

JAERI-Research
97-002



**EFFECT OF CURRENT IMBALANCE ON STABILITY OF A CABLE-IN-CONDUIT
CONDUCTOR CONSISTING OF CHROME-PLATED STRANDS**

February 1997

**Norikiyo KOIZUMI, Yoshikazu TAKAHASHI, Masataka NISHI
Takaaki ISONO, Hiroshi TSUJI, Michitaka ONO*
Takataro HAMAJIMA* and Tsutomu FUJIOKA***

日本原子力研究所
Japan Atomic Energy Research Institute

本レポートは、日本原子力研究所が不定期に公刊している研究報告書です。

入手の間合わせは、日本原子力研究所研究情報部研究情報課（〒319-11 茨城県那珂郡東海村）あて、お申し越してください。なお、このほかに財団法人原子力弘済会資料センター（〒319-11 茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

This report is issued irregularly.

Inquiries about availability of the reports should be addressed to Research Information Division, Department of Intellectual Resources, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan.

© Japan Atomic Energy Research Institute, 1997

編集兼発行 日本原子力研究所
印刷 (株)原子力資料サービス

Effect of Current Imbalance on Stability of a Cable-in-conduit
Conductor Consisting of Chrome-plated Strands

Norikiyo KOIZUMI, Yoshikazu TAKAHASHI, Masataka NISHI, Takaaki ISONO
Hiroshi TSUJI, Michitaka ONO* , Takataro HAMAJIMA* and Tsutomu FUJIOKA*

Department of Fusion Engineering Research
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

(Received January 7, 1997)

The effect of an unbalanced current distribution in a conductor consisting of chrome plated strands on stability was investigated using a cable-in-conduit conductor (CICC) consisting of 27 NbTi chrome-plated strands. In addition, the quench behavior when a non-uniform current distribution was produced in the conductor was studied from the experimental results. Moreover, impedance of the chrome-plated strands was measured using the sample conductor. The results show that the stability is determined by the largest strand current when it is sufficiently large otherwise by the transport current when it is not high enough. It was found that it took a long time to make the conductor quench from the onset of the normal transition of the strands carrying the large current. This is explained by the good diffusivity of the coolant temperature in the conductor's cross section. Since the ramp-rate limitation cannot probably take place if the coolant temperature is diffused well in the conductor's cross section, it is expected the ramp-rate limitation can be prevented using this effect. It is also shown that the chrome-plated strands come into contact with one another with uniform transverse conductance on the order of 10^3 S/m

Keywords: Current Imbalance, Ramp-rate Limitation, CICC, Stability

* Toshiba Corporation

クロムメッキ素線からなるケーブル・イン・コンジット導体内
電流分布不均一の安定性への影響

日本原子力研究所那珂研究所核融合工学部

小泉 徳潔・高橋 良和・西 正孝・磯野 高明

辻 博史・小野 通隆*・浜島高太郎*・藤岡 勉*

(1997年1月7日受理)

クロムメッキされた素線からなる導体内の電流分布不均一の安定性への影響を、27本のクロムメッキNbTi線からなるケーブル・イン・コンジット導体(CICC)を用いて調査した。また、電流分布が不均一な場合のクエンチの機構を検討した。その上、サンプル導体を用いて、クロムメッキ素線間のインピーダンスを測定した。実験結果より、過剰電流を流す素線の電流値が十分大きい場合は、過剰電流を流す素線の電流値により、また、過剰電流が十分大きくない場合は、導体の通電電流によって安定性が決定されることが分かった。その上、過剰電流を流す素線が常電導転移してから導体のクエンチに至るまでには、長い時間がかかることが示された。これは、導体断面内で冷媒温度がよく拡散されるためである。冷媒温度が導体断面内で均一に保たれる場合は、励磁速度依存不安定性が起りにくいので、本性質を利用することにより、励磁速度依存不安定性を回避できるものと考えられる。また、クロムメッキされた素線は、導体内で互いに電氣的に一様に接触しており、そのコンダクタンスは、 10^3 S/m のオーダーであることが示された。

Contents

1. Introduction	1
2. Major Parameters of the Sample	1
3. Impedance between Chrome-plated Strands	2
4. Stability Experiment	3
4.1 Experimental Method	3
4.2 Results	5
4.2.1 Stability	5
4.2.2 Voltage Behavior	5
5. Considerations	7
5.1 Calculation of Current of Strand 1 after Normal Transition	7
5.1.1 Transient-state Model	7
5.1.2 Steady-state Model	10
5.2 Coolant Temperature Rise by Joule Heating from Strand 1	11
5.3 Prevention of Ramp-rate Limitation	13
6. Conclusions	13
Acknowledgments	13
References	14
Appendix	15

目 次

1. はじめに	1
2. サンプル主要緒言	1
3. クロムメッキ素線間インピーダンス	2
4. 安定性実験	3
4.1 実験方法	3
4.2 結 果	5
4.2.1 安 定 性	5
4.2.2 クエンチ	5
5. 考 察	7
5.1 素線1常電導転移後電流の計算	7
5.1.1 過渡モデル	7
5.1.2 定常モデル	10
5.2 素線1からのジュール発熱による冷媒温度上昇	11
5.3 励磁速度依存不安定性の防止法	13
6. 結 論	13
謝 辞	13
参考文献	14
付 録	15

1. Introduction

The superconductor for pulse operation is generally composed of twisted multistrands to reduce AC losses. In addition, the strands are insulated from one another or coated with a hard surface such as chrome plating to reduce the contact area between the strands for reduction of coupling AC losses among the strands.

It was however reported that a non-uniform current distribution was produced in the conductor if the conductor consists of insulated strands. The conductor results in instability¹⁻⁵. In addition, the experimental results of US-DPC⁶ and DPC-EX⁷ showed that the large cable-in-conduit conductor (CICC) whose strands were plated by chromium exhibited the instability, *so-called* ramp-rate limitation, such as the quench current decreasing as result of increasing of the ramping rate of the magnetic field. Vysotsky *et al*⁸ experimentally showed that a non-uniform current distribution was produced in the conductor consisting of chrome-plated strands. Authors theoretically showed that the ramp-rate limitation was attributable to the current imbalance in the conductor⁹.

The effect of current imbalance on the stability was experimentally investigated using a 6.3 m long CICC consisting of 27 NbTi chrome-plated strands. The current imbalance was forcibly established using two power supplies¹⁰ and initial normalcy was obtained using an inductive heater^{11,12}.

It is thought that the conductor quenches as a result of the coolant temperature's rise due to Joule heating of the strands carrying large currents when the unbalanced current distribution is produced in the conductor consisting of the insulated strands³. The quench behavior in case the non-uniform current distribution is produced in the conductor consisting of the chrome-plated strands is studied to clarify the quench process. From these investigations, we consider the method to prevent a ramp-rate limitation.

The deterioration of the stability can be prevented if the current in a normal-state strand, which initially is in the normal state as a result of its large current, can transfer to the adjacent superconducting strands in a sufficiently short time¹³. The impedance between the strands is the most influential determining factor of the capability of the current transferring among the strands. The impedance between the chrome plated strands was then investigated using the sample conductor.

2. Major Parameters of the Sample

Table 1 shows the main parameters of the sample conductor. Figure 1 shows the cross-sectional view of the sample conductor. The 6.3-m long sample conductor was wound into a solenoid 18 cm in diameter and impregnated with epoxy resin for reinforcement and thermal insulation from the surrounding helium.

1. Introduction

The superconductor for pulse operation is generally composed of twisted multistrands to reduce AC losses. In addition, the strands are insulated from one another or coated with a hard surface such as chrome plating to reduce the contact area between the strands for reduction of coupling AC losses among the strands.

It was however reported that a non-uniform current distribution was produced in the conductor if the conductor consists of insulated strands. The conductor results in instability¹⁻⁵. In addition, the experimental results of US-DPC⁶ and DPC-EX⁷ showed that the large cable-in-conduit conductor (CICC) whose strands were plated by chromium exhibited the instability, *so-called* ramp-rate limitation, such as the quench current decreasing as result of increasing of the ramping rate of the magnetic field. Vysotsky *et al*⁸ experimentally showed that a non-uniform current distribution was produced in the conductor consisting of chrome-plated strands. Authors theoretically showed that the ramp-rate limitation was attributable to the current imbalance in the conductor⁹.

The effect of current imbalance on the stability was experimentally investigated using a 6.3 m long CICC consisting of 27 NbTi chrome-plated strands. The current imbalance was forcibly established using two power supplies¹⁰ and initial normalcy was obtained using an inductive heater^{11,12}.

It is thought that the conductor quenches as a result of the coolant temperature's rise due to Joule heating of the strands carrying large currents when the unbalanced current distribution is produced in the conductor consisting of the insulated strands³. The quench behavior in case the non-uniform current distribution is produced in the conductor consisting of the chrome-plated strands is studied to clarify the quench process. From these investigations, we consider the method to prevent a ramp-rate limitation.

The deterioration of the stability can be prevented if the current in a normal-state strand, which initially is in the normal state as a result of its large current, can transfer to the adjacent superconducting strands in a sufficiently short time¹³. The impedance between the strands is the most influential determining factor of the capability of the current transferring among the strands. The impedance between the chrome plated strands was then investigated using the sample conductor.

2. Major Parameters of the Sample

Table 1 shows the main parameters of the sample conductor. Figure 1 shows the cross-sectional view of the sample conductor. The 6.3-m long sample conductor was wound into a solenoid 18 cm in diameter and impregnated with epoxy resin for reinforcement and thermal insulation from the surrounding helium.

Table 1 Main parameters of sample conductor

<u>Strand</u>	
Superconducting material	NbTi
NbTi : Cu : CuNi	1:3.88:1.07
Strand diameter	1.115 mm
Thickness of chrome plating	5 μ m
Critical current at 4.2 K and 7 T	155 A
<u>Conductor</u>	
Number of strands	27 (3^3)
Conductor length	6.3 m
Coolant cross sectional area	15.52 mm ²
Hydraulic diameter	0.3776 mm
Residual resistance ratio of copper	53
Conduit material	SS304
Conduit thickness	1.1 mm

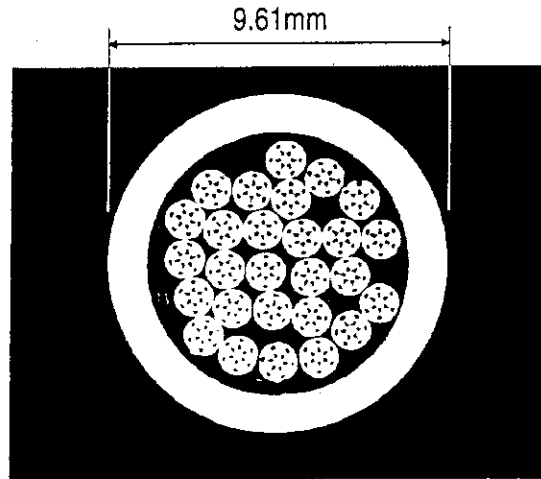


Fig. 1. Cross-sectional view of the sample conductor

3. Impedance between Chrome-plated Strands

The impedance between the chrome plated-strands were measured using the sample conductor. After the stability experiment, which will be described later, all strands were removed from the current terminals and the impedances between the strands in the same triplex and in a different third twisting stage were measured by applying AC current between these strands at one end of the conductor. All the strands were electrically separated at the other end. The schematic configuration of the experimental setup is shown in Fig. 2.

Figure 3 shows the measured impedance between the strands in the same triplex, z_1 [Ω], and in the different third twisting stage, z_3 [Ω], as a function of the frequency of the applied AC current, f [Hz]. The impedance calculated by the following equation by assuming $G = 10^{-3}$ S/m and $\Delta L = 0.3$ and 0.7 μ H/m for z_1 and z_3 , respectively, are shown in Fig. 3.

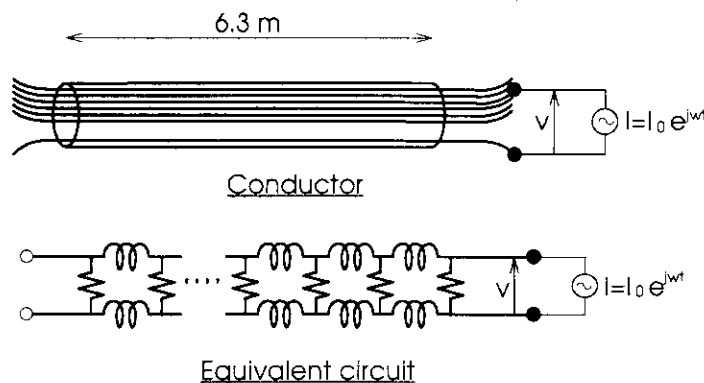


Fig.2. Schema of the sample preparation for impedance measurement.

Table 1 Main parameters of sample conductor

<u>Strand</u>	
Superconducting material	NbTi
NbTi : Cu : CuNi	1:3.88:1.07
Strand diameter	1.115 mm
Thickness of chrome plating	5 μ m
Critical current at 4.2 K and 7 T	155 A
<u>Conductor</u>	
Number of strands	27 (3^3)
Conductor length	6.3 m
Coolant cross sectional area	15.52 mm ²
Hydraulic diameter	0.3776 mm
Residual resistance ratio of copper	53
Conduit material	SS304
Conduit thickness	1.1 mm

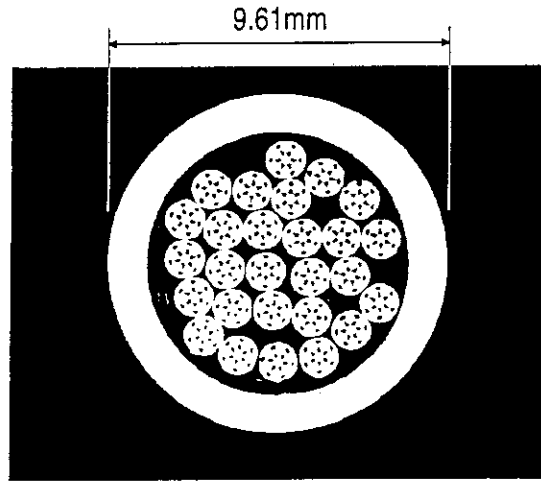


Fig. 1. Cross-sectional view of the sample conductor

3. Impedance between Chrome-plated Strands

The impedance between the chrome plated-strands were measured using the sample conductor. After the stability experiment, which will be described later, all strands were removed from the current terminals and the impedances between the strands in the same triplex and in a different third twisting stage were measured by applying AC current between these strands at one end of the conductor. All the strands were electrically separated at the other end. The schematic configuration of the experimental setup is shown in Fig. 2.

Figure 3 shows the measured impedance between the strands in the same triplex, z_1 [Ω], and in the different third twisting stage, z_3 [Ω], as a function of the frequency of the applied AC current, f [Hz]. The impedance calculated by the following equation by assuming $G = 10^{-3}$ S/m and $\Delta L = 0.3$ and 0.7 μ H/m for z_1 and z_3 , respectively, are shown in Fig. 3.

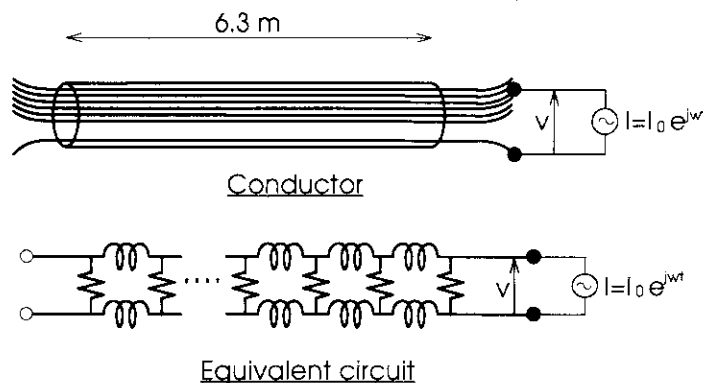


Fig.2. Schema of the sample preparation for impedance measurement.

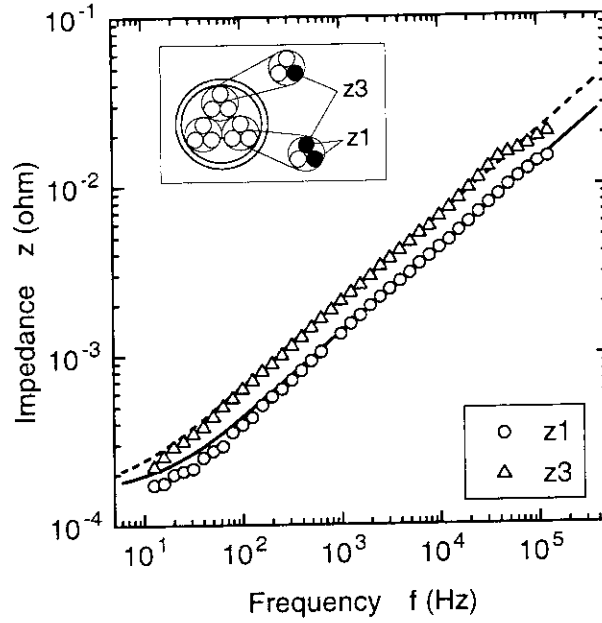


Fig. 3. Impedance as a function of the frequency of the applied AC current. Solid and dash lines show the z_1 and z_3 calculated from Eq. (1).

$$z = \sqrt{\frac{2\pi f \Delta L}{G}} \coth\left(X \sqrt{2\pi f G \Delta L}\right) \quad (1)$$

Where z [Ω] denotes the impedance between the strands, ΔL [H/m] the inductance of a unit length loop consisting of the two strands, G [S/m] the transverse conductance and X [m] the conductor length. The calculation and experimental results are in good agreement as can be seen in Fig. 3. This indicates the transverse conductance between the chrome-plated strands is uniform along the conductor¹⁴. In addition, it is shown that the transverse conductance is in the order of 10^3 S/m¹³.

More detail about the experimental method and theory has been described in Refs. 13 and 15.

4. Stability Experiment

4.1 Experimental method

It has been reported a large current in a strand as a result of an asymmetric strand transposition cannot decrease to zero at a normal transition during a pulse charge⁹. This situation was simulated by electrically separating the strand conducting the large current from the others at the current terminals. The cable was consequently separated into a single strand, hereinafter referred to as 'strand 1' and 26 strands excluding strand 1 at the current terminals at both ends of the conductor. Since they could be charged individually using two current supplies, current imbalance could forcibly be produced using these power supplies. Figure 4 shows the electrical scheme of the experimental

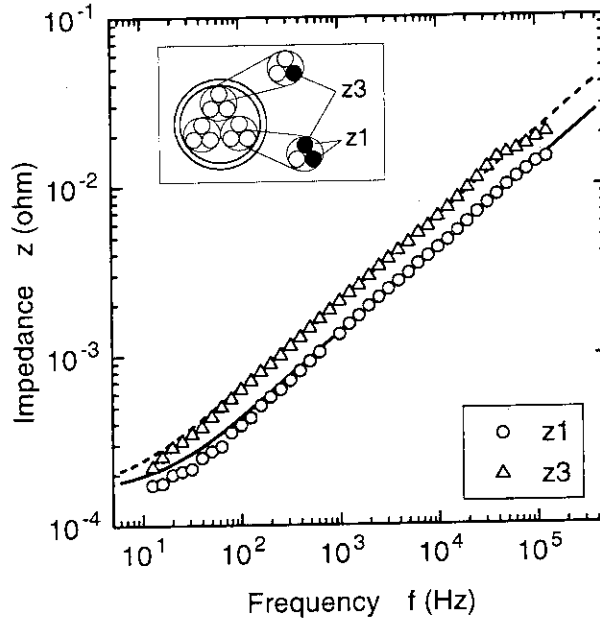


Fig. 3. Impedance as a function of the frequency of the applied AC current. Solid and dash lines show the z_1 and z_3 calculated from Eq. (1).

$$z = \sqrt{\frac{2\pi f \Delta L}{G}} \coth\left(X \sqrt{2\pi f G \Delta L}\right) \quad (1)$$

Where z [Ω] denotes the impedance between the strands, ΔL [H/m] the inductance of a unit length loop consisting of the two strands, G [S/m] the transverse conductance and X [m] the conductor length. The calculation and experimental results are in good agreement as can be seen in Fig. 3. This indicates the transverse conductance between the chrome-plated strands is uniform along the conductor¹⁴. In addition, it is shown that the transverse conductance is in the order of 10^3 S/m¹³.

More detail about the experimental method and theory has been described in Refs. 13 and 15.

4. Stability Experiment

4.1 Experimental method

It has been reported a large current in a strand as a result of an asymmetric strand transposition cannot decrease to zero at a normal transition during a pulse charge⁹. This situation was simulated by electrically separating the strand conducting the large current from the others at the current terminals. The cable was consequently separated into a single strand, hereinafter referred to as 'strand 1' and 26 strands excluding strand 1 at the current terminals at both ends of the conductor. Since they could be charged individually using two current supplies, current imbalance could forcibly be produced using these power supplies. Figure 4 shows the electrical scheme of the experimental

setup.

The ratio of the current supplied to strand 1 and the average current of the others is hereafter called the 'initial current imbalance ratio', n_{r0} . Thus, n_{r0} is defined by,

$$n_{r0} = \frac{I_1}{I_2/26} \quad (2)$$

Where I_1 [A] and I_2 [A] denote the currents supplied to strand 1 and the others, respectively.

The sample was placed in the bore of a backup coil and subjected to magnetic fields of 4 and 7 T. The stability experiment was performed by immersing the sample into liquid helium. The heat diffusion length, defined by $\sqrt{\kappa\tau}$, is evaluated to be 0.6 mm for the temperature of 4 K and time of 10 ms, which is perturbation period in the stability experiment as will be described later. Where κ [m²/s] denotes the thermal diffusivity of the epoxy resin¹⁶. The heat generated in the conductor can move to the thin layer of the epoxy resin around the conductor surface until 10 ms. It is therefore expected that the conductor is thermally insulated from the surrounding liquid helium during the heat input. In addition, the specific heat of the epoxy resin is smaller by two orders of magnitude than that of the helium at 4 K. Consequently, the heat leak to the epoxy resin is negligible in the stability experiment. On the other hand, after a few seconds, the heat diffusion length becomes in the order of centimeter. The heat moving to the epoxy cannot be neglected in this case.

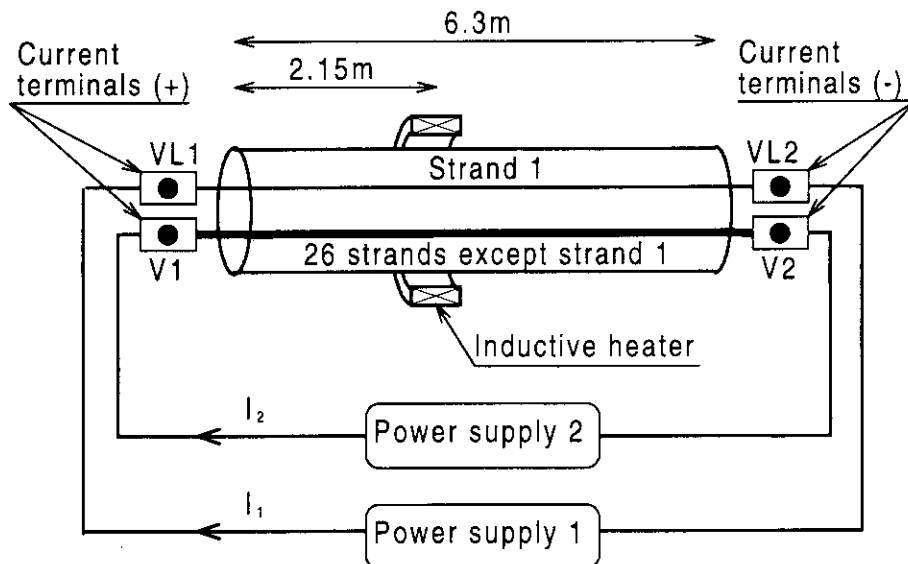


Fig. 4. Electrical schema for the stability experiment. The cable consisting of 27 strands were twisted in a conduit. V1-V2 and VL1-VL2 indicate the voltage taps to measure the normal voltage generated in strand 1 and the others, respectively.

Supercritical helium (SHe) was forcibly flowed in the conductor. The temperature, pressure, coolant flow rate were 4.2 - 4.3 K, 0.6 MPa, 0.5 g/s, respectively.

Voltages of normalcy generated in strand 1 and the others were observed by the voltage taps of V1-V2 and VL1-VL2, respectively, each of which were attached on the current terminals of strand 1 and others, as shown in *Fig. 4*.

The stability was measured as follows: First, sufficiently small heat energy so as not to make the conductor quench was deposited on the conductor to obtain the maximum energy which does not make the conductor quench. The input energy was raised step by step until the sample conductor quenched. The stability margin is defined as the boundary between the energies which make the conductor quench or otherwise. This process was repeated at various transport currents and for various initial current imbalance ratios.

The heat energy was deposited on the conductor by applying 1 kHz and 10 ms sinusoidal current pulse to the inductive heater. The length of the inductive heater is about 8 cm and its center is 2.15 m downstream from the inlet of the coolant as shown in *Fig. 4*. The input energy by the inductive heater was previously calibrated by a calorimetric method¹¹.

4.2 Results

4.2.1 Stability

Figures 5 and 6 show the stability margin measured at 4 and 7 T, respectively, as a function of the transport current of the conductor and the current supplied to strand 1. The stability of the conductor is determined by the current of strand 1 when it is sufficiently large, as shown in *Figs. 5 (b) and 6 (b)*. This shows that the stability deteriorates when a large current imbalance is produced in the conductor consisting of the chrome-plated strands. However, the stability margin is still larger than the one in case of $n_{r0} = 1$. This verifies that the current transferring among the strands improves the stability. On the other hand, the stability is determined by the transport current in case the current of strand 1 is small as shown in *Figs. 5 (a) and 6 (a)*.

4.2.2 Voltage behavior

Figure 7 shows the typical voltage behaviors at the quench when the initial current distribution was not uniform. The magnetic field and initial current imbalance ratios were 4 T and 2 and 4. The currents supplied to strand 1 and the others were 196 and 2414 A in case of $n_{r0} = 2$ and 187 and 1213 A in case of $n_{r0} = 4$.

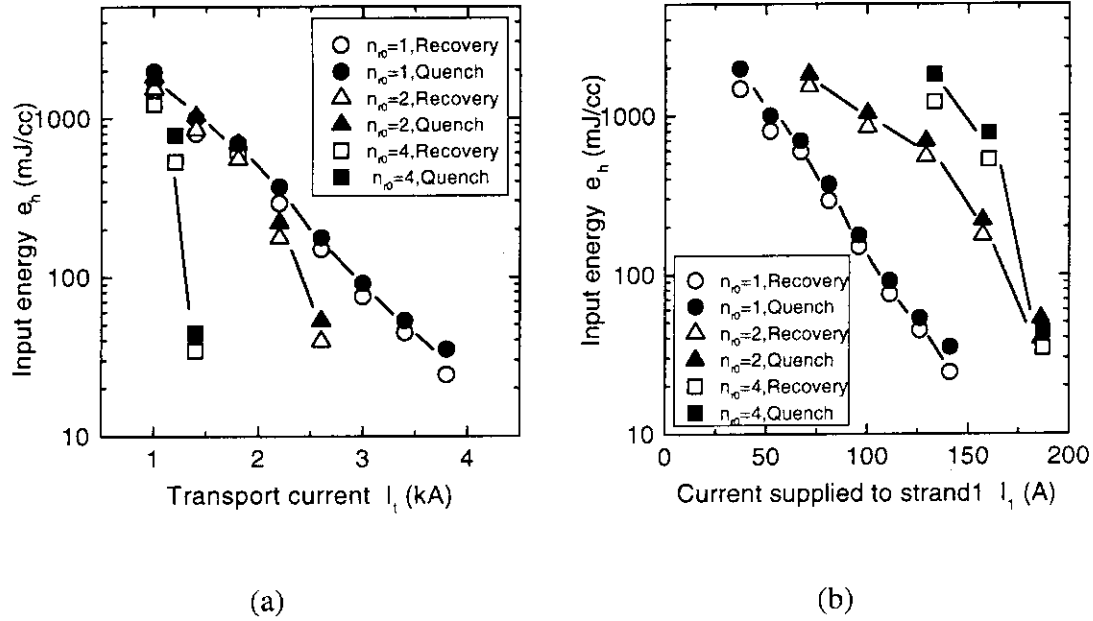


Fig. 5. Stability margin at 4 T. (a) and (b) show the stability margin as a function of the transport current and current supplied to strand 1. The input energy was calibrated at 7 T.

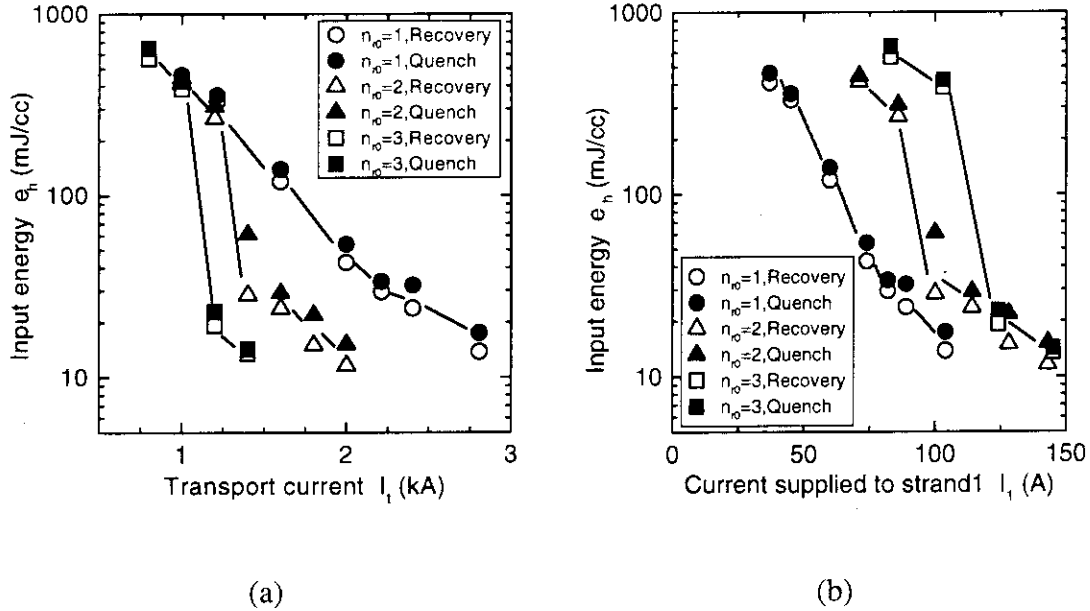


Fig. 6. Stability margin at 7 T. (a) and (b) show the stability margin as a function of the transport current and current supplied to strand 1.

It took a long time from the initiation of the normalcy in strand 1 until the conductor quench. The elapse of time until the conductor quench became longer as the current imbalance was larger, as can be seen in Fig. 7.

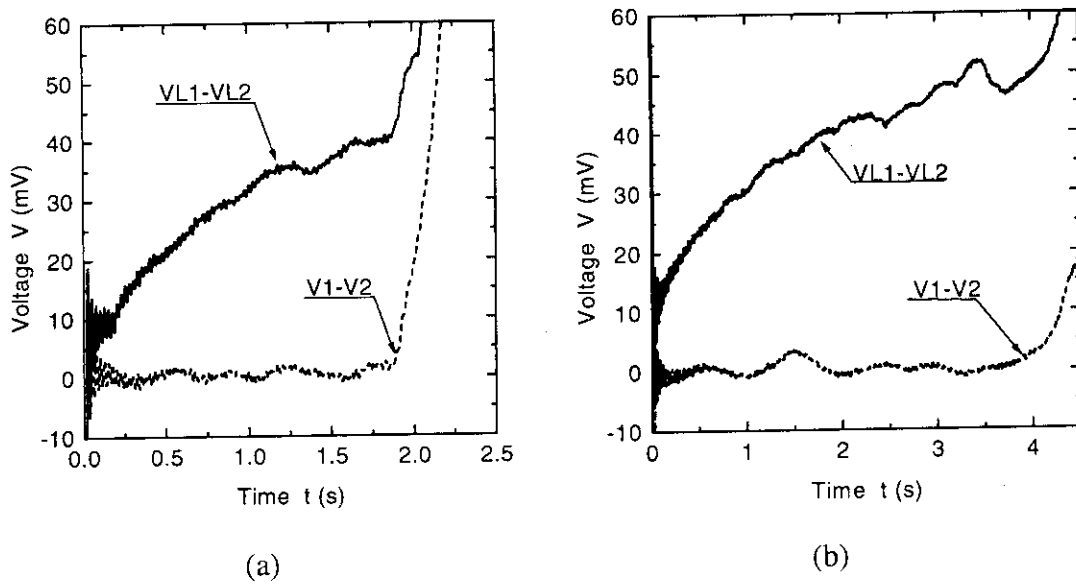


Fig. 7. The voltage profile of strand 1 and the others. (a) The currents supplied to strand 1 and the others were 196 and 2414 A, resulting in $n_{r0}=2$. (b) The currents supplied to strand 1 and the others were 187 and 1213 A, resulting in $n_{r0}=4$.

The resistive voltage of strand 1 occurs just before the conductor quench took place between the ones shown in Fig. 7 (a) and (b). This indicates that the current of strand 1 is the same between the cases shown in Figs. 7 (a) and (b) before the conductor quench. Since the current supplied to strand 1 is almost the same (186 and 187 A), this shows that the same current transfers to the other strands from strand 1 during mere strand 1 transits to the normal state. It is therefore thought that the transverse conductance has no dependence on the magnetoelectrical force in our experiment although Takayasu *et al.*¹⁷ reported the transverse conductance was a linear function of the magnetoelectrical force.

5. Considerations

5.1 Calculation of current of strand 1 after normal transition

It is investigated in this and following sections how the conductor quench took place in the sample conductor when the unbalanced current distribution was produced in it. The current in strand 1 is calculated from the measured voltage to evaluate the coolant temperature rise by the Joule heating from strand 1.

5.1.1 Transient-state model

When the normal zone length varies in terms of time, we cannot obtain the analytical solution of the circulation current using the transient model⁹. On the other hand, if the transient term of the circulation current decays in a sufficiently short time after a normal

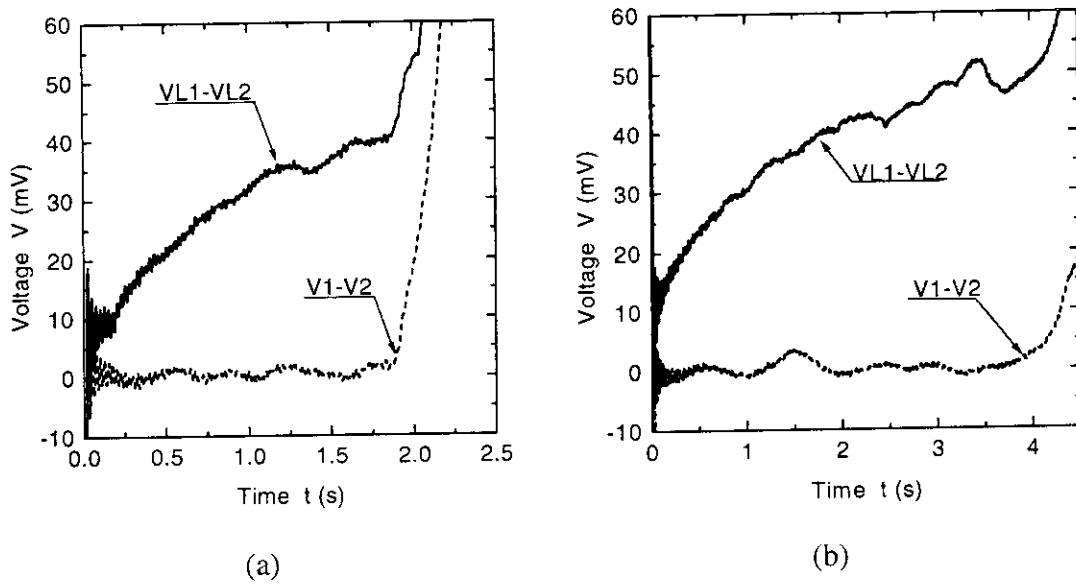


Fig. 7. The voltage profile of strand 1 and the others. (a) The currents supplied to strand 1 and the others were 196 and 2414 A, resulting in $n_{r0}=2$. (b) The currents supplied to strand 1 and the others were 187 and 1213 A, resulting in $n_{r0}=4$.

The resistive voltage of strand 1 occurs just before the conductor quench took place between the ones shown in Fig. 7 (a) and (b). This indicates that the current of strand 1 is the same between the cases shown in Figs. 7 (a) and (b) before the conductor quench. Since the current supplied to strand 1 is almost the same (186 and 187 A), this shows that the same current transfers to the other strands from strand 1 during mere strand 1 transits to the normal state. It is therefore thought that the transverse conductance has no dependence on the magnetoelectrical force in our experiment although Takayasu *et al.*¹⁷ reported the transverse conductance was a linear function of the magnetoelectrical force.

5. Considerations

5.1 Calculation of current of strand 1 after normal transition

It is investigated in this and following sections how the conductor quench took place in the sample conductor when the unbalanced current distribution was produced in it. The current in strand 1 is calculated from the measured voltage to evaluate the coolant temperature rise by the Joule heating from strand 1.

5.1.1 Transient-state model

When the normal zone length varies in terms of time, we cannot obtain the analytical solution of the circulation current using the transient model⁹. On the other hand, if the transient term of the circulation current decays in a sufficiently short time after a normal

transition, the circulation current is approximately calculated using a steady model. The current of strand 1 after its normal transition is calculated to know if this assumption is valid.

The distributed circuit should be used for the analysis of the current distribution in the conductor consisting of the chrome-plated strands since the strands electrically come into contact with one another in the conductor. We use a two-parallel distributed strand model shown in Fig. 8, for simplicity.

The current of strand 1 at the heated zone is calculated since the coolant is heated most here. This current can be evaluated if the current upstream or downstream from the heated zone is calculated. This calculation follows.

When the normalcy appears, the governing equation should include the terms concerning to the normal resistance⁹. However, this makes analytical solution using the transient model to be impossible. The normal resistive voltage is then substituted by the voltage difference, V_n [V], due to the normal resistance at the heated zone^{9,13}. In this case, the governing equation is,

$$\frac{\partial \Delta i_c}{\partial t} - \frac{1}{G \Delta L} \frac{\partial^2 \Delta i_c}{\partial x^2} = 0. \quad (3)$$

Where Δi_c [A] shows the circulation current in the loop composed of strand 1 and the others. Thus, Δi_c satisfies the following equation:

$$\begin{aligned} i_1 &= i_{m1} + \Delta i_c, \\ i_2 &= i_{m2} - \Delta i_c. \end{aligned} \quad (4)$$

Where i_{m1} [A] and i_{m2} [A] show the currents of strand 1 and the others in case of a uniform current distribution, respectively.

The boundary condition at the heated zone, $x = 0$ m, is as follows:

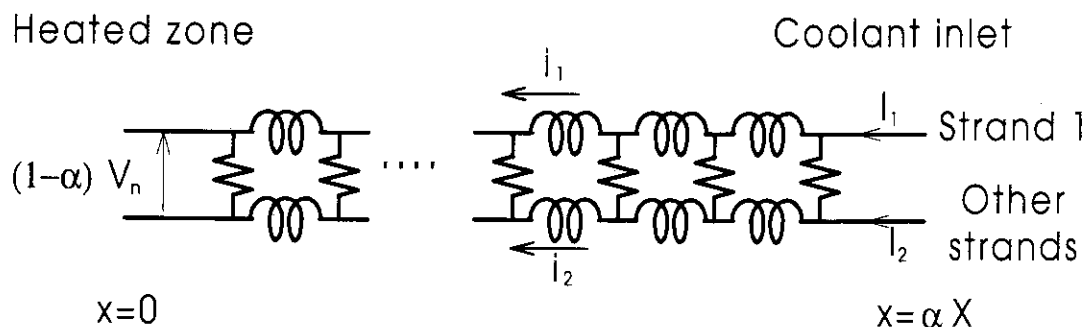


Fig. 8. A two-strand distributed model circuit.

$$\left. \frac{1}{G} \frac{\partial \Delta i_c}{\partial x} \right|_{x=0} = R(1-\alpha)X_n(\Delta i_c + i_{m1}) = (1-\alpha)V_n. \quad (5)$$

Where R [Ω/m] and X_n [m] denote the normal resistance per a unit length strand and normal zone length, which is assumed to be a constant for simplicity; and α is the ratio of the distance from the center of the heated zone to the coolant inlet and outlet as shown in *Fig. 8*.

The boundary condition at the end of the conductor (coolant inlet) is as follows since strand 1 and the others are electrically separated at the ends of the conductor

$$\Delta i_c|_{x=\alpha X} = \Delta i_{c0}. \quad (6)$$

Where Δi_{c0} [A] denotes the circulation current at the end of the conductor and α equals 0.34 (2.15/6.3) in our sample conductor. Δi_{c0} can be calculated from Eq. (4) since we know i_1 , which is identical to I_1 at the current terminal, and i_{m1} , which is calculated from I_1/n_{r0} .

The initial condition is as follows since there is no current transferring between the strands before the normal generation.

$$\Delta i_c|_{t=0} = \Delta i_{c0}. \quad (7)$$

The solution of Eqs. (3)-(7) is as follows:

$$\Delta i_c = \Delta i_{ct} + \Delta i_{cs}. \quad (8)$$

$$\Delta i_{cs} = \frac{(RGx + 1)\Delta i_{c0} - RG(X - x)i_{m1}}{RGX + 1} \quad (9)$$

$$\Delta i_{ct} = \sum_{n=0}^{\infty} s_n e^{-\frac{\xi_n^2}{G\Delta L}t} \sin(\xi_n x). \quad (10)$$

Where,

$$s_n = \frac{-4(\Delta i_{c0} + i_{m1})\cos(\xi_n X)}{2\xi_n X - \sin(2\xi_n X)} \quad (11)$$

$$\xi_n + RG \tan(\xi_n X) = 0 \quad (n\pi < \xi_n < n(\pi + 1)) \quad (12)$$

Δi_{cs} is independent from time and Δi_{ct} decays as time elapses. The current of strand 1 does not therefore become zero as expected.

Figure 9 shows the current imbalance ratio n_r , defined by i_1/i_{m1} , at $x = 0$ m after the normal transition as a function of time in case of $n_{r0} = 4$. In the calculation, R , X_n and ΔL were set at $7.75 \times 10^{-4} \Omega/\text{m}$, 10, 20 and 40 cm, and 0.5 μH , respectively.

The circulation current is convergent to Δi_{cs} after a few milliseconds from the normal generation, as shown in *Fig. 9*. Since the normal resistance changes much slowly in comparison with this decay time as shown in *Fig. 7*, we can conclude that the circulation current is approximately calculated using a steady-state model.

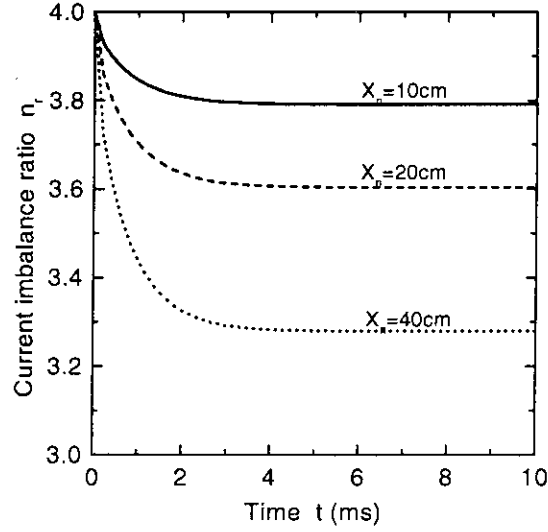


Fig. 9. Calculated current imbalance ratio at the heated zone after normal generation in the stability experiment.

5.1.2 Steady-state model

The current of strand 1 after the normal transition is evaluated taking into account the variation of the normal zone length by using the steady-state model. The following equation therefore governs the current of strand 1 providing the strands excluding strand 1 is in a superconducting state.

$$\frac{d^2 i_1}{dx^2} - GR_1 i_1 = 0. \quad (13)$$

The normal resistance, R_1 [Ω/m], is assumed to satisfy the following equation for simplicity.

$$R_1 = \begin{cases} R_{10} & (0 \leq x < X_{n1}) \\ 0 & (X_{n1} < x) \end{cases} \quad (14)$$

Where X_{n1} [m] and R_{10} [Ω/m] denote the normal zone length upstream the center of the heated zone and normal resistance of the unit length of strand 1, 0.775 m Ω/m , at the fully normal state at 4 T.

The current of strand 1 is the same as the current supplied from the power source at the end of the conductor and minimum at the heated zone. The boundary conditions are consequently as follows: At $x = 0$ m,

$$\left. \frac{di_1}{dx} \right|_{x=0} = 0. \quad (15)$$

At the end of the conductor,

$$i_1|_{x=\alpha X} = I_1. \quad (16)$$

Thus, the current of the strand 1 at $x = 0$ m is calculated as follows:

$$i_1 = \frac{i_1'}{\cosh(\sqrt{RG}X_{n1})}, \quad i_1' = \frac{I_1}{1 + \sqrt{R_1 G}(\alpha X - X_{n1}) \tanh(\sqrt{R_1 G}X_{n1})} \quad (17)$$

Where X_{n1} [m] satisfies the following equation.

$$X_{n1} = \alpha X - \frac{(I_1 - i_1')}{GV_1'} \quad (18)$$

Where V_1' [V] denotes the normal voltage on the region of $x > 0$ m and is calculated from,

$$V_1' = (1 - \alpha)V_n \quad (19)$$

The transverse conductance is set at 10^3 S/m. *Figure 10 (a)* shows the calculated current of strand 1 for the measured resistive voltage shown in *Fig. 7 (b)*. The current of strand 1 in case of the quench shown in *Fig. 7 (a)* is the same as that shown in *Fig. 10 (a)* as has been described previously.

5.2 Coolant temperature rise by Joule heating from strand 1

The coolant temperature rise from strand 1 transits to the normal state until the onset of the conductor quench is evaluated for the current of strand 1 which in turn is calculated as shown in *Fig. 10 (a)*. The coolant temperature rise in case of *Fig. 7 (a)* can also be estimated since the current of strand 1 in case of *Fig. 7 (a)* is the same as that in *Fig. 10 (a)* as is mentioned previously.

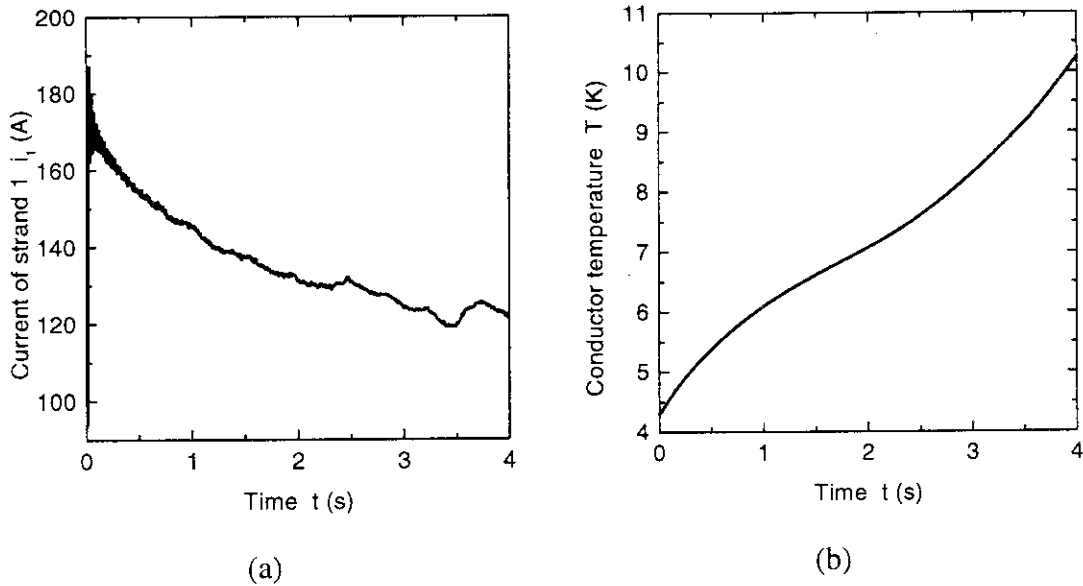


Fig.10. Calculated current of strand 1 at $x=0$ m, (a), and coolant temperature, (b), for the case shown in *Fig. 7 (b)*. Those for the normal voltage shown in *Fig. 7 (a)* are the same as the ones in these figures.

The strands excluding strand 1 arrive at the normal state after a long elapse from the normalcy origination in strand 1. Reynolds number is calculated to be 3000 for the initial coolant flow. It is therefore expected the temperatures of the strands excluding strand 1, conduit and coolant are almost the same because of good thermal diffusivity due to the coolant convection in the turbulent state. The conductor temperature, θ [K], is therefore calculated from the following equation,

$$\gamma_{con} S_{con} \frac{d\theta}{dt} = \frac{r i_1^2}{S_{Cu}} \quad (19)$$

Where γ [J/m³K] denotes the volumetric heat capacity, S [m²] the cross-sectional area and r [Ω m] the electrical resistivity of copper stabilizer, respectively; and subscripts *con* and *Cu* are for the conductor and copper in strand 1. The heat capacity of unit volume conductor is defined by the following equation:

$$\gamma_{con} S_{con} = \gamma_{Cu} S_{st} + \gamma_{SS} S_{SS} + \gamma_{He} S_{He} \quad (20)$$

Where subscripts *st*, *SS* and *He* indicate the values for the strands, conduit and coolant, respectively. The heat capacity of the strand is substituted by the one for copper in Eq. (20), for simplicity. During the normal propagation, the coolant pressure would be raised as a result of a large induced coolant flow due to Joule heat generation. However, the Joule heat generation is not large when only strand 1 is at the normal state. The pressure rise is therefore small before all of the strands transit to the normal state. The volumic heat capacity of the coolant is therefore calculated by assuming a constant coolant pressure.

Figure 10 (b) shows the calculated conductor temperature. The current sharing temperature of the strands excluding strand 1 are evaluated to be 6.6 and 7.1 K for the cases shown in Figs. 7 (a) and (b) by linearly interpolating the critical current and critical temperature, which is derived from the formula studied by Spencer¹⁸. The calculated conductor temperature is almost the same as the current sharing temperatures of the strands excluding strand 1 in case of $n_{r0} = 2$. However, it exceeds the current sharing temperature of the 26 strands by 4 s when the conductor quench began to take place in case of $n_{r0} = 4$. One possible explanation of this is heat leak from the conductor to the epoxy since the thermal insulation of the epoxy is not effective for long heating periods. Also, lack of a sufficient model is another reason for the error because the thermal diffusion by the coolant convection was neglected in our model. However, we can say that the conductor temperature sufficiently rises by the Joule heating from strand 1 after the long elapse of time from the initial normal transition until conductor quench. It can be therefore concluded that the conductor quench is attributable to the coolant's temperature rise.

5.3 Prevention of ramp-rate limitation

When the coolant temperature is diffused well in the conductor's cross section, it takes a long time to make the conductor quench as a result of the current imbalance. If it takes a long time to initiate the conductor quench, it is difficult to make the conductor consisting of chrome-plated strands quench⁹. The diffusion of the coolant temperature is good in case the coolant flow is in a turbulent state. On the other hand, there may appear a laminar flow region during a pulse charge due to the induced coolant flow by heat generation due to AC losses⁹. It was thought that the ramp-rate limitation takes place from this region. It is consequently expected that the instability due to current imbalance, ramp-rate limitation, in the conductor consisting of chrome-plated strands can be prevented by avoiding the generation of the laminar flow region, *i.e.*, keeping the coolant flow in a turbulent state.

6. Conclusions

The effect of current imbalance on stability was experimentally investigated using conductor consisting of chrome-plated strands. The results are:

- 1) The stability deteriorates when the current distribution is not uniform in the conductor. The stability is determined by the largest strand current if it is sufficiently large.
- 2) If the strand flowing the large current transits to the normal state, the conductor quenches due to the coolant temperature rise by the Joule heating of the strands in the normal state. It took a long time, *i.e.* a few seconds, to make the conductor quench by the coolant temperature rise since the coolant temperature was diffused well in the conductor's cross section in case the coolant flow was turbulent. Such a long elapse of time makes the conductor difficult to quench in a pulse charge. Using this effect, the ramp-rate limitation can possibly be prevented.
- 3) The transverse conductance between the chrome-plated strands was in the order of 10^3 S/m and uniform along the conductor's axis.

Acknowledgments

The authors would like to thank Drs. S. Shimamoto, M. Ohta and T. Nagashima in Japan Atomic Energy Research Institute (JAERI) and Dr. S. Ito in Toshiba corporation for their encouragement and support during this work. Thanks are also due to all staff members in superconducting magnet laboratory in JAERI and all others concerning this work at Toshiba corporation.

5.3 Prevention of ramp-rate limitation

When the coolant temperature is diffused well in the conductor's cross section, it takes a long time to make the conductor quench as a result of the current imbalance. If it takes a long time to initiate the conductor quench, it is difficult to make the conductor consisting of chrome-plated strands quench⁹. The diffusion of the coolant temperature is good in case the coolant flow is in a turbulent state. On the other hand, there may appear a laminar flow region during a pulse charge due to the induced coolant flow by heat generation due to AC losses⁹. It was thought that the ramp-rate limitation takes place from this region. It is consequently expected that the instability due to current imbalance, ramp-rate limitation, in the conductor consisting of chrome-plated strands can be prevented by avoiding the generation of the laminar flow region, *i.e.*, keeping the coolant flow in a turbulent state.

6. Conclusions

The effect of current imbalance on stability was experimentally investigated using conductor consisting of chrome-plated strands. The results are:

- 1) The stability deteriorates when the current distribution is not uniform in the conductor. The stability is determined by the largest strand current if it is sufficiently large.
- 2) If the strand flowing the large current transits to the normal state, the conductor quenches due to the coolant temperature rise by the Joule heating of the strands in the normal state. It took a long time, *i.e.* a few seconds, to make the conductor quench by the coolant temperature rise since the coolant temperature was diffused well in the conductor's cross section in case the coolant flow was turbulent. Such a long elapse of time makes the conductor difficult to quench in a pulse charge. Using this effect, the ramp-rate limitation can possibly be prevented.
- 3) The transverse conductance between the chrome-plated strands was in the order of 10^3 S/m and uniform along the conductor's axis.

Acknowledgments

The authors would like to thank Drs. S. Shimamoto, M. Ohta and T. Nagashima in Japan Atomic Energy Research Institute (JAERI) and Dr. S. Ito in Toshiba corporation for their encouragement and support during this work. Thanks are also due to all staff members in superconducting magnet laboratory in JAERI and all others concerning this work at Toshiba corporation.

5.3 Prevention of ramp-rate limitation

When the coolant temperature is diffused well in the conductor's cross section, it takes a long time to make the conductor quench as a result of the current imbalance. If it takes a long time to initiate the conductor quench, it is difficult to make the conductor consisting of chrome-plated strands quench⁹. The diffusion of the coolant temperature is good in case the coolant flow is in a turbulent state. On the other hand, there may appear a laminar flow region during a pulse charge due to the induced coolant flow by heat generation due to AC losses⁹. It was thought that the ramp-rate limitation takes place from this region. It is consequently expected that the instability due to current imbalance, ramp-rate limitation, in the conductor consisting of chrome-plated strands can be prevented by avoiding the generation of the laminar flow region, *i.e.*, keeping the coolant flow in a turbulent state.

6. Conclusions

The effect of current imbalance on stability was experimentally investigated using conductor consisting of chrome-plated strands. The results are:

- 1) The stability deteriorates when the current distribution is not uniform in the conductor. The stability is determined by the largest strand current if it is sufficiently large.
- 2) If the strand flowing the large current transits to the normal state, the conductor quenches due to the coolant temperature rise by the Joule heating of the strands in the normal state. It took a long time, *i.e.* a few seconds, to make the conductor quench by the coolant temperature rise since the coolant temperature was diffused well in the conductor's cross section in case the coolant flow was turbulent. Such a long elapse of time makes the conductor difficult to quench in a pulse charge. Using this effect, the ramp-rate limitation can possibly be prevented.
- 3) The transverse conductance between the chrome-plated strands was in the order of 10^3 S/m and uniform along the conductor's axis.

Acknowledgments

The authors would like to thank Drs. S. Shimamoto, M. Ohta and T. Nagashima in Japan Atomic Energy Research Institute (JAERI) and Dr. S. Ito in Toshiba corporation for their encouragement and support during this work. Thanks are also due to all staff members in superconducting magnet laboratory in JAERI and all others concerning this work at Toshiba corporation.

References

- 1 Faivre, D. and Truck B. *IEEE Trans. Magn.* (1981) MAG-17 p.1048.
- 2 Schermer, R. and Truck, B. *Adv. Cryog. Eng.* (1980) 26 p.599.
- 3 Koizumi, N., Okuno, K., Takahashi, Y., Tsuji, H., *et al.* *Cryogenics* (1994) 34 p.155.
- 4 Koizumi, N., Okuno, K., Takahashi, Y., Tsuji, H., *et al.* *Cryogenics* (1994) 34 p.1015.
- 5 Koizumi, N., Okuno, K., Takahashi, Y., Tsuji, H., *et al.* *Cryogenics* (1996) 36 p.409.
- 6 Steeves, M., Takayasu, M., Painter, T., Hoenig, M., *et al.* *Adv. Cryog. Eng.* (1991) 37 p.345.
- 7 Ando, T., Nakajima, H., Sasaki, T., Hiyama, Y., *et al.* *Adv. Cryog. Eng.* (1994) Vol. 39 p.335.
- 8 Vysotsky, V., Takayasu, M., Ferri, M., Minervini, J. *et al* *IEEE Trans. on ASC* (1995) Vol.5 No.2 p.580.
- 9 Koizumi, N., Takahashi, Y., Nishi, M., Isono, T. *et al* "Ramp-rate Limitation due to Current Imbalance in a Large Cable-in-conduit Conductor Consisting of Chrome-plated strands" *Cryogenics Under contribution*.
- 10 Wadayama, Y., Koizumi, N., Takahashi, Y., Matsui, K., *IEEE Trans. Magn.* (1996) Vol. 32 No. 4 p.2858.
- 11 Ito, T., Koizumi, N., Wakabayashi, H., Miura, Y., *et. al.* *JAERI-Research* (1996) 96-042.
- 12 Koizumi, N., Takahashi, Y., Okuno, K., Nishi, M. *et al* "Stability and Heat Removal Characteristics of a Cable-in-Conduit Superconductor for Short Length and Short Period Perturbation" *Cryogenics Under contribution*.
- 13 Ono, M., Wachi, Y., Hamajima, T., Yamaguchi, M., *et al.* *IEEE Trans. on ASC.* Vol. 5 No.2 p.564.
- 14 Ono, M., Wachi, Y., Hamajima, T., Yamaguchi, M., *et al.* "Electrical Circuit Model among Superconducting Strands in Real-scale CICC's" *ASC 1996 Under contribution*.
- 15 Ono, M., Hamajima, T., Yamaguchi, M., Sawada, Y., *et al.* *Cryog. Eng.*(1996) Vol. 31 p.518.
- 16 Hartwig, G. *Adv. Cryog. Eng.* (1991) Vol. 24 p.17.
- 17 Takayasu, M., Gung, C., Steeves, M. and Menervini, J. "Measurements of transverse resistance of multi-strand superconducting cable", MIT Plasma Fusion Center Internal report.
- 18 Spencer, C., Sanger, P. and Young, M. *IEEE Trans. Magn.* (1979) MAG-15 p.76.

Appendix

The voltage in the case of quench under a uniform current distribution is shown in *Fig. A1* as a reference. The voltage of strand 1 and the others are in good agreement.

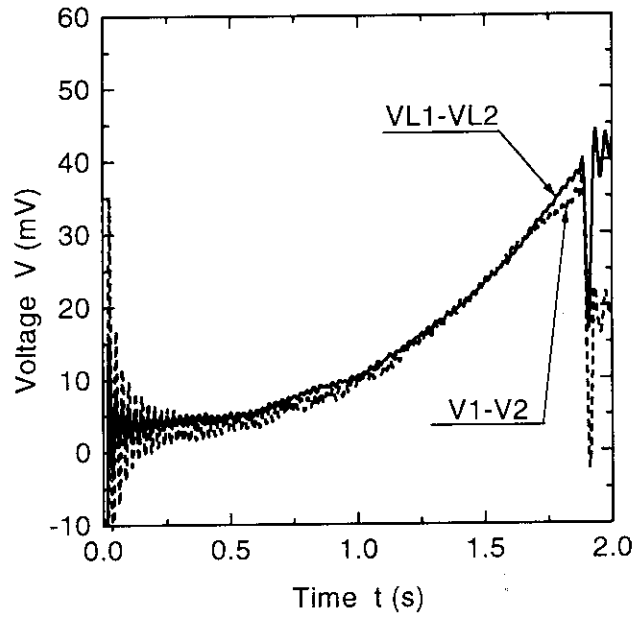


Fig. A1. The voltage profile of strand 1 and the other strands. The currents supplied to strand 1 and the others were 52 and 1348 A, resulting in $n_{r0}=1$.