Superconducting Coil Stability and Interaction between the Transport Current and Diamagnetic Currents

A.P. Martinelli

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Contents

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Abstract

A number of stability tests were made on superconducting samples (Nb-25 % Zr, Nb-48 % Ti, stabilized and non-stabilized) of single-layer coils in which a critical state was reached by applying transport current I and transverse field H in the procedures (I-H), (H-I), and H and I simultaneously (coil simulation).

By using the coil simulation procedure, and also pulsed fields, indirect experimental evidence is given of minimum stability of the parts of the coil winding located in the 15 - 20 kOe region. The test results are related to results of similar tests reported in the literature.

Particular attention is devoted to the interaction between the transport current and diamagnetic currents and to its effect on stability. The results suggest an additional general approach to the known methods of stabilizing coils by scaling the superconductor cross section to the transverse field. This approach should make it possible, by reducing the diamagnetic currents in the superconductor, to attain better field homogeneity and improve material utilization and coil stability.

1. Introduction

In a series of tests conducted with the intent of studying the stability of superconducting materials and coils under externally imposed magnetic perturbations (Ref. 1), a critical state (Ref. 2) is induced in the samples by using essentially three different energization procedures: 1) a magnetic field H is superposed on the sample, and then a current I is fed into it ((H-I) sequence); 2) a current I is fed into the sample, and then a field H is superposed ((I-H) sequence); 3) the current I is applied to the sample at the same time as the field H ((HI=), coil simulation procedure).

One particular requirement of the investigation was to find out whether the behaviour of hard superconductors acted on by pulsed fields depends on the procedure by which the critical state is attained in the superconductors, with the ultimate aim of correlating the results to others obtained for the stability of superconductors energized by the (H-I) or (I-H) procedure (Ref. 3, 4, 5).

In each of these procedures the current I, the field H, and the current I and field H are increased until the sample reverts to normality. Three different curves A, B, C are obtained respectively in Fig. 1 for a single-layer sample of non-copper-plated Nb-25 % Zn 0.25 mm diameter wire which also differ from the H_cI_c characteristics (curve D in Fig. 1) given by the wire manufacturer. The latter was measured again by the customary method, viz. first superposing a field H on the sample, and then quenching the sample with increased I a few times until the I_c value does not increase further.

It is here attempted to correlate the above experimental results with those obtained by other authors and to add something to our understanding of the physical processes involved in the instability of superconducting coils. Although the composite structure (superconductor plus substrate) and later particularly the filamentary structure used for high field superconductors largely settles the instability problem and the degradation effect in practice for NbTi and NbZi alloys, these problems are still of interest from the point of view of basic understanding and economy (cost of filamentary superconductors compared with that of single-core types) (Ref. 6). Furthermore, a basic physical understanding of instability is essential for coil design and construction using Nb_3Sn superconducting material.

The experimental results here show the region of highest instability in a coil and indicate improved methods of stabilization (more substrate in the region of higher instability) or utilization of the superconductor (less superconductor in the regions of lower instability).

It is pointed out how useful the coil simulation process is for the experimental determination of a H_cI_c characteristic that describes the coil behaviour more adequately.

2. Experimental setup

The experimental setup consists essentially of a cryostat system containing both the d.c. field superconducting coil and sample. The field coil is powered by a Westinghouse magnet controller (0 - 25 A, 0 - 10 V, with programmable linear current increase rate), the sample by a Kepco power supply (KS - 8 - 100 M, 0 - 100 A, 0 - 10 V), which was fitted with a programmable linear current increase rate apparatus, developed at IPP. The field H and the current I were recorded by an XY recorder. A pulsed coil internal and concentric to the d.c. coil and surrounding the sample allows an axial pulsed field to be superposed on the sample. All the samples used are in the form of single-layer coils about 20 mm long, 14 mm in diameter.

3. Experimental results and analysis

3.1 (I-H) and (H-I) energization procedure

Curve B of Fig. 1 depicts the normalization points during the process (I-H). The rate of increase of field dH/dt is about 15 Oe/sec. No noticeable difference is seen in the normalization points when using higher field increase rates (up to 100 Oe/sec). The instability was observed by Riemersma et al. (Ref. 7) to be independent of the rate of field increase within the range 0.1 to 100 Oe/sec.

The maximum field H which can be reached before the sample quenches increases with decreasing of the preset current I and reaches values beyond 15 - 20 kOe for values of I equal to or smaller than about 22 A. The value of I = 22 A therefore represents an upper limit to the preset current I beyond which the field H cannot reach values higher than 15 - 20 kOe without the sample reverting to normality.

During the (H-I) sequence (curve A of Fig. 1) higher values of current I can be reached at any preset field than in the(I-H) case (curve B of Fig. 1).

The different stability behaviour in the above two processes (I-H) and (H-I) is ascribed to the decay of the magnetization currents I_m which are induced by the changing field H. The reduction of I_m due to decay is observed (experimentally, in Ref. 8, 9, 10, while a theoretical derivation is reported in Ref. 10) to be proportional to the amplitude of the transport current (the transport current I replaces the I_m, which gradually collapse) and dependent on the application sequence of H and I. To be precise, the magnitude of the reduction in the (H-I) sequence is greater than in the (I-H) one.

It is then apparent that in the sequence (H-I) the I_m decay takes place mainly at low values of the transport current (I increases from zero to its final value), and finally, after this sequence, the sample is in a more stable condition (smaller I_m means that less energy is susceptible to thermal decay) than the sample after the sequence (I-H), where more I_m are present. The same trend is observed by Schrader and Kolondra (Ref. 5); a marked region of low current quenching in a low field range (10 - 20 kOe) is described when a stack of 12 series-connected Nb_3Sn coils are energized by the sequence (I-H). No similar region is observed in the sequence (H-I) of applying the current and field.

3.2 (HI=) procedure (coil simulation test)

Neither sequence (I-H) nor (H-I) by which the critical state is reached in the sample reproduces the procedure to which a layer in a real coil is actually subjected (simultaneous increase of H and I, depending on the coil geometry). The (I-H) and (H-I) sequences represent two extreme cases between which the real case lies. In fact, several parameters are reported (Ref. 6) as influencing the coil stability to a certain extent, such as the thermal contact between the wire and surroundings, the previous magnetic and thermal history of the coil, perturbations caused by movements of the wire, magnetic perturbations due to flux jumps in neighbouring wires, current changes brought about by ripple of the power supply, the actual field and current distributions in each region of the coil, etc.

However, the results obtained (curve C of Fig. 1, also Ref. 11) when testing the sample with the coil simulation procedure (HI=) provide ample evidence that the interaction between the transport current and magnetization currents on increasing I and H simultaneously is by far the most important factor in determining the behaviour of superconducting coils and includes, more or less directly, the above mentioned parameters.

Therefore the coil simulation sequence (HI=) could be applied to advantage in determining a more adequate wire characteristic for the coil performance than the one ($I_c(H)$) given by the wire manufacturer.

Curve C of Fig. 1 shows results of tests carefully and repeatedly carried out on the same Nb-Zr sample by increasing H and I simultaneously. The curve C is enveloped by a dashed region which covers the scattering of the results. Flux jumps are generally observed to scatter 5 - 20 % under equal conditions (Ref. 12).

The current increase rate is kept constant at about 0.1 A/sec, and the field increase rate is changed for the different points depicting curve C. The field increase rate therefore varies approximately between 15 and 120 Oe/sec from the point of curve C corresponding to a field of about 10 kOe to the point corresponding to 36 kOe, which is the maximum available stationary field. In this fashion (constant current increase rate and different field increase rate for each layer) the behaviour of a layer in a real coil (self-field) is simulated. Some extra points are, however, obtained using different (current and field) increase rates (current 5 - 15 A/min, field 15 - 120 Oe/sec) which coincide with the points already obtained.

It should be noted here that the layer sample is located in the centre of the field magnet, the field of which is constant within 1.5 % along the whole length of the sample. The same holds approximately for the radial field. The self-field of the layer sample (when inductively wound) produced by the current I adds to the H field. The points depicting curve C (also A, B, D) represent spontaneous normalization of the sample (without superposition of external magnetic disturbance).

3.3 Interaction of the transport current and diamagnetic currents. Instability region

The following observations were made (see Fig. 1):

1) Curve C sets a limit of the current (threshold value) beyond which the single-layer sample cannot be energized. A similar limit is also set by the curve B (sequence (I-H)), but at lower fields than curve C since in this case the magnetization current decay takes place at higher values of the transport current I (which is initially preset). Similar considerations hold for curve A ((H-I) sequence), which represents an upper limit of possible sample energization.

2) At about 10 kOe (curve C) the sample closely approaches the critical current I_c at that field (curve D). That is, in the energization process described by the load line OC_1 (see curve C) the mechanism by which the field-induced magnetization currents are replaced by the transport current I (with subsequent decay and heating of the superconducting material) takes place at "favourable" values of the field and transport current. That is, when the replacement of the I_m by the I takes place at values of I low relative to I_c (or at low ratio I/I_c), the thermal disturbance produced by the I_m decay is not sufficiently large to be propagated by this low value of the transport current I.

This explains the shape of curve B in Fig. 1 and its minimum (22 A) corresponding to the knee (beginning of the plateau) of the curve $I_c(H)$ (curve D). In this sense the knee of the $I_c(H)$ characteristic is expected to be related to the maximum instability region of the superconducting material (coil behaviour). The generality of this trend is further substantiated in the following.

3) The curve C drops noticeably at 12 - 15 kOe and reaches a minimum between 15 and 20 kOe. It is attractive to identify this minimum as corresponding to the maximum instability region of superconducting coils.

Although a number of methods of and attempts at detecting the quench region in superconducting coils have been described (e.g. Ref. 7, 13 to 16), the experimental results available are surprisingly scarce. Riemersma and co-workers (Ref. 7) indicate as the most probable region of instability that between 10 and 20 kOe for the coil tested, although their coil is reported to be somewhat erratic in its critical current. Iwasa and Montgomery (Ref. 3) report about a field area near 15 kOe of maximum sensitivity to magnetic field pulses externally superposed on a bifilar non-copper-plated Nb-25 % Zr sample induced to the critical state by the sequence (I-H). Their results largely correspond to those obtained here by the (HI=) procedure, particularly as to the maximum instability region near 15 kOe and also to the threshold transport current (23 A).

A qualitative explanation to relate the two sets of results obtained in different ways is attempted here. For this purpose some other results of pulsed field work on superconductors (Ref. 4, to be reported extensively elsewhere) will also be used.

3.4 Spontaneous and pulsed field triggered quench of (I-H) and (HI=) energized samples. Correlation of results.

3.4.1 Spontaneous quenching

The current density at a point in a hard superconducting material in the critical state (Ref. 2) when the transverse magnetic field has penetrated the sample (at a field greater than approximately 5 kOe) can be schematically expressed in vectorial form as

$$J_s + J_m = J_c , \qquad \text{(a)}$$

where J_s = transport current density
J_m = magnetization current density ($J_m(H)$)
J_c = critical current density ($J_c(H)$).

J_c decreases noticeably with increasing H in the region 0 - 20 kOe, then reaches a plateau at about 20 kOe (curve D in Fig. 1). $J_m(H)$ also decreases with increasing H at approximately the same rate as $J_c(H)$ (Ref. 8, also expression (a)). $J_m(H)$ also decreases approximately linearly with increasing J_s (Ref. 8, 9, 10). $J_m(H)$ decays and thus generates heat.

It is experimentally seen (curve B) that for each value of the preset current I_s (sequence (I-H)) there is a value of H at which the layer sample reverts to normality. Each value of the current I_s of curve A is interpreted as the threshold current value (maximum current value) which can withstand the thermal decay of the corresponding I_m without going normal. It is observed that this threshold current decreases with decreasing I_c. The minimum value of this threshold current on curve B is 22 A and coincides with the beginning of the plateau of the curve D ($I_c(H)$ characteristic), or, more properly, with the end of the slope of curve $I_c(H)$ (field region 15 - 20 kOe).

If a slightly smaller current (e.g. 21 A) is applied, the sample can be brought well beyond 20 kOe without undergoing transition since the I_m decay continues in the plateau region more gradually than in the preceding one (the I_c remains almost constant in this region), and any thermal disturbance due to magnetization current decay is smaller here than that along the steep path of the H_cI_c curve (up to the plateau), which is sufficient to quench any current greater than 22 A.

In the real case of energization (HI=) I_s is a linear function of H (particularly in the central region of the coil) and can be expressed as:

$$J_s = kH ,$$

where k is a factor allowing for the coil geometry.

Expression (a) becomes:

$$J_m (H) = J_c (H) - kH.$$

Similar considerations to those in the previous case (I-H) also hold here. Now the current I_s (which starts from the value $I_s = 0$ at $H = 0$) reaches a minimum value of 22 A between 15 and 20 kOe, which coincides with the minimum value of the (I-H) sequence.

Although the procedures are different, the above coincidence confirms that a value of the transport current of about 22 A determines a normal transition when a magnetization current decay (expected to be greater in magnitude than a threshold value) takes place in the region 15 - 20 kOe and would indicate a strict connection between I_s and I_c or, better, a strict dependence on the ratio I_s/I_c.

3.4.2 Pulsed field induced quenching

A set of measurements made by superposing a pulsed field on the sample brought to the critical state further confirms the above.

For example, in a 8 kOe (and also 30 kOe) field region and for a preset current I_s = 22 A, a threshold value H_{po} of the pulsed field is found at which neither I_m nor I_s decays; then a second threshold value H_{pm} is found ($H_{pm} > H_{po}$) at which the I_m decay, but I_s does not; finally, a third threshold value H_{ps} is found ($H_{ps} > H_{pm} > H_{po}$) at which both I_m and I_s decay. (The rise time of the pulsed field is about 7 μsec, and the amplitudes a few tens of Oe).

At a field of 15 - 20 kOe and I_s = 22 A it is not possible, within the limits of our measuring equipment, to discriminate between the two values H_{ps} and H_{pm}, that is, any H_p which makes the I_m decay also causes a decay of I_s. This is taken as evidence of a direct and unavoidable connection between the decay of I_m and I_s at this value of the background field and again shows the state of particular sensitivity to instabilities, since any I_m decay is accompanied by an I_s decay (normalization of the sample).

As confirmation of the above, it should be noted that the mentioned strict connection between I_m and I_s decay in the field range 15 - 20 kOe is observed for all three procedures ((I-H), (HI=), (H-I)), that is, irrespective of the magnitude of the magnetization currents, which decrease in the above order of the procedures. This emphasizes the critical role played by the transport current level together with that played by the I_m; or, better, the critical role played by the ratio I_s/I_c. This also assures the validity, at least in this very sensitive region, and for the rise time of the pulsed field used, of each of the three energization procedures for attaining the critical state; a pulsed field of approximately the same amplitude is in fact observed to trigger the sample normal in the three different cases of energization. The pulsed field measurements will be reported elsewhere in more detail.

It is also observed (curve C, sequence (HI=)) that raising the rate of current increase at constant field increase rate the sample reaches at about 15 kOe first a value of I = 22 A and then I = 40 A. The higher value of the current reached in the second case can be ascribed to the decay of the magnetization currents which occurs rather at low field in the second case (owing to the higher value of the transport current I_s) than in the first case (steep drop of curve C in the region of about 15 kOe).

3.5 Stability regions

If the sample is energized by the (HI=) procedure up to 20 kOe (beginning of the plateau region) with a current smaller than about 22 A, the sample can be further energized until the current reaches values of 29 - 30 A at 36 kOe (field limit of our magnet coil) without quenching. This fact is ascribed to the same mechanism of I_m decay which takes place at values of I_s sufficiently low for fields below 15 - 20 kOe, so that the sample can pass beyond the sensitive region without quenching.

In the plateau region the I_m continue to decay gradually, reaching very small values (Ref. 4) and therefore indicating a second equilibrium region beyond about 30 kOe, together with the region below approximately 8 kOe, as reported in Ref. 12. This also explains why the threshold pulse power needed to quench the sample in the critical condition increases by one order of magnitude (Ref. 3) between 13.5 kOe (sensitive region) and 36 kOe (equilibrium region).

Since curve C can be interpreted as representing the terminal points (normalization points) of the load lines of each layer of a superconducting coil, the minimum current (22 A) is interpreted as the threshold (maximum) current a non-stabilized coil (Nb-25 % Zr wire, diameter 0.25 mm) can be energized to, owing to the layer in the coil that is located at that current and field (15 - 20 kOe).

The existence of a threshold current as described above is confirmed by a number of test results on unstabilized multilayer coils which could not be energized to a current greater than 20 - 22 A (Ref. 3, 6, 11, 14, 17). and by a number of test results on multilayer coils which carried currents greater than 22 A and which reached fields up to 12 - 15 kOe in the centre (Ref. 11, 14).

In this sense the degradation effect or degraded performance can be interpreted, from the practical point of view, as the fact that not the whole length of the wire constituting the coil is exploited to the same extent, but the layer which first quenches (region 15 - 20 kOe) determines and limits the performance of the coil.

It is also interesting to note that superposing 8 - 10 kOe (path ON in Fig. 1) induces in our sample a critical magnetization current which is then reduced by the transport current applied during the (HI=) procedure represented by path NZ (a current I = 27 A at the maximum available field of 36 kOe is reached without quenching of the sample). Path OK, which is parallel to path NZ, corresponds to the minimum (threshold current) of curve C and would represent the layer which governs the coil performance. Again, this behaviour is ascribed to the decay of I_m which mainly occurs at a low level of transport current (path ONZ) compared with the case of the energization path OK.

Lack of degradation is observed by several authors with coils on which a field (8 - 10 kOe) is initially superposed (Ref. 18, 19). The characteristic curve of the single-layer sample with the ONZ type of energization is expected (as confirmed by some experimental points) to lie in the region limited by curves A and C. It is also seen that any other energization procedure of the type OME (Fig. 1) would cause premature quenching with respect to the curve C, procedure OME being somewhat intermediate between the (HI=) procedure (curve C) and the (I-H) one (curve B).

The foregoing results and considerations hold also for Nb-Ti. A Nb-48 % Ti wire (0.25 mm in diameter, non-copper-plated) sample was tested, yielding essentially the same results as those reported and discussed for Nb-25 % Zr.

3.6 Utilization of (HI=) energization procedure

The foregoing also indicates the importance of the (HI=) procedure for measuring the superconducting material characteristic as regards obtaining results which allow a precise estimate of the coil behaviour.

This procedure should also prove useful for partially stabilized materials, possibly to estabilish the minimum necessary substrate quantity (and a suitable non-constant distribution along the coil radius).

The (HI=) procedure applied to Nb_3Sn material, for which no intrinsic stabilization (filamentary structure) is feasible, should also prove useful especially for low field instability detection.

4. Improved performance and filling factor of superconducting coils

The above experimental work and results suggest a possible approach to improved material utilization in superconducting coils by using the mechanism of quenching the diamagnetic currents I_m and replacing them by the transport current I_s. This approach combined with the other known methods (Ref. 20) of improving the performance of superconducting solenoids should make it possible to improve the coil stability without increasing the copper substrate or to reduce the quantity of stabilizing and/or superconducting material without impairing the solenoid stability or even while improving it.

4.1 Stability methods

Several treatments are offered in the literature as to the adiabatic stability of a sample of a high-field high-current superconductor subjected to decay of the circulating supercurrents (flux jumping). Although none of them affords strictly quantitative results, a good qualitative understanding is arrived at (Ref. 12). Our results and the interference mechanism between the transport current and magnetization currents are here related to the stability criteria reported in the literature, which are now briefly recalled following closely the treatment given in Ref. 20.

Lange and Verges (Ref. 20) define the virtual specific heat of the superconducting sample as

$$c_s^+ = d/dT\,(E/V)_{therm} + d/dT\,(E/V)_{magn}. \qquad (1)$$

The first term represents the specific heat c_s of the sample, the second the specific magnetic energy stored in the sample in the form of superconducting magnetization current, which is liable to degenerate into heat owing to a disturbance (e.g. thermal, magnetic).

A condition of stability is ensured if $c_s^+(T) > 0$, that is, if

$$d/dT\ (E/V)_{therm} > d/dT\ (E/V)_{magn} .$$

The first term c_s of the expression (1) can be subjected to the so-called enthalpy stabilization method, which consists in providing a good thermal contact between a material of high specific heat (e.g. lead, mercury) and the superconductor.

The second term can be handled in several ways. The mean density of the magnetic energy is

$$(E/V)_{magn} = a/u_o\ \bar{j}_c^2\ \ d^2 \qquad (2)$$

where $\bar{j}_c^2$ = mean square critical current density

d = dimension perpendicular to the magnetic field direction (e.g. diameter of the wire).

a = constant depending on the geometry and the $j(H)_c$ relation.

Assuming further $j_c = b\ f(T)$, one obtains:

$$d/dT\ (E/V)_{magn} = 2\ a\ /u_o\ d^2\ j_c\ d/dT\ j_c = $$
$$= 2a/u_o b^2 d^2 f(T) d/dT\ f(T). \qquad (3)$$

By analyzing the expression (3) a series of stabilization methods can be obtained.

Method 1: Using superconducting materials with positive slope $d/dT\ f(T)$;(Ref. 21).

Method 2: Reducing the diameter d of the superconducting wire (multifilamentary structure (Ref. 22)).

Method 3: Reducing the critical current density j_c, e.g. by increasing the temperature of the coil (Ref. 23). In terms of our experimental results this can be interpreted as due to the fact that the I_m become smaller at temperatures higher than 4.2 ^oK, and the ratio I_m/I_s will also be smaller at each value I_s, particularly at the threshold value determined by curve C (Fig. 1) at 4.2 ^oK. Consequently, the coil will reach values beyond this curve, behaving in a more stable manner. The corresponding increase of the ratio I_s/I_c due to the higher temperature appears to impair the stability to a lesser extent than the reduction of I_m/I_s improves it.

Method 4: Using wire with low magnetization.

Method 5: Superposing on the superconducting solenoid an outer magnetic field higher than the field H_m at the maximum of the magnetization curve (H_m = 4 to 8 kOe for wire 0.25 mm in diameter).

In this connection our experimental results indicate the mechanism by which the background field provides a stabilizing influence by causing the major flux jumps in the sample layer to occur at low values of the transport current (as already mentioned, see path ONZ in Fig. 1).

Such major flux jumps at a preset background field are directly observed (Ref. 24) to take place at lower values of the transport current than in the case of no superposed magnetic field. It should therefore be emphasized that it is not the exclusion of the low field region (0 - 8 kOe) of the coil due to the superposed field (8 kOe) that is responsible for eliminating degradation (Ref. 20), but rather the resulting elimination of diamagnetism (owing to decay) at transport current levels lower than in the case of no field superposition.

To substantiate the above, it is further experimentally observed (Ref. 4) that in the low field region (4 - 8 kOe) the magnitude of the threshold pulsed field (rise time as already indicated) necessary for triggering the I_m decay and normalizing the sample (at I_s = 22 A) is five to ten times as large as the value needed in the region 15 - 20 kOe. This difference is here ascribed to the smaller ratio I_s/I_c in the low field region compared with the 15 - 20 kOe one.

As already stated, the collapse of magnetization does not necessarily also imply a collapse of the transport current I_s (at I_s = 22 A or so) in the low field region (below about 12 kOe), and the normalization of the sample appears to be dependent, beside on the magnetization currents, also primarily on the ratio I_s/I_c.

In particular, it is reasonable to extend the above considerations to the zero field region, which is present in the part of the winding close to the outer circumference of a coil (the ratio I_s/I_c has in this region a minimum value), even considering the presence of a maximum value of I_m (e.g. due to hysteresis processes, as supposed by Taquet (Ref. 16)). Taquet investigated, as a possible cause of degradation, the fact that those parts of the windings near the outer circumference of a coil experience a field first in one direction and then in the opposite one during the energization of the coil (as the coil is energized, the zero field region moves inwards in the coil). Taquet, moreover, finds quantitative evidence that the degradation of the coils he tested is not to be attributed to the above fact.

The above considerations do not prevent the diamagnetism decay in low field regions (0 - 10 kOe) of the wire from triggering a quench in the coil owing to the sudden current and field changes accompanying the diamagnetism decay. These may cause the region of higher sensitivity (15 - 20 kOe) to quench, thereby triggering a premature quench (i.e. at transport current lower than 22 A, as observed in coils of greater dimensions and left open to interpretation (Ref. 3)).

Furthermore, the collapse of magnetization triggered by possible causes other than a pulsed field (e.g. rotation of the field vector around the axis of the wire during the coil energization, and possible diamagnetism collapse when the "angular" strain on the pinning centres exceeds a critical value (Ref. 6)) would be covered by the above results and considerations inasmuch as they exclude the low field region as a possible location of quenching as an alternative to the 15 - 20 kOe region.

Method 6: The last criterion given in Ref. 20 suggests the use of wire with a flat characteristic $j_c(H)$, obtained by appropriate heat treatment of the superconducting material.

This criterion is derived by considering the useless region of the current density, as schematically shown in Fig. 2. The load line OP drawn in Fig. 2 (Ref. 20) is, however, to be considered as ideal (the fact that the end of the coil load line coincides with P on the short sample characteristic would in fact mean that there is no degradation). From Fig. 1 it is observed that the region enclosed between the abscissa I = 22 A and the curve C should rather be considered as the useless region. As already said, the current I = 22 A represents a threshold current beyond which no unstabilized coil capable of producing more than about 20 kOe can be energized.

4.2 Approach using higher transport current density

In addition to the foregoing methods aimed at improved utilization of the wire material, each layer of a coil could be made to have the same quenching current as the critical layers (region 15 - 20 kOe) by reducing the total section of the superconductor in correspondence with the non-critical layers (field-scaled cross section method). By this approach one obtains a flat $I_c(H)$ characteristic as an alternative or supplement to the heat treatment method suggested by Lange (Ref. 20).

As a simple example, in a partially stabilized multistrand superconductor (see curve C of Fig. 1) about 2/3 and more of the superconducting wires constituting the cable could be taken away in the region of the coil winding below 12 kOe, and 1/3 and more in the region beyond 30 - 35 kOe, thus saving 25 to 30 % of superconducting material for a magnet capable of producing 45 - 48 kOe in the centre. Scaling the superconductor cross section down to the field is easy in this example since copper-stabilized superconductors can readily be joined together by soldering, the resulting contact resistances being negligible (Ref. 25).

Exact dimensioning of the superconductor cross section A(H) as a function of the field follows directly from the $I_c(H)$ characteristic. Suppose a coil wound with a wire of constant cross section has the load line OP drawn in Fig. 2, and suppose $I_s = I_o$, where

I_s = coil transport current

I_o = critical current of the superconductor at the field H_o

I_1 = critical current (Fig. 2) of the superconductor at the field H_1.

The section A_o, which corresponds to the field H_o, is utilized by the current $I_s = I_o$. The section $A_1 = A_o$ corresponding to the field H_1 is not completely utilized since $I_s < I_1$. For full utilization of the material corresponding to the section A_1, the section A_1 should be reduced to

$$A_1' = A_1 \cdot I_s/I_1 = A_o \cdot I_o/I_1 \ .$$

This expression can be written in the general form

$$A(H)\, I(H) = \text{const.} = A_o\, I_o \ .. \qquad (4)$$

A(H) can therefore be calculated from the characteristic I(H). I_o is the maximum current which the superconducting coil can carry (referred to above as the threshold current), and A_o the superconductor cross section corresponding to the field H_o, where the threshold current I_o is determined.

With the wire cross section dimensioned according to the expression (4), each section of the superconductor (each layer of the coil) will carry its own critical current, in contrast with a coil wound with wire of constant cross section (constant transport current density). The $I_c(H)$ characteristic of the shaped wire will now be a straight line of abscissa $I = I(H) = I_o$, which corresponds to the flat $I_c(H)$ (or $J_c(H)$) characteristic (straight line parallel to the H axis) reported by Lange (Ref. 20) and obtained by long time heat treatment.

4.2.1 Low field stabilization

The saving of superconducting material and the higher current densities achieved by dimensioning the superconductor cross section as a function of the applied transverse magnetic field is secondary in principle, however, to the stabilization obtained by the relevant reduction of the magnetization currents.

Considering again the example of a superconducting stabilized stranded cable, the total magnetization current in each section of the superconducting cable is decreased owing to the reduction of the number of superconducting wires constituting the cable.

Furthermore, the magnetization currents in each wire of the reduced section will be considerably reduced (to values near zero) owing to the higher transport current flowing in each wire of the reduced section (the total transport current being, of course, the same along the cable). In this fashion one gets the desirable situation where the magnetization currents (which tend to decay as result of magnetic disturbance, increase of transport current, etc.) are practically absent, having been replaced by the transport current.

In the case of a coil with reduced section (RS) the magnetization currents are made to decay earlier during the coil energization (i.e., at lower transport current level), since the transport current density is higher than for the constant section case (CS). This is favourable to stability: if the magnetization current decay takes place at lower values of the transport current I_s ((RS) case), and if the same quantity of stabilizing copper is present in both the (RS) and (CS) cases, then the transport current I_s diverted into the copper in the (RS) case (assuming that the superconductor reverted for a moment to normality owing to magnetization current decay) is smaller than in the (CS) case, where the decay takes place at higher transport current I_s and hence normalization of the whole sample (implying also transport current decay) is more likely to occur.

4.2.2 Partially stabilized superconductors

In addition, experimental work on partially stabilized superconductors, which will be reported later in full detail, supports the validity of the suggested field-scaled cross section method.

For instance, a copper-stabilized NbTi wire sample (Supercon T48B, copper-superconductor ratio 3:1, external diameter 0.020", core 0.010") was tested in the same setup consisting of a d.c. coil and a pulsed coil (Ref. 4). A critical state is induced in the sample ((H-I) procedure) by presetting a field H = 10 kOe and then feeding a current I_1 = 40 to 50 % of the I_c at that field (condition 1). Then a pulsed field H_{p1} (threshold value) is superposed on the sample and triggers it normal. Afterwards the sample is cooled down again in the same background field, the same current I_1 = 40 to 50 % I_c is applied again, and the sample is normalized by a pulsed field H'_{p1}. The pulsed field H'_{p1} is about one order of magnitude greater than H_{p1}, this difference being ascribed to the initial presence and subsequent absence of magnetization currents, which are quenched with the first normalization of the sample.

The sample now undergoes a second cycle similar to the first. A critical state is induced ((H-I) procedure), the current applied here being I_2 = 80 to 100 % I_c (condition 2). A pulsed field H_{p2} (again threshold value) is then superposed, and the sample is driven normal. After it cools down and the same current I_2 is applied, the sample is again driven normal by a pulsed field H'_{p2}. It is noted that $H_{p2} = H'_{p2}$, as is to be expected, owing to the absence of magnetization currents in both cases.

It should further be noted that $H_{p2} = H'_{p2} = H_{p1}$, that is, from the point of view of the externally applied pulsed field the sample has the same stability under conditions 1 and 2, although the sample under condition 2 carries twice as much current as under condition 1.

The sample under condition 1 carries a current I_1 = 40 to 50 % I_c and magnetization currents as well. To make the transport current value in the sample under condition 2 equal to that under condition 1, and eliminate the magnetization currents in the latter case, the cross section of the sample can be regarded as reduced by half. Allowing exactly for the effect of reducing the geometry on the magnetization of the sample would actually decrease the magnetization currents even more. However, apart from the saving of material, the superconductor with reduced section and without magnetization currents can be considered preferable as regards stability of the coil. In fact, if it has the same sensitivity to external pulsed fields (which is taken as an indication of the sensitivity of the sample to flux jumps) as the superconductor with the original cross section, it is not itself susceptible of producing flux jumps in the environment owing to the decay of its own magnetization currents, which have already been reduced to very low values for low total transport current during its energization.

4.2.3 Fully stabilized superconductors

Even in fully stabilized coils instabilities can occur because of the presence of magnetization currents at low fields (Ref. 22). Calculations are reported by Smith et al. (Ref. 22) for a fully stabilized, strip-shaped superconductor with a safety factor of 2 (safety factor being defined as the ratio between surface heat transfer and power dissipation when the total transport current flows in the normal metal), where, owing to the magnetization current collapse in the low field region, a temperature rise up to 15 - 25 ^{o}K is expected. This could lead to instability if the increased heat transfer associated with the higher temperature is sufficient to vaporize the liquid helium in the cooling channel, after which the transport current would no longer be stabilized.

This possible source of instability can generally be avoided by reducing the number of superconducting wires embedded in the substrate, so that the left superconducting material works at 80 - 100 % of its performance given by the $I_c(H)$ characteristic (that is, without the presence of significant magnetization currents).

4.2.4 Nb_3Sn

Nb_3Sn ribbon of high current rating (e.g. 1200 A at 100 kOe) is known (Ref. 26) to show much greater instabilities than Nb_3Sn ribbon rated at lower current (e.g. 300 A at 100 kOe), when they are used at low currents and fields. This also supports the criterion of field-scaled cross section method which, in principle, is particularly advantageous for Nb_3Sn since no alternative solution is as yet known for Nb_3Sn of the type available for NbTi (filamentary structure), and which practically eliminates the presence of diamagnetic currents.

5. Conclusions and further experiments

The critical state is induced in superconducting Nb-Zr and Nb-Ti samples in the form of single-layer coils by three methods of energization: (H-I), (I-H), and (HI=). The normalization characteristics are reported and correlated to the results appearing in the literature.

The mechanism by which the magnetization currents are replaced by the transport current and decay is described, and its effect on the stability of the superconductor is pointed out.

In particularly, the decay of the magnetization currents is related to the transport current level and shown to be the main factor governing the normalization characteristic.

The characteristic obtained by means of the (HI=) energization method has a minimum value of the current corresponding to the field region 15 - 20 kOe. This value indicates the field region of greatest instability in a superconducting coil (wound with non-stabilized wire 0.25 mm in diameter), and it is suggested as corresponding to the knee of the curve $H_c I_c$ (beginning of the plateau of curve D in Fig. 1).

The minimum value of the current (about 22 A) represents a limit value which is confirmed by the maximum current values (reported in the literature) reached by coils made of the same material and capable of producing more than about 20 kOe.

In the cas: of non-copper-plated materials the (HI=) procedure appears to yield a characteristic which allows us to predict the coil behaviour in each layer. This procedure could also prove very useful for Nb_3Sn, and possibly also generally for copper stabilized materials, to establish experimentally the critical region and the quantity of copper required to achieve a given degree of stabilization and/or a uniform stabilization level throughout the coil, with consequent saving of substrate material (larger filling factor).

Pulsed field work done on a Nb-Zr sample induced to the critical state by the procedure (I-H) indicated the 15 - 20 kOe region as the most unstable one (Ref. 3). Pulsed field tests repeated here using the (I-H), (H-I), and (HI=) energization procedures confirm the 15 - 20 kOe region as the most unstable one and give approximately the same results in the sensitive region (15 - 20 kOe) and beyond. This makes it legitimate to do pulsed field work using any of the three above procedures to induce a critical state in the sample. Since, moreover, the magnetization current value varies with the energization process, the importance of the transport current level is also stressed, especially in the sensitive region, where the collapse of any small value of the magnetization currents is followed by normalization of the sample when currents close to the current threshold value (about 22 A) flow through it.

The mechanism of gradual decay of the diamagnetic currents and their replacement by the transport current also explains the higher pulsed field power level needed to trigger the sample normal at fields higher than 25 - 30 kOe (Ref. 3). It also explains the different characteristics obtained (Ref. 5) by the procedures (H-I) and (I-H).

The experimental results and considerations reported suggest a method of minimizing the magnetization currents in superconducting coils by scaling the cross section of the superconductor to the transverse self-field of the coil, that is, by making the superconducting material work at transport current densities (particularly at low fields) close to the critical current densities given by the $H_c I_c$ characteristic. This method can be ranked with and used in addition to existing methods to obtain better material utilization and stability in superconducting coils. Besides giving better stability conditions and improving the filling factor, it also results in better field homogeneity since field distortion due to the diamagnetic currents is minimized. Its claim to general applicability derives from utilization of the basic physical process of interaction between the transport current and magnetization currents in superconductors.

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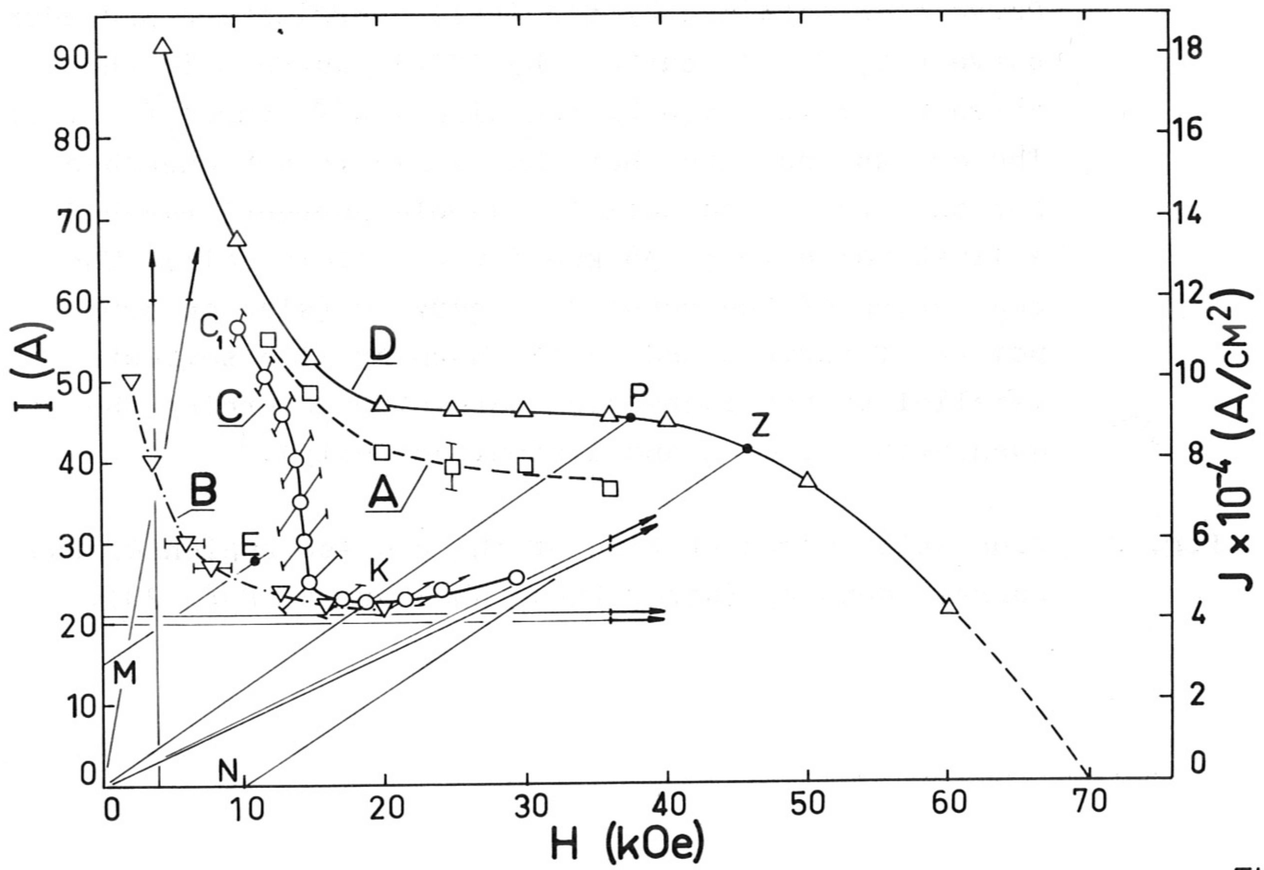
Figure captions

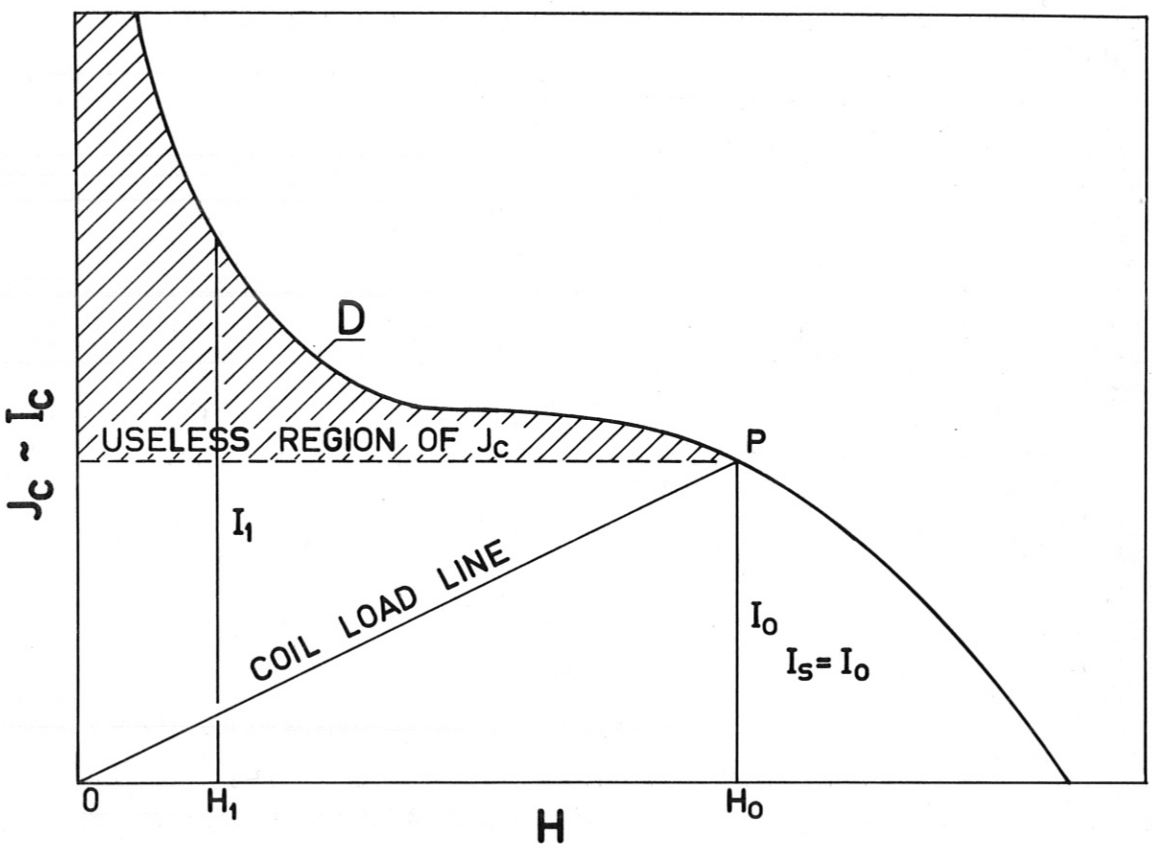
Fig. 1 Critical current characteristics of a non-copper-plated Nb - 25 % Zr sample, 0.25 mm in diameter. Curve A is obtained by the (H-I) energization procedure, curve B by (I-H), curve C by (HI=). Curve D is the characteristic given by the wire manufacturer (Ref. 27). The arrows indicate that the sample is not quenched, but that the field coil (or sample current) reached a limit value (e.g. 36 kOe for the field coil). The scattering of the results on curve C (also on some points of curve A and B) is shown by line segments parallel to the increasing parameter governing the quench (H, I, or H and I simultaneously).

Fig. 2 Schematic representation of the useless region of the current density (after Lange and Verges, Ref. 20).



90
80
70
60
50
40
30
20
10
0
I (A)
18
16
14
12
10
8
6
4
2
0
J x 10^-4 (A/cm^2)
0
10
20
30
40
50
60
70
H (kOe)
C1
C
D
A
B
E
K
P
Z
M
N

FIG. 1



D
USELESS REGION OF J_c
P
I_1
COIL LOAD LINE
I_0
$I_s = I_0$
$J_c \sim I_c$
0
H_1
H
H_0

FIG. 2