THIN-FILM WASHERS AS SECONDARIES IN SUPERCONDUCTING INDUCTIVE FAULT CURRENT LIMITERS: THE ROLE OF THE COOLING ATMOSPHERE

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Abstract. Recently, we showed that the use of thin-film superconducting washers as secondaries in inductive fault current limiters may have considerable advantages when compared with the more conventional bulk rings or cylinders. Here we extend those previous works to determine if the cooling atmosphere plays a significant role on the recovery time, $\tau_R$, of the inductive fault current limiter based on thin film superconductors. We have used helium as a cooling gas, from primary vacuum to atmospheric pressure. We have found that gas pressure has an appreciable influence on the recovery time of our inductive fault current limiter. For instance, our results show that $\tau_R$ under atmospheric pressure is almost thirty per cent shorter than when measured in primary vacuum. A numerical simulation realized by the finite element method shows that just after the fault the substrate is thermalized and, therefore, during the recovery convection is the only working heat exchange mechanism. To avoid this undesirable thermalization and to further reduce the recovery time the substrate should either be much more thicker or be in good contact with a thermal sink capable of removing the heat by conduction.

1. Introduction
Superconducting thin films have been extensively employed to design and fabricate superconducting fault current limiters (SFCL), mainly of the resistive [1, 2, 3] or hybrid type [4], although the pure inductive configuration has been also studied in some works [5, 6, 7]. In all cases the thin films are grown on suitable substrates, whose lattice is quite similar to that of the superconducting material. They are always much thicker than the film (typically about 0.5 mm while the film is several hundred nm thick) and their thermal conductivity is much greater. This implies that, during the first instants of transition, the film quickly transfers the generated heat to the substrate which, in a first approximation, can be considered as infinite. This is a model that has been extensively used in the study of microbridges [8, 9] when applying pulses of about 1 ms in duration. Nevertheless, the time interval comprised between the reaction of a limiter
and the thermal recovery can be as long as 1 s. In such a scenario, it is less clear whether the substrate can still be considered as a thermal sink. In case not, the properties of the cooling atmosphere could play a relevant role, as the produced heat should be removed as fast as possible to avoid the thermalization of the film/substrate assembly and so an undesirable long recovery time. This is of great importance if the thin films are within a gaseous environment; this would occur, for instance, if a mechanical compressor is used for cooling [10, 11] or if the refrigeration is accomplished by means of a thermoacoustic device [12, 13], where an acoustic wave generated inside a resonant tube filled with gas allows attaining a low temperature at certain regions of the duct [14].

Thus, if the exchange of heat from the substrate to the environment (gas, sample holder) plays a noticeable role in the thermal recovery of the limiter, a variation in the recovery time should be expected and it could be experimentally observed. On the other hand, if the substrate is capable of absorbing the heat in such an efficient way that the system remains at a temperature equal or very close to 77 K, then \( \tau_R \) will not change no matter the used cooling atmosphere.

In this work we present some experimental results on the recovery time of an inductive limiter whose secondary is a YBCO thin film washer. This study has been realized in a gaseous atmosphere and for different values of the static pressure in order to observe if a noticeable change of \( \tau_R \) occurs. Then, a numerical simulation developed by using the finite element method is accomplished to study the thermal behaviour of the film/substrate assembly during and after a fault.

2. Experimental details and results

To study the thermal recovery of our YBCO thin film washers, the limiter was introduced in a sealed cavity filled with different pressures of Helium gas, from primary vacuum to atmospheric pressure, and surrounded by a bath of liquid Nitrogen. All the measurements were preceded by a long waiting time to obtain a stable state of temperature and pressure. The secondary was an Au/YBCO/Al\(_2\)O\(_3\) washer of 2.1 cm in inner diameter and 4.5 mm in width. The YBCO and gold layers were 300 nm and 100 nm in thickness, whereas the substrate is 0.5 mm. The critical temperature was \( \sim \) 89 K and the critical current density around 10\(^6\) Acm\(^{-2}\). The characteristics of the limiter and the whole set-up have been described elsewhere [6].

Figure 1 shows the data of \( \tau_R \) calculated for faults undertaken under different pressure conditions. The applied voltage is normalized to threshold value, \( V_{\text{th}} \), i.e. the voltage needed to trigger the reaction of the limiter. In this case, \( V_{\text{th}} = 0.9 \) V. The recovery time is computed as the interval between the end of the fault and the point at which the original current amplitude (i.e., the amplitude before the fault) is observed again. Experimental data in Figure 1 have appreciable dispersion due to the fact that, during the recovery, the current amplitude approaches the original value asymptotically, and this makes difficult to determine the recovery time accurately. In spite of this, the data show a clear tendency, emphasized by the dashed lines; \( \tau_R \) is higher at lower pressures. This difference is significative, being around 20% for \( V_{\text{ap}}/V_{\text{th}} = 3.0 \) and around 30% for \( V_{\text{ap}}/V_{\text{th}} = 7.3 \). The difference is greater when the voltage is higher, because the dissipation is more pronounced, thus allowing a higher temperature to be reached.

3. Discussion

From these results it is clear that the typical duration of the actuation of the SFCL is long enough for that the recovery time to become somewhat affected by the environmental conditions of the substrate. This is related not only to the pressure of the gaseous atmosphere, but also to the sample holder to which the substrate is attached. The values of \( \tau_R \) obtained in this work are considerably longer than those obtained before [6], that were below 1 s. It is likely that a significant difference could be found on the utilized sample holder, so that the substrate would encounter greater difficulty in exchanging heat with the environment. This suggests that a faster
Figure 1. Recovery time as a function of Helium gas pressure and for two different applied voltages, normalized to the threshold value, $V_{th}$. The dashed lines are guides for the eye.

Figure 2. (a) Schematic representation of the cross-section of the YBCO film / sapphire substrate assembly. (b) Temperature map in the cross-section of the sapphire substrate for $t = 20$ ms. The difference between the upper and bottom temperatures is very small.
recovery could be obtained just by attaching the substrate to a thermal sink. This would be of the greatest interest when using large superconducting films for high power devices, in which the dissipated power can be really important.

To see how fast is the thermalization of the assembly YBCO film/sapphire substrate, we have used a simple 2–D model developed in FEMLAB (COMSOL AB., USA). In this way, it was considered a system made up of a 0.5 mm thick slab of sapphire substrate (Figure 2 (a)). The increase of temperature in the film during the fault has been modelled as a time dependent temperature boundary condition. This is reasonable since the YBCO thin film and the upper side of the substrate are in very good thermal contact and, therefore, their temperatures will be roughly equal. The shape of the time evolution of this boundary condition was suggested by the exponential temperature rise observed in the readings of thermocouples attached on the surface of the gold layer of the washers. Thus, the boundary condition was defined by means of this equation:

\[ T(t) = T_{bath} + T_0 \times (1 - \exp(-t/\tau_0)), \]

\( \tau_0 \) being a characteristic time (0.1 s for our calculations), \( T_0 = 20 \) K and \( T_{bath} = 77 \) K. The thermal parameters of the superconducting film are not necessary, since the thermal behaviour of the system is governed by the substrate. During the recovery the convection to the surrounding atmosphere was taken into account by using a Neumann boundary condition on both sides of the substrate of the form \( \kappa \mathbf{n} \nabla T = h(T_{bath} - T) \), \( h = 5 \) Wm\(^{-1}\)K\(^{-1}\) being the convection heat transfer coefficient [15], and \( \mathbf{n} \) the vector normal to the boundary. For sapphire it has been used the density \( \rho = 3980 \) Kgm\(^{-3}\), heat capacity \( C_p(T) = 7.7 \times 10^{-5}T^3 + 0.34T \) JKg\(^{-1}\)K\(^{-1}\) [16], and thermal conductivity \( \kappa(T) = 1.19 \times 10^9T^{-3.2} \) Wm\(^{-1}\)K\(^{-1}\) [16]. The duration of the simulated fault was 100 ms.

In Figure 2 (b) the temperature map of the cross-section of the substrate at \( t = 20 \) ms is shown. It can be seen that the difference between the temperature of the upper side of the substrate and that of the lower side is only 5 mK. This is the highest value of \( \Delta T \) found in the calculation, and at the end of the fault this value is even lower. Nevertheless, the substrate can not be considered thermalized because, due to the high thermal conductivity of sapphire, such a small temperature difference implies a very high heat flux by conduction. This is depicted
in Figure 3, which shows, on the left, the value of heat flux in the upper side of the substrate and, on the right, the temperature of the film. The heat flux decreases roughly linearly as the temperature of the thin film increases but it is still well above 1 kWm$^{-1}$K$^{-1}$ at the end of the fault. Immediately after the fault the heat flux suddenly decreases and its value becomes almost zero in less than 100 $\mu$s. It is at this moment when the substrate can be considered thermalized since the heat exchanges by conduction are negligible. This sudden dissapearing of the mechanism of conduction is easily understood by noting that the characteristic time in which steady state is reached in a body of characteristic length $L$ is $L^2/\alpha$ [15], being $\alpha$ the thermal diffusivity. In the case of the substrate under consideration this time is of the order of 100 $\mu$s, in good agreement with Figure 3.

Figure 4 displays the cooling curve of the film during the first ms of the thermal recovery. Initially the temperature decreases at a rate of $\sim 200$ Ks$^{-1}$ until the substrate is thermalized and, after that, the cooling rate is only $\sim 1$ Ks$^{-1}$. The cause of this great difference is that until thermalization is not reached the film will continue giving its heat off to the substrate by conduction, which is a much more efficient mechanism than convection.

Since during most of the recovery process the heat will be evacuated by convection it is now clear that this fast thermalization is the reason why varying the pressure of helium gas in Figure 1 caused a variation in the recovery time of the device. Thermalization should be avoided in order to take advantage of the high cooling rate of the first instants after the fault so that the recovery time could be further reduced. In this way the substrate should either be linked to a thermal sink or be much more thicker. This is important because sapphire substrates with a thickness of the order of 1 mm are widely used in superconducting fault current limiters ([17, 18, 19, 20]) and our results suggest that, if the substrate is not linked to a thermal sink, such a thickness is not the most suitable for the thermal recovery of the device.

4. Conclusions
Experimental results on the recovery time of an inductive fault current limiter with thin film superconducting washers as secondaries have been presented. These results show that the recovery time decreases when the pressure of the exchange gas is increased. Differences in the recovery time up to 30% have been measured when varing the pressure from primary vacuum to
the atmospheric one, and this difference increases with the applied voltage. Also, a numerical simulation has been performed, whose results suggest that the variations found in the recovery time are due to a fast thermalization of the substrate in the first instants after the fault. In this way the cooling would be performed almost entirely by convection. If such a thermalization is not avoided, either by linking the substrate to a thermal sink or by increasing its thickness, the cooling atmosphere would play a key role in the thermal recovery of the limiter

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