Characterization of electrical resistance of HTS coated conductors at high currents using ultra-fast regulated current pulses

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Abstract. This paper focuses on the experimental determination of the electrical resistance (R) of commercial high temperature superconductor (HTS) coated conductors (CC) at currents well above their critical current. The major novelty of this work relies in a unique experimental capability of applying constant current pulses in the sample (up to 1000 A) for durations as short as 15 microseconds, which allows controlling very precisely the amount of energy dissipated in the sample (Joule effect), as well as the resulting temperature rise. By varying finely the applied current and the duration of the pulses, we show that we can achieve a relatively accurate characterization of $R(I,T)$ simply from the measured dynamical $V - I$ characteristics of CCs. The resistance model so-obtained is very important as it is the most fundamental design parameter in many practical HTS applications, especially fault current limiters.

1. Introduction

The modeling of High Temperature Superconductors (HTS) above their critical current density (J_c) requires a good knowledge of their Voltage-Current ($V - I$) characteristics over a wide range of experimental conditions. Expressed in local form, one requires experimental data of their intrinsic $E(J, B, T)$ characteristics, where E is the electric field, J is the current density, B is the magnetic flux density, and T is the temperature. This kind of model is of prime importance in order to use numerical techniques such as the finite element method to design and optimize power applications involving HTS materials, especially superconducting fault current limiters.

The major challenge for obtaining such experimental data is that as soon as the transport current (I) in a HTS sample becomes higher than its macroscopic critical current (I_c), heating effects and thermal instabilities (either homogeneous or of the normal zone propagation type) occur and quickly destroy the sample if nothing is done to protect it. The classical way to overcome this problem and characterize the over-critical current regime (i.e. $I > I_c$) is to use a Pulsed Current Measurement (PCM) technique, for instance see [1]-[5]. A summary of previous works in this area is provided in [5], and therefore is not repeated here.

The most important thing to note from previous works is that they mostly addressed samples that were reduced in size prior to be measured (either by cutting or polishing them), in order to fit within the range of the available pulsed current system. With the possible exception of

[1], no system so far combined simultaneously high currents (hundred of amps) and rise times in the scale of microseconds.

In this paper, we present results of pulsed current measurements performed on off-the-shelves, commercial HTS CCs, with no prior sample preparation other than the setting-up the necessary current and voltage contacts. These results were obtained with a custom-built, high power PCM system, able to drive the full over-current conditions required to characterize the electrical resistance of full size samples. The source is capable of driving up to 1000 A, with a stabilization time of 3-10 μs followed by a very flat current plateau. As far as the authors know, this is the first implementation of a system combining such speed, power and accuracy, and therefore, the resistance measured on commercial CCs as a function of the applied current could be pushed to unprecedented limits.

2. Experimental setup
2.1. Sample mounting
The objective of this experiment is to acquire the time dependant voltage, $V(t)$, developed in HTS samples submitted to over-critical current pulses of constant amplitude, and extract their resistance $R(I)$, which is a strong function of the applied current, $I(t)$. In order to avoid artifacts related to voltage drop at current contacts, a conventional four-points measurement scheme was adopted. Details about sample mounting are provided in figure 1.

During the experiments, the samples were immersed in a liquid nitrogen bath kept at ambient pressure, so the initial temperature of the sample (at the beginning of each pulse) was roughly 77 K in all cases presented below.

2.2. Pulsed Current Measurement (PCM) system
The basic operation of the PCM system used in this experiment is similar to the one already described in [5], where several Current Generation Modules (CGMs) are used in parallel to control the discharge of a large capacitor bank through the HTS sample. However, in addition to several low-level refinements enhancing the performance of the system, significant modifications have been implemented in the most recent version, illustrated schematically in figure 2.

Regarding current generation, each CGM operates independently and generates its own control signals using a slave Micro-Controller Unit (MCU) commanded by a unique master MCU. Calibration data specific to each CGM can be used to optimize the precision and dynamic performance of the system. Also, the system can be completely interfaced through a personal computer (P/C) and highly automated, greatly reducing the risk of user errors prone to destroying the samples.

Also, a dynamic time-varying feedback control circuit enables the system to operate in one of two modes, providing a pulse with either a fast or smooth rising edge. In the latter, the current rate of change decays gradually until the target current is attained. The fast mode provides a high and relatively constant rise until the target current is reached, where a sharp

Figure 1. Sample holder used in pulsed current experiments. All samples measured were 10 cm long, with the first 2 cm at each end overlapping with current contacts (thick copper blocks). Indium foil was used to ensure low contact resistance between copper and sample. Voltage contacts separation was 4.2 cm.
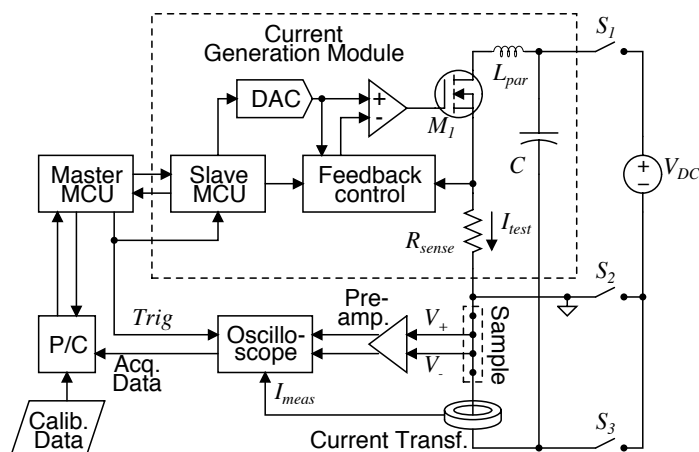
Figure 2. Schematic of the PCM measurement system used in this experiment. The system shown here is a significant upgrade over the previous system described in [5].
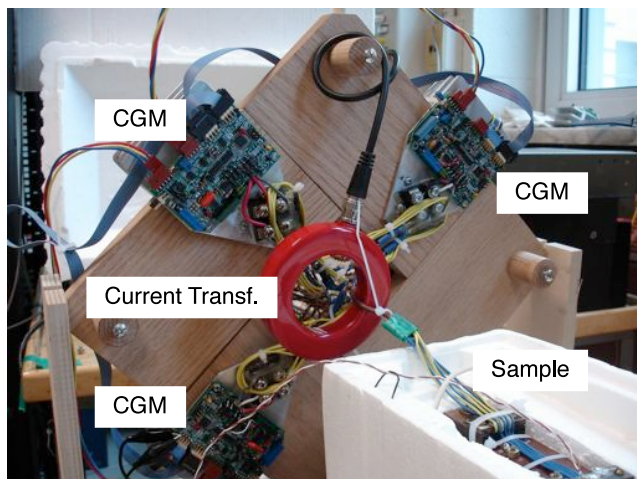

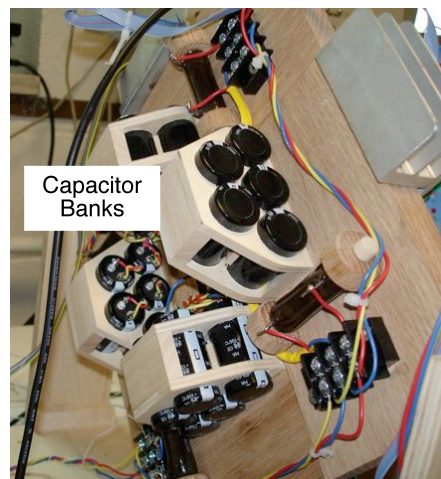**Figure 3.** Main components of the PCM system seen from the front.

Figure 4. Same as left, seen from the back.

transition is observed, quickly bringing dI/dt to zero and maintaining a constant current. Details of the implementation of the feedback control circuit are out of the scope of this paper, but considerations regarding both modes of operation are discussed hereafter.

It should be noted that the fast rise mode requires, in the current stage of development of the system, a somewhat tedious calibration procedure. For this reason, it was used only for the shortest pulses, where the longer rise time in the smooth mode accounted for a significant portion of the total pulse duration. Moreover, at very high currents, the actual operating voltage (90 V across capacitor C, limited by the drain to source breakdown voltage of transistor M_1) was insufficient to accommodate the total voltage across the sample, the sense resistor R_{sense}, and the parasitic inductance L_{par}, while keeping transistor M_1 into saturation. In these circumstances, pulses were only possible in smooth mode, since in this case dI/dt, and consequently the voltage across L_{par}, is reduced. A future more mature and higher voltage system is expected to overcome both constraints, allowing fast rise pulses to be applicable in all cases.

Finally, the large common capacitors feeding all CGMs in the previous system have been replaced by one bank of parallel capacitors per module, and mechanical assembly has been significantly modified, as seen in figures 3 and 4. All this was done in an attempt to improve modularity and reduce the parasitic inductance L_{par}.

2.3. Voltage and current measurements

Modifications to the previous system regarding the measurement setup include the fact that the sample is now referenced to the ground, with the negative terminal of capacitor C floating below ground level. This eliminates the need for voltage level shifting circuitry in the measurement signal path. Also, a current transformer is used to directly acquire the test current waveform, rather than monitoring the voltage across R_{sense}, hence eliminating possible heating effects impacting the data analyzed. The transformer specifications (droop rate = 0.001%/μs, -3 dB cutoff frequency = 20 MHz, accuracy = 0.5% [7]) allow for its use without any form of compensation in our application. Finally, a differential pre-amplifier with selectable gains of 1, 10 and 100 is used when appropriate in order to enhance the signal-to-noise ratio at low-level outputs.

3. Measurements

3.1. Samples

The samples characterized in this experiment were commercial CCs provided by *SuperPower* [6]. Two types of sample were considered, i.e.

- Sample 1: SCS4050 (silver coating + 40 μm of copper stabilizer);
- Sample 2: SF4050 (silver coating only).

Both samples were 4 mm wide, and consisted in 1 μm of YBCO deposited on a 50 μm *Hastelloy* substrate. On top of the YBCO layer, there was a 2 μm layer of silver providing limited thermal stabilization. For sample 1, there were additional 20 μm copper layers (copper clad) on each side of the tape, providing a good thermal stabilization and shunt path to transport current. The critical current of sample 1 was $\approx$ 94 A, and that of sample 2 was $\approx$ 89 A (1 μV/cm criterion).

The resistance per unit length of both samples as a function of temperature was also characterized (see [5]). Simple linear expressions fitted very well the experimental data over the temperature range between 95 K and 295 K, i.e. $R_1(T) = 0.322 + 0.00424(T - T_0)$ mΩ/cm (sample 1, with silver coating + copper stabilizer) and $R_2(T) = 3.229 + 0.0389(T - T_0)$ mΩ/cm (sample 2, silver coating only). In these expressions, T_0 represents the temperature of the liquid nitrogen bath, i.e. $\approx$ 77 K. Therefore, the constant parts in the latter expressions give directly the extrapolated resistance per unit length of the metallic layers at 77 K, which could not be measured directly since YBCO critical temperature is around 90 K. It is also worth mentioning that no particular care was taken for insulating electrically the *Hastelloy* substrate from the other layers, therefore it is likely that the latter carries a small fraction of the total imposed current.

3.2. Current pulses

As mentioned earlier, pulsed $V - I$ measurements were realized with two types of pulses:

- Fast rise pulse: very high and nearly constant dI/dt ($\approx$ 300 A/μs);
- Smooth rise pulse: dI/dt decays quasi-exponentially.

Both types of pulses are shown in figures 5, together with the associated voltage signals recorded (figure 6). All data shown here are for sample 2 (silver coating only). We clearly observe that smooth rise pulses progressively reach the constant current regime in $\approx$ 10 μs. In fast rise mode, the current increases as fast as supported by the control circuit (in the range of $\approx$ 300 A/μs), and suddenly tries to satisfy the requested current. This works very satisfactorily for currents up to $\approx$ 250 A, but for higher currents, oscillations and/or overshoots were observed. Nevertheless, the current generally rose from zero to 95% of its final value (and remained within 5%) in less than 3 μs.
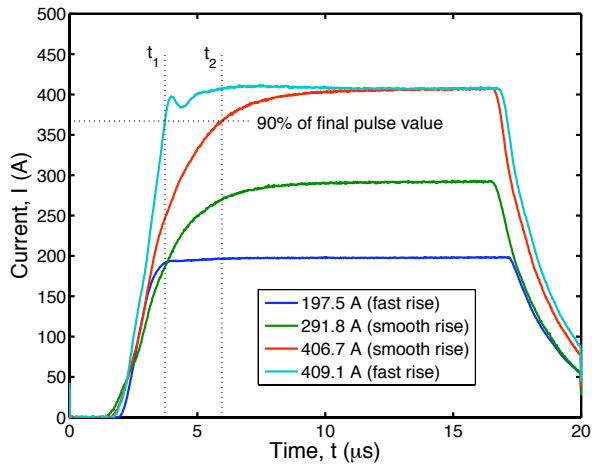
Figure 5. Typical current pulses applied to HTS CC samples. For the sake of illustrating the technique, both smooth and fast rise pulses are shown. Current waveforms were measured with a very fast *Bergoz* current transformer.
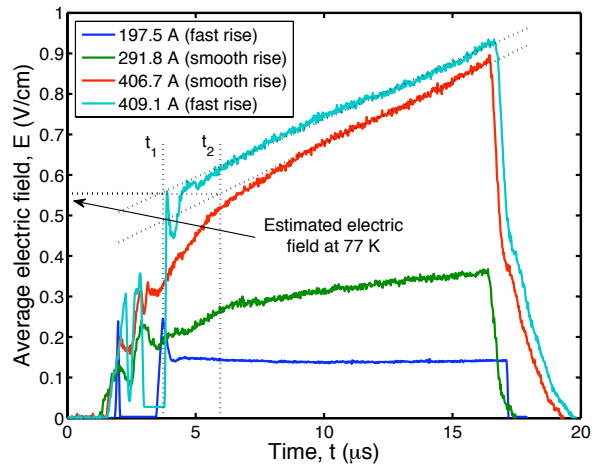
Figure 6. Typical voltage measured in HTS CC samples corresponding to current pulses in figure 5. Data points before ≈ 4 μs are not reliable as the inductive pick-up saturated the voltage probes.

In figure 6, we easily notice a steady and nearly linear increase of the voltage curves for all but the lowest pulse. Since the current is regulated and essentially flat in the last microseconds of the pulse, there is no inductive component at the end of the voltage signal, and therefore the positive slope that is observed is a clear sign of sample heating, although the exact nature of the associated resistivity increase is not trivial to explain. As this paper focuses exclusively on the experimental technique and data, physical interpretations will be deferred to future works.

Before extracting any useful data from figure 6, and therefore determine the sample resistance at 77 K (initial temperature), one has to extrapolate the measured voltage slope back to a time that would correspond to zero energy injected in the sample, assuming a perfectly square current pulse [1]. This fictitious "zero-energy point" is not obvious to find, as we would need to known *a priori* the exact $R(I,T)$ characteristic of the sample in order to calculate accurately the energy injected as a function of time, i.e.

$$\varepsilon(t) = \int_0^t R(I,T)\,I^2(t)\,dt\,, \tag{1}$$

which becomes a "recursive" problem, since $R(I,T)$ is precisely the quantity that we want to determine experimentally.

However, since the integrand $R(I,T)\,I^2(t)$ exhibits a power law behavior, we know that most of the pulse energy during the rise period will be dissipated near the top of the pulse. Therefore, for the purpose of this work, we arbitrarily selected the point where the pulse has attained 90% of its final value as the criteria for determining the extrapolating time. The application of this procedure is demonstrated in figures 5 and 6. It is interesting to note that, in this case, the criteria allowed to find very similar values of electric field for two current pulses of similar amplitudes (i.e. 406.7 A and 409.1 A) but different rise modes. Indeed, despite the clear offset between the voltage curves (different total energy injected), the extrapolated voltage is almost the same, which suggest that the criteria was well chosen.

From the experience acquired so far by the authors, it seems that extrapolated voltage, hereafter noted $\widetilde{E}$, is relatively insensitive to the above criteria when working with fast rise pulses, mainly because they are very sharply defined, leaving little margin of error on t_1 (see

figure 6). On the other hand, in the case of smooth rising pulses, changing the criteria by only a few percents may significantly affect the extrapolation time (e.g. t_2 in figure 6), and consequently the associated electric field.

The resistance per unit length of a sample, $R(I, T)$, is easily found after one has completed the extrapolation procedure, i.e.

$$R(I, T) = \widetilde{E}(T)/I_{top}, \qquad (2)$$

where T is the temperature of the sample prior to applying the pulse (here $T = T_0 = 77$ K everywhere), $\widetilde{E}$ is the extrapolated value of electric field at the "zero-energy point", and I_{top} is the value of the current at the top of the pulse, after it has fully stabilized.

3.3. PCM characterization of sample 2 at 77 K

Current pulses of various durations and amplitudes were applied to sample 2, i.e. the one that is stabilized with only 2 μm of silver. The current and voltages waveforms were recorded in all cases, and $\widetilde{E}(I, 77$ K$)$ was estimated for each pulse data, according to (2). The global $E - I$ curve built from these sets of measurements is shown in figure 7.

As a first observation, one can see that most points follow the same path, and this path lies below the $E - I$ ohmic curve of the silver coating at 77 K, as we would expect for a superconductor. As a further validation, we verified that the $E - I$ curve obtained with the PCM technique is consistent with the quasi-dc $E - I$ characteristic obtained at lower currents, with a completely independent experimental setup (dc current source and nano-voltmeter). The quasi-dc measurements (pulses of ≈ 1 second) were performed only in the vicinity of the critical current of the sample (≈ 89 A) to avoid destroying it.

Despite this good agreement, there are a number of points that do not fall on the main $E - I$ characteristic. However, these points all present the same pattern: they constitute the extension of a given set of data at low currents, i.e. towards the left of the graph. The shorter the pulse, the higher is the asymptotical value at low currents. For pulses in the range of 1000 μs, this behavior tends to disappear, and the connection with the quasi-dc $E - I$ curve is almost complete.

This asymptotical effect can easily be explained by incomplete magnetic relaxation in the sample at low currents. Indeed, the diffusion time of the self-field in the sample increases exponentially as the resistance decreases, and therefore pulses must be longer at low current in order to avoid biasing the extrapolated electric field. Flux relaxation results in a voltage
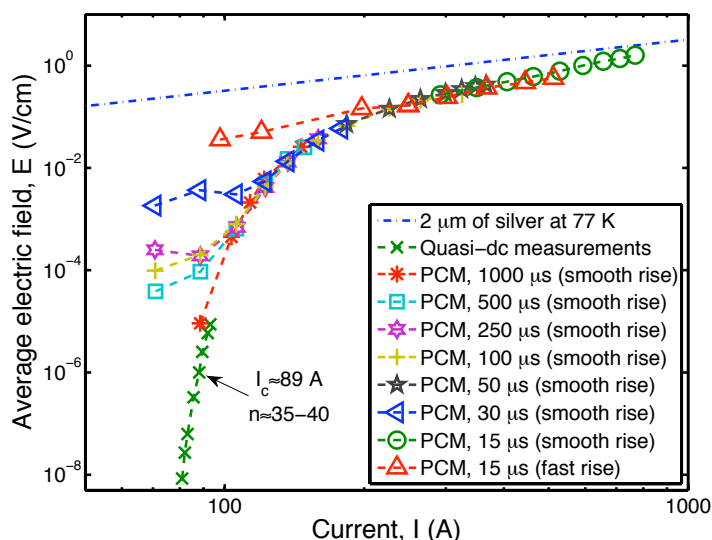

Figure 7. Electric field extrapolated at 77 K vs current for various PCM experiments realized on sample 2 (shunted with 2μm of silver only). The total number of points measured is about twice as shown here, but not all of them were plotted in order to enhance figure's readability.

contribution that tends to mask the heating effect, and leads to a negative $V(t)$ slope that over-estimates the extrapolated voltage, as shown in figure 8.

The last remark about figure 7 is related to 15 μs smooth rise pulses, which are not perfectly aligned with other data points. These measurements were among the last ones performed on the sample, and also the most violent in term of power dissipation. The origin of this discrepancy could not be confirmed yet, but is likely due to either small localized sample damage, or perhaps simply the combined effect of high power and slower rise time (10-15 μs), which could make the extrapolation technique doubtful here. In any case, this highlights the need for very short and fast rising pulses, and adds to the motivation to making fast mode available for the highest levels of currents.

3.4. Approximate $R(I)$ curves of both CC samples at 77 K

The same measurement methodology as in previous section was also applied to sample 1 (copper stabilized CC), with pulses durations of $80-135$ μs and currents between 90 and 1050 A [5]. The major difference with respect to sample 2 (silver stabilized CC) is that very little heating effects were observed, and therefore the voltage correction was straightforward (hardly noticeable slope in the voltages curves, even for $I = 1000$ A).

Figure 9 summarizes the results of this paper by presenting the $R(I)$ curve at 77 K of both CC samples considered in our experiment. These curves were produced by keeping only a relevant subset of the measured points. No curve fitting was attempted yet.

The curve suggests that current sharing happens between the stabilizer and the HTS even at currents well above I_c, where we would expect most of the current to flow in the shunt layer. This can be seen as an offset between the CC curve and that of the corresponding stabilizer, which means that upon pulse initiation (i.e. at 77 K), a certain amount current flows in the YBCO layer. It also suggests that the self-field flux flow resistivity is in the same range of values as that of the shunt layer. This will be explored in more details in future works.

Finally, it is interesting to estimate the losses per unit length generated in each tape at their maximum test current. For sample 1, the power injected is limited to ≈ 200 W/cm^2 at $I_{max} = 1050$ A, whereas for sample 2, this power is rather in the range of ≈ 1200 W/cm^2 at $I_{max} = 515$ A. This is a tremendous amount of power that would definitely burn the tape in the absence of an ultra-fast and reliable PCM system.
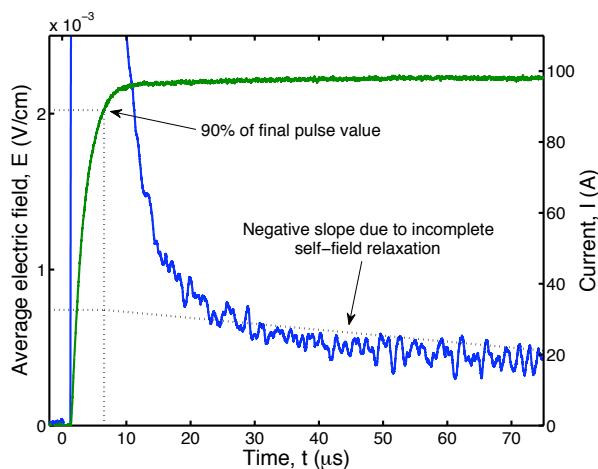

Figure 8. Typical relaxation effect of the self-field, leading to an over-estimate of the extrapolated voltage.
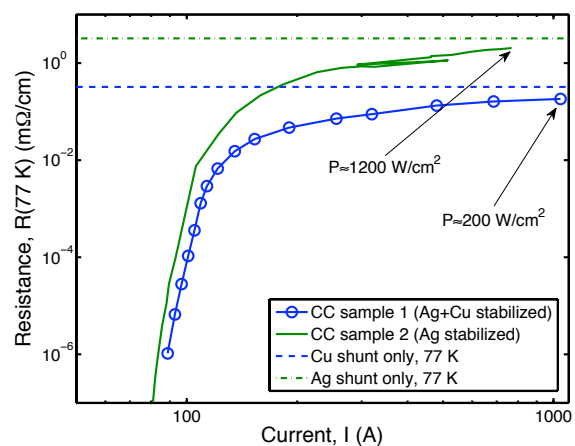

Figure 9. Resistance of CC samples 1 and 2 as a function of the current, at 77 K, obtained with the PCM technique.

4. Conclusion

In this paper, we have demonstrated that current-voltage characteristics of full-size commercial samples of coated conductors can be characterized over a wide range of electric field values (up to 7 decades), thanks to a home-made, high current pulsed source capable of delivering flat current pulses of 1000 A for durations as short as 15 μs.

In a near future, bulk HTS samples will be also considered, as well as experiments in variable temperature and magnetic field. Additional voltage taps and instrumentation (temperature and Hall probes, etc.) is also planned. The pulse current system developed in this project will also be further improved, especially to enable its operation at higher voltage, which was the major remaining obstacle before applying large current pulses in the fast rise time mode.

The type of results obtained with this experimental technique will serve as the basis for other works about more accurate HTS material models. It could also be used to improve our understanding of the physics of HTS at high current densities. Finally, it is an extremely powerful tool to assess the robustness of various designs of HTS applications under fault current conditions.

References

[1] Kunchur M N 1995 *Modern Physics Letters* B **9** 399–426
[2] Gonzalez M T, Vidal S, Vina J, Osorio M R, Maza J and Vidal F 2002 *Physica C* **372-376** 1852–54
[3] Therasse M, Decroux M, Antognazza L, Abplanalp M and Fischer O 2008 *Physica C* **468** 2191–96
[4] Frolek L and Souc J 2009 *IEEE Trans. on Appl. Supercond.* **19** 3581–4
[5] Sirois F, Coulombe J and Bernier A 2009 *IEEE Trans. on Appl. Supercond.* **19** 3585–90
[6] SuperPower Inc. [Available on-line] http://www.superpower-inc.com/
[7] Bergoz Instrumentation [Available on-line] http://www.bergoz.com/products/CT/CT.html