High Field, Large Aperture HTS Solenoid for Axion Dark Matter Search

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August 30, 2017

70 YEARS OF DISCOVERY
A CENTURY OF SERVICE

MT25
25th International Conference
on Magnet Technology

RAI - Amsterdam
August 27 - September 1, 2017

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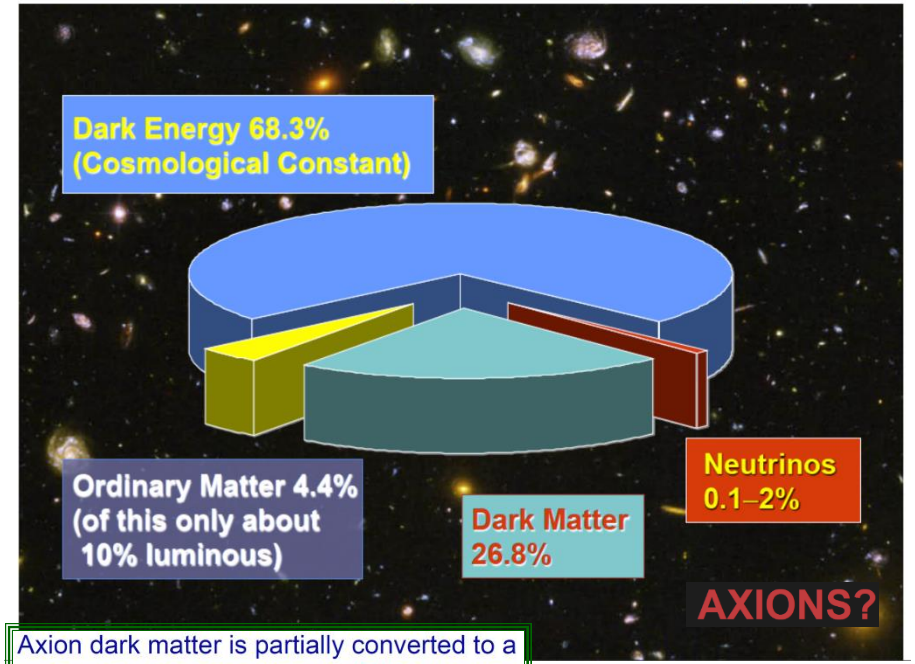
Overview

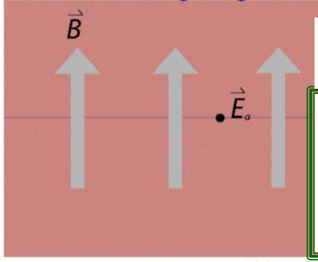
- Motivation and Design Requirements
- Present Design (25 T, 100 mm, all HTS)
- Conductor Requirements (12 mm 2G Tape, ~10 km)
- Conductor Mechanical Performance Tests
  - Loading on the narrow side of conductor
- No-Insulation Double Pancake Coil
  - One made with 550 meters of 12 mm wide ReBCO
- Summary

Axion Dark Matter Search Program at IBS

Cosmological inventory



Axion dark matter is partially converted to a very weak flickering Electric (E) field in the presence of a strong magnetic field (B).



Animation by Kristian Themann

J. Hong, J.E. Kim, S. Nam, YkS
hep-ph: 1403.1576

Scanning Rate:

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1\ \mathrm{GHz}}{year}\left(g_{a\gamma\gamma}10^{15}\,\mathrm{GeV}\right)^4\left(\frac{5\ \mathrm{GHz}}{f}\right)^2\left(\frac{4}{SNR}\right)^2\left(\frac{0.25\ \mathrm{K}}{T}\right)^2$$
$$\times\left(\frac{B}{25T}\right)^4\left(\frac{c}{0.6}\right)^2\left(\frac{V}{5l}\right)^2\left(\frac{Q}{10^5}\right)$$

Key to possible breakthrough: high field, large volume magnet

- **High field: B (B^4)**
- **Large volume: V (V^2)**

IBS found that the parameters of SMES HTS solenoid (25T, 100mm) were a good fit.

Contract awarded to BNL!

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Requirements for IBS Solenoid

- ☐ High Field : 25 T (must use HTS)
- ☐ Large Volume: 100 mm bore, +/-100 mm long

Stresses: J X B X R

- ☐ Field quality: ~10%
- ☐ Ramp-up time: up to 1 day

Relaxed field quality and slow charging

- ☐ User magnet: robust design, large Margin

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Design Choices

- ☐ **No Insulation**
  - ➢ **Takes benefit of relaxed field quality and slow charging time**
  - ➢ **Most reliable quench/defect forgiveness scheme in HTS magnets**
    (S. Hahn - Mon-Af-Or9-01)
- ☐ **Single Layer**
  - ➢ **Two layers may create unbalanced force condition between the two layers, particularly for "No Insulation" option**
- ☐ **Conductor: High Field, High Strength 2G ReBCO Tape**
- ☐ **Critical current margin : ~50%**
  - ➢ **High performance needed at high fields @ 4 K**
- ☐ **Stress/strain margin : ~50%**
  - ➢ **Multi-width option increases maximum stress (NOT acceptable here)**

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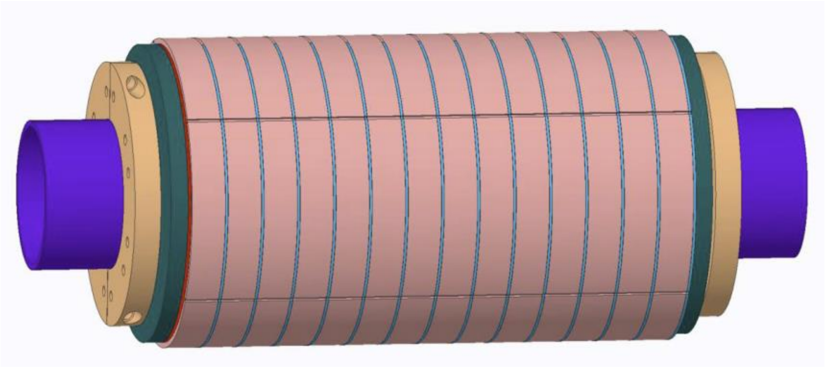
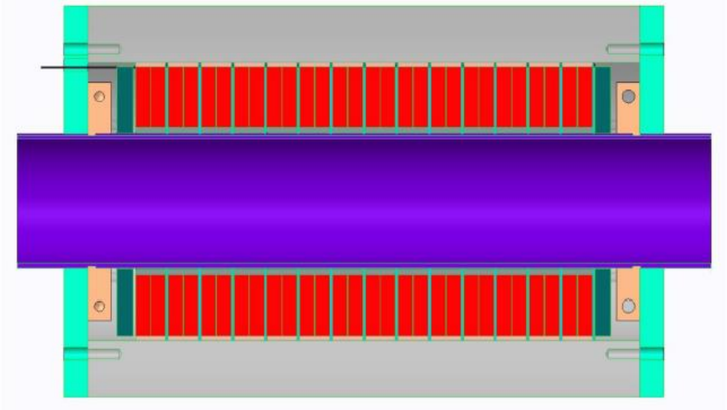
Major Parameters of the IBS HTS Solenoid



- **Field: 25 T@4 K**
- **Single Layer**
- **Cold Bore: 100 mm**
- **Coil i.d.: ~118 mm**
- **Coil o.d.: ~214 mm**
- **Conductor: 12 mm wide ReBCO**
- **Current: ~450 A**
- **Current Density: ~490 A/mm^2**
- **Stored Energy: ~1.6 MJ**
- **Max. Hoop Stress: ~500 MPa**



Key Conductor Specifications

- **Width: 10-13 mm**
- **I_c (8T, 4K) > 675 A, any direction (no spec on the Max.)**
  - ➢ **Price/performance matrix requested**
  - ➢ **Monitor I_c at 77K, self field; but assure it at 4K, 8T**
- **Mechanical: 50 micron Hastelloy, 20 micron Cu**
  - ➢ **More details to vendors on mechanical specifications**
- **Piece Length: Minimum 100 m (flexibility to vendors)**
- **Total Required: ~10 km**
  - ➢ **Quotes request for two range of lengths**

- **Vendors are allowed to present exceptions**
- **First order for 5 km of tape should be out soon**

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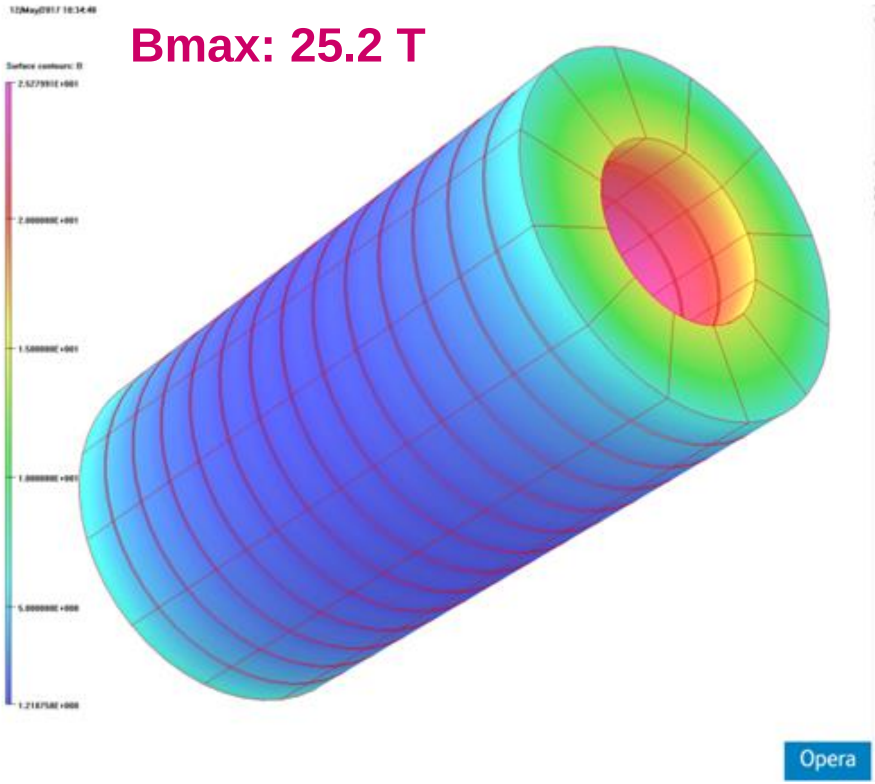
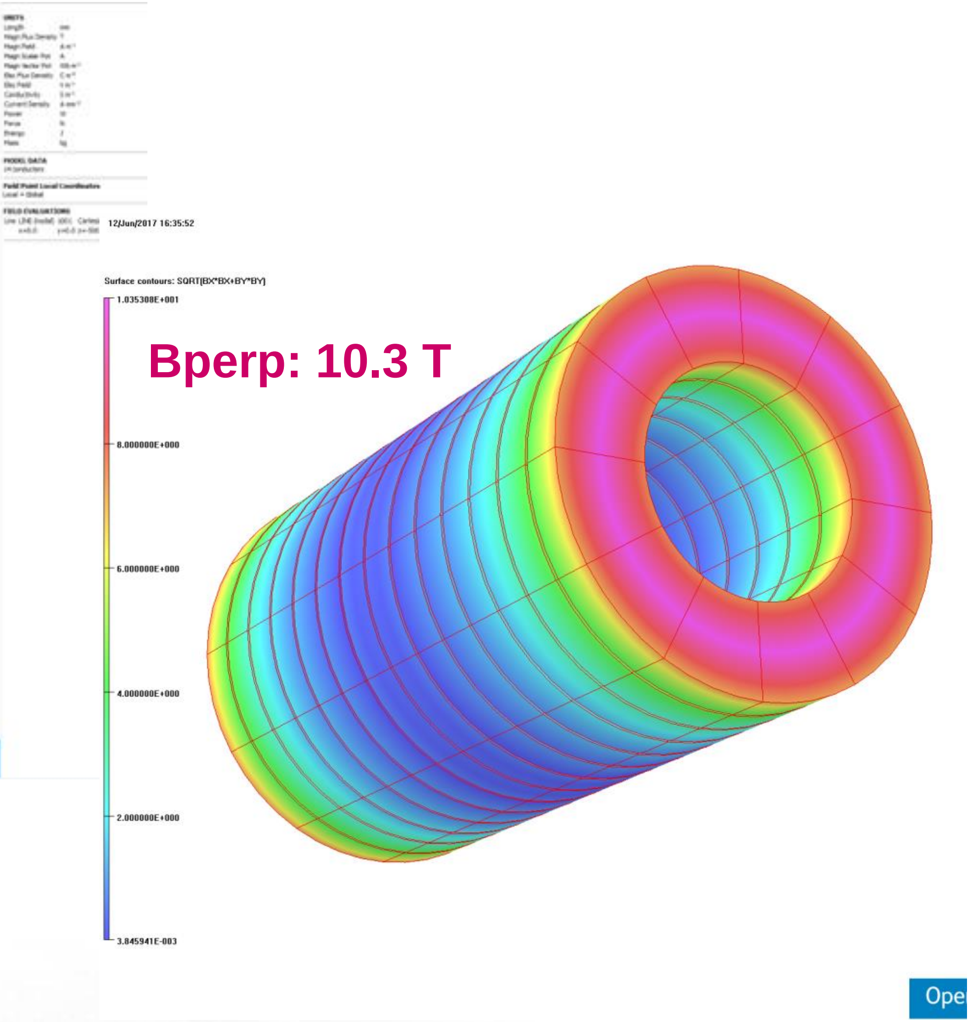
Basic Magnetic Analysis



Bmax: 25.2 T



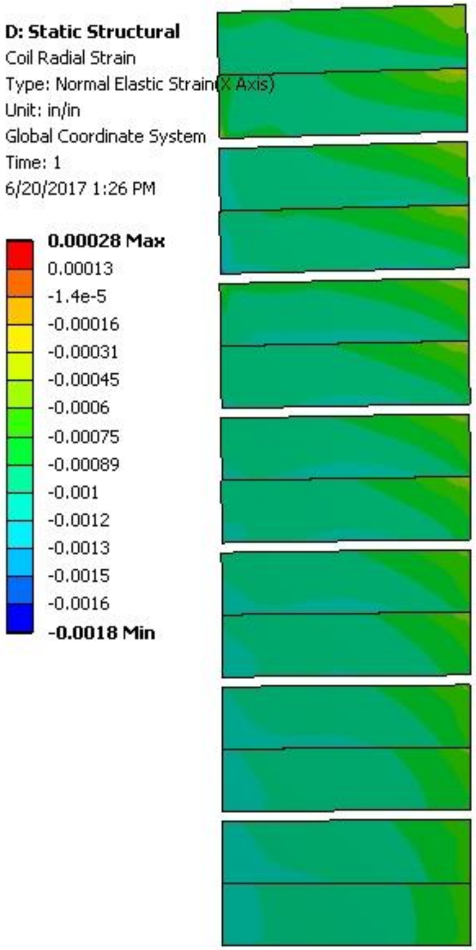
Bperp: 10.3 T

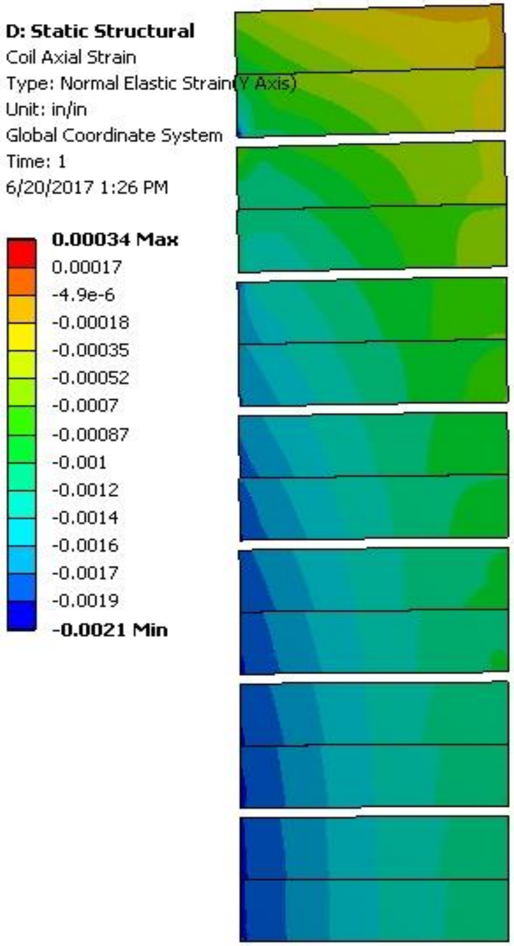
Simple constant Je model

(in reality Je may vary across the tape width)

Mechanical Analysis

Orthogonal Coil Strains @ 4 K, 25 T


D: Static Structural
Coil Radial Strain
Type: Normal Elastic Strain(X Axis)
Unit: in/in
Global Coordinate System
Time: 1
6/20/2017 1:26 PM


D: Static Structural
Coil Axial Strain
Type: Normal Elastic Strain(Y Axis)
Unit: in/in
Global Coordinate System
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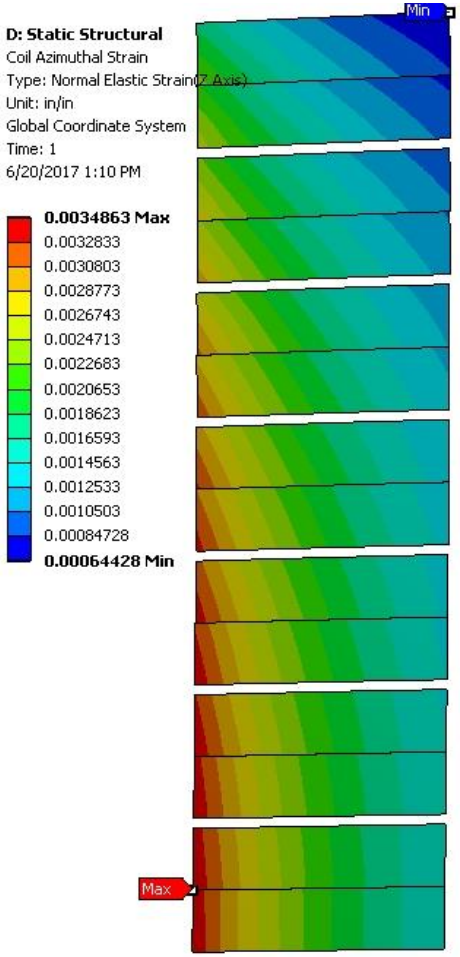

D: Static Structural
Coil Azimuthal Strain
Type: Normal Elastic Strain(Z Axis)
Unit: in/in
Global Coordinate System
Time: 1
6/20/2017 1:10 PM

-.10% Max Strain

Radial

-.21% Max Strain

Axial

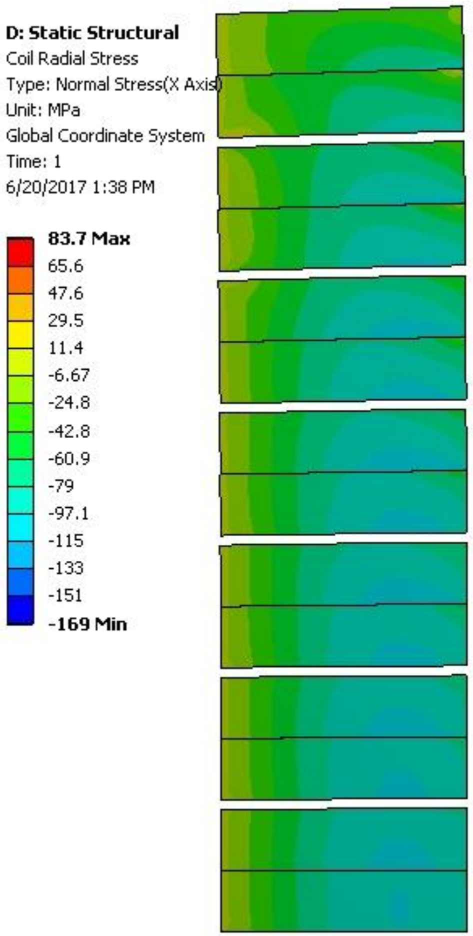
+

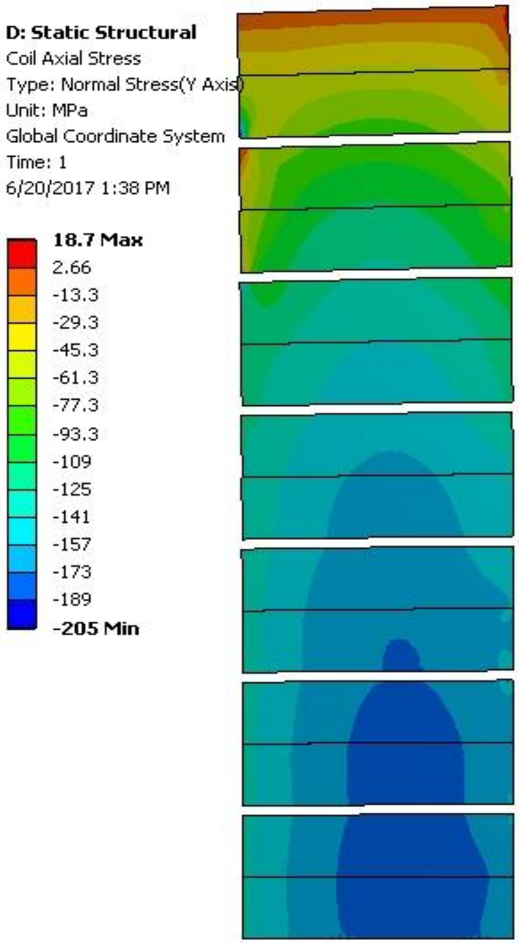
+

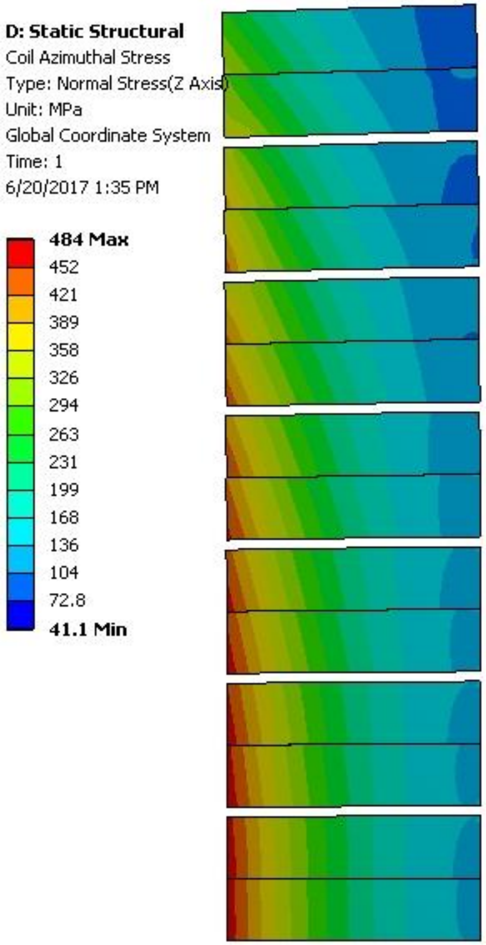
Azimuthal

.35% Max Strain

Orthogonal Coil Stresses (MPa) @ 4 K, 25 T







484 MPa Max Stress

-100 MPa Max Stress

Radial

+

-205 MPa Max Stress

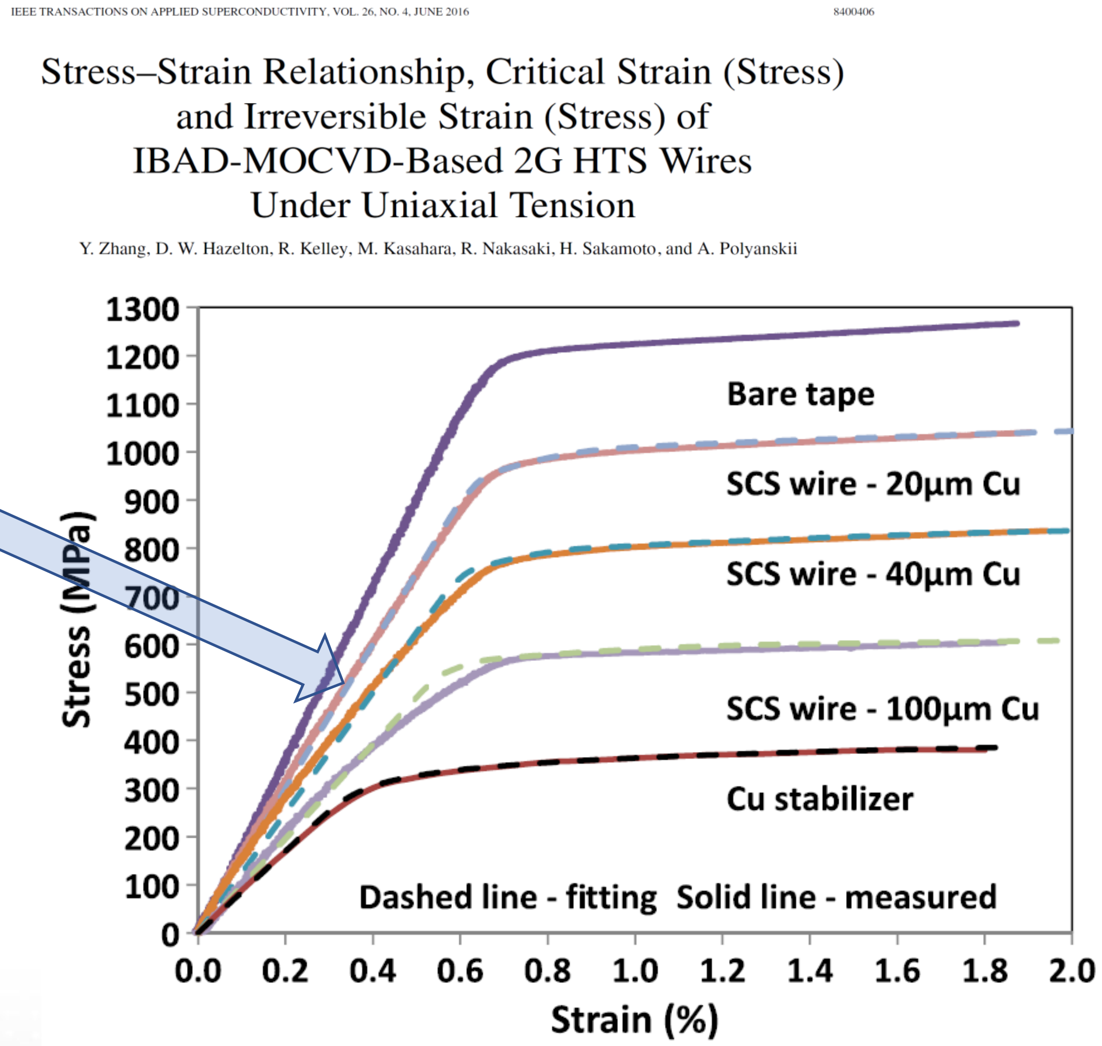
Axial

+

Azimuthal

Mechanical Properties of the Conductor

Requirement of Azimuthal stresses of ~500 MPa is met with 2G Tape having 50 micron Hastelloy and 20 micron Copper



IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 26, NO. 4, JUNE 2016 8400406

Stress–Strain Relationship, Critical Strain (Stress) and Irreversible Strain (Stress) of IBAD-MOCVD-Based 2G HTS Wires Under Uniaxial Tension

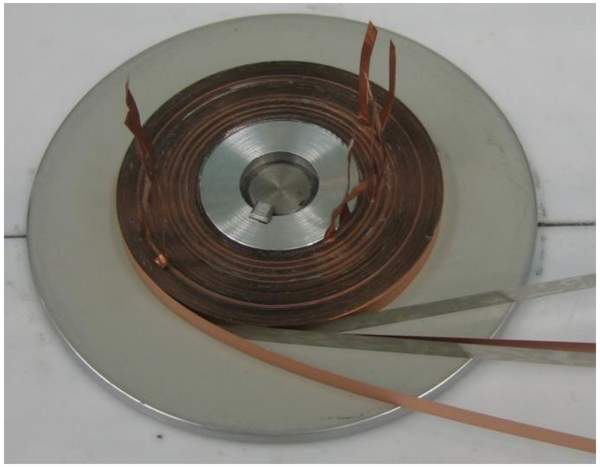
Y. Zhang, D. W. Hazelton, R. Kelley, M. Kasahara, R. Nakasaki, H. Sakamoto, and A. Polyanskii

Meeting requirement of ~200 MPa on the narrow side of the tape needs to be checked as no such data is available

Courtesy: SuperPower

Previous Apparatus at BNL to Study Influence of Load on the Narrow side of HTS Tape (~decade ago)

Works well to 100 MPa
(criterion used in many designs)



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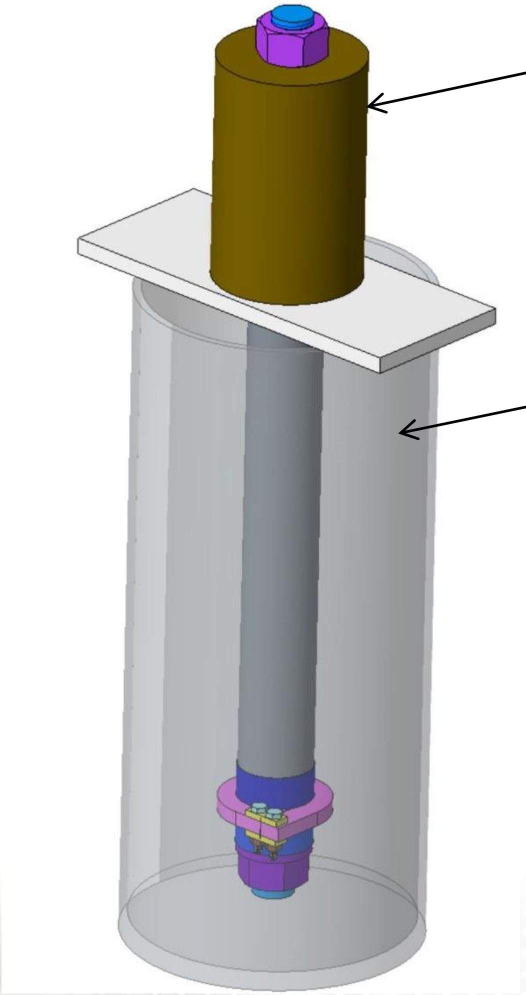
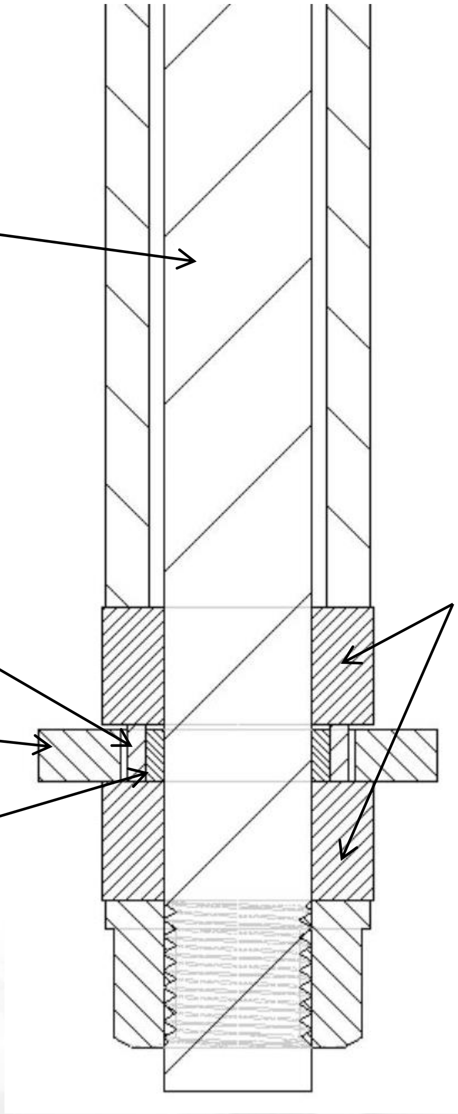
New Apparatus to Apply 300 MPa Load on the Narrow Side (design needs 200 MPa)





Hydraulic Cylinder

32 mm dia. actuator rod

LN_2 Dewar

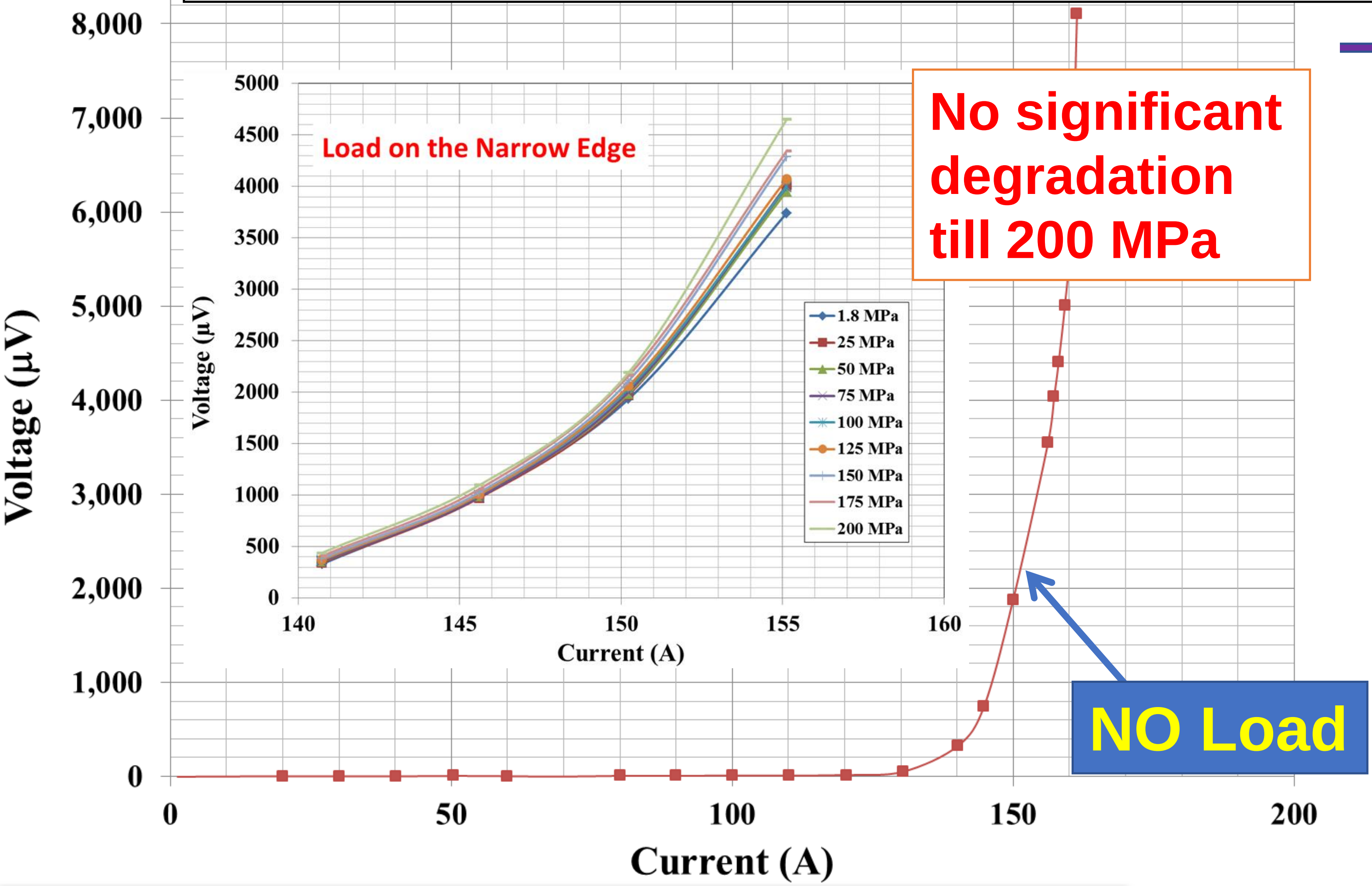
HTS Test Sample

Sample O.D. Support

Sample Bobbin

Press Platens

Impact of Load on the Narrow face of the Conductor



No significant degradation till 200 MPa

NO Load

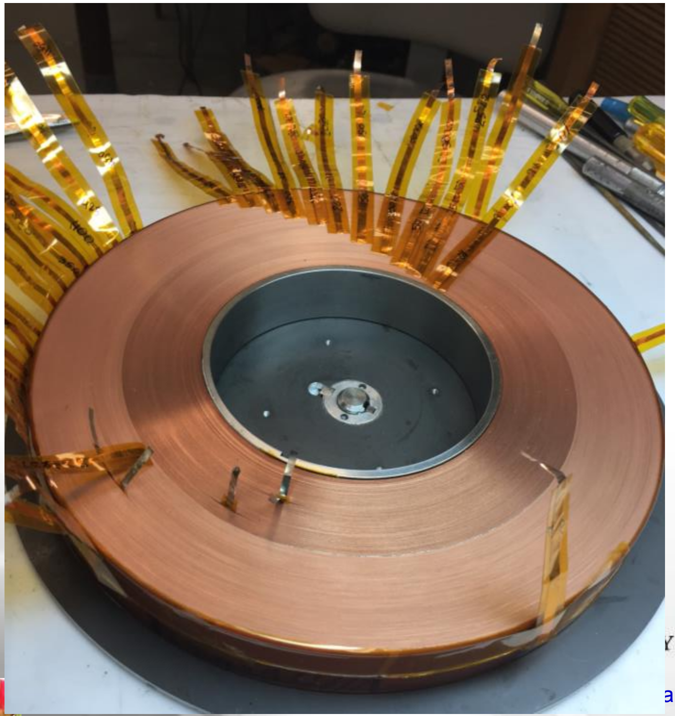
Test for : SuperPower, 50 μm Hastelloy, 65 μm Cu
Used in design: 50 μm Hastelloy, 20 μm Cu (more robust)

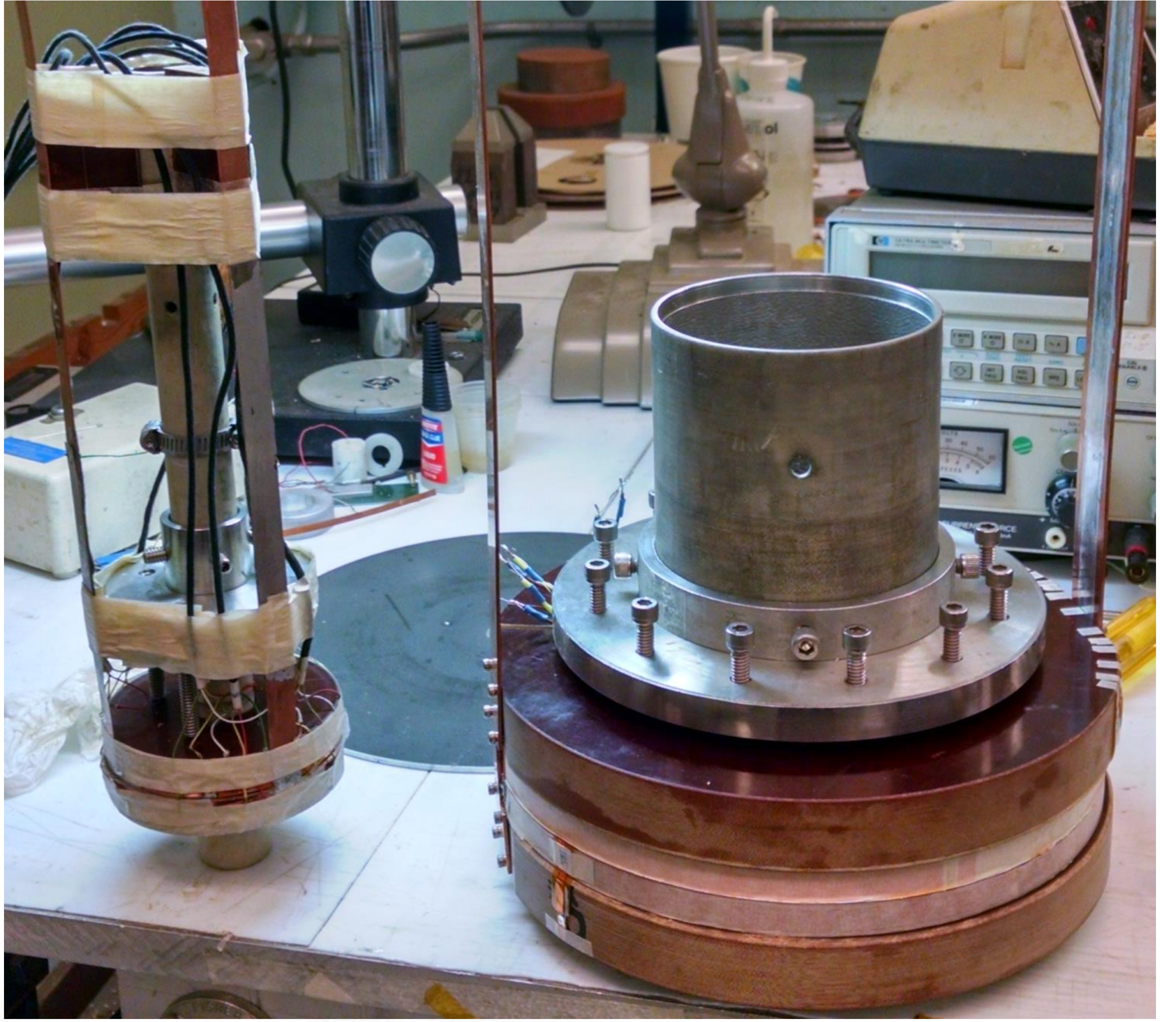
No Insulation Coil Construction and Partial Test Results

No Insulation Double Pancake Coils

To obtain data and 4 K test experience with large “NI” coil early on, a coil wound with ~550 m of 12 mm wide ReBCO tape

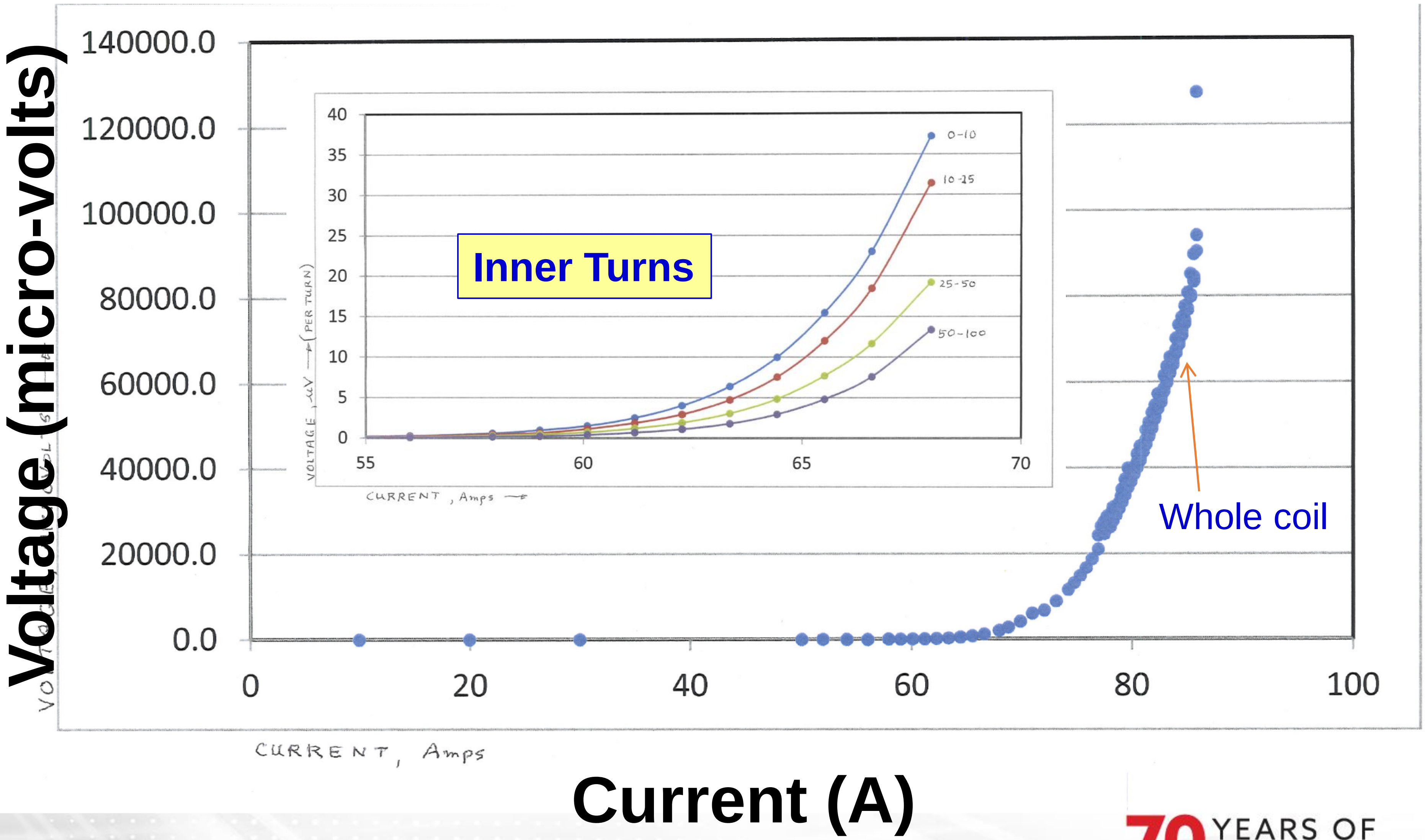
- **i.d. = 100 mm**
- **o.d. = 220 mm**
- **Turns = 971**



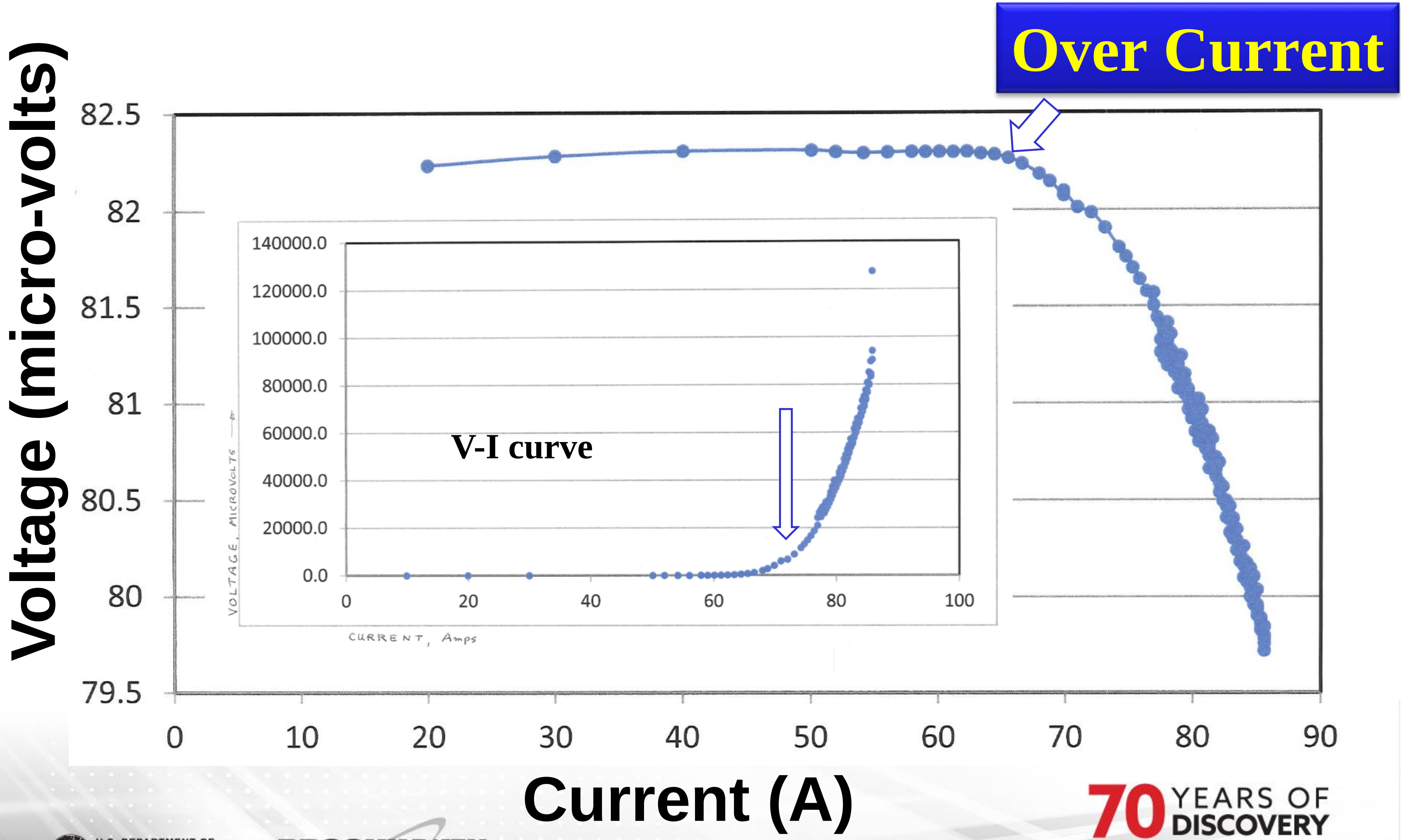


Significant instrumentation and 3 heaters for simulated defects

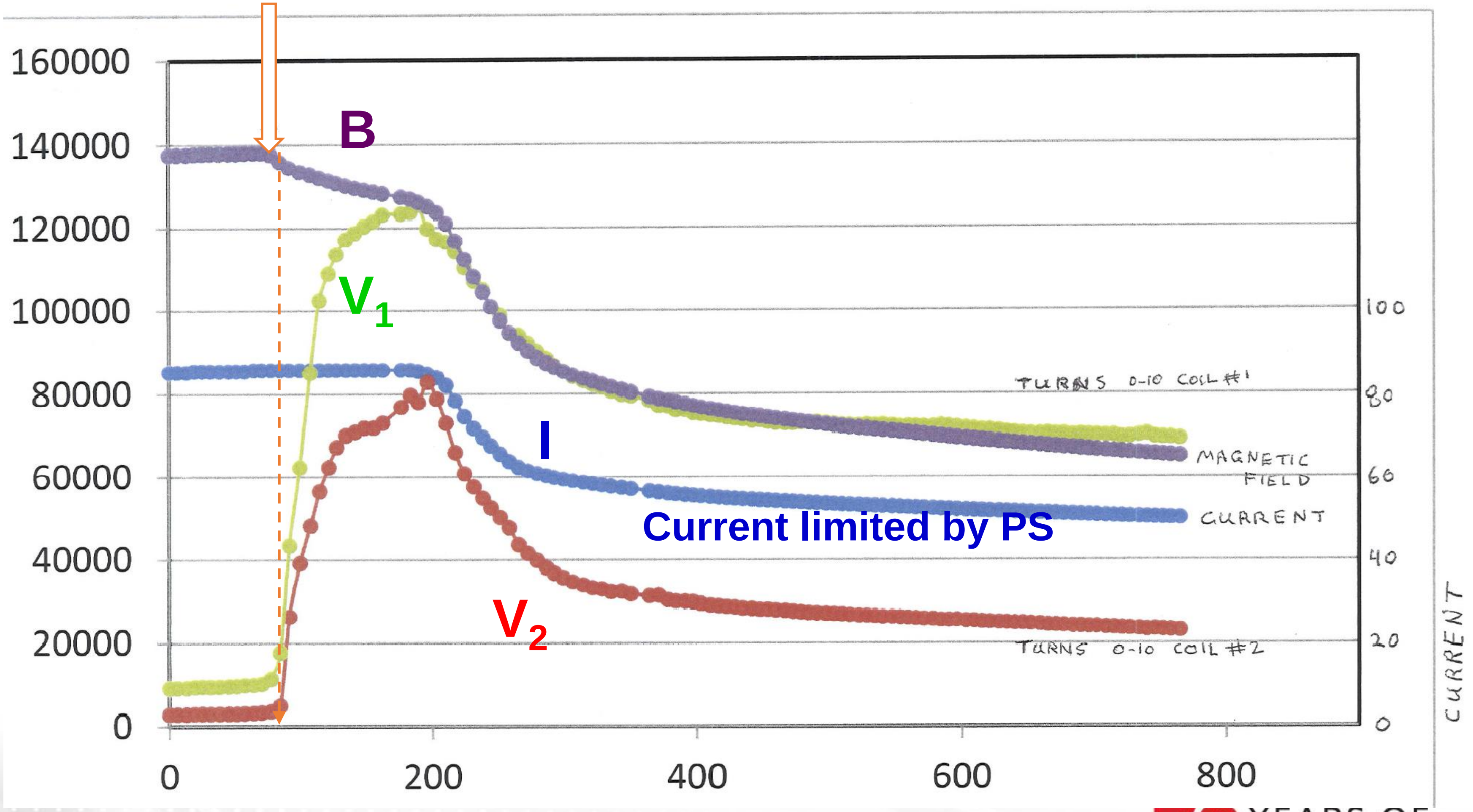
V-I Curve for the Whole Magnet and I the Inner Turns of No Insulation Coil



Transfer Function Vs. Current in No Insulation Coils



B, V and I in No Insulation Coil at Thermal Runaway



Thermal Runaway

B

V_1

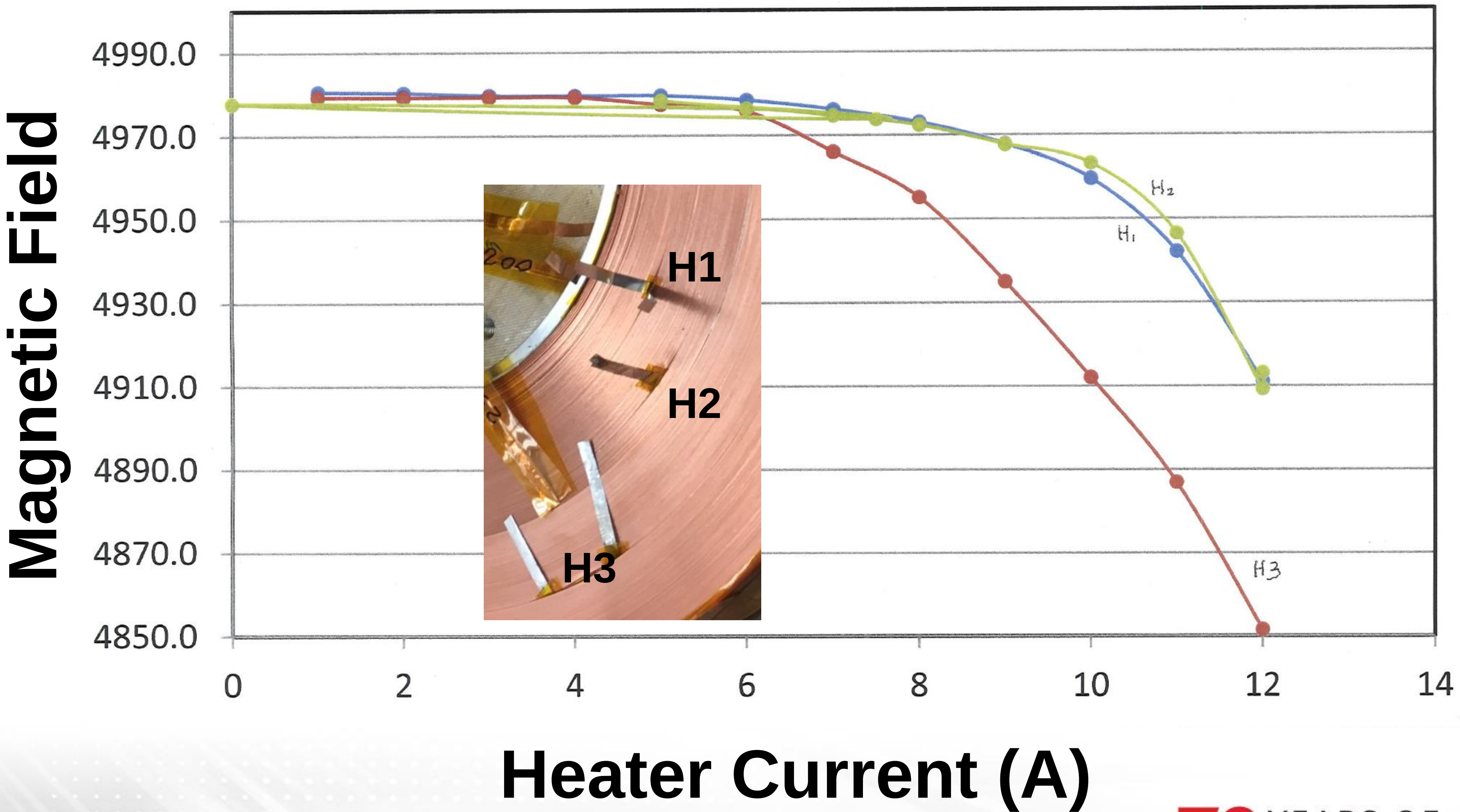
I

Current limited by PS

V_2

Time (seconds)

Field as a Function of Heater Current at 60 A in Coil



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Experience with No-insulation in a Large Coil (~550 meters of 12 mm wire)

Only 77 K tests yet

- High stability (~100 mV at thermal runaway)
- Tolerates delayed shut-off (magnet protection)
- Heater induced simulation of the tolerance against local defects (ok at 77 K)

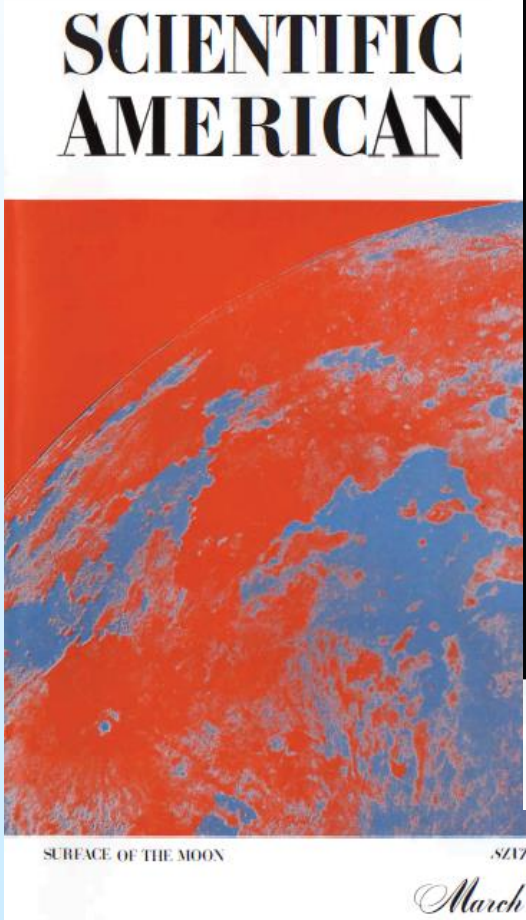
Next: 4K tests

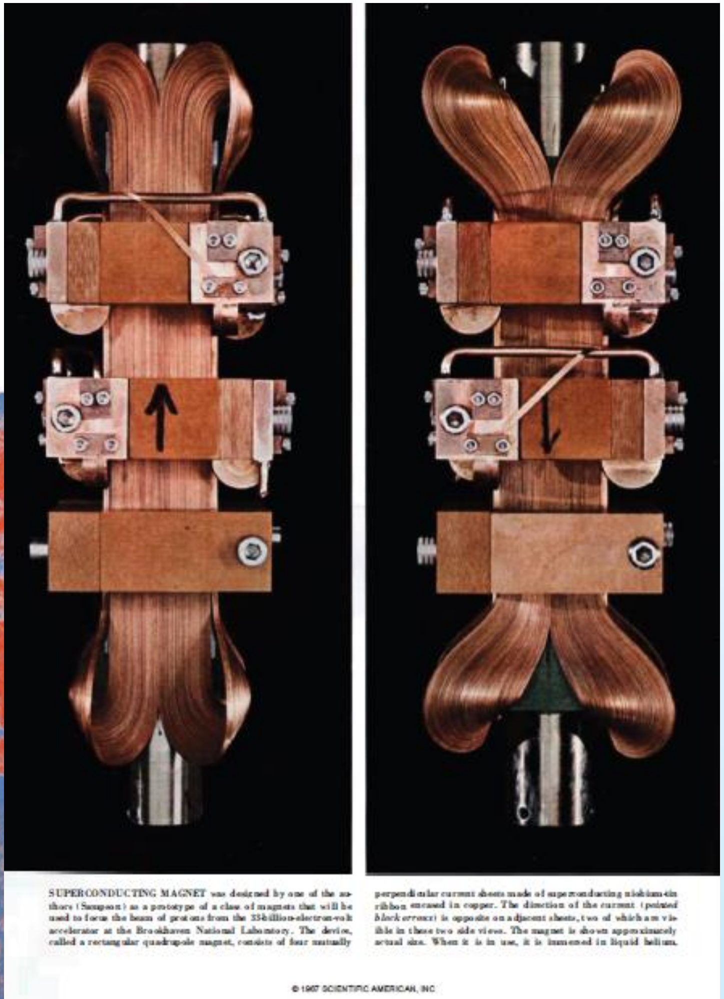
- BNL’s advance quench detection and protection system **(Joshi: this conference)**

Fifty Years of “No-Insulation” Superconducting Tape Magnets

Bill Sampson 1967

Nb_3Sn Tape Quadrupole (still available to touch)





SUPERCONDUCTING MAGNET was designed by one of the authors (Sampson) as a prototype of a class of magnets that will be used to focus the beam of protons from the 33-billion-electron-volt accelerator at the Brookhaven National Laboratory. The device, called a rectangular quadrupole magnet, consists of four mutually perpendicular current sheets made of superconducting niobium-tin ribbon encased in copper. The direction of the current (*pointed black arrows*) is opposite on adjacent sheets, two of which are visible in these two side views. The magnet is shown approximately actual size. When it is in use, it is immersed in liquid helium.

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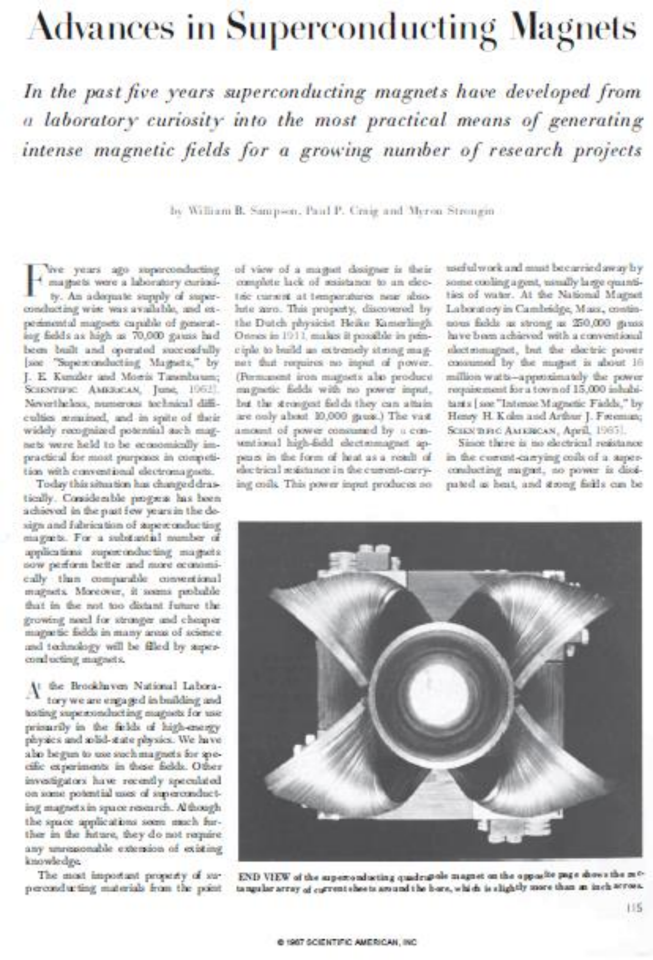

Advances in Superconducting Magnets

In the past five years superconducting magnets have developed from a laboratory curiosity into the most practical means of generating intense magnetic fields for a growing number of research projects

by William B. Sampson, Paul P. Craig and Myron Strongin

END VIEW of the superconducting quadrupole magnet on the opposite page shows the rectangular array of current sheets around the bore, which is slightly more than an inch across.

115

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However, no-insulation coils were made for different reasons

SUMMARY

- **Unique requirements offer challenges and opportunities:**
  - **High field, large aperture (25 T, 100 mm)**
  - **Relaxed field quality, slow charging time**

- **“No Insulation (NI)”, single layer design**

- **Conductor: ~10 km, 12 mm wide ReBCO tape**

- **Initial test results on loading on the narrow face of 2G tape**

- **77K tests on large bore (id/od : 100/200 mm) double pancake “NI” HTS coil (~550 m of 12 mm wide tape)**
  - **Next 4K tests**