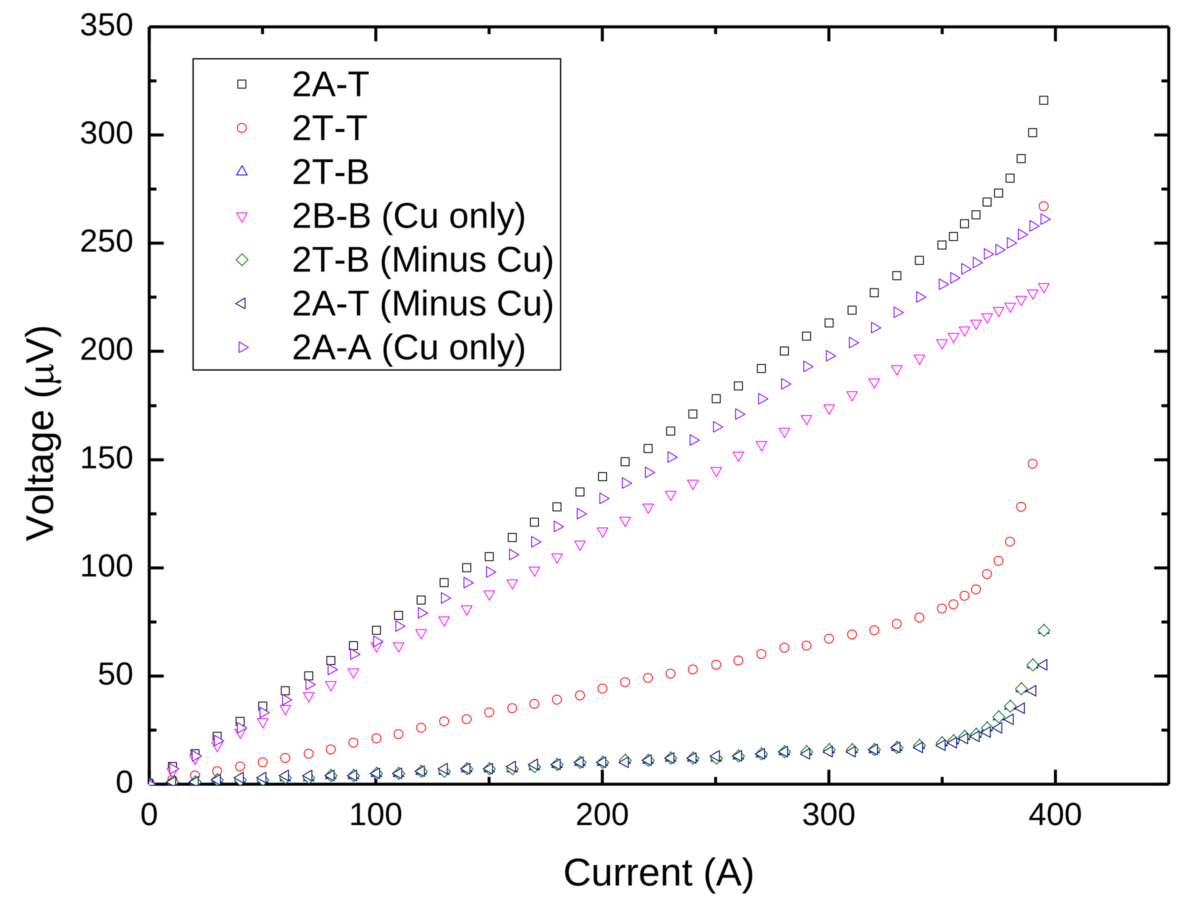

Fig. 2: Plots of sample no2 – After subtraction of the copper only values both HTS to copper terminals show very similar resistance. The HTS to HTS tape joint resistance is higher due to the smaller joint area.

Results - The I-V plots in Figs.1+2 of the HTS joints show a linear behavior up to approximately 350A. This is close to the manufacturers quoted value of minimum I_c= 367A. In order to separate the copper terminal contribution from the contact resistance of the HTS-tape to copper interface resistance, we added an additional voltage tap on the copper terminal (see Fig. 3, results are shown Figs. 1+2).

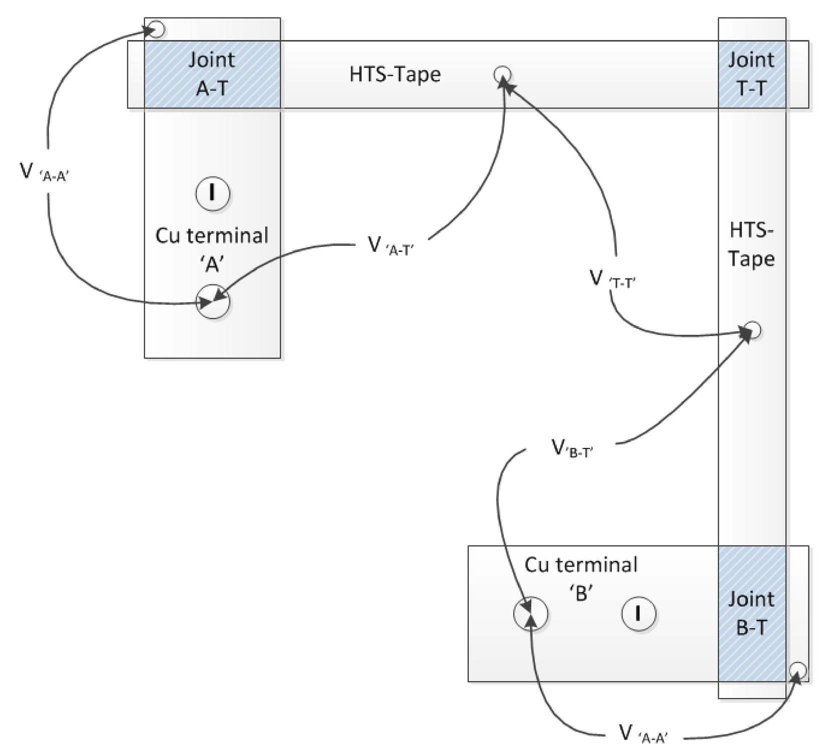

Fig. 3: Schematic of the measurement setup showing the voltage tap positions.

	A - T	T - T	T - B
Sample no. 1	270 nΩ cm²	310 nΩ cm²	1,100 nΩ cm²
Sample no. 2	150 nΩ cm²	310 nΩ cm²	150 nΩ cm²

Table 2: Contact resistance of joints independent of area*: 'A' & 'B' = copper terminals; 'T'= HTS-tape*

Despite tripling the tin thickness on copper terminal 'B' relative to 'A' we couldn't measure any differences between the contact resistance of those joints in sample 2, neither was there any difference in the contact resistance of the HTS/HTS tape joints of both samples. They are all remarkably similar, indicative of an inherently reproducible process. However, the variation of contact resistance on terminals 'A' and 'B' in sample no.1 is suspected to be due to some variation in the process parameters. An interesting result shown in table 1 indicates, that the contact resistance between copper terminals and HTS tape is approx. half the value of the HTS – HTS tape joints. This is now being further investigated.

Conclusion – We have developed a reliable process for low contact resistance lap joints between two HTS wires and HTS wire to copper terminals operating in a cryogenic environment ((patent applied for GB20140001694). Their low contact resistance make them ideally suitable for high current connections in our ST25-HTS Tokamak operating below 50K. HTS wire repairs are possible as the joints can be made *'in-situ'* as no heating is required during the manufacture of the joint.

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