MAGNETIC INSTABILITY AND TRANSIENTLY STABILIZED MAXIMUM CURRENT OF V_3Ga TAPE COILS

Teruo Noguchi
Institute for Super Materials, ULVAC Corporation
523, Yokota, Sanbu-machi, Chiba Pref., Japan

Abstract

A small coil made from superconducting V_3Ga tape is located in a superconducting solenoid so that their central axes cross at right angle. Various coils which differ in cooling conditions, thickness of stabilizing copper foils and width of the tape are tested in a preset current-increasing field. For a preset current which is smaller than a threshold value, coils do not go normal even if large flux jumps are observed. But for a current over the threshold value, a first flux jump makes the coil normal. The threshold current depends on the tape width, cooling conditions and the thickness of stabilizing copper. This threshold current is considered to be a transiently stabilized maximum current which is expressed by

$$I/I_c < phS(Tc-Tb)/\rho I_c^2.$$

It is found that the threshold current is very close to the quenching current of a larger V_3Ga tape coil.

I. Introduction

The transition of a V_3Ga tape wound magnet to the normal state is ordinarily initiated from the end piece of stacked pancakes at which radial field component is highest. Relatively small field component perpendicular to the broad surface of a tape in the end pancake brings about an instability.

Theoretical study of this phenomenon was presented by H.R. Hart,[1] and some experimental investigations[1,2] were also reported for Nb_3Sn tapes. Experimental result on a cusp coil[3] made from Nb_3Sn tapes and some ways of over-coming the instability were presented by other authors.[3-5]

However it is not economical from the view of a great deal of labor, materials and liquid helium that this instability is investigated by using a large magnet. Study of the magnetization of tapes is also not enough to solve the instability problem of a magnet which has a transport current.

In this paper, the stability of a superconducting tape against a flux jump is first analyzed for non-zero transport current. Secondly a simple method of testing the stability is proposed. Experimental results and discussions are described in the last part of this paper.

II. Analysis

A superconducting tape is usually quite stable against a high field parallel to its broad surface. It is considered that the thickness of a superconducting layer, usually less than ten micron, is thin enough to fulfill the criterion of intrinsic stabilization. Width of a superconducting tape, however, is usually of several millimeters, which does not satisfy the criterion against a high field perpendicular to its broad surface. A temperature rise following a flux jump often makes the critical current of a tape low. If the tape has a transport current corresponding Joule's heat is generated by a current shared by normal materials used as the back-up to the superconducting layer. Assuming a linear relation between the critical current and the temperature T, the rate of heat generation per unit length is given by

$$IV = I\left(\frac{\rho}{S_1}\right)\left\{I - I_c\left(1 - \frac{T-T_b}{T_c-T_b}\right)\right\}, \qquad (1)$$

where T_c, T_b are the critical temperature and the bath temperature, respectively, and ρ, S_1 are the resistivity and the cross-sectional area of the stabilizing material, respectively. I_c is the critical current at the bath temperature.

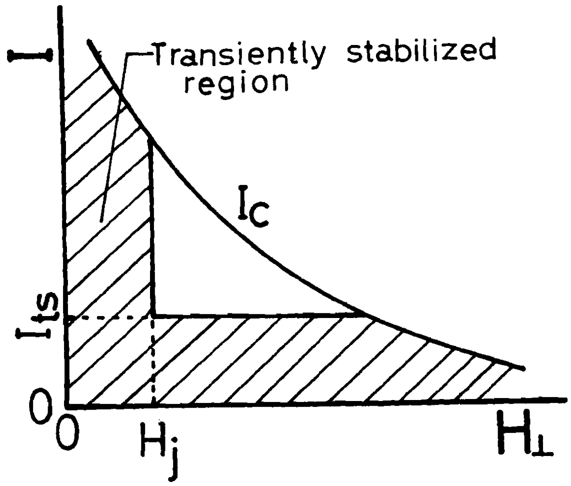

Fig. 1. Illustration of Transient Stabilization.
H_j: Field at which flux jump occurs.
Its: Transiently stabilized max. current.

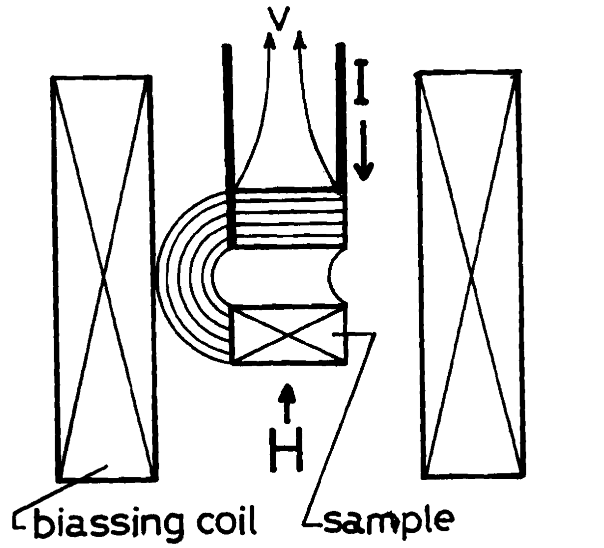

Fig. 2. Experimental arrangement.

On the other hand the absorption of heat is written by

$$CS_2 \frac{dT}{dt} , \tag{2}$$

where C and S_2 are the average heat capacity and the overall cross-sectional area of the tape, respectively. If the uniform temperature distribution is assumed in the tape, and allowing the tape to be cooled by liquid helium, the heat removal is given by

$$ph(T - T_B) \tag{3}$$

where p and h are the cooling perimeter and the heat transfer co-efficient, respectively. Thus, the energy balance equation is expressed in equation (4).

$$CS_2 \frac{dT}{dt} = I\left(\frac{\rho}{S_1}\right) \left\{I - I_c\left(1 - \frac{T-T_B}{T_c-T_B}\right)\right\} - ph(T-T_B) \tag{4}$$

Equation (4) is rearranged as follows:

$$\frac{d\theta}{dt} - \left\{\frac{\rho I_c{}^2 i}{CS_1S_2(T_c-T_B)} - \frac{ph}{CS_2}\right\}\theta = \frac{\rho I_c{}^2 i(i-1)}{CS_1S_2(T_c-T_B)} , \tag{5}$$

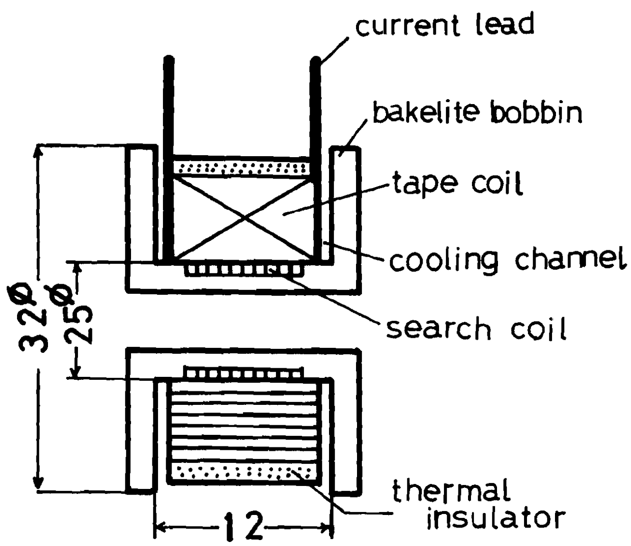

Fig. 3. Cross-sectional view of sample coil.

where $\theta = \frac{T - T_B}{T_c - T_B}$ and $i = \frac{I}{I_c}$.

If the temperature independence of ρ and C is assumed, the solution of Eq.(5) is given by

$$\theta = B + A \exp(\alpha t) \tag{6}$$

TABLE I. Samples Used for Experiments

SAMPLE NO.	TAPE WIDTH (mm)	THICKNESS of Cu (μ)	COOLING	INTERLEAVING MATERIAL
1	10	20	A*	NONE
2	10	20	B**	NONE
3	10	30	A	NONE
4	10	30	B	NONE
5	10	50	A	NONE
6	10	50	B	NONE
7	10	20	A	5-N Al tape 100μ in. thick.
8	10	20	B	same as No. 7
9	4	20	A	NONE
10	4	20	B	NONE

* Better edge cooling with cooling channels of 1mm width.
** Poor cooling with Apiezon N grease.

where

$$B = \frac{-\rho I_c^2 i(i - 1)}{\rho I_c^2 i - phS_1(T_c - T_B)}$$

$$\alpha = \frac{\rho I_c^2 i - phS_1(T_c - T_B)}{CS_1S_2(T_c - T_B)}$$

$$A = -B + \frac{T_i - T_B}{T_c - T_B}$$

T_i is the initial temperature raised by a flux jump. If $T_i < T_c$ and T decreases from T_i with time the superconducting tape is transiently stabilized.[6] This condition is obtained if $\alpha < 0$, or

$$i < \frac{phS_1(T_c - T_B)}{\rho I_c^2} \qquad (7)$$

Equation (7) represents the existence of a maximum current for the transiently stabilized condition. If i = 1, then Eq. (7) reduces to

$$\frac{\rho I_c^2}{phS_1(T_c - T_B)} < 1 \qquad (8)$$

This is nothing but the criterion for full stabilization. A superconducting tape which has a smaller transport current than the value determined by Eq.(7) will not go normal if a flux jump is brought about.

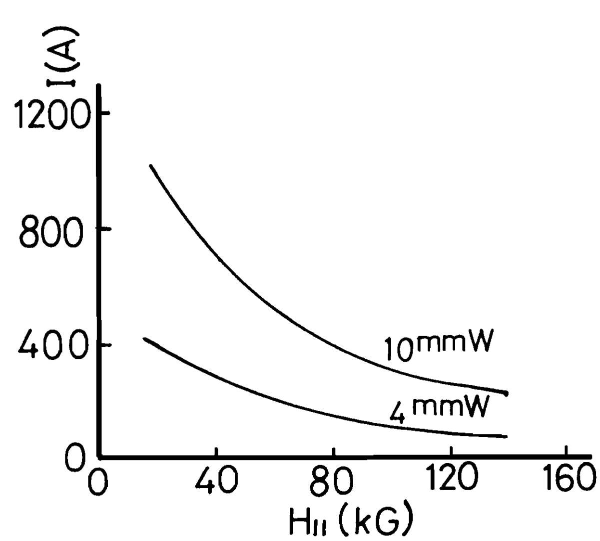

Fig. 4. Short sample characteristics of V_3Ga tape.

Now, according to H. R. Hart,[1] when a field is applied to the broad surface of a superconducting tape, a flux jump can occur at a field determined by

$$H = \{\frac{\pi^4}{25}\frac{\bar{K}}{\bar{\rho}f}(-\frac{1}{J_c}\frac{\partial J_c}{\partial T})^{-1}\}^{1/2} \qquad (9)$$

or

$$H = \frac{4\pi\bar{h}}{10\ \bar{J}_c\bar{\rho}f}(-\frac{1}{J_c}\frac{\partial J_c}{\partial T})^{-1}, \qquad (10)$$

where $\bar{K}$, $\bar{\rho}f$, $\bar{J}_c$, $\bar{h}$ are the average thermal conductivity, the average flow resistivity, the average current density and the average heat transfer coefficient, respectively. Equation (10) is used for the case where an efficient cooling by liquid helium is attainable.

Therefore, we can image the concept of the transient stabilization as illustrated in Fig. 1.

III. Experimental Method

A sample for test must satisfy the following requirements:

1) A transport current can be supplied.

2) A field perpendicular to the plane of the tape is applicable.

3) Cooling conditions can be controlled.

4) The amount of the stabilizing material can be controlled.

5) The width of the tape can be controlled.

The above requirements can be attained by using a method illustrated in Fig. 2. Details of the sample are shown in Fig. 3. Two gaps between the wound tape and the bakelite bobbin are used as cooling channels for better cooling, and also used as thermal insulators for poor cooling by being filled up with Apiezon N grease. In order to control the amount of the stabilizing material some tapes which are soldered with copper foils of different thickness are prepared.

In this experimental arrangement, as is seen in Fig. 2, the direction of the field is not uniform along the wound tape. Only the top and the bottom of the winding are perpendicular to the field direction. In these two parts, however, a transport current flows in the opposite directions to each other. Therefore, the relation of directions among the tape surface, the field and the transport current are somewhat complex. In spite of the above-mentioned complexity, it is regarded that the magnetic

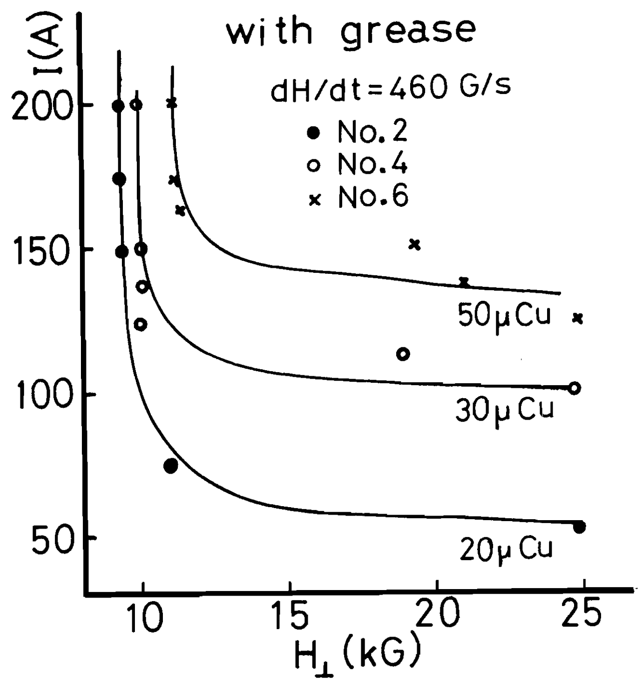

Fig. 5. Transiently stabilized current of samples No.2, 4 and 6, vs perpendicular field.

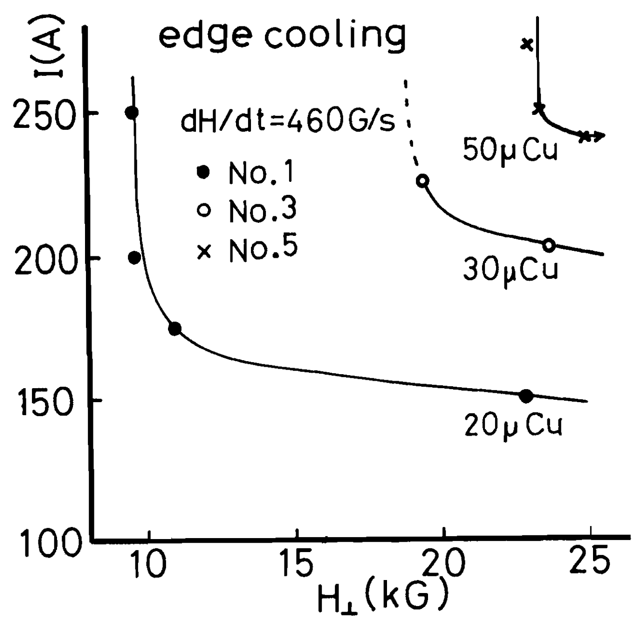

Fig. 6. Transiently stabilized current of samples No. 1, 3, and 5.

instability will occur at the top or bottom of the winding, where the field perpendicular to the tape surface is highest. The self-field produced by the test sample is negligibly small as compared to the biassing external field.

The test was conducted according to the following procedure. A transport current is supplied to the sample at first and then a biassing external field is increased from zero up to an appropriate value at a constant rate. An X - Y recorder is used for recording the current of the biassing magnet (X-axis), the terminal voltage across the sample (Y_1-axis) and the induced voltage on the search coil (Y_2-axis). In this process, some flux jumps will be observed, some of which may make the sample quench, if the sample has a larger transport current than the value determined by Eq.(7). Thus for a given sample we can get the field at which the magnetic instability occurs as well as the value of a transport current which is stable against flux jumps. The samples used in this experiment are tabulated in Table 1. Figure 4 shows the I_c-H (parallel to the plane of the tape) characteristics of the short sample which was used for this investigation. The biassing field is produced by a superconducting solenoid of 50mm in inner diameter, 60mm in outer diameter and 135mm in length. The maximum central field produced is about 30 kG.

IV. Experimental Results and Discussion

Effect of Copper Thickness

The transiently stabilized currents of the samples which are filled up with Apienzon N grease (No. 2, 4 and 6), are plotted against the perpendicular biassing field in Fig. 5. The stabilized current becomes larger as the thickness of copper increases, but the minimum field which makes samples quench is little varied. The results obtained when these samples are cooled by liquid helium through their edges (No. 1, 3 and 5), are shown in Fig. 6. As is seen, both the stabilized currents and the minimum quenching field increase with increasing copper thickness. For the above-referred six samples, the stabilized currents are plotted in Fig. 7 as a function of copper thickness. For three edge cooled samples, the stabilized currents are about two times as large as those of the greased ones. As a whole, these results show that the most important thing for the stabilization of a superconducting tape is good cooling. The transiently stabilized currents do not increase linearly with increasing copper thickness. This is inconsistent with Eq.(7). But qualitatively this result is well consistent with Eq.(7).

As the heat transfer coefficient is not measured, and further as the effective heat transfer coefficient for samples filled up with Apiezon N grease is not known, quantitative comparison between the data and Eq.(7) cannot be made. As for the heat transfer coefficient, however, the value will be estimated as about 1 W/cm^2K for the nucleate boiling heat transfer. It is questionable that this value could be used for calculation because an initial temperature rise following a flux jump might exceed the temperature range of the nucleate boiling of liquid helium. But this temperature rise is pulsive, and for such a transient phenomenon, the heat must be transferred also transiently. The transient heat transfer coefficient has been measured by J. Jackson,[7] who has reported the value as about 0.5 $\sim$ 1.5 W/cm^2K for a temperature rise of 2 $\sim$ 5 K.

Therefore, the value of 1 W/cm^2K is reasonable. The values of other variables in the right-hand side of Eq.(7) are chosen as follows:

$$\rho = 1.6 \times 10^{-8}\ \Omega\text{-cm},\quad I_c = 900\text{A (at 25kG)}$$

$$T_c - T_B \cong 10\text{K}$$

and pS_1 = 1.2, 2, 4 x $10^{-4}cm^3$ for the copper layer of 20, 30 and 50μ in thickness respectively. The result of calculation is plotted by a dotted line in Fig. 7. Though an agreement with experiments is not always good, Eq.(7) is useful for estimating the value of the transiently stabilized current.

Effect of Interleaving Material

Now the effects of the interleaving material will be studied. Samples No.7 and 8 are co-wound with a high purity aluminum tape having an oxidized film on its surface for electric insulation. The purity and the thickness of the aluminum tape is 99.999% and 0.1mm, respectively.

The experimental results are shown in Fig. 8. For a greased sample (No.8), both the transiently stabilized current and the field which makes the sample quench are little increased. But for a cooled sample (No.7), they are both

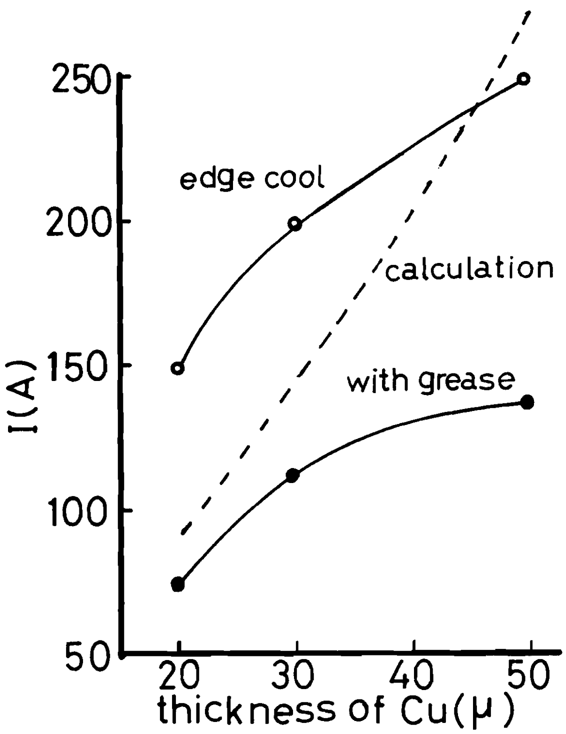

Fig. 7. Transiently stabilized current vs thickness of copper. A dotted line is calculated by Eq. (7).

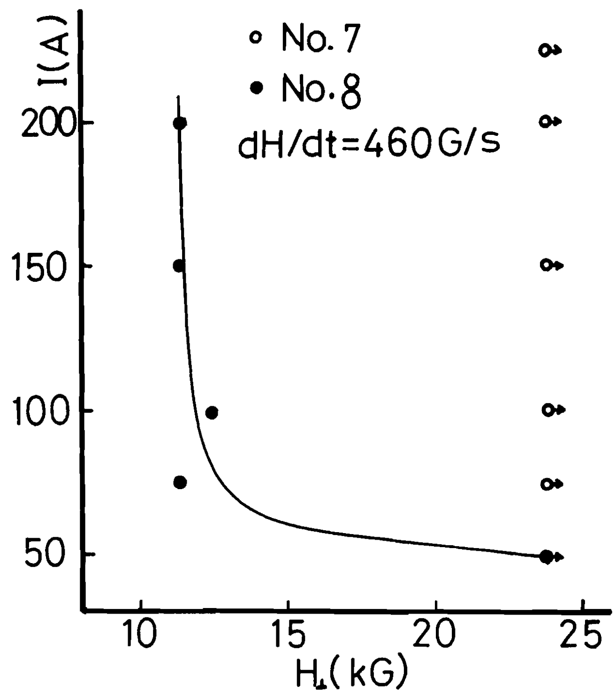

Fig. 8. Transiently stabilized current of samples No. 7 and 8.

considerably increased, and are almost equal to those of the sample No.5 which has a copper layer of 50μ in thickness.

From these results, it appears that the interleaving aluminum is not useful for dampling a flux motion, and that it is useful only for a cooling effect. Presumably our aluminum tape was not pure enough to damp a flux motion.

Effect of Tape Width

Since an energy released by a flux jump is proportional to the cube of a tape width,[5,8] the resulting rise in temperature of a narrower tape should be much lower than that of a 10mm tape. Therefore, a narrower tape should be more stable against a flux jump. In addition to the above consideration, Eq. (7) shows that the ratio of the stabilized current to the critical current is doubled if the tape width is halved, because S_1/I_c^2 is doubled by halving the tape width.

Experiments are made for a tape of 4mm in width whose characteristics are shown in Fig. 4. The results are shown in Fig. 9. Obviously the ratio I/I_c is just as predicted for a greased sample (No.10). As for a cooled sample (No.9), the results are not the same as that of the sample No.9, but the stability is much improved. In Fig. 9, it is to be noted that the field which makes the sample quench increases considerably. This effect will be explained by the fact that the central part of the tape is cooled better as the tape width becomes narrower.

Effect of the Rate of Field Increase

If the magnetic diffusivity of a superconductor is negligibly small as compared to its thermal diffusivity, the heat generated in the process of flux redistribution will be carried away rapidly into the surroundings, such as a normal metal or liquid helium. Accordingly a flux jump cannot occur in this case.

But in the case where the above assumption is not realized, a flux jump would occur except for the case of the intrinsic stabilization. If a field is increasing or decreasing fast, a flux in a superconductor is redistributing fast, too. Thus for rapid change of the field, the magnetic diffusivity is not negligibly small, and the superconductor is more unstable. Speaking about our experiments, this can be said that the field which makes a sample quench becomes lower as the rate of field change becomes faster. Experiments were made for the samples No.2, 8 and 10, and the results are shown in Fig. 10. In these experiments, the value of the transport current is chosen in such manner that the first flux jump can make the sample quench. As is seen in Fig. 10, the experimental results are identical with the above prediction. Thus it is found that the slower sweep is also useful to improve the stability of a superconducting tape.

A distinct dependence on dH/dt could not be obtained for all the samples which were better cooled by liquid helium. This is the reason why a flux jump does not occur always at a constant value of the field for better cooled samples. With regard to the field strength at which a flux jump occurs, more detailed analysis will be difficult, because, as mentioned previously, the field is not uniform throughout the tested samples. In order to do this, and to compare with various theories, more precise and more careful experiments must be made.

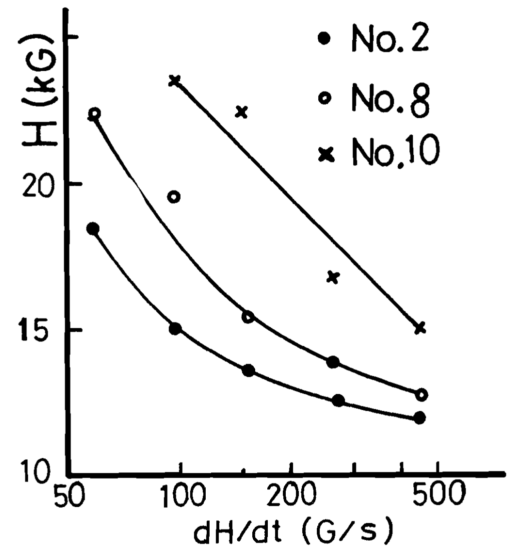

Fig. 10. First quenching field of sample No. 2, 8 and 10, vs rate of increasing field.

Larger Coil Test

A larger coil was wound with 10mm width V_3Ga tape soldered with a 20 microns copper foil per side. The dimensions of the coil are 30mm in i.d., 150 mm in o.d. and 110 mm in length. Two end pancakes of this coil were co-wound with 4-N aluminum foils of 50 microns in thickness. The coil current was between 190A and 210A, and resulting central field and the maximum radial field were about 67 kG and 17 kG, respectively.

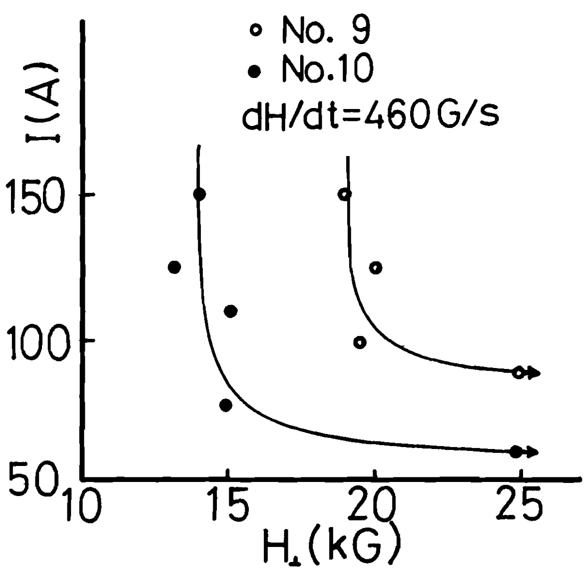

Fig. 9. Transiently stabilized current of samples No.9 and 10.

The test for the 10 turns small coil co-wound with 4-N aluminum (50 microns in thickness) showed that the transiently stabilized current and the field which mades the sample quench were 190A and 16 kG, respectively. This result is identical with that of the above larger coil. Thus we can see that the degradation of a tape wound coil is brought about by a flux jump which occurs at an end pancake, and that the degraded current of the coil can be predicted by measuring the transiently stabilized maximum current.

V. CONCLUSION

The instability of a superconducting V_3Ga tape is brought about by a field which is perpendicular to its broad surface. If the tape has a transport current, its maximum value which is stable against a flux jump is determined by the criterion,

$$i < \frac{phS_1(T_c - T_B)}{\rho I_c^2}$$

In order to improve the instability, all of the following ways are effective; i.e. to increase the thickness of stabilizing copper, to achieve better cooling, to co-wind a high purity material and to make narrower the tape width. But the most important thing is the better cooling. Even if a thicker stabilizing material is used, or even if a higher purity material is co-wound, the instability could not be improved so much, unless the tape is cooled better by liquid helium.

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