

The critical current in a NbTi tape measured in different directions of magnetic field and the current reduction due to the self field.

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Abstract - For the application of NbTi tape in a superconducting thermal switch, the critical current of a 20 micrometers thick NbTi tape is measured in several directions of the magnetic field. The critical current is found to behave strongly anisotropically, due to the deformation of the NbTi.

The tape is extra sensitive for the component of the magnetic field perpendicular to the surface. Without external field this component of the self field reduces the critical current far below its intrinsic value. A one dimensional model can describe the reduction of critical current due to the self field in a thin tape.

I. INTRODUCTION

A bare NbTi tape conductor is an interesting alternative for the fabrication of a fast superconducting thermal switch. In the next section an estimation is made for the critical current density necessary for a tape conductor to compete with the best switches of NbTi wire as made up to now.

The anisotropic behaviour of the critical current in the tape is investigated by changing the directions of the magnetic field on the superconductor. In that way the three main directions for the Lorentz force in the tape are investigated, plus the situation with the Lorentz force absent (field and current parallel). The measured influence of the field direction on the critical current for this NbTi tape is compared with the behaviour of a Nb₃Sn tape.

The influence of the self field on the overall critical current of the tape is investigated by changing the geometry of the sample. If two pieces of tape are placed close to each other, the self field is dependent on the direction of the current (parallel or antiparallel). Finally a one dimensional model to calculate the influence of the self field on the critical current of a single straight piece of tape is described.

II. APPLICATION IN A THERMAL SWITCH

In a thermal switch the temperature of the superconductor is swept between the superconducting and the normal state. In practical applications the heat capacity of the (thermal) insulation layer can be negligibly small, compared to the capacity of the heated volume containing the superconductor.

A. Switching Efficiency

In the center of the switch a volume (V) of superconductor, plus eventually some epoxy material, is responsible for the heat capacity of the switch (C). So the enthalpy used to raise the temperature of the switch to the normal state (T_{st}) is:

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$$\Delta H = C V (T_{st} - T_0). \quad (T_0 = \text{Bath temp.}) \quad (1)$$

The maximum switching velocity is proportional to the time constant (τ) of the system defined as:

$$\tau = \Delta H / P_{st} \quad (2)$$

Where P_{st} is the power dissipation necessary to maintain the normal state. Therefore fast (small τ) and efficient (small P_{st}) switch design is a question of minimizing the enthalpy.

It is clear that for a switch of a certain current and desired resistance the amount of material is determined by the critical current density and the electrical resistivity of the superconductor:

$$\Delta H \propto V \propto \rho J_c^3 \quad (3)$$

Taking into account all the relevant material properties (J_c, ρ, T_{st}, C) it appeared that NbTi is a good material for applications in liquid helium [1].

B. Critical Current in a Thermal Switch

Several types of fast switches have been investigated mainly for the application in superconducting rectifiers [1]. For a high current (2 kA) switch the best results have been achieved with a multifilamentary conductor of bare NbTi filaments impregnated in epoxy resin [2]. Two important factors limited the performance of this switch:

1) The current density in the bare filaments is relatively poor: $3 \cdot 10^9 \text{ A/m}^2$ (without external field).

2) The heat capacity of the switch is increased with approximately a factor of 6, due to the epoxy material.

If one considers to make a switch from NbTi tape the amount of epoxy material necessary for mechanical fixing and thermal contact can be negligibly small. In a switch made of bare NbTi filaments the volume of the epoxy material is responsible for the main part of the heat capacity of the switch. According to (3) the application of a NbTi tape in a switch is interesting if the tape exceeds a critical current of: $1.7 \cdot 10^9 \text{ A/m}^2$.

C. Magnetic Field in a Switch

The external magnetic field is small in most of the switching applications. In such a case the self field of the tape can be the largest contribution to the magnetic field on the superconductor. Usually a switch is designed to have a low (self) inductance, in that way the self field is also minimized. A low inductance is achieved by using a bifilar geometry (=antiparallel) for the conductor inside the switch.

III CRITICAL CURRENT IN DIFFERENT FIELD DIRECTIONS

In the experiments described in the next sections the critical current of a NbTi tape is investigated. The magnetic field and the electrical current is applied in all the possible main directions, and compared with a Nb₃Sn tape. The self field in the NbTi tape is changed by preparing samples of different geometries.

A: Experimental Conditions

The NbTi tape is produced by rolling a slab of NbTi to a final thickness of 20 μm between two copper plates. In our case a high electrical resistivity is desired therefore the copper layers are etched away from the superconductor except for the connecting areas. After the rolling process one can expect an anisotropic behaviour in the superconducting properties of the NbTi, due to the deformation of the material.

The samples are placed into a superconducting magnet and tested in a 4.2 K helium bath, with direct contact to the liquid helium. The length of the testing section is 20 mm and the voltage criterion used for all the experiments is 10^{-4}V/m . The width of the samples varied from 1 to 20 mm, in this range the critical current density appeared to independent of the width.

B. Perpendicular Field and Current

To investigate the dependence of the field and current direction dependence the samples are cut in two directions from the tape and placed in two different directions of the magnetic field. As a result the Lorentz force is acting in all three possible main directions of the tape, as pointed out in figure 1. For practical applications only the samples with the current flowing parallel to the rolling direction are relevant. In the other direction the sample length is limited, in our case to approximately 80 mm.

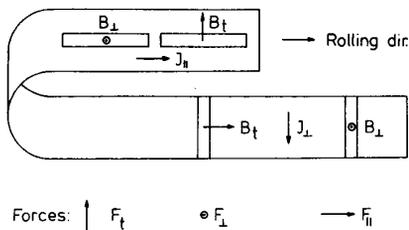


Fig. 1: Definition of the directions for the electrical current, magnetic field and Lorentz force

1) *Results:* The critical current versus magnetic field of the tape in the four situations described above is presented in figure 2. The most striking result is the extreme difference in the critical current between the two directions of the magnetic field on the tape. A relatively small difference appears for the two different directions of the current in the tape.

For both the directions of the current in the tape, the critical current decreases rapidly if a magnetic field is applied perpendicular to the surface of the tape. In an external field of 1 tesla the critical current is reduced with a factor of 100. The first part of this curve matches good with the kim relation: $I \propto 1/(B+B_0)$ for a value of $B_0 = 0.02$ tesla (figure 3).

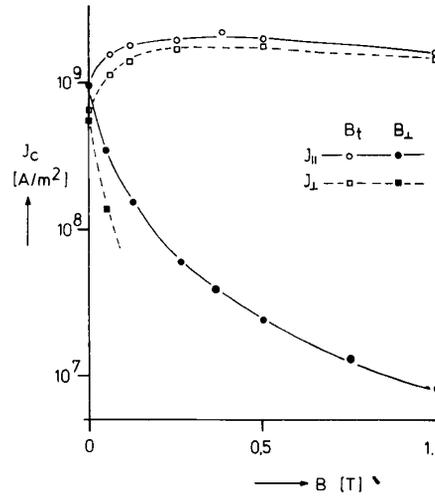


Fig. 2: The critical current versus magnetic field, in different directions of field and current.

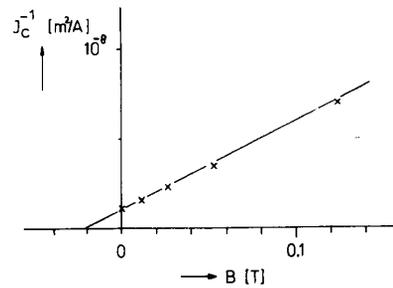


Figure 3: Test of the Kim relation for a magnetic field perpendicular to the surface.

If the magnetic field is parallel to the tape surface, but perpendicular to the current the behaviour is somewhat similar to as it is found in NbTi (multifilamentary) wires. Above 1 tesla the critical current decreases, indicating an upper critical field near 10 tesla (see also figure 5). Below 0.5 tesla the critical current, in the two investigated directions, decreases to a value of $0.95 \cdot 10^7$ and 0.58 A/m^2 for a vanishing field.

2) *Instabilities:* Usually, e.g. in NbTi wires, a decrease of the critical current for small fields is due to the instability of the conductor. In this material there are no instabilities found. Clear voltage current characteristics are measured in this range for all the directions of current and magnetic field. This is in agreement with the simple adiabatic stability criterion which predicts no stability problems for this combination of relatively low critical current and thickness [3].

3) *Pinning Forces:* It is interesting to summarize the previous results in terms of pinning forces. Using the direction definitions of figure 1, the results are presented in figure 4. The shape of the curve for the pinning force as a function of the field is completely different for the investigated directions. Only if the pinning force acts in the direction perpendicular to the tape surface shows reasonable high values. In the other directions the pinning mechanism is several orders of magnitude weaker.

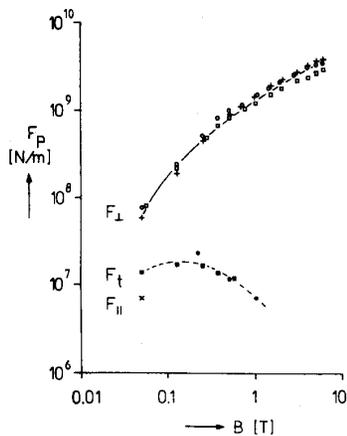


Fig. 4: The pinning forces in the NbTi tape.

C. A Comparison of NbTi and Nb₃Sn Tape.

After analyzing the results of the NbTi tape, for the different directions of the magnetic field and current, it is concluded that the strong anisotropy of the current in an external field is caused by the production process. The deformation of the NbTi, after rolling the tape, creates directionally dependent pinning centers. To state this conclusion a comparison is made with Nb₃Sn tape made by Horizont (USSR). This tape is produced by reacting a Nb tape between two tin layers covered with a copper stabilizer.

The dimensions of the Nb₃Sn tape are comparable to the NbTi tape, the Nb₃Sn layer is approximately 24 μm thick and the width of the tape is 4.5 mm. This material is tested in the two directions of magnetic field perpendicular to the current. The Nb₃Sn tape showed no detectable dependence for the direction of this field, in the field range from 10 to 15 tesla.

D. Critical current and Magnetic Field Parallel

The next situation to consider is the magnetic field acting parallel to the electrical current, so the Lorentz force is diminishing. The critical current in this geometry is plotted in figure 5 together with the two perpendicular directions of the magnetic field, for the same samples, all with the current flowing parallel to the rolling direction.

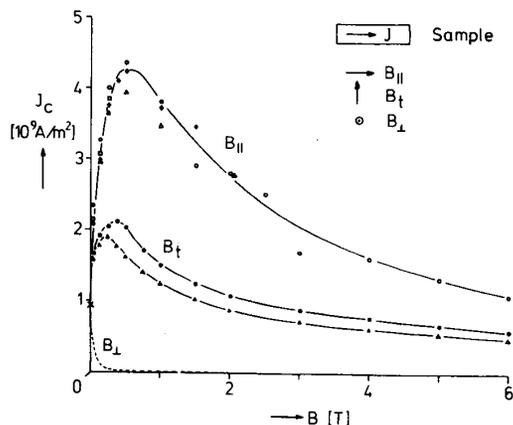


Fig. 5: Critical current for parallel and perpendicular directions of the magnetic field.

As usual the critical current density shows the highest values for a small magnetic field (≈ 0.5 tesla) in the parallel direction. An interesting phenomena is that it is possible to measure a voltage near the critical current for low field values, without any stabilizing material (no current sharing) or perpendicular field (flux flow). The only mechanism left for a voltage rise is the flux flow due to the self field in the superconductor.

E. The Influence of the Self Field

A simple method to change the self field inside the conductor, is to put two tapes near to each other. If the current is flowing in the opposite direction (antiparallel) the field components perpendicular to the surface cancel each other. Otherwise the self field in this direction is doubled. The other component of the magnetic field will act in the opposite way, but it is expected to have only a negligible influence on the critical current.

The experimental results (table 1) indicate that indeed the perpendicular component of the self field is responsible for a decrease of the current in the situation where one single piece of tape is used, reducing this component of the self field in the antiparallel situation increases the critical current with a factor two, in the parallel case a decrease of approximately 0.75 is found. One can assume that in the antiparallel geometry the critical current density is close to the intrinsic value.

TABLE I
CRITICAL CURRENT IN SELF FIELD FOR THREE GEOMETRIES

Sample shape	Critical current density
Two antiparallel	$2.00 \pm 0.20 \cdot 10^9 \text{ A/m}^2$
Single tape	0.95 ± 0.05 ..
Two parallel	0.73 ± 0.04

IV CRITICAL STATE IN A THIN TAPE

In our case the tape's width (W : 1 to 20 mm) is in the order of 10^3 times of its thickness (d). It is reasonable to reduce our problem to an infinite thin thickness. Consider an infinitely long straight and thin tape with a position(x) dependent current density (J), flowing in the z -direction. The magnetic self field (B), pointing in the y -direction, at a certain position ($x=a$) inside the tape is calculated with the integral form of amperes law:

$$B(a) = \int_{x=-W/2}^{W/2} \frac{\mu_0 d J(x)}{2\pi(a-x)} dx \quad (4)$$

The assumption of a infinite thin tape reduces the self field to one component inside the tape pointing in the perpendicular (y) direction. In that way the problem is restricted to the most important component of the field as deduced from the experiments described before. The second step is to assume that the entire tape is in the critical state, making the current equal to the critical value in the field along the x -coordinate:

$$J(x) = J_c(B(x)) \quad (5)$$

It is convenient to rewrite the $J_c(B)$ relation used in (5) by normalizing it at $B = 0$ ($J_c = J_0$) and $B = B_{c2}$ ($J = 0$):

$$j = 1 - f(b), \quad (6)$$

with $j = J/J_0$, $b = B/B$. The normalized function $f(b)$ contains the information of the actual $J_c(B)$ relation. Combining the previous relations (4), (5) and (6), an integral equation of the Fredholm type is received:

$$j(x) = 1 - \lambda \cdot f \left(\int_{x=1}^1 \frac{j(a)}{(a-x)} dx \right), \quad (7)$$

defining the parameter $\lambda = (\mu_0 J_0 d) / (2\pi B_{c2})$. This equation (7) shows that the width of the tape (W) is not playing a role in our problem. Besides the characteristic parameter λ only the shape of the $J_c(B)$ relation in the function f is important for the current profile in the tape.

A. Linear Approximation

Assuming a linear $J_c(B)$ relation, with the normalization function simplified to $f(b) = |b|$, and using the symmetry at the center ($x = 0$) the integral equation is simplified to a linear type. An analytical solution, as an approximation for small values of λ , is found by integrating a constant current ($j(x) = 1$):

$$j(x)_1 = 1 - \lambda \ln \left| \frac{1-x}{1+x} \right| \quad (8)$$

With this approximation for the overall current density the relative current in the self field is:

$$\int (j(x)_1) dx = 1 - \lambda \ln 4 \approx 1 - 1.4 \lambda \quad (9)$$

Using a value of 10 tesla for the upper critical field, and the critical current found in the antiparallel geometry the characteristic parameter is approximately: $\lambda = 0.008$, according to (9) the reduction of the critical current is negligible.

B. Solutions for Large λ

So far the strong decrease of the critical current in the perpendicular field as found in the experiments has not been taken into account. There are two ways of improving the approximation mentioned above:

- 1) *Increasing λ* : Approximate the experimental $J_c(B)$ curve by fitting it with a much smaller critical field.
- 2) *Changing $f(b)$* : Another way to change the $J_c(B)$ relation in the model is by changing the function f .

A numerical calculation is made for a wide range of the characteristic parameter λ . The integral equation (5) in its linear approximation is solved by building a set of linear equations for the solution $j(x)$. If an equidistant distribution for the points at the x -axis is used the solution becomes unstable, except for a specific range near $\lambda = 0.3$. These instabilities appear on the edges (for smaller λ) or in the center of the tape (for larger λ).

An improvement of the calculation is found by adjusting the points along the x -axis to build an equidistant distribution, along in the j - b plane. This iterative produces a consistent and non oscillating solution for $j(b)$ (figure 6).

Again a simple integration completes the calculation of the overall critical current in the tape. Together with the analytical solution, only valid for $\lambda \ll 1$, this result is plotted in figure 7. The calculated result indicates that the critical current in the NbTi tape, under self field conditions, can be described by a λ value near unity. Reducing the current to 50% in a single tape and 35% in a parallel tape were λ is doubled, as it is proportional with the thickness.

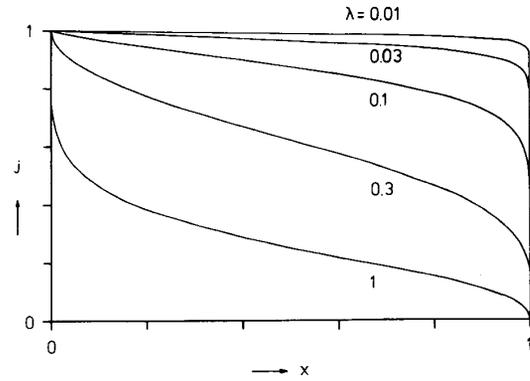


fig. 6: Calculated profiles for the current in the tape in self field, using a linear approximation.

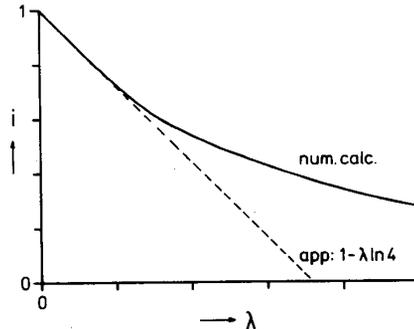


fig. 7: Calculated current reduction as a function of the characteristic parameter λ .

V CONCLUSIONS

1. The critical current density in NbTi tape depends on the direction of the magnetic field. A magnetic field of 1 tesla perpendicular to the surface of the tape reduces the critical current with a factor of 100. A magnetic field in the other direction, perpendicular to the current but along the surface of the tape, shows a less pronounced critical current decrease.

2. Without an external field the critical current density in the tape is limited below the intrinsic value, due to the self field component pointing perpendicular through the surface.

3. The current reduction caused by the self field is described in a one dimensional model, and appears to be independent of the width of the tape as it was also found experimentally.

4. The highest value for the critical current in self field appears when the tape is put in a bifilar geometry. This is a favourable property for using this tape in a superconducting switch.

5. The maximum critical current density of $2 \cdot 10^9 \text{ A/m}^2$ is just enough to match the properties of the best switches as known. In this case it is necessary that the heat capacity of the switch is not further increased with additional (stabilizing) materials.

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