09/26/02
TD-02-039

Interstrand Resistance Measurements in Nb_3Sn Rutherford-type cable

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1.0 *Introduction*

A superconducting Rutherford-type cable is composed of many strands wound together. The electrical resistance between the strands may vary by several orders of magnitude, depending on the characteristics of the wires and on the procedures used during cabling and magnet fabrication. The magnitude of the interstrand resistance in a cable has a great impact on the performance of the magnet. Therefore the knowledge and control of this resistance is an important factor in the design and the fabrication of superconducting magnets.

Contacts between a strand and those on either side of it result in adjacent resistance, Ra. The resistance between the strand and those that it crosses over is referred to as the crossover resistance, Rc. For the measurement of interstrand resistance in a cable, current leads are attached to strands at opposite corners of the cable, shown below in Fig. 1, and the voltage drop from the negative current lead to a given strand is measured. The results from this type of measurement should match one of the following plots shown below in Fig. 2. If the increase in voltage from the negative to the positive current lead is linear, then Ra << Rc. If the voltage jumps initially after the negative current lead, plateaus, and then jumps again near the positive current lead, then Rc << Ra. Between these two extremes, Ra and Rc are closer in value. [1] [2]

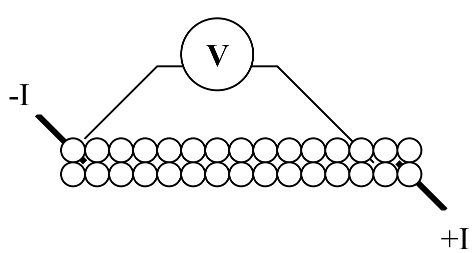

Figure 1. Sample schematic

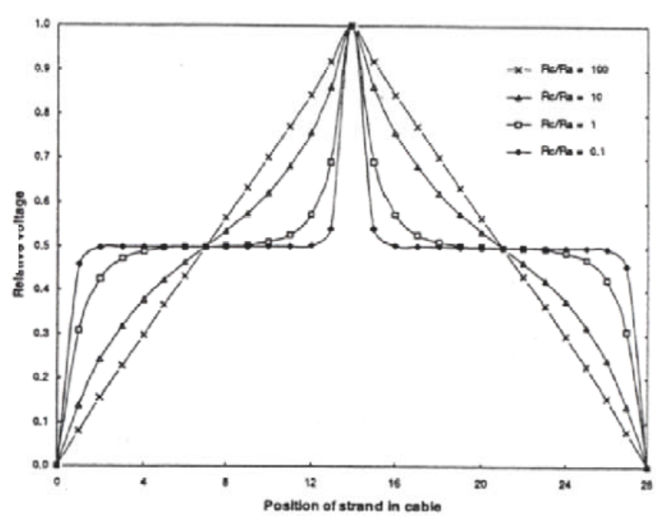

Figure 2. Voltage vs. Strand

2.0 ***Experimental Set-up***

The measurement apparatus was assembled using the following equipment:

- Sample Holder
- Cryostat with Load Cell
- Nanovoltmeter & Scanner
- Power Supply
- Computer running Labview program

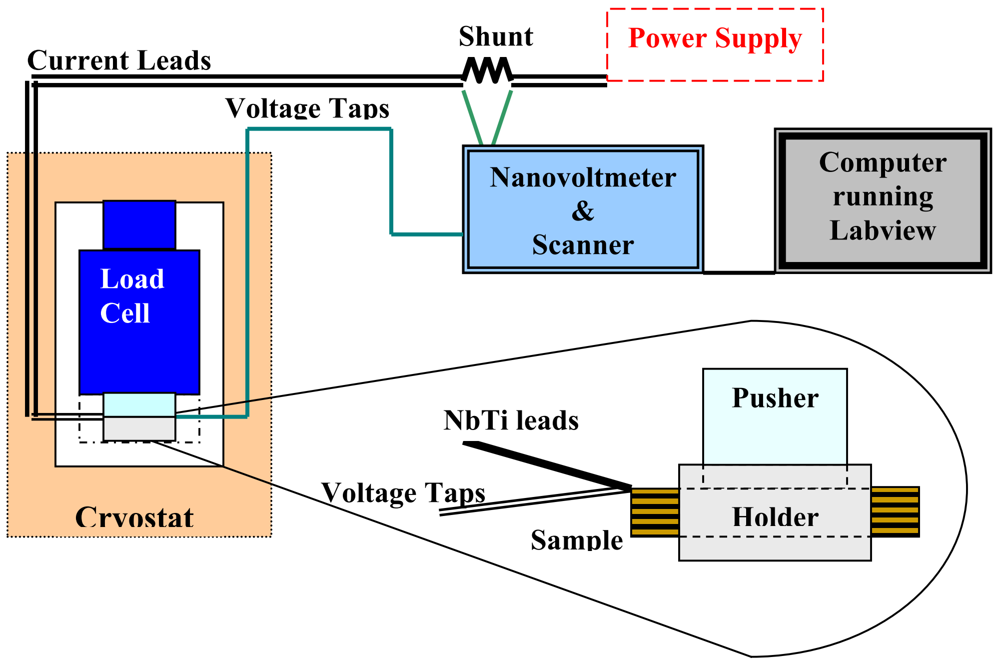

Figure 3. Experimental Set-up

As seen above in Fig. 3, the current leads and voltage tap wires were run from the sample out of the inner chamber of the cryostat (used for the load cell) to the outer chamber. The voltage tap wires were then connected to leads that went out of the cryostat and were connected to the nanovoltmeter.

The current leads coming from the sample were NbTi strands with copper wires connected in parallel (in the event of the NbTi wires quenching). Voltage taps were connected at each end of the NbTi leads so that the voltage drop could be monitored and a quench detected. These NbTi leads where connected to copper wire leads that went from the outer chamber of the cryostat to the outside. The copper leads on the outside where then connected to a 50-A power supply. Indium was placed between all contacts, from the NbTi leads to the power supply, in order to achieve better electrical contact.

A shunt was connected in series with the power supply's positive current lead to measure the current. For the shunt, 100 A corresponded to 100 mV. Indium was also placed between all contacts with the shunt. A pair of voltage taps was connected from the shunt to the nanovoltmeter so that the current could be recorded during testing.

The nanovoltmeter was connected to a computer running Labview. The Labview program recorded all the voltages measured and plotted the voltage drop for each voltage tap as a function of time. The Labview program also controlled the load cell in the cryostat.

3.0 ***Sample Preparation and Results***

3.1 *Sample prepared from a coil of the first Racetrack*

The sample used in this test was cut from the coil of HFDB-01, [3] the first Racetrack built at Fermilab using Nb_3Sn and the React-and-Wind technology. The cable had 41 strands (0.7 mm diameter made by IGC), 110 mm pitch length. The sample used was a coil section 133 mm in length that had been poorly impregnated, so separating strands and soldering voltage taps to them was not too difficult. The current leads were soldered to strands 1 and 21, and the taps were connected to strands as shown below in Fig. 4.

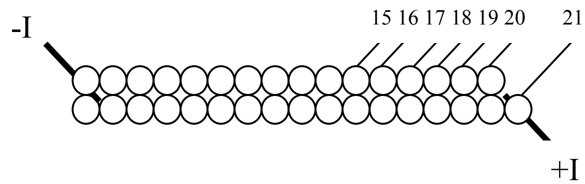

Figure 4. Racetrack 1 voltage taps and current leads

The sample was tested under a pressure of 10 and 35 MPa. A small increase in the effective resistance (voltage drop divided by the current) with current was noted in the results, as seen in Fig. 5.

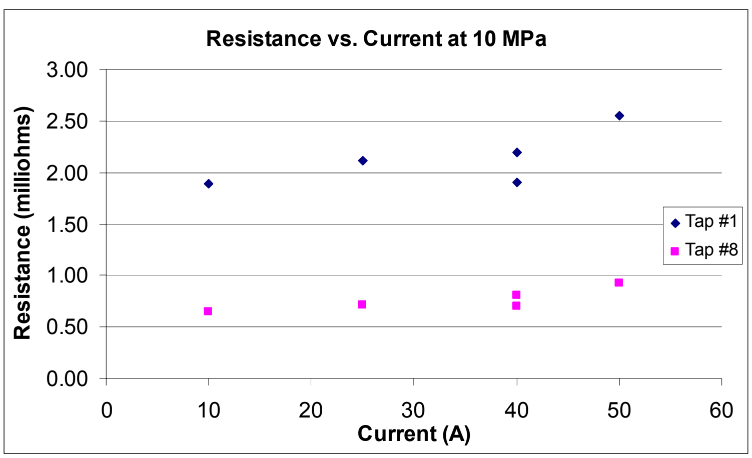

Figure 5. Effective resistance vs. current

The voltage tap distribution (Fig. 6) was unlike anything expected. It looked most similar to the plot for Rc << Ra (see figure 1), but no tap voltages should have been below 50% of the maximum voltage, because all of the taps were much closer to the positive current lead than to the negative. The whole length of the sample was not under pressure, however, and this could account for the unexpected pattern of the data.[4] Moreover, the sample was 133 mm in length, longer than the 110 mm pitch length. When the sample length is not exactly one pitch length, measuring the contact resistance can be very complicated. [2]

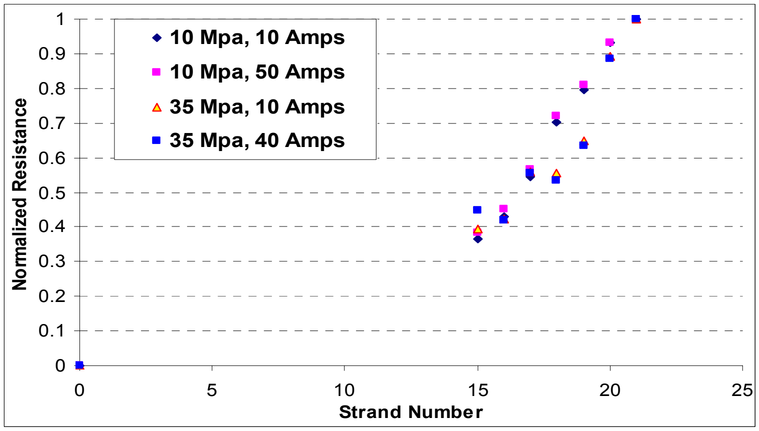

Figure 6. Normalized Voltage vs. Strand Number

3.2 *Sample prepared from cable of Second Racetrack*

The Nb_3Sn Rutherford cable used in this experiment was taken from the leftovers of the cables used for HFDB-02 (2nd Racetrack). [5] This cable was made of 41 strands (0.7 mm diameter made by OST) and had a pitch length of 110 mm. The oil used during the cable fabrication contained 5% Mobil-1 synthetic oil. More synthetic oil was added after cabling by an oil-impregnation under vacuum. [5] The cable was insulated with 0.005 in. fiberglass tape. Three-stack of cables were prepared for testing, with the top and bottom cables being one twist pitch in length. The middle cable was 130 mm in length. A side view of the stacking of these cables is shown below in Fig. 7.

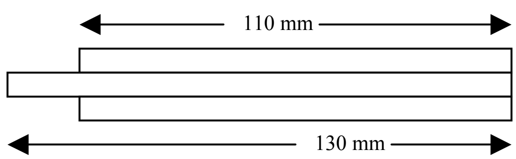

Figure 7. Side-view of three-stack sample

When the sample was impregnated with epoxy, it was under a transverse pressure of 7 MPa. The protruding end of the middle cable did not get coated with epoxy so that it would be possible to connect voltage taps and current leads to individual strands in the cable.

The voltage taps were soldered to strands 5, 7, 9, 15, 17, 19, and 21, and the current leads were soldered to strands 1 and 21. Shown below in Fig. 8 is the distribution of voltage taps and current leads for this sample.

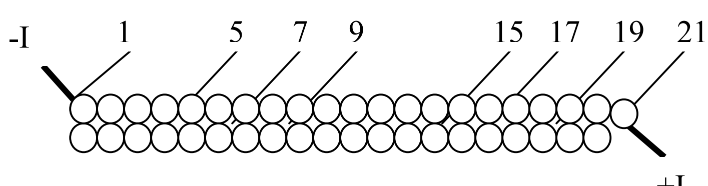

Figure8. Sample made of 2nd Racetrack cables: voltage taps and current leads

Steel bars, 110 mm in length, were then laid on top of and below the sample to ensure that the entire pitch length of the sample would be under pressure in the load cell. This three-piece stack was then set in a U-shaped holder to keep the arrangement stable during testing.

Two sets of data were collected for this sample, first at a pressure of 10 MPa, and then at 35 MPa. The voltages recorded were very small, in the order of 40 μV, and the offset voltage at 0 A was taken into account during analysis. During data collection, the current was slowly ramped up at ~1 A/s to a given current settings, and then 35 to 70 data points were collected at each current setting.

Shown below in Fig. 9 is the plot of the current vs. time at 10 MPa and ~40 A. The ramping up of the current to 40 A was stopped at time 518, and any change after this was due to drifting. The current was measured using a shunt with the relation 100 mV = 100 A. Figure 10 is the plot of the voltage drop from strand number 19 to the negative current lead, measured at the same time as the current shown in Fig. 9.

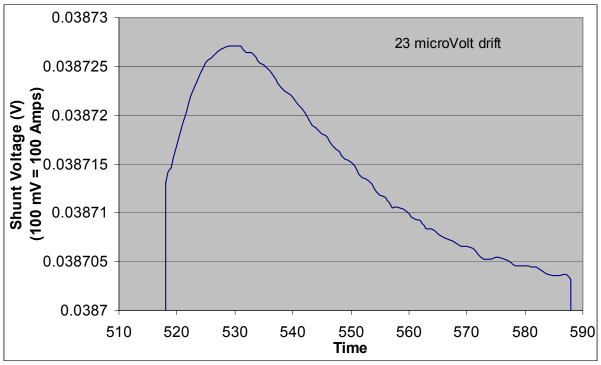

Figure 9. Current vs. time at 10 MPa

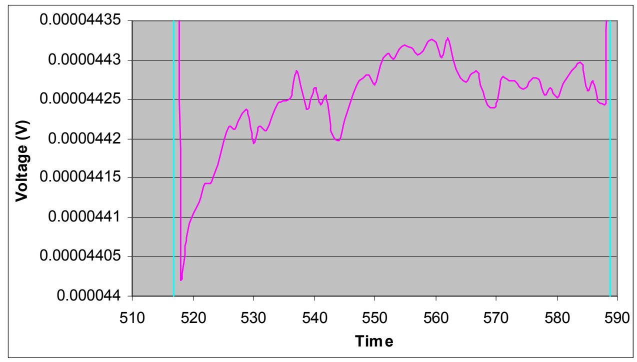

Figure10. Voltage vs. time at 10 MPa, Strand #19

Figure 9 shows a typical drift of the current of about +/- 12 mA (i.e. 0.03 %), while the voltage taps showed a larger drifts at the beginning of each current level, as shown in Fig. 10, followed by a saturation to an almost stable value. Because of this drift the plots were used to determine which segment of data points should be used in the analysis, by selecting the time interval when all voltage taps appeared the most stable. For example, the portion from time 545 to time 575 was used in the case shown in Fig. 10.

After a portion of data points for a given current had been selected, the average of these points was taken, along with the average of the voltage recorded at 0 A (for instance: 55 µV +/- 30 nV for the voltage tap #19 at 10 MPa). The difference in these voltages was obtained for each of the voltage taps, and the voltages were then normalized with reference to the voltage drop from the positive to negative current lead. A plot was then made of normalized voltage vs. strand number. The results at 50 A and 10 MPa are shown below in Fig. 11. Note the equation for the best linear fit to this data that intercepts the point (1,0).

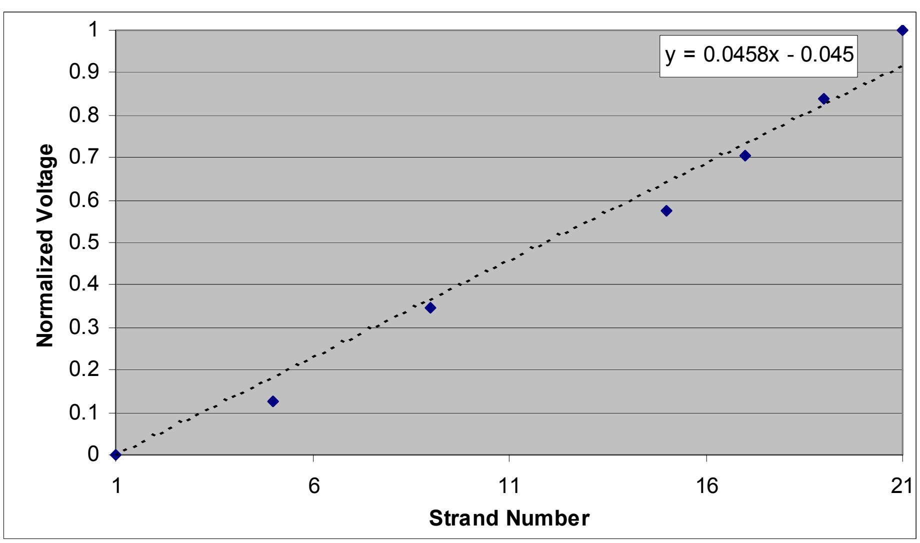

Figure11. Sample using 2nd Racetrack cable: normalized voltage vs. strand number at 50 A and 10 MPa

From the plot it appeared that the relation of normalized voltage to strand number was linear, in which case the adjacent resistance, Ra, is much lower than the crossover resistance, Rc. A linear fit, which intercepted the point (1,0), was then made for each set of data.

A new set of normalized voltages was then obtained from the linear fit equation, and from these, a linearized set of voltages. Then, since it appeared that Ra dominated the contact resistance, Ra was calculated using the following relationships [1]:

$$r_a = \frac{R_a}{2N} \quad (1) \qquad \text{and} \qquad V_k - V_i \approx \frac{(k-1)(N-j+i)r_a}{N} I \quad (2)$$

to yield

$$R_a \approx \frac{2N^2(V_k - V_i)}{I(k-1)(N-j+i)} \quad (3)$$

where r_a is the overall adjacent resistance per pitch length, i and j designate the strand number corresponding to the negative and positive current leads (i.e. 1 and 21 in this case), k is the number of a strand instrumented with a voltage tap, N is the number of the strands in the cable (i.e. 41 in this case).

Adjacent resistance values calculated for different pressures and currents are listed below in Table I. The adjacent resistance values were much lower than anticipated, but this may be due to the fact that the sample was under a larger pressure (7 MPa) during impregnation than the previous sample. There was no space for the cable to expand width-wise during this compression, which would increase the contact resistance. A reduction of the adjacent resistance in the cable edge region [4] may also explain these results.

Table 1. Ra values for the sample using the cable of the 2nd Racetrack

Pressure (Mpa)	Current (A)	Ra (μΩ)
10	10	2.44
10	25	2.44
35	40	2.39
35	50	2.42

3.3 *Sample prepared using the cable for the Cos(theta) dipole*

This sample was made of reacted left-over cable from the cos(theta) dipole model [6] R&D program. It was a keystoned Nb_3Sn Rutherford cable with 28 strands (1 mm diameter) and had a pitch length of 110 mm. It contained a stainless steel core, and was insulated with ceramic tape painted with ceramic binder. A four-stack of cables was prepared for testing. The middle cable was 130 mm in length, and the other cables were one pitch length. A side view of the stacking of these cables is shown below in Fig. 12.

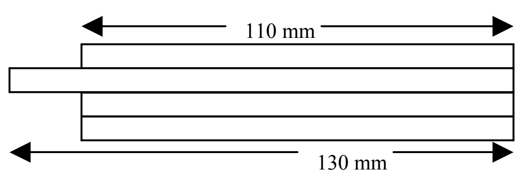

Figure 12. Side-view of four-stack sample

This sample was impregnated and tested (sandwiched between two steel bars) in the same way as the previous sample. The current leads where soldered to strands 1 and 15. The voltage taps were soldered to strands 3, 5, 7, 9, 11, and 13. Since the cable strands were very brittle, they were not separated for tap connections. Instead the voltage taps were soldered to the tops of the individual strands. A thin piece of kapton was slipped beneath strands 1 and 15, to isolate them from the surrounding strands. They were pre-tinned and then the current leads were soldered to those strands. The kapton prevented the solder from flowing onto other strands. Fig. 13 shows how the sample looked after soldering. The silver strand in the top of this picture had been pre-tinned and was connected to the positive current lead. The kapton goes underneath this silver strand and is above all other strands. Some strands have voltage taps connected to them. Two of the strands at the bottom were pre-tinned for practice, but were not fitted with voltage taps.

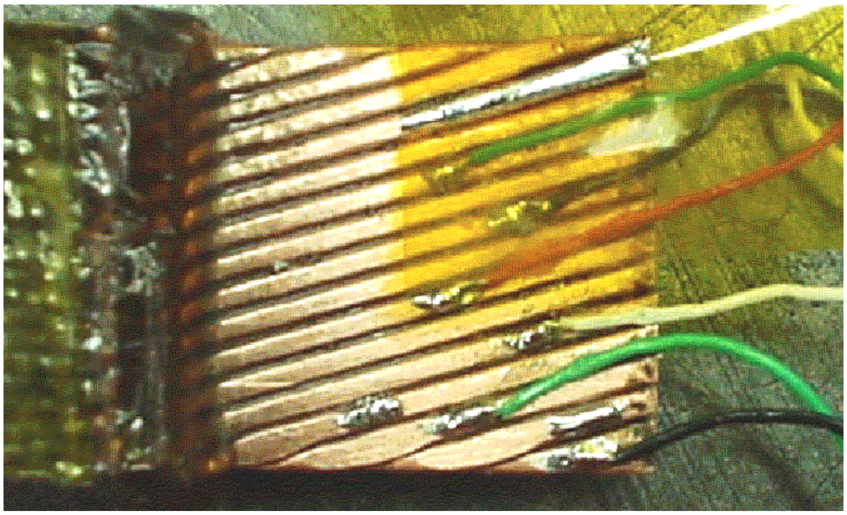

Figure 13. Cos(theta) sample with voltage taps and isolated current leading strand

The position of the current leads and distribution of the voltage taps are shown below in Fig. 14, with the numbers corresponding to the strand number.

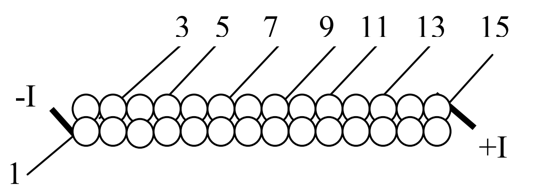

Figure 14. Cos(theta) voltage taps and current leads

Steel bars, 110 mm in length, were then laid on top of and below the sample to ensure that the entire pitch length of the sample would be under pressure in the load cell. This four-piece stack was then set in a U-shaped holder to keep the arrangement stable during testing.

Data was collected on two separate days for this sample, the first day at a pressure of 10 MPa, and the second day at pressures of 0, 35, and 50 MPa. The voltages recorded were very small, in the order of microvolts, and the offset voltage at 0 A was subtracted during analysis.

During the first day of data collection, the procedure was the same as for the previous sample. However, on the second day of data collection, a new method was used. After waiting for three points of data to be collected at all the voltage taps, the current was ramped up at 1 A/s to the given current setting. The current was then held at that level for another three points of data, and then ramped back to zero. This procedure was repeated multiple times at various current levels.

Shown below in Fig. 15 and 16 is a plot of voltage vs. time for strand 15 of this sample under a pressure of 10 and 35 MPa. Notice in Fig. 16 the shorter amount of time at a current level and the number of times the current is ramped up and down. Also note the difference in overall time between the two graphs; there were not as many readings taken at 35 MPa because time had to be made for readings at 0 and 50 MPa also.

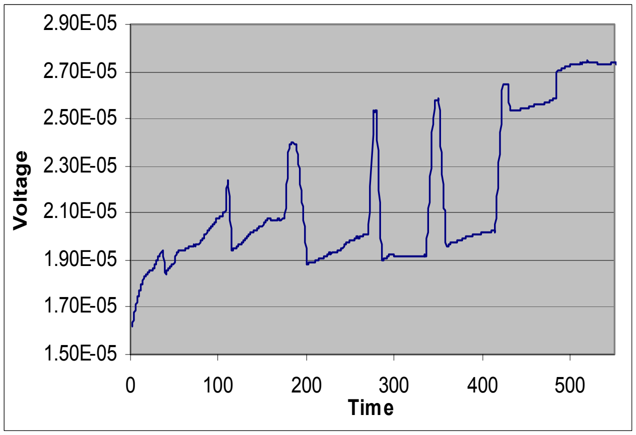

Figure 15. Cos(theta) sample: voltage vs. time at 10 MPa

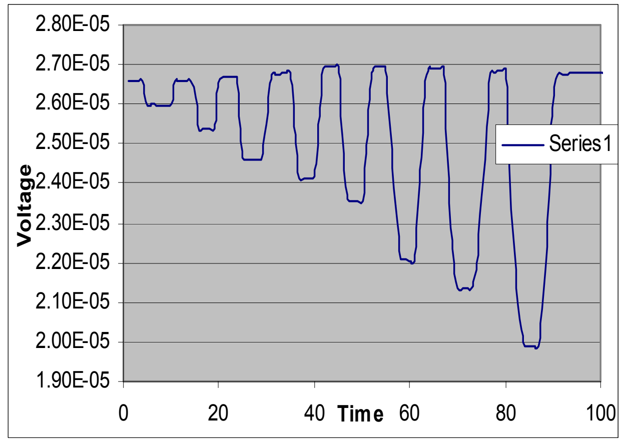

Figure 16. Cos(theta) sample: voltage vs. time at 35 MPa

After collection of the data, plots of normalized voltage vs. strand number were made, and the distribution of the data was not as expected. This is shown below in Fig. 17 for different pressures at a current of 50 A.

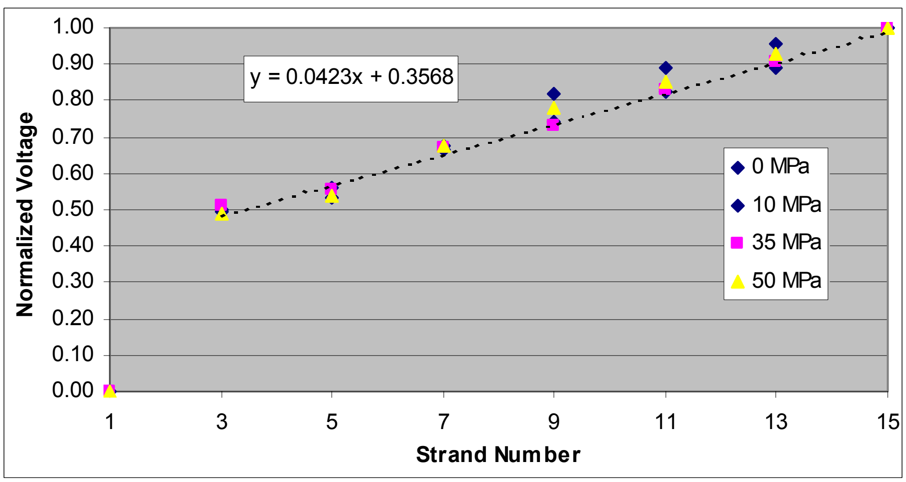

Figure 17. Cos(theta) sample: normalized voltage vs. strand number at 50 A

As seen in Fig. 17, there appears to be a linear relation between the voltage and strand position in the cable for the strands from 3 to 15, but in theory this linear relation should intercept the x-axis at 1, the strand number of the negative current lead. The voltage taps at the negative and positive current leads were not soldered directly to the strand in the cable, though. Each tap was soldered to its current lead, which was then soldered to the strand. Thus the voltage tap probably measured an extra resistance from the tap through the current lead to the strand. As a result, the point (1,0) was excluded when making a linear fit for the data. The adjacent resistance was then calculated using this best-fit equation and the same method as described for the previous sample. The Ra values obtained are shown below in table 2.

Table 2. Ra values for Cos(theta) sample at 50 A

Pressure (Mpa)	Ra (μΩ)
0	1.82
10	1.64
35	1.87
50	1.81

The amount of pressure applied during testing does not appear to affect the voltage readings. This may be due to the fact that the sample was under a pressure of 7 MPa during impregnation, and after being impregnated, the contact resistance was unaffected by transverse pressure on the sample, as seen in Fig. 17.

One should also note that the sample was not under uniform compression during impregnation. The pressure distribution on the sample was measured by placing Fuji film between the sample and the steel bars above and below it, and then compressing it to 35 MPa. The Fuji film revealed that the sample had an uneven surface, and this may be the sign that the sample was under an uneven pressure during impregnation. Below in Fig. 18 is a picture of the Fuji film coloration after being compressed by the sample. The darker the pink, the higher the pressure, with white implying no pressure. The top strip was on top of the sample, and the bottom strip on the bottom of the sample. The left side of the strips corresponds to the side where the voltage taps and leads were soldered.

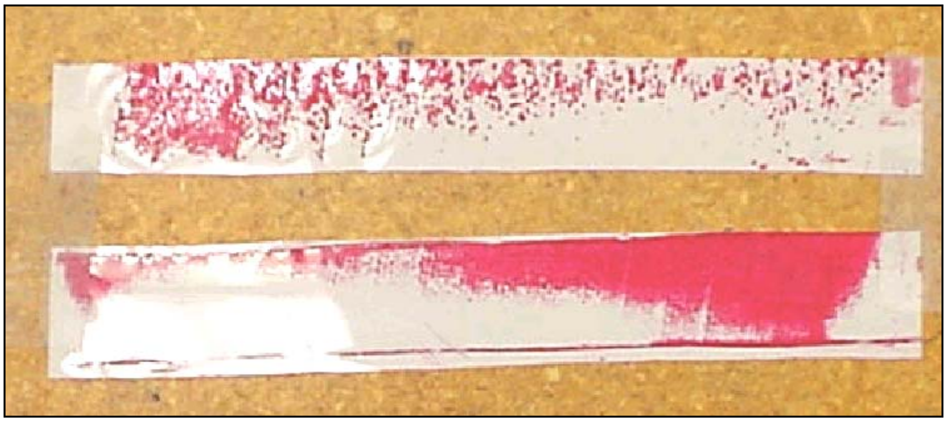

Figure 18. Fuji film results for the cos(theta) sample

When the sample of cos-theta cable was prepared, the cables were cut at one end to the desired lengths, but afterwards the strands were not polished and no precautions were taken to ensure that the different strands had not been smeared into contact with one another by the cutting of the cable. This was not thought about until after the sample had been impregnated, and had not been considered in the preparation of the sample from 2nd Racetrack cable, either. If the strands were in contact with one another due to the cutting of the cable, then current may have been shared between strands this way and would skew the contact resistance measurements. This is an issue to be further examined in the future.

4.0 *References*

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[2] Devred, *et al., "Interstrand Resistance Measurements on Nb_3Sn Rutherford-Type Cables",* CEA/F-91191, 1998

[3] G. Ambrosio, *et al.,"Development and test of a Nb_3Sn Racetrack magnet using the React and Wind technology"* Advances in Cryogenic Engineering 47A, pp. 329 336 (2002)

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[6] N. Andreev, *et al., Nb_3Sn Cos (theta) Dipole Magnet, HFDA-01 Production Report,* TD-00-069