ELSEVIER

Journal of Nuclear Materials 258–263 (1998) 1940–1945

journal of nuclear materials

Developments of high-T_c superconducting current feeders for a large-scale superconducting coil system

T. Mito [a,*], K. Maehata [b], M. Mizokami [b], K. Ishibashi [b], M. Takeo [b], A. Iwamoto [a], N. Hirano [c], T. Shintomi [d], K. Kimura [e], M. Sawamura [e], S. Yamada [a], S. Satoh [a], O. Motojima [a]

[a] *National Institute for Fusion Science (NIFS) Toki City, Gifu Prefecture 509-5292, Japan*

[b] *Faculty of Engineering, Kyushu University Fukuoka City, Fukuoka Prefecture 812-8581, Japan*

[c] *The Graduate University for Advanced Studies Toki City, Gifu Prefecture 509-5292, Japan*

[d] *High Energy Accelerator Research Organization (KEK) Tsukuba City, Ibaraki Prefecture 305-0801, Japan*

[e] *Advanced Technology Research Laboratories, Nippon Steel Corporation Kawasaki City, Kanagawa Prefecture 211-0035, Japan*

Abstract

A large-scale superconducting coil system, which is an essential technology for a fusion reactor, requires large capacity and high performance current feeders from the power supplies at the room temperature to the superconducting coils at the operating temperature, which is usually liquid helium temperature at present. The superconducting current feeders are being considered as a promising application of a high temperature superconductor (HTS), which can satisfy the requirements of a large current capacity and a low heat in-leak, simultaneously. To study the feasibility of the HTS current feeders, a melt-textured YBCO bulk superconductor was selected as a candidate material because of its high current transport characteristics. The YBCO disk fabricated by quench and melt growth process was cut into a short sample with the cross section of 7 mm × 7 mm and the length of 40 mm and was mounted on the copper bars to perform the actual large current transport tests. The sample could be successfully excited up to 20 kA at 4.2 K and 10 kA at 77 K. These performance test results and the further R&D items for the HTS current feeders are discussed.

1. Introduction

A large-scale superconducting system consists of many components; superconducting coils, supporting structure for a large electromagnetic force, a cryostat, a cryogenic system, a power supply system, a protection system and their interfaces. As the system becomes large, the peripheral devices such as a cryogenic system and a power supply system are set up away from the superconducting coils. For the Large Helical Device (LHD) [1], which is the first fully superconducting heliotron type experimental fusion device under construction at the National Institute for Fusion Science (NIFS), the distances between the superconducting coils and the power supplies become 45–66 m. A current feeder connecting the power supply and the superconducting coil is a key component of the superconducting system, which is used not only to supply current to the coil but also to extract the large magnetic stored energy from the coil when the coil quenches. A current feeder is composed of current leads, a bus line, a coil lead and their interfaces. These components are being considered as a promising application of a high temperature superconductor (HTS), which can satisfy the requirements of a large current capacity and a low heat in-leak, simultaneously.

Recently, many types of HTS based on Bi-compounds have been developed and were applied to the current leads [2]. However, the current leads consisting of Bi based conductors need large geometrical dimensions for high current capacities above 10 kA due to the limit of the critical current density under the large self

* Corresponding author. Tel.: +81 572 58 2123; +81 572 58 2616; e-mail: mito@nifs.ac.jp.

0022-3115/98/$19.00
PII: S 0 0 2 2 - 3 1 1 5 (9 8) 0 0 3 4 1 - 9

magnetic field. Porcar et al. demonstrated the feasibility of a high current transport device made of HTS based on $YBa_2Cu_3O_x$ (YBCO) [3]. Because of the large pinning force, YBCO have a high critical current density, which is about 10 times higher than that of the Bi-compounds. We have been developing a compact high current feeder based on YBCO [4]. In this paper, we present feasibility test results of YBCO conductor and discuss the further R&D items, which are necessary for the application of HTS current feeders.

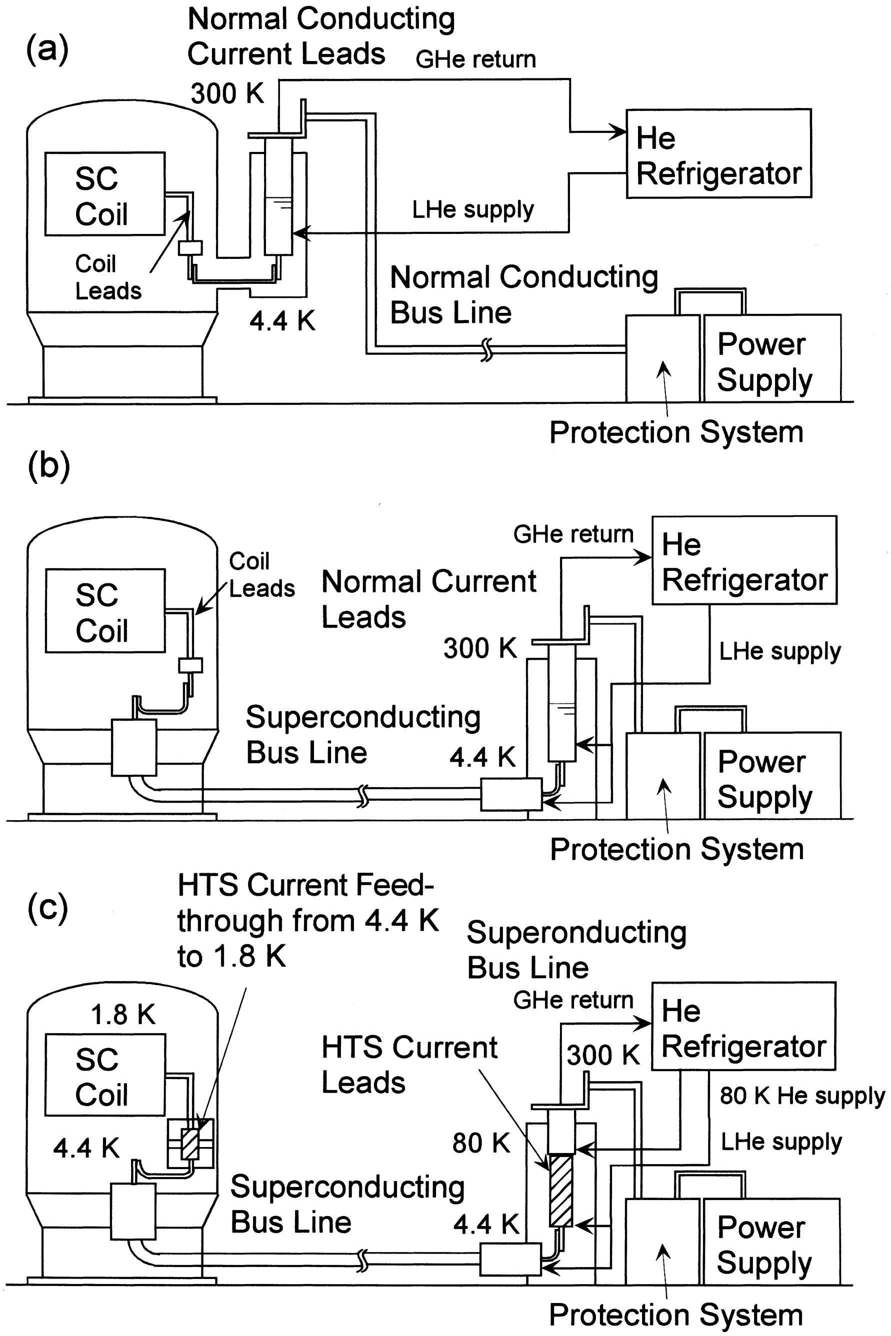

Fig. 1. Typical setups of current feeders for a large-scale superconducting system: (a) a conventional setup using a normal conducting bus line and normal conducting current leads; (b) an advanced setup using a superconducting bus line and normal conducting current leads; (c) a future setup corresponding to the LHD in phase II operation using a HTS current feed-through from 4.4 to 1.8 K, a superconducting bus line and HTS current leads.

2. Current feeders for a large scale superconducting system

Fig. 1 shows typical setups of current feeders for a large-scale superconducting system. Fig. 1(a) is a conventional setup using a normal conducting bus line and normal conducting current leads. The current leads cryostat is settled adjacent to the coil cryostat and the 4.4 K terminals of the current leads and the terminals of the coil leads are connected with short superconducting bus lines. In this case, the energy consumption of the normal conducting bus lines becomes large according to the distance of the power supply and the superconducting coil and which may wipe out a merit of the superconducting system. Fig. 1(b) is an advanced setup using a superconducting bus line and normal conducting current leads, which is adapted as an actual system for the LHD in phase I operation [5]. The current leads cryostat is settled near the power supply. The current leads and the coil leads are connected with long flexible superconducting bus lines. Fig. 1(c) shows a future setup for the LHD in phase II operation using HTS current feeders from 4.4 to 1.8 K, a superconducting bus line and HTS current leads. The helical coils of the LHD are planned to be cooled to 1.8 K with superfluid helium. The current feed-through from 4.4 to 1.8 K made on an HTS is an indispensable part, which enables stable and safety high current transfer to the coils keeping the heat in-leak to 1.8 K within an acceptable level. The HTS current leads is also necessary to reduce the large liquid helium consumption of the normal current leads.

3. Large current transport tests of HTS sample

3.1. Experimental setup

To study the feasibility of the HTS current feeders; the HTS feed-through and the HTS current leads, a melt textured YBCO bulk superconductor was selected as a candidate material and high current transport tests of the short samples were performed.

The $YBa_2Cu_3O_x$ (YBCO) bulk was fabricated into the shape of a disk 65 mm in diameter and 15 mm thick using the modified quench and melt growth (QMG) process developed by Morita et al. [6]. For the high current transport tests, the short sample was cut into an H shape from the disk sample to keep joint areas to the normal conductors large about 800 mm^2 as shown in Fig. 2. The cross sectional area and the length of the current transport test region are 7 mm × 7 mm and 20 mm, respectively.

The H shaped sample was mounted in the copper bus bar as shown in Fig. 3. The copper bus bar consists of two layers 45 mm wide and 13 mm thick for the current supply to the sample and the current return from the sample. The current is supplied to the sample through the upper layer and returns through the lower layer. The GFRP plate 2 mm thick was inserted between the current supply- and return-layers. The joints between the sample and the copper bus bars were done with solder. The voltage taps B and C were attached on the front surface of the sample, and the voltage taps A and D on the joint ends of the supply- and return-layers of the copper bus bars. We can measure the superconducting sample voltage with the voltage drop between B and C and the joint voltages with those of A and B or C and D. The temperature rises of the joint regions were monitored with platinum–cobalt (Pt–Co) resistive thermometers inserted in the holes of the joint ends of the supply- and return-layers.

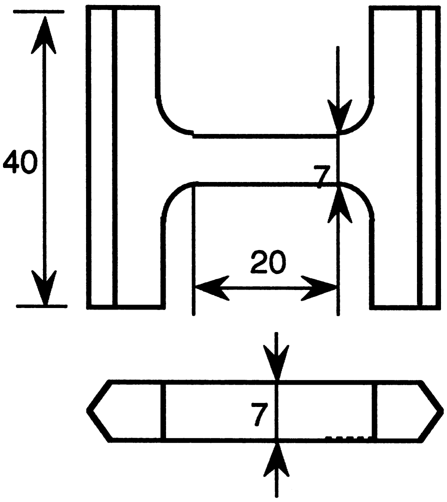

Fig. 2. Schematic drawing of the "H" shaped sample for the high current transport tests.

High current transport tests were carried out using the short sample test facilities at the cryogenics and superconducting laboratories of NIFS [7]. The test facility consists of a 30 kA DC power supply with an active filter, 30 kA He gas cooled short sample current leads and 8 T superconducting split coils with a sample area of 30 mm gap and 50 mm wide. The sample and its holder were designed to be able to do the current transport tests under the external field inserting the sample into the split coils. However, we could not apply an external magnetic field to the sample during this experiment.

3.2. Experimental results

The sample was cooled down slowly to 4.2 K with liquid helium keeping the temperature difference between the joint ends of the supply- and return-layers below 1 K. We conducted high current transport tests with a trapezoidal-shape current-changing-pattern increasing a flat-top current from a small current to a large

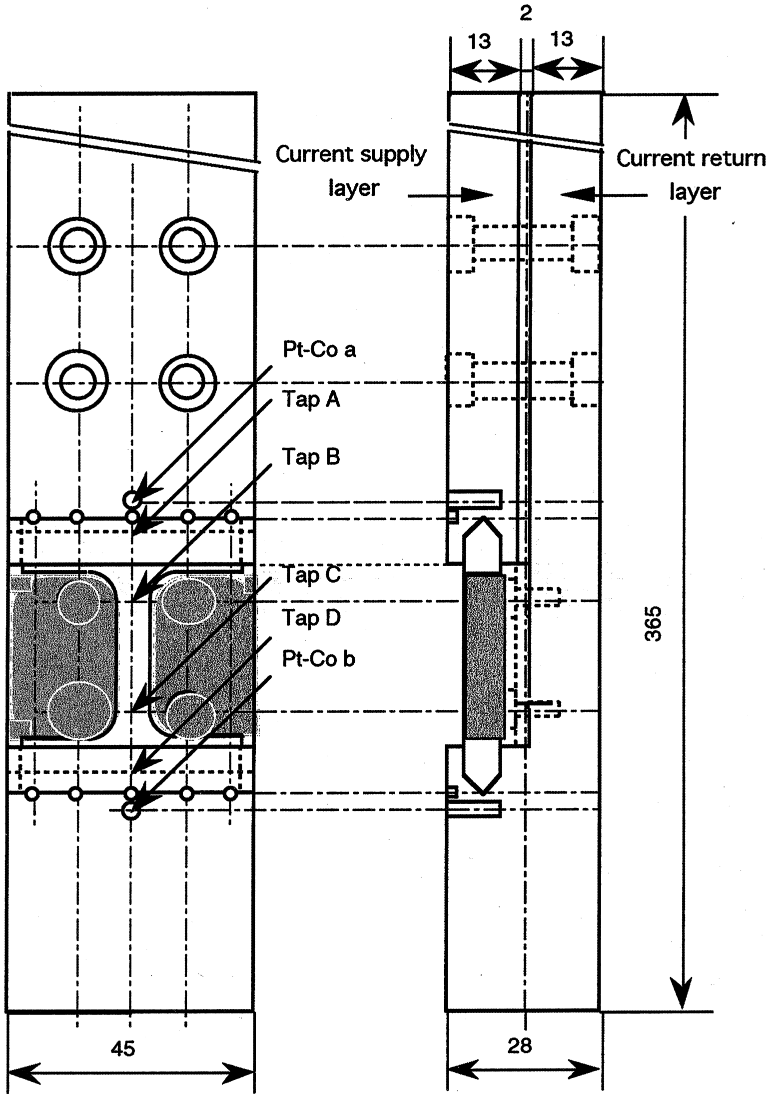

Fig. 3. Schematic drawing of the sample mounted in the copper bus bar for the current supply and return.

current step by step. The maximum transport current of the first sample in liquid helium reached 20 kA without a normal transition. Fig. 4 shows results of a 20 kA transport test. As shown in Fig. 4(a), the sample current was increased up to 20 kA with a ramping speed of 150 A/s and was held at 20 kA for about 10 s, then the current decreased quickly. Fig. 4(b) shows V_{BC}; the voltage drop of the current transport region in the sample. The inductive voltage of +0.5 μV was observed corresponding to the ramp up of the sample current. The negative voltage was observed after 95 s corresponding to the current over 14.5 kA, which was due to the difference of the thermoelectromotive force between each of the voltage taps. There were large heat generations from both joint regions and the sample had a large temperature gradient. There was no obvious normal transition in the current transport region of the sample. Fig. 4(c) shows the voltage drop V_{AB} between the taps A and B in the upper joint region and the voltage drop V_{CD} between the taps C and D in the lower joint region. Fig. 4(d) shows the corresponding temperatures of both joint region measured by the thermometers embedded in the copper bus bars at the upper joint T_a and the lower joint T_b. The voltage drop V_{AB} at the upper joint region increased corresponding to both the sample current and the joint temperature T_a. After 140 s from the start of the current ramp up at the flat top current of 20 kA, V_{AB} jumped over the upper range. This jump of V_{AB} implied the appearance of a normal conducting zone in the sample at the upper joint region, which was also

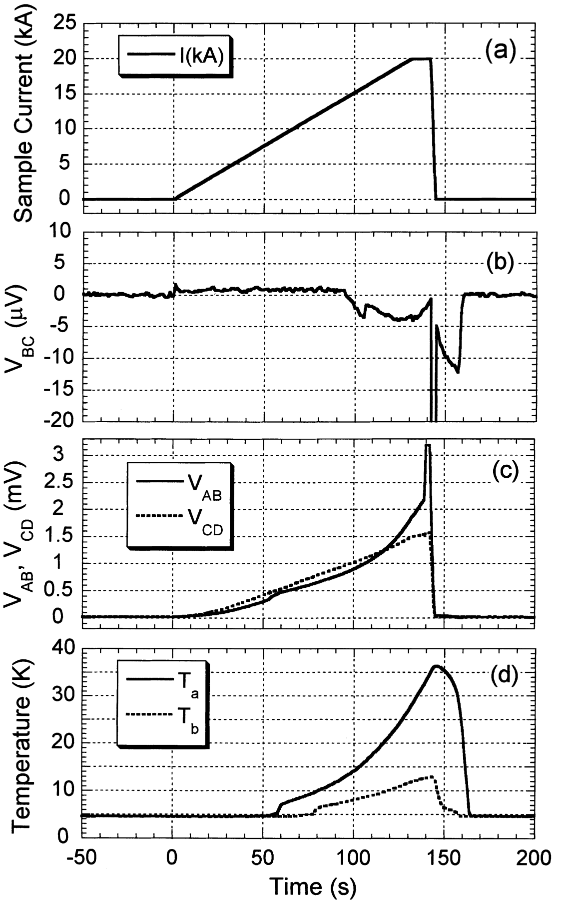

Fig. 4. Results of a 20 kA transport test of the YBCO bulk sample in liquid He: (a) transport current; (b) voltage drop of the current transport region in the sample; (c) voltage drops of the joint regions; (d) temperatures of the joint regions.

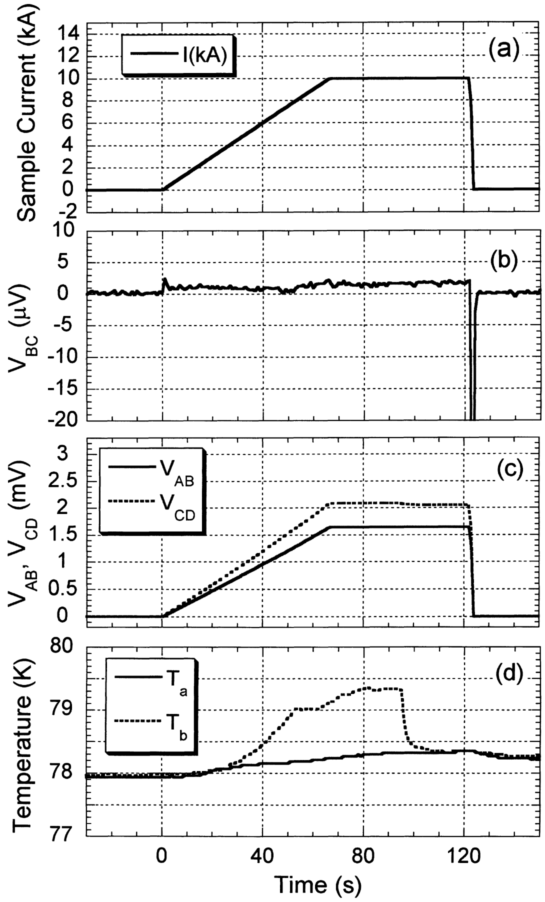

Fig. 5. Results of a 10 kA transport test of the YBCO bulk sample in liquid N_2: (a) transport current; (b) voltage drop of the current transport region in the sample; (c) voltage drops of the joint regions; (d) temperatures of the joint regions.

estimated from the sharp temperature rise of T_a up to 37 K. The voltage drop V_{CD} at the lower joint region increased almost linearly corresponding to the sample current. The temperature rise T_b was kept less than 13 K and there was no normal transition in the sample at the lower joint region.

From above results, it was considered that there was no normal transition at least in the current transport region of the sample. However the voltage drops of both joint regions were larger than the expected value and we could not hold the sample current at 20 kA more than 10 s due to the large heat generations at the joint regions. The joint voltages (resistances) at 20 kA were 2.2 mV (0.11 μΩ) at the upper joint and 1.5 mV (0.075 μΩ) at the lower joint. The heat generations at 20 kA became 44 W at the upper joint and 30 W at the lower joint.

After the high current transport tests in liquid helium, we conducted tests at 77 K in liquid nitrogen with the same sample. Fig. 5 show results of a 10 kA transport test. Small voltage drop of 2 μV was observed in V_{BC}. This voltage drop was thought corresponding to the normal resistance of the sample at 77 K. However the heat generation from this resistance was only 20 mW at 10 kA operation. The total heat generation from both joints was 35 W at 10 kA and the temperature of the both joints was kept less than 80 K. The gradual increases of the joint temperature came from the temperature rise of liquid nitrogen due to the pressure rise of the cryostat.

Fig. 6 shows results of a 12 kA transport test. At the sample current of 11.7 kA, the sample was suddenly broken due to the large thermal stress caused by the overheating of the lower joint. V_{CD}, the lower joint voltage, jumped over at 68 s (10 kA) and a sharp increase of V_{BC}, the sample voltage was observed at the same time. However the temperature profiles of the both joints were almost the same as those of a 10 kA test. This means that the temperature rises in the sample after the

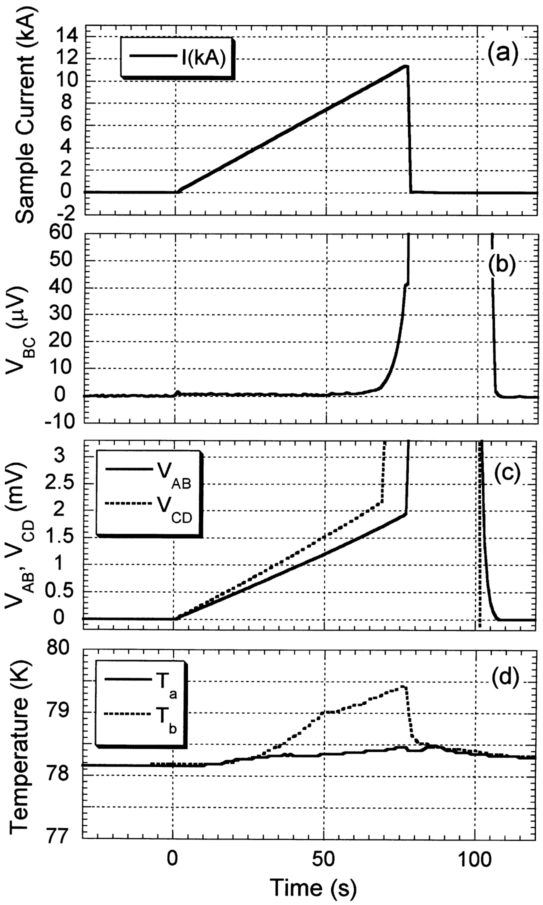

Fig. 6. Results of a 12 kA transport test of the YBCO bulk sample in liquid N_2: (a) transport current; (b) voltage drop of the current transport region in the sample; (c) voltage drops of the joint regions; (d) temperatures of the joint regions. The sample was broken at 11.7 kA.

normal transition cooled by liquid nitrogen were extremely localized comparing to those cases cooled by liquid helium, which becomes difficulty for safety detection and protection to a quench.

4. Conclusion

Applications of high-T_c superconductors to current feeders for a large-scale superconducting system are investigated. High current transport characteristics were examined for a melt textured $YBa_2Cu_3O_x$ bulk sample to study the feasibility for the current feeders. In the experiments at 4.4 K cooled with liquid helium, the transport current of the bulk sample was successfully reached up to 20 kA. During the 20 kA test, however, large joule heat over 70 W was generated in the upper and lower joint regions of the bulk sample and the copper bus bar. In the experiments at 77 K cooled with liquid nitrogen, the bulk sample demonstrated stable current transport up to 10 kA. During the 12 kA test, the bulk sample was suddenly broken due to the large thermal stress caused by the local overheating in the joint region. We could confirm that the YBCO bulk sample has an extreme ability for high current transport without energy consumption. For application to actual current feeders, however, low-resistive joint techniques of the YBCO bulk conductor and normal metal should be improved for further reduction of the joule heat generation and stable operation of high current transport.

References

[1] O. Motojima et al., Large helical device project for SC steady-state fusion experiment, Proceedings of the 16th ICEC/ICMC, Kitakyushu, Japan, 1997, pp. 725–730.
[2] S.M. Ting et al., IEEE Trans. Appl. Supercond. 7 (1997) 700.
[3] L. Porcar et al., Physica C 275 (1997) 293.
[4] K. Maehata et al., High current transport characteristics of a melt-textured YBCO conductor up to 20 kA, presented at MT-15 at Beijing in China, 20–24 October 1997.
[5] S. Yamada et al., IEEE Trans. Magn. 32 (1996) 2422.
[6] M. Morita et al., Physica C 235–240 (1994) 209.
[7] N. Hirano, et al., IEEE Trans. Appl. Supercond. 7 (1997) 770.