

Characterization of the Superconducting to Normal Transition of HTS Coated Conductors by Fast Pulsed Current Measurements

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Abstract—In this paper, we present measurements of the superconducting to normal transition (extended $V - I$ curves) of commercial coated conductors with and without stabilizing copper layer. These measurements were realized with a custom developed pulsed current measurement (PCM) system. Currents between 5 to 10 times the critical current of commercial wires (up to 1000 A) can be applied for a period as short as 50-80 μ s, limiting the energy released in the sample to a fraction of a Joule. For such short pulses, the temperature rise in the sample is relatively small, which allows characterizing the electrical resistivity of high temperature superconductors (HTS) at high current densities and electric fields. The data obtained will be used to develop more accurate models of HTS in the over-critical current regime, which is major issue for allowing the development of quality simulation tools for optimizing the design of superconducting fault current limiters. The PCM technique is also a very powerful tool for investigating the transient thermal behavior of coated conductors, whose better understanding is required in order to devise reliable fault current limiters based on this technology. So far, the measurements have been restricted to 77K and self-field, but further works will extend the range of measurements to higher fields and temperatures.

Index Terms—Fault current limiters, high-temperature superconductors, thermal factors, pulse measurements, thin films.

I. INTRODUCTION

THE pulsed current measurement technique (PCM) has been used for a long time for characterizing superconductors at current densities near or above their critical current (I_c), in order to minimize heating effects. Such measurements are of prime importance when considering the optimization of applications such as superconducting fault current limiters, whose principle of operation is based on the superconducting to normal transition of the superconductor.

In order to generate current pulses of sufficient amplitude for testing full-size HTS samples (typically many hundred amperes), various approaches are possible. The simplest one consists in applying a half-sine voltage wave in series with a current limiting resistor and the HTS sample, which allows applying large currents (easily up to 15 kA). The pulse duration in this case is in the range of a few milliseconds [1], [2]. A similar approach for measurements in the same

experimental range is to generate a transient electrical impulse, typically by discharging a capacitor into a RLC circuit that includes the sample under test [3], [4]. Some authors have also combined pulsed currents and pulsed external fields in the same measurement event [5], [6]. However, the major drawback of the above techniques is the high induced voltage in the voltage measurement circuit, which has to be subtracted from the useful signal in order to obtain meaningful $V - I$ curves. The classical approach for isolating this inductive contribution is to use an extra, contactless voltage loop in the measurement circuit, as explained in [3], [4]. In order to simplify this correction scheme, it is also possible to use a linearly ramping current source, in which case the induced voltage becomes approximately constant [7], [8], and the $V - I$ curve can be traced in a single acquisition run, although in a limited range of electric field (the duration of such a measurement is relatively long, i.e. much above tens of milliseconds).

A further improvement is the application of constant current pulses (square pulses that are very well regulated in the plateau region), which eliminates most induced voltage issues. Indeed, once the current has stabilized, the voltage measured is a direct image of the resistive voltage drop in the sample. This is easy to achieve in slow systems (1 ms and above), for currents between 100 A and 10 kA, [9]–[16], but becomes quite challenging in the microseconds range. As far as the authors know, no commercial systems can be found for this purpose, even in the field of semiconductors, where currents used in characterization rarely exceed 5 – 10 A.

A few authors have devised their own lab apparatus to perform constant pulsed current measurements. For instance, Decroux et al. have devised a pulsed current generator, able to drive a relatively constant 30 A during $\approx 15 \mu$ s [17]. At another scale, Kunchur mentioned that he built a similar system for currents up to 500 A for testing bulk HTS samples, although he does not present any experimental results obtained with this system [18]. The interested reader may consult some of the following references for details about how to build a constant pulsed current generator [7], [8], [18]–[20].

In this paper, we present a novel design of PCM system that allows to generate constant current pulses up to ≈ 1000 A, and for duration as short as 50-80 μ s, thus pushing further the limits of previous systems (in term of applied current). The motivation of this design is to characterize commercial HTS materials at very high current densities, with no need for sample preparation such as cutting/etching operations for

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reducing the cross-section. This approach makes sure the sample is unaltered prior to being characterized.

The small amount of energy injected in the HTS material during the pulses reported here (typically below 25 mJ) allowed us to reach very high values of electric fields without destroying the sample. For instance, in the experiment reported here, up to 3 V/cm was safely reached on commercial coated conductors *without* stabilizing layer, corresponding to a dissipation level of 1800 W/cm² (sample in liquid nitrogen and self-field). This is more than 80 times the level of dissipation this material can normally withstand in steady-state. The sample voltage waveforms were also recorded for further analysis, as they contain very important information about the thermal dynamics of the sample.

The system developed is a promising tool for investigating the performances of HTS materials for application in superconducting fault current limiters, as well as for developing better HTS models for finite-element-type numerical analysis packages. The latter approach is particularly important in order to achieve a better understanding of the heat transfer phenomena occurring in coated conductors in the over-critical current regime.

II. EXPERIMENTAL SETUP

A. Pulse current measurement system (PCM)

The PCM system presented in this paper applies short current pulses of moderate to high amplitudes (100 – 1000 A) to HTS samples mounted in a standard four points measurement configuration, as shown in Fig. 1. The current is generated by the controlled discharge of a large bank of capacitors (C), while the voltage between sample taps is acquired using a custom measurement circuit (discussed in the next section) and a digital oscilloscope. The duration and amplitude of the test current (I_{test}) are controlled by one or several parallel Current Generation Modules (CGM) driven by a low-power, pulsatile voltage source (V_{pulse}). Each module can generate a current I_{test} ranging from 25 to 340 A, so up to three modules have been used simultaneously for the purpose of the experiments reported in this paper, where currents up to 1000 A have been applied.

The procedure for each current pulse and associated data acquisition is as follows:

- 1) switch S is closed and capacitor C is charged to V_{DC} , typically close to 100 V;
- 2) switch S is opened to prevent noise induced by V_{DC} , a switching power supply, from adversely affecting the results;
- 3) a short pulse is applied at the input of the CGM(s). The test current is then regulated by amplifier U_1 and power MOSFET M_1 to a value defined by the sensing resistor R_{sense} and the resistive feedback network made of R_1 and R_2 such that

$$I_{test} = \frac{V_{pulse} \left(1 + R_2/R_1\right)}{R_{sense}}. \quad (1)$$

- 4) during the pulse, data from the sample and CGM(s) are acquired by a fast digital oscilloscope;

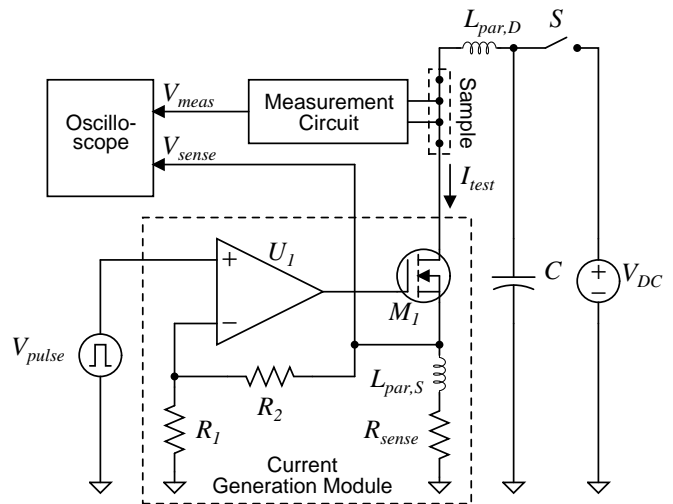


Fig. 1. Simplified schematic of the PCM system including custom circuits for current regulation and measurement, as well as few external components, namely power supplies, signal generator and a digital oscilloscope.

- 5) for experiments where the dynamic response is not regarded (e.g. $E - I$ curves), data acquired over a period of several microseconds are averaged (in post-processing) in order to enhance the signal-to-noise ratio.

Employing short pulses enables the PCM system to use currents significantly higher than the rated maximum for all electronic components in the high current path. However, the duration of the pulses can only be reduced to a certain extent, limited by the time required for the regulating circuit to stabilize (currently 20-80 μ s). Indeed, despite the use of a fast amplifier (U_1) to drive the large capacitive load M_1 (gate of power MOSFET), oscillations arise due to the presence of parasitic inductances $L_{par,S}$ and $L_{par,D}$, and a few tens of microseconds are required for these oscillations to die out.

B. Voltage measurement circuit

1) *Gain and common mode rejection:* The primary purpose of the voltage measurement circuit is to shift the small differential signal measured between the voltage taps of the sample to a level that is appropriate for acquisition by the oscilloscope, referenced to the ground. Basically, a simple difference amplifier could be used to reject the common mode voltage. However, due to the capacitor discharge during the PCM and to voltage drop across the current contact resistance, a common mode voltage variation of a few to several volts may occur during the pulses. As a result, the output of a non-ideal amplifier showing common mode rejection of 60-80 dB would include an undesirable component with a magnitude in the range of or above 1 mV. This is unacceptable for measurements where the sample is in the superconducting state, in which differential signals are of the same order of magnitude or even less. For this reason, a floating preamplifier with a gain and output range sufficient for making the contribution of common mode variations negligible is used when measuring small signals, as seen in Fig. 2. For input signals saturating the preamplifier output, the circuit configuration is changed such

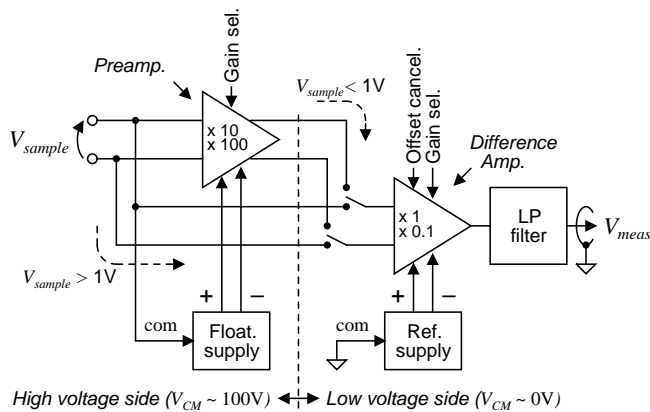


Fig. 2. Simplified schematic of the voltage measurement circuit used to shift the input to a ground referenced signal, highlighting the two separate signal paths used for inputs below and above a ~ 1 V threshold.

that the measured voltage is directly applied to the difference amplifier input (see dashed arrows in Fig. 2). Note that, in this case, the differential signal is much larger than the common mode contribution to the output signal.

Both the preamplifier and the difference amplifier have selectable gains resulting in four different scales with combined gains of 100, 10, 1 and 0.1, allowing for inputs up to 100 V to be acquired on a 10 V scale on the oscilloscope. While realizing the measurements presented in this paper, voltages ranging from hundreds of microvolts to nearly 20 V have been successfully measured.

2) *Dynamic response and filtering*: Measuring the voltage at high pulsed currents is very different from making conventional DC $V - I$ measurements, in which it suffices to average the measured voltage over a given period of time. In the pulsed case, measurements must be performed very rapidly, as soon as the current has reached a stable value, in order to avoid damaging the sample. As dI/dt is non-zero during the settling time of the pulse (20-80 μ s), the voltage measurement contains a significant inductive component. This can be seen here as damped high frequency oscillations added to the pulse of interest, even if the voltage leads are well twisted together and brought in close proximity of the sample (see Fig. 3). A low-pass (LP) filter is used to reject this undesirable component, retaining only the lower frequency pulse. As a result, a stable response can be obtained for precise measurements much sooner than what would be possible by waiting for the oscillations to cease, enabling shorter pulses. This, however, is achieved at the expense of inducing a delay of a few microseconds in the response. While this has no significant impact at moderate currents, where the pulse response is essentially flat, care has to be taken when sample's resistivity changes during the pulse, due to heating effects. As seen in Fig. 3, an offset between the raw and filtered voltage waveforms is then present, potentially affecting the interpretation of the results, as discussed in Section IV.

C. System calibration and validation

Every pulse current event is preceded by a calibration phase where the difference amplifier is adjusted in order to cancel the

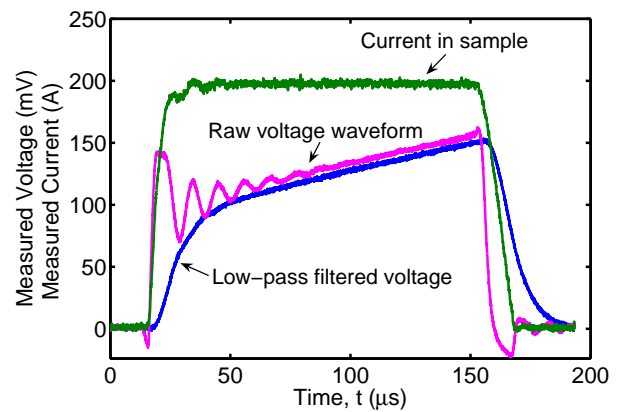


Fig. 3. Typical current and voltage signals measured across the voltage taps of the sample during a $\approx 150 \mu$ s pulse. The oscillating curve is the raw data, and the smooth curve is the filtered signal. As can be seen, small oscillations in current translates in large induced voltage across the sample's voltage taps. The filtering of the raw voltage can produce a delay between 0 and 20 μ s, based on authors current experience with this PCM system. The current was measured with a precision high current transformer from *Bergoz Instrumentation* (rise time < 100 ns).

DC common mode voltage at $I_{test} = 0$. The CGMs, however, do not require calibration prior to apply a pulse.

In order to validate the system, characterization of a reference copper wire was performed and its resistivity compared to the one previously measured using conventional $V - I$ DC measurements (DC current source + precision nanovoltmeter), at a reference temperature. Our confidence in the accuracy of the system was further increased by the good overlap of $E - I$ curves obtained for HTS samples at the high end of $V - I$ DC measurements and the low end of the PCM ones, slightly above I_c (see Section III-D).

The precision of the whole system is estimated to be well within 5% when properly calibrated. Further work will be undertaken to enhance and evaluate more precisely its performances.

III. MEASUREMENTS

A. Description of samples

The samples used for our first measurements were 4 mm wide, commercial coated conductors provided by SuperPower [21]. All samples were made on a 50 μ m hastelloy substrate, over which were deposited 1 μ m of YBCO and 2 μ m of silver. Three samples were considered, i.e.

- Sample 1: SCS4050 (40 μ m of copper stabilizer)
- Sample 2: SF4050 (no stabilizer)
- Sample 3: SF4050 (no stabilizer)

Note that the hastelloy substrate was in electrical contact with the other layers, as opposed to similar experiments performed at the University of Geneva [22]. The third sample, identical to the second one, has been used to complete the measurements after the blowing up of the second one due to an experimental error. The critical currents of the three samples were very similar, i.e. ≈ 94 A (1 μ V/cm criterion).

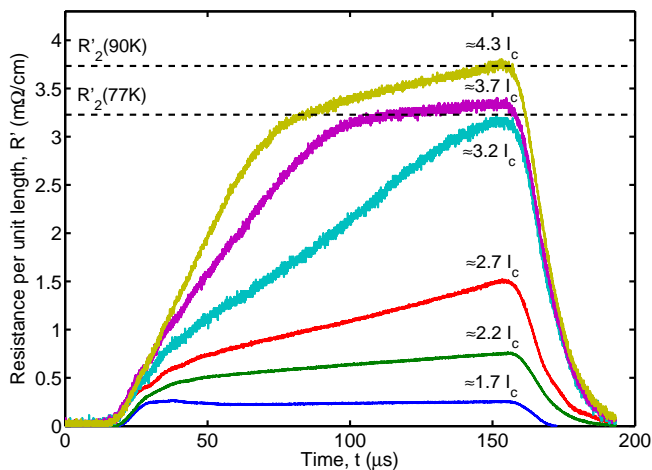


Fig. 4. Voltage recorded for sample 2 (no stabilizing layer, $I_c = 94$ A) for various amplitudes of current pulses ($\approx 135 \mu\text{s}$ each). Heating effects are clearly observed. The dotted lines represent the resistance per unit length of the metallic layers at 77K and 90K.

B. Resistance of samples in the non-superconducting state

The resistance of the metallic layers of the samples was characterized as a function of the temperature between 95K and 295K. Both curves were very well fit with a linear approximation. The fits obtained were: $R'_1(T) = 0.322 + 0.00424(T - 77) \text{ m}\Omega/\text{cm}$ (hastelloy/Ag/Cu) and $R'_{2,3}(T) = 3.229 + 0.0389(T - 77) \text{ m}\Omega/\text{cm}$ (hastelloy/Ag only). We clearly see that the sample with copper stabilizer (sample 1) has a resistivity that is one order of magnitude lower than the samples without stabilizer (samples 2 and 3). But the most important is the extrapolation of the resistance below T_c of YBCO ($\approx 90\text{K}$), which can be used for: 1) providing reference values for the $V - I$ measurements to be performed with the PCM system, and 2) estimating the temperature rise in the samples metallic layers during the PCMs.

C. Short pulses in the over-critical current regime

Pulses of $135 \mu\text{s}$ with current amplitudes ranging from $1.1I_c$ up to more than $10I_c$ were applied to all samples using the PCM system. Some data acquisitions for the voltage measurements on sample 2 (no stabilizer) are shown in Fig. 4. The results obtained agree well with similar experiments realized recently in other laboratories on similar coated conductors, e.g. see [22]–[24]. In particular, we clearly see the different thermal regimes induced by increasing the test current. Indeed, for $I \lesssim 1.7I_c$, heating effects are very weak, and the sample's voltage stabilizes at a steady-state value, with most of the current carried by the superconductor. For currents between $\approx 1.7I_c$ and $\approx 3.2I_c$, the voltage no longer stabilizes, but rather increases until the end of the pulse, indicating a rise in temperature. In this regime, there is a progressive current transfer from the HTS layer to the metallic layers. Finally, for current $I \gtrsim 3.2I_c$, we observe an abrupt change of slope in the $R'_2(t)$ curve, which is likely to correspond to a sudden increase of the YBCO resistivity (all current in the metallic layers, which have a higher heat capacity than YBCO, and therefore require more energy for the same increase in temperature).

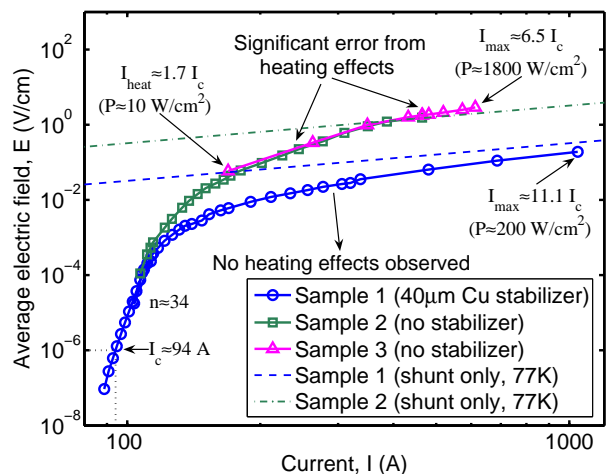


Fig. 5. $E - I$ curves for samples 1, 2 and 3, obtained with the PCM system. Heating effects are well visible for sample 2 and 3, where the electric field value goes beyond the resistance of the metallic layers (silver + hastelloy) at 77K.

D. E-I curves

The $E - I$ curves (electric field vs sample current) were plotted for all three samples considered in this experiment (see Fig. 5). However, for sample 1, values below 10^{-3} V/cm were obtained using a conventional DC $V - I$ measurement system, and were intended to 1) determine the critical current and the n value of the sample and 2) validate the accuracy of the PCM system by overlapping curves from both methods (between 10^{-4} and 10^{-3} V/cm). These measurements were also realized on samples 2 and 3, but were not plotted here to avoid overloading Fig. 5.

In the case of sample 1 (with copper stabilizer), pulse measurements did not show any heating effects up to 1000 A. That is, all voltage curves were similar to the one corresponding to $I = 1.7I_c$ shown in Fig. 4, with a well defined plateau region. Therefore, the $E - I$ curve obtained is accurate and does not need any correction. This is well supported by the fact that the $E - I$ curve of sample 1 is slightly lower than the $E - I$ curve of the metallic layers alone (dotted line, extrapolated at 77K), which means that the YBCO layer still contributes to the current sharing even at $I > 10I_c$, despite that the power dissipation measured is rather elevated (200 W/cm^2).

The $E - I$ curve of samples 2 and 3 (without stabilizer) presents much higher electric fields for the same applied current, as expected. No significant heating effects are observed up to $1.7I_c$, as expected from Fig. 4, but beyond that point, heating effects tends to shift up the $E - I$ curve. All E values plotted in Fig. 5 consists in a time average over $25 \mu\text{s}$ of the measured voltage at $t = 100 \mu\text{s}$. This is an arbitrary choice used here for convenience, but a more physical approach is discussed in next section.

IV. DISCUSSION

This section presents an open interpretation from the authors to explain the diverse thermal effects observed during the PCMs. It is intended to align the direction of future works

to be undertaken in order to improve the understanding of the complex underlying phenomena.

A. Heating effects during pulsed current measurements

The double slope characteristic observed in Fig. 4 when $I > 3.2I_c$ is puzzling. Intuitively, we would expect that, as the voltage/temperature increases, the HTS resistivity would vary relatively continuously from a very low value (well below the silver layer resistivity) to the normal state resistivity of YBCO (about 100 times that of silver). The fact that the slope varies abruptly over $\approx 10 - 15 \mu\text{s}$ suggest that the cross-over of both resistivities occurs very sharply. In addition, the “knee” on these curves seems to always correspond to the sheath’s resistance at 77K, which is surprising since at this temperature, YBCO should still be in a low resistivity state. However, this apparent threshold might be somewhat erroneous due to the artificial delay introduced by the low-pass filter used in the voltage measurement circuit.

Another possible phenomenon involved is the heat diffusion between the layers, which may introduce a delay between the quench of the superconductor (at $\approx 90\text{K}$) and the temperature rise observed in silver. However, this is unlikely since the diffusion of heat from $1 \mu\text{m}$ of YBCO to $2 \mu\text{m}$ of silver in very good electrical contact should be almost instantaneous, even on the scale of microseconds.

The above analysis is based on a simple current sharing model. Whether the current sharing is uniform along the sample’s length rather thermally propagated from localized hot spots is also to be investigated in more details. A priori, at such high current densities, it is likely that most of the sample’s volume finds itself in a highly dissipative flux flow state immediately at the beginning of the pulse, and therefore exhibit large (and relatively homogeneous) dissipation all along its length. This would support the simple picture of the current sharing model.

Finally, the reduced slope in the last part of the pulse for $I > 3.2I_c$ contains important information about the dynamics of the heat transfer inside coated conductors. From simple calculations, if the system were fully adiabatic, most energy released in the sample during the pulse would contribute to raise the temperature of the silver layer at a rate $dT_{Ag}/dt = 10^{-6} R_{Ag} I_{Ag}^2 / m_{Ag} C_{Ag} \text{ K}/\mu\text{s}$. Supposing that all current flows in the metallic layers (YBCO quenched), and that 80–90% of this current flows into the silver layer (the balance flowing into the substrate), we find for the case $I = 4.3I_c$ that $dT_{Ag}/dt \approx 2$ to $2.5 \text{ K}/\mu\text{s}$, whereas the experimental value appears to be only $dT_{Ag}/dt \approx 0.2 \text{ K}/\mu\text{s}$. In the above calculations, we used $R_{Ag} = \rho_{Ag} L_{Ag} / S_{Ag} = 3.75 \text{ m}\Omega$, with $\rho_{Ag} \approx 0.3 \mu\Omega\text{cm}$ (resistivity at $\approx 80\text{K}$), $L_{Ag} = 1 \text{ cm}$ (elementary length), $S_{Ag} = 2 \mu\text{m} \times 4 \text{ mm}$ (cross-section of silver layer), $I_c = 94 \text{ A/cm}^2$, $m_{Ag} = 10500 \text{ kg/m}^3 \times L_{Ag} S_{Ag} = 8.4 \times 10^{-7} \text{ kg}$ (mass of 1 cm of silver layer), and $C_{Ag} = 235 \text{ J/kgK}$ (specific heat of silver). The difference of one order of magnitude found above could be partly explained by the heat diffusion from the silver layer to the substrate, which has a high specific heat ($C_{hast} = 425 \text{ J/kgK}$), and can therefore absorb a significant amount of energy. However, as the hastelloy layer is not in

direct thermal contact with the silver layer (heat must diffuse through a low thermal conductivity path formed by the YBCO and buffer layers), it is likely that convective heat transfer in liquid nitrogen (in direct contact with the silver layer) also plays a role here, maybe more important than expected in previous works. Further experiments will be required in order to conclude.

B. Possible approach to correct thermal effects in $E-I$ curves

A simple approach that would allow correcting the error on voltage caused by heating of the sample would be to use the intersection of the rising slope with $t = t_0$, where t_0 is the beginning of the pulse. That way, the voltage obtained would be the one before heating starts. A similar compensation scheme was proposed by Kunchur many years ago [18].

This approach would be valid only for very short pulses, with limited temperature rise, such as the ones reported here, for which we can assume a first order series development of the resistivity around given J and B (constant during the pulse), i.e. $\rho(T - T_0) \approx \rho(T_0) + \alpha(T - T_0)$, where T_0 is the initial temperature of the sample (before the pulse), and α is a coefficient to be determined experimentally. This approach was not carried out further here, but will be investigated in future works.

V. CONCLUSION

This paper introduced a new and fast pulsed current measurement (PCM) system for the characterization of high temperature superconductors (HTS) at current densities well above J_c . This new PCM system generates regulated current pulses up to 1000 A, for durations as short as 50-80 μs , the limit being the stabilization time of the test current. Measurements realized with this new system on coated conductors provided by SuperPower were also presented. The results are in accordance with similar measurements realized in other laboratories, except that, for the first time, measurements could be performed directly on full size commercial samples. The system is intended to be used for developing better models of commercial HTS materials to be used in numerical analysis tools, as well as for improving the understanding of the thermal behavior of coated conductors and other heat sensitive materials submitted to over-critical current conditions. This knowledge is critical to achieve an efficient use of HTS materials in superconducting fault current limiters.

Further works will address, among others: 1) the optimization of the current regulating circuit to further reduce the length of the pulses; 2) the development of a temperature correction method for extracting $E-I$ curves at constant temperature; 3) the realization of further measurements (in liquid and gas environments) in order to improve our understanding of the thermal dynamics in coated conductors.

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