The Influence of the Diffusion Barrier on the AC Loss of Nb_3Sn Superconductors

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Nb_3Sn superconductors as they are applied in the ITER fusion programme, are equipped with diffusion barriers made of V, Ta, and V-Nb, all having superconducting properties. If an external ac magnetic field is applied, superconducting shielding currents are induced in the barrier which enclose a bundle of Nb_3Sn filaments. As a consequence they are shielded and no ac loss will occur in the filaments. When the penetration field of the barrier material is exceeded, additionally the loss of the barrier and for higher fields also the loss of the Nb_3Sn multifilamentary zone is generated. As long as the barrier is superconducting it will cause a substantial increase of ac loss. As a consequence the ac loss of the conductor in terms hysteresis loss per cycle and coupling time constants are strongly influenced. This aspect has to be considered carefully when properties of Nb_3Sn conductors are determined at low magnetic fields.

INTRODUCTION

The stabilising copper in Nb_3Sn composite wires is protected from mobile tin during heat treatment by diffusion barriers. In order to preserve the quality of the copper (and the RRR value), the barrier material must not interdiffuse with the copper while being an adequate barrier against tin flow. It has been demonstrated that a pure niobium barrier is not suitable for ac applications even at high fields since a Nb_3Sn layer is formed on the inner surface of the barrier causes a considerable increase of ac loss [1,2]. The additional loss originates from the different return path of the coupling currents now flowing in the superconducting Nb_3Sn shell in the barrier instead of returning through the outer copper shell. Therefore, it is essential that diffusion barrier are made of Ta, V-Nb or V, having superconducting properties only at very low fields. Miyahara et al [2], for example, presented some experimental results and a theory for bronze-processed Nb_3Sn with a Nb or Ta barrier. He analysed the case of a transverse magnetic field with trapezoidal wave form and for relatively low sweep rates and a Nb_3Sn shell inside the Nb barrier.

The major part of the windings in (ITER) fusion magnets are exposed to a relatively large dc magnetic field of 13 tesla maximum. In these parts the mentioned effect is not significant. However, other parts of the windings are subjected to rapidly changing fields passing zero field. So, it is not only for scientific reasons to study the contribution of the ac loss due to a superconducting barrier. A second motivation is that most of the ac loss characterisation of conductors is carried out in low fields as, for example, the hysteresis loss tests at +/- 3 T and the time constants test at 50-500 mT ac fields. Here we present some important observations concerning ac losses at low fields of heat treated and virgin Nb_3Sn wires with Nb-V barriers based on calorimetric and electrical magnetisation measurements.

AC Losses in superconducting composites

The ac loss of mf superconductors in transverse ac fields can be described by coupling current and a hysteresis losses. In general the hysteresis loss goes with power three of the applied ac magnetic field B_a when the amplitude is below the penetration field B_p and it behaves linearly for fields exceeding B_p. The penetration field $B_p=\mu_0.J_{cz}.d_{fil}/\pi$, in which J_{cz} is the critical current density and d_{fil} is effective filament diameter. The coupling loss can be described with the (dominant) time constant $n\tau$ following

$$Q_{cpl}=(\pi/\mu_0).B_a^2.\varpi.n\tau/(1+\varpi^2.\tau^2);\ \ \varpi=2\pi.f;\ \ \tau=\mu_0/2.(L_p/2\pi)^2.\sigma_\perp, \qquad (1)$$

where L_p is the twist pitch of the filaments and $\sigma_\perp$ is the effective transverse conductivity of the matrix. The coupling loss time constant for a multifilamentary wire can also be defined as $\tau_0=1/(2\pi.f_0)$, in which f_0 is the frequency of the ac field at which the maximum loss per cycle appears versus frequency.

SET-UP FOR CALORIMETRIC AND ELECTRICAL LOSS MEASUREMENTS

The ac loss is measured of an ITER based NbSn superconductor produced by LMI, $\varnothing_{strand}$=0.73 mm, n_{fil}=5832, $d_{Cr\text{-}layer}$=2 μm, ratio Cu/nonCu= 1.7 and L_p=12 mm. The cross-section of the conductor shows 36 bundles of filaments each surrounded by a cylindrical V-Nb barrier. A sinusoidal ac magnetic field is applied perpendicularly to the strand in liquid helium at 4.2 K.

The calorimetric loss is determined by measuring the He gas flow from the calorimeter that encloses the sample and which is in an ac dipole magnet. The sample consists of 50 straight pieces of wire each having a length of 309 mm. The strands are electrically insulated.

The pick-up coil based magnetometer is built up as an insert for a low frequency 8 T magnet with 60 mm bore. The sample is ring shaped (coil, spiral or bend pieces of wire). Additionally there is a low inductance ac solenoid between pick-up coils and high field magnet to facilitate high frequency analysis up to 0.6 T with a field homogeneity of ±1 % at the position of the sample.

OBSERVATIONS BY THE EXPERIMENTS

The calorimetric determined coupling losses following $Q_{cpl}(f)=(Q_{tot}-Q_{hys})/B_a^2$ are shown in Figure 1 for various amplitudes of B_a, between 25 and 400 mT and zero background field. In the figure we clearly observe a jump in the ac loss between 100 and 150 mT. The frequency where the loss is maximum jumps from 2 Hz to 0.2 Hz which also corresponds to a jump in the initial slope of the curves for f=0.

A more precise analysis of the same effect is measured with the magnetometer which enables a very sensitive and highly accurate investigation of a larger range of frequencies. The ac loss measured with the magnetometer versus frequency and various amplitudes of the ac field and without bias field, are shown in the Figures 2 and 3. In addition to the previous observation we now notice the following behaviour. Below 100 mT we see a nice curve with a maximum at about 2 Hz. Above 100 mT a strong asymmetry grows into the curves and at 130 mT the curve is almost flat. Then the maximum appears at about 0.2 Hz. But, starting from an amplitude of 200 mT the shape of the curves again changes drastically and the position of the maximum shifts with growing amplitude to more than 3 Hz at 400 mT. It is obvious that in this range of fields the coupling loss can not be satisfactory described by equation (1).

In order to exclude the contribution of NbSn also the ac loss of the virgin wire (not heat treated) is investigated. The hysteresis losses versus field, determined by extrapolation of $Q_{tot}(f)$ to f=0 Hz, of both the virgin and heat treated wires are shown in Figure 4.

The coupling loss "time constants" determined from the slope of the curve $Q_{tot}(f)$ at f=0 and by the frequency f_0 where the maximum loss in $Q_{tot}(f)$ occurs ($n\tau=1/(2\pi f_o)$) are presented in Figure 5. Note that in fact this operation is not justified because the curves can not be modelled with a single time constant in accordance with eq.(10) which is in fact immediately clear from Figure 5. The "time constant" of the virgin wire is also indicated in the same figure. For ac fields beyond 0.4 T the time constants decreases gradually.

The behaviour of the "time constants" at non zero bias fields is illustrated in Figure 6. The time constants are shown for an amplitude of 400 mT as function of the bias field between 0 and 4 T. The magnetisation curves of the heat treated and non-heat treated samples without bias field are shown in Figure 7. Note that above 1 T the magnetisation is zero in the virgin wires because the Nb (not reacted filaments) and the Nb-V (barrier) are completely normal conducting.

DISCUSSION

The data taken by the calorimeter and the magnetometer as well, pictured in Figures 1,2,3 evidently prove that the maximum in ac loss and therefore the "time constants" strongly depends on the magnetic field B_a. This means that the commonly used models can not be applied if superconducting barriers are present in the wire section and if the applied total magnetic field is less than 0.5 T or even lower. Several regimes can be distinguished if the applied field is raised from zero to a level B_a higher than the B_{c2} of the barrier.

(I) Close to zero field the critical current of the V-Nb barrier is high. From B_a=0 to B_{c1} no hysteresis loss is generated because of the perfect diamagnetic behaviour excluding the magnetic field from the interior of the barrier and the filaments enclosed. The B_{c1} of $Nb_{1\text{-}0}\text{-}V_{0\text{-}1}$ is between 36 and 118 mT [3]. In Figure 4 the shielding effect is present up to apparently $B_a \approx 80$ mT (B_{c1}) in both the heat treated and non-heat treated samples. Nevertheless Figure 2 shows, that inter-bundle coupling loss due to coupling currents between the various barriers (hollow filaments) is present at B_a=50 mT. The calculated time constant amounts to $n.\tau_{(I)}$=20 ms and this agrees very well with the values determined from the slope, see Figure 5. However, the time constant obtained from the maximum in Qtot(f) is $n.\tau_0 \approx 160$ ms for which no explanation is found. The difference in the time constants found for the non-heat treated and heat treated samples at 50 mT can be explained by the reduced resistivity of the copper in the heat treated wire.

(II) Above B_{c1}, the barrier ceases to be diamagnetic, vortices will appear and hysteresis loss is generated. Still the inner region of the barrier and the NbSn filaments are shielded from the external field.

(III) If B_a passes the penetration field B_{p2} [4] of the barrier material, the Nb_3Sn filaments (or in the virgin wire the Nb filaments) contribute to the hysteresis and coupling losses. The additional loss caused by the coupling currents between the Nb_3Sn filaments and the surrounding superconducting barrier can lead to relatively high losses [1,2]. In Figure 5 it can be seen that $B_{p2} \approx 130$ mT. If B_a reaches B_{c2} of the barrier, the coupling currents in the barrier will be reduced remarkably due to a sharp decrease of the J_{cz}.

(IV) If the field is well above the B_{c2} , the barriers will act as a normal layer enclosing the filament bundles and they can be treated with the usual loss models as for example given by Turck [5]. The effective B_{c2} of the barrier material and the Nb is between 0.3 and 0.5 T as can be seen in Figures 5 and 7.

In absence of any bias field, all regimes are involved and the dominating coupling loss time constant will show up in each amplitude range. If a dc bias field is present exceeding $B=B_{c2}(\text{barrier})+B_a$, the barrier can be treated as a normal layer. The evidence is shown in Figure 6 where we see a time constant $n.\tau_{(IV)}$ =4 ms when the bias field exceeds B_{dc}>0.9 T. The time constant $n.\tau_{(IV)}$ is smaller then $n\tau_{(I)}$. This is attributed mainly to the presence of a highly resistive normal layer surrounding the bundles with Nb_3Sn filaments carrying the inter-bundle coupling currents. The contribution of the intra-bundle (or inter-filament) coupling loss among the Nb_3Sn filaments inside a bundle can be neglected.

The ratio between the deformed "coupling loss" (Q_{tot} -Q_{hys}) and the calculated loss based on $n\tau_{(IV)}$=4 ms, versus the frequency is shown in Figure 8. Note that the additional loss due to the presence of the barrier not only depends on the amplitude, but it also decreases with the frequency.

CONCLUSIONS

In a Nb_3Sn multifilamentary composite with a superconducting barrier the ac magnetic field can not penetrate into the filaments if the ac field is less than the B_{c1} of the barrier material and if no bias field is present. Still some coupling loss is present if each bundle of filaments is surrounded by a barrier. If the applied field exceeds B_{c1} hysteresis loss is produced in the barrier. In the case the applied field exceeds the penetration field B_{p2} of the hollow barrier, the barrier itself is a path for the coupling currents and therefore the loss increases significantly. If the field exceeds B_{c2} of the barrier, then it can be considered as a normal layer surrounding the filament bundles. The presence of a bias field will reduce the additional coupling loss. Moreover the effect is less for high sweep rates. The described loss effect is relevant for the magnet operation when the total field passes zero as it occurs in certain low field parts of the windings of, for example, the ITER magnet system. The presence of a superconducting barrier can result, at low fields, in enhanced losses far beyond the estimated loss based on time constants determined at high fields.

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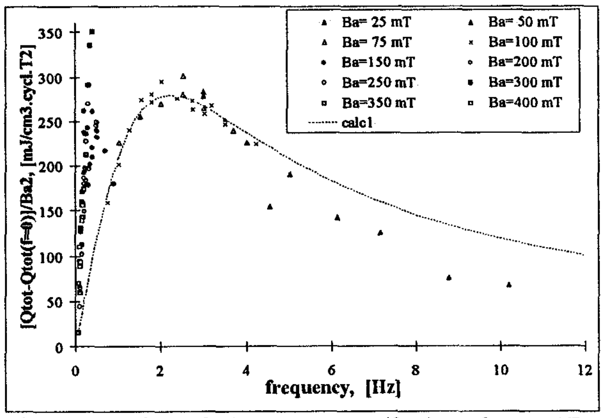

Fig .1 Calorimetric loss, Q_{tot}-Q_{tot}(f=0)vs. f, B_{dc}=0T

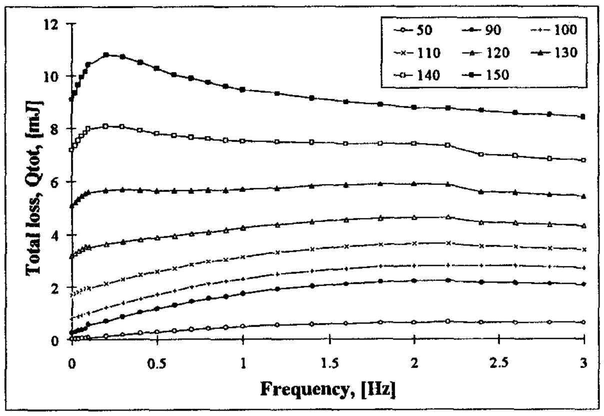

Fig. 2 Q_{tot} versus f, B_{dc}=0, 50 < B_a.< 150 mT

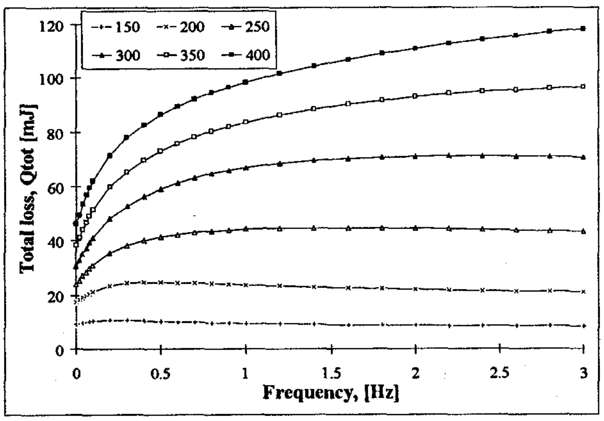

Fig. 3 Q_{tot} versus f, B_{dc}=0, 150 < B_a. < 400 mT

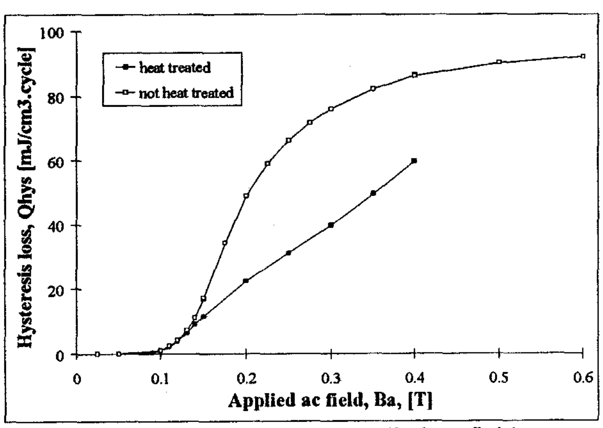

Fig. 4 Hysteresis loss versus applied ac field, B_{dc}=0T, heat treated and non-heat treated samples

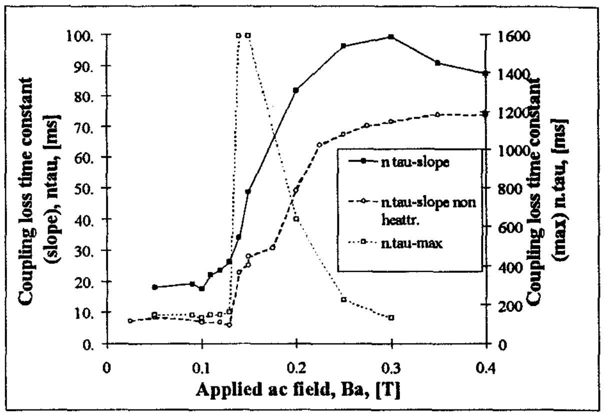

Fig. 5 Coupling loss time constants n.τ versus B_a

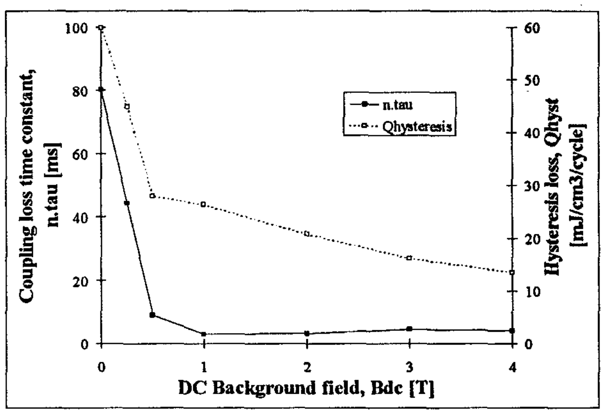

Fig. 6 Coupling loss n.τ versus B_{dc} with B_a=0.4 T

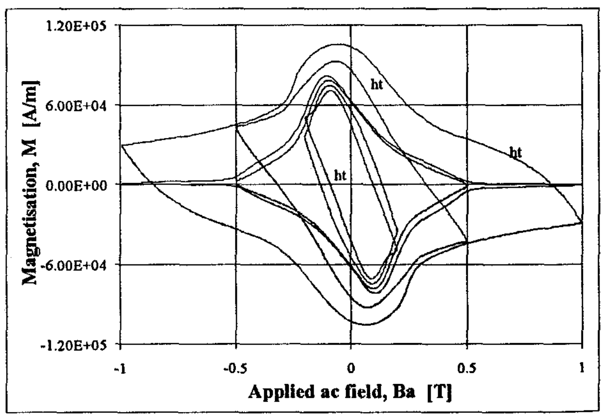

Fig. 7 Magnetisation vs. B_a, B_{dc}=0 T, ht=heat tr.

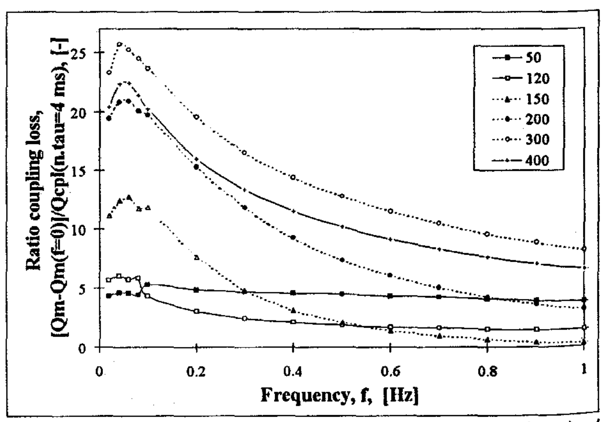

Fig. 8 Ratio (total loss minus hysteresis loss) / (coupling loss if n.τ=4 ms)