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LOW-FIELD INSTABILITIES IN Nb_3Sn MULTIFILAMENTARY WIRES: THE POSSIBLE ROLE OF UNREACTED Nb

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We report an experimental study aiming to demonstrate the not negligible role of unreacted Nb on the magnetic instabilities in superconducting Nb_3Sn multifilamentary wires, observable through partial flux jumps at magnetic field values below 0.5 T. The analysed wires were recently developed for use as dipoles required in future high-energy proton accelerators and are based on powder-in-tube technology. We studied both unreacted (only involving Nb filaments) and reacted wires, finding flux jump instabilities in both cases when performing magnetic measurements. The results can be interpreted on the basis of the critical state model and are coherent with the intrinsic stability criterion.

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RAPID COMMUNICATION

Low-field instabilities in Nb3Sn multifilamentary wires: the possible role of unreacted Nb

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Abstract
We report an experimental study aiming to demonstrate the not negligible role of unreacted Nb on the magnetic instabilities in superconducting Nb_3Sn multifilamentary wires, observable through partial flux jumps at magnetic field values below 0.5 T. The analysed wires were recently developed for use as dipoles required in future high-energy proton accelerators and are based on powder-in-tube technology. We studied both unreacted (only involving Nb filaments) and reacted wires, finding flux jump instabilities in both cases when performing magnetic measurements. The results can be interpreted on the basis of the critical state model and are coherent with the intrinsic stability criterion.

(Some figures in this article are in colour only in the electronic version)

In recent years we have observed renewed interest in Nb_3Sn superconductors. In spite of the progress with high-T_c superconductors optimized for applications (e.g. YBCO-coated conductors) and of very promising developments of magnesium diboride wires, large projects involving high-field superconducting magnets are still looking for conductors based on Nb_3Sn. The ITER project, aiming to develop a Tokamak fusion reactor, envisages a cable in a conduit Nb_3Sn conductor for toroidal and poloidal coils and for the central solenoid. American and European teams are developing high-field-gradient quadrupole and high-field dipole magnets (15 T) for the interaction regions of the Large Hadron Collider at CERN, based on a multistrand conductor, made of Nb_3Sn multifilamentary wires [1, 2]. The basic feature making Nb_3Sn so appealing is its ability to carry very high current density in practical wires, typically 2400 A mm^{-2} at a temperature of 4.5 K and applied magnetic field of 12 T. Unfortunately, recent developments in high-field accelerator magnets showed the Achilles' heel of wires carrying high current density [3, 4]. It is a well-known problem since the early developments of superconducting wires in the 1960s: a local temperature increase, due to a disturbance, causes a sudden magnetic flux penetration into the superconductor, generating a further heat dissipation [5, 6]. This avalanche process can be controlled (no transition to normal state occurs) if the wire is thin enough according to the formula

$$b < \sqrt{\frac{3\gamma C_p(T_c(B) - T_{op})}{\mu_0 J_c^2(B, T_{op})}}, \quad (1)$$

where b is the wire diameter, γ is the mass density, C_p is the specific heat, T_c is the critical temperature at a given magnetic field B, T_{op} is the operating temperature and J_c is the critical current density at the operating temperature. On the basis of this simple formula (the adiabatic stability criterion) the need to develop multifilamentary wires was understood with

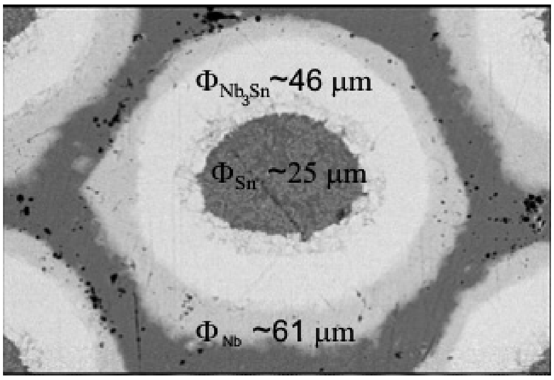

Figure 1. SEM image showing the cross section of a single filament of a PIT wire developed in the framework of the NED project. The approximate dimensions of each filament phase (Sn, Nb and Nb_3Sn) immersed in a Cu matrix are reported too.

filament size of the order of 100 μm for NbTi (at 4.2 K and 5 T magnetic field) and 30 μm for Nb_3Sn (at 4.2 K and 12 T magnetic field), the most used superconductors in practical applications. One can see in equation (1) that the higher the current density the lower the filament diameter. At a low field the current density of the Nb_3Sn wire is so high as to require filaments of 6–10 μm in diameter. The most advanced technological developments of Nb_3Sn wires are based on three main processes [7]: powder in tube (PIT), internal tin (IT) and modified jelly roll (MJR), all leading to filament dimensions ranging from a minimum of 50 μm to 100 μm. We have focused our attention on wires produced through the PIT process because, apart from the very promising developments, their response to an applied dc magnetic field can be easily analysed. Figure 1 shows a cross section of a PIT wire developed for the Next European Dipole (NED) project [2] with a detail of a single filament, obtained by scanning electron microscopy (SEM) micrography. The unreacted filament has a Sn core diameter of 25 μm, immersed in a Nb hexagon having a short diameter of about 61 μm. When curing the wire, the Sn diffusion into the Nb creates a 46 μm wide annular region of Nb_3Sn.

With respect to the adiabatic stability criterion, this wire would be unstable at a low field (below 1 T), the Nb_3Sn size being about four times the critical size expressed by equation (1). In fact partial flux jumps are observed in the dc magnetic moment measurements, as shown in figure 2.

Indeed the measurements in figure 2 highlight not only the presence of partial flux jumps at a low field for a reacted wire in the range $\pm$0.6 T as expected (panel (a)), but also for an unreacted wire in the range $\pm$0.15 T (panel (b)). We can see that most of the partial flux jumps in the reacted wire are confined in a field range lower than 1 T, where the unreacted niobium can have a role (at least up to 0.5 T). We have quantified this role of niobium on the basis of the Bean critical state model [8] applied to a simple multi-shell model. The single filament can be schematized with a slab model with a cross section in the x–y plane as shown in figure 3(a), representing the case with only the Nb_3Sn in the superconducting state. Following the classical approach, a disturbance causing a temperature increase produces in a time interval Δt a field penetration from a field profile defined by

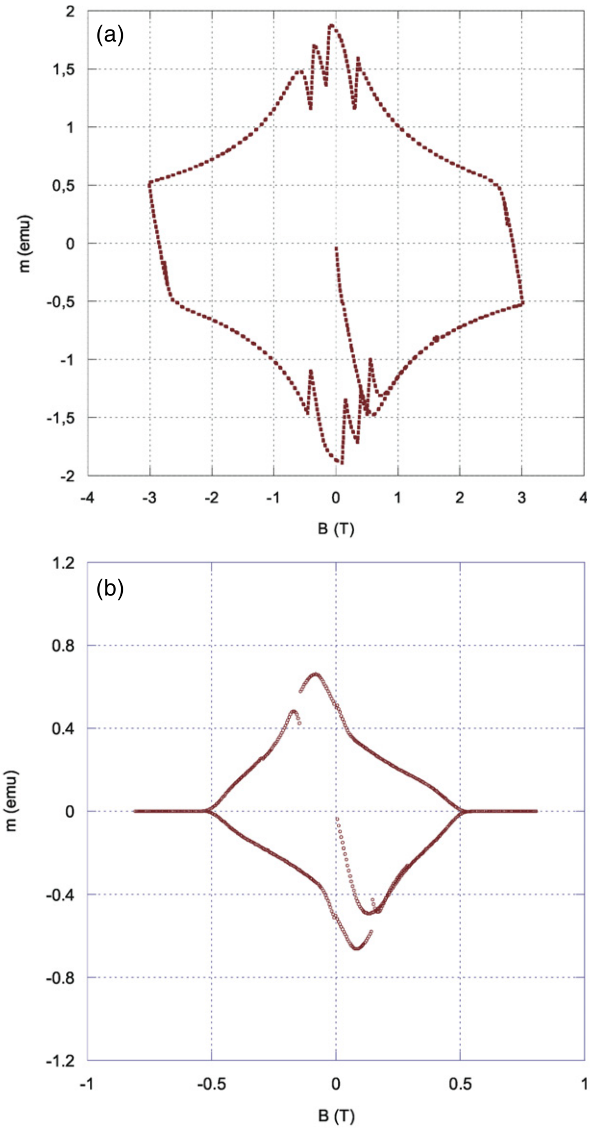

Figure 2. The dc magnetic moment as a function of the magnetic field (transverse to the wire) measured in 5 mm long samples of NED wire at 4.5 K. In (a) the measurement on a reacted wire is shown. In (b) one can see the measurements on an unreacted wire (so only Nb properties affect the magnetic moment).

$B(x) = \mu_0 J_c x$ to a new one $B'(x) = \mu_0 (J_c - \Delta J_c) x$. The flux penetration generates an energy dissipation per unit volume in the Nb_3Sn region $e = \frac{1}{b-a}\int_a^b E_z(x) J_c \Delta t \, dx$, where $E_z(x)$ is the electrical field in the z-direction normal to the x–y plane. Using Faraday's law, $E_z(x)$ can be simply calculated at a location x of the Nb_3Sn region defined by $a \leqslant x \leqslant b$ (figure 3(a)) as

$$E_z(x) = \mu_0 \frac{|\Delta J_c|}{\Delta t} \left(\int_0^a (b-a) dx + \int_a^x (b - x') dx' \right)$$
$$= \mu_0 \frac{|\Delta J_c|}{\Delta t} \left(bx - \frac{a^2}{2} - \frac{x^2}{2} \right).$$

In this formula the magnetic flux is calculated as the sum of the component in the core (where the magnetic field is spatially constant) and the component in the Nb_3Sn. It is worth mentioning that we have an electrical field at $x = a$

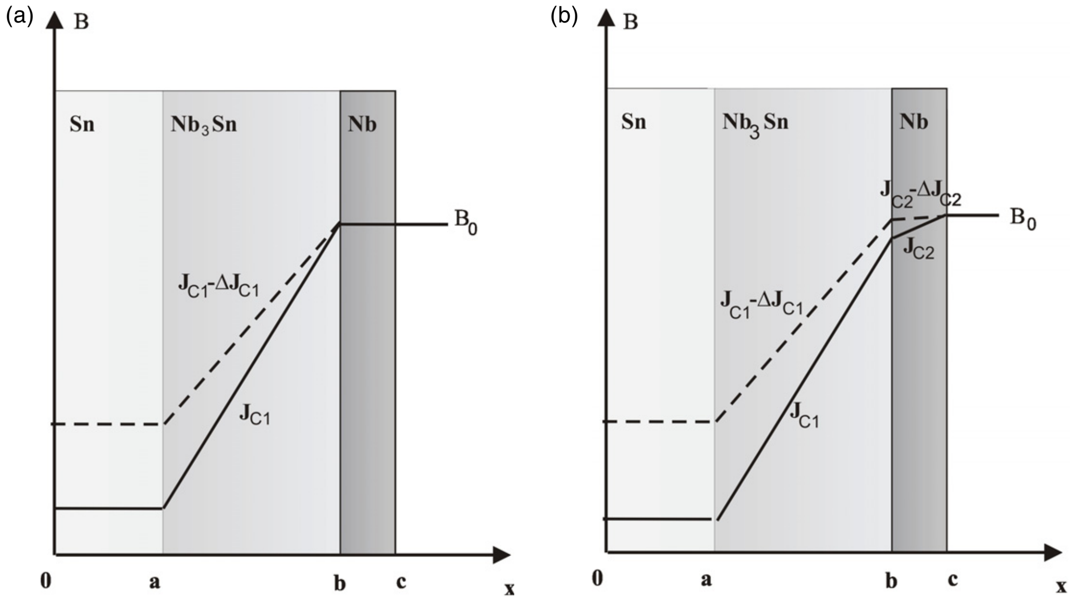

Figure 3. Simple shell model of a PIT filament, with a Sn core, a Nb_3Sn region and an outer Nb shell. In (a) only Nb_3Sn shields the field, in (b) Nb also contributes to the magnetic shielding. The continuous lines show the unperturbed field profiles (according to the Bean critical model), while the dotted lines show the field penetration after a temperature increase of ΔT, causing a critical current variation of $-\Delta J_{c1}$ in Nb_3Sn and $-\Delta J_{c2}$ in Nb.

due to the flux variation in the Sn core. The dissipated energy density is then given by the integration $e = \frac{\mu_0|\Delta J_c|J_c}{b-a}\int_a^b (bx - \frac{a^2}{2} - \frac{x^2}{2})\mathrm{d}x = \frac{1}{3}\mu_0|\Delta J_c|J_c(b^2 + ab - 2a^2)$. This dissipation can be balanced by the heat capacity of Nb_3Sn, if the size b of the Nb_3Sn phase is restricted to values lower than a critical dimension $b < \sqrt{\frac{3\gamma C_p(T_c(B)-T_{op})}{\mu_0 J_c^2(B,T_{op})(1+\alpha-2\alpha^2)}}$, where α is the ratio between the normal core diameter and the Nb_3Sn diameter ($\alpha = a/b$). This formula is a generalization of equation (1) in the presence of a normal core and it is based on the consideration that the thermal diffusivity of Nb_3Sn in the superconducting state is much lower than those of niobium in the normal state and of tin (so the power generated in Nb_3Sn is adiabatically dissipated within it). Below 9.2 K, the niobium shell also contributes to the magnetic shielding, as shown in figure 3(b). Then we can consider a more general situation where a disturbance causes a temperature variation ΔT in both Nb_3Sn and Nb. In this case the field penetration in Nb_3Sn is coupled with a field penetration in Nb as shown in figure 3(b).

Setting $\chi = c/b$ (i.e. the ratio between the Nb and Nb_3Sn diameters) and assuming again that the heat dissipated in Nb_3Sn is adiabatically dissipated only inside itself, we find a new limitation on the maximum Nb_3Sn dimension. Let us call it b' to distinguish it with respect to the previous case:

$$b' < \{\{6\gamma C_p(T_{c1}(B) - T_{op})(T_{c2}(B) - T_{op})\} \times\{\mu_0 J_{c1}(B, T_{op})[2J_{c1}(1 + \alpha - 2\alpha^2)(T_{c2}(B) - T_{op}) + 3J_{c2}(1 + \alpha)(\chi - 1)(T_{c1}(B) - T_{op})]\}^{-1}\}^{1/2},$$

where index 1 is referred to the Nb_3Sn shell and index 2 to the Nb shell. The maximum Nb_3Sn dimension is reduced, as can be seen by writing b' as a function of b:

$$\frac{b'}{b} = \sqrt{\frac{1}{1 + \frac{(T_{c1}(B)-T_{op})}{(T_{c2}(B)-T_{op})}\frac{J_{c2}}{J_{c1}}\frac{3(1+\alpha)(\chi-1)}{2(1+\alpha-2\alpha^2)}}}. \qquad (2)$$

This is the central formula of the paper. The maximum allowed size of Nb_3Sn is in any case reduced by the presence of the external niobium shell. The reducing factor depends on the ratios between the critical current densities and the temperature margins of the two superconducting materials, as well as on the geometrical factors α and χ. There is a significant role of the geometrical factor $g(\alpha, \chi) = \frac{3(1+\alpha)(\chi-1)}{2(1+\alpha-2\alpha^2)}$ (0.79 for the case in figure 1, with $\alpha = 0.54$ and $\beta = 1.33$). In order to quantify the reduction of the filament size, we needed information on the critical currents and critical temperatures of niobium and Nb_3Sn, which we obtained from magnetic moment measurements on both reacted and unreacted wires. Figures 2(a) and (b) show typical measurements of magnetic moment versus field at 4.5 K. The critical currents at field B are calculated from the Δm of the magnetization loop between lower and upper branches. In order to avoid including the niobium contribution to the current, for the reacted wire, we evaluate the critical current of Nb_3Sn at a magnetic field greater than 0.7 T. Incidentally, the measurements in figure 2 highlight the presence of partial flux jumps at low fields for both the reacted wire (in the range ± 0.6 T) and the unreacted wire (in the range ± 0.15 T). This latter is an important additional piece of information, proving that the Nb shell can be affected by partial flux jumps alone, supporting experimentally the model schematized in figure 3(b), showing a sudden field penetration for both Nb and Nb_3Sn.

We are interested in the field range 0 to 0.5 T, i.e. up to Nb contributing to the transport properties. Though all properties of our interest depend on the field (T_{c1}, T_{c2}, J_{c1} and J_{c2}), we evaluate $\frac{J_{c2}}{J_{c1}} \approx 0.02$ and $\frac{(T_{c1}(B)-T_{op})}{(T_{c2}(B)-T_{op})} \approx 10$. Considering that, in our case, the geometrical factor is $g(\alpha, \chi) = 0.79$, we have $\frac{b'}{b} \approx 0.93$. The presence of niobium depresses the maximum filament size by 7%. Its effect is enhanced as the unreacted region increases. As an example, figure 4 shows the magnetic

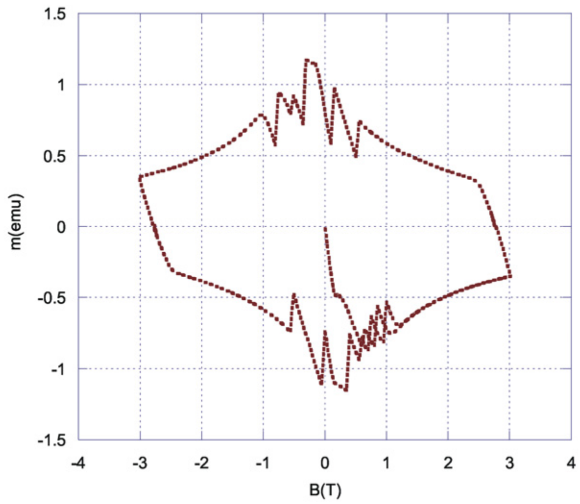

Figure 4. The dc magnetic moment as a function of the magnetic field (transverse to the wire) measured in a sample of a PIT wire composed of 192 filaments at 4.5 K. With respect to the case of figure 1, the unreacted region is larger ($\chi = 1.48$).

moment cycles for a different PIT wire having 192 filaments, for which $\alpha = 0.48$ and $\chi = 1.48$, resulting in a geometrical factor of $g(\alpha, \chi) = 1.05$ and $\frac{b'}{b} \approx 0.90$. For this wire the flux jumps at low fields are present in larger numbers.

In conclusion, this study shows that, though the magnetic instabilities in Nb_3Sn wires are basically due to the high current density in this material, the unreacted Nb can play a significant role in enhancing the instabilities at low field (up to 0.5 T). There are two ways to reduce the effect of niobium: (1) to involve very pure Nb in the wire manufacture so as to limit the unwanted electrical transport properties of the Nb shell (i.e. reduce J_{c2} in equation (2)); (2) to react all the Nb phase (i.e. $\chi \rightarrow 1$ in equation (2), though this latter solution seems to produce tin infiltration in the external copper with a severe worsening of the dynamic stability of the wire [4].

Acknowledgments

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