Stability and Safety Estimates and Tests of a Superconducting Bus-Line for Large-Scale Superconducting Coils

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Abstract—We have been developing a flexible superconducting bus-line as a unit electrical feeder between large-scale superconducting coils and their power supplies away from the coils. The designed superconducting bus-line consists of a pair of +/- aluminum stabilized NbTi/Cu compacted strand cables and a coaxial four-channel transfer line. A full-scale model of the SC bus-line (20 m long) has been constructed and tested successfully up to 40 kA without a quench under the short-circuit condition. Stability tests were also done by inducing a forced quench with heaters. A minimum propagation current larger than 32.5 kA was confirmed. Thus, the bus-line was cryogenically stabilized at the rated current of 30 kA. We have examined the test results and evaluated the stability and safety margins of this bus-line. The design criteria for a superconducting bus-line are also shown for large-scale superconducting coils with operating current as a parameter.

I. INTRODUCTION

In scaling up superconducting coils, it becomes difficult to place and install large power supplies and current-leads near the coils because of spatial restrictions. For the case of the Large Helical Device (LHD) [1], which is a heliotron/torsatron type fusion experimental device under construction at the National Institute for Fusion Science (NIFS), the distances between the superconducting coils and the power supplies are 45 - 65 m. The superconducting coils for LHD consist of two helical coils (each coil has 3 blocks) and three pairs of poloidal coils (IV, IS and OV coils). We have been developing a flexible superconducting bus-line for LHD to connect the coils and the power supplies without energy consumption. The total number of superconducting bus-lines for LHD is nine, of which six are for the helical coils and three are for the poloidal coils. The operating current of the helical coils is 17.3 kA. The operating currents of poloidal coils IV, IS and OV are 20.3 kA, 21.3 kA and 31.3 kA, respectively.

The superconducting bus-line requires excellent stability and safety exceeding that of the superconducting coils themselves because the large magnetic stored energy of the coils must be extracted through the bus-line if and when the coils quench.

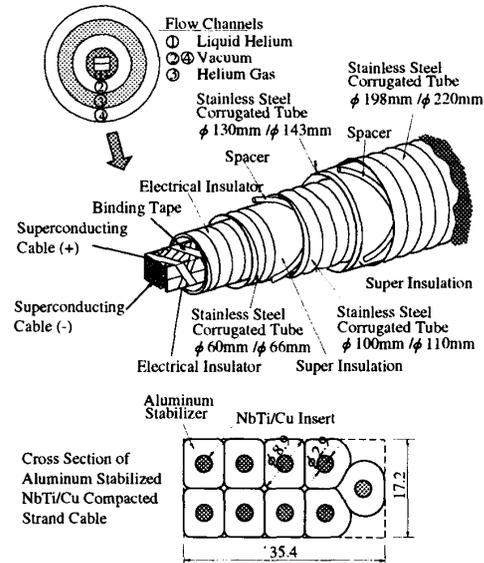## II. DESIGN AND CONSTRUCTION OF A SUPERCONDUCTING BUS-LINE

Fig. 1. Configuration of a flexible superconducting bus-line.

A full-scale model with a length of 20 m was constructed to investigate the feasibility and performance of the flexible superconducting bus-line [2]. The configuration and the specifications of the bus-line are shown in Fig. 1 and Table 1, respectively. A +/- pair of superconducting cables is separated with Nomex sheets for the electrical insulation and is bound with Kevlar tapes for mechanical support against the repulsive electromagnetic force between two cables. The vacuum-insulated transfer line consists of four corrugated tubes assembled coaxially. Two-phase helium flows through the innermost channel, and returning helium gas flows through the outer annular channel as a thermal shield.

To guarantee stability, the bus-line was designed cryostable at the operating current of 30 kA. The bus-line was designed with a safety criterion specifying that the maximum temperature rise after a quench should be less than 77 K when the current decays with a time constant of 20 s.

III. SHORT SAMPLE TESTS OF A SINGLE STRAND

We conducted short sample tests of one strand of the compacted nine-strand cable preceding the tests of the bus-line. Fig. 2 shows the measured and calculated minimum propagation currents of a strand with a cooling perimeter of 11.4 mm (37.5 % of the total perimeter of a strand). The calculations were done according to Maddock's equal area

TABLE 1 SPECIFICATIONS FOR A SUPERCONDUCTING BUS-LINE

Superconducting Bus-Line	
Operating current	30 kA
Breakdown voltage	DC2 kV (design)
(in helium gas at 1 atm and 77 K)	>DC5 kV (measured)
Length	20 m
Maximum temperature rise after a quench calculated by hot-spot model	<77 K with current decay time constant of 20 s
Aluminum Stabilized, Compacted Strand Cable	
Critical current	180 kA at 1T, 4.2 K
Size	17.2 mm × 35.4 mm
Operating current density	53.0 A/mm^2
Number of strands	9
Twist pitch of strands	374 mm
Cooling perimeter	35.4 mm
Minimum propagation current	>30 kA
Superconducting Strand	
Outer diameter	8.95 mm
NbTi/Cu insert diameter	2.91 mm
Al:Cu:NbTi ratio	8.4:0.5:0.5
Al resistivity	3×10^{-11} Ωm at 1 T, 4.2 K

theorem [3] using the measured strand resistance and boiling heat transfer. (An aluminum resistivity derived from the measured strand resistance was 3×10^{-11} Ω m which is the same as the design value.) Below 2 T, the measured minimum propagation currents coincide with the calculated values. Above 2 T, the minimum propagation current exceeds the critical current. When the current exceeds the critical current, the current transfers from the NbTi insert to the surrounding pure aluminum. However the cooling power exceeds the heat generation and the self-field at the NbTi insert decreases because of the current transfer to the surrounding aluminum. Therefore, a singular oscillation phenomenon was observed between the normal transition and the recovery to the superconducting state. The measured minimum propagation current was taken as the current when this oscillation stopped and jumped to the normal state. Therefore the measured minimum propagation current above 2 T was imprecise and differs from the calculation.
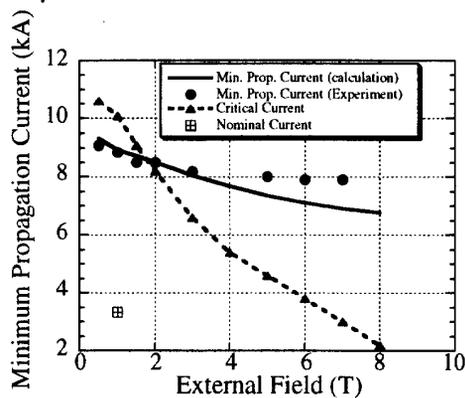
IV. STABILITY TESTS OF THE SUPERCONDUCTING BUS-LIN

A. Experimental Set-up

Two kinds of heaters (H1 and H2) were placed on the cable at the center of the bus-line. H1 is a resistive film heater attached to one strand of the cable. H2 is a stainless-steel foil heater which covers a flat surface of the cable.

An excitation test of the bus-line was carried out under short-circuit condition. The flow rate of the two-phase helium was kept constant at 11-12 g/s. We conducted successful overcurrent operation of 40 kA without training.

B. Stability Tests

The stability margin and the minimum propagation current were measured by adding perturbation energies with heater H2 under the condition of the bus-line's self field. The input signal of the heater had a rectangular pulse with a duration of 1 s. Keeping the bus-line transport current at a constant value, we increased the heater energy step by step. Fig. 3 shows the stability margin as a function of the perturbation energy required to initiate a quench. Below the current of 32.5 kA, the initiated normal zone recovered even with the maximum heat input energy of 80 J. Fig. 4 shows short voltage taps signals when the normal zone propagated at a transport current of 35 kA and the heat input energy was 60 J. The heater was attached inside the voltage taps V7V8. The short voltage taps have a sensitive length of about 100 mm and were attached at an interval of one strand twist pitch (374 mm) of the superconducting cable. The voltage signals increased with two steps and then reached a plateau. The conductor resistance corresponding to this plateau was 5.9 - 6.5×10^{-8} Ω/ m which nearly equals the design value. The first step voltages, which were about half of the plateau levels, indicate current sharing from quenched strands to other strands. When the normal zone recovered at a transport current of 35 kA and the heat input energy was 50 J, the voltage signals of V7V8 and V9V10 did not exceed the first step level of Fig. 4 and recovered to the superconducting state.
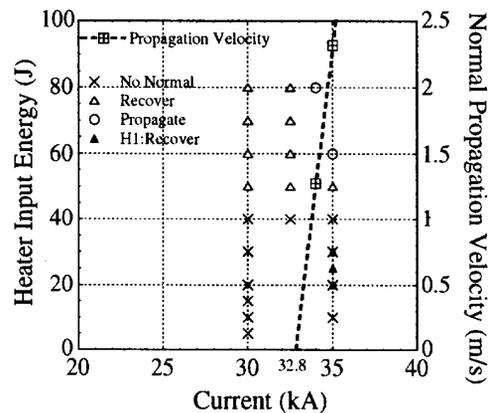

Fig. 2. Measured and calculated minimum propagation currents for a single strand.

Fig. 3. Stability margin of the bus-line as a function of the perturbation energy required to initiate a quench.

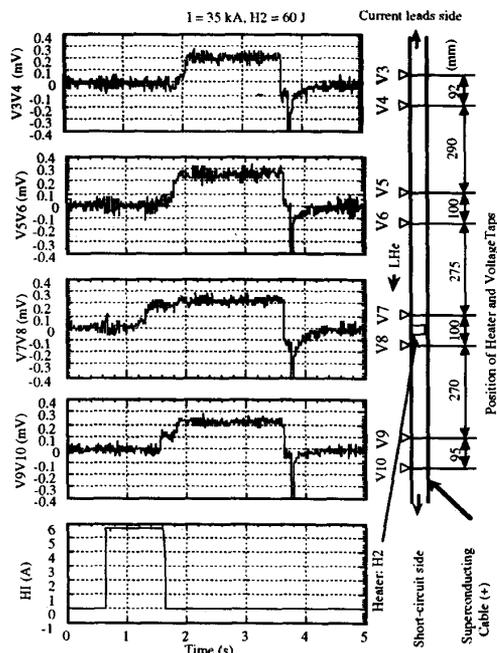I = 35 kA, H2 = 60 J   Current leads side

Fig. 4. Short voltage signals when the normal zone propagated at a transport current of 35 kA and the heat input energy of H2 heater was 60 J.

In Fig. 3, the stability margin measured with heater H1 (the heater attached to one strand of the nine-strand cable) is also shown. Keeping the operating current at 35 kA, we increased the heater H1 energy step by step in the same manner as that of the heater H2. Up to the heater limit of 30 J, the initiated normal zone recovered to the superconducting state. It is considered that the current sharing from quenched strands to other strands can increase the stability of a multistrand superconducting cable.

Fig. 5 shows total voltage signals (for a sensitive length of 10 m) of the normal propagation at the operating currents of 34 kA and 35 kA. The voltage signals increased linearly
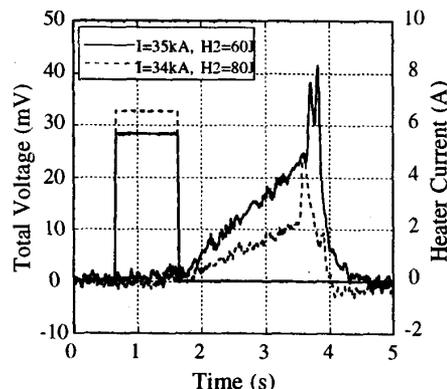

Fig. 5. Total voltage signal (for a sensitive length of 10 m) of the normal propagation at the operating currents of 34 kA and 35 kA.
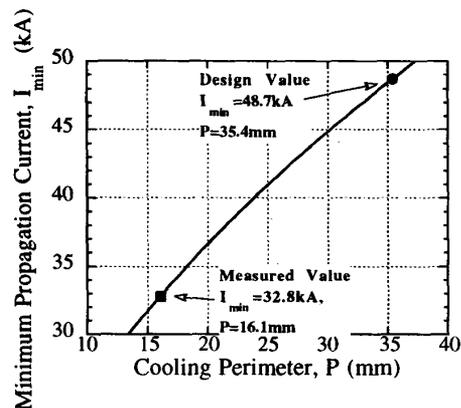

Fig. 6. Calculated minimum propagation current as a function of cooling perimeter for the superconducting bus-line.

after 2 s, so that we could estimate the normal zone propagation velocities and plot them in Fig. 3. The normal propagation velocity increases linearly with the operating current. The minimum propagation current estimated from the cross point where the normal propagation velocity becomes zero is 32.8 kA.

V. ESTIMATES OF STABILITY AND SAFETY

A. Estimate of Stability Including a Cooling Perimeter

Fig. 6 shows the calculated minimum propagation current as a function of cooling perimeter for the superconducting bus-line. The design value of the cooling perimeter was set as 35.4 mm which corresponds to the flat surface of the superconducting cable that is not covered with an electrical insulator. The calculated minimum propagation current for this cooling perimeter (35.4 mm) is 48.7 kA. The cooling perimeter corresponding to the measured minimum propagation current (32.8 kA) is 16.1 mm, which is half of the design value. The decrease of the cooling perimeter is caused by the large heat input required to initiate a forced quench. The amount of liquid helium in the innermost channel is such that a heater input of 80 J fills a 76 mm length of the innermost channel with vaporized helium. Assuming no heat input, the minimum propagation current is 48.7 kA, or 1.62 times larger than the operating current of 30 kA.

B. Estimate of Safety with a Hot Spot Model

Fig. 7 shows the calculated maximum temperature rises of the bus-line as a function of the current decay time constant. We calculated them with a hot spot model [5] using a measured resistance of the superconducting cable. At the design current decay time of 20 s, the maximum temperature rise is 45.8 K. The limit of a decay time, when the maximum temperature becomes 77 K (which was decided to prevent electric break down in helium gas), is 30 s. The bus-line has a safety margin of 10 s in terms of decay time.
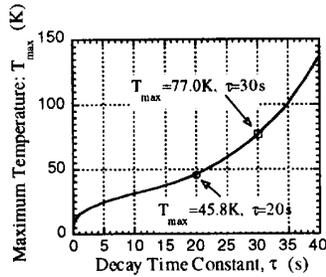
Fig. 7. Calculated maximum temperature rises of the bus-line as a function of the current decay time constant (the operating current density is 53 A/mm^2).
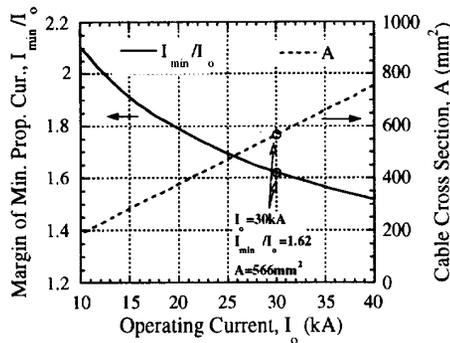

Fig. 8. Stability margin (the ratio of minimum propagation current to operating current) and cross section area as a function of operating current, keeping the operating current density constant at 53 A/mm^2.
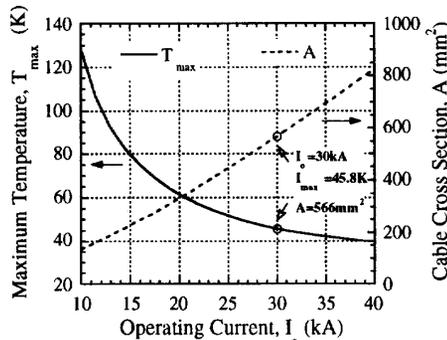

Fig. 9. Maximum temperature rises with a hot spot model and cross section area as a function of the operating current, keeping stability margin constant at 1.62.

C. Design Criteria of Bus-Lines

The evaluated stability and safety margin of this bus-line are sufficient and proper for the use of large-scale superconducting coils. We investigated the design criteria for a superconducting bus-line with operating current as a parameter based on this 30 kA design. We assume that the basic superconducting cable design is not changed and is similar in shape. The composition and number of strands of a

superconducting cable are the same and only the cross section area varies as a function of the operating current.

At first, we kept the safety margin the same as that of the 30 kA design. Fig. 8 shows the stability margin (the ratio of a minimum propagation current to an operating current) and the cross section area as a function of operating current, keeping the operating current density constant at 53 A/mm^2. The safety margin is the same as shown in Fig. 7, if we keep a constant operating current density. The stability margin increases as the operating current decreases.

The calculated temperature rises with a hot spot model are overestimated since the cooling effect of liquid helium and the longitudinal heat conduction of the superconducting cable have been neglected. Then we keep the stability margin the same as that of the 30 kA design. Fig. 9 shows the maximum temperature rises with a hot spot model and the cross section area as a function of the operating current, keeping the stability margin constant at 1.62.

VI. CONCLUSION

The stability and safety of the superconducting bus-line were confirmed experimentally, and their margins were evaluated. The measured minimum propagation currents of a single strand coincide with the calculated values using Maddock's equal area theorem. The measured minimum propagation current of the bus-line was 32.8 kA, which is decreased from the design value of 48.7 kA. This degradation of the stability can be explained as the decrease of the cooling perimeter from the design value of 35.4 mm to 16.1 mm. The decrease of the cooling perimeter is caused by the large heat input required to initiate a forced quench. Assuming no heat input, the minimum propagation current is 48.7 kA, or 1.62 times larger than the operating current of 30 kA. At the design current decay time of 20 s, the calculated maximum temperature rise of the bus-line is 45.8 K. The evaluated stability and safety margin of this bus-line are sufficient and proper for the use of large-scale superconducting coils. Based on this 30 kA bus-line design, the necessary cross section areas of the bus-line cable are calculated as a function of operating current, under the constant safety margin condition or the constant stability margin condition.

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