High Field HTS Solenoid for CAPP

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Towards Building A High Field Solenoid for Axion Search at CAPP

- **What is needed and what is available?**
  - **Basic requirements, design and technology in hand**
- **Status/Progress (most of this presentation)?**
  - **CAPP/BNL HTS demo solenoid with SuNAM conductor**
- **What is needed to reach the goal while minimizing the risks?**
  - **Path forward**

What is needed and what is available?

- Basic requirements
- Challenges
- Design and technology in hand

Design Considerations

Large aperture, high field

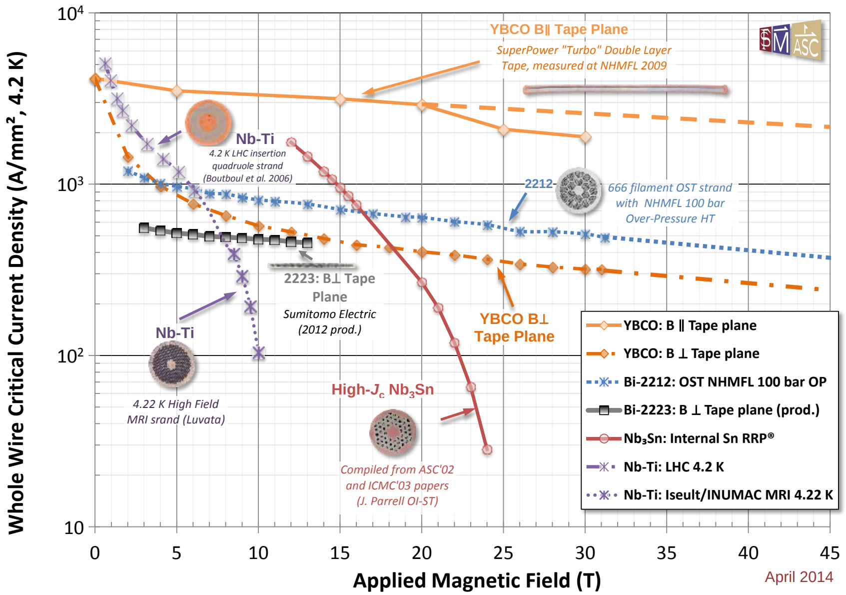
- 35 – 40 T , 100 mm

HTS must be used

- But HTS is expensive

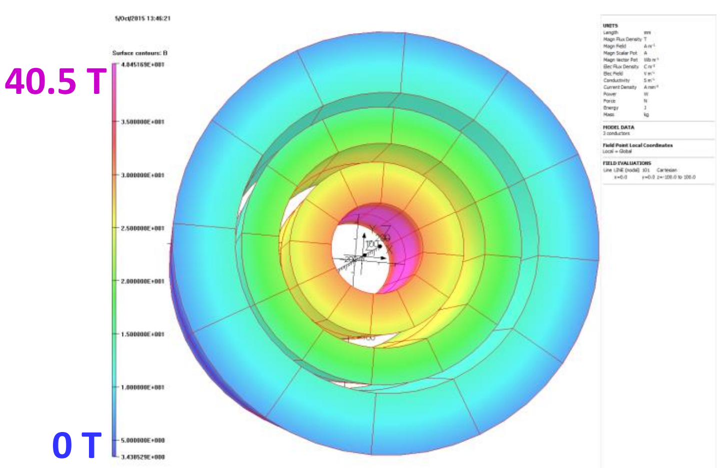
HTS/LTS hybrid design

- ~25 T HTS and 10-15 T LTS



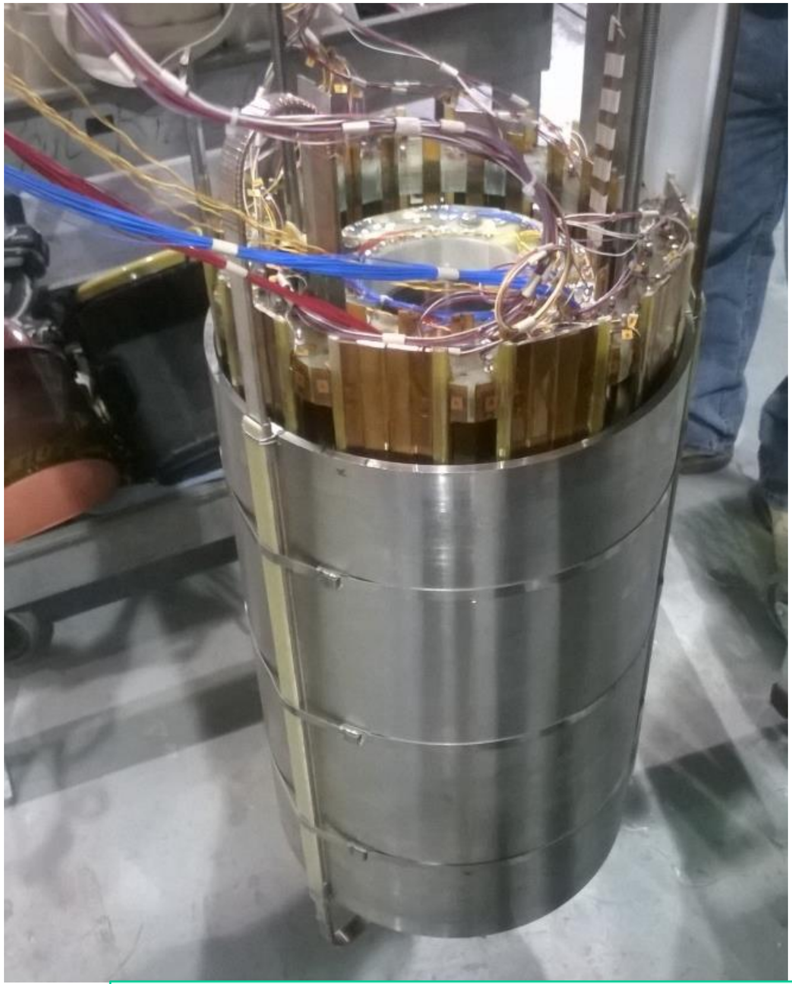
This magnet pose huge challenges

- Large stresses
- Quench protection
- New conductor



Previous experience with large aperture, high field solenoid?

HTS Solenoid for SMES (similar parameters)



- Field: 25 T@4 K
- Bore: 100 mm
- Stored Energy: 1.7 MJ
- Hoop Stresses: 400 MPa

Amount of ReBCO HTS Used:

Over 6 km, 12 mm wide from SuperPower

- Reached a critical or maximum expected field at 27 K - 12.5 T (new record for over T>10 K)
- Test terminated due to electrical issues

Key Points in Following Slides

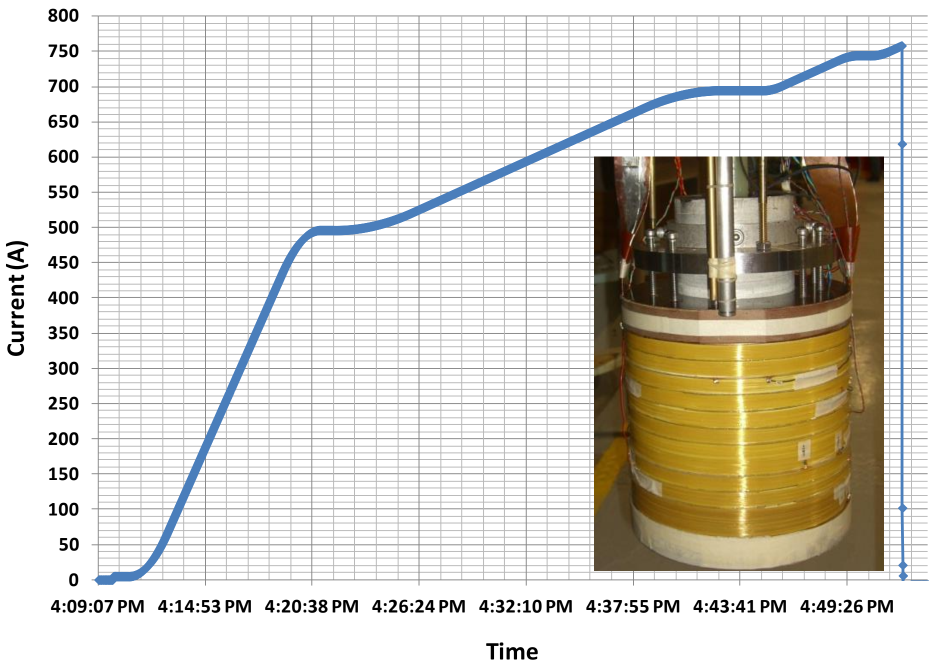
Guiding Principles

- High strength ReBCO 2G HTS tape optimized for high fields
- Co-wind with stainless steel insulating tape for high strength
  - Stainless steel insulation also helps in quench protection
- Subdivide structure to keep stress accumulation within limit
- Use copper discs for uniform cooling and to reduce thermal strain
  - Copper discs also help in rapid energy extraction *after quench*
- Advanced quench protection system
- Strong QA with several intermediate tests (R&D conductor)
  - ✓ Each pancake was tested at 77 K
  - ✓ Intermediate high current 4 K tests

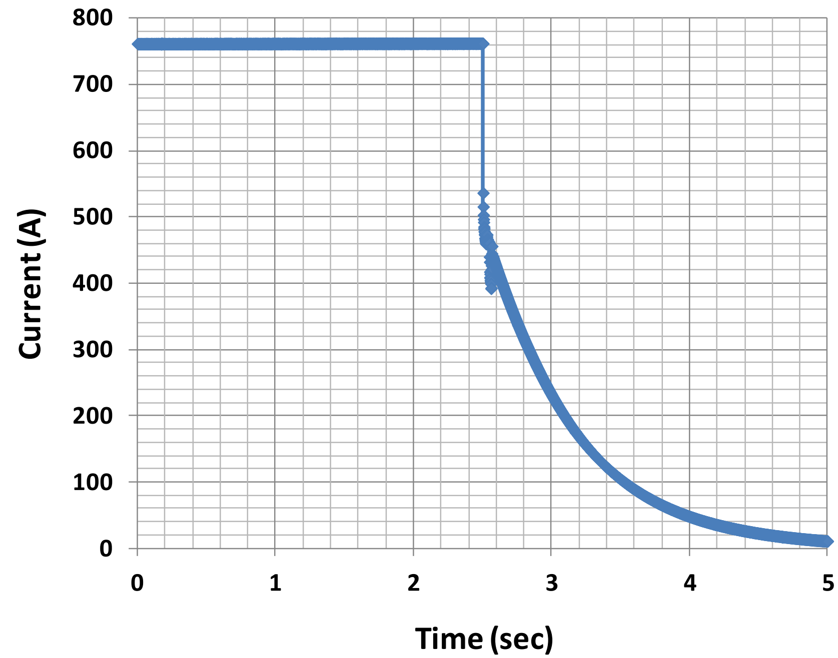
12 Pancake Coil Test

11.4 T in 100 mm bore

Charge

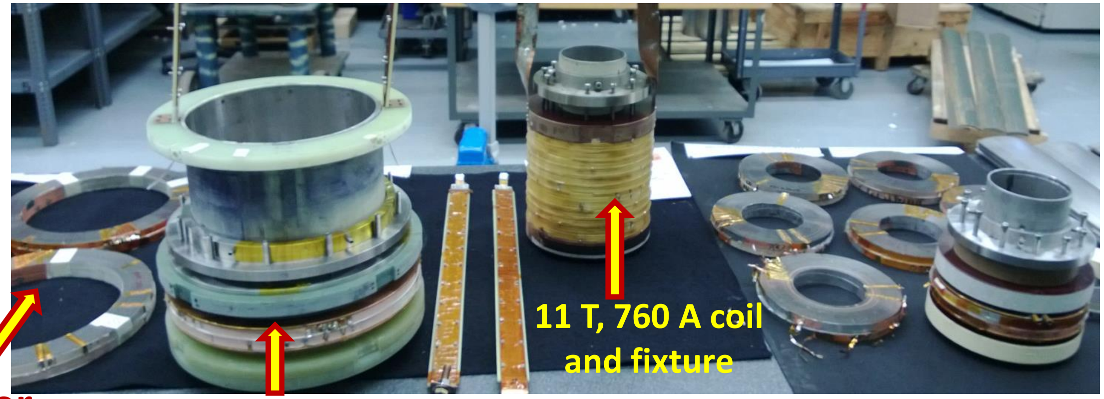


Quench



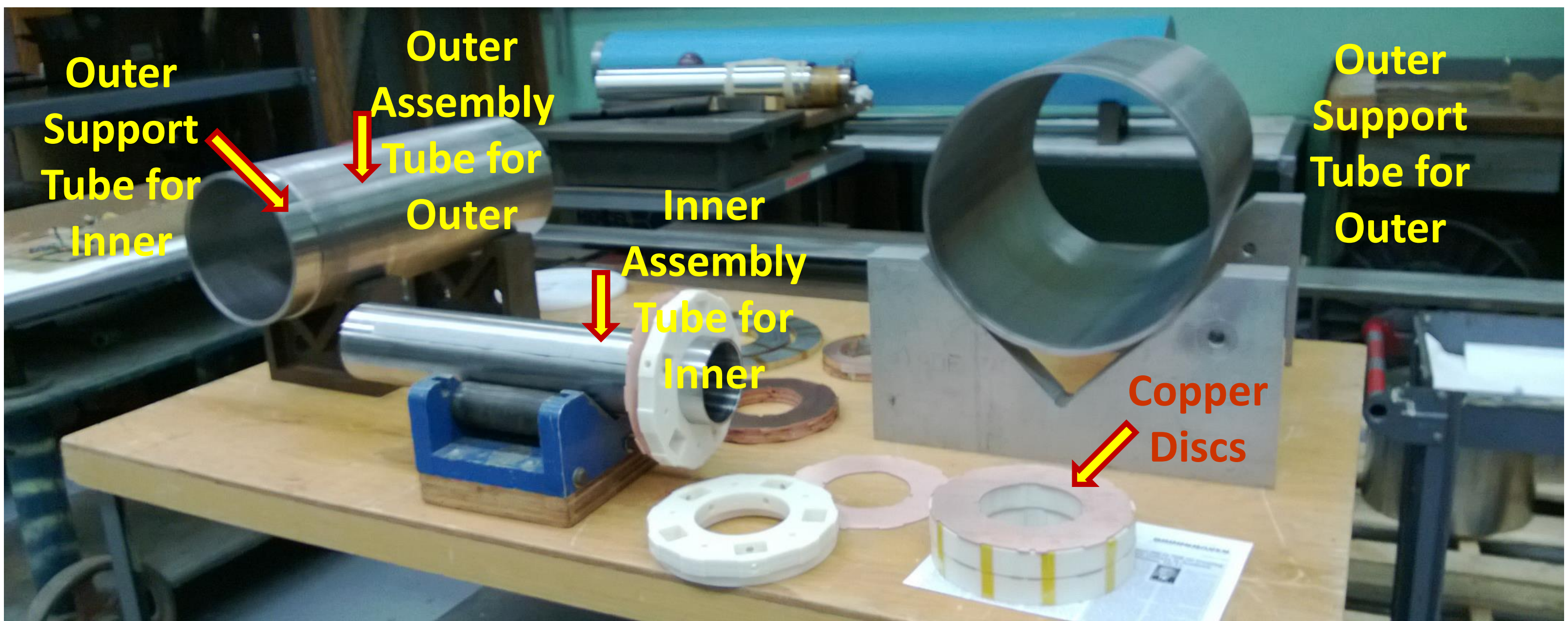
This test was similar to CAPP/IBS solenoid test performed with the 6 pancake of similar size

Coils, Test Fixtures and Support Structure



Pancake coils: inner and outer

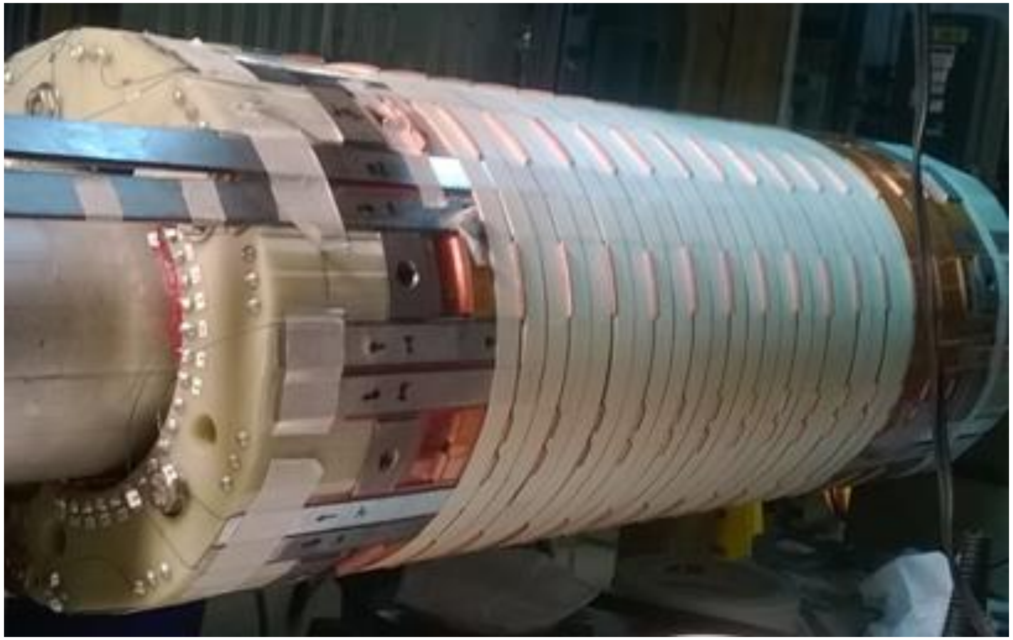
77 K Test Fixture for outer



Special Considerations

- Only one test run was possible due to project limits.
- This posed considerable challenge. Particularly since the conductor was in R&D stage and still showing a significant variation in properties.
- One weak link in over 6 km conductor and 46 pancake could limit the performance of the entire system.
- To mitigate this situation, we installed additional current leads to bypass a weaker performing coil, if needed.
- The idea was to demonstrate the maximum achievable field in one test run with only minor adjustments.

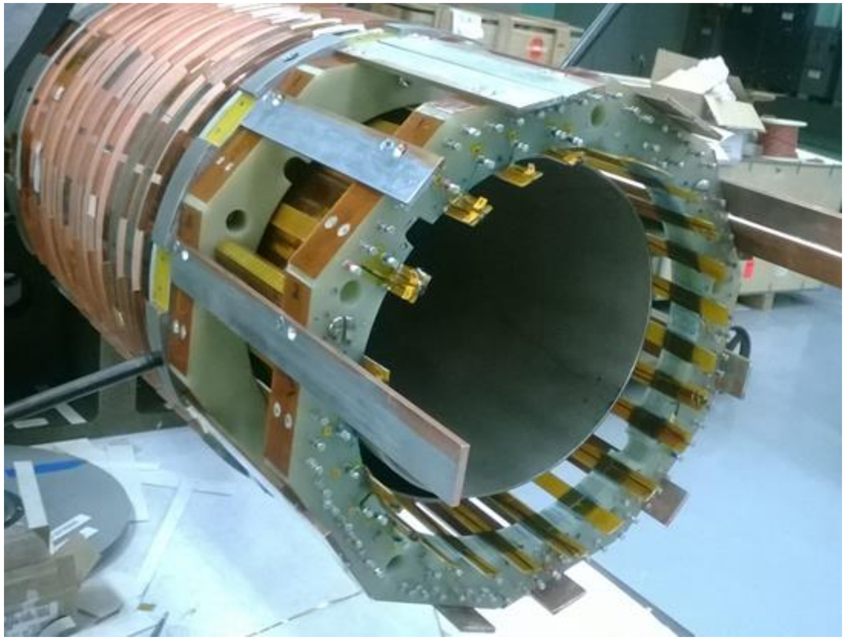
Inner and Outer Coils Assembled with Bypass Leads



Inner Coil

(102 mm id, 194 mm od)

28 pancakes



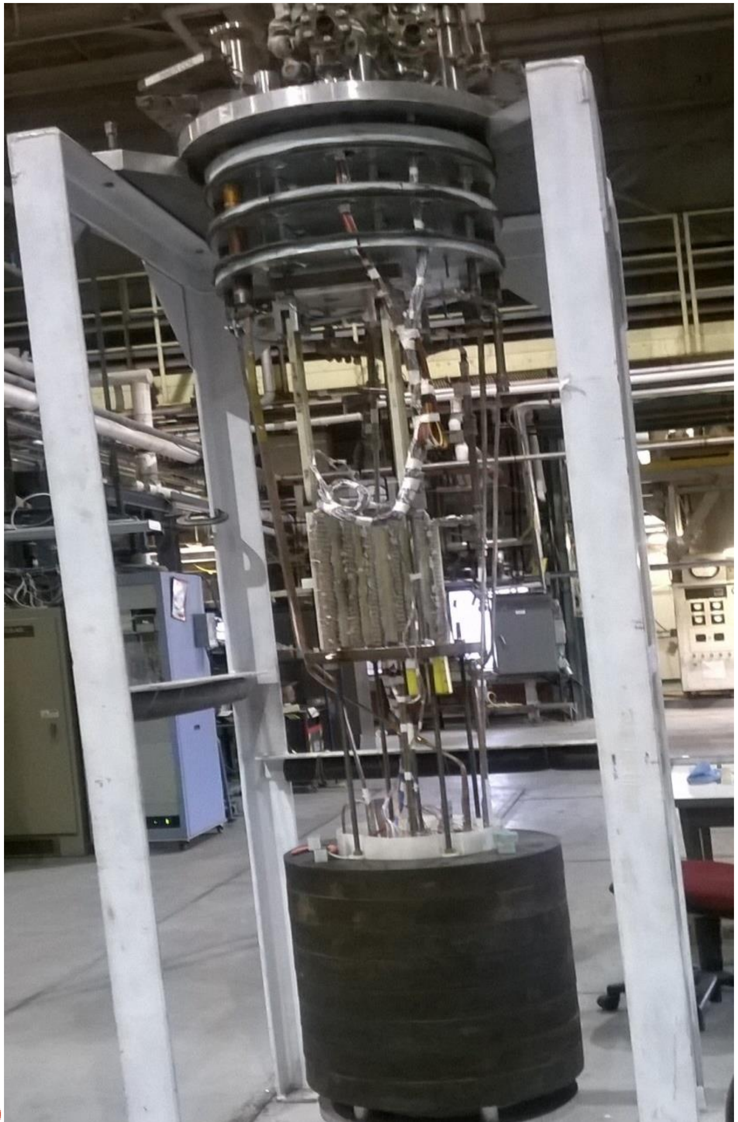
Outer Coil

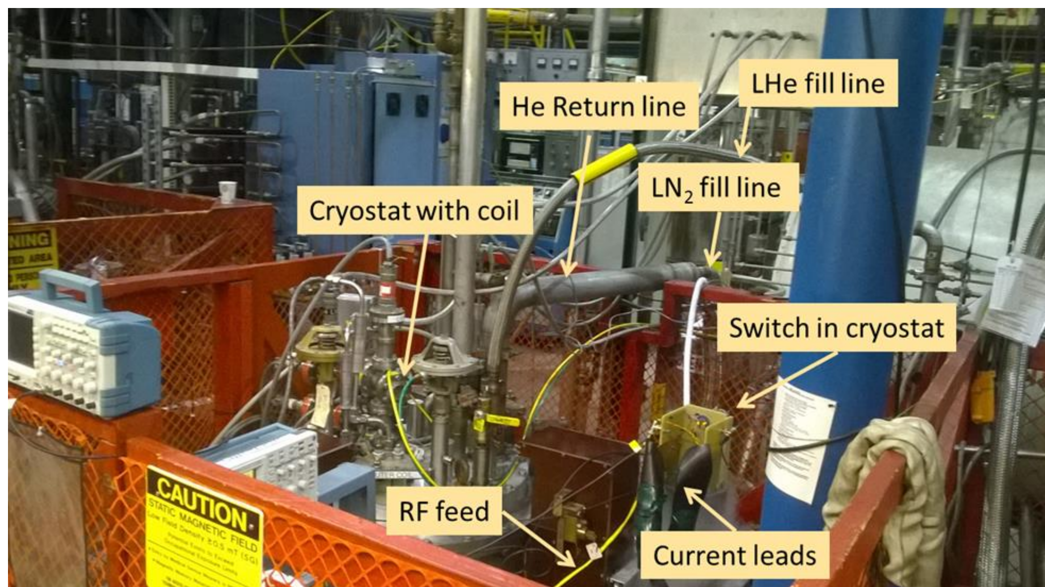
(223 mm id, 303 mm od)

18 pancakes

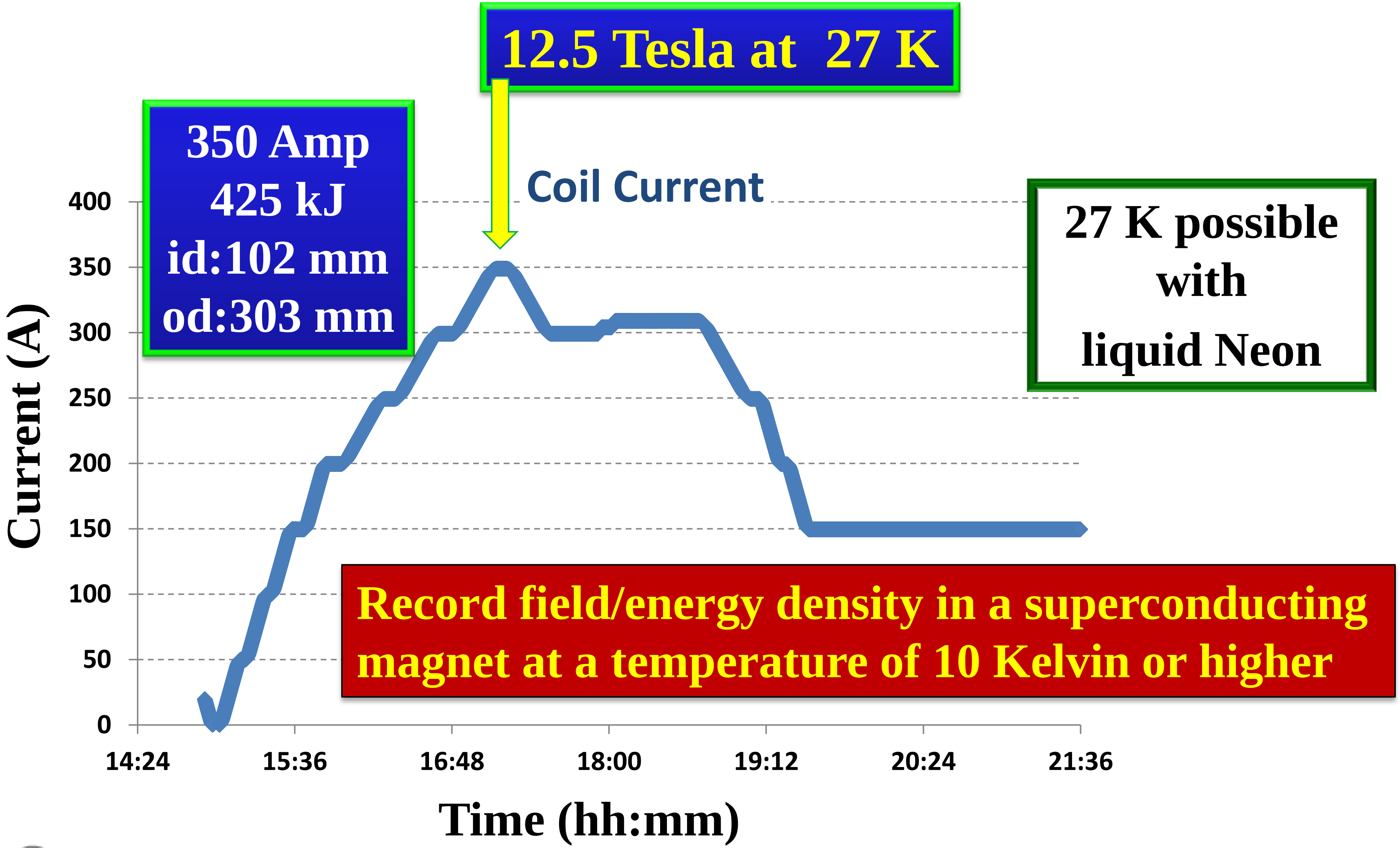
Total: 46 pancakes

Preparation for the Final Test





SMES Coil Test @50%
Critical Current Reached at 27 K



An Incident During the Test

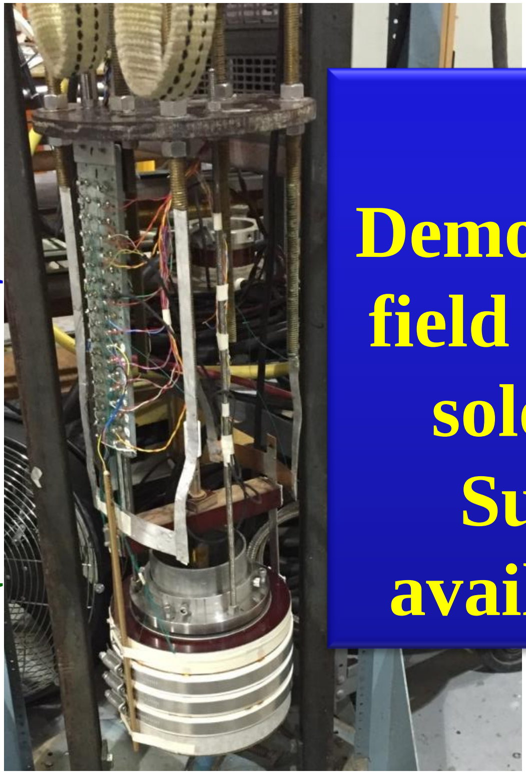
- We ramped the unit several times between 20-80 K.
- The test run at 350 Amp - 12.5 T at 27 K was already a record demonstration.
- During one such tests, the system tripped due to a data entry error at ~165 A – well below the current the coil was powered earlier.
- This trip resulted in arcing between two current leads in the inner coil and some damage. This was not part of the normal magnet construction. These leads were added to bypass weaker coil.
- The issue is not related to the high field HTS SMES technology.
- The coil still has the potential to reach higher fields after repair.

Status/Progress

- **CAPP HTS demo solenoid with SuNAM conductor**

Work Performed for CAPP/IBS

- Conductor Test
- Coil Construction
- Coil Test
- Magnet Assembly
- Magnet Test

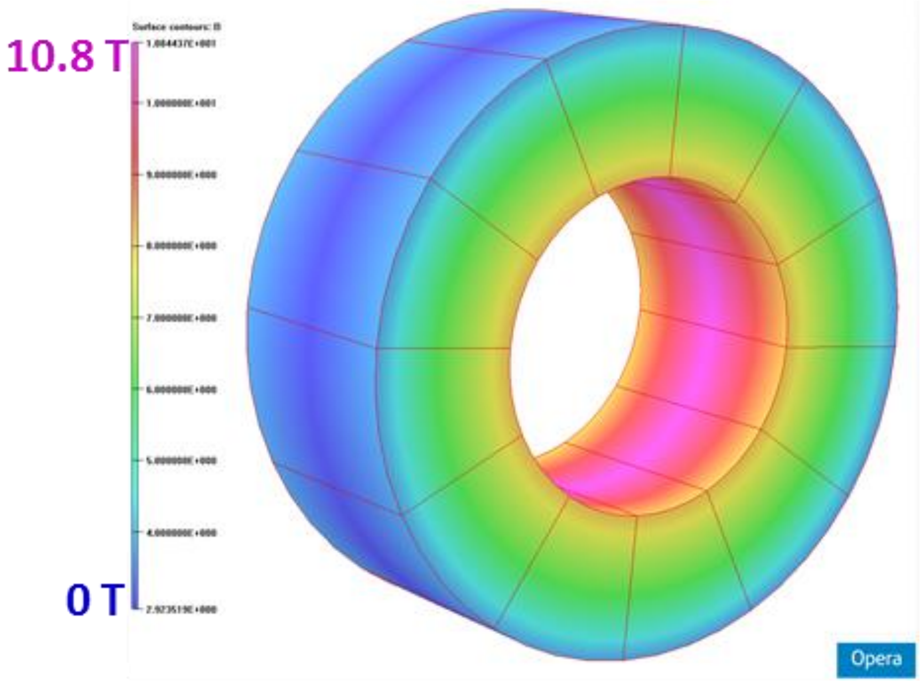


Task:

Demonstrate 10 T peak field in a 100 mm bore solenoid built with SuNAM HTS, as available at that time

CAPP/IBS Phase I HTS Solenoid

- Peak Field : 10.8 T
- Aperture : 100 mm
- Stored Energy : 66 kJ
- Temperature : 4.2 K
- Number of Turns: 1881
- Number of Pancakes : 6
- Conductor: 12 mm wide ReBCO HTS Tape
- Insulation: Stainless Steel



Conductor

Test Results of 12 mm Wide Tape

Last visit : Test results of 4 mm tape

This time : Test results of 12 mm tape used in the actual magnets

ReBCO HTS from SuNAM

Specifications:

- I_c (77 K, self-field): > 600 A
  - Original spec was 700, revised to 600A
  - All batch except one met the spec
- I_c (4K, 8T) : > 550 A (expected)
- Width: 12 mm
- Thickness : 100 micron
- Piece Length: 140 meter
- Internal splices: None
- Cu thickness: 40 micron

SuNAM HTS

- ❑ Uniform Properties
- ❑ Good Copper Plating

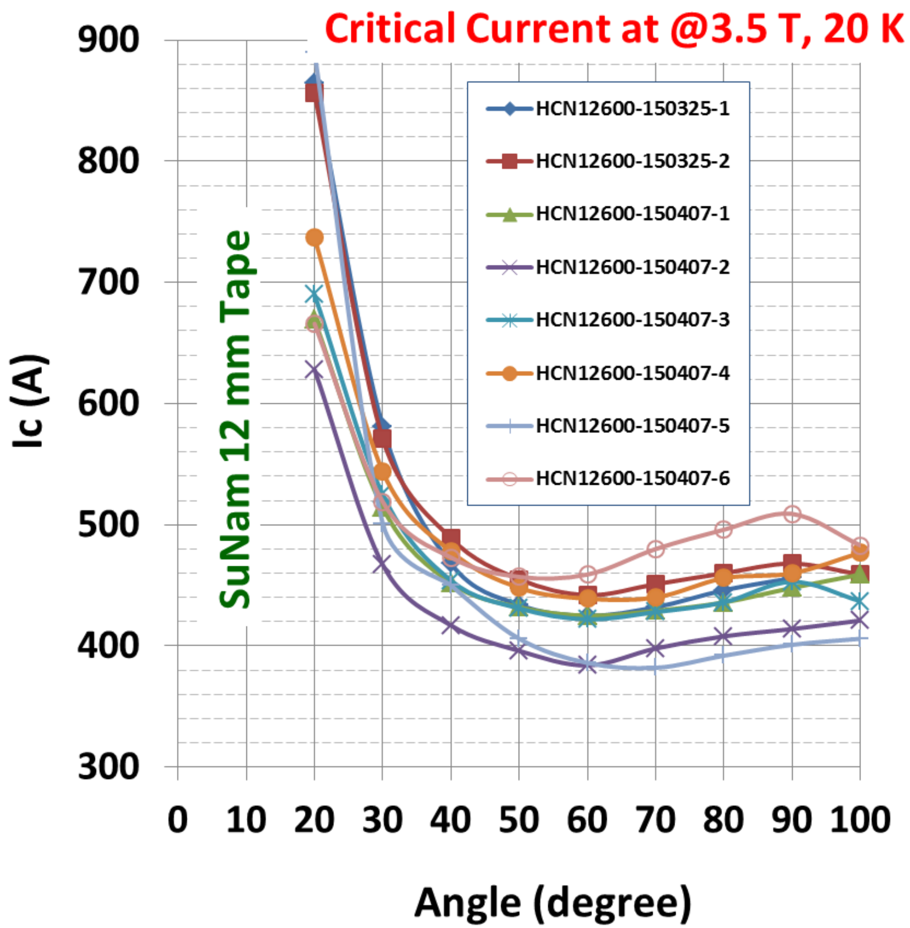
Conductor measurements:

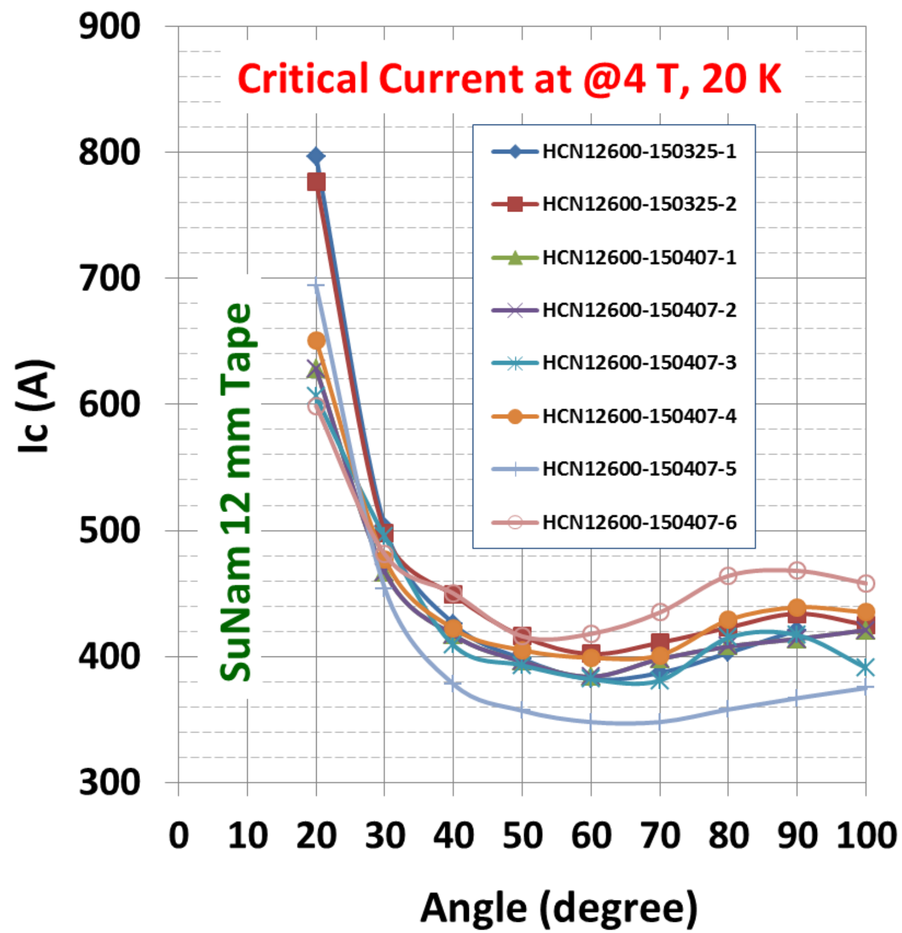
- ➢ 77 K, self-field both at SuNAM and at BNL
- ➢ 20 K, 3.5 T and 4T at SuNAM
- ➢ 4 K, 4-8 T at BNL

Conductor Data from SuNAM

77	0	-	615	650	605	650	612	691	582	665		
Temp.	Field	Angle	HCN12600-150325-1	HCN12600-150325-2	HCN12600-150407-1	HCN12600-150407-2	HCN12600-150407-3	HCN12600-150407-4	HCN12600-150407-5	HCN12600-150407-6	Average	STDEV
20	3.5	20	864	856	669	628	690	737	890	666	750	104
20	3.5	30	581	571	514	467	525	544	501	519	528	37
20	3.5	40	468	489	452	417	454	478	450	473	460	22
20	3.5	50	434	455	432	396	431	448	406	457	432	22
20	3.5	60	425	442	425	384	422	439	386	459	423	26
20	3.5	70	432	451	429	398	428	440	382	480	430	30
20	3.5	80	446	460	436	408	436	456	392	496	441	32
20	3.5	90	456	468	448	414	453	460	401	509	451	33
20	3.5	100		459	459	421	437	477	406	483	449	29
20	4	20	797	777	628	628	606	651	694	599	673	77
20	4	30	503	498	467	467	495	477	454	481	480	17
20	4	40	426	449	417	417	409	422	378	450	421	23
20	4	50	398	416	396	396	393	405	357	416	397	19
20	4	60	382	402	384	384	382	399	348	418	387	20
20	4	70	387	411	398	398	381	401	348	435	395	25
20	4	80	403	423	408	408	415	429	358	464	414	30
20	4	90	421	434	414	414	417	439	367	468	422	29
20	4	100		425	421	421	391	435	375	458	418	27

Measurements at SuNAM (@3.5T & 4T, 20 K - I_c Vs. θ)





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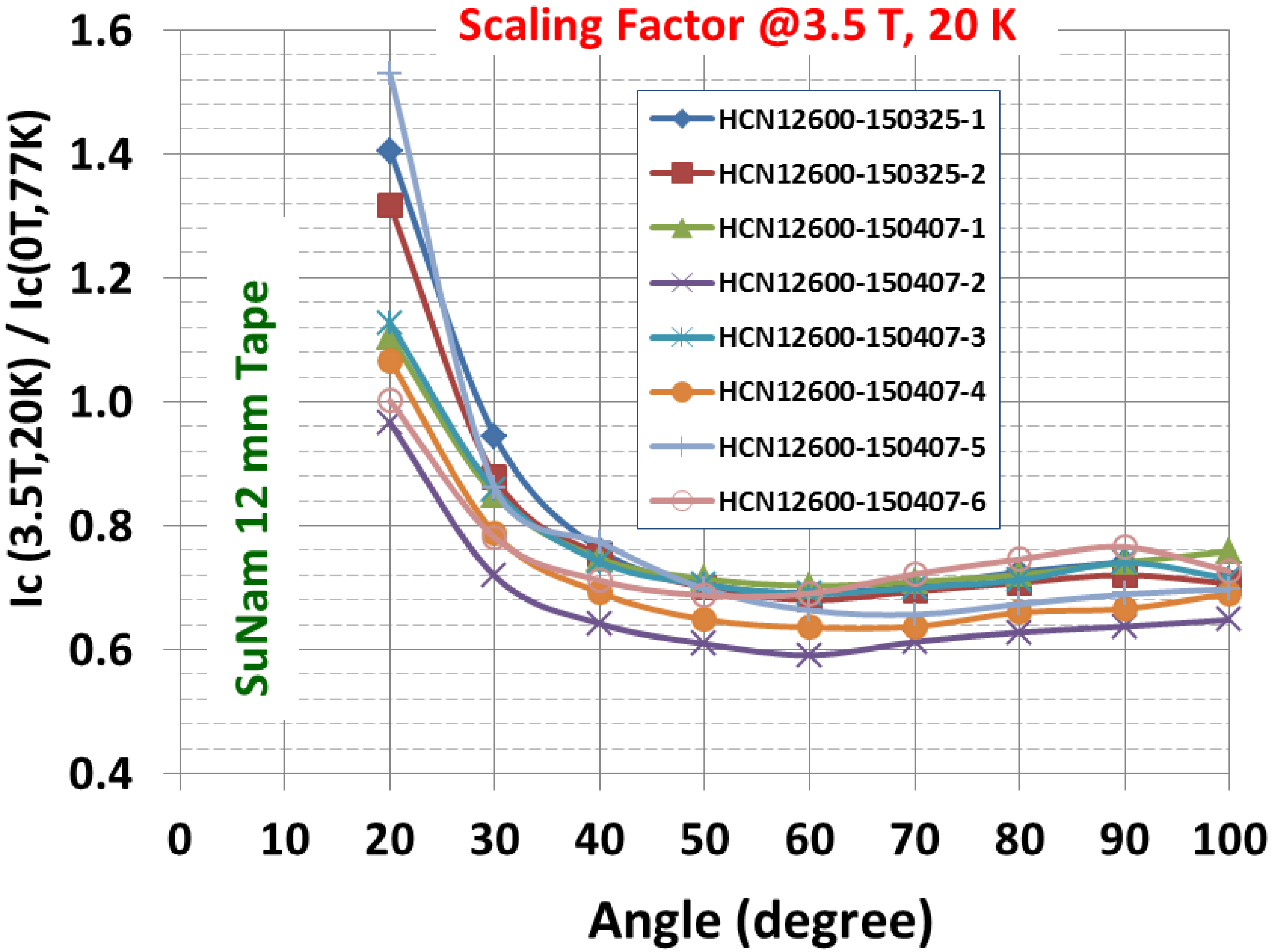
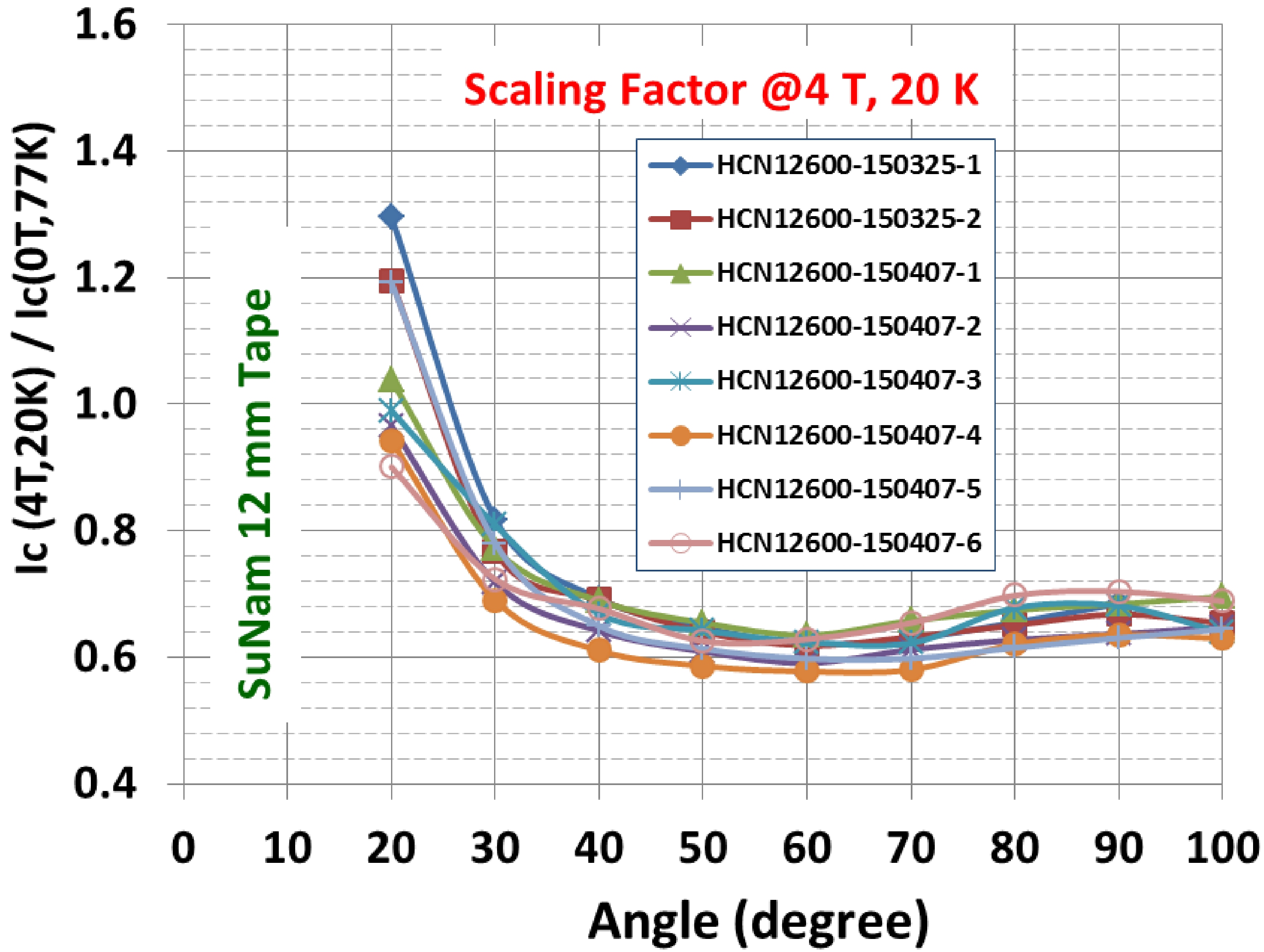
Scaling Factor at 20K, 3.5 T



Scaling Factor at 20K, 4 T



BNL Study of SuNAM Conductor

Variety of Measurements at 77 K

For example: Bending test

Small (no insulation) coil test

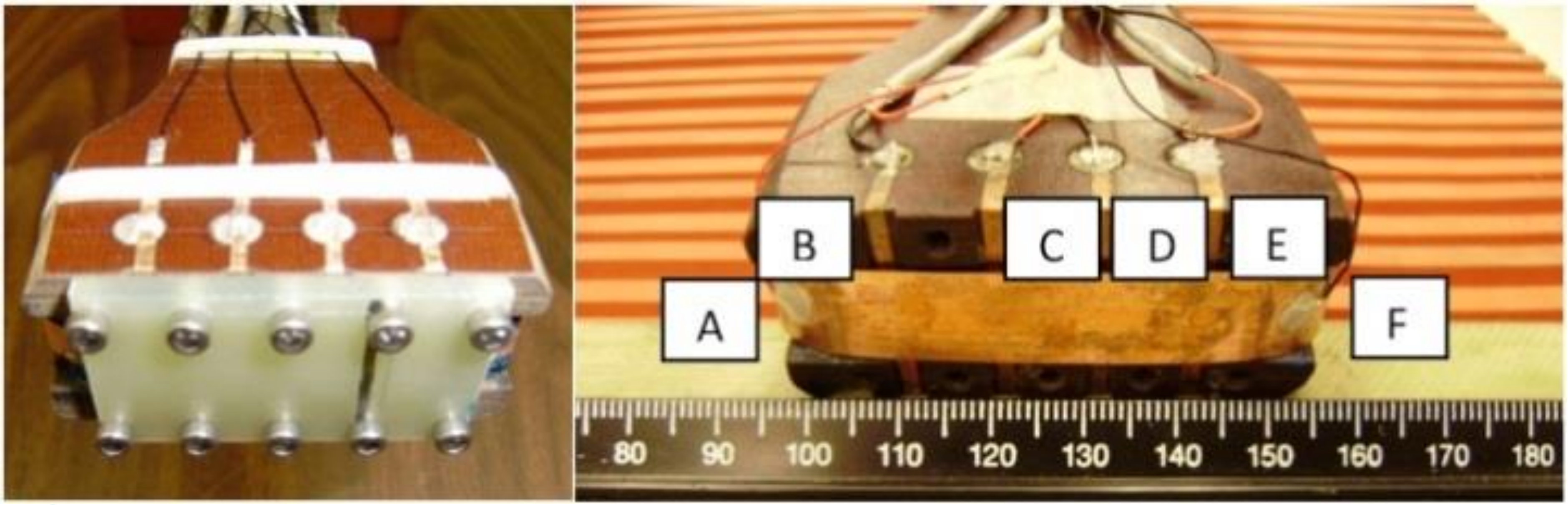
(proper safety equipment used)

We also train technicians

BNL Measurements at 4K, 4-8T (15 T test station also available)

More Relevant to our application:

❖ Performance at 4 K in high fields

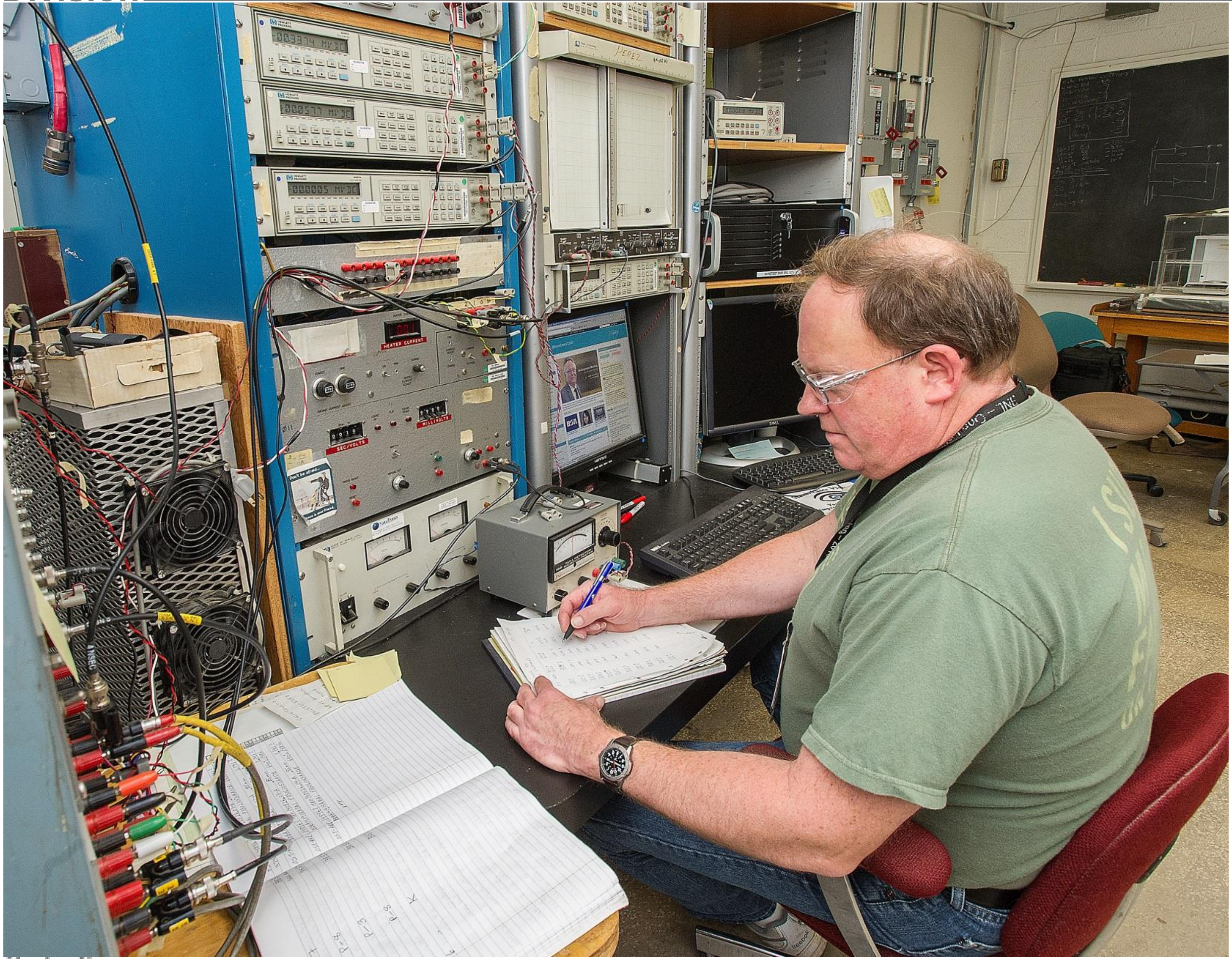


Sample Holder for in-field Ic Measurements at BNL

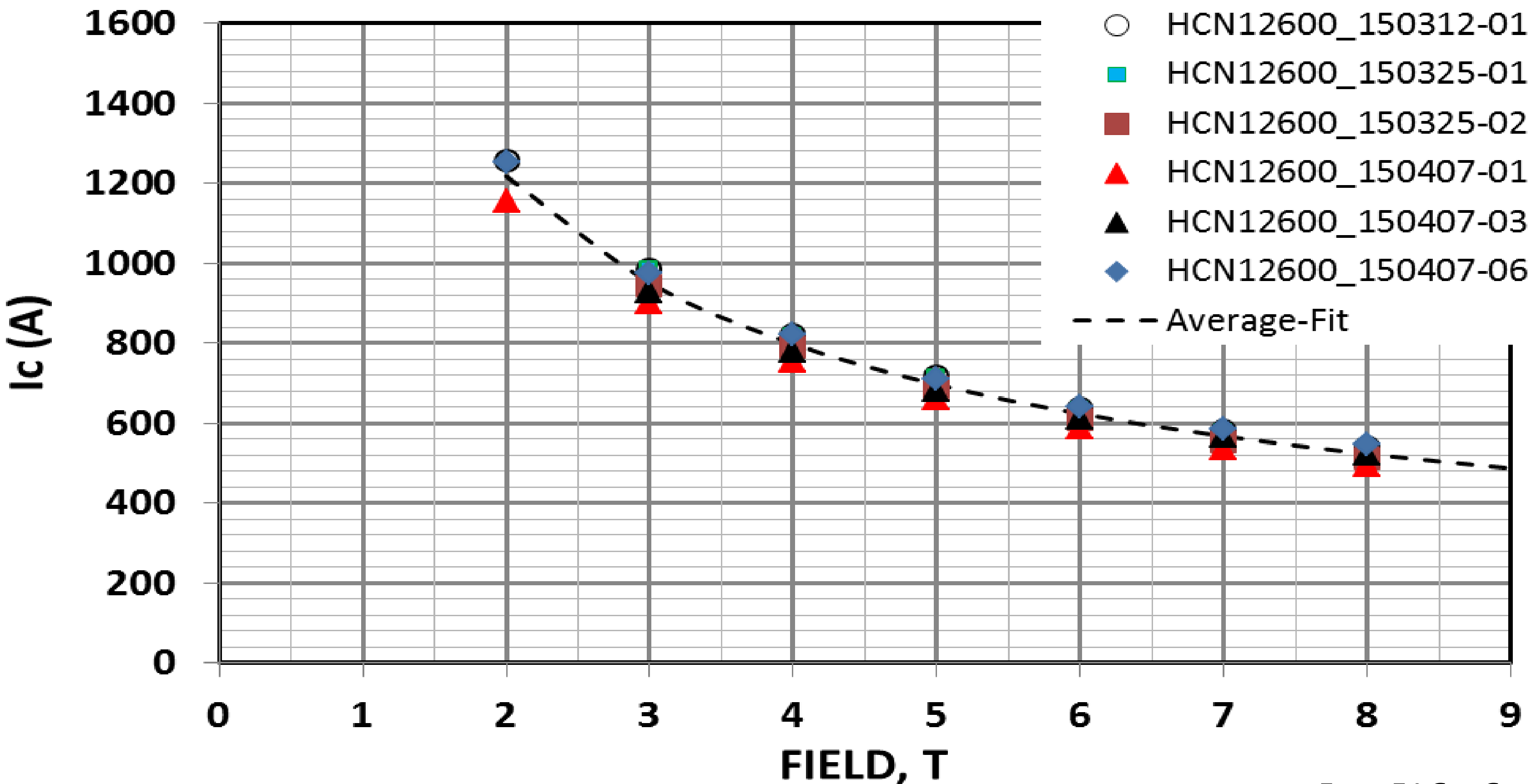
A. Ghosh/SMD/BNL

Pictures of Conductor Test Station

Pictures of Conductor Test Station



Measurements at BNL (@4K, $B_\perp$ - I_c Vs. Field)



Remarkably uniform performance

(specially for conductor delivered in 3 batches)

However, the lift factor is significantly lower than in SuperPower

Summary of Conductor Measurements

CRITICAL CURRENT OF SHORT SAMPLES TAKEN AT BNL AND AT SUNAM

Lab	Temp. [K]	Field [T]	Average [A]	σ [A]	σ/Average
SuNAM	77	0	634	36	5.7%
SuNAM	20	4	423	28	6.7%
BNL	77	0	628	51	8.1%
BNL	4.2	4	793	28	3.5%
BNL	4.2	8	524	20	3.7%

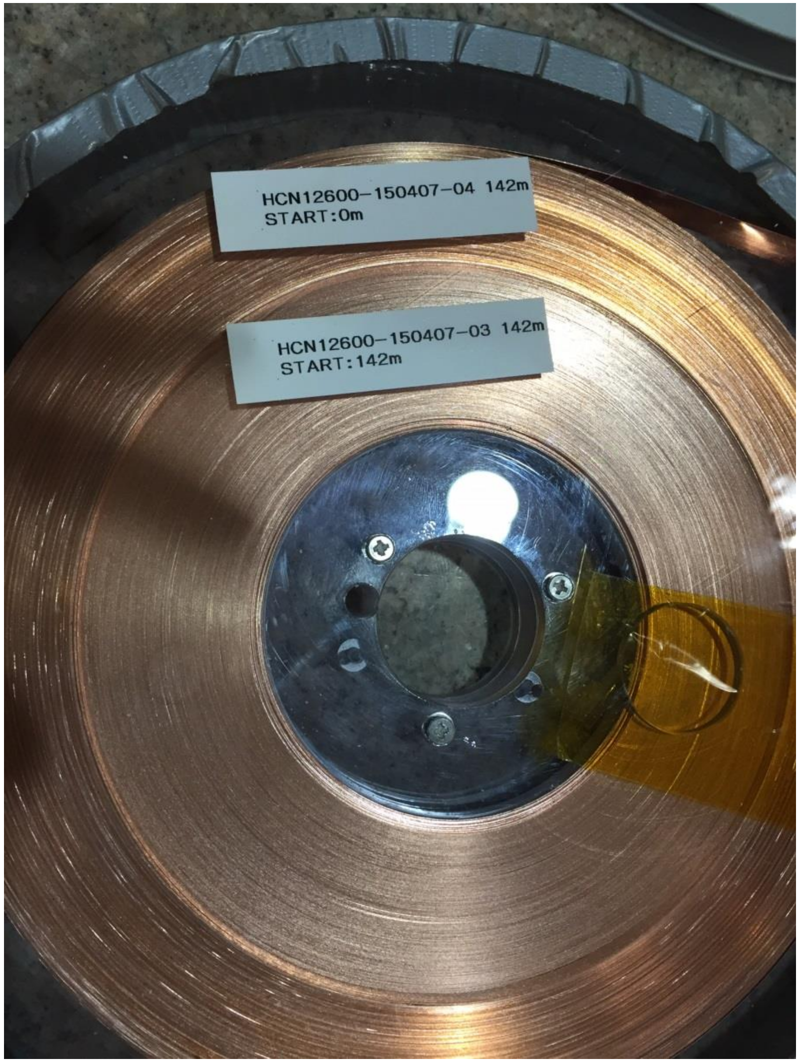
Pinning can improve the in-field performance at 4K

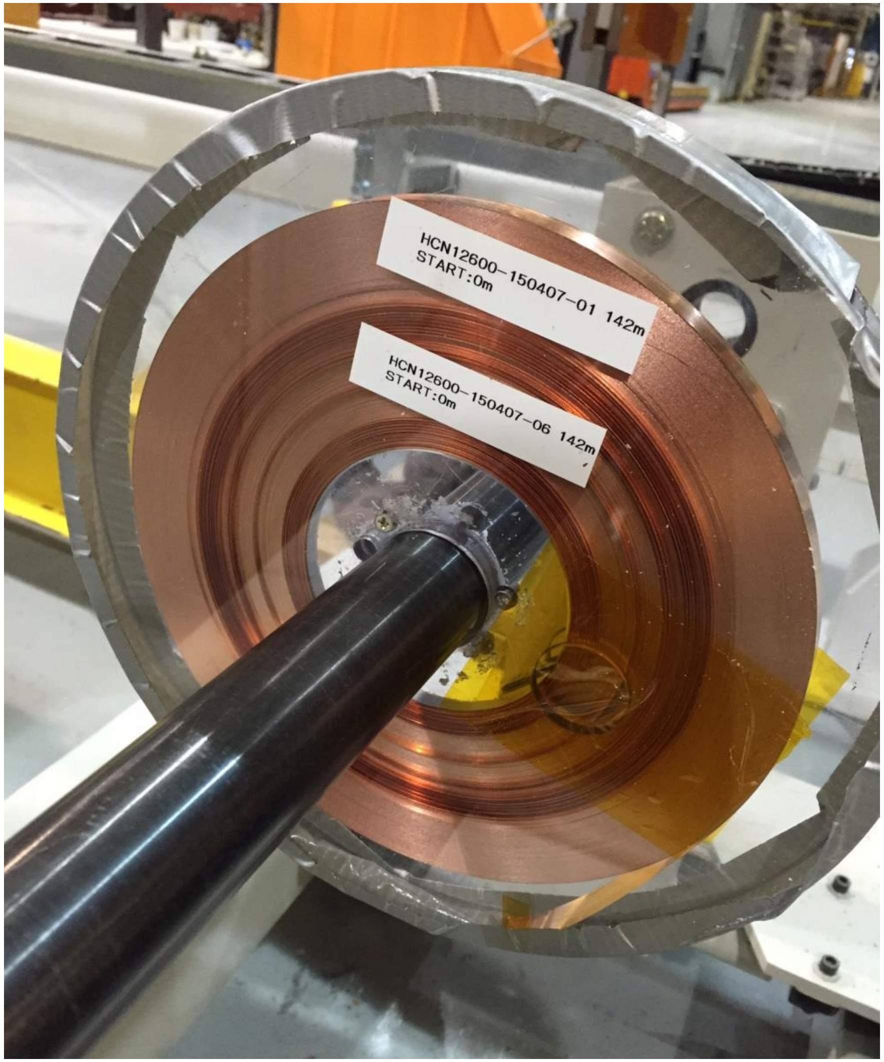
As compared to SuperPower, SuNAM has lower lift factor

Also the thickness of copper plating was lower

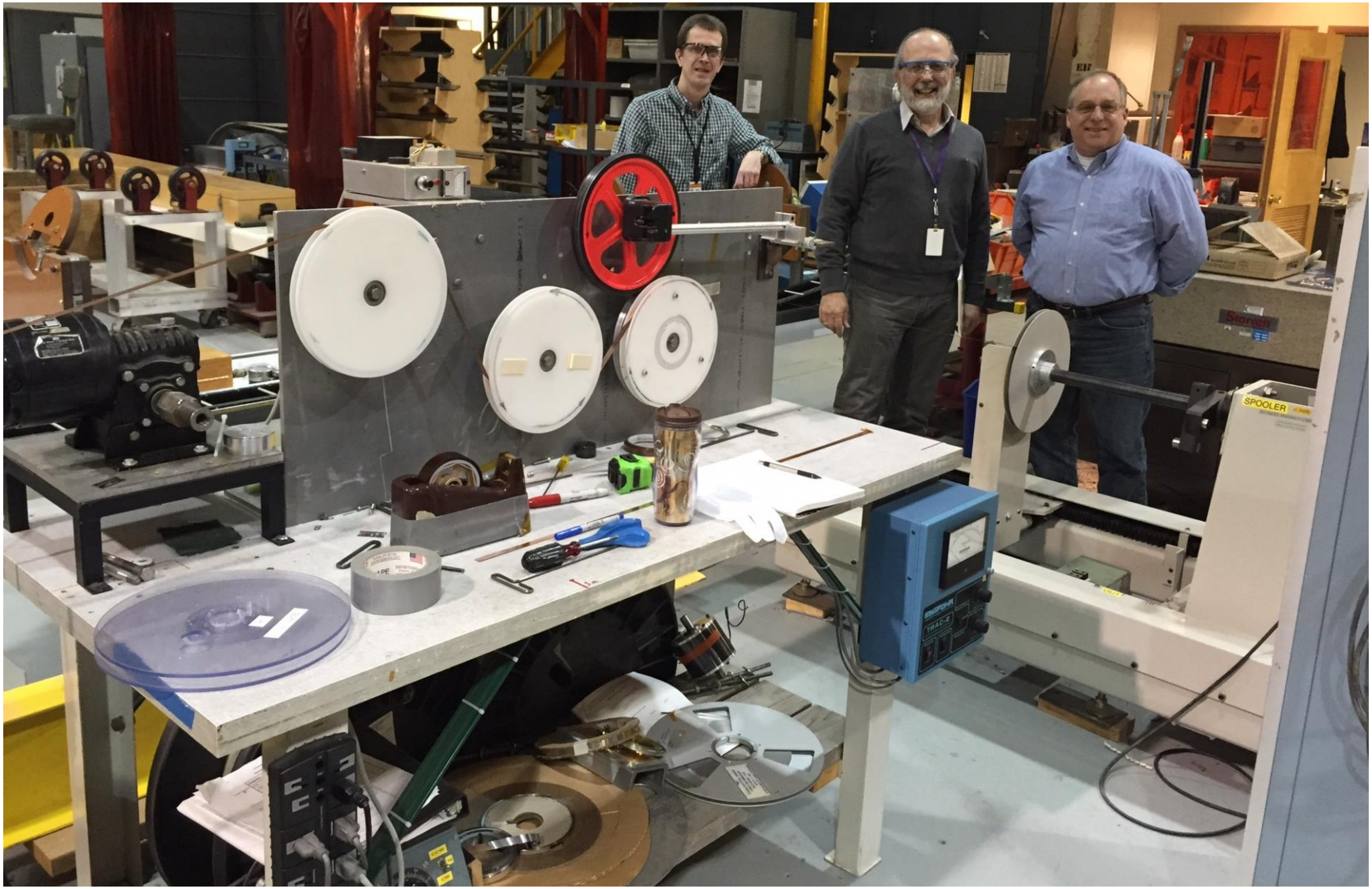
Construction

Transferring the Conductor





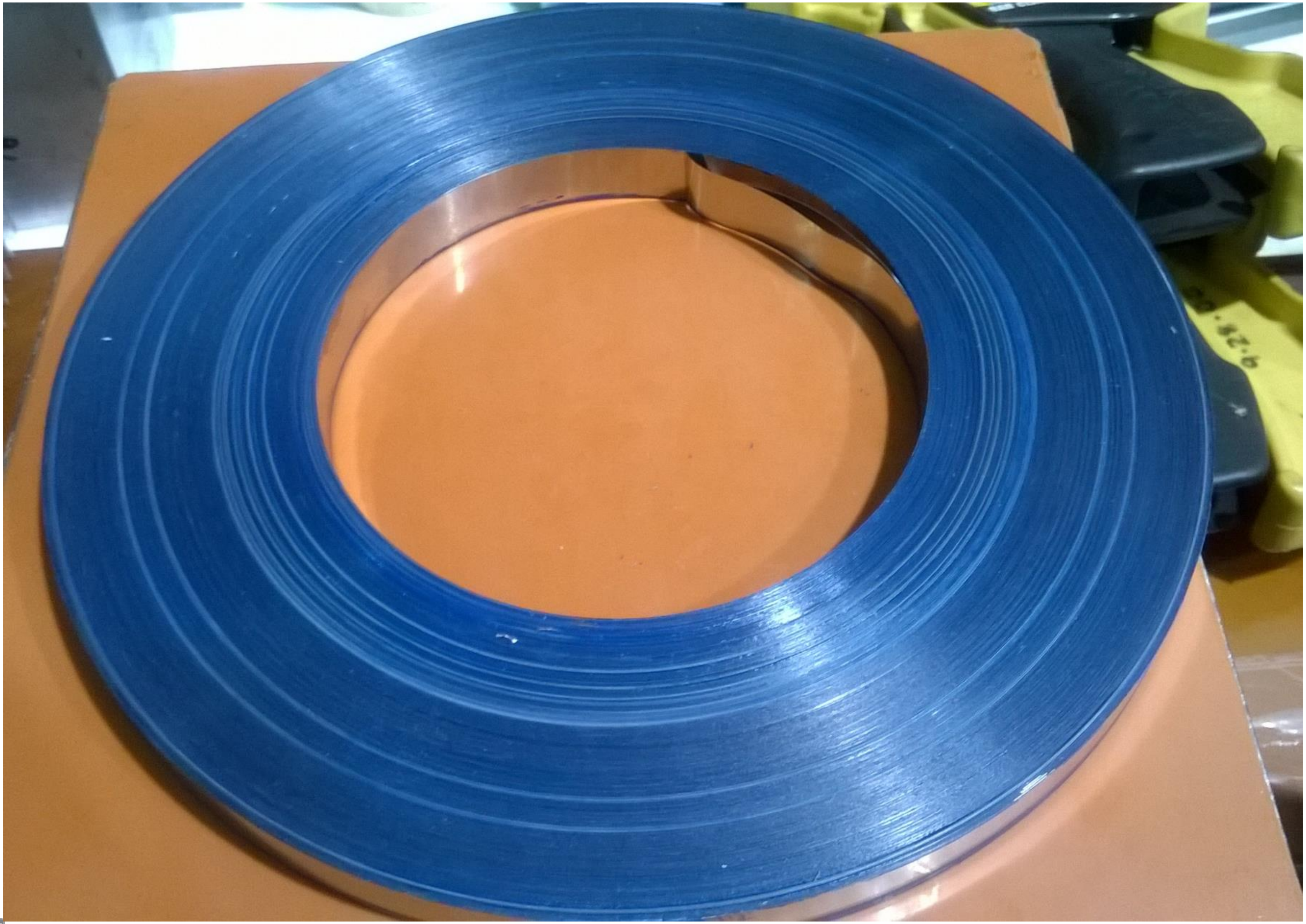
Reel-to-Reel Transfer (acrylic to metallic with proper hub)



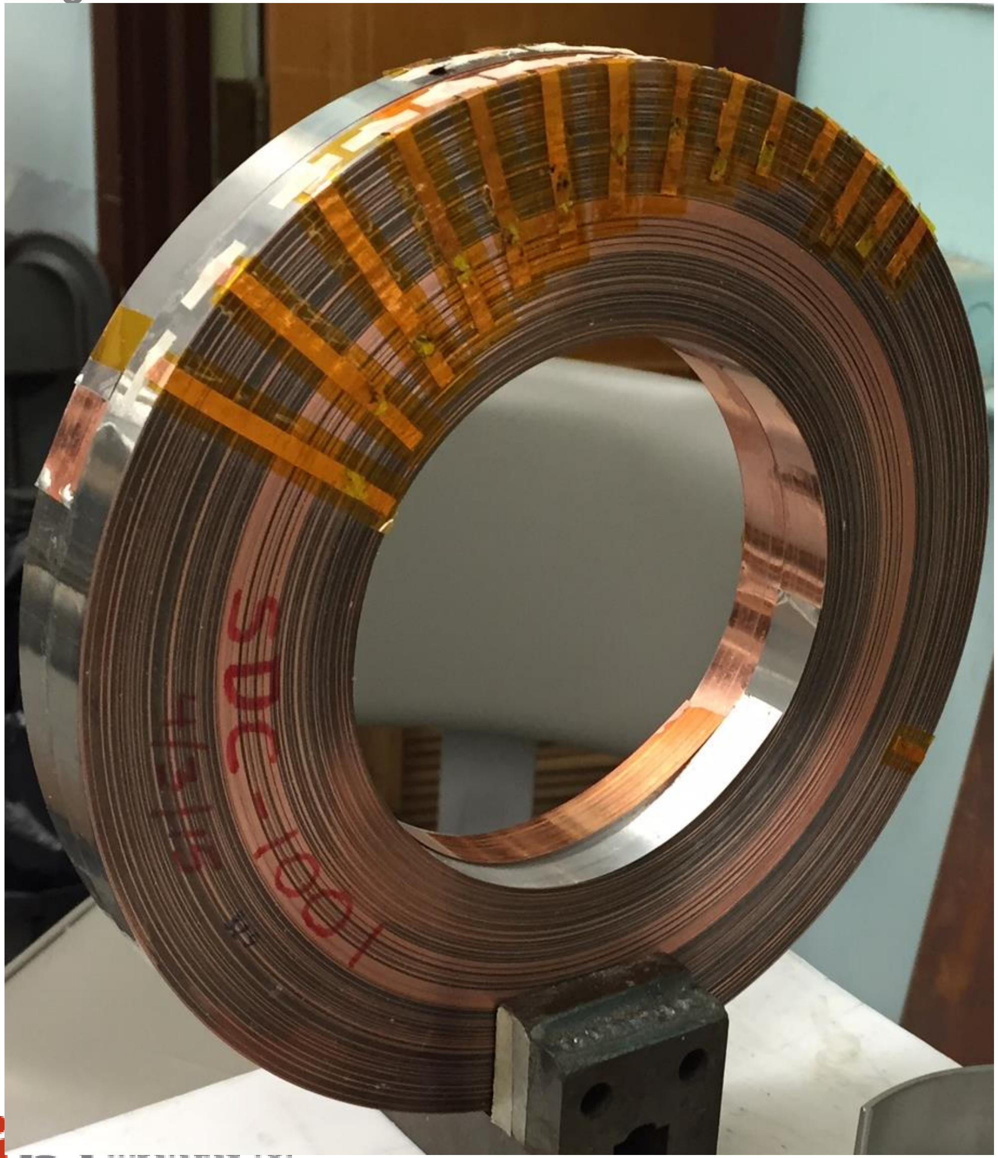
Coil Winding Machine

Coil Winding

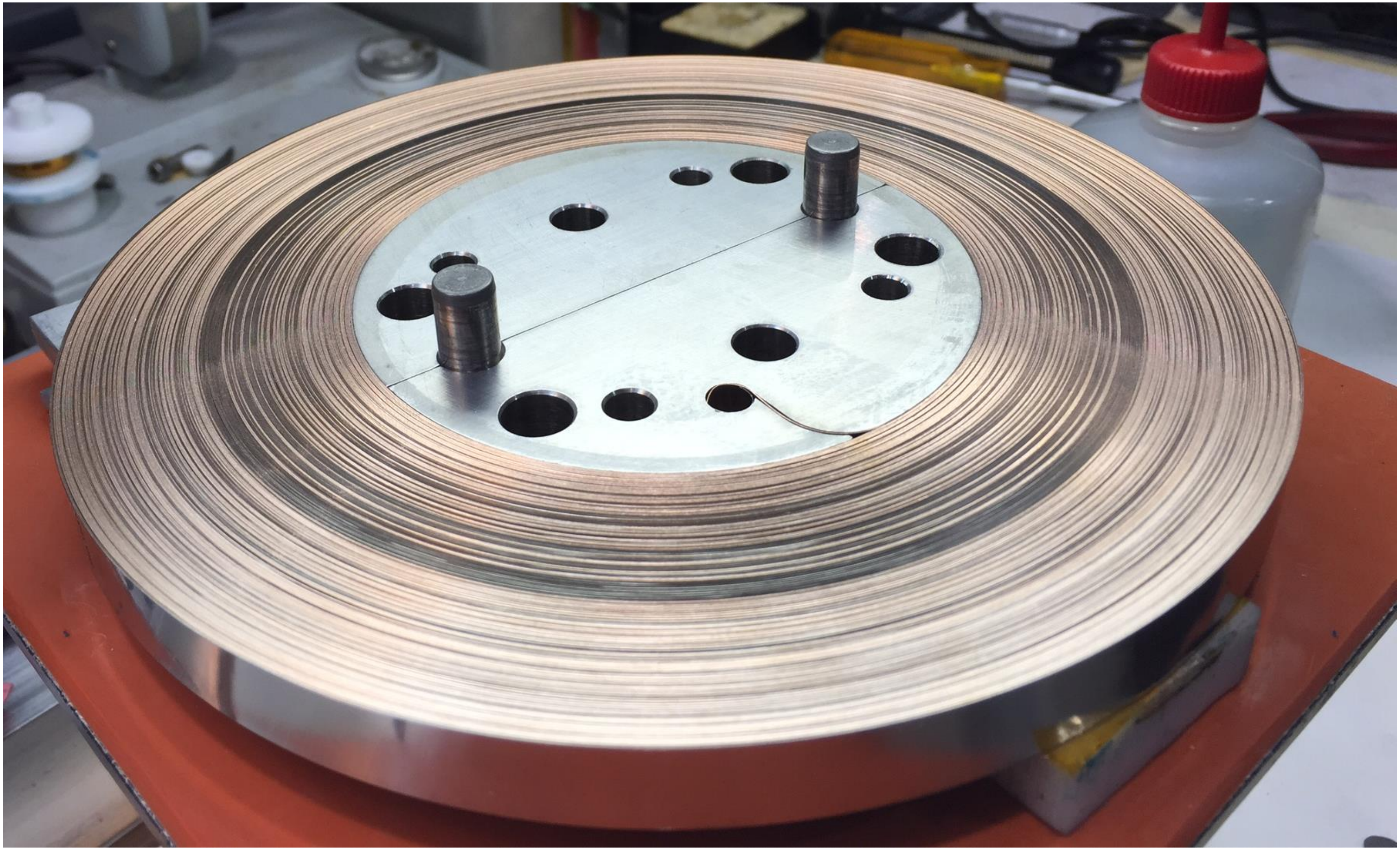
Practice Coil



Actual Pancake Coil with V-taps

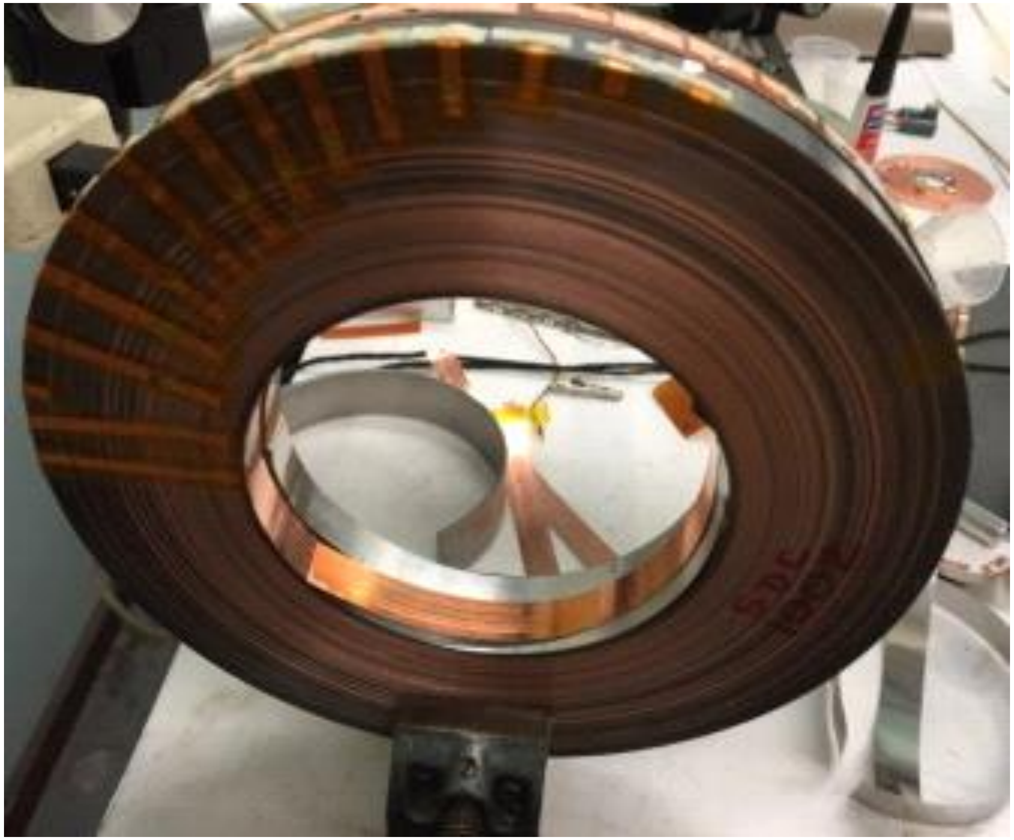


Other-side of the Pancake Coil



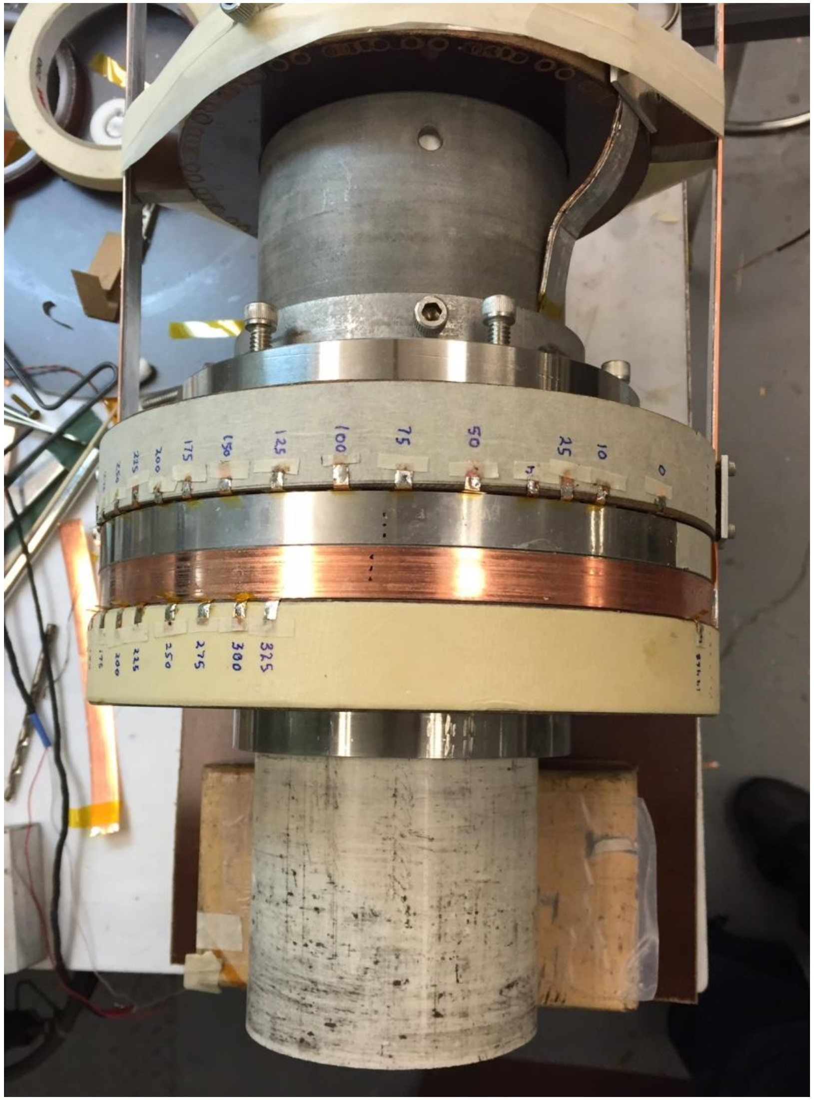
i.d.=101.6 mm, o.d.=192 mm

Single Pancake to Double Pancake

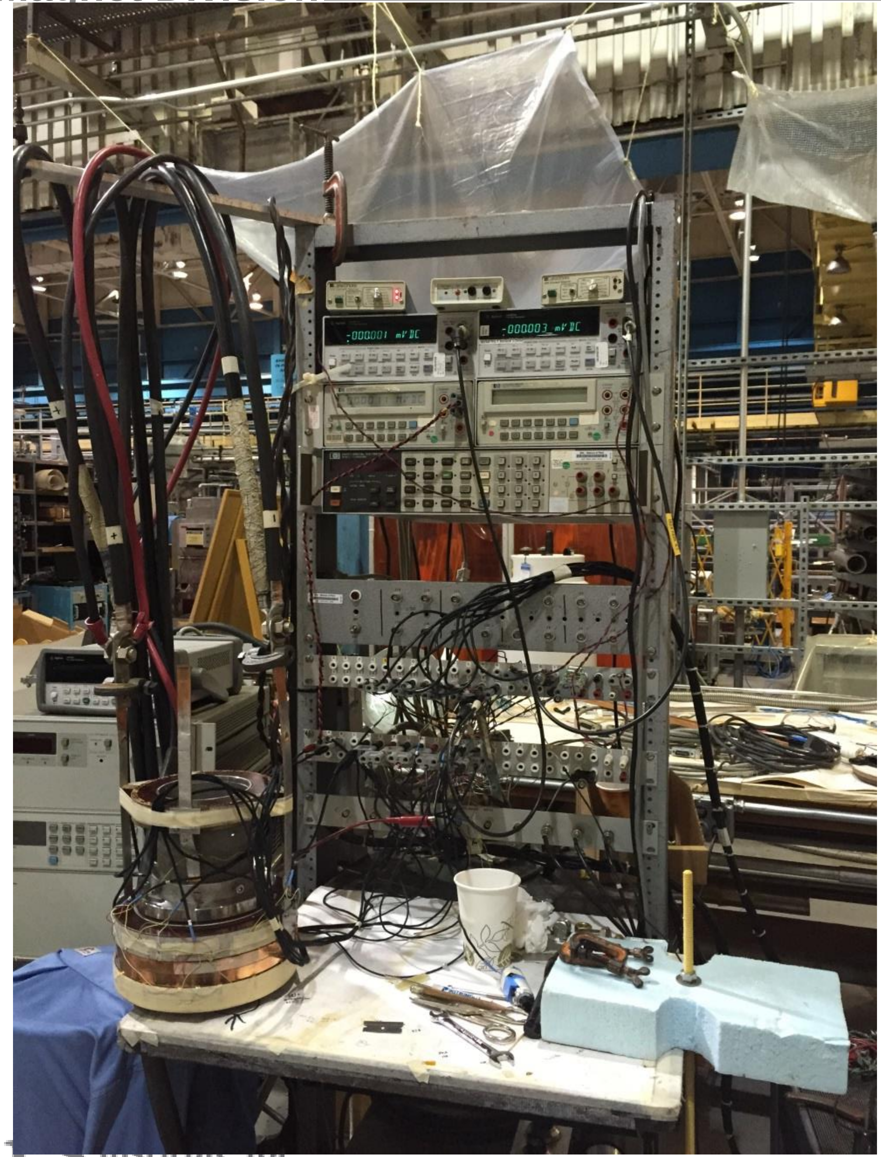


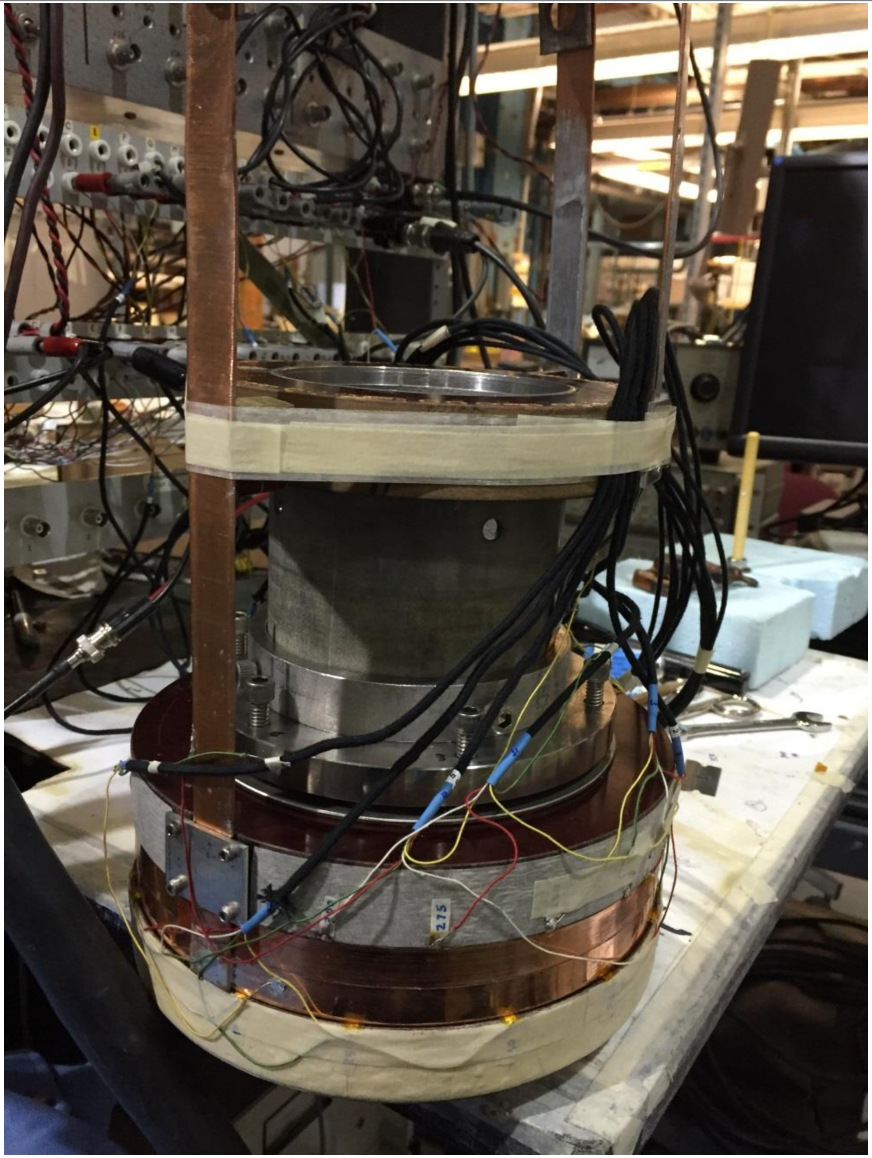
Spiral Splice for making Double Pancakes

Double Pancake Coil Test Setup



Double Pancake Coil at Test Station

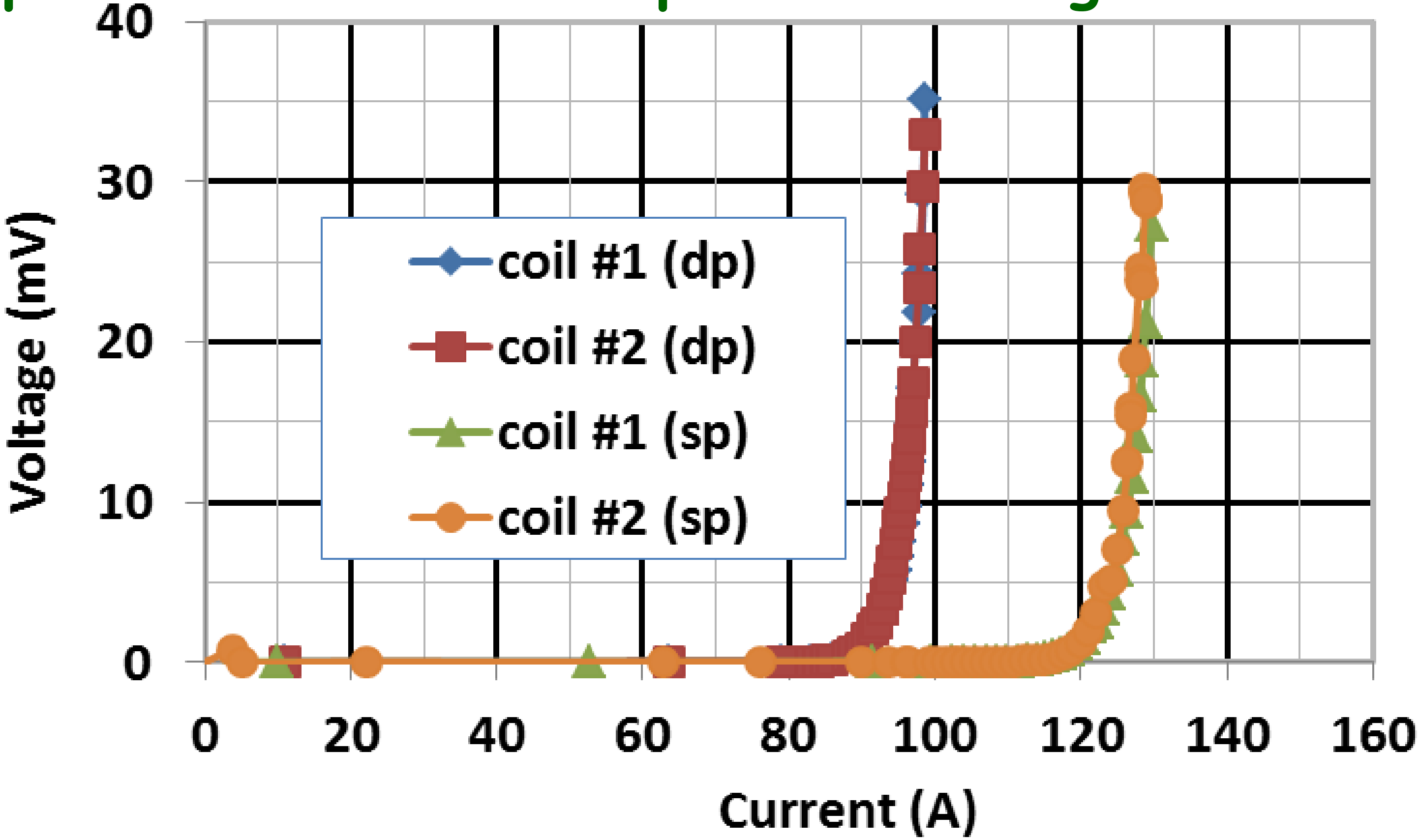




77 K Test of Individual Coils

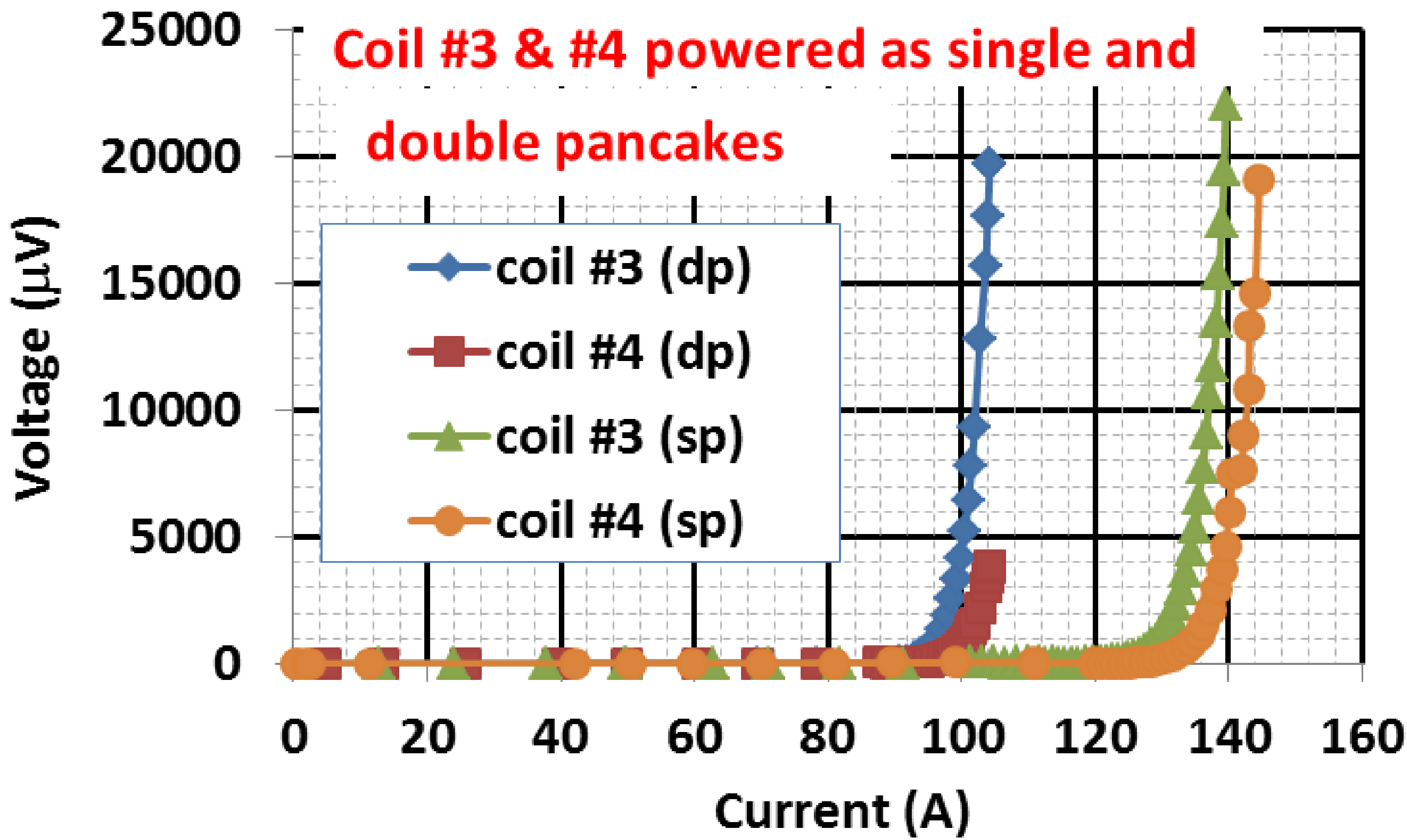
77 K QA Test of Double Pancakes

Three leads to power coils either in single pancake or in double pancake configurations

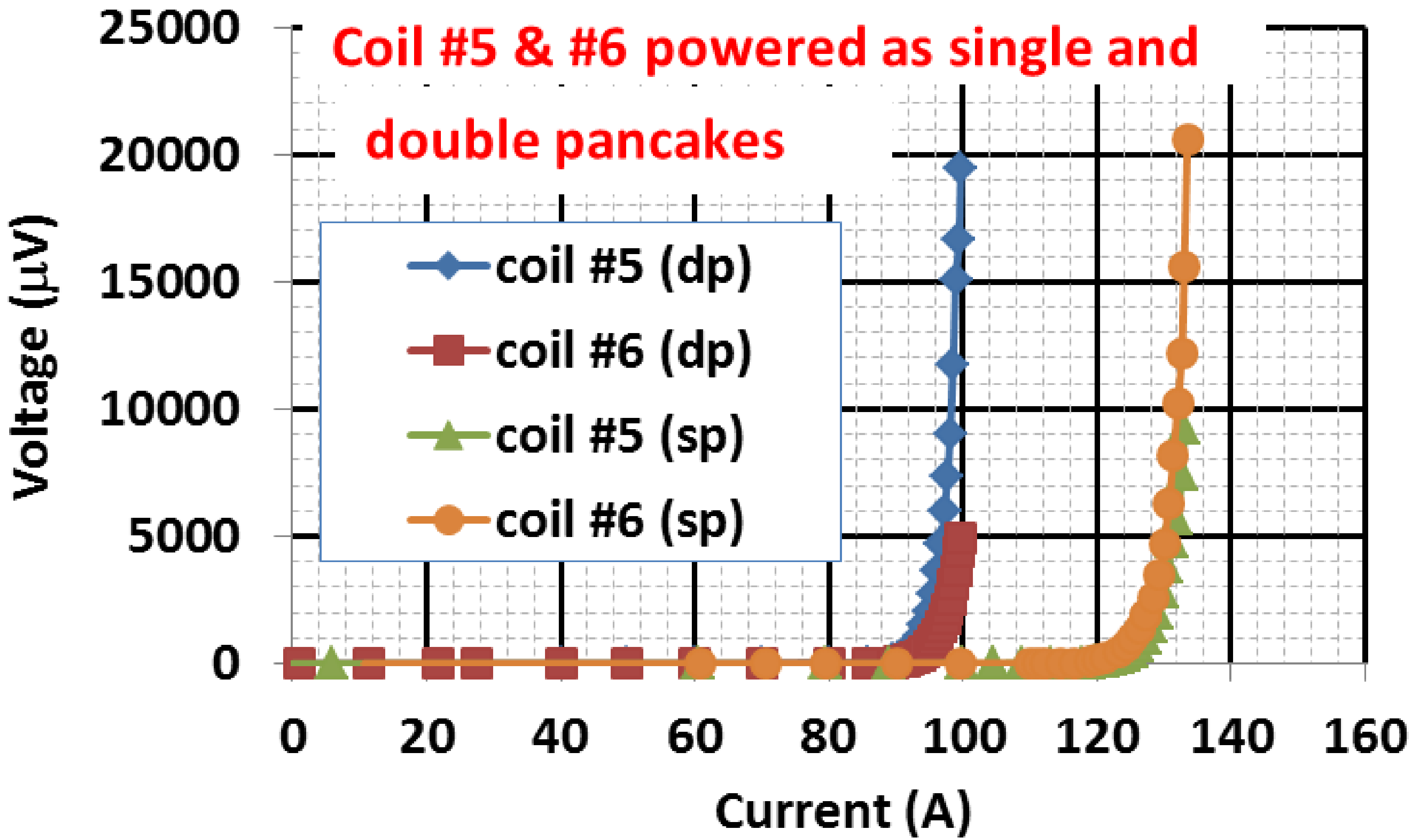


Higher field means lower current in a double pancake

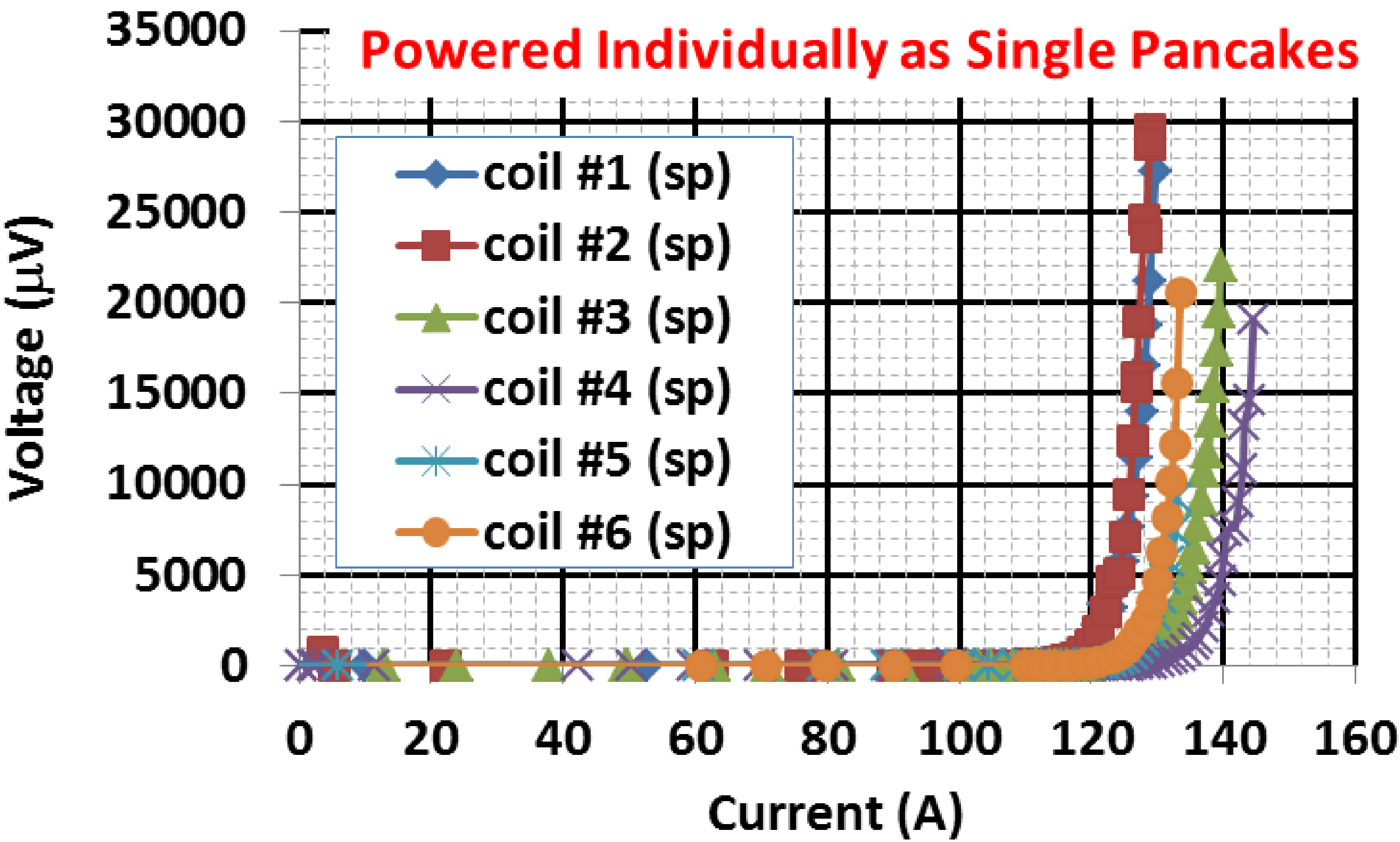
Coil #3 & #4


Coil #3 & #4 powered as single and double pancakes
coil #3 (dp)
coil #4 (dp)
coil #3 (sp)
coil #4 (sp)
Voltage (µV)
25000
20000
15000
10000
5000
0
0
20
40
60
80
100
120
140
160
Current (A)

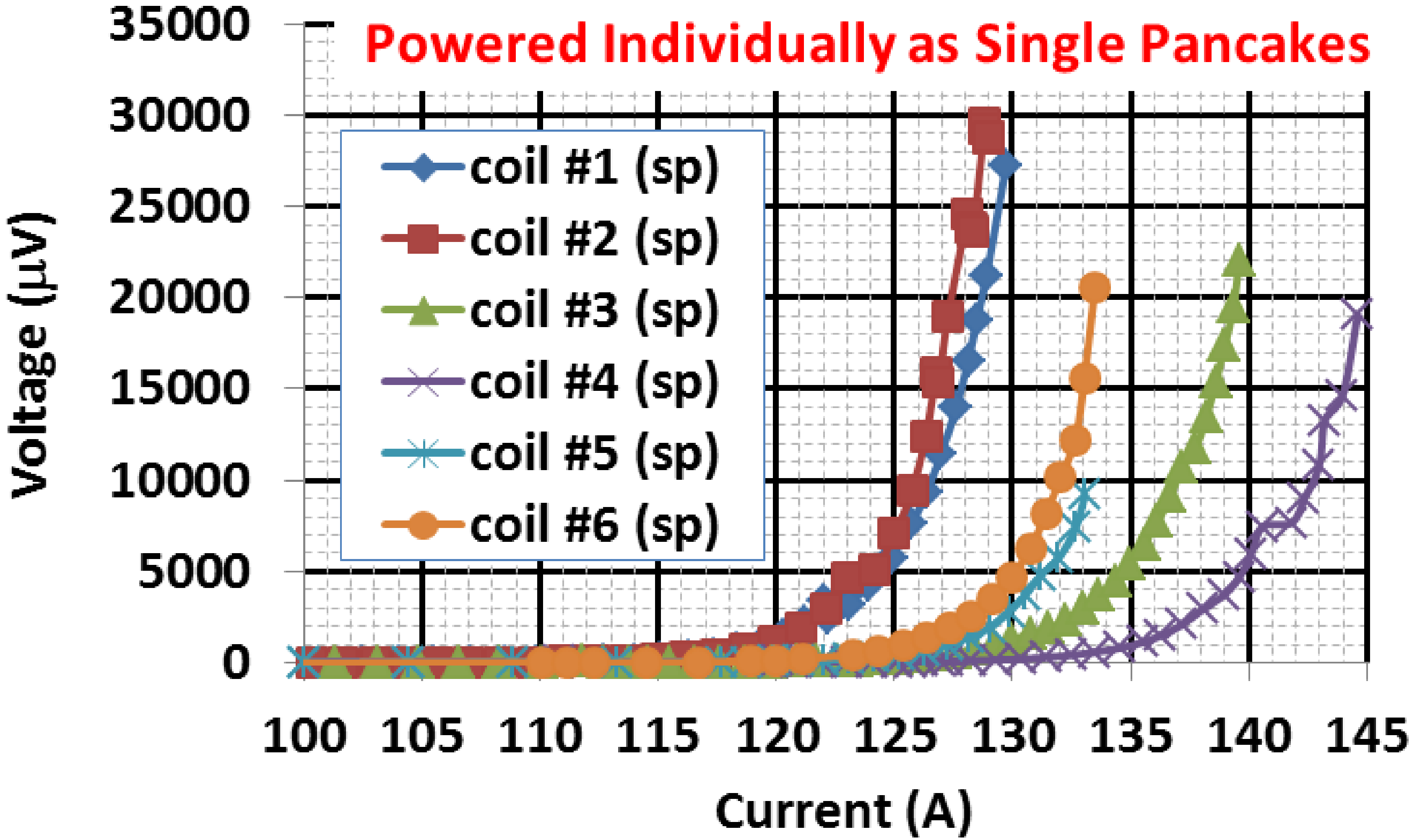
Coil #5 & #6


Coil #5 & #6 powered as single and double pancakes
Voltage (µV)
25000
20000
15000
10000
5000
0
coil #5 (dp)
coil #6 (dp)
coil #5 (sp)
coil #6 (sp)
0
20
40
60
80
100
120
140
160
Current (A)

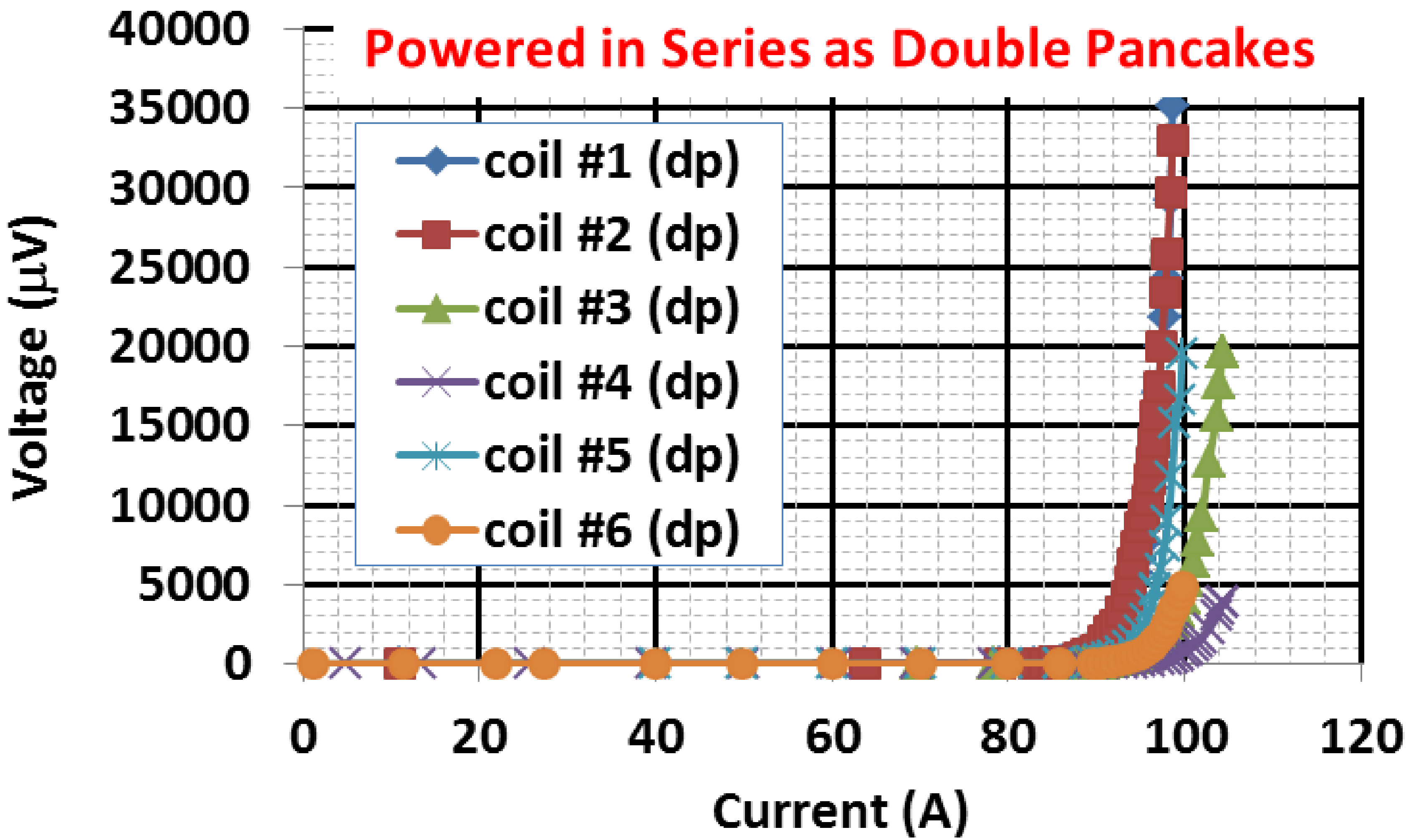
Coil #1 to #6 Tested as Single Pancakes (Full Run)



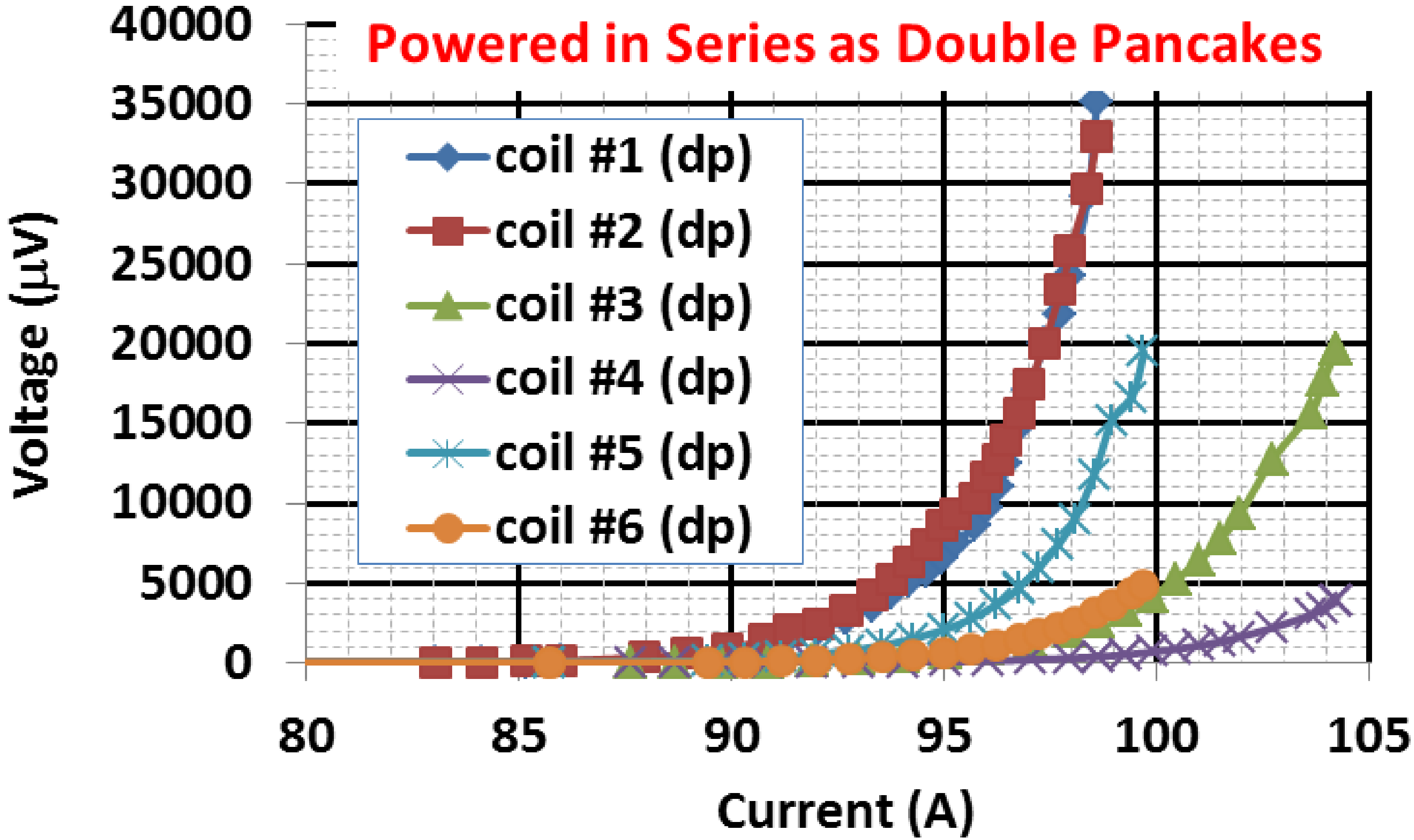
Coil #1 to #6 Tested as Single Pancakes (100 A-145 A)



Coil #1 to #6 Tested as Double Pancakes (Full Run)



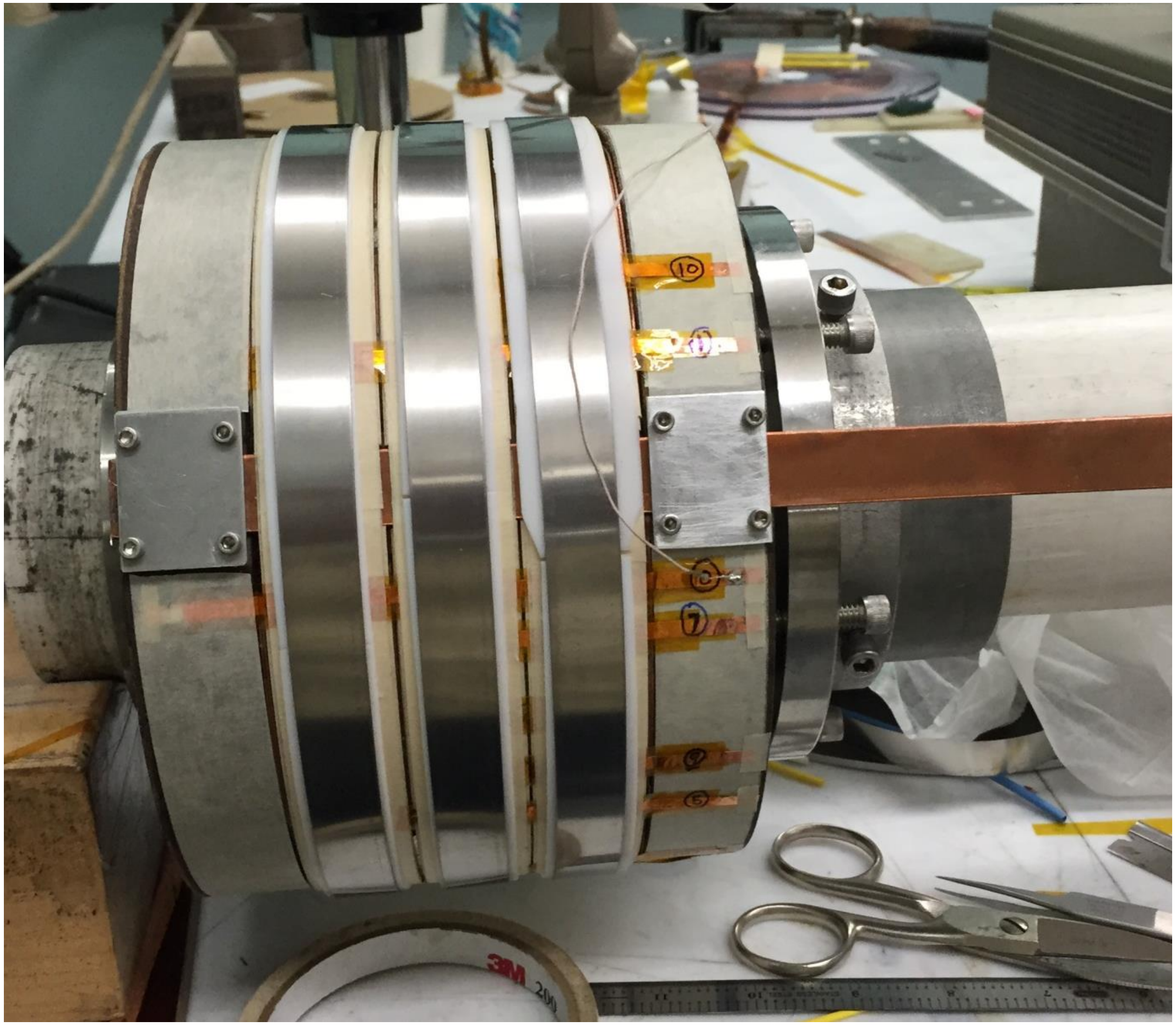
Coil #1 to #6 Tested as Double Pancakes (80 A-105 A)



Final Assembly and Testing

6 Pancakes Assembled for 77 K Test

SS Clamps over Fiberglass Epoxy Structure to Contain Hoop Stress



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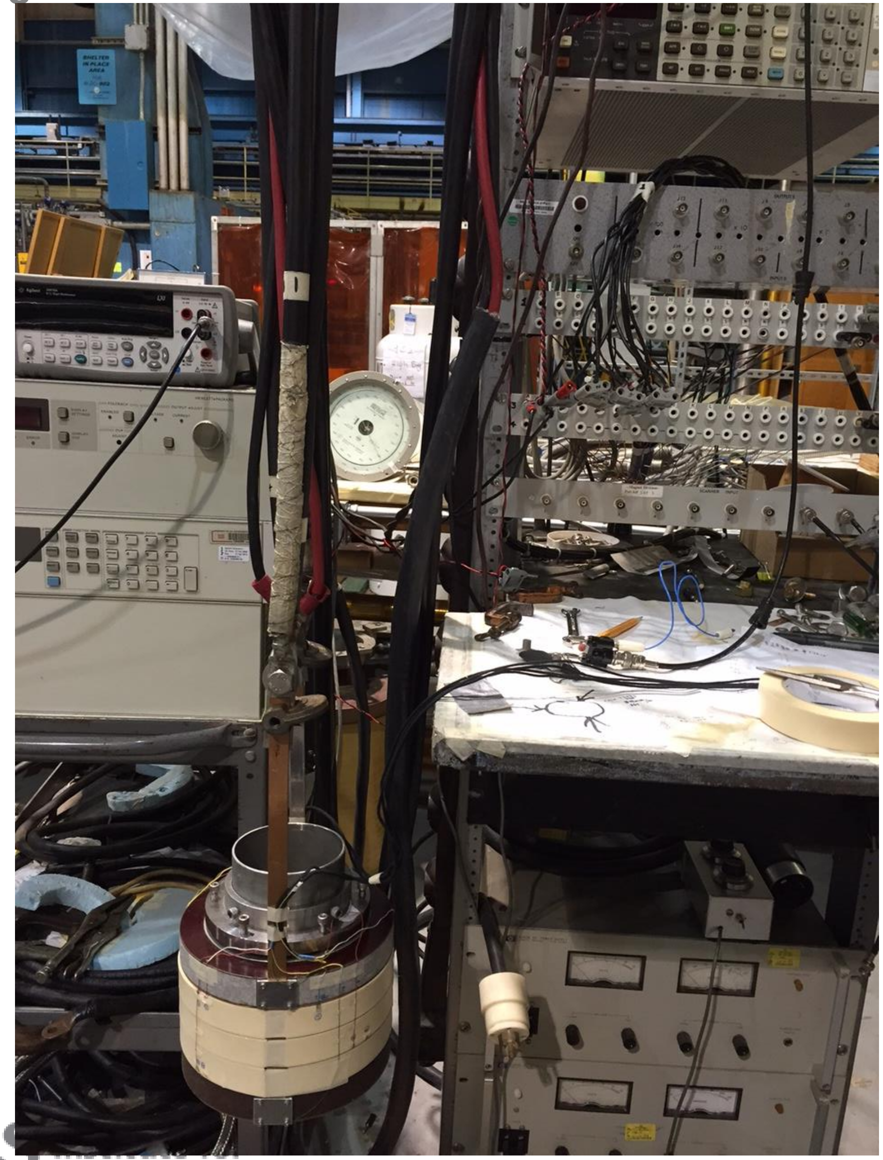
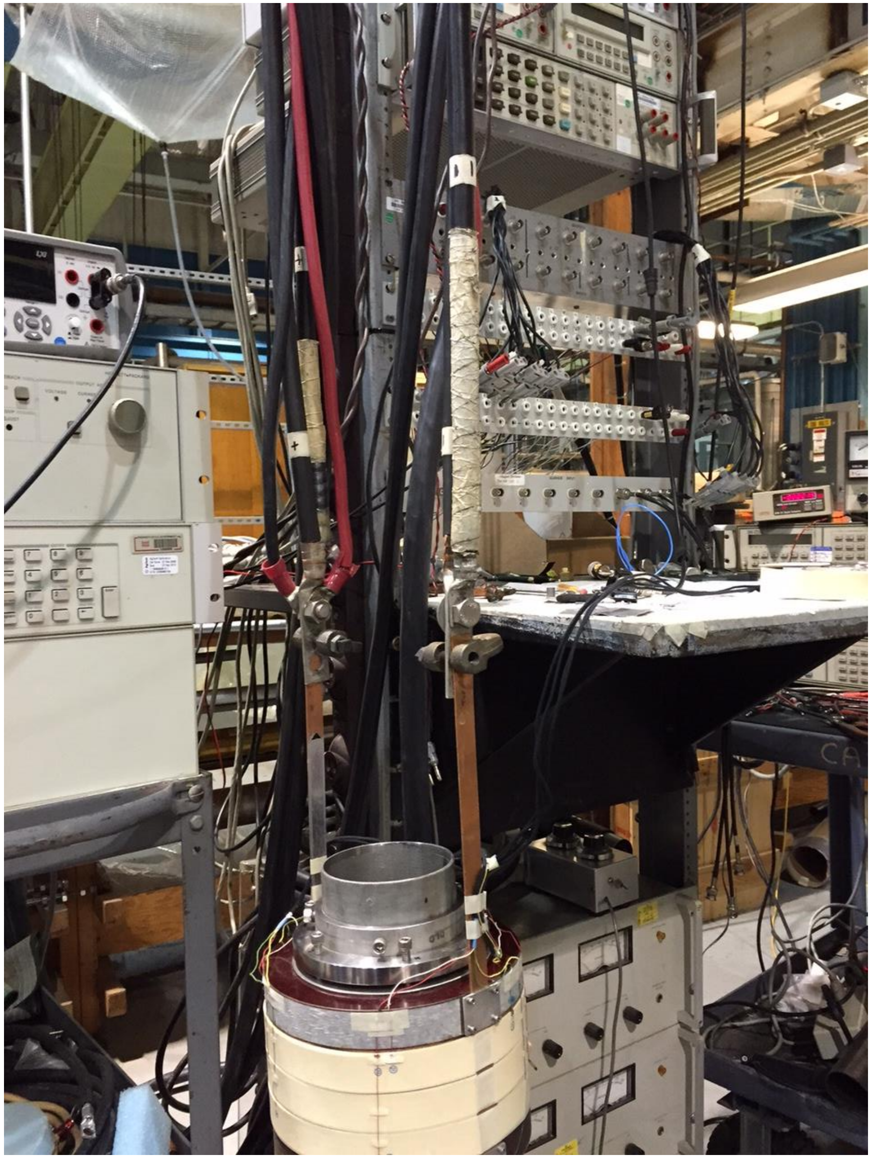
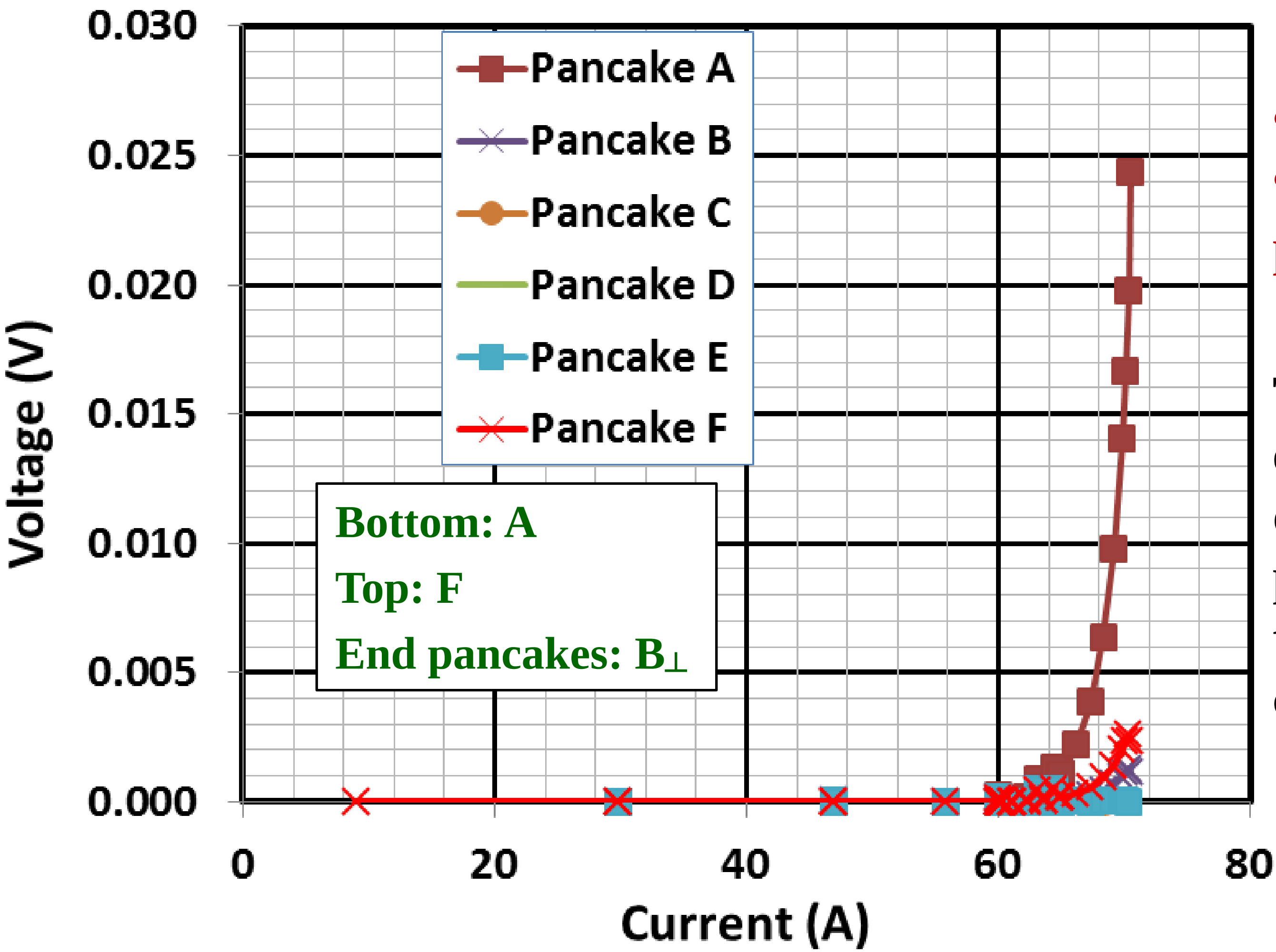
100 mm Solenoid at Test Stand





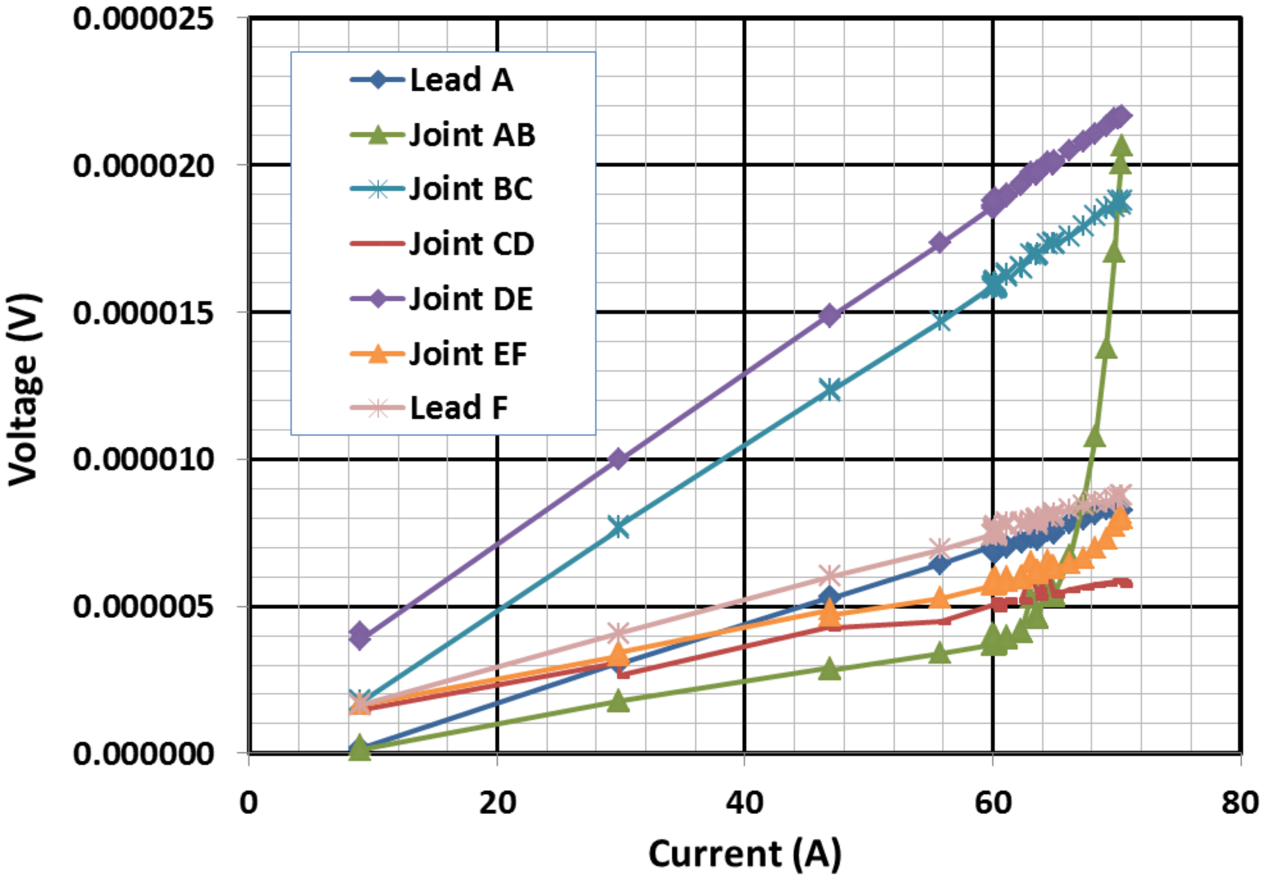
77 K Test of Completed Solenoid (6 HTS Pancakes)



"*Pancake A*" and "*Pancake F*" are two pancakes at two ends.

The pancakes at the ends are expected to define the magnet performance because of the perpendicular component of the field.

77 K Test of the Splices

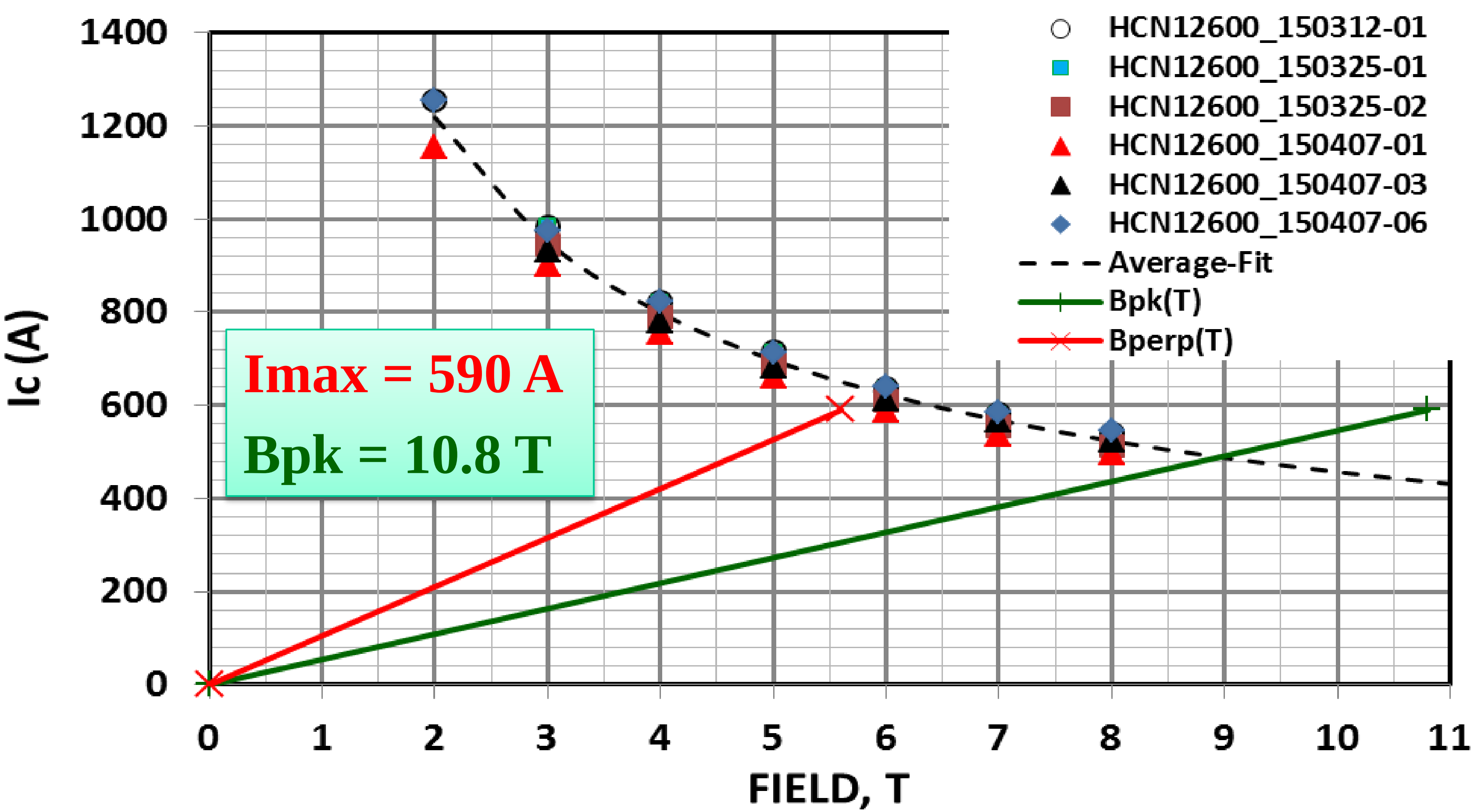


"Joint AB"*, *"Joint CD" **and *"Joint EF"* are spiral joint between two pancakes (inside).**

"Joint BC" **and *"Joint EF"* are joint between double pancakes (outer).**

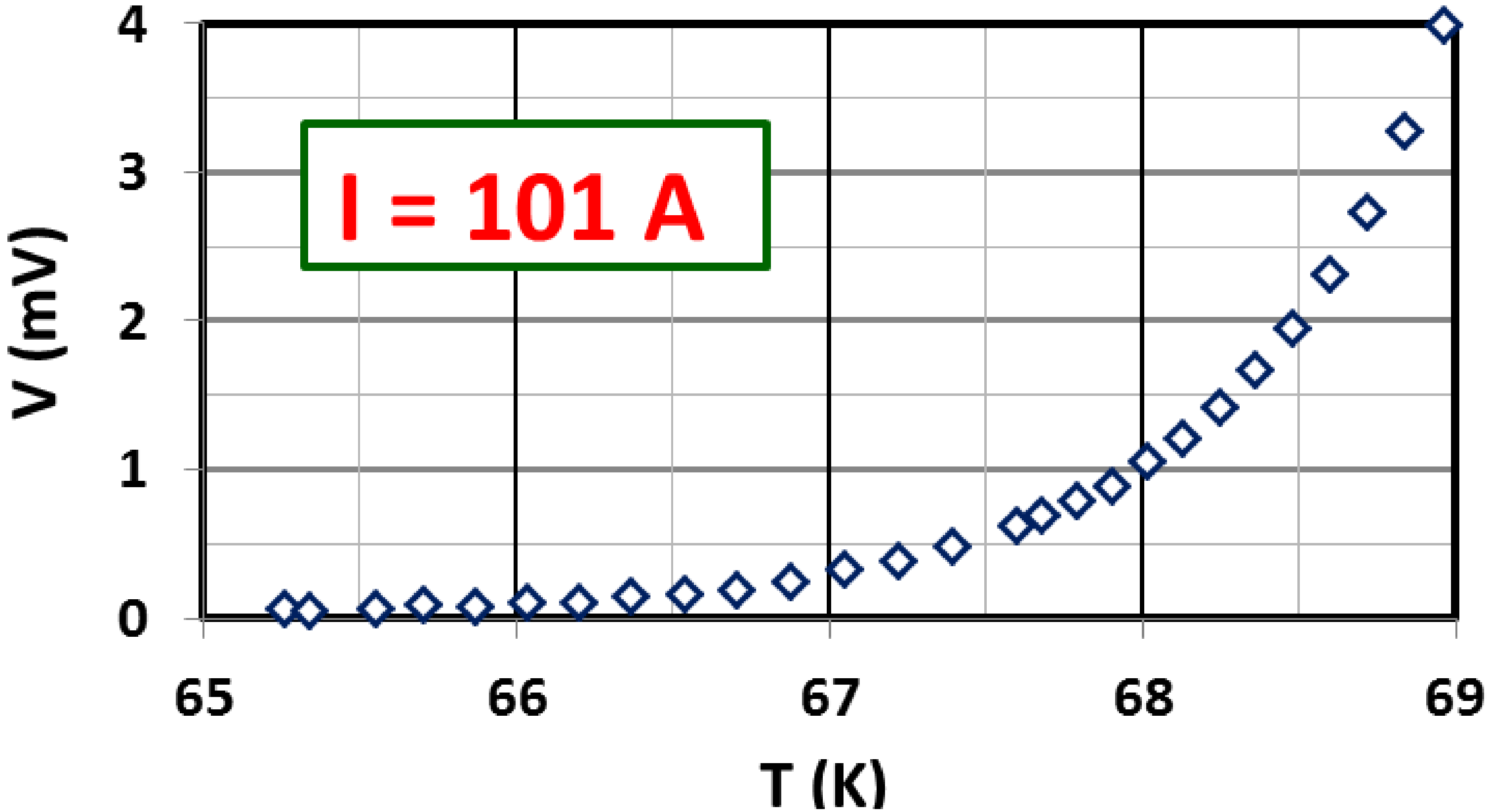
"Lead A" **and *"Lead F"* are joints to the lead.**

Final Test of the CAPP HTS Solenoid (Target 10 Tesla Reached/Exceeded)



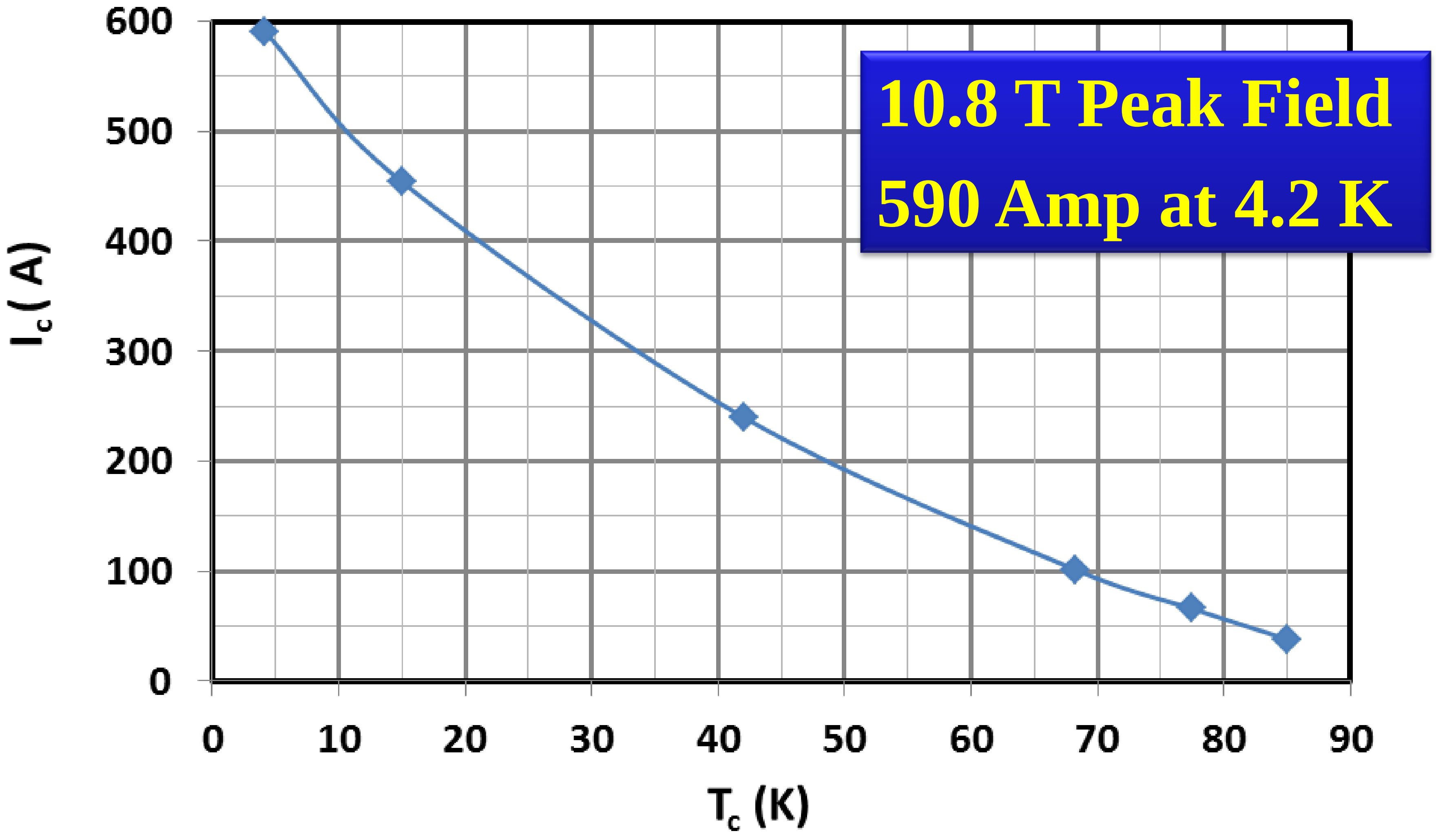
Performance is primarily limited by perpendicular component. We essentially reached that. Peak field of 10.8 T was higher.

Critical Current Measurements



Least noise (least inductive voltage) when the current is held constant and temperature is allowed to rise slowly to hit the critical surface/temperature

Critical Current Vs. Temperature



What is Needed to Reach the Final Goal (25T HTS, 35T Hybrid)

- **Understanding the challenges**
- **Minimizing the Risk**

Understanding the Challenges

- **High Field solenoid brings Axion dark matter search to a level that was never possible before. This also involves building a state-of-art solenoid.**
- **Future work should be towards minimizing risks.**
- **Intermediate steps and demonstrations to better assure.**
- **10 T, 100 mm HTS demonstration solenoid was the first step of this program.**
- **This should be followed by more.**

A Few Possible Demonstration for Near Future

- Comprehensive testing of the partial inner layer with significant stored energy built with the type of conductor to be used in actual magnet. These coils may be used in the actual magnet.
  - This should involve several power cycles, several thermal cycles and several quench cycles.
- Comprehensive testing of the partial outer layer with even larger stored energy and stresses. These coils may be later used.
  - This would also involve several power cycles, several thermal cycles and several quench cycles.
- Assembly of inner and outer layer together
- Test of CERN's CLIC quench protection system with BNL's advance quench detection system. BNL quench system detects pre-quench phase early on and CLIC acts fast in quenching entire coil without quench heaters (which acts slow) and without causing excessive voltage.

SUMMARY

- **HTS offers an opportunity to create very high fields to facilitate Axion dark matter search to a resolution never possible before.**
- **Major challenges: huge hoop stresses due to large bore, high field; quench protection; working with still developing conductor, etc...**
- **Due to similar parameters, the design and technology developed for SMES at BNL is found to be directly applicable to CAPP/IBS.**
- **The performance of SuNAM HTS was uniform and copper plating strong. High critical current at 77 K; pinning will improve at 4 K.**
- **CAPP/IBS solenoid reached its Phase I goal of demonstrating over 10 T in a 10 cm solenoid with SuNAM HTS and SMES coil design.**
- **Next phase should minimize the risk in reaching the final target – 25 T in 100 mm HTS, 35 T in 100 mm Hybrid.**

Differences between SuNAM and BNL Solenoids

- BNL made all its recent magnets with 12 mm tape
- SuNAM made with 4 mm wide tape but in the end went to large increasing the larger width
- 4 mm tape increase the cost (as you need to wind three times more coil)
- Larger width (higher current) also helps in quench protection
- Moreover, the fractional influence of weak spot along the width is larger
- BNL co-winds with stainless steel to deal with large hoop stress (issue in coils with larger bore magnets)