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Test of Position Dependent Distribution of Interstrand Contact Resistance in a Coil of HFDA04 Nb_3Sn Magnet

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Abstract

This paper presents a continuation from an earlier set of measurements of the Interstrand Contact Resistance (ICR) in the HFDA04 superconducting dipole made of Nb_3Sn strands [1]. Seven turns were measured in the first set of measurements. This report includes the second and third measurements. This new set included five new turns from the same coil sample. These measurements were performed to test if the voltage distribution is dependent on the position of the turns within the coil cross-section. The results showed that there are significant differences in resistances between turns on the midplane and close to the pole.

Introduction

Fermilab's HFM (High Field Magnet) program is designed to develop the next generation of superconducting accelerator magnets with high operating fields and margins for different applications. Possible applications of HFM include superconducting magnets for the Tevatron, for an energy upgrade of the large hadron collider, and for other applications such as beam transfer lines. A very likely application is for second-generation LHC IR dipoles and quadrupoles with larger apertures and higher operating margins for higher luminosity.

The goal of the experiment was to test whether the positions of the turns will yield different resistances. This report describes the new set of measurements and the results. A series of tests of the ICR in HFDA04 dipole superconducting magnet made of Nb_3Sn strands showed that the R_a, adjacent resistance, values of the samples were similar to each other [1]. However, the crossover resistance in the midplane was extremely higher than that of turns close to the pole. These measurements were performed on a 5-inch long coil section extracted from the straight section of the magnet. All turns in the midplane were measured. Some of the pole-1 turns were measured. Pole^{-}1 turns were measured instead of pole turns because the cables closest to the pole were damaged (pole $^{-}$1 is a term describing the second turn from the pole). This first set of data can be seen in Table 1.

Position	Sample	Coil Layer	Ra (μΩ)	Rc (μΩ)
Midplane	A	Outer	**3**	**30**
	B	Inner	**~3**	**≥ 500**
	C	Inner	**2.6 - 3**	**≥ 500**
	D	Outer	**2.5**	**20**
Pole^{-}1	2	Inner	**1.88**	**6**
	3	Inner	**0.75**	**4.45**
	4	Outer	**4.25**	**4.38**

Table 1. Previous series of tests

There was a question after examining those set of results. Are the positions of the turns tested causing this large difference of the R_c, crossover resistance, between the midplane and pole of the magnet? More tests of turns extracted from the same magnet were needed to make a scientific conclusion. Therefore, some more turns between the midplane and the pole were measured after removing the previously measured external turns. These turns are individual cable strips that make the whole of the sample (as shown in Fig. 1).

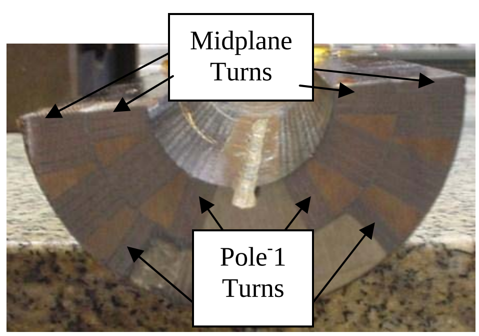

Figure 1. Parts of a magnet coil tested

Experimental Set-up

The set-up for the experiment was the same as in [1]. There were a couple of new additions. A larger cryostat was used. Also, the test station was upgraded to have forward and reverse current switch. It was assembled using the following equipment:

- Cryostat
- Nanovoltmeter & Scanner (7 channel max)
- Power Supply (maximum current = 100A)
- Computer and LabVIEW® program
- Forward and Reverse Current Switch

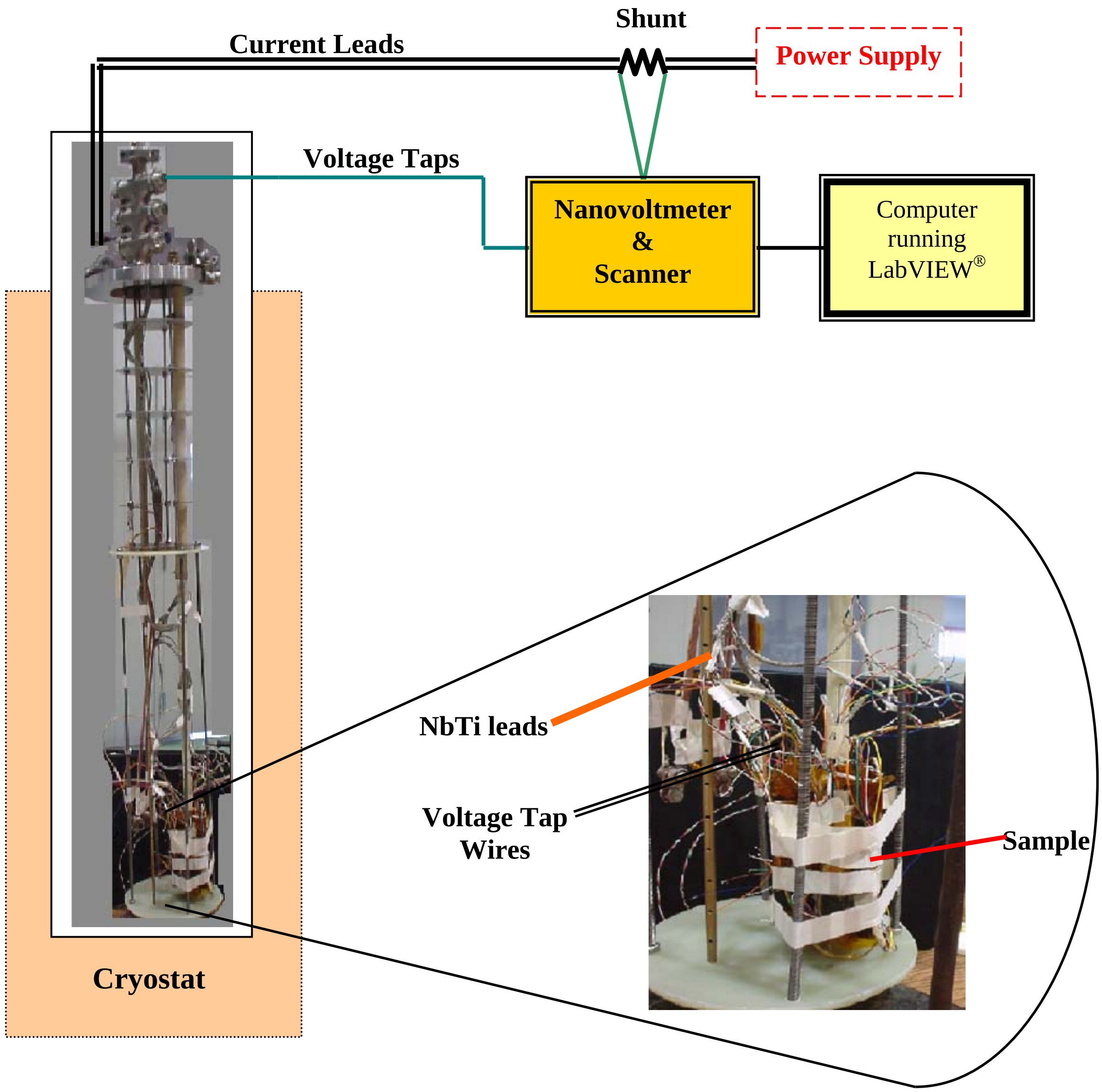

Figure 2 Apparatus Set-up

Sample Description

This was the same sample that was used in HFDA04-#2 test. The only difference was that the data was taken from cables a little deeper into the magnet (Fig. 3).

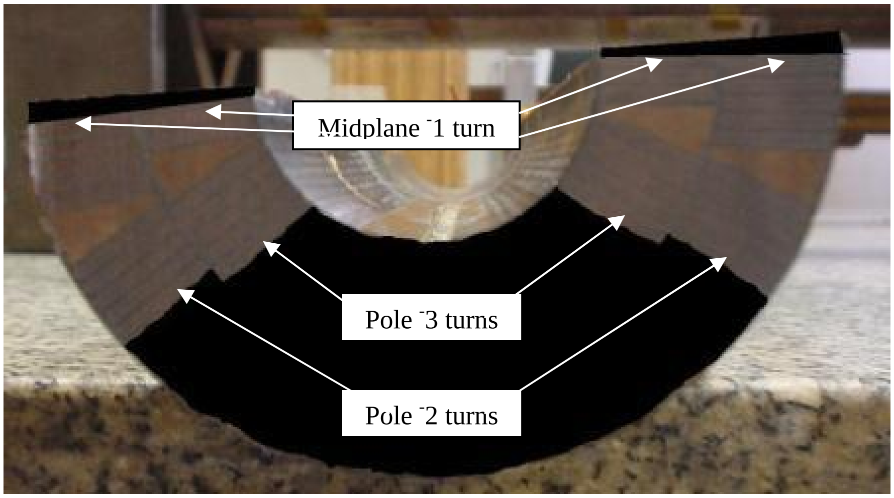

Figure 3. Removed Sections of Coil

All cables tested were made of wires produced by Oxford Superconducting Technology using the Modified Jelly-Roll fabrication method. They had 54 subelements surrounded by a Nb barrier [2]. The coil sample was a five-inch (127 mm) long section of the straight part of a coil of HFDA04. The HFDA-04 magnet was a cos-θ magnet fabricated with the Wind-and-React technology using the ceramic binder and cable 28-1-No. [1]. The cable parameters are presented in Table 2.

TABLE 2: HFDA04-03 Cable parameters

Cable	28-1-No
Strand diameter (mm)	1
Number of strands	28
Cable width (mm)	14.23
Cable thickness: thin-thick edge (mm)	1.69-1.91
Cable pitch length (mm)	110
Stainless steel core thickness (μm)	No core

Five cables were instrumented and tested. Two of the instrumented cables came from the pole side of the magnet (Fig. 4). On the other side of the sample three of the four midplane-1 turns were tested (Fig. 5). The technique used to instrument the cables was described in [3].

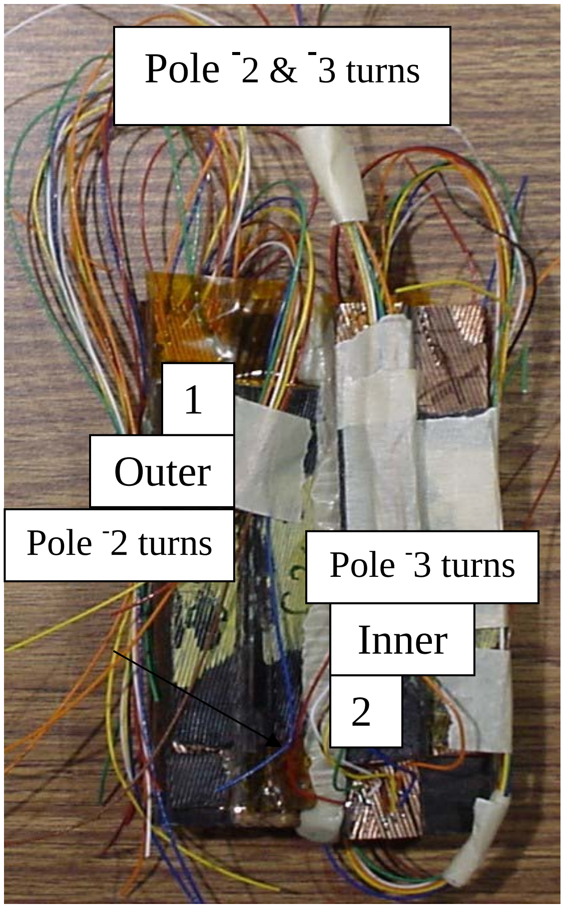

Figure 4. Pole Portion of Magnet Coil

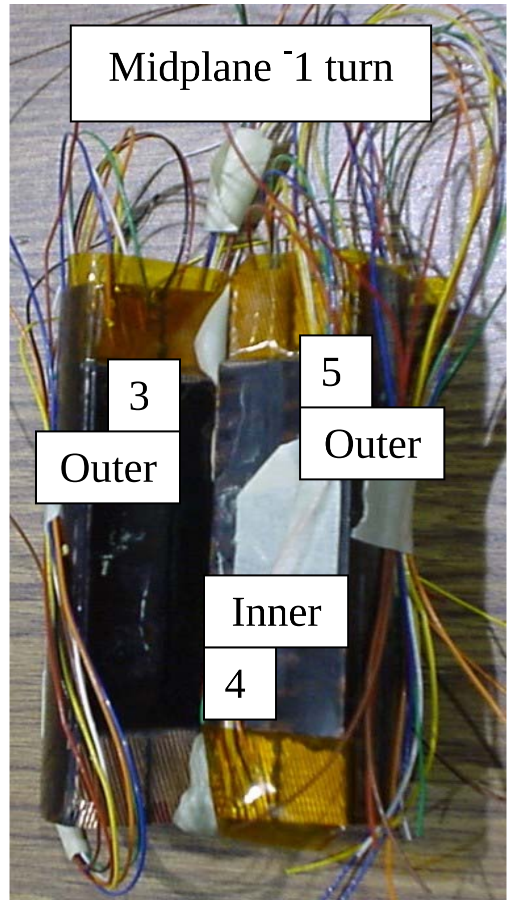

Figure 5. Midplane Portion of Magnet Coil

Sample Preparation

The goal of the sample preparation was to modify a section of the magnet coil for cryogenic testing to measure the adjacent and crossover resistance in the selected cables of the sample. The cryostat used can handle up to five samples. The samples tested were instrumented with eight voltage taps each. These samples were prepared according to the following procedure.

✳ Make a cut of the magnet where the coil has a straight section (Fig. 6).

- ⇒ This section was reduced to the final length (10 mm longer than a transposition pitch) by removing 25 mm from each end.

- ⇒ These last two cuts were performed with a wet saw taking particular care not to "open" the ends of the sample (for instance some samples were cut after immersion in liquid nitrogen) [1].

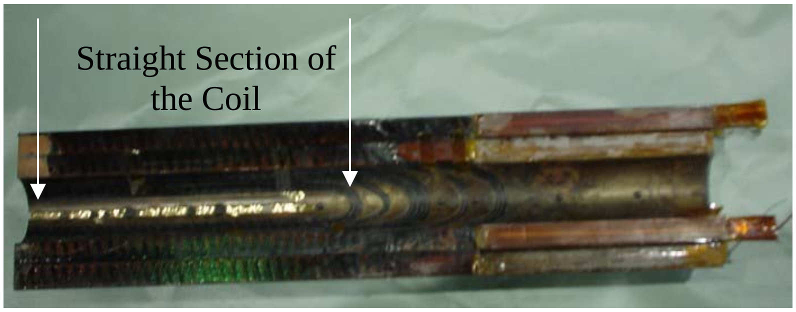

Figure 6. Long View of Magnet Coil

- Carefully polish the ends.
  - ⇒ This was done in order to avoid contacts among strands by residues from the cut.

- Remove the epoxy and insulation from a 10-mm long section at the end of the cables to be tested.

- Polish the section again where the epoxy and insulation was removed.
  - ⇒ This removes most of the residue from the epoxy. The polishing was performed with a cotton swab and alcohol.

- After polishing, remove about a 6 mm section from strands 10 – 13 (Fig. 7).
  - ⇒ These strands were removed to solder the lead onto strand 15 because it was on the bottom layer of the cable.

- Now the cable is ready for soldering of the voltage taps and leads.

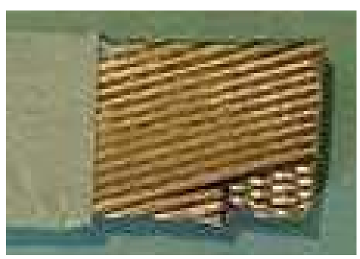

Figure 7. Nb_3Sn Cable with strands 10 – 13 removed

Soldering

Voltage taps were soldered on selected strands (Fig 8): those to which the leads were soldered and 6 additional strands.

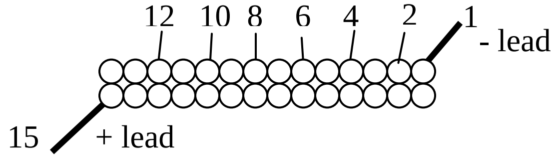

Figure 8. Cross-sectional view of a Nb_3Sn Cable

Two techniques were alternatively used in order to prevent bonding adjacent strands during soldering of leads or voltage taps: the target strand was isolated from the adjacent by a U-shaped thin layer of Kapton, or the adjacent strands were protected by insulating varnish and masking tape [1]. The most effective of the two methods is to make a U-shaped layer of Kapton. The Kapton acted as a great insulator against the solder connecting adjacent strands together. The easiest way to prepare the sample is to attach the voltage taps first and the current leads second. Figure 9 shows an example of how a cable properly prepared should look. Since soldering is a delicate process, the person preparing the sample MUST have steady hands and a lot of patience.

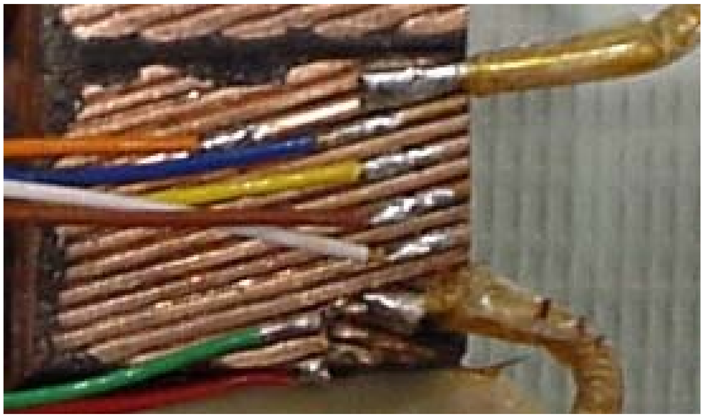

Figure 9. Sample with voltage taps and NbTi current leads

If the person preparing the sample is right handed, it might be easier to solder starting at strand 1 and ending with strand 15.

- ✳ Use a scalpel to gently separate strand 1 from the rest of the sample.
  - ⇒ Move it just enough to put a U shaped strip of Kapton around the selected, isolated strand.
- ✳ Next, pre-tin the strand and the wire used as a voltage tap before soldering them together.
  - ⇒ Pre-tinning is used to prevent cold soldering. A bond made of cold solder can easily be broken.
- ➢ Complete these steps for each of the 7 other strands.

In this area, current leads were soldered to two strands at the edges of the cables. Because of the transposition angle a strand of these lies on the bottom side of the cable. Therefore, that is why the 6 mm sections of some strands above it were removed for the lead (NbTi wire) to be soldered on strand 15. Now the current leads must be attached. Use the Kapton as an insulation again as it was done with the individual strands.

- ✳ Pre-tin the NbTi current lead and the strand 1.

- ✳ Next carefully solder the leads to the cable being careful not to break the fragile Nb_3Sn strands.

After all of the leads and voltage taps have been connected, the wires from the sample holder can now be connected to the wires from the sample. Solder them together and use shrink wrap to cover the exposed area of the soldered wire. Now is a good time to check the continuity of the sample. Next safely secure the sample in the sample holder so that it will not rattle or move. Also secure the loose wires in the sample holder so that it will reduce the noise during cryogenic testing. The final step is to put the sample holder into the cryostat for testing.

Measurement Procedure

Measurements were performed in boiling liquid helium at atmospheric pressure. It followed the same procedure as in [1]. The current was ramped from zero to the set value in a few seconds, held for about 30 seconds and then turned off to zero. This procedure was repeated for several different current values, first increasing the set point, and then decreasing it (i.e. 0, 5, 0, 12, 0, 16, 0, 20, 0, 30 …)[4]. Since the addition of a way to change the current flow, measurements were also taken with reverse current. The data with reverse current were only taken at 30 and 40 amps. This full set of measurements was repeated one or more times in order to check reproducibility (sometimes with different current steps). This process was repeated for each of the samples by changing the connector above the top of the cryostat. The use of a stepped current profile was preferred to the slow constant increment used by other authors, [5], because it allows for a more precise correction of the voltage offset at zero current.

Data Analysis

The goal of the data analysis is to obtain the voltage distribution across the cable cross-section when a constant current (for instance 100 A) is flowing from one edge of the cable to the other. The voltage of the instrumented strands is measured at several currents and a linear interpolation is used to obtain an effective resistance. This method is used in order to reduce the noise and to see if deviation from linearity occurs above a current threshold. The voltage distribution (at fixed current) obtained in this way is compared with a simulated voltage distribution (using VIRCAB [6]). The main cable parameters (strand and cable dimensions & strand number…) and guess values for Ra and Rc are used to generate the simulated voltage distribution. The guess values are changed until a good fit of the experimental data is achieved. The procedure for data analysis is explicitly described in [1].

Results

These are the results from testing HFDA04-#3 sample. The following charts display the voltage (scaled at 100A) of the instrumented strands on all cables tested. They also show the best fit obtained using VIRCAB. The Ra (adjacent resistance) and Rc (crossover resistance) are the only true parameters of the fit. The values producing the best fits are reported in each chart below.

First Set of Measurements

HFDA04-#3 pole-3,
-- Sample 2

In the first measurement, Channel 8 of Sample #2 showed a non-linear behavior of voltage versus current. The reason for this behavior is due likely to the position of the voltage tap that was very close to the soldering between the strand and current lead. Because of this non-linear behavior, current values greater than 15 amps were disregarded for Channel 8. Nonetheless the fit of channel 8 may still be biased by the problem causing the non-linear behavior (resulting in a value for strand 15 in Chart 1 higher that the actual). Chart 2 shows the voltage drop on each channel for different current values.

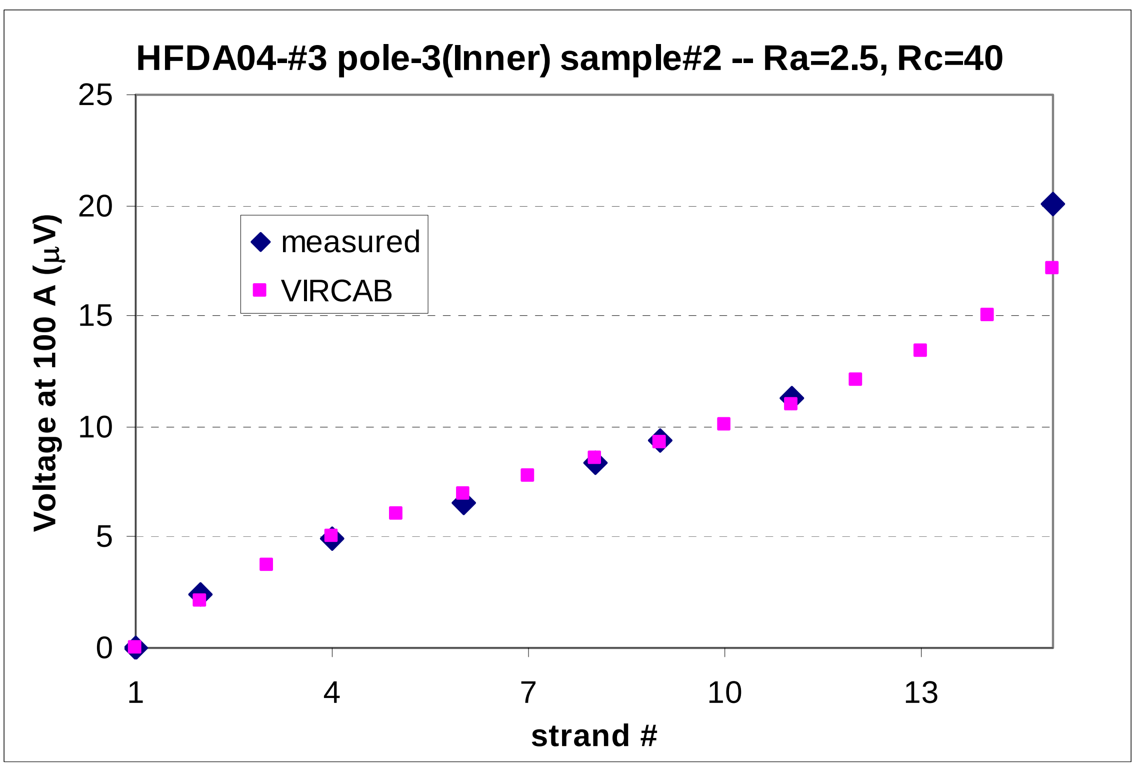

Chart 1

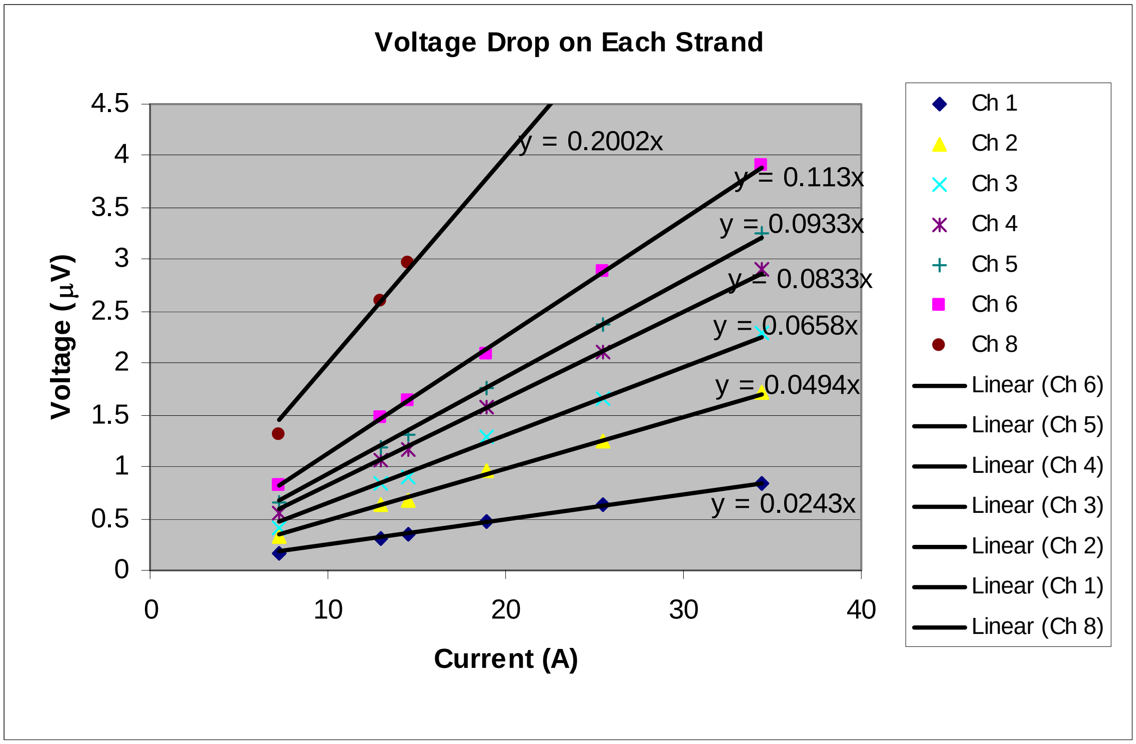
Voltage Drop on Each Strand
Voltage (μV)
Current (A)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
y = 0.2002x
y = 0.113x
y = 0.0933x
y = 0.0833x
y = 0.0658x
y = 0.0494x
y = 0.0243x
Ch 1
Ch 2
Ch 3
Ch 4
Ch 5
Ch 6
Ch 8
Linear (Ch 6)
Linear (Ch 5)
Linear (Ch 4)
Linear (Ch 3)
Linear (Ch 2)
Linear (Ch 1)
Linear (Ch 8)

Chart 2

HFDA04-#3 midplane-1,
-- Sample 3

Sample #3 had two different voltage distributions. To accommodate the situation, two charts were made to get a range of data. These arrangements were made because the way data was inputted into VIRCAB assumed symmetric distribution across the cable. Chart 3 used the resistances of the first four voltage taps. Chart 4 used the resistances for the last four voltage taps.

Fit#1

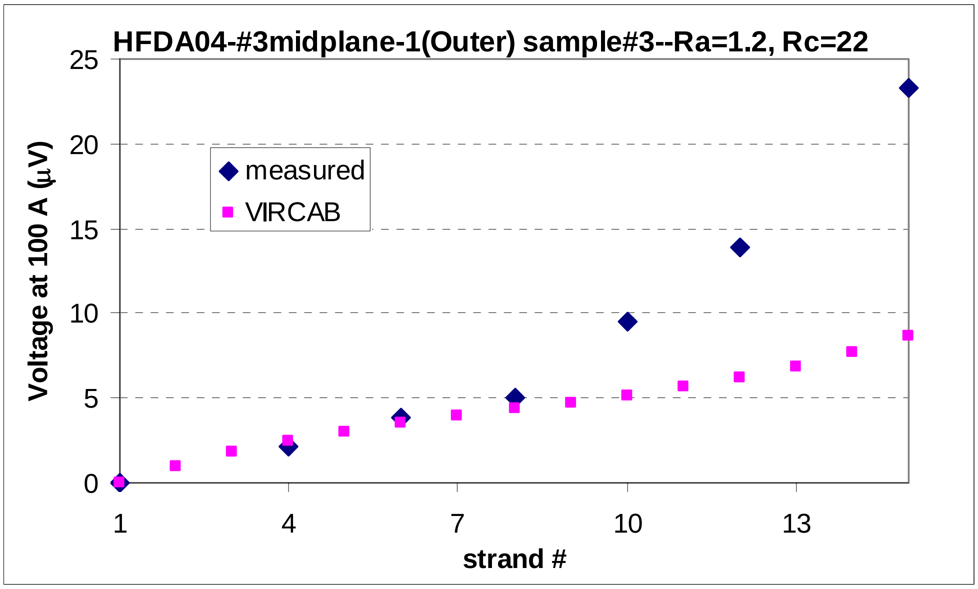

Chart 3

Fit #2

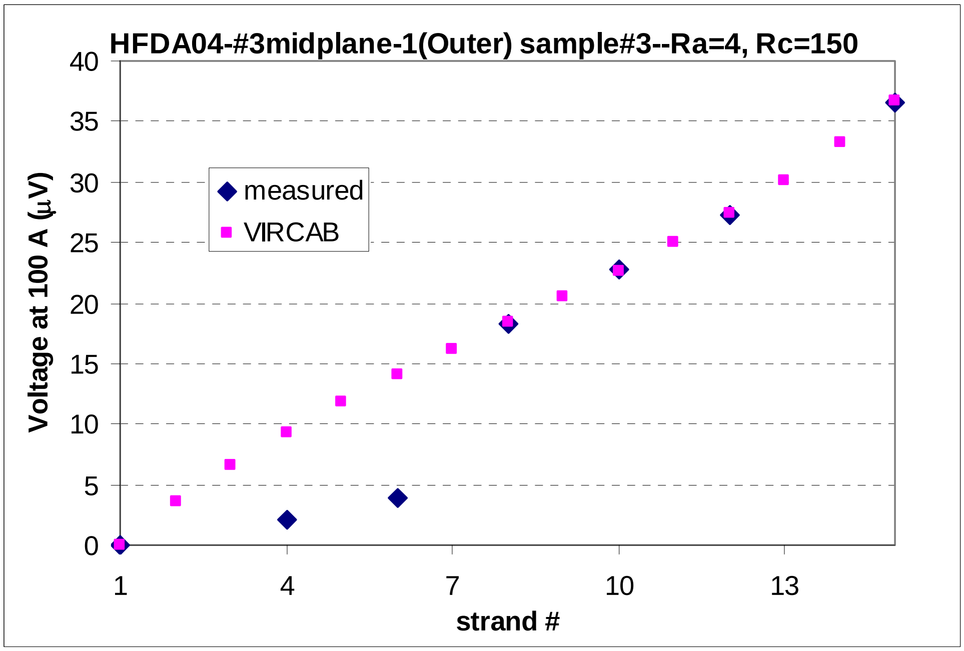

Chart 4

HFDA04-#3 Midplane-1,
-- Sample 4

Like Chart 4 of sample #3, sample #4 had linear behavior of voltage versus current. Lines of these slopes are caused by extremely high crossover resistance values. Chart 6 shows that the change of voltage is almost constant between each strand.

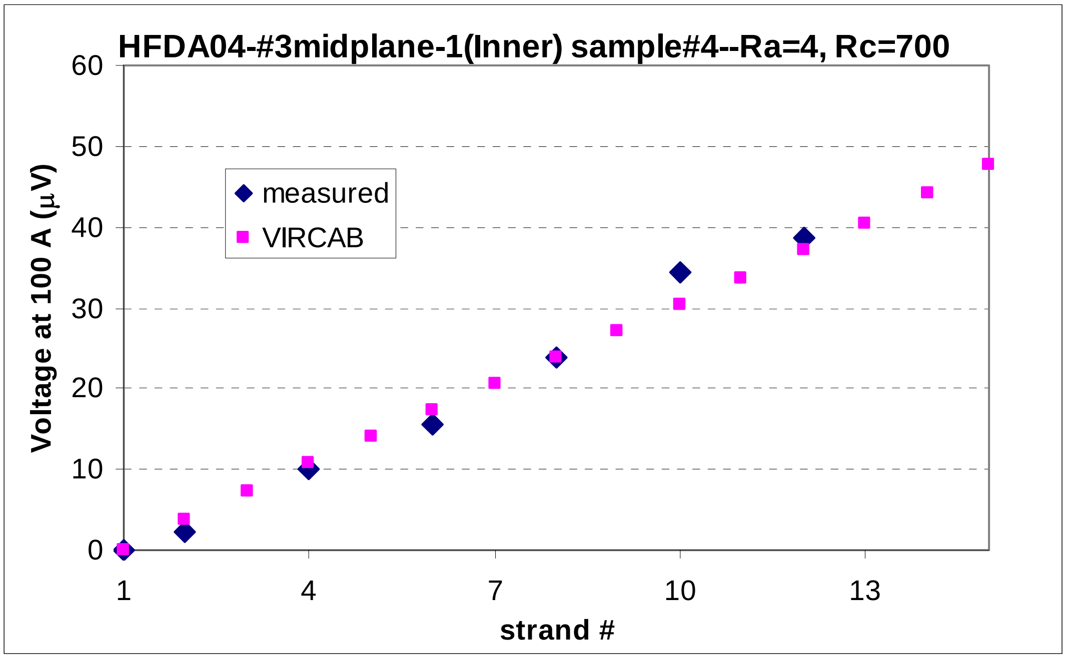

Chart 5

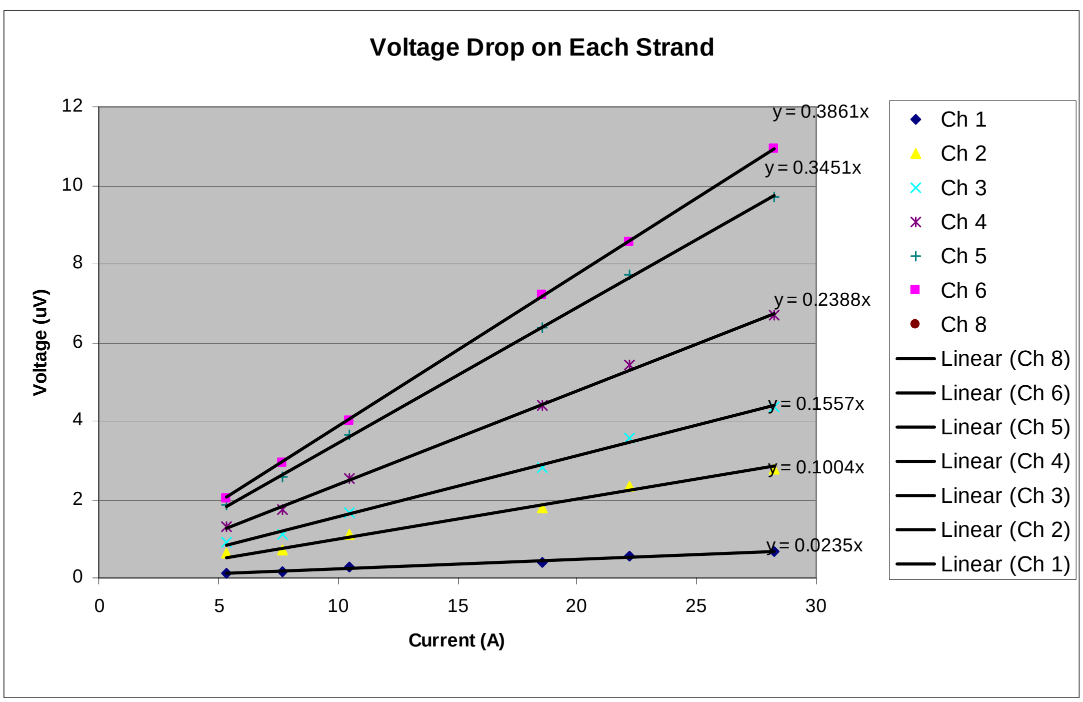

Chart 6

Second Set of Measurements

HFDA04-#3b Pole ˉ2,
-- Sample 1

The plateau from Strand 4 to 10 indicates that Rc . Ra.

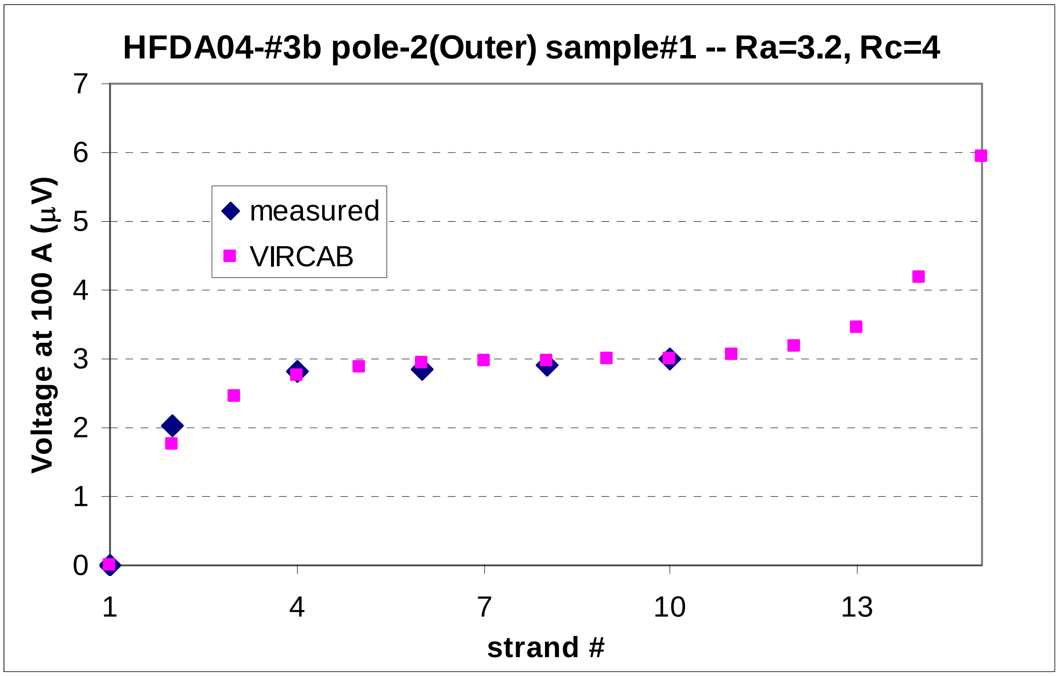

Chart 7

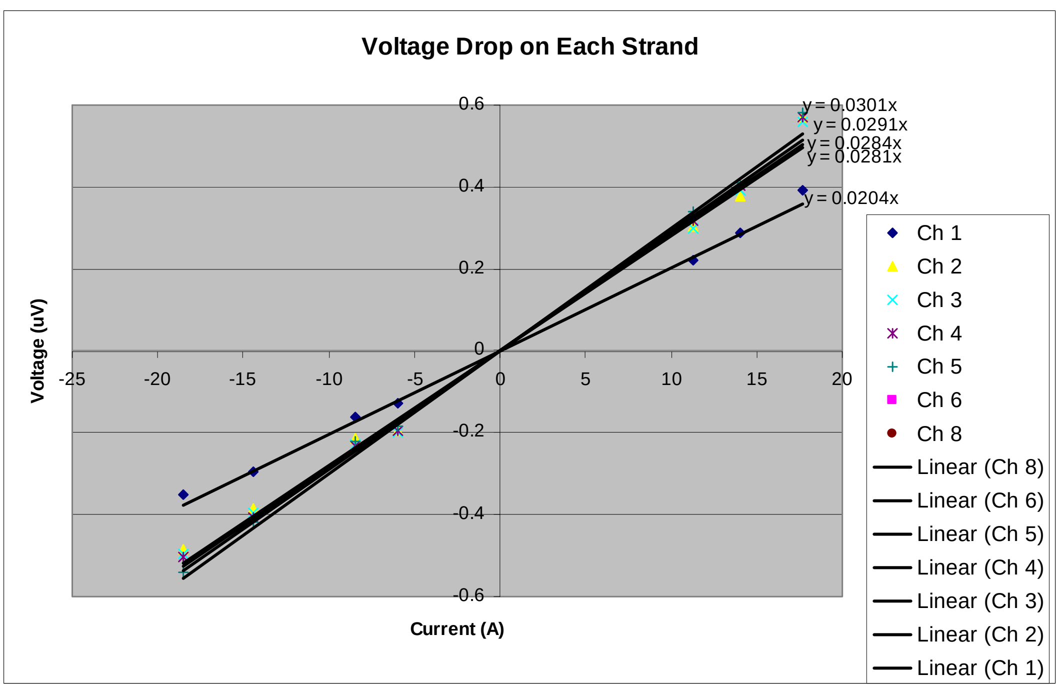

Chart 8

HFDA04-#3b Pole ¯3,
-- Sample 2

The high measured value of Strand 15 in chart 9 is assumed to be caused by the voltage tap being soldered close to the lead. Chart 10 shows the voltage drop on each strand as a result of current.

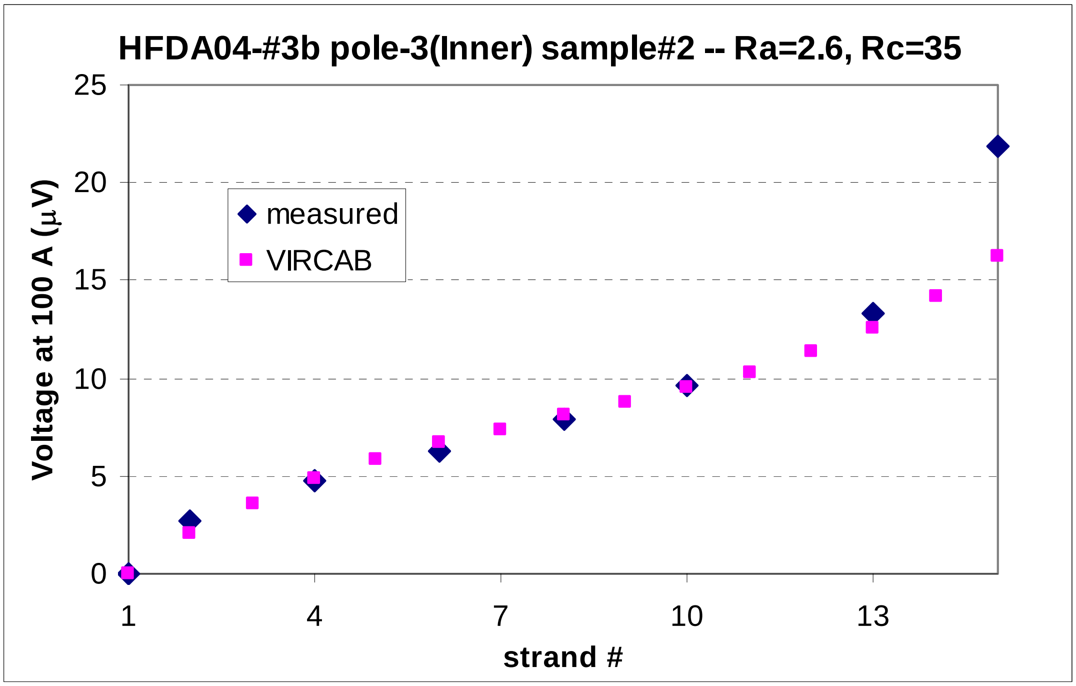

Chart 9

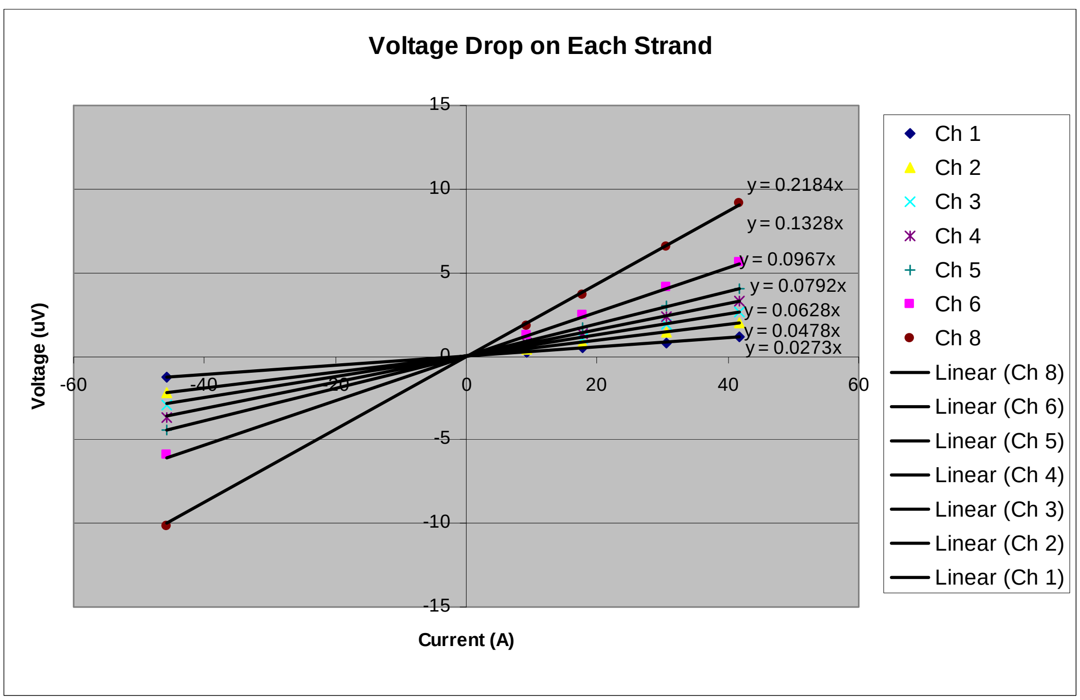

Chart 10

HFDA04-#3b Midplane -1,
-- Sample 3

As in the first set of measurements, this sample needed two fits to get a range for the resistances.

Fit #1

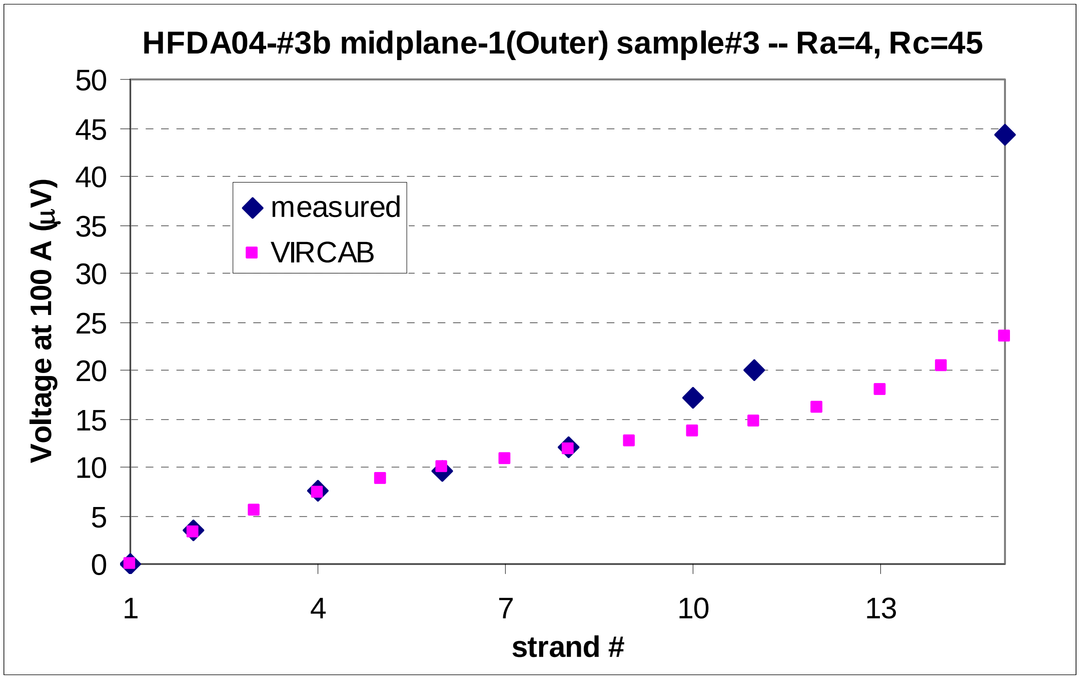

Chart 11

Fit #2

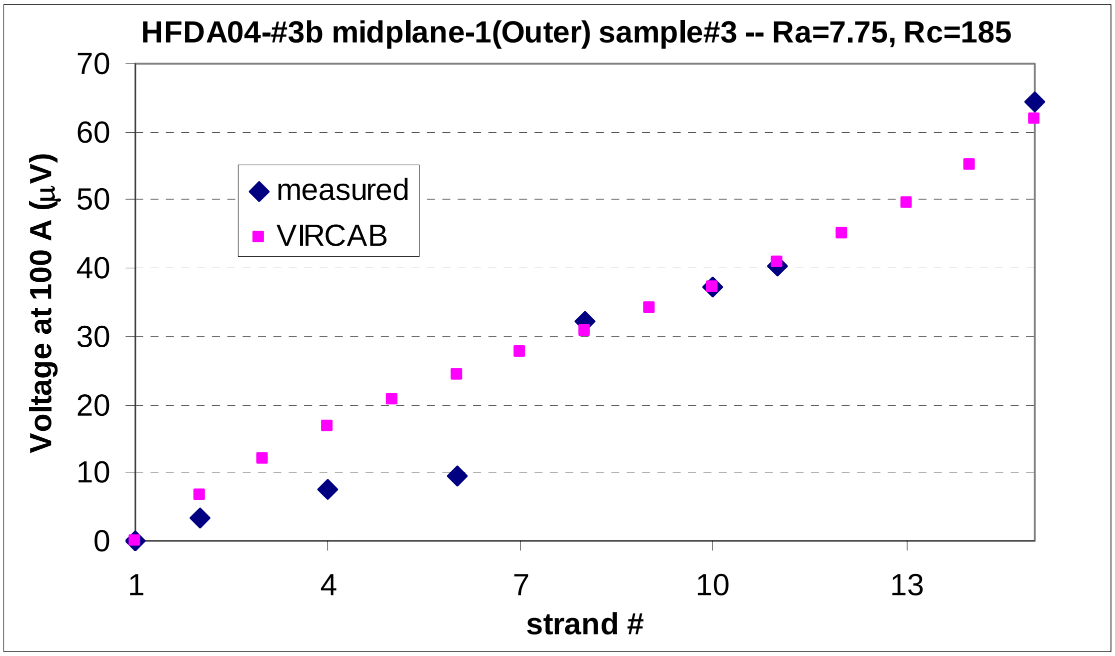

Chart 12

HFDA04-#3b Midplane ¯1,
-- Sample 4

The second set of measurements for sample 4 showed the same linear behavior as in its first set of measurements.

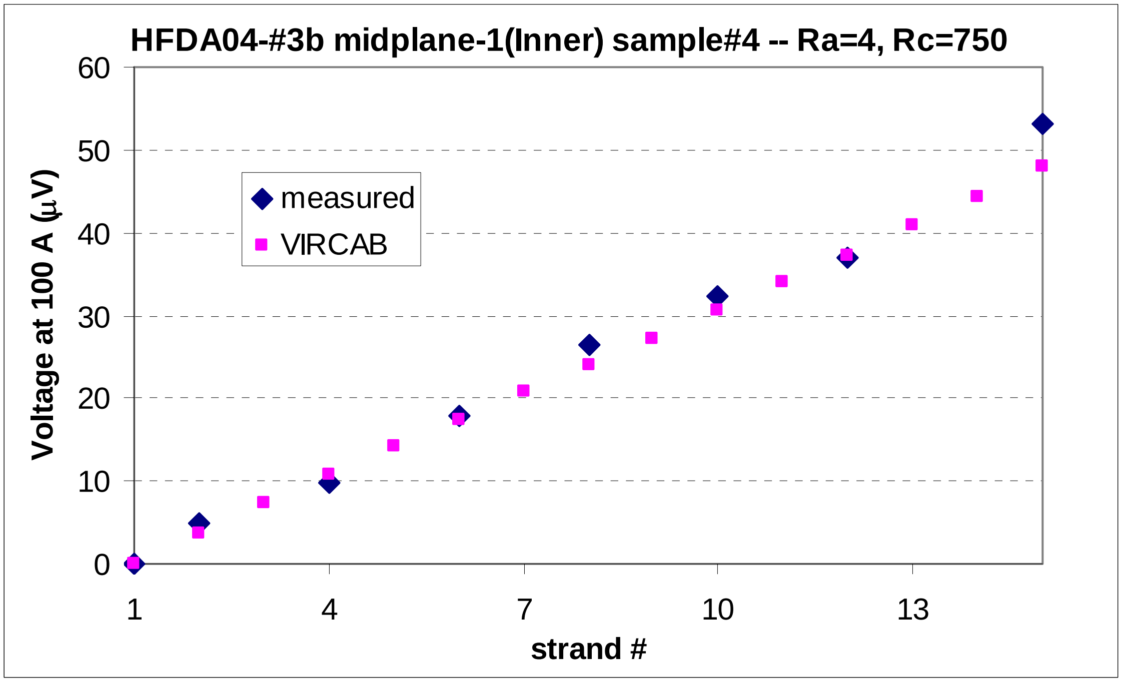

Chart 13

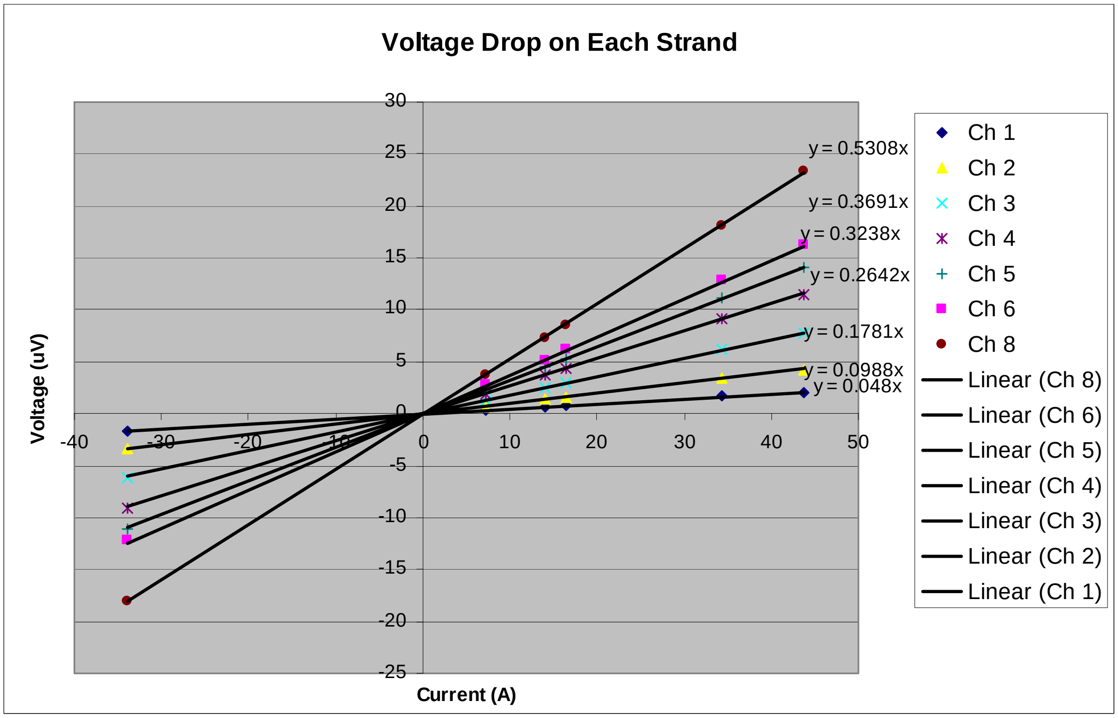

Chart 14

HFDA04-#3b Midplane ¯1,
-- Sample 5

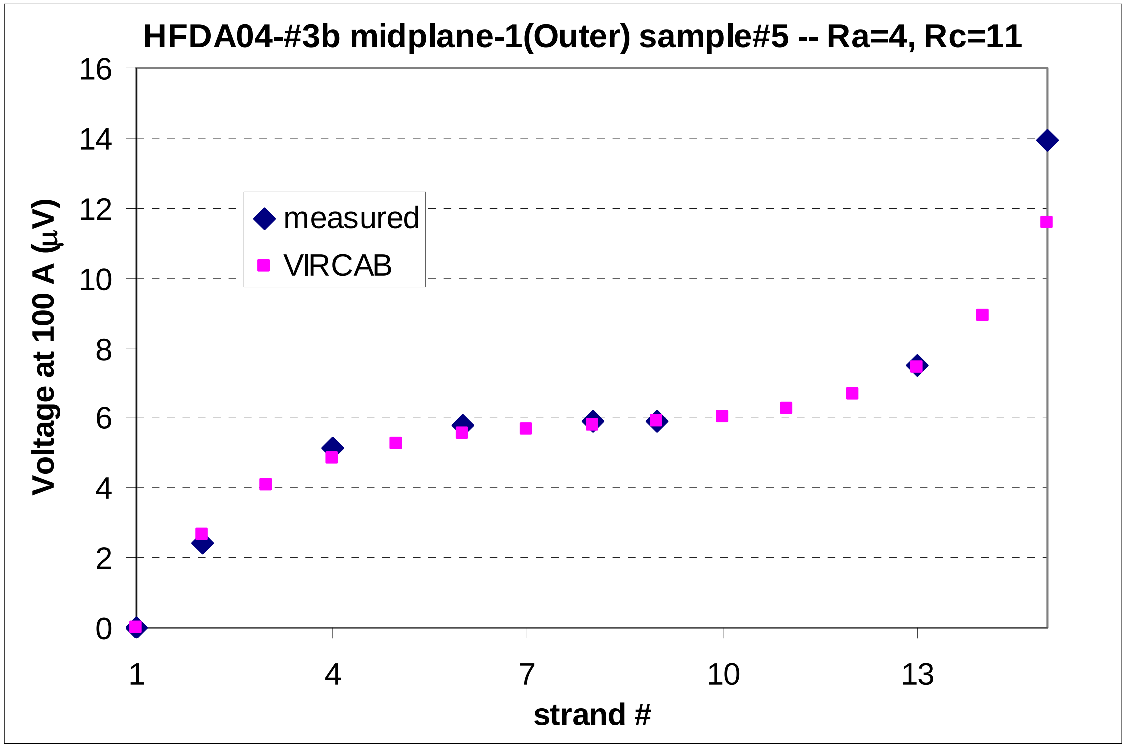

Chart 15

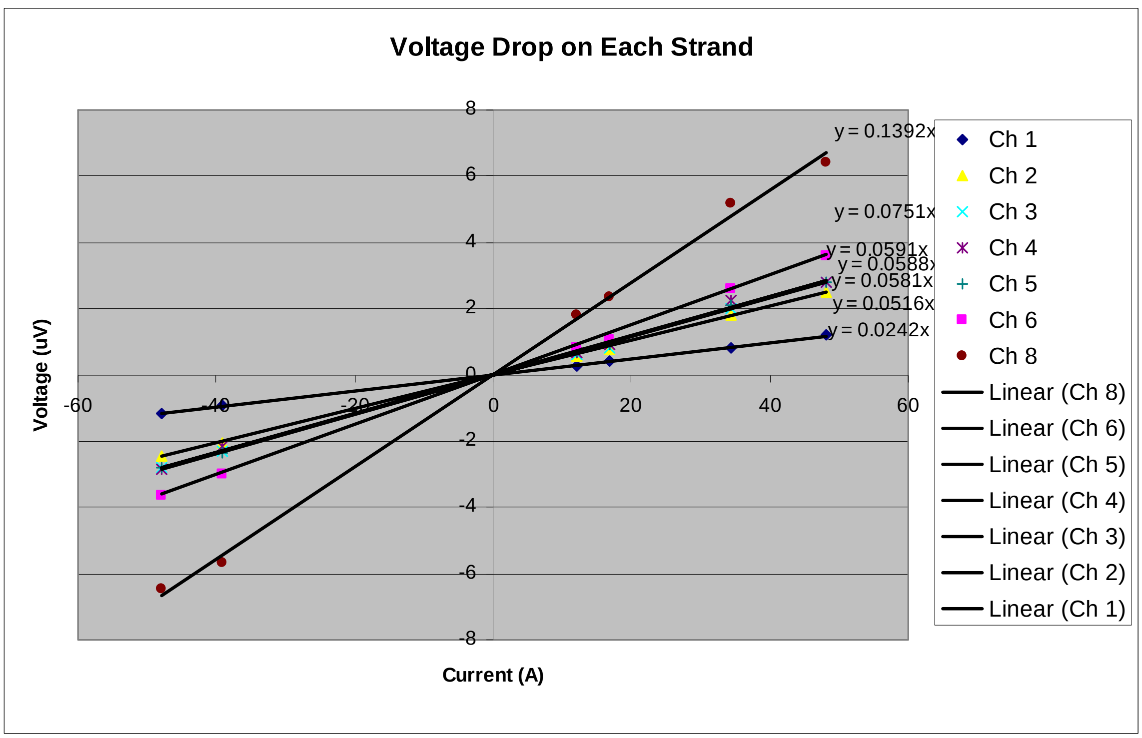

Chart 16

Final Results

All results are summarized in the following table.

Position	Sample	Run	Coil Layer	Ra (Ωμ)	Rc (Ωμ)
Pole -2	1	1	Outer	3.2	4
Pole -3	2	1	Inner	2.5	40
		2		2.6	35
Midplane -1	3	1	Outer	1.2 – 4	22 – 150
		2		4 – 7.75	45 – 185
Midplane -1	4	1	Inner	4	>300
		2		4	>300
Midplane -1	5	1	Outer	4	11

Table 3. The Results of all the Samples Tested from HFDA04-#3

For easy comparison, the results of the previous set of measurements are reported below.

Position	Sample	Run	Coil Layer	Ra (μΩ)	Rc (μΩ)
Midplane	A	1	Outer	**3**	**30**
	B	1	Inner	**~3**	**≥ 500**
	C	1	Inner	**2.6 - 3**	**≥ 500**
	D	1	Outer	**2.5**	**20**
Pole -1	2	1	Inner	**1.88**	**6**
	3	1	Inner	**0.75**	**4.45**
	4	1	Outer	**4.25**	**4.38**

Table 4. The Results of all Samples Tested from HFDA04-#2

Conclusion

The analysis confirmed the hypothesis that there are significant differences between turns on the midplane and of the pole. The values of Rc in the inner layer are higher than in the outer layer. The values for Sample 3 differ because the distribution across the strands is not constant. Therefore, it is not possible to make only one fit for this sample.

During the impregnation process, the coils are filled with epoxy while they are under pressure. If the pressure is not uniform, the amount of epoxy into the cable will depend on the local pressure. If the magnet was not evenly compressed during impregnation and curing, the resistance throughout the magnet will be different. From these results, it is assumed that the low azimuthal pressure was applied on the midplane of the inner layer.

References

[1] D. Tooke, G. Ambrosio, L. Elementi, "Interstrand Contact Resistance of Nb_3Sn Superconducting Cables Extracted from Magnets", TD-04-037

[2] E. Barzi, et al., "Superconductor and Cable R&D for High Field Accelerator Magnets at Fermilab", in *IEEE Trans. Appl. Supercond*., **12**, no.1, pp. 1009-1013 (2002).

[3] D. Chichili, et al., "Nb_3Sn Cos (theta) Dipole Magnet, HFDA-04 Production Report", Fermilab Technical Division report TD-02-025 (2002).

[4] G. Ambrosio, E. Barzi, L. Elementi, A.V. Zlobin, "Measurement of Inter-Strand Contact Resistance in Epoxy Impregnated Nb_3Sn Rutherford Cables", CEC/ICMC03

[5] R. Soika, et al., "Inter-Strand Resistance Measurements in Cored Nb-Ti Rutherford Cables", in *IEEE Trans*. *Appl. Supercond*., **13**, pp 2376-2379 (2003).

[6] A.P. Verweij, CERN, private communication

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