Optical investigation of the quenching of coated conductors

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Abstract. The superconducting fault current limiter (FCL) offers great opportunities to improve the security and the power quality for electric networks, two real demands today. This innovative device is based on the quench of a superconductor when its critical value is overstepped. The quench initiation and propagation are of prime importance for a safe operation. The hot spot problem with local high temperature excursions must be avoided. The visualization of the quench and its propagation can be observed at the beginning by filming the bubbles produced in the liquid nitrogen by local dissipations. We study YBaCuO coated conductors, which show great promises for superconducting FCL. A special cryostat has been used with windows in order to film the bubble generations. The nitrogen bath temperature may be adjusted by heating/pressurising the bath. We have indeed shown previously that the quench is much more « homogeneous » when the temperature goes closer to the critical one. This is confirmed by the optical measurements: the bubble generation is completely different when the temperature increases. Other parameters play an important part such as the tape itself (AMSC and IGC tapes show different behaviours) and the applied voltage or current (nature of the power source). In some conditions, the quench is initiated in bands across the tape and these bands are regularly distributed along the tape. The distance between the bands depends on the voltage inter alias. The experience and the different observations are presented. The tape nature and different parameters (temperature, voltage, …) will be investigated. These works complete the magneto optical investigations carried out also in Grenoble

1. Introduction
The electricity networks play a key role in our societies. There are a critical infrastructure and their security is then of prime importance. The voltage quality (no amplitude variation) is another relevant point. A Fault Current Limiter (FCL) could improve both the security and the power quality through a higher interconnection of the grids that FCLs make possible. However no very satisfying FCL still exist for high voltage networks. High Temperature Superconductor (HTS) are extremely attractive materials for a FCL. The first pre-commercial SC FCL is under installation in Lancashire (UK) [1]. It is based on bulk BSCCO materials. YBCO Coated Conductor (CC) shows still better performances in terms of AC losses among other things whereas their cost should be much lower.

The electricity networks experience large changes and in the future we will talk about “smart grids” where FCLs will play a key part. In the future smart grid architecture, DC links are a very interesting option above all with a FCL which brakes the bold of the absence of zero crossing for the DC fault current. DC currents perfectly suit to superconductors since they fully take advantage of superconductivity: the total absence of losses. AC currents lead to AC losses.
The possibilities of the SC FCLs explain the numerous researches and developments throughout the world [2, 3, 4, 5, 6]. Most of the SC FCL are based on the quench of a SC element. The quench initiation is of highest importance. The quench must be as homogeneous as possible along the total SC element. If only a part remains a long time in the normal state, excessive local heating and possible degradation may occur. Furthermore the SC material is not optimally used.

Quench initiations may be observed through the bubbles created by the dissipative zones in the cooling fluid [7]. We have mounted an experimental bench for these optical visualizations. We have changed the experimental conditions (temperature and voltage) for two types of YBCO CC and correlated the observations with electrical measurements. These make possible some thermal useful calculations [8].

2. Experimental set-up

2.1. Optical measurements

The temperature has emerged as an important parameter for the quench homogeneity. When the temperature approaches the critical value, the homogeneity is improved [9]. To vary the temperature, we pressurize the nitrogen bath. A heater at the bottom of the bath accelerates its thermal balancing. We use a metallic cryostat with lateral windows to see the bubbles. The lighting is especially important because we use a fast camera with then short exposure times. Since external lighting induces reflections in the window we opted for a lighting inside the bath. The light comes from two LEDs through fiber optic patch cables to greatly reduce any parasite bubbles (LED dissipate up to 30 W each). The LEDs are above the nitrogen bath.

We have used a digital high speed camera MOTIONeer from AOS Technologies®. With a reduced resolution of 1280 x 512 pixel (black and white), the speed was 1000 fps (frame per second).

2.2. Electrical measurements

The electrical data (current and voltage) are two relevant parameters. They make possible to characterize the quench homogeneity. The division the voltage by the distance between the voltage taps gives the mean electric field between these taps. The comparison of mean electric fields along the SC elements shows its homogeneity.

It is also possible to characterize the homogeneity between two voltage taps by calculating the maximum and the mean temperatures. Subsequently adiabatic conditions will be assumed. It is not fully right but it does not change the conclusions for homogeneity. Likewise the temperature is considered as the same across the conductor.

The maximum temperature ($T_{\text{max}}$) is the hot spot temperature and requires only the current $i(t)$, the same along the superconductor.

\[
\int_0^L i(x)^2 \, dx = A_{\text{cond}} \left[ \int_{T_c}^{T_{\text{max}}} \frac{c_p^m(\theta)}{R_i(\theta)} \, d\theta + \int_{T_{\text{max}}}^{T_c} \frac{c_p^m(\theta)}{R_i(\theta)} \, d\theta \right]
\]

with: $c_p^m(T) = \frac{1}{A_{\text{cond}}} \sum_{\text{Materials}} c_p^\text{layer}(T) A_{\text{mat}}$

$c_p^\text{layer}$ and $A_{\text{mat}}$ are the specific heat per unit volume and cross section of the different materials of the conductor. $R_i$ is the resistance per unit length of the conductor. If this parameter is well know above $T_c$ (it can be easily measured and only depends on temperature), its value under $T_c$ remains problematic so the split into two integrals. The final temperature is most of the time much higher compared to $T_c$ and the first integral is not taken into account for the maximum temperature calculation. Another possibility is to start the calculation of the square of the current only when the critical temperature has been reached. This time is obtained by observing the electric field versus current. Highly non linear under $T_c$, the non linearity decreases at $T_c$.
\[ T < T_c \quad E = E_i \left( \frac{J}{J_c(T)} \right)^{n(T)} \quad ; \quad T > T_c \quad E = \rho(T) J \] (2)

The quench must be however homogeneous (same electric field along the superconductor) to extract this time.

The mean temperature calculation is based on the energy dissipated.

\[ \int_0^{T_{\text{mean}}} v(t(x)) \, dx = \ell \frac{S_{\text{tot}}}{T_s} \int_{\theta_s}^{\theta} c_p(\theta) \, d\theta \] (3)

\( v(t) \) is the voltage between two voltage taps (distance: \( \ell \)) and \( i(t) \) the current.

This calculation assumes that the total length experiences the same dissipation. If only a part of the length quenches, its temperature is much higher compared to the mean value.

The comparison between \( T_{\text{max}} \) and \( T_{\text{mean}} \) give information about the homogeneity: if they are close the quench may be considered as homogeneous. Otherwise \( T_{\text{max}} \) is higher compared to \( T_{\text{mean}} \).

We have shown that these temperatures are very well correlated to measured temperatures using micro-sensors directly deposited on the CC [7].

Most of the experiments were carried out using AC conditions since the current amplitude may be very high especially at 77 K.

3. Results

3.1. Samples

Two types of YBCO CC have been used (table). The conductor is wound on a fiber glass mandrel (diameter: 130 mm). Several voltage taps are positioned along the conductor.

| Table : Parameters of the studied coated conductors. |
|-----------------|-----------------|
| **Type**        | **Super Power [10]** | **AMSC [11]** |
| Width           | 12 mm            | 4.1 – 4.3 mm |
| Substrate       | Hastelloy (100 \( \mu \)m x 12 mm) | NiW (75 \( \mu \)m x 4 mm) |
| SC              | YBaCuO (2.7 \( \mu \)m x 12 mm) | YBaCuO (1 \( \mu \)m x 4 mm) |
| Buffer layers   | MgO              | Y_2O_3, YSZ, CeO_2 |
| Shunt           | Ag (2.5 \( \mu \)m x 12 mm) | Ag (3+4 \( \mu \)m x 4 mm) |
| Lamination      | No               | Stainless steel |
| Solder          | No               | Mixture (Sn, Pb, Ag) (3 \( \mu \)m x 2 x 4.2 mm) |
| \( I_c \) (77 K, 100 \( \mu \)V/m) | 350 A            | 85 A          |
| \( I_c \) (77 K, 100 \( \mu \)V/m) | 292 A/cm-w       | 202 A/cm-w   |
| Sample length   | 1 m              | 10 m          |
| \( R_c \) (77 K) | 0.12 \( \Omega \)/m | 0.097 \( \Omega \)/m |

The resistance per unit length of both CC are close but the AMSC CC is 3 times narrower. That means that the AMS CC is much less resistive. This certainly plays an important part for the limiting behavior.

3.2. AMSC Sample

Figure 1 gives two pictures at different times after the short circuit at 77 K. They show an homogeneous distribution of bubbles along the conductor even for a low overstep of the critical current (about two times). The bubbles firstly appear at the edges of the conductor and then in the centre. On the figure the bubbles seem to appear only at the bottom edge but it is an optical effect due
to the contract with fiber glass support. The bubbles well appear symmetrically at both edges. The dissipation is higher at the periphery of the conductor due to the current distribution in the tape. On both sides there is solder to connect top and bottom stainless steel laminations. This solder has a low resistivity ($\rho_{\text{solder}}$) so that the dissipation is high in voltage source conditions ($e^2 / \rho$, where $e$ is the electric field).

The bubble distribution is similar to the one for a copper sample we tested.

These results are correlated to electrical measurements: the electric fields are close along the sample (figure 2) whereas the mean and maximum temperatures are comparable (figure 2). The current is inversed for a better reading. The maximum temperature was calculated once $T_c$ was reached. The voltage taps are regularly distributed along the sample (about 100 mm between). There are 9 electric fields and the total electric superposed on figure 2. The differences remain under about some percents. The electric fields are not very high in amplitude due to the relatively low resistance of the tape. But the current excursion above the critical one is high (factor 4 in figure 2). This is certainly favourable to homogenise the quench: no part may remain in the non dissipative state when it carries $4 I_c$.

At higher temperatures, the results are nearly the same. The bubbles are different due to the higher pressure.

![Figure 1. Bubbles picture at two times for AMSC YBCO CC at 77 K ($V_{\text{rms}} = 150$ A; $i_{\text{max}} I_c = 4$).](image)

![Figure 2. Electric fields along the sample (7 parts) and current for AMSC YBCO CC at 77 K ($I_c = 85$ A), calculated temperatures (150 $V_{\text{rms}}$).](image)

A very important result is that the quench remains homogeneous even under low voltages. Figure 3 shows that the different electric fields are very close for such conditions. The dissipation is limited so that the temperature increase is low and remains under $T_c$, explaining the very non linear E(i) behavior. The calculated mean temperature is 95 K at the end but it is no more possible to neglect the thermal exchanges with the bath. The electric fields become surprisingly slightly more different at the
end. It may be explained by the high non-linearity close to \( T_c \); a very little temperature difference leads to large differences in terms of electric fields.

![Figure 3. Electric fields along the sample (7 parts) and current for AMSC YBCO CC at 77 K (\( I_c = 85 \, \text{A} ; U = 55 \, \text{V}_{\text{rms}} \)).](image1)

3.3. SuperPower Sample

The bubble behavior at 77 K (figure 4) is rather different when compared to the previous sample. The bubbles form several bands across the sample and these bands are slowly expending with time. The propagation is thermal. The distances between the bands may be sufficiently low that the total conductor quenches even if the propagation (thermal) is slow. The number of bands depends on the voltage amplitude (figure 5) or the current excursion above the critical current. The current excursion above the critical one is certainly more the relevant parameter for the superconductor compared to the voltage. It would be interesting to have the \( I_c \) distribution to see if there is a correlation between the bands and the lowest \( I_c \) values.

![Figure 4. Bubbles pictures at 3 times for SuperPower YBCO CC at 77 K (\( U_{\text{rms}} = 16 \, \text{V} ; \frac{i_{\text{max}}}{I_c} = 2.3 \)).](image2)

![Figure 5. Bubbles picture versus short-circuit voltage for SuperPower YBCO CC at 77 K.](image3)

This non-homogeneous behavior is correlated by electrical measurements (figure 6): the electric fields vary along the sample and the maximum temperature is higher compared to the mean one. As
for the AMSC sample, the voltage taps are regularly distributed along the sample, but with a distance of about 10 mm between. Figure 6 shows 4 electric fields (markers) and the total mean electric field (continuous line). The difference between the electric field amplitudes may reach a factor 3.

![Figure 6. Electric fields and current for SuperPower YBCO CC at 77 K (I_c = 350 A), calculated temperatures (U_{RMS} = 16 V).](image1)

Under a higher voltage, when the current excursion is higher (2.6), the homogeneity is very well improved (figure 7). The different electric fields are close as the maximum and mean temperatures.

The current excursion above I_c certainly explains the different behaviors. It is much lower for the SuperPower conductor compared to the AMSC one especially at low voltages (2.3 (figure 6) compared to 4 (figure 2)). The maximum limitation current may be roughly expressed by:

\[
I_{\text{max}} = k I_c + \frac{V_{\text{max}}}{R_n}
\]  

(4)

Where the coefficient k is about 2 and \( R_n \) is the resistance of the SC element at \( T_c \).

Due to the high resistance of the SuperPower CC, the current excursion above I_c is lower and the initial current limitation is sharper (it will clear on figure 7 compared to figure 2). This leads to transient higher electric fields (no real transient on figure 2 compared to figure 7). A higher limitation current may be favourable for homogeneity since it forces the entire superconductor to quench.

![Figure 7. Electric fields and current for SuperPower YBCO CC at 77 K (I_c = 350 A), calculated temperatures (U_{RMS} = 32 V).](image2)

The FCL behavior under different voltages is very important. The voltage across the FCL under limitation may indeed vary: maximum for a dead short-circuit, it decreases for impedant short-circuits,
which are the most common. When the fault impedance is high enough, the source is no more a voltage source but a current source. The test of the FCL under lower voltages compared to the rated must be carried out. The risk of damage paradoxically increases when the voltage is lower.

At 84 K, the bubble bands disappear (figure 8) and the behavior is close to the AMSC conductor. The electric field and temperature differences decrease a lot.

Several explanations may be put forward to explain the better behaviour when the temperature increases. The coherence length characterizes the size for a defect to be effective against the current transport. Since the coherence length increases when the temperature goes closer to $T_c$, small defects are no more effective and “large” defects are more homogeneously distributed along the conductor. When the temperature increases, the critical current decreases and the current excursion above the critical current is higher since a fraction is given by the CC resistance.

Figure 8. Bubbles picture at two times for SuperPower YBCO CC at 84 K ($U_{\text{rms}} = 16 \text{ V}$).

This behaviour has been confirmed by Magneto-Optical (MO) imaging [12]. This investigation method gives the local magnetic flux density distribution. With some assumptions it is possible to extract the local current. MO images for currents over $I_c$ show heterogeneities along the sample.

4. Conclusions
The visualization of the bubbles at the beginning of a quench gives very useful informations about the quench starting and deepens our understanding. Phenomena may be rather different in function of the operating temperature and the CC itself. There are good correlations between the visualizations and the conclusions we can draw from electric quantities (current and voltage) about homogeneity. Correlations with local current densities would be interesting, but it leads to a low electric field under limitation.

The regime with a low prospective fault current (impedant fault) is a very severe regime for the superconductor. The current excursion above the critical current is a key parameter for homogeneity. An important overstepping of the critical current forces the entire superconductor to be in the dissipative state and homogeneize the quench. A rather low normal state resistance for the CC is certainly favourable in this view point.

Optical visualization should be also an interesting tool for the recovery of the superconducting state in order to reduce the recovery time. It is very important for some FCL locations in the network.

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