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Development of Magnet Technologies for HTS Insert Coils

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Abstract

An existing Nb_3Sn laboratory magnet generating a magnetic field of 12 T is intended to be upgraded to 16 T by means of the use of a high temperature superconductor (HTS) insert coil. An outline design of the HTS insert coil is presented. In the design, the aspects of the maximum achievable operation current, the required copper cross-section to ensure a hot spot temperature below 200 K and the resulting forces and stresses have been considered. The length of the insert coil has been selected in such a way that the field uniformity will be better than 1% within a sphere of 3 cm diameter. The protection of the whole magnet system (LTS & HTS insert) is briefly described.

Keywords: Coated conductors; HTS insert coils; HTS magnets, magnet design; protection; second generation HTS

1. Introduction

Second generation HTS, which exhibit excellent superconducting and mechanical properties, have the potential to be used at low temperatures as insert coils that allow new high field hybrid magnets as well as upgrades of existing low temperature superconductor (LTS) coils. Due to upper critical fields of less than 26 T at 4.2 K the maximum field achievable with Nb_3Sn magnets is around 24 T. The superconducting properties of RE-123, Bi-2212, and Bi-2223 would provide the possibility to generate fields well above 30 T. In Fig. 1, the critical current (I_c) of RE-123 coated conductors at 4.2 K is shown as a function of the perpendicular magnetic field (Fig. 1a) and the angle between the broad face and the field direction (Fig. 1b). Furthermore, the HTS must be able to withstand the large stresses caused by the Lorentz forces. A disadvantage of Bi-based HTS is their mechanically weak silver alloy matrix. Second generation RE-123 coated conductors using Hastelloy substrates provide a stress tolerance of better than 600 MPa, which is considerably better than that of Nb_3Sn (200 MPa). The envisaged inner radius of the HTS insert coil is as small as 22 mm, which is well below the minimum tolerable bending radius of Bi-2223 tapes. Consequently it was decided to use RE-123 coated conductors for the manufacture of the HTS insert coil.

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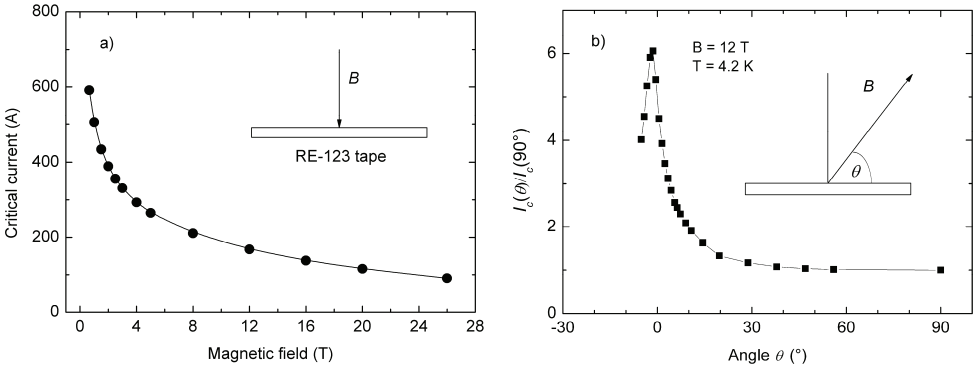

Fig. 1. (a) I_c of RE-123 tapes (4 mm width) at 4.2 K versus perpendicular magnetic field; (b) Dependence of I_c on the angle θ between the field direction and the broad face of the tape [1]. Higher values and a less pronounced anisotropy are expected for the new coated conductors with artificial pinning centers now in production.

2. Outline Design of the Insert Coil

The main design parameters of the RE-123 insert coil are gathered in Table 1. In a background field of 12 T a field of 4 T is added by the insert coil leading to a total central field of 16 T. Because of the anisotropy of I_c with respect to the field direction (see Fig. 1) the operation current (I_{op}) is limited by the maximum radial field component close to the outer radius at the coil ends. Here, the total field is about 12 T with an angle θ of 10°. Fig. 1 indicates that the envisaged I_{op} = 260 A is well below the estimated I_c of 320 A in RE-123 tapes of 4 mm width. Due to the mismatch of the maximum possible I_{op} values in the LTS magnet (82 A) and the HTS insert (260 A) it will be necessary to use a separate power supply to energize the insert coil. The selected height of the insert coil of 122 mm is sufficient to ensure a field uniformity of better than 1% in a central sphere of 3 cm diameter. The added field depends on the overall current density of the winding pack. It is therefore necessary to make the insulation of the RE-123 tapes as thin as possible. The use of Kapton insulated RE-123 tapes would lead to a total thickness of ≈0.3 mm, which is three times the thickness of the bare tape. Therefore, it was decided to apply a UV cured epoxy acrylate insulation of only 0.025 mm thickness on both sides leading to a total thickness of 0.21 mm.

A further aspect of importance is the hot spot temperature in case of a quench, which should not exceed 200 K in order to avoid detrimental thermal stresses in the winding. Supposing that the quench process is adiabatic the hot spot temperature was estimated.

Table 1. Main design parameters of the HTS insert coil.

Parameter	Value	Parameter	Value
Inner diameter (mm)	44	Total number of turns	1680
Outer diameter (mm)	68	Number of layers	58
Height (mm)	122	Inductance (mH)	50
Required tape length (m)	300	Insert coil current (A)	260
Total thickness of tape (mm)	0.21	Winding current density (A/mm^2)	290
Thickness of Cu per side (mm)	0.05	Energy stored in the insert coil (J)	1800
Thickness of insulation (mm)	0.03	Added / total field (T)	4 / 16

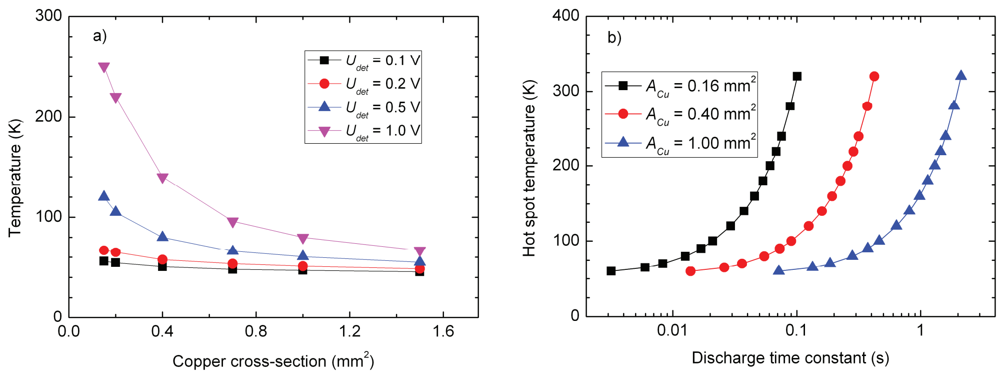

Fig. 2. (a) Temperature reached at the detection voltage U_{det} versus the Cu cross-section of the RE-123 tape; (b) Hot spot temperature versus the discharge time constant τ for selected values of the Cu cross-section.

In Fig. 2a, the temperature reached before current dump is shown as a function of Cu cross-section, while the maximum hot spot temperature T_{hs} reached after a current dump with exponentially decreasing current is presented in Fig. 2b. In the calculation of T_{hs} it was assumed that the temperature at the initiation of the current dump is 50 K. The data clearly indicate that a detection voltage of 0.5 V or higher leads, in connection with a small copper cross-section, to temperatures above 100 K at the initiation of the current dump. Increasing the Cu cross-section from 0.16 mm^2 to 0.4 mm^2 provides considerably larger safety margins, whereas the central field is reduced by only 5%. For example, the tolerable discharge time constant $\tau = L/R$ (L inductance, R dump resistance) is enlarged by at least a factor of 2.

In the mechanical design the hoop force and the radial stress need attention. The field distribution in the insert was calculated using the code MAD (Cryosoft). The contribution of the 12 T LTS magnet was estimated from the field map provided by the manufacturer. Using the expression $F = I\,B\,r$ a hoop force of 94 N was calculated at the inner radius of the insert coil, which increases to 111 N at the outer radius. Taking into account that the Young's modulus of the RE-123 tapes, which is estimated to be 130 GPa for the tape with 0.4 mm^2 copper, a tensile strain of less than 0.20% was found at the outer radius, which is well below the critical tensile strain of 0.45%. The radial stress was calculated analytically following the procedure described in [2]. The increase of the hoop stress with increasing radius leads to a tendency that the layers detach from each other. The maximum radial stress in the winding is ≈4.2 MPa as indicated in Fig. 3. Because of the sensitivity of RE-123 tapes to de-lamination it is foreseen to counteract the radial stress by a sufficiently large winding tension.

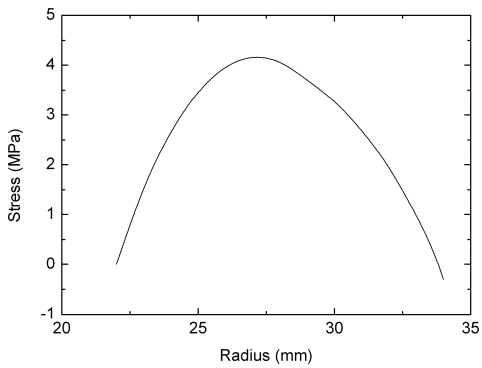

Fig. 3. Radial stress in the central plane of the insert coil as a function of the radial position.

3. Winding and Insulation

Single, double pancake, or layer winding methods are all possible using tape conductors. Traditionally the double pancake technique is used with tape conductors. In spite of recent calculations showing that a large strain may be induced on layer-wound coils of small inner diameter examples of successfully tested layer-wound coils can be found in the literature [3-5]. In case of a double pancake construction 15 double pancakes, each wound with 20 m long tapes, would be required. A layer-wound coil could be wound using a single piece of tape of 300 m length or with two pieces of 150 m length, with a joint. First trials to apply an epoxy acrylate resin, which was cured under UV light, were successfully performed.

4. Quench

The coil is protected by a resistor in parallel with the insert coil. The signal of voltage taps attached to the coil will be used for controlling the “Remote Inhibit” digital input of the HP power supply. The power supply will be switched off, when the voltage exceeds a threshold value of 100 mV. The size of the dump resistor is selected in such a way that the τ value of the insert coil is less than 0.1 s. The use of a separate power supply for the insert provides the advantage that the insert can be dumped more rapidly than the main LTS magnet. More details of the quench protection have been published elsewhere [6].

5. Conclusion

An HTS insert coil, made of tapes with a Cu stabilizer optimized for quench protection, will be used to enhance the field of an existing LTS magnet from 12 to 16 T. To achieve a sufficiently high winding current density a very thin UV cured epoxy acrylate insulation will be used. The field homogeneity in a sphere of 3 cm diameter is better than 1%. The calculated stresses are well below the critical values.

Acknowledgements

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