Quench and thermal recovery in a superconducting fault current limiter with artificial weak zones

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Abstract. We report results on the behaviour of an inductive fault current limiter prototype with weak zones artificially created. The superconducting elements are Bi-2223 rings and the tests have been realized with the device on a Helium gas environment at 77.3 K. We found that the artificial weak zones can play the main role during the limitation under a current fault and on the thermal recovery process after the fault, which could be used to improve the performance of these devices. Our results show also that the artificial weak zones could balance, in addition, the influence of other natural defects which could lead to non-uniform normal-superconducting transitions, the formation of hot spots, etc.

1. Introduction
One of the problems found to improve the efficiency of the superconducting fault current limiters (SFCL) [1, 2, 3, 4] switched by high temperature superconductors (HTSC) is the presence in these elements of natural defects which, under a current fault, lead to drawbacks as an inhomogeneous quenching, the formation of hot spots, etc. Therefore, a lot of work is being done to improve the quality of the HSTC materials used in SFCL, but fabricating samples with an adequate homogeneity is very hard and expensive, specially for the large superconducting elements used in high power devices. It has been found, however, that the presence of weak zones artificially created can strongly reduce the effect of the natural defects leading to a much more full and homogeneous quench of the superconducting elements. These weak zones can be microscopic [5] or macroscopic [6, 7, 8] and they have been tested both in bulk samples operating in inductive SFCL [7] or in resistive limiters based on thin films [6]. In addition, the interest of the weak zones should be not only on their role during the quench, but also on their influence on the thermal recovery process after a fault [8].

In this work we present experimental and simulation results on the behaviour of a SFCL whose secondary is a Bi-2223 ring in which several weak zones are created by reducing the cross section of the sample’s wall. Temperature and voltage measurements realized on different parts of the ring, included the own weak zones, allow us to analyze the role played by them on the quench and on the thermal recovery.
2. Numerical simulation

The details of the numerical simulation are extendedly given elsewhere [8]. Due to the interrelation between all the involved magnitudes (the resistance of the superconducting element, \( R_{\text{sup}} \), the circulating current \( i_{\text{sup}} \), the temperature of the sample \( T \), etc) it is required a self-consistent numerical procedure in order to solve the equations of the transformer, and this is realized by using a simple iterative numerical routine in Matlab (The MathWorks, Inc, USA). The input variable is the applied voltage \( v_{\text{ap}} \) kept as constant (in this case 700 V peak), while the fault is simulated by reducing the impedance of the circuit. During the iterative process, the circulating currents \( i_{\text{p}} \) and \( i_{\text{sup}} \) are first calculated at a time \( t \), and then the inductance coefficients and the temperature and the resistivity of the superconducting element. These steps are repeated till it is reached a set of self-consistent values, so the routine advances to time \( t + \delta t \) and so on.

3. Experimental details

The characteristics of the SFCL devices used in our present experiments are very similar to those we have previously employed to study several aspects of their response to a fault [7, 8]. Our devices consist of a core comprised of two pieces with and E shape and made of silicon(3%)-iron. The material is prepared into wound sheets in order to minimize the Foucault losses. The primary coil is divided into two equal bobbins of 100 turns which are located in the side branches. They are made of copper wire of 0.6 mm in diameter. As secondary we use rings of 5 mm in height obtained from commercial cylinders of Bi-2223 (Can Superconductors, Czech Republic) of 120 mm in height, 21 mm in inner diameter and 2.4 mm in wall thickness. The superconducting material is not a single phase, having a minor Bi-2212 phase, which represents around a 15% of the total sample [7]. Its zero-resistance temperature, \( T_{\text{c0}} \), is around 108 K and its critical current density at 77 K about 1000 Acm\(^{-2}\).

Several type-E thermocouples attached to different points along the circular perimeter of the rings are used to measure the temperature evolution of the superconducting element in each experimental run. Also, several voltage paths were attached to measure the voltage drop in different zones located around the contact points of the thermocouples. These voltage drops and temperature measurements show that the transitions of our superconducting elements during the faults are very inhomogeneous, with a part of the sample reaching a highly dissipative state, displaying therefore a high temperature increase well above \( T_{\text{c0}} \), while the rest remains in a low dissipative state or even superconducting [7, 8]. The measurements are performed with the limiter put in a Helium gas environment, inside a sealed cavity at atmospheric pressure.

4. Results and discussion

4.1. Simulation results

In figure 1 it is displayed the primary current during the limitation process when using a hypothetic homogeneous sample and when it is created weak zones of different size. In our calculations, the length, \( \ell_{\text{h}} \), and the cross section, \( A_{\text{h}} \), along the circular perimeter of these zones are included through the ratios \( \lambda = \ell_{\text{h}}(\ell_{\text{total}})^{-1} \) and \( \alpha = A_{\text{h}}(A_{\text{total}})^{-1} \), \( \ell_{\text{total}} \) and \( A_{\text{total}} \) being, respectively, the length and the cross section of the ring’s walls along the circular perimeter.

We can observe that the cross section reduction leads to a better limitation of the current, as the resistance of the weak parts is increased by the narrowing. Despite this benefit, the thermal recovery of samples with large weak zones is not as fast as when using homogeneous samples, as the temperature of the hottest part can be much higher [8]. Nevertheless, this drawback can be compensated if the weak zone is split in \( n \) non-connected thinner parts [8] of length \( \ell_{\text{n}} = \ell_{\text{h}}(n)^{-1} \).

In figure 2 it is shown the recovery time as a function of \( n \) for a hypothetical ring with a weak zone split in \( n \) non-connected parts normalized to the recovery time of an homogeneous sample. As can be seen, the recovery time diminishes as the number of slices increases. Circles correspond
to $\lambda = 0.3$, $a = 0.9$ and triangles and squares to $\lambda = 0.2$, $a = 0.8$ and, respectively, $\lambda = 0.1$, $a = 0.8$. The heat which is generated in the weak parts is removed, not only by convection with the environment (supposed to be Helium gas), but also by conduction with the cold surrounding parts, and this occurs in a more effective way for thinner slices [8].

**Figure 1.** Current waveforms for a hypothetical homogeneous sample and when different weak zones are made.

**Figure 2.** Recovery time with an artificially created weak zone split in slices, normalized to the value for the hypothetical homogeneous sample.

### 4.2. Competition between natural and artificial weak zones

In figure 3 it is displayed the temperature distribution along the circular perimeter of a superconducting ring under a current fault and after its clearing. Measurements were done at the points indicated in the drawing (inset). The voltage drops measured around each one of these points are displayed in figure 4. Both temperature and voltage measurements shown the inhomogeneous quench of our samples, previously reported in other works [7, 8]. Only a part of the ring (the zone $ef$) really contributes to the current limitation, which provokes that the temperature of this natural weak zone (NWZ) increases much more than that of the remainder parts.

In figure 5 it is displayed the temperature distribution under the same current fault, but once the wall of the ring was narrowed along the $z$ axis in the zone $ha$, far away from $ef$. This artificial weak zone (AWZ) has a length $\ell_h = 0.02 \times \ell_{\text{total}}$ and a depth of 0.5 mm (i.e. represents a 20% reduction of the wall section). As can be seen, now the highest temperature is reached at the AWZ, indicating that is the zone which effectively limits the current as it is also observed in the voltage measurements in the different zones. Although the maximum temperature reached in the ring was not lowered in this case, our results suggest a possibility of overcoming the drawbacks derived from the unpredictable behaviour of the weak zones by making artificial weak zones with the adequate size and distribution.

### 5. Conclusions

It has been presented experimental and simulation results on the behaviour of a SFCL whose secondary has artificially created weak zones. It has been found that the presence of artificial weak zones, made by reducing the cross section of a superconducting ring at some points, would allow a faster cooling and so a shorter recovery time. In addition, it has been observed that
Figure 3. Temperature curves as recorded by several thermocouples attached on the sample’s surface.

Figure 4. Voltage measurements realized in different parts of the ring.

Figure 5. Temperature evolution once a reduction in the sample’s wall section was made in the region ha.

these artificial weak zones could also allow to balance the influence of a natural defect already present in the ring.

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