Winding and 77K Testing of Non-Insulated Coils for the IBS 25T, 100 mm bore HTS Solenoid

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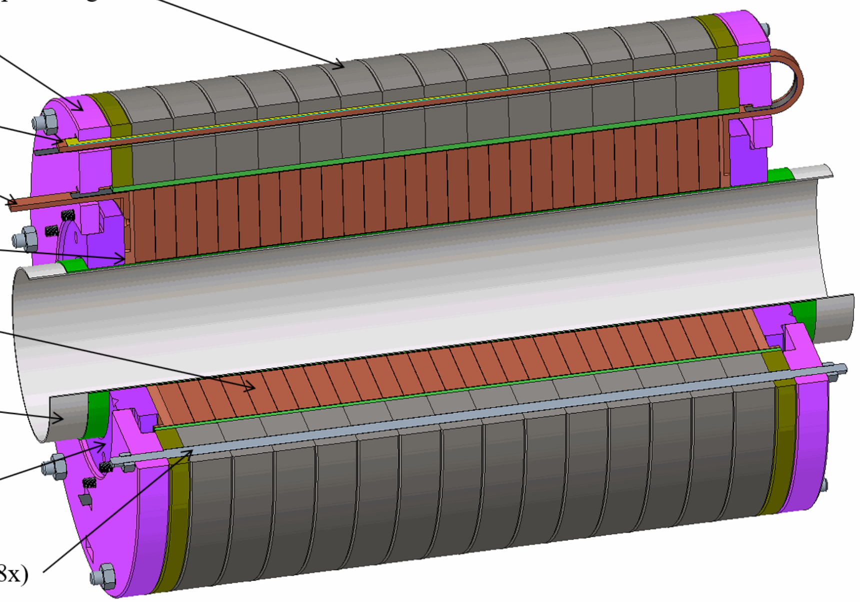
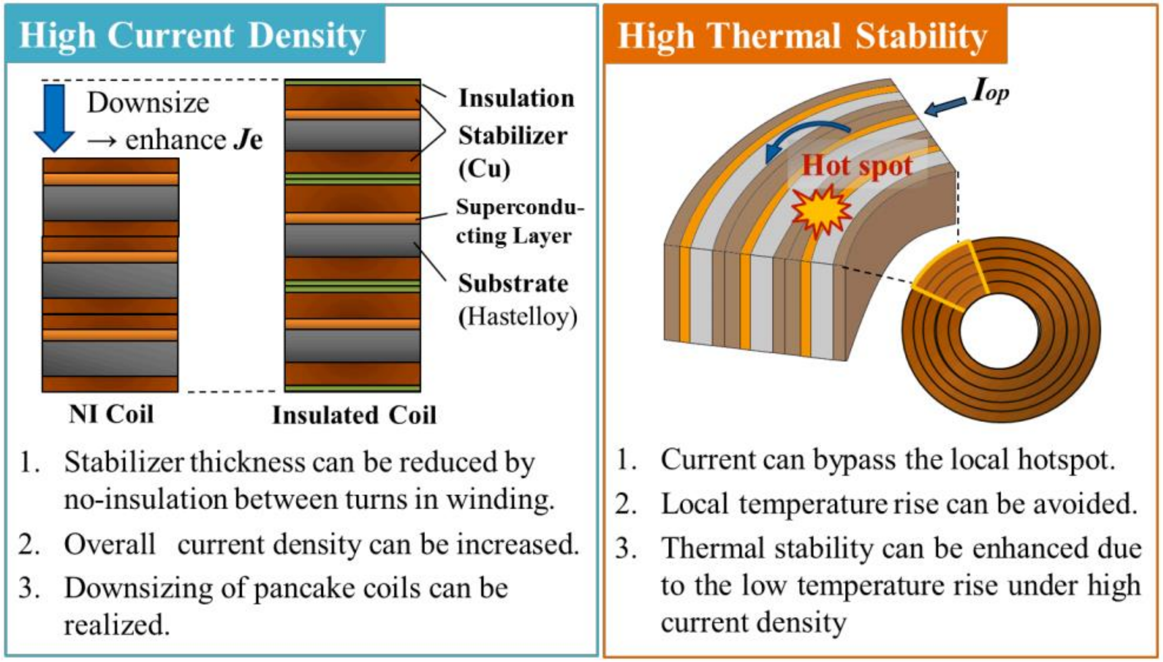
INTRODUCTION



- The Institute of Basic Science (IBS) in South Korea requires a **25 Tesla, 100 mm bore solenoid for experiments searching for dark matter axions search**.
- The Superconducting Magnet Division at Brookhaven National Laboratory received a contract to design and build this magnet.
- The **design is based on no-insulation approach using second generation HTS**.
- **BNL has built 16 of the 28 coils needed; tested 12 (@ 77 K) of the 16 built**.
- This presentation summarizes the construction and 77 K test results.

NO-INSULATION



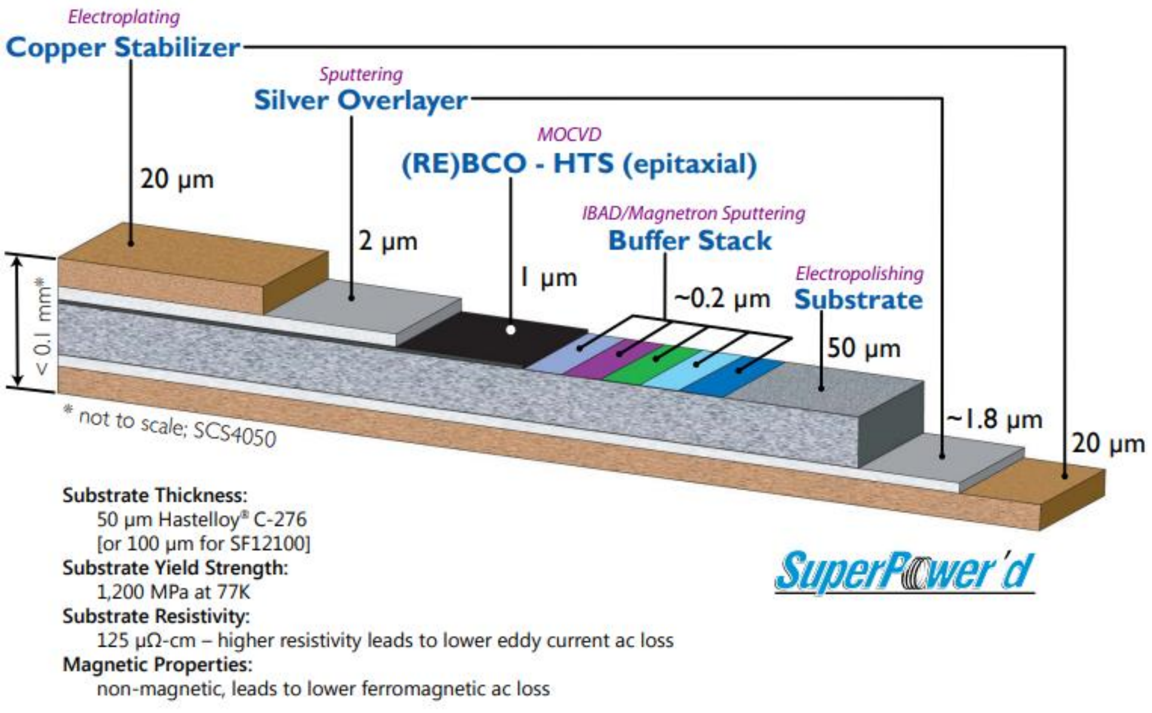
Non-Insulated (HTS) Magnet coils offer:

- **reliable intrinsic quench protection**
- the **ability to tolerate local defects** in the conductor or **sudden changes in operation**

as compared to HTS coils made with metallic or non-metallic insulation.

Reference:
Wang, T., Noguchi, S., Wang, X., Arakawa, I., Minami, K., Monma, K., … Iwasa, Y. (2015). Analyses of transient behaviors of no-insulation REBCO pancake coils during sudden discharging and overcurrent. *IEEE Transactions on Applied Superconductivity*. https://doi.org/10.1109/TASC.2015.2393058

CONDUCTOR



Reference:
http://www.superpower-inc.com/system/files/SP_2G+Wire+Spec+Sheet_2014_web_v1_0.pdf

- Width of the tape : 2 mm to 12 mm
  - ➢ **12 mm gives larger current, smaller impact of local defect and fewer coils**
- Choice of substrate: Hastelloy, SS, Ni and others
  - ➢ **Hastelloy for the best mechanical properties**
- Amount of copper : 20 micron to 100 micron
  - ➢ **20 micron gives the best mechanical properties**

DESIGN SPECIFICATIONS

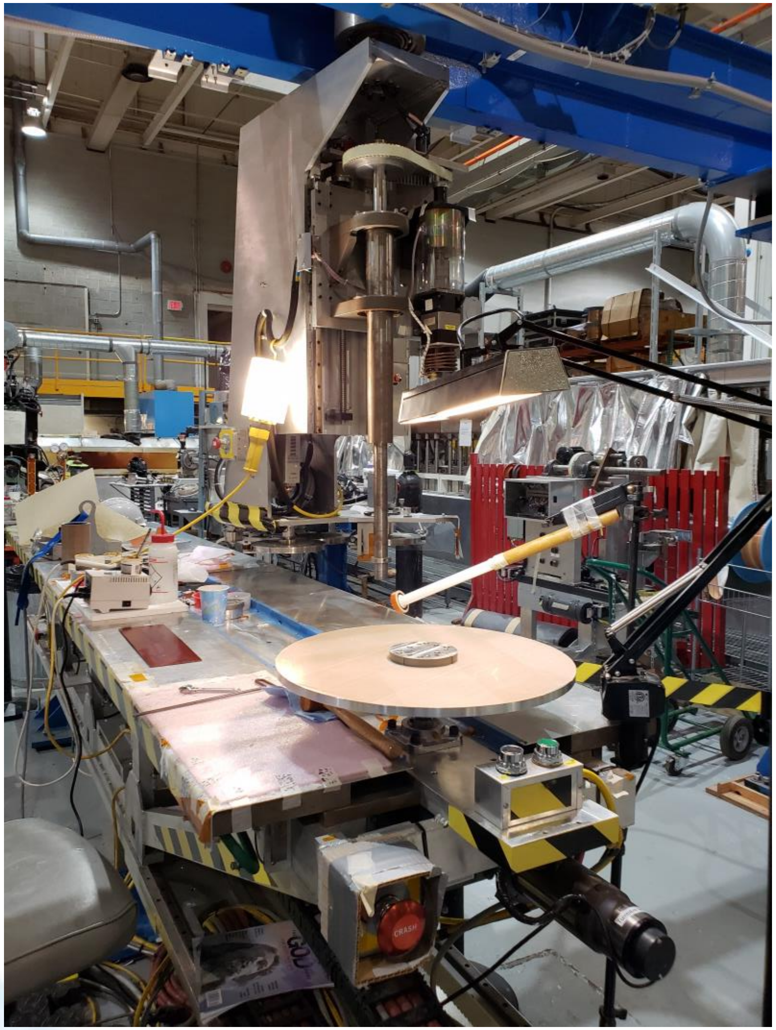
Conductor Information

Manufacturer	SuperPower Inc.[10]
HTS	REBCO
Stabilizer	Copper
Stabilizer thickness (each side)	10 μm
Substrate	Hastelloy
Substrate thickness	$\sim$50 μm
Nominal tape width	12 mm
Nominal tape thickness	0.075 mm
Critical bend radius	11 mm

Coil Specifications

Maximum center-axis field	25 T
Operating temperature	4.2 K
Number pancake coils	28
Inner diameter (ID)	105 mm
Outer diameter (OD)	200 mm
Insulation	None
Winding tension	9 lbs (40 N)
Total turns	$\sim$630
Total length of conductor	$\sim$300 m

COIL WINDING

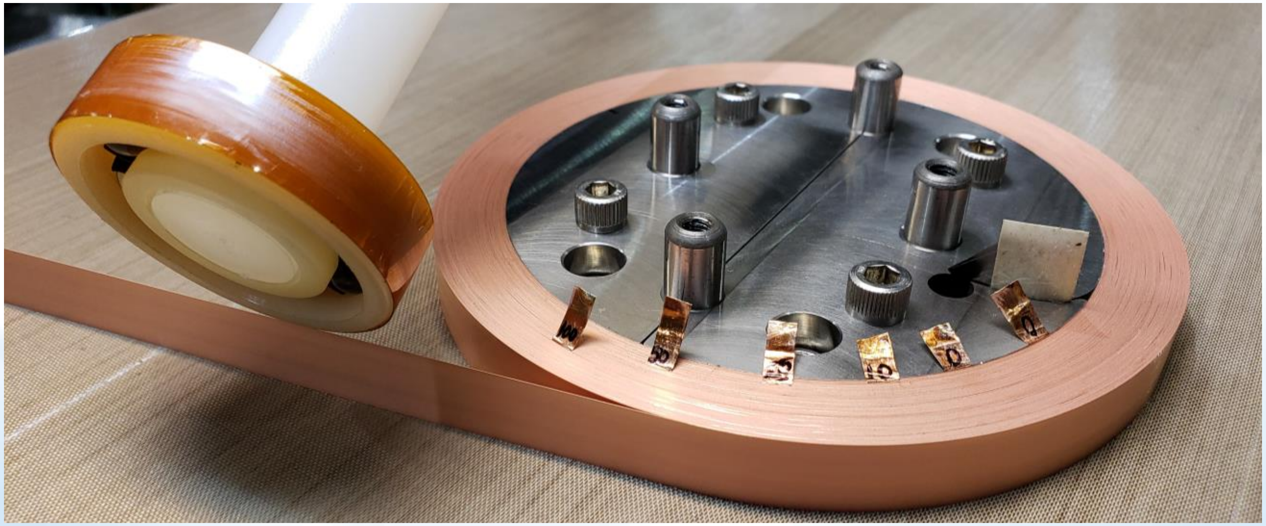


Above, left to right: **Multi-Axis Coil winding Machine, Designed and Built at BNL**; LabView based coil winding machine control program; Coil winding tension control

COIL WINDING

Above: Tin first turn for future leads and or coil inter-connections – **HTS side FACING bobbin**

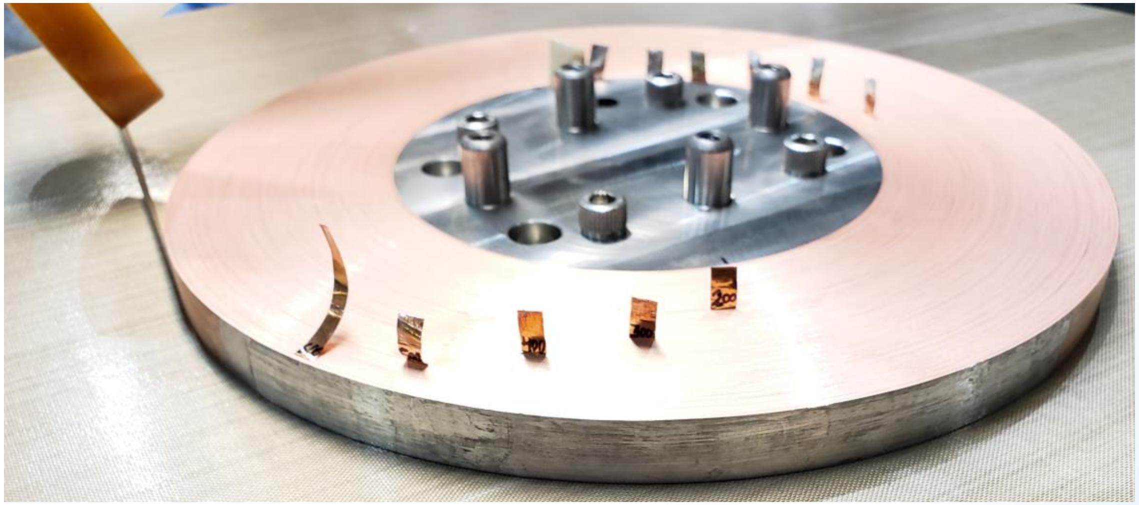
Above: Solder first turn to itself to secure inner part of coil for **reusable bobbin** removal



Left: Continue winding, with conductor under **9 lbs of tension**, until conductor runs out or splice needs to made to reverse HTS orientation (**conductor HTS side has to be FACING AWAY from bobbin on the final turn** for future leads and or coil inter-connections)

COIL WINDING

Left: Line up conductors together using splicing tool. Splice **(~23 cm in length)** conductors using Indium solder and scrape away access Indium – minimize the thickness of the splice



Above: Spliced joint being wound into the coil

Left: **Continue winding coil until coil O.D equals 200mm (~625-630 turns of 20µm Cu HTS tape).** Solder last turn to itself to hold outer part of coil together once conductor is disconnected from spool.

CONTACT RESISTANCE AND TIME CONSTANT

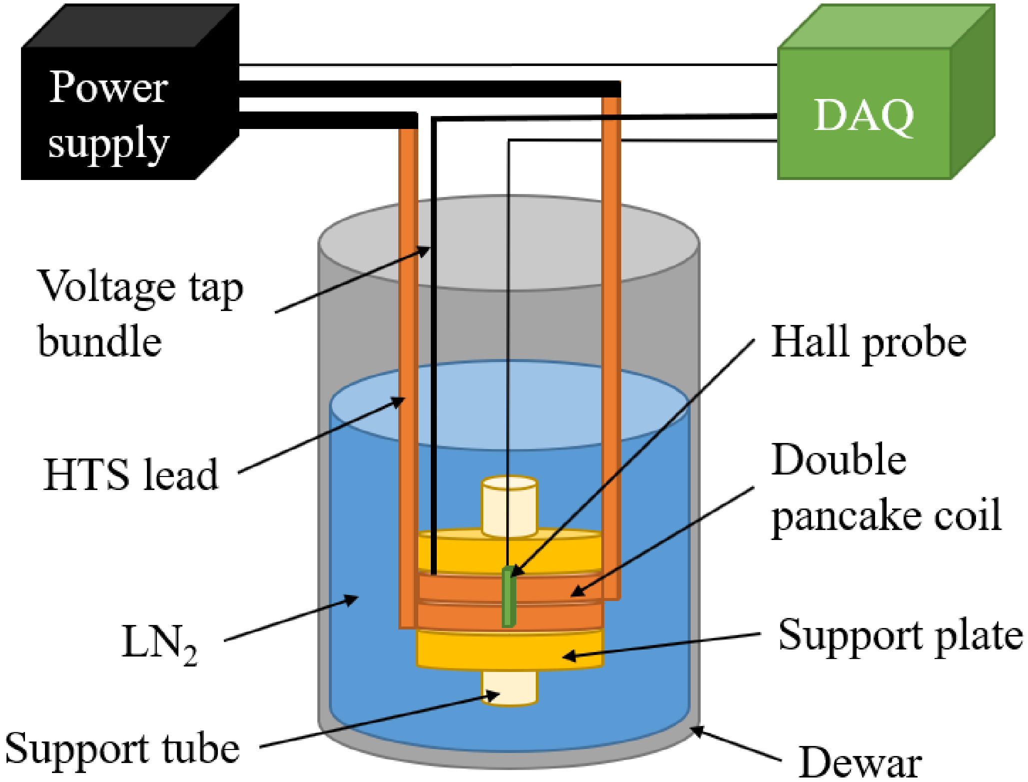
		COIL	#1		at 1 A	at R.T							
	mV	mV	mV	mV	mV	mV	mV	mV	mV	mV	mV	mV	
TURN	0-10	0-25	0-50	0-100	0-200	0-300	0-400	0-500	0-600	0-630	Outside		
10	0.452	-	-	-	-	-	-	-	-	-	-	-	6/6/18
25	0.275	0.727	-	-	-	-	-	-	-	-	-	-	6/6/18
50	0.252	0.539	1.145	-	-	-	-	-	-	-	-	-	6/6/18
100	0.242	0.52	0.993	2	-	-	-	-	-	-	-	-	6/6/18
150*	0.238	0.512	0.974	1.873	-	-	-	-	-	-	-	-	6/6/18
150*O.N	0.231	0.5	0.951	1.827	-	-	-	-	-	-	-	-	6/7/18
200	0.231	0.499	0.95	1.821	3.344	-	-	-	-	-	-	-	6/7/18
300	0.23	0.496	0.94	1.793	3.333	4.692	-	-	-	-	-	-	6/8/18
400	0.228	0.494	0.937	1.785	3.298	4.62	5.79	-	-	-	-	-	6/8/18
500	0.231	0.497	0.94	1.788	3.298	4.595	5.794	6.789	-	-	-	-	6/8/18
600	0.231	0.499	0.945	1.795	3.307	4.604	5.788	6.824	7.705	-	-	-	6/8/18
630 N.T	0.229	0.496	0.942	1.795	3.312	4.61	5.793	6.82	7.77	8.29	-	-	6/8/18
630 NT/ON	0.228	0.492	0.932	1.774	3.27	4.544	5.701	6.7	7.619	7.914	-	-	6/11/18
630 (in coil fixture)	0.199	0.487	0.959	1.83	3.36	4.672	5.854	6.878	7.826	-	8.431	-	6/20/18

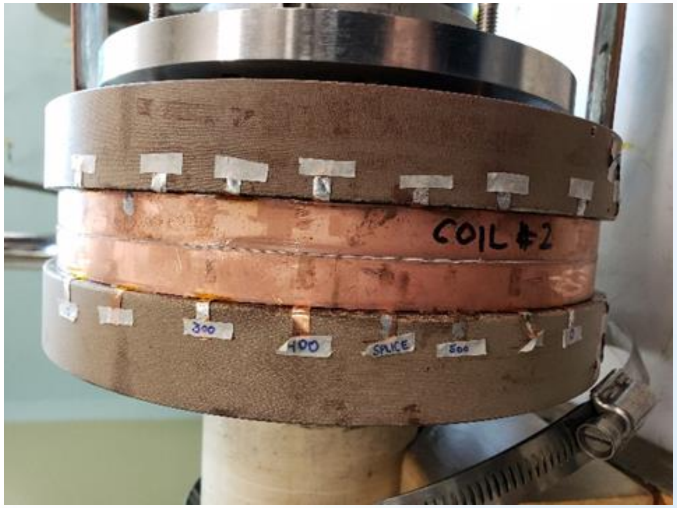
		COIL	#2		at 1A	at R.T.							
	mV	mV	mV	mV	mV	mV	mV	mV	mV	mV	mV	mV	
TURN	0-10	0-25	0-50	0-100	0-200	0-300	0-400	0-500	0-600	0-630			
10	0.409	-	-	-	-	-	-	-	-	-	-	-	6/14/18
25	0.276	0.675	-	-	-	-	-	-	-	-	-	-	6/14/18
50	0.25	0.499	1.113	-	-	-	-	-	-	-	-	-	6/14/18
50 O.N	0.241	0.485	1.088	-	-	-	-	-	-	-	-	-	6/15/18
100	0.241	0.482	0.87	1.862	-	-	-	-	-	-	-	-	6/15/18
200	0.235	0.474	0.857	1.598	2.883	-	-	-	-	-	-	-	6/15/18
300	0.234	0.474	0.855	1.593	2.921	4.111	-	-	-	-	-	-	6/15/18
400	0.234	0.474	0.856	1.594	2.916	4.136	5.199	-	-	-	-	-	6/15/18
400 O.N	0.228	0.464	0.839	1.553	2.874	4.074	5.107	-	-	-	-	-	6/18/18
500	0.228	0.466	0.844	1.576	2.881	4.08	5.184	6.16	-	-	-	-	6/18/18
600	0.229	0.468	0.847	1.581	2.888	4.089	5.186	6.216	7.117	-	-	-	6/18/18
629 ON/NT	0.228	0.466	0.844	1.575	2.879	4.074	5.165	6.183	7.148	7.535	-	-	6/19/18

- **Resistance measurements were taken** while Coils 1 and 2 were being wound at **intervals of 10, 25, 50, 100, 200, 300, 400, 500, 600, and finished coil**.

- The **resistance of the inner turns decreased, due to compression, as more turns were wound. This signifies better conductor to conductor contact between the turns.**

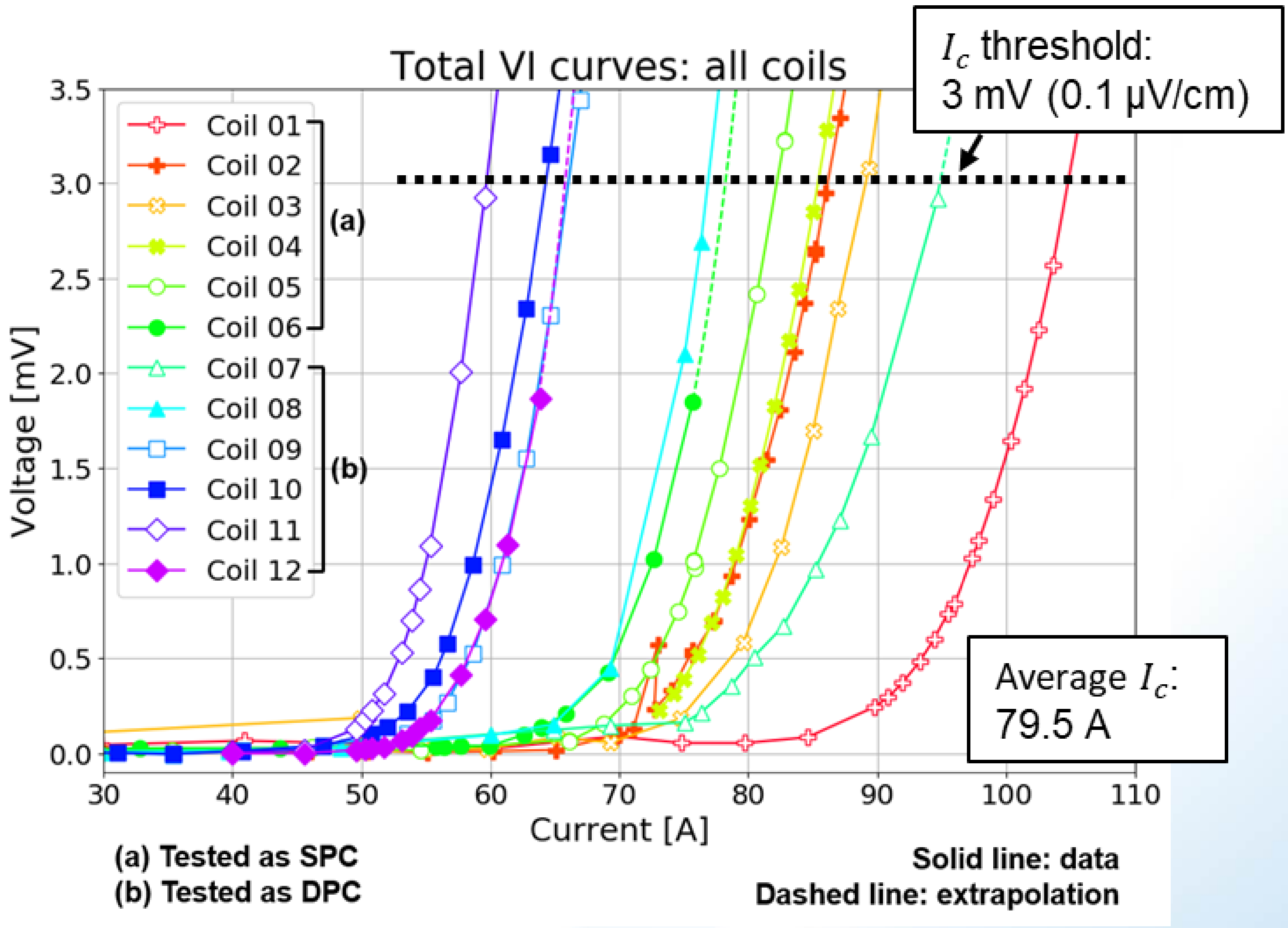
COIL TESTING - SETUP





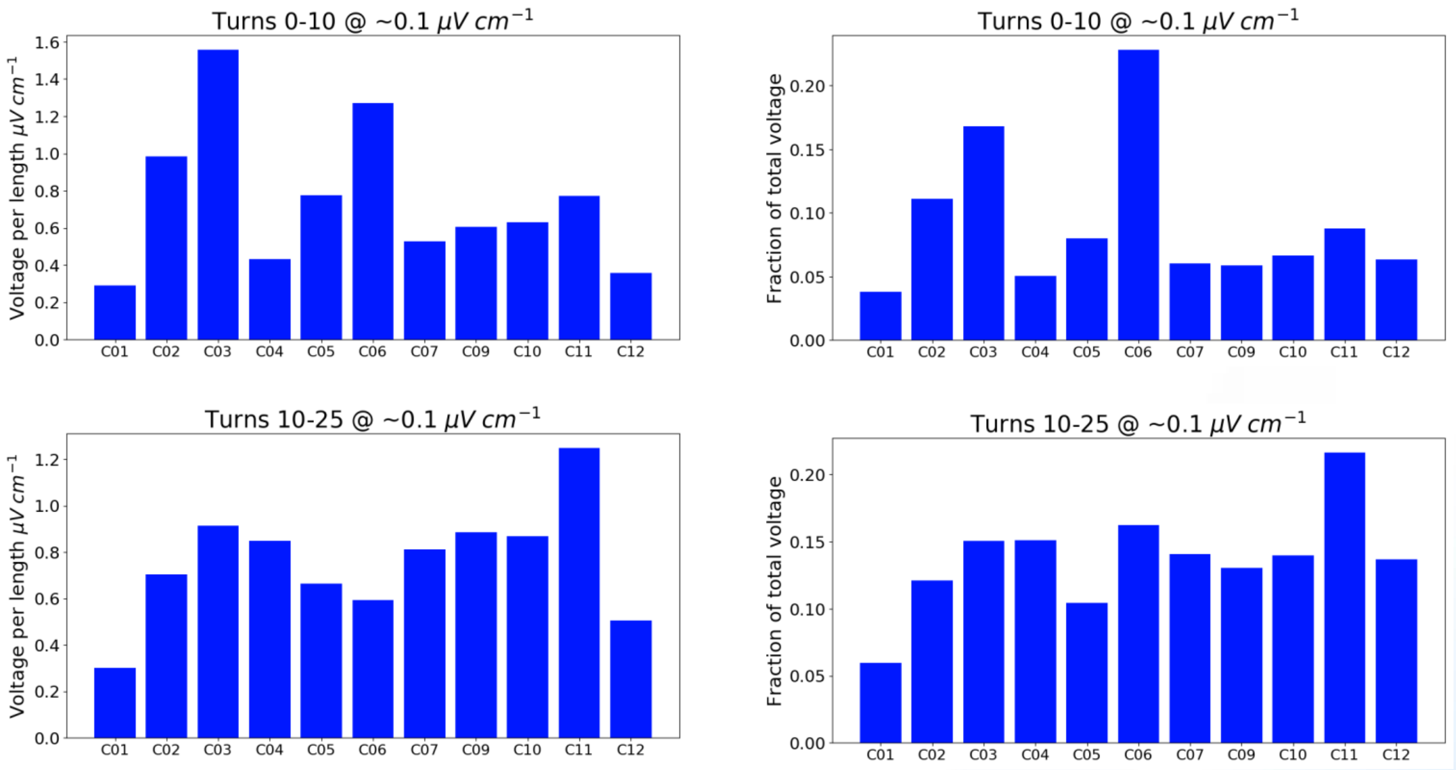
- Coils 1-6 were tested in a Single Pancake configuration;
- Coils 7-12 were tested in a Double Pancake configuration.

OVERALL LN2 TEST RESULTS FOR TESTED COILS



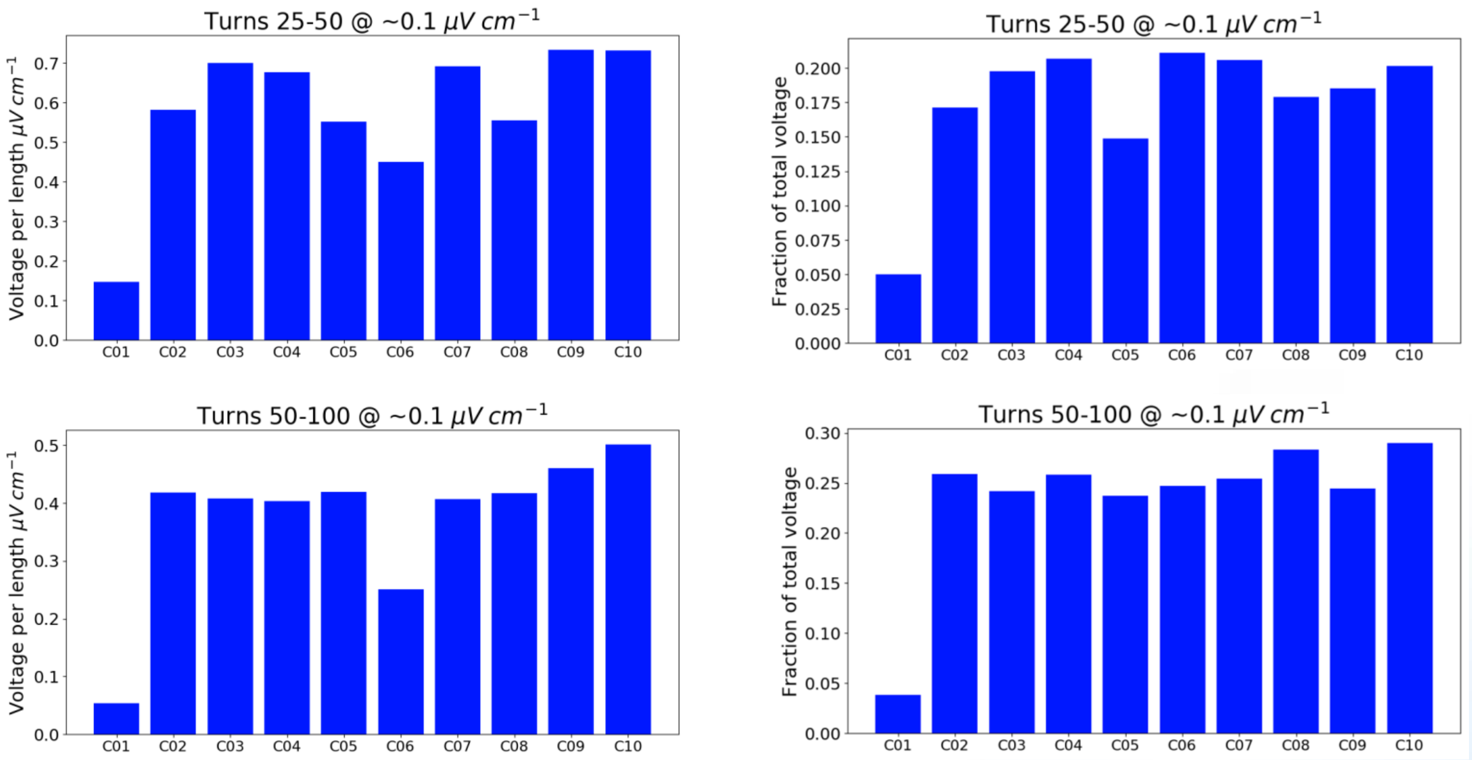
SIGNIFICANT VARIATION IN COIL I_C FROM COIL TO COIL

LN2 TEST RESULTS COMPARISON



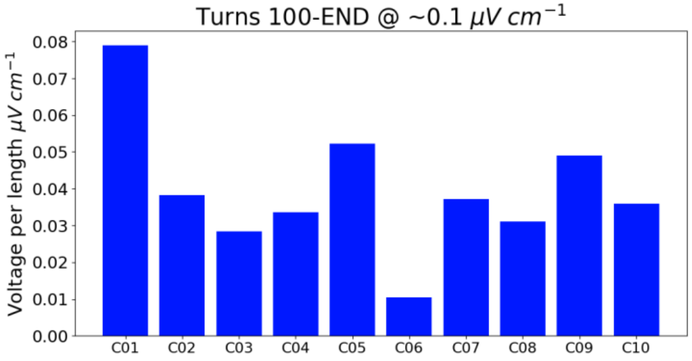
- **Variation in voltage distribution observed throughout all coils.**
- ~ 10% of the total coil voltage, on the average, was developing the first 10 turns
- ~ 15% of the total coil voltage, on the average, was developing between turns 10 and 25

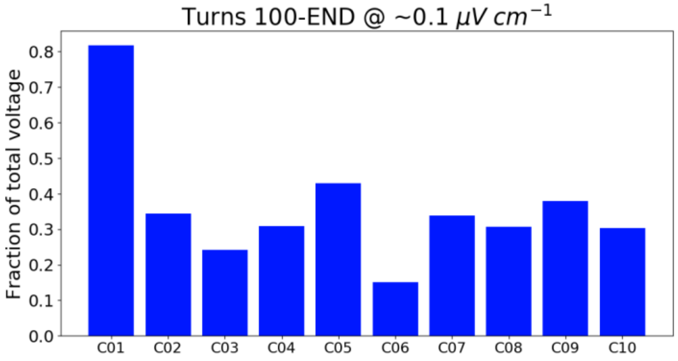
LN2 TEST RESULTS COMPARISON (continued)

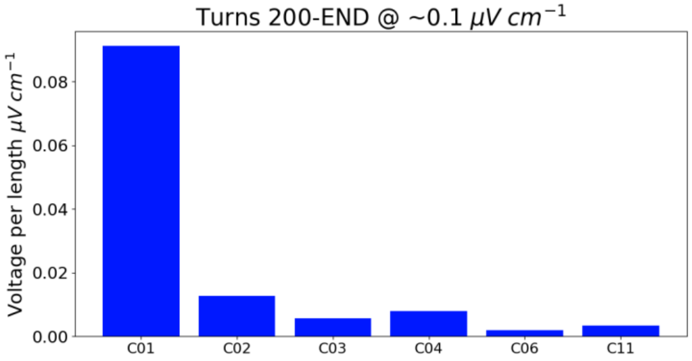


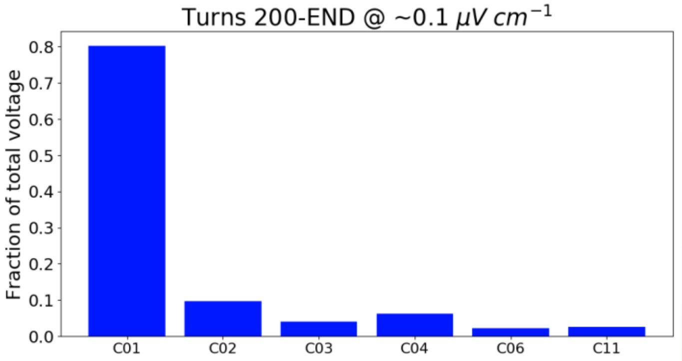
- Variation in voltage distribution observed throughout all coils.
- ~ 18% of the total coil voltage, on the average, was developing between turns 25 and 50
- ~ 25% of the total coil voltage, on the average, was developing between turns 50 and 100

LN2 TEST RESULTS COMPARISON (continued)



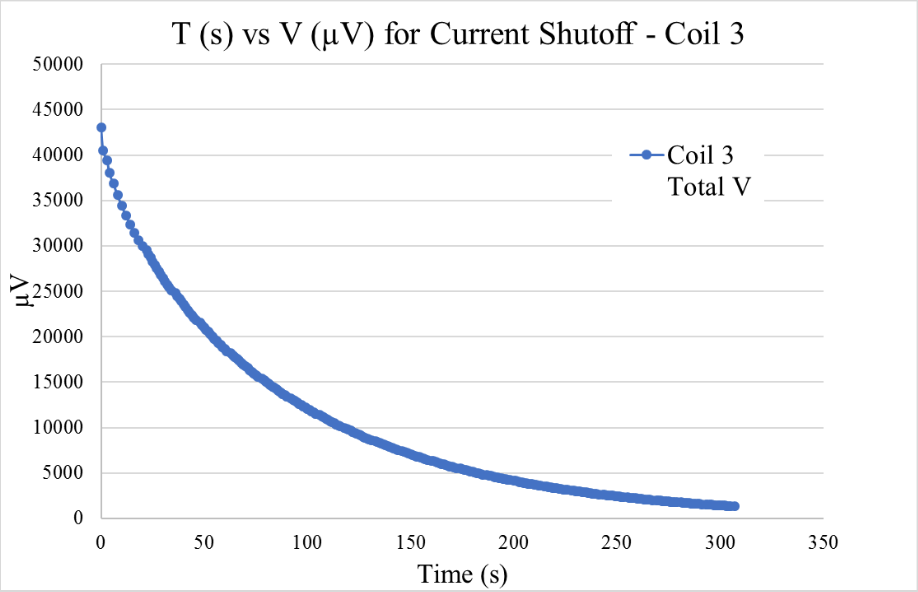


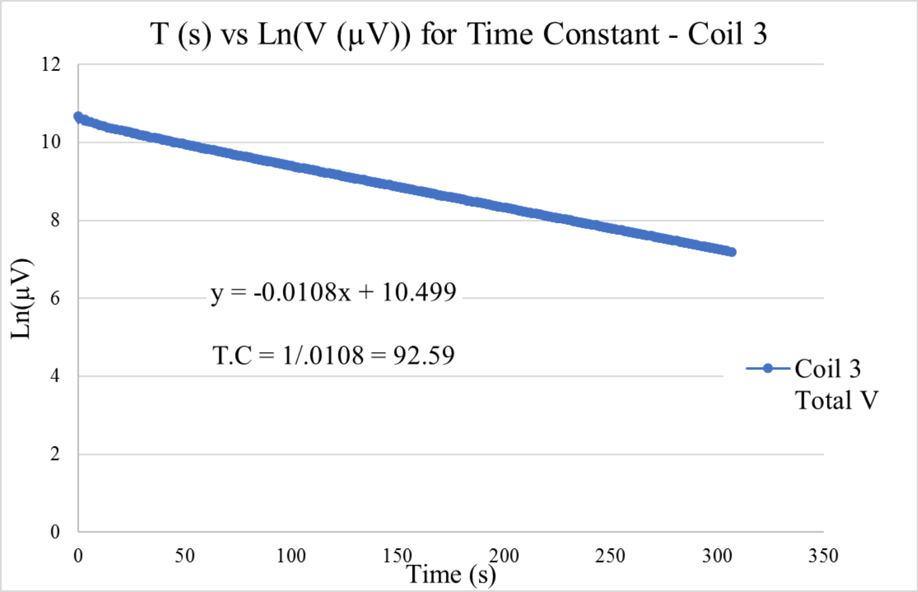




- Variation in voltage distribution observed throughout all coils.
- ~ 30% of the total coil voltage, on the average, was developing between turns 100 and the remaining ~520 turns of the coil
- Less than 10% of the total coil voltage, on the average, was developing between turns 200 and the remaining ~420 turns of the coil

CONTACT RESISTANCE AND TIME CONSTANT

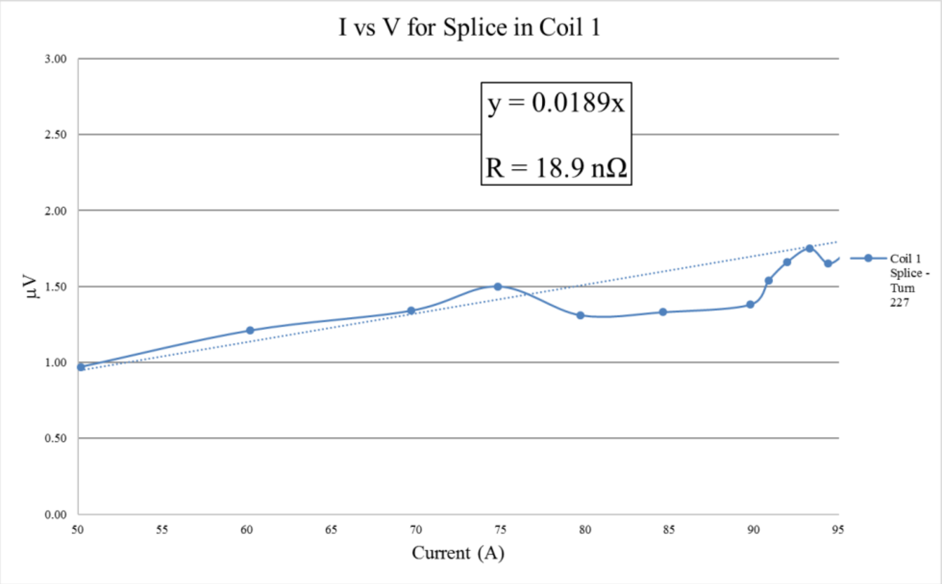


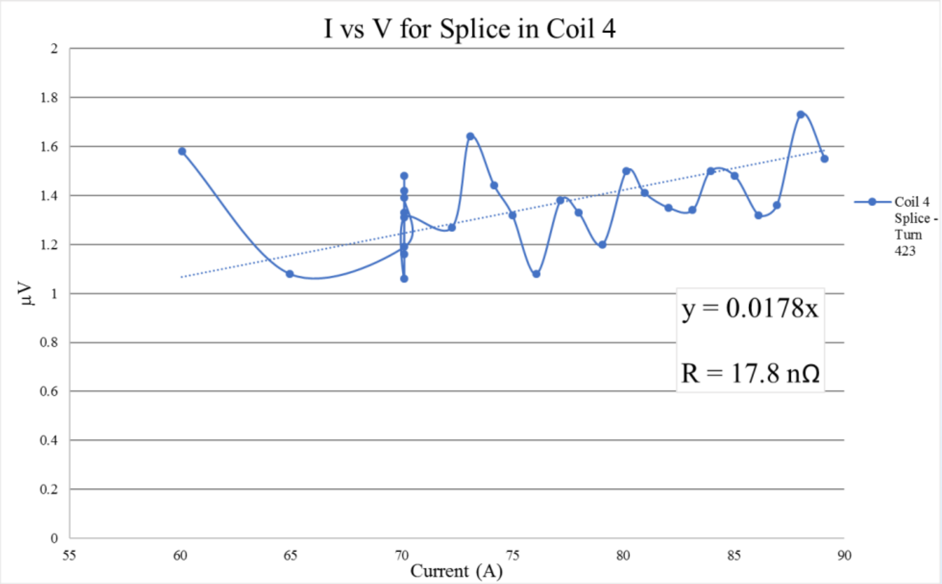


After Coil 3 was **ramped up to and stabilized at 50 A (@ 77 K)**, the **power supply was shut off**. The time constant of Coil 3 was calculated to be 92.59 seconds. **Generally, higher contact resistance results in a smaller time constant**.

Coil #	Contact Resistance @ ~1 A (mV)	Time Constant (s)
1	9.1	78.4
2	8.3	97.1
3	8.4	92.6
4	8.5	95.2

INNER-COIL SPLICE

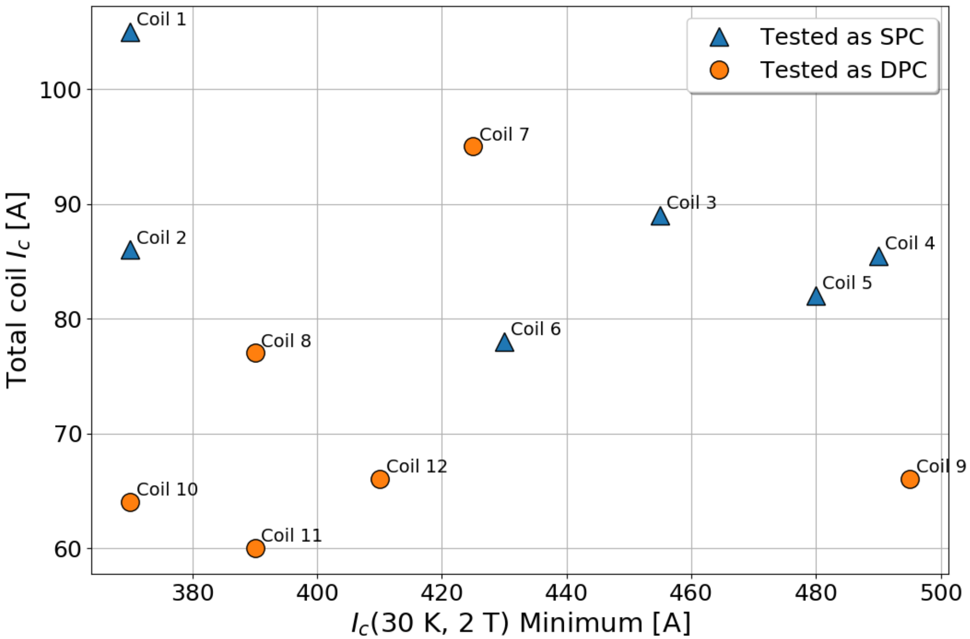




Above: I vs V curve for the splice in coil 1 @ turn 227. The resistance from the splice averages out to **18.9 nΩ**.

Above: I vs V curve for the splice in coil 4 @ turn 423. The resistance from the splice averages out to **17.8 nΩ**.

CORRELATION BETWEEN CONDUCTOR I_C AND COIL I_C AT 77 K



Coil I.D	Coil I_c (A) [@3000μV]	Conductor Used	Amount Used (estimate)	Turns	Transfer Current	Tapestar I_c (77K)	30K, 2T I_c
Coil 1	105	20180509-2b "M3-1311-5"	90	0-227	570	578	450/560
		20180509-1a "M4-430-5"	215	227-630	383	390.7	400/370
Coil 2	86	20180509-1a "M4-430-5"	300	0-611	383	390.7	400/370
		20180509-1a "M4-430-5"		611-629	383	390.7	400/370
Coil 3	89	20180625-1a "M4-462-5"	143	0-346	405	407	475/525
		20180625-1d "M3-1309-6"	158	346-629	424	-	455
Coil 4	85.5	20180625-1b "M3-1309-6"	183	0-423	410	407	490
		20180625-1c "M3-1309-6"	117	423-624	399	-	-
Coil 5	82	20180509-1b "M4-430-5"	186	0-429	348	368.2	480/395
		20180625-1c "M3-1309-6"	116	429-627	399	-	-
Coil 6	78	20180730-4b "M4-465-5"	147	0-354	349	358.4	430
		20180911-1a "M4-478-2"	154	354-624	416.2	415.1	550/495
Coil 7	95	20180730-3a "M4-424-5"	113	0-283	385	369	425
		20180911-1a "M4-478-2"	187	283-626	416.2	415.1	550/495
Coil 8	77	20180730-1a "M3-1320-2"	175	0-406	589	594.6	390/430
		20180911-1a "M4-478-2"	125	406-627	416.2	415.1	550/495
Coil 9	66	20180911-1a "M4-478-2"	194	0-444	416.2	415.1	550/494
		20180911-2a "M3-1330-3"	106	444-623	382	363.7	-
Coil 10	64	20180730-1b "M4-424-5"	100	0-255	367	346	460
		20180730-2b "M3-1320-3"	106	255-466	599	599	410
		20180509-1a "M4-430-5"	56	466-557	383	390.7	400/370
		20180911-2b "M3-1330-3"	38	557-626	410.9	403.6	390
Coil 11	60	20180911-2b "M3-1330-3"	100	0-249	410.9	403.6	390
		20181116-2 "M4-470-55"	200	249-622	430	449.2	430/390
Coil 12	66	20180911-1b "M3-1326-3"	100	0-255	370.6	354.3	410/490
		20181116-1 "M3-1324-A"	200	255-630	391	373.5	500/485

There was **no obvious or significant correlation between quality of the conductor** (defined though Transport, TapeStar, and In-Field (@30K, 2T I_c measurements conducted by the manufacturer) **and the quality of the coil performance at 77 K** (defined by its I_c – I_c threshold being 3mV as per .1μV/cm industry standard) after winding.

SUMMARY

- Winding Techniques, Procedures, and Instrumentations have been optimized for consistency in coil quality.
- 16 coils have been wound; 12 coils have been tested in LN2.
- The 12 tested coils show an average I_c of 79.5A @ 77K.
- **Coil performance varies from coil to coil**.
- **Inner-Coil splices show ~18 - 19 nΩ of resistance at 77K**.
- **Generally, higher contact resistance results in a smaller time constant**
- **Approximately 70% of the coils voltage was developed within the first 100 turns – where the magnetic field is the highest**
- No significant correlations was found between quality of the conductor (defined though Transport, TapeStar, and In-Field (@30K, 2T I_c measurements conducted by the manufacturer) and quality of the coil (defined by its I_c) after winding.