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Research paper

# Test results of 12/18 kA ReBCO coated conductor current leads

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ABSTRACT

A pair of hybrid current leads (brass + stacked & soldered ReBCO tapes) rated for 12 kA in steady state and for up to 18 kA at pulsed over current conditions was designed, developed and tested at NRC "Kurchatov Institute" (NRC "KI"). During the experiment at LN2 temperature, the current leads (CLs) were successfully charged with 18 kA at 100 A/s ramp rate. To date, as far as we know, this is the highest current capacity achieved for 2G HTS current leads. The feasibility of "stack-and-soldering technique" for 10 kA+ class coated conductor CLs for accelerators and fusion was demonstrated. This paper gives an overview of the leads design and presents the preliminary test results. Detailed studies of magnetic properties and current sharing process for the stacked and staggered HTS joints are also reported.


## 1. Introduction

Today the technology of fabrication of Bi2223-based hybrid current leads for accelerators is well developed. During the last 20 years, 1G HTS current leads have passed their way from first prototypes to mass production. In general, it is one of the largest practical applications of HTS materials. 1074 Bi2223 CLs with the rating current values 0.6 kA, 6 kA, 7.5 kA and 13 kA have been successfully operating in LHC for 3 years [1]. The current capacities up to 68 kA were achieved on 1G CL prototypes for ITER, where 60 CLs with more than 2.5 MA total current will be needed [2–5]. A few special test facilities were constructed for fast commissioning of dozens and even hundreds 1G HTS CLs for HEP and fusion [6,7]. Science has finally grown into reliable technology.

What about 2G coated conductors for CL application? The price of a Bi2223 wire for current leads with Ag-Au matrix is 5 times higher than for a 2G tape with the same current capacity. The coated conductor SF12100 (without copper stabilizer) fabricated by SuperPower Inc. has high critical current (Fig. 1a and b) and better in-field properties (Fig. 1c) combined with very low thermal conductivity (Fig. 1d). Nevertheless, there are still lots of technical issues to overcome.

Different attempts of 2G CL development were reported recently [8–14]. A few scientific groups proposed a design of 1 kA-class CLs made with 6 ReBCO tapes mounted on hexagonal supporting bars [8,9,11]. The authors [10] investigated a simple stack of two soldered 2G tapes 344S (AMSC) and showed that the resistance of the joint for the upper tape in the stack is approximately 33 times higher than that for the lowest one. In this context, they did not recommend stacking method for coated conductors. Chang et al. [11] proposed a solution for the current distribution problem formulated as an "individual current path terminal method". It was based on making low-resistance copper terminals with multiple rectangular holes for CC insertions.

Thus, all mentioned prototypes used arrays of single tapes, not stacks. To date, the highest current capacity of 2G CL was independently demonstrated by two scientific groups from the USA and Japan. Both teams designed hybrid leads with a single-layer parallel structural support of HTS tapes. The first pair of 4 kA CLs was developed by NHMFL with a single layer of slightly spiraled tapes SuperPower SF12050 [12]. The authors [12] don't recommend soldering of CCs over their full length either. The second team constructed 5 kA CLs assembled from ten flat elements (5 un-stacked ReBCO tapes on a fiberglass bar) connected in parallel [13,14].

HEP accelerator magnets and thermo-nuclear reactors require leads with the highest current capacities up to 100 kA. Therefore, a method of combining of 2G tapes into high current elements is

*Abbreviations:* HTS, high temperature superconductor; LTS, low temperature superconductor; CC, coated conductor; 2G, second generation; CL, current lead; LN2, liquid nitrogen; GN2, gaseous nitrogen; SHe, supercritical helium; LHC, large hadron collider; HEP, high energy physics; RT, room temperature; SEI, Sumitomo Electric Industries; AMSC, American Superconductor; s.f., self field; FEM, finite element method.

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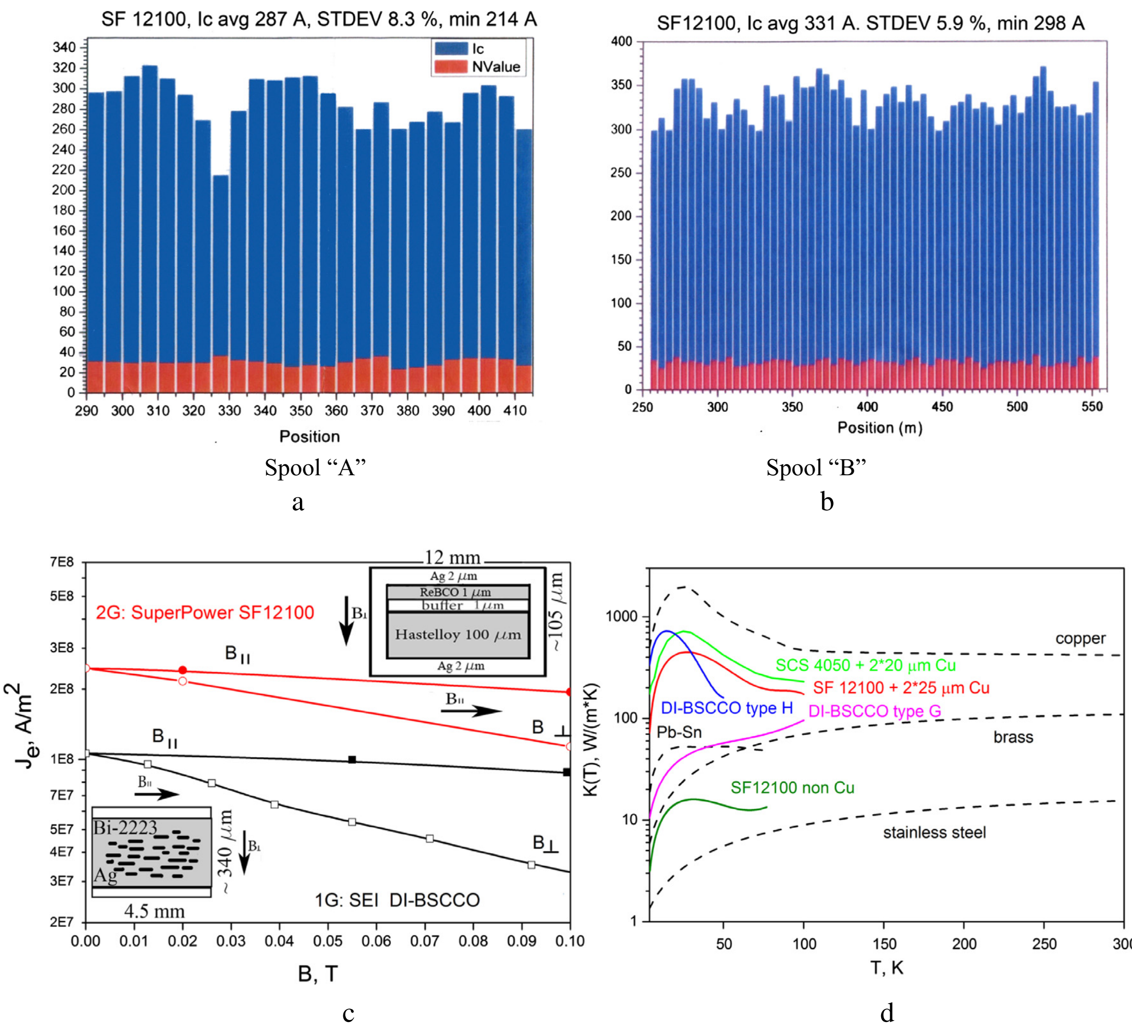


| Parameter/ data source | HTS materials | | | | Resistive materials |
|---|---|---|---|---|---|
| | SF 12100 (SuperPower) | SCS 4050 (SuperPower) | DI-BSCCO type G (SEI) | DI-BSCCO type H (SEI) | |
| Thermal conductivity vs. *T* | NRC "KI" | NRC "KI" | [21] | [21] | [22],[23] |
| Critical current vs. length | [12] | [12] | - | - | - |
| Critical current density vs. *B* | NRC "KI" | - | NRC "KI" | NRC "KI" | - |

**Fig. 1.** Critical currents at 77 K, s.f. (a,b); in-field engineering critical current density (c) and thermal conductivity (d) for HTS tape SF12100 in comparison with other materials [21–23].

strongly needed. The development of low-ohmic reliable joints is another challenge.

The objective of our research activity was to verify the "stack-and-soldering technique" for 10+ kA class 2G CL applications. Below we give an overview of the CCs stacking, soldering and termination methods, discuss thermal and magnetic properties of the leads and present the preliminary test results.

## 2. Design

### 2.1. Resistive section

Fig. 2 shows a design overview of 2G hybrid current leads rated on 12 kA in steady state and up to 18 kA in a pulse mode. The design summary is given in Table 1.

The current lead is divided into two parts: a resistive section (300–77 K) and a conduction cooled HTS module (77–5 K). In future projects, the design of the cold end can be developed in accordance with the particular magnetic system specification.

CLs made of pure metals are very sensitive even to a slight (<25% of the optimal value) overcurrent due to a positive feedback in the material resistivity accompanied with an unacceptably fast temperature rise [16]. That's why most of binary 1G CLs have copper heat exchangers, cooled with forced-flow of gaseous helium [1–5]. In this effective but rather complicated scheme the temperature of the upper end of an HTS section must be carefully monitored.

We used more common approach for the resistive section design: two un-cooled brass rods covered with a stainless steel tube 100 mm dia. The length and the diameter of each rod are 200 mm and 40 mm correspondingly.

Fig. 3 shows FEM simulated temperature distribution along the CL and the heating loads for different currents in stationary modes calculated with Comsol MultiPhysics software [24]. The temperature of the ambient copper terminal is supposed to be maintained at 300 K. Based on the thermal conductivity of the materials (Fig. 1d) and Wiedemann – Franz law the heating load to the LN2 vessel was calculated as 250 W at zero current and 550 W for the