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# *Recent developments in superconducting materials used to build short-circuit current limiters*

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## Introduction

A short-circuit current limiter, also alternatively called fault current limiter (FCL) is a device that limits the occurred fault current, in a most cases in a power transmission network, without the need to completely disconnect the power supply system. In order to increase a current carrying capacity and economical efficacy of the FCL production, the superconducting fault current limiters (SFCL) have been developed (Figure 1b and 1c).

The first attempts to build FCLs using superconductors (SC) were realized with Nb-Ti superconducting wires (critical temperature $T_c$ about 9.0 K). This material is a low-temperature superconductor (LTS), and devices made of it must operate in a liquid helium bath (4.2 K), which generates a high cooling effort that makes their operating costs prohibitive [1]. Practical LTS are usually manufactured as a wire composed of thin superconducting filaments embedded in copper or copper alloy [2]. In 1986, a revolution in SC applications was the discovery of a superconductor with $T_c$ above 30 K [3,5]. The new SC materials were called high-temperature superconductors (HTS). Hundreds of new HTSs have been discovered, but only three of them could reach the development level needed for energy applications: $YBa_2Cu_3O_{7-y}$ (or YBCO, with $T_c$ = 92 K), $Bi_2Sr_2CaCu_2O_8$ (Bi-2212, with $T_c$ = 92 K), and $Bi_2Sr_2Ca_2Cu_3O_{10}$, Bi-2223, with $T_c$ = 110 K. Yttrium can be replaced by most other rare earth elements (or a mixture of them). In such case, the superconducting variant is called $[RE]Ba_2Cu_3O_{7-y}$ or REBCO, where RE = Y, La, Nd, Sm, Eu, Gd, Ho, Er, Tm, Lu. The resulting compound is an HTS with about the same $T_c$. In 2001, a new superconductor MgB2 with $T_c$ = 39 K was discovered. It demonstrates properties intermediate between LTS and HTS and may be useful in power applications [2].

SC can be produced in bulk [3] or as wires [2, 4] for SFCL applications. The first generation of HTS wires (1G) was made by processing Bi-2223 or Bi-2212 powder inside a silver (or silver alloy) tube, stretching it into a wire, and then laminating it into a tape. Currently, REBCO-based tapes, known as second-generation HTS (2G), are the most suitable materials for power applications and SFCL production [5-7]. The 2G wire consists of a thin REBCO ($[RE]Ba_2Cu_3O_{7-y}$) layer deposited on a metal substrate tape and covered with a silver layer. The paper describes the most commonly used 1G and 2G HTS tapes for SFCL production.

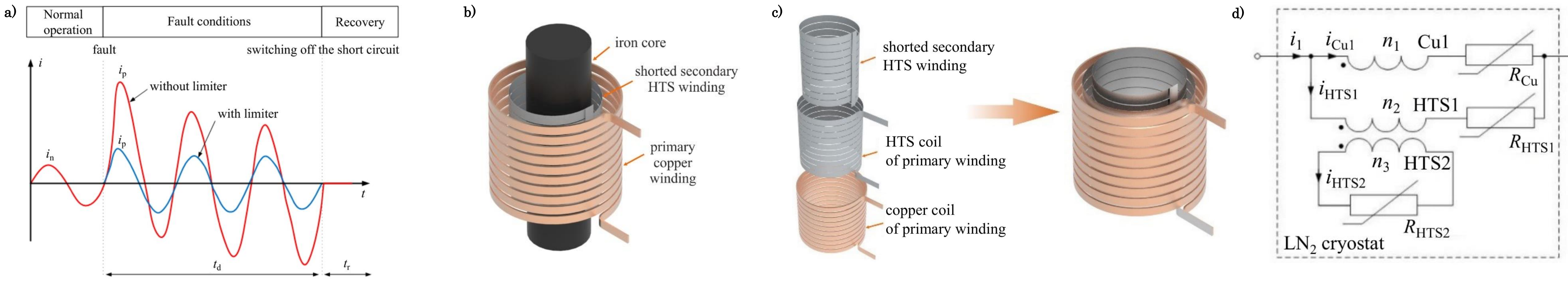


**Figure 1. [8]: a) The principle of SCFL operation, b) exemplary inductive type of SCFL with open shielded core, c) inductive type triple-winding coreless SCFL, d) substitute electrical diagram of triple-winding coreless SCFL**

Three states of operation of superconducting current limiters can be distinguished (Figure 1a): the waiting state, the current limiting state and the reactivation state. In nominal conditions, the limiter is in the waiting state, the impedance of the limiter should now be close to zero, and losses for the cooling of superconducting components should be minimised. The operating time in the current limiting state is limited by the maximum temperature of the superconducting elements that can be permitted without damaging them. The duration of the reactivation state depends primarily on the temperaturę to which the superconductor will be heated in the current limiting state and secondarily on the cooling system used. Typical SFCL consists of two (Figure 1b) or three (Figure 1c) windings and can have an iron core or just be coreless as shown in Figure 1 [8]. Exemplary substitute electrical diagram of triple-winding coreless SCFL is swon in Figure 1d.

## HTS 1G tapes for SFCL production

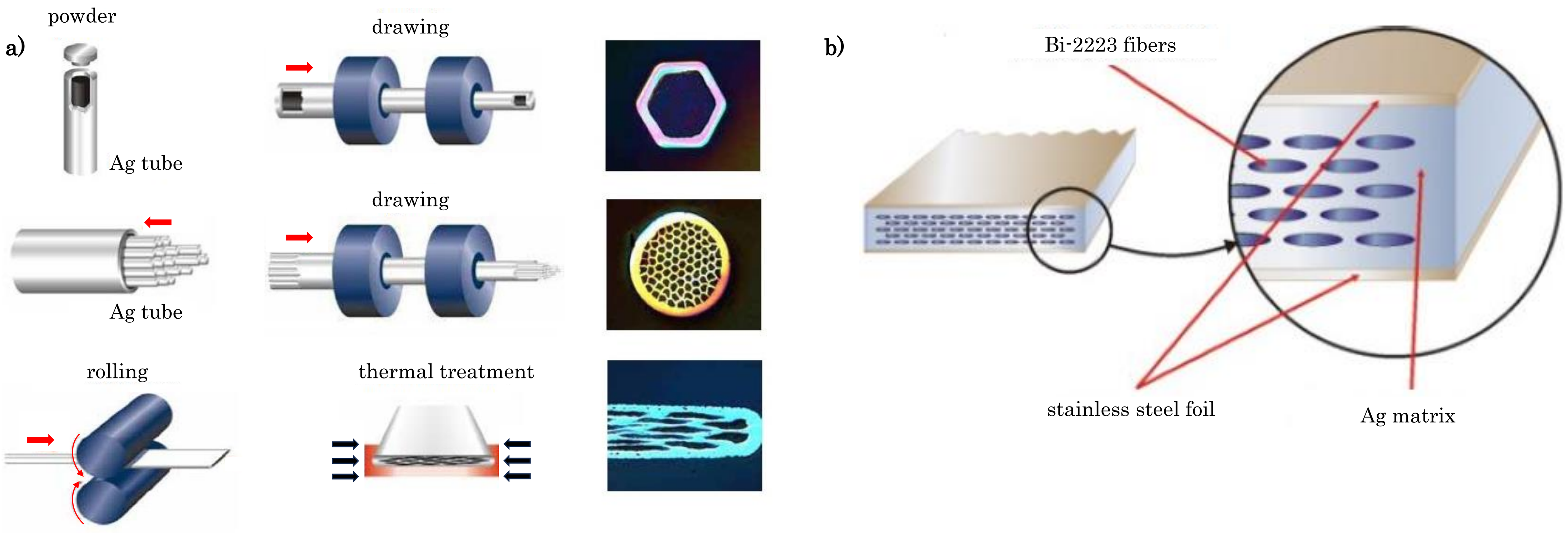


**Figure 2. a) 1G multi-fiber composite cable manufacturing proces, b) exemplary construction of 1G SC tape**

SC tapes consist of HTS fibers Bi–2223 or Bi–2212. They are manufactured in the tube-powder process [9] as shown in Figure 2a. The precursor of the SC material in the form of powder is placed in a silver tube (matrix) of an appropriate diameter, and then the tube with the powder is subjected to preliminary drawing to reduce its diameter. Harness of the thus prepared tubes with SC powder are placed in a silver tube of a larger diameter and drawn until a wire of an appropriate diameter and number of fibers is obtained. In the next stage of production, the tubes are rolled to give them a flat shape. After mechanical processing, the wire is subjected to thermal treatment. 1G superconducting tapes have a composite structure and consist of several dozen SC fibers (Bi–2212 or Bi–2223) placed inside a silver matrix (Figure 2b) [10]. The matrix can be pure silver, silver-gold alloys or alloys of other metals [11]. The matrix material has a decisive influence on the mechanical strength of the tape. Additionally, they are laminated with a thin layer of stainless steel to increase the mechanical strength of HTS 1G tapes. The maximum length of the 1G tapes produced is currently 1000 meters with a critical current from 115 A to 200 A at a temperature of 77 K with a width of about 4 mm and a thickness of 0.3 mm. The value of the critical current of the first generation superconducting tape depends on the temperature of the conductor and the value of magnetic induction on its surface.

## HTS 2G tapes for SFCL production

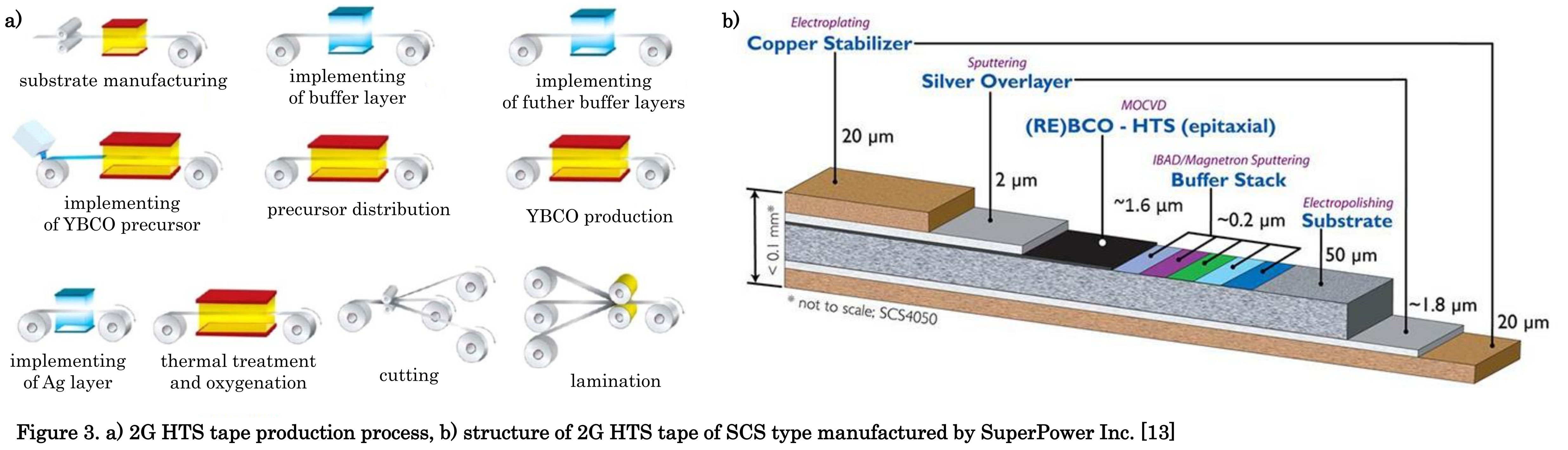


**Figure 3. a) 2G HTS tape production process, b) structure of 2G HTS tape of SCS type manufactured by SuperPower Inc. [13]**

HTS 2G cables are manufactured in the form of tapes with a layered structure [12]. In the production process of 2G superconducting tapes (Figure 3a), buffer layers are applied to the metal substrate, followed by a layer of a suitable superconductor precursor, from which a superconductor is formed after heat treatment in an oxygen atmosphere. A silver layer is applied to the superconductor layer, and then the tape is cut into narrower tapes and laminated depending on the tape type. The superconductor in 2G cables is yttrium–barium copper oxide YBCO or other rare earth elements (gadolinium, neodymium, samarium) in connection with barium–copper oxide ReBCO [10]. In HTS 2G superconducting tapes, the substrate layer is made of a non-magnetic material with high resistivity. In the most cases, it is the Hastelloy C276 alloy with the percentage composition: Ni–57%, Mo–16%, Cr–15.50%, Fe–5.50%, W–4.00%, Co–2.50%. A layer of silver about 2 μm thick is deposited on the superconducting layer. The SCS type SC tape is additionally covered with a 20 μm layer of copper [13].

## Recent manufacturers of 1G and 2G HTS tapes

Currently, there are several manufacturers on the market that supply 1G superconducting cables, including: Sumitomo Electric, American Superconducto Bruker HTS (Figure 4 a-c). The main manufacturer of first-generation superconducting tapes is Sumitomo Electric. HTS 1G tapes of the HT type (Figure 4a) ar characterized by a reinforced mechanical construction, thanks to a double-sided coating of stainless steel, copper or nickel. Additionally, the tape is sealed on bot sides with solder to limit the penetration of cryogenic liquid into the tape. The High Strength Plus Wire tape (HSPW, Figure 4b) consists of several doze superconducting fibers placed in a silver matrix. The SC tape is protected against the penetration of cryogenic liquid under pressure into the inner part of th tape due to lamination. Another solution available on the market is the Bi-2223/Ag superconducting tape manufactured by Bruker HTS (Figure 4c).

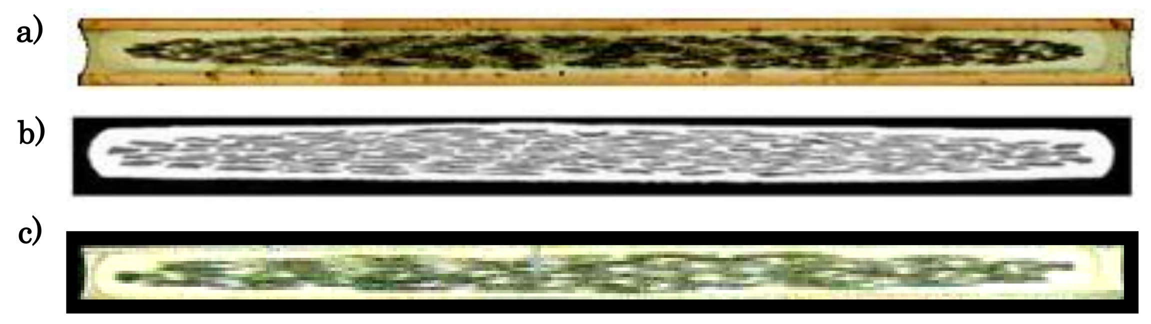


**Figure 4. Cross section of: Sumitomo Electric BSCCO type HT wire (a) [14], Bi-2223/Ag Bruker HTS tape (b), and HSPW tape produced by American Superconductor (c)**


**Figure 5. 2G HTS tapes produced by: a) and b) – Super Power Inc., c) – Bruker Inc., d) – Shanghai Superconductor Inc.**

SF type 2G HTS tapes (Figure 5a) are specially designed for use in SFCLs, in which a 1 μm thick SC layer is covered only with a thin 2 μm - 4.5 μm layer of silver. For the windings of electromagnets, motors, generators and transformers, as well as for the construction of SC cables, SuperPower Inc. produces SCS tapes (Figure 5b) laminated with copper. Another manufacturer of second-generation SC tapes is American Superconductor, which produces three types of HTS 2G SC tapes laminated using: brass, copper, and stainless steel. The manufacturer of second-generation YBCO SC tapes is Bruker HTS (Figure 5c). Shanghai Superconductor Inc. Produces REBCO S.C. tapes of 2G (Figure 5d) for applications in power cables, SFCLs, transformers, etc.

## Conclussions

- Currently, the most commonly used superconducting materials for SFCL construction are 1G and 2G SC tapes.
- 1G tapes are composed of Bi–2212 or Bi–2223 SC fibers and a matrix of metals or their alloys. They are used in: SC current bushings, SC cables, SC electromagnets, SC electric machines.
- 2G tapes have a chemical structure [RE]BCO, where Re are materials such as Y, La, Nd, Sm, Eu, Gd, Ho, Er, Tm, Lu. The REBCO structure is multi-layered and contains: stabilizer layers, metal overlayes, REBCO superconductor, buffer layer and substrate. They are often coated (laminated) with copper, brass, stainless steel. They are used in: SFCLs, electric motors, generators, transformers.
- At liquid nitrogen temperature (77.4 K), HTS 2G tapes show advantages over HTS 1G tapes. HTS 2G tapes can operate with higher critical currents and in higher external magnetic fields.

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