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SOME EXPERIMENTAL RESULTS OF SUPERCONDUCTING SOLENOIDS

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Phenomena which limit the performance of superconducting solenoids are reviewed, and the experimental data obtained in designing, building and testing several coils employing Nb-Zr wires at different percentages of Zr is summarized.

A superconducting solenoid is described in which a field of 49.3 kG was obtained in an internal region of diameter 1 cm and height 7 cm. The results obtained with other coils of smaller dimensions and lower maximum field are tabulated.

In addition, measurements of the residual magnetic fields are reported, as well as a brief description of the experimental apparatus.

1. Introduction

At the present time it is possible to construct high magnetic field solenoids by taking advantage of the exceptional properties exhibited by certain superconducting (s.c.) alloys[1–9]).

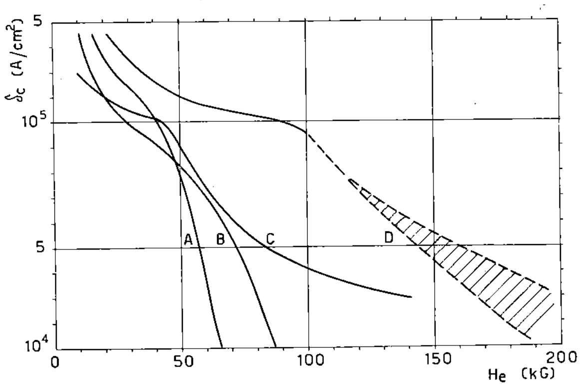

Fig. 1. Approximate behaviour of the critical current density (δ_c) as a function of the applied external magnetic field (H_e) for various types of superconductors:
curve A – wire of Nb-25% Zr, ⌀ = 0.25 mm (from the Wah Chang Corp., Albany, Oregon, U.S.A.);
curve B – wire of Nb-33% Zr, ⌀ = 0.25 mm (from the Wah Chang Corp., Albany, Oregon, U.S.A.);
curve C – ribbon of Nb with an external layer of Nb_3Sn, of over-all cross section $1.6 \times 3 \times 10^{-2}$ mm². ("Niostan Ribbon" of the National Research Corp., Cambridge, Mass., U.S.A.);
curve D – Cilindrical conductor with a Nb outer shell and a Nb_3Sn inner core. $⌀_{ext.} = 0.38$ mm, $⌀_{int.} = 0.15$ mm.
The dotted part of curve D and the shaded area indicate the uncertainty of the knowledge of δ_c over 100 kG.

Such alloys, whose behaviour is very similar to hard superconductors, exhibit a number of characteristics which are very sensitive to the crystalline state of the material.

Approximate curves of $\delta_c(H_e)$ and $H_c(T)$ * are shown in figs. 1 and 2 for the alloys and intermetallic compounds (Nb-Zr, Nb_3Sn, Va_3Ga) of most interest at present for the construction of magnets.

From these curves we see that the critical current in these materials remains large even in the presence of strong magnetic fields.

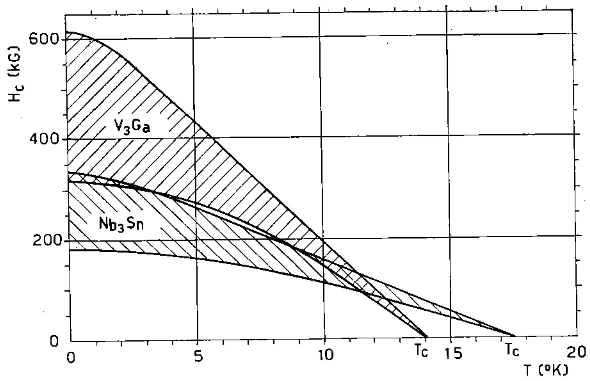

Fig. 2. Approximate behaviour of the critical magnetic field (H_c) as a function of the temperature (T) for the intermetallic compounds V_3Ga and Nb_3Sn. The shaded area shows the incertainty of the existing knowledge of the critical magnetic field.

This is, in short, the physical phenomenon which allows the realisation of coils able to attain high fields.

The metallurgical techniques involved in the fabrication of these alloys is especially complex[10]), particularly with regard to obtaining wires of sufficient mechanical strength and flexibility to be wound into coils. At the start of the experiments described in the present paper we direct our attention to Nb-Zr solenoids because the alloys of such metals, even though their s.c. properties are inferior to the other two compounds mentioned above, are the only products commercially available in wire which is easy to handle.

The magnets constructed of niobium-stannide (Nb_3Sn) were, until recently, prepared by delicate and complicated procedures[8,11]) which lead to an expecially brittle wire structure, thus making recovery and reuse of

* For the meaning of the symbols used, see the mentioned figures.

the wire in other experiments impossible. This fact made experiments with such conductors particularly expensive.

Recently, however, flexible Nb ribbons have been realized over which Nb_3Sn has been deposited by a special procedure and which can be directly utilized for winding without any need of further heat treatment* [12]).

2. Phenomena which limit the performance of superconducting solenoids

The most important information which must be known in order to design a s.c. solenoid is the curve which relates the critical current to the critical magnetic field for the material selected. The practical possibilities of constructing magnets of large dimensions, which can be used for research applications, depend on the behaviour of this curve and on the cost of the material. This curve $I_c(H_e)$ is very dependent on the metallurgical treatment which the alloy has undergone[13,14]); it depends on the temperature and on the annealing time of the material, on the hardening, on the impurities present (especially oxygen and carbon), and also, for conductors which have a diameter less than one millimeter, on the surface condition.

Also, the etching† of the wire and the type of insulation, in case this is obtained by electrolytic metallic deposit, influence the superconducting properties of the material. When the curve $I_c(H_e)$ and the geometry of the winding are known, the maximum magnetic field theoretically obtainable may be calculated immediately[16−21]). However, in practice the maximum current which the solenoid can carry is in general less than the theoretical value, and consequently the value of the field is less than that predicted.

Many reasons have been suggested to explain this phenomenom. First of all is the "training effect": the measurements from which the $I_c(H_e)$ curve is made are performed on segments of wire in a fixed external magnetic field, by increasing the current up to the resistive transition.

Performing several such transitions, the value of I_c increases until it stabilizes itself at a value above those of previous transitions. In certain cases an increase of over 50% is obtained, and the number of transitions necessary to have reproducibility in measurements is from 3 to 5 [22,23]).

In the coils the transition does not occur under the same conditions, because the field is not constant but is produced by the excitation current itself. In these conditions the phenomenon of "training" takes place to a much lesser and irregular extent. Furthermore, if the superconducting state is lost in a segment of the wire (commonly this transition is limited to an extremely short segment of the wire constituting the entire coil), the current decays in a sufficiently long time, because of the high inductance of the coil, to cause heating (and even annealing) of this segment of the wire.

Aside from this, there are other factors which make the working conditions different for a straight piece of wire with respect to wire wound in a coil. For example, mechanical stresses, temperature gradients, curvature of the wire, effects due to closeness of the wires which cause non uniform concentrations of magnetic field in some regions of the wires; furthermore it is plausible that over a considerable length of the wire there are some segments with inferior superconducting characteristics.

Finally, it has been observed that, after exciting a solenoid and returning the current to zero, a residual magnetic field remains[16,24−27]).

The origin of this magnetic field is not clear. Evidently, this is not due to the effect of persistent currents in a closed path connecting different turns of the solenoid, because these are electrically insulated from each other.

A current description of the phenomenom (hypothesis of Montgomery[22])) supposes that inside the wire small loops of current are generated, which corresponds to the formation of magnetic dipoles distributed in space in a certain manner. The overall effect of these dipoles is to generate a magnetic field which is superimposed on that created by the coil current and which remains even when the excitation of the magnet ceases.

Physically, it is thought that these dipoles are associated with local crystalline deformations or with chemical impurities, which appears plausible because many properties of "hard" superconductors are related to such factors.

From what has been said, it is clear that these dipole currents, superimposed on the excitation current, can bring some zone of the coil to critical conditions before such conditions are reached thoughout the solenoid.

Research on these limiting factors for superconductive solenoids has not yet provided definitive conclusions. Nevertheless, superconducting coils of satisfactory performance have been constructed[16−18]).

3. Experimental apparatus

In the course of experimentation, the coils of external diameter less than six centimeters were tested in ordinary glass dewars. For magnets of greater diameter,

* See, for instance, the "Niostan Ribbon" of the National Research Corp. Cambridge, Mass., U.S.A.

† The etching[15]), because of surface contamination of hydrogen, increases the critical current.

a special stainless steel dewar was constructed, schematically illustrated in fig. 3 (see also fig. 4).

The helium consumption of the dewar, equiped with all the apparatus for the experiment (including three copper conductors of mean diameter 1.5 mm which enter the helium bath from above) was about 1 liter/hour (in good agreement with the calculations). The consumption (calculated) of the dewar alone was 0.25 liter/hour.

To excite the coils, a circuit, employing transistors and batteries at low voltage (6 V), was used, able to deliver a maximum current of 50 A with very fine regulation of the current itself by means of a helipot potentiometer.

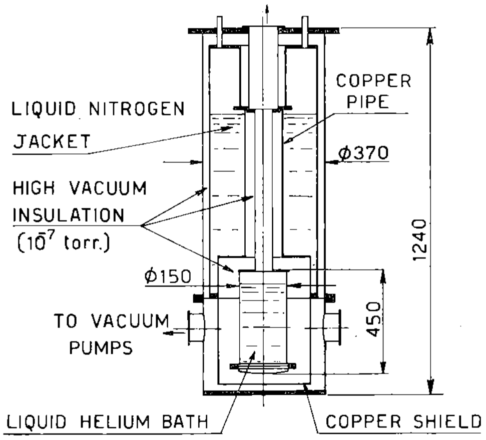

Fig. 3. Schematic view of the metallic dewar used in the experiments with coils of diameter larger than 6 cm. All parts of the dewar are of stainless steel except those otherwise indicated in the figure. All dimensions indicated are in millimeters.

To measure the magnetic field, a search coil connected to an electronic integration fluxmeter was used. We should note that the contacts between the power supply bars and the superconducting wire were made in two different ways:

a) pressing a 20 cm length of Nb-Zr wire between two well-cleaned discs of copper.

b) ultrasonic soldering using pure indium as soldering material.

To join the various pieces of superconducting wire, both electric spot welding and ultrasonic soldering was employed. All three of these types of contact proved, in numerous trials, able to carry currents above the maximum current of our power supply (50 A) without losing superconductivity.

4. Results obtained

For the construction of our solenoids we used Nb-Zr wire of 0.25 mm diameter, with various percentages of Zr*.

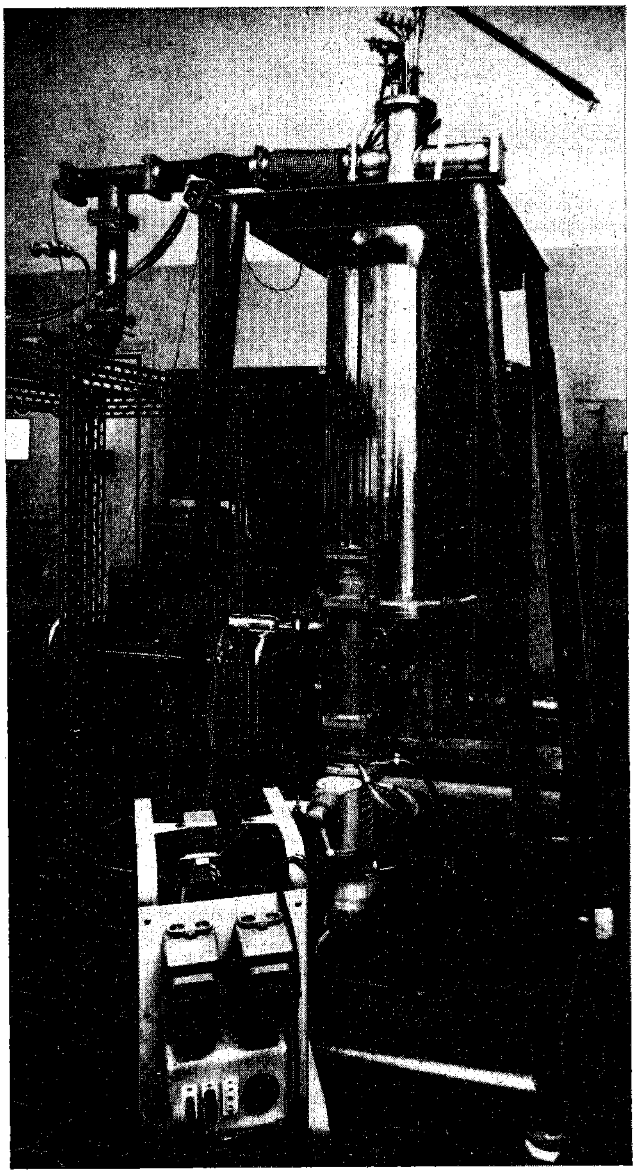

Fig. 4. View of dewar shown in axial section in fig. 3. The vacuum system and part of the helium recovery line are visible.

Tables 1 and 2 summarize, respectively, the principal construction data and the experimental results for our coils, excluding those which gave less interesting results.

The values of field and current given in table 2 are those just below the transition to the normal state. The value of the transition current was read directly from the power supply ammeter, whereas the maximum field was determined by extrapolating the excitation charac-

* This wire was furnished to us by the Wah Chang Corporation, Albany, Oregon, U.S.A.

TABLE 1

Coil	Number of coaxial sections	Weight of wire (kg)	Total number of turns	Number of turns of the internal section	Internal diameter (mm)	External diameter (mm)	Height (mm)	Material
A	2	0.220	6 686	2 666	6	48	30	Nb-Zr25%
B	1	0.950	21 320	–	6	57	85	Nb-Zr33%
C	1	0.280	8 260	–	22	38	120	Nb-Zr33%
D*	4	2.9	32 600	–	10	109	70	Nb-Zr25%

N.B. Coil A was of bare wire; the surface oxide was sufficient to assure the insulation between turns; between the layers was placed a sheet of copper. Coils B, C, D were made by nylon insulated wire.
* See further details in the text and in fig. 5.

TABLE 2

Coil	Maximum field (G)	Maximum current (A)		Observations
		External section	Internal section	
A	36 000	11	24	
A	38 000	30	19	After having unwound and rewound the 36 kg coil, exchanging the wires of the two sections.
B	29 000	9	–	
B	16 000	5	–	After having unwound and rewound 29 kg coil.
B	29 500	10	–	After having unwound and rewound 16 kg coil.
C	8 200	8	–	With this current the coil was still superconductive.
D	49 300	–	13	

teristic (straight line) of the solenoid, obtained experimentally, to that value of current.

The coil D, which gave the best result, was constructed of four concentric sections whose dimensions and number of turns are shown in fig. 5. The first measurement performed with this coil was that of the maximum current which could be carried by each section, leaving the other three not excited. The results were as follows:

section 4 $I_{c4} = 6.5$ A
section 3 $I_{c3} = 13.5$ A
section 2 $I_{c2} = 15$ A
section 1 $I_1 = 14$ A.

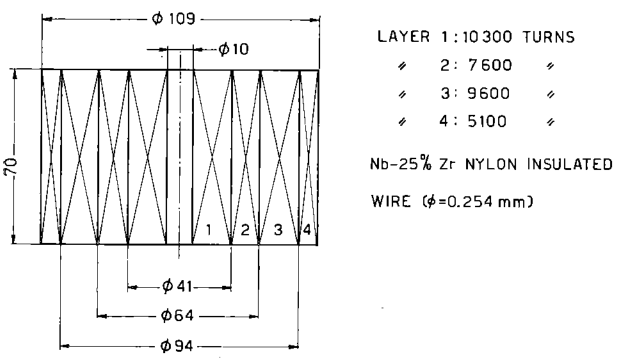

Fig. 5. Schematic view of coil D(H_{max} = 49.3 kG). The external and internal diameters of the four sections and the number of turns are shown.

Section 1 did not "collapse" for $I = 14$ A and furthermore, exciting section 3 as well with an increasing current, while section 4 remained excited, there was destruction of the superconductivity in both sections only for $I_3 = 12$ A; this suggests that a current considerably greater than 14 A is necessary, to bring section 1 to the normal state and probably greater than 15 A for section 2.

This linearly-increasing dependence of the critical current, going from the external to the internal section, enhances the hypothesis that this current is considerably affected by the form of the section, whereas the current did not appear much affected by the length of the wire in the section (in fact, section 4 is much shorter than section 3).

The values of the critical currents given above, as well as other preliminary experiments, lead us not to use section 4 and to excite the other three sections in series in order to test for the maximum field obtainable with coil D.

In addition to the measurements given above, we have measured the behaviour of the axial component of the residual magnetic field along the axis of symmetry for coils B and C. The measurements were taken after having excited the coil with a current slightly less than the critical current indicated in table 2 (except for coil C)

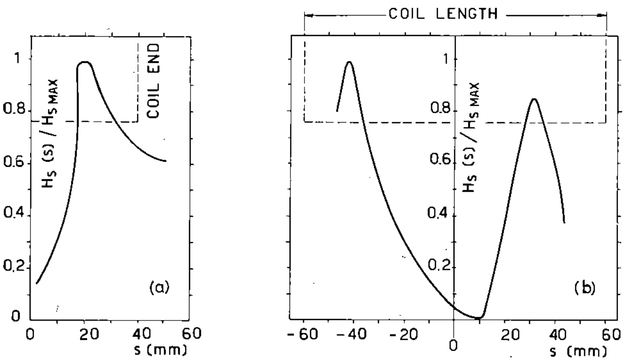

Fig. 6. (a) Map of the axial component of the residual magnetic field measured along the axis of solenoid B. The ordinates are normalized to 1 in correspondence with the maximum value of H_s ($H_{s\,max} = 730$ G). (b) Similar map for solenoid C ($H_{s\,max} \approx 40$ G). The curve shown in fig. 6(a) was obtained after having excited the solenoid to a current slightly less than the critical current indicated in table 2 and after having reduced the current to zero without losing the superconducting state; while the curve of fig. 6(b) was obtained after having excited the coil C to the field indicated in table 2.

and then having brought back the current to zero without losing the superconducting state.

The results are plotted in figs. 6(a) and (b). These results seem to agree with those of other experimenters[27,28]), that is:

a) the axial distribution of this field is approximately symmetrical, with respect to the center of the coil;

b) the residual magnetic field is a maximum near the ends of the coil;

c) the direction of this field is usually opposite to that of the principal field produced during the excitation.

We also noted that coil B, which reached a magnetic field stronger than that of coil C (see table 2), had a much higher residual field.

Finally, measurements performed after the loss of superconductivity showed a residual magnetic field with a very irregular axial distribution.

5. Conclusions

We have found, as have other researchers, that it is impossible in the design stage to predict the performance of a superconducting coil because of the different behaviour of a piece of wire and the same wire wound in a coil. This is due, as we have pointed out in the preceding paragraphs, to causes still under investigation.

We have also found the lack of complete reproducibility of the performance of the coils in a given series of trials, as well as in successive trials.

Among the causes of non-reproducibility, some of the phenomena, mentioned in paragraph 1 as limiting the performance of solenoids, may also be enumerated (for example, the "training", local annealing of the wire caused by transitions to the normal state, residual fields, etc.). Furthermore, it is not possible to exclude various phenomena, such as mechanical vibrations and shocks, electrical oscillation caused by the high inductance, the high stray capacitance, and the very low resistance of the circuit. As for the first of these two causes, it may be pertinent to observe that we noticed that the flux trapped in a small lead superconducting ring can be made to decay by repeated mechanical shocks.

It appears interesting to observe that a considerable quantity of magnetic energy is concentrated in a small volume, and that rough calculations for magnets near transition show that this stored energy is of the order of magnitude of the total energy necessary to make the superconducting electrons go into the normal state.

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