New Mechanism for Fast Quench Propagation in Coated Conductors

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Abstract. We address the use of coated conductors for resistive fault current limiters. Fast quench propagation is required to let the conductor switch on the full length within milliseconds. But the ordinary quench propagation mechanism is too slow because of the small heat diffusivity in typical materials of substrate tapes. Here we present a new mechanism which is not based on heat diffusion. Rather, we have chosen a conductor geometry such that any quench leads to a distortion of the current flow pattern and therefore to current bunching. Thereby the critical current density is locally exceeded and the superconductor turns normal without the necessity of heating. In this way the resistive state is quickly spreading until the current flows mainly through the substrate from end to end. Thus, the conductor develops its full normal resistance and is homogenously warming further up. The mechanism was confirmed by a numerical simulation and by experiments on samples of short and medium length. In general, coated conductors can be made self-protecting by the new mechanism, so that the use of thick normal conducting stabilizers is no longer necessary.

1. Introduction

YBCO coated conductors are presently being introduced in the market. In the superconducting state these conductors can carry hundreds of Amperes, and in the normal state they have a high resistance. So they appear to be ideally suited as low cost resistive fault current limiters.

But a fault current limiter must be able, once that the first quench has occurred, to switch into the normal state on its full length within milliseconds. This means that the initial quench must propagate very fast along the conductor. But quench propagation usually relies on thermal conductivity. The heat generated by a quench warms up the neighbouring superconductor and makes it quenching too. While this process works well in sapphire substrates with their high thermal diffusivity it cannot possibly work in typical substrate tapes used for coated conductors because their thermal diffusivity is more than 3 orders of magnitude lower. Therefore the quench remains localized, the total resistance remains small, the current is not limited, and the hot spot eventually burns out.

One possibility to protect the tape against burnout is using a thick normal conducting shunt layer as stabilizer. Then the quench is simply bypassed by a low resistance and cannot heat up appreciably. But such a conductor is no longer effective as a fault current limiter, because the normal state resistance is greatly reduced. And although the copper provides more heat conduction, quenches propagate only slowly because of the low heat generation. So the conductor remains mostly in the superconducting state, and the overall resistance is by far too low.
It was also suggested to use the substrate alone as a stabilizer by establishing a flat contact between the superconductor and the substrate which is distributed over the full area.[3] Such a contact actually prevents the quench propagation method we are suggesting here, and the shunting effect is less than that of the copper stabilizer, due to the higher substrate resistance.

We have found a new mechanism of quench propagation which is not based on heat diffusion and works therefore well for coated conductors.[4] In fact, we observe the coated conductors switching on their full length into the normal state within a few milliseconds, both theoretically and experimentally.

2. Principle of operation
It is always necessary to connect the superconductor in some way with the substrate. Otherwise large voltage drops can build up during switching when the superconductor is only partially in the normal state. But it is not necessary to make the contact continuous along the length of the tape. Rather, it is useful to provide separated contact points of only limited size. The principle is illustrated in figure 1:

![Figure 1. Substrate and film are separately drawn. At the sides they are connected by periodic contact points. In case of a quench, the current is diverted into the substrate. Current bunching occurs near contact points 2 and 3.](image)

In normal operation the current is totally carried by the superconductor. But when overcurrent arises, the superconductor will turn resistive at some weakest spot. Suppose this occurs between contacts 2 and 3 in figure 1. Then the resulting voltage drop will divert part of the current into the corresponding substrate segment. Thereby the current must pass through the small contact points which cause the current lines to bunch up so that the critical current density $j_c$ is surpassed. So two new quenching regions are formed around the contacts 2 and 3.

The new quenches develop resistance of their own, so that currents also start flowing through the second nearest contacts 1 and 4. At the same time the current flow along the superconductor is constricted by the regions 2 and 3, so that the quenches spread across the film. So the total resistance of the superconductor increases, and still more of the total current is dumped into the contacts 1 and 4. This way the initial quench is jumping from contact to contact in both forward and backward directions until the full length is in the normal state and the current is mostly flowing in the substrate.

Obviously this mechanism does not require heat conduction. Therefore it provides fast quench propagation even if the thermal diffusivity of the substrate is low. Of course, heat is generated during the process and must therefore be taken into account in a quantitative model.

3. Numerical Simulation
To get a better theoretical insight into the new mechanism we set up a numerical simulation. In principle, one has to calculate the current distribution for a given external circuit and for a given distribution of material properties in the sample at a fixed point in time. From the current distribution one finds the generated heat. The heat diffusion into the substrate and into the liquid nitrogen then determines the temperature distribution in the sample. The latter determines a new distribution of material properties from which the current distribution is newly calculated. This process is repeated many times so that the simulation reaches a quasi stationary state. Then the next point in time is chosen where the external circuit has changed due to an ac voltage or an inductance.

For the current-voltage characteristic of the superconductor we used the familiar power law $E = A j^n$ where $j$ is the current density and $E$ is the electric field strength. The coefficients $A$ and $n$ were fitted to
measured data on our films in function of temperature. The power law was cut off at normal state resistance.

Since the superconducting film is very thin in comparison with its lateral dimensions, it is sufficient to assume a 2d current flow parallel to the film surface. Although the substrate is less thin, around 0.1 mm, it has a homogenous resistivity and can therefore be also treated in 2d. Because the film and the substrate are electrically insulated from each other by the buffer layer, one can imagine them being placed side by side in the same 2d plane, as shown in figure 1.

The current distribution in the sample was then calculated on a 2d quadratic net. The task was greatly simplified by using a pseudo scalar potential $W(x,y)$ so that $j_x = \partial_y W$ and $j_y = -\partial_x W$. This guarantees automatically source-free flow (Kirchhoff’s junction rule). The calculation is then left with minimizing curl $E$ (Kirchhoff’s loop rule) by iteration.

For the heat diffusion the substrate must be treated in 3d because large temperature gradients can occur. We have used temperature dependent thermal conductivity and heat capacity data. A thermal resistance representig the MgO buffer layer is introduced between the film and the substrate. All surfaces are coupled to liquid N$_2$ using heat flow data from the literature[5].

Figure 2 shows results of the simulation for a sample 500 mm long and 10 mm wide with a ±15% statistical variation of $j_c$. The switching behaviour as a function of time is shown for a sample with contact points 9 mm apart (left) and for comparison for a sample without contact points (right). Note that the maximum temperature stays below 280 K with contacts but shoots up to 570 K without contacts. So the sample without contacts would have been destroyed in reality.

![Figure 2](image.png)

**Figure 2.** Calculated time variations of current, voltage, resistance, and maximum temperature; the latter represents always the hottest spot on the sample; left: conductor with contact points, right: without contacts. Note the different behaviour of the maximum temperature.

The corresponding current patterns for the sample with contact points is shown in figure 3 for various points in time. It is nicely seen that the quench propagates continuously inspite of the assumed inhomogeneity in $j_c$ of ±15%. The quench even propagates with ±50% variation.

![Figure 3](image.png)

**Figure 3.** Calculated current line diagrams of the sample of figure 2 with contact points, for various points in time; each diagram shows the substrate and film separated as in figure 1; from top to bottom: 2 ms, 2.5 ms, 3 ms, 3.5 ms, 4 ms, and 15 ms.
For the right sample in figure 2 the current lines are not so interesting because they are always straight from end to end of the sample. Therefore we better show the calculated temperature distribution of the superconductor in this case. We take the point in time of 3.6 ms, when the hot spot is at 560 K, see Fig. 4.

**Figure 4.** Calculated temperature distribution of the film surface of the sample without contact points at the time of 3.6 ms; the two strips show the same distribution on different scales; the upper ranges from blue = 77 K to red = 127 K, the lower from 77 K to 577 K. Only the narrow hot spot has a high temperature (560 K).

It is obvious that the hot spot has remained fully localized. In the rest of the sample the temperature has risen only slightly (we find 86 K in the calculation), which can be seen in the upper strip which ranges from 77K to 127 K. This comes from a small current in the substrate which flows from end to end because of the finite resistance of the hot spot.

### 4. Experiments

We first made photographs on short samples of coated conductors to visualize the quenching regions by bubbles forming in liquid nitrogen. We used a high speed camera and grazing illumination. Obviously the quenches form at the contacts first and then propagate across the sample, see figure 5.

**Figure 5.** Photographs of a short sample at two different times marking quenches by N₂ gas bubbles (dark regions). The arrows highlight quenches emerging from the contacts and across the sample.

More recently we made experiments on medium size samples using a high power facility at Forschungszentrum Karlsruhe.[6] With a sample 420 mm long and 10 mm wide we were able to limit a prospective current of 8000 A down to 270 A with a voltage drop of 112 V for 60 ms (2.7V/cm). Switching was observed on the full length as seen by bubble formation and from the total resistance. This is an impressive confirmation that the new mechanism is working properly.

### 5. Conclusion

We have found a promising new way of stabilizing coated conductors, not by thick shunting layers, but by quench propagation, so that the conductor develops resistance and protects itself. The principle is ideally suited for an application as resistive fault current limiter. We have tested coated conductors (made by THEVA) with up to 50 cm in length. They were switching on the full length, and we believe the same will hold for any longer tapes. The power levels are much higher than for ceramic conductors. So real devices will be much more compact using coated conductors.

### References

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