Co-wound superconducting wire for quench detection in fusion magnets

N. Bykovskiy, D. Uglietti, P. Bruzzone, and K. Sedlak

***Abstract*—High temperature superconducting (HTS) materials are widely utilized in various design proposals for fusion magnets, resulting in enhanced performance of the machines compared to the past. However, a reliable quench detection in HTS conductors remains an open issue. Using a co-wound superconducting wire of high normal state resistance as an electrically insulated and thermally coupled sensor provides strongly increased sensitivity for the voltage-based quench detection methods. Furthermore, resistance of the wire can be practically proportional to the size of the normal zone, even though the location of the hot-spot cannot be identified. We present adaptation of this method for fusion conductors by considering various wire options, such as MgB_2 wires in a highly resistive matrix, non-stabilized Nb_3Sn wires and (K,Na)-Ba122 wires. The insulated wire of a small diameter (<1 mm) can be embedded in the steel jacket, thus barely affecting the conductor design and manufacturing aspects. Alternatively, if installed within the cable space, the wires might even allow monitoring of quench dynamics among the strands. Our first experimental demonstration is planned in a sub-scale ReBCO cable-in-conduit sample, which will be tested in the SULTAN test facility recently upgraded for DC operation in resistive samples with the transport currents up to 15 kA and maximum voltage of 10 V.**

***Index Terms*—Quench detection, Fusion magnets**

I. Introduction

LARGE energy stored in superconducting magnets and highly non-uniform process of spontaneous thermal runaway, called quench, often result in stringent requirements for the quench detection and protection. In the case of HTS coil windings, the situation is further complicated by relatively low quench propagation velocity in these materials, thus postponing a detection trigger and leading to higher temperatures developed at the quench hot-spot. Hence, a large variety of quench detection methods based on different physical principles (electrical, magnetic, optical, etc) are being actively studied [1].

Fusion magnets, commonly designed using a forced flow of supercritical helium for cooling, feature specific methods for quench detection such as measurements of flow and absolute pressure in their hydraulic circuit [2]. Nonetheless, using voltage taps in combination with various techniques for inductive voltage cancellation still remains the main detection approach for the magnets already in operation (KSTAR [3], JT60-SA [4]) and yet being in construction (ITER [5]) or design phase (CFETR [6]).

In a presence of electromagnetic noise arising from the transient operations and plasma instabilities in fusion systems, co-wound voltage taps allow for a most advanced cancellation of large parasitic inductive signals [7]. Being applied initially as internal instrumentation in cable-in-conduits conductors, the method matured towards external instrumentation applied over the conductor turn-to-turn insulation, substantially simplifying manufacturing protocols and minimizing risk of failures, but also reducing the effectiveness of noise cancellation.

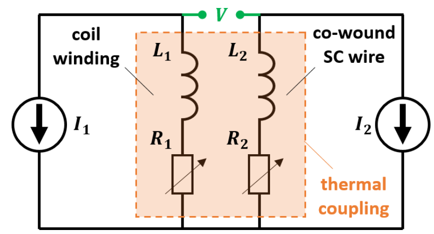

Figure 1. Schematic of a quench detection diagram using co-wound superconducting wire, which is electrically insulated from the coil winding, but situated in a good thermal contact.

Considering HTS coil windings in fusion magnets, preliminary studies of quench detection based on co-wound voltage taps and protection by external energy dump showed acceptable results in terms of the 150 K hot-spot requirement and maintaining the discharge voltage below 10 kV (see [8], [9]). As the key parameter, the copper current density of fusion conductors is typically set in the range of 100–120 A/mm^2, e.g. large amount of stabilizing copper has to be present, thus reducing engineering current density and magnet performance correspondingly. Extremely high discharge voltage developed during quench is also of high concern, thus triggering various proposals on potential design improvements [10].

Aiming at increased sensitivity of voltage-based measurements for quench detection, the idea of using superconducting wire as a detection sensor was first proposed in [11]: essentially, resistance measurements of the wire, which is electrically insulated but thermally in contact with the main conductor. It was developed into a miniature thin-foil non-stabilized Nb-Ti sensor of high normal state resistance [12] and further evolved toward a distributed co-wound sensor, being discussed for application in HTS pancake coils [13] and accelerator magnets [14].

As illustrated in Figure 1, the detection signal can be obtained by measuring voltage between the co-wound wire and the coil winding, thus written as:

$$V = V_{R_2} - V_{R_1} + V_{L_2} - V_{L_1},$$

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The authors are with the Ecole Polytechnique Fédérale de Lausanne, Swiss Plasma Center, CH-5232 Villigen PSI, Switzerland (e-mail: nikolay.bykovskiy@psi.ch).

$$V_{R_i} = \int E_i(T(x))dx = \int I_i R_i(T(x))dx,$$

where the inductive components along the winding V_{L_1} and the detection wire V_{L_2} are nearly cancelling each other. At the quench beginning, the resistive voltage along the winding V_{R_1} is relatively low due to large amount of stabilizer and the total voltage should represent the resistance of the co-wound wire over the quench zone $V \approx V_{R_2}$, implying that the temperature distribution $T(x)$ is nearly identical along the wire and the main conductor. As a result, the key requirements of the application are as follows:

- Critical temperature (T_c) of the detection wire at peak magnetic field has to be above the minimum current sharing temperature within the coil winding,
- High voltage developed along the normal zone of the detection wire ($\gtrsim$ 0.1 V/m), resulting from the corresponding material composition and operating current of the wire.

Although a relatively low operating current of the detection wire I_2 is assumed ($\lesssim$1 A), it can be set in a rather wide range in order to increase the detection response as needed. Further details, such as preparation procedures (i.e. need of heat-treatment, etching of stabilizer, insulation), long-length availability and cost, must also be considered. Note that proper operation of the wire is expected as long as its critical current is higher than the operating current, i.e. high Ic reduction can be tolerated.

Compared to fiber optics, being widely studied for various HTS applications (see [15], [16], [17]), the co-wound superconducting wires feature simplified and more robust instrumentation. However, they cannot be used to identify location of the hot-spot and their step-like response is fully determined by the material properties, thus cannot be arbitrarily tuned.

The applicability of the concept for fusion conductors is discussed below, presenting first suitable superconducting materials for the application, then planned activities for the first experimental demonstration and potential impact on the design of fusion magnets.

II. Material selection

Considering DEMO CS coils [18] as the target application, the detection wire should be superconducting in their regular operation at 5 K and 18 T peak magnetic field. In terms of irreversibility field, all of the practical superconductors except Nb-Ti can be considered suitable, see data compiled from various sources in Figure 2.

Measurements of T_c as a function of external magnetic field, and normal state resistance R_{ns} as a function of temperature have been performed on MgB_2, Nb_3Sn and (Na,K)-Ba122 wires using a variable temperature insert operated down to 4 K in the 11 T magnet at EPFL-SPC. The wires are operated at 0.1 A, which is sufficiently low to determine properly the T_c value by the resistance method [19].

A. MgB_2 wires

Un-doped in-situ non-insulated MgB_2 wires have been received from Hyper Tech Research, Inc.: (1) 0.52 mm diameter wire containing 60 filaments in Cu-Ni matrix and (2) 0.30 mm diameter / single-filament wire in stainless steel matrix. After winding on the ITER barrel sample holder, sintering of the wires has been performed at 650 ºC during 1 hour.

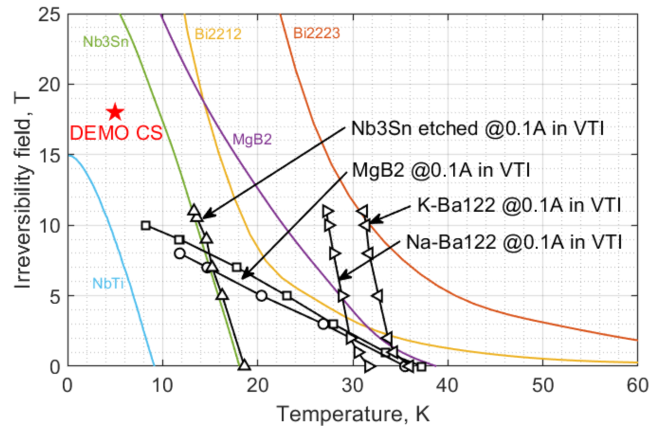

Figure 2. Dependence of irreversibility field upon temperature of various materials. The data obtained in this work (indicated with arrows) is compared versus those compiled from various sources. The target operating point of DEMO CS is also shown.

The wires feature high resistance in the normal state, up to about 2 Ω/m for sample 1 and 10 Ω/m for sample 2 at room temperature. The values decrease with temperature, down to ≈0.2 Ω/m and 5 Ω/m, respectively, at 40 K.

The measured $T_c(B)$ performance is similar and rather poor for both samples. Starting from ≈38 K at zero field, it rapidly decreases down to ≈10 K at 10 T magnetic field (see Figure 2). Although not suitable for the application at 5 K / 18 T, more advanced T_c performance has been reported for doped MgB_2 materials, up to 10 K at 20 T [20]. Therefore, the materials should still be considered promising for the DEMO CS application, especially accounting for the direct possibility of using highly resistive materials for the wire manufacturing by industry.

B. Nb_3Sn wires

Being extensively developed for many decades, Nb_3Sn wires are expected to have reliable and sufficiently high T_c performance for the application. Three wire compositions have been considered: (1) internal-tin 1.0 mm diameter wire from the WST company used for the DEMO R&W conductors, (2) bronze-route 0.8 mm wire from the Bochvar Institute used for the ITER conductors, (3) external-tin 0.13 mm wire used for the SULTAN conductor [21].

The first two options are copper stabilized. In order to increase R_{ns}, short-length samples were etched by nitric acid before and after sintering for sample 2 and 1, respectively. The measured $T_c(B)$ dependence is in-line with a typical curve for the Nb_3Sn materials (see Figure 2), fulfilling the target requirement. As regards R_{ns}, ≈0.5 Ω/m is obtained on the internal-tin wire and ≈0.3 Ω/m on the bronze-route at room temperature. Opposite to that, as presented in Figure 3, R_{ns} ≈ 0.13 Ω/m is higher for sample 2 at low temperatures (from 20 K to 40 K) than that for sample 1, increasing with temperature from 0.04 Ω/m to 0.13 Ω/m. Impact of the R_{ns} temperature dependence on a sensitivity of quench detection is further discussed in the next section.

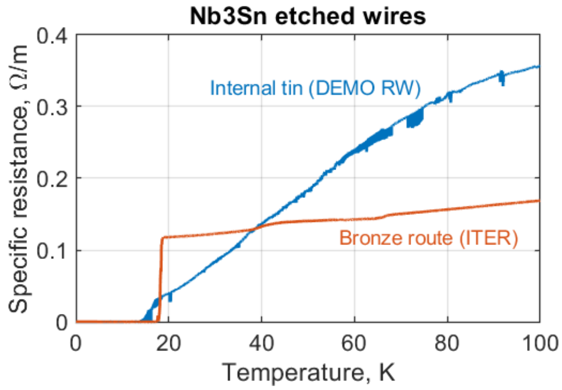

Figure 3. Specific resistance of internal-tin and bronze-route Nb_3Sn wires as a function of temperature.

The third wire option would feature, so far, the most advanced performance in terms of its normal state resistance due to absence of stabilizer materials and small size, thus reaching up to ≈60 Ω/m assuming 100% fraction of superconductor in the wire cross-section. Considering the $R_{ns}(T)$ dependence of pure Nb_3Sn material [22], this value should scale down to ≈8 Ω/m at 20 K, e.g. by far the highest value among the other options. Unfortunately, it is only left available at Swiss Plasma Center as a multi-stage twisted sub-cable and cannot be used immediately in an experiment. The feasibility of its long-length manufacturing has been demonstrated in the past development, thus leaving the potential for future re-establishment once the need will become apparent.

C. *(Na,K)-Ba122 wires*

Iron-based superconducting wires of 1 m length have been received from the University of Tokyo. Being previously used in a coil winding (see details in [23]), the single-filament wires of 1 mm diameter are stabilized by silver and copper layers.

Comparing with the previous materials, the T_c performance (see Figure 2) is least affected by external magnetic field, decreasing from 36 K at zero field down to 31 K at 11 T for the K-Ba122 sample. Hence, sufficiently high T_c is expected for the DEMO CS operating conditions. Furthermore, the materials can also be considered for operating conditions of compact fully HTS tokamaks (≈20 T / 20 K, see [24]).

However, high values of R_{ns} should yet be demonstrated. Etching stabilizers is likely no longer possible since, in contrast to the Nb_3Sn wires, diffusion barrier is not present, thus homogeneous properties along long lengths can hardly be achieved and exposing As-contained materials might be hazardous. Alternatively, in a view of the recent attempts of excluding silver from the wire manufacturing [25], further steps can be made by using highly resistive materials instead of copper. Although critical current density will be further reduced, achieving critical currents even as low as 10 A at the target operating conditions should actually be sufficient for the application.

III. Application in HTS fusion conductors

Following the recent upgrade of the SULTAN test facility [26], the first demonstration of using superconducting wire for a quench detection in fusion conductors is planned in a SULTAN 'quench experiment', which allows sample operation up to 15 kA / 10 V in 4 K – 300 K temperature range. As shown in Figure 4, the 3.6 m-long test conductor is composed of 21-tape stack of 3.3 mm-wide ReBCO tapes soldered in a copper profile (e.g. a single strand) and compressed by a steel jacket between two copper bars. The strand is cooled either directly by a forced flow supercritical helium or through a thermal contact with the copper bars, if the helium flow is only present in a separate cooling channel.

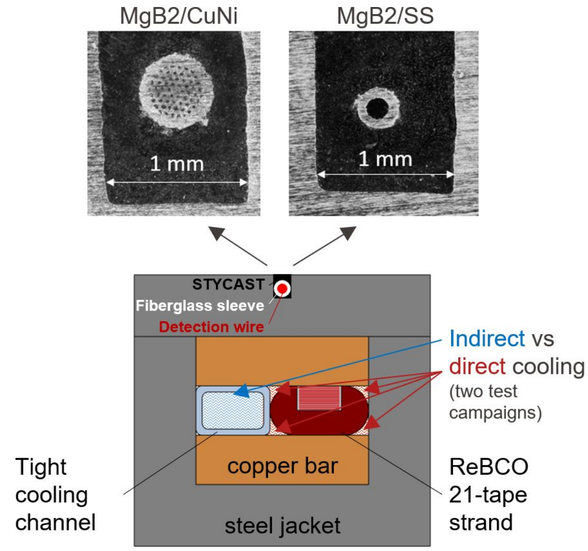

Figure 4. Sketch of HTS sample cross-section for a quench experiment in SULTAN. Detection wires will be installed in a steel groove on outer surface of the conductor, insulated by a fiberglass sleeve and glued using STYCAST.

Detection wires are installed after the heat-treatment in a 2 m long groove machined in the steel jacket. After insulating by a fiberglass sleeve, the wires are glued in the groove using STYCAST. A direct contact between the wires and STYCAST is expected, as observed on short test pieces (see top photos in Figure 4). Although some thermal gradient between the HTS tapes and detection wires is expected due to rather poor thermal conductivity of steel and uncertainty in thermal resistances between solid components, this location was chosen by practical considerations. Rather low values of the thermal resistance is expected due to jacket pre-compression and it will be evaluated from the measurements in SULTAN based on array of temperature sensors attached to the steel jacket, copper plates, ReBCO strand and cooling channel in the SULTAN high-field zone. Installing detection wires within the cable space would lead to a faster response and even potential study of quench dynamics in a multi-strand assembly (assuming that the detection voltage is proportional to the size of a quench zone), but compromised by issues of leak-tightness and electrical insulation at instrumentation feedthroughs.

In order to avoid bending strain exceeding the limits, the detection wire has to be placed near the neutral line of the conductor. However, it was not possible for the discussed conductor due to protruding temperature sensors occupying that location. Even though there is no risk of the wire damage (no bending strain), actual temperature gradients will have to be evaluated

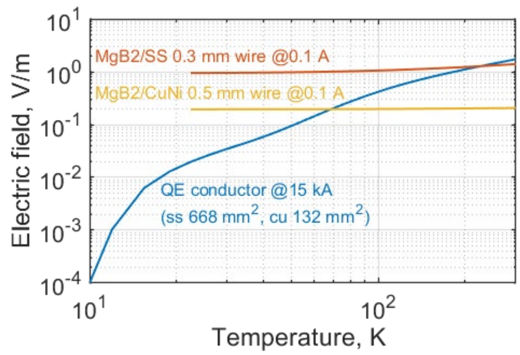

Figure 5. Electric field as a function of temperature developed in the quench experiment conductor at 10 T with the cross-section of steel and copper relevant for the DEMO CS. For comparison, expected performance of MgB_2 wires in stainless steel and Cu-Ni matrix operated at 0.1 A is also shown.

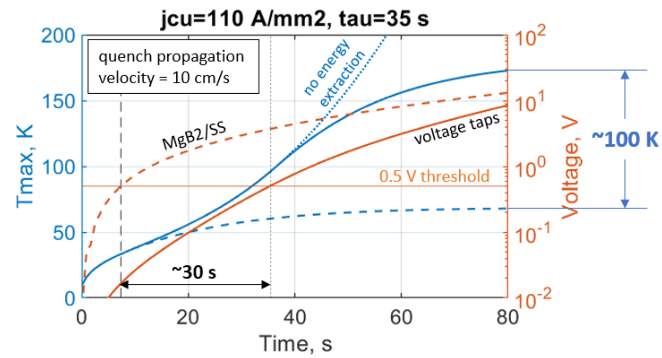

Figure 6. Comparison of voltage and hot-spot temperature for a quench detection based on voltage taps installed on the conductor (solid lines) and on the MgB_2/SS detection wire (dashed lines). After reaching 0.5 V detection threshold, magnet energy is dumped externally with the time constant 35 s.

based on experimental results to assess properly the detection sensitivity.

The total cross-section of copper used in the quench sample is about 130 mm^2, corresponding to the copper current density 110 A/mm^2 for the operation at 15 kA. Operation up to 60 kA is considered for DEMO CS using the copper cross-section of 550 mm^2 (i.e. nearly the same copper current density) and the steel cross-section order of 3000 mm^2. Hence, considering near the same material proportions, rough estimates for the quench sample using adiabatic 0-D quench model (presented below) should also be relevant for the case of DEMO CS.

First, accounting for a current sharing between tapes, copper and steel, the electric field as a function of temperature can be evaluated for the conductor. As presented in Figure 5, it starts rising from 0.1 mV/m at 10 K up to 2 V/m at 300 K. About 10 and 100 times higher electric field is developed along the MgB_2 wires in Cu-Ni and stainless steel at 20 K and 0.1 A operating current, respectively.

In the previous SULTAN quench experiments, the quench propagation velocity of the order of 10 cm/s has been measured on the HTS conductors. Considering this value and assuming a purely resistive signal measured by voltage taps, the detection threshold of 0.5 V is reached only in about 35 s, see Figure 6. The hot-spot temperature should reach about 100 K at this moment and further increase up to about 170 K during the exponential fast discharge with the time constant of 35 s. In contrast, the voltage along the MgB_2/SS wire hits the detection threshold about 30 s earlier, when the hot-spot temperature is near 35 K. At the end of the fast discharge, it increases only up to 70 K, almost 100 K below the hot-spot temperature reached with the traditional quench detection. This difference highlights the advantage of using co-wound superconducting wires compared to the voltage taps.

Reducing the diameter of the detection wires is favored by the application, allowing strong increase of R_{ns}. However, even if R_{ns} as high as that of the MgB_2/SS wire would not be achieved (though shaping solutions like wire swaging can be attempted), the detection response can still be increased by adjusting the wire operating current, which was so far considered to be fixed to 0.1 A. Hence, if reliable operation of the detection wire could be ensured (so far, the reparability is the main issue), the quench protection requirements can be fulfilled at much lower amount of stabilizing copper and/or reduced magnet discharge voltage.

Conclusion

Co-wound superconducting wires are proposed for quench detection in fusion magnets. Similar to co-wound voltage taps, the inductive contributions can almost be cancelled, but the possibility for independent resistance measurements over the non-stabilized wires, subjected to near the same temperature distribution as the main conductor, allows a strong increase of the detection sensitivity compared to the voltage measurements on the conductor, up to a factor 100.

MgB_2 in highly resistive matrix and etched Nb_3Sn wires are considered suitable for the application as detection wires in DEMO CS coils operated at 5 K and 18 T peak magnetic fields. If their HTS coil sections will be designed for high current sharing temperature (>~10 K) to account for high transient AC losses, the iron-based wires may still be used, although a non-stabilized composition is yet to be demonstrated.

As a result, the first experimental demonstration of the detection concept for fusion conductors will be carried out using the 15 kA ReBCO conductor being constructed for a quench experiment in the SULTAN test facility and containing the detection wires on the outer surface of the steel jacket.

Once experimentally proven useful, the detection concept may either allow to reduce significantly the hot-spot temperature or enable potential improvements in the magnet design such as reduced amount of the copper stabilizer required for the fusion conductors and/or lower magnet discharge voltage. Further increase of the detection sensitivity is expected by using superconducting wires dedicated for the application, i.e. of small size, high normal state resistance and sufficient critical temperature for the target operation.

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