

High Field, Large Aperture HTS Solenoid

for Axion Dark Matter Search

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70 YEARS OF
DISCOVERY

A CENTURY OF SERVICE

MT25

25th International Conference
on Magnet Technology

RAI - Amsterdam
August 27 - September 1, 2017



U.S. DEPARTMENT OF
ENERGY

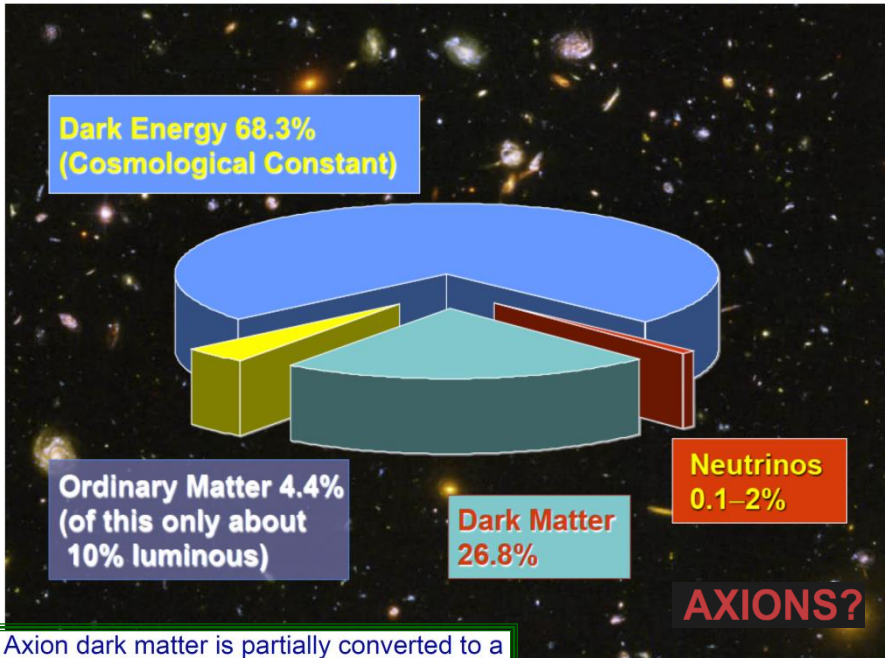
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Overview

- *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



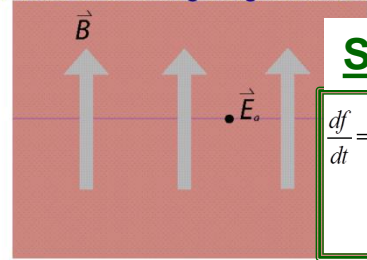
Key to possible breakthrough:
high field, large volume magnet

- 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!

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



Scanning Rate:

$$\frac{df}{dt} = \frac{f}{Q} \frac{1}{t} \approx \frac{1 \text{ GHz}}{\text{year}} (g_{\text{arr}} 10^{15} \text{ GeV})^4 \left(\frac{5 \text{ GHz}}{f}\right)^2 \left(\frac{4}{\text{SNR}}\right)^2 \left(\frac{0.25 \text{ K}}{T}\right)^2$$

$$\left(\frac{B}{25T}\right)^4 \left(\frac{c}{0.6}\right)^2 \left(\frac{V}{5l}\right)^2 \left(\frac{Q}{10^5}\right)$$

Animation by Kristian Themann J. Hong, J.E. Kim, S. Nam, Y.K.S hep-ph: 1403.1576



Requirements for IBS Solenoid

- ❑ High Field : 25 T (must use HTS)
 - ❑ Large Volume: 100 mm bore, +/-100 mm long
- Stresses: $J \times B \times R$
- ❑ Field quality: ~10%
 - ❑ Ramp-up time: up to 1 day
- Relaxed field quality and slow charging
- ❑ User magnet: robust design, large Margin

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%

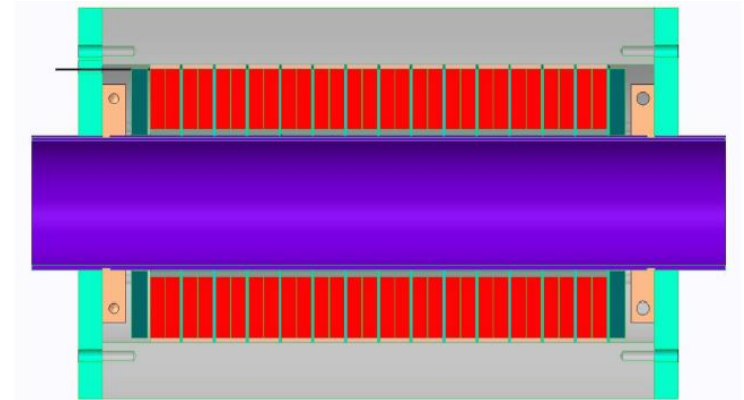
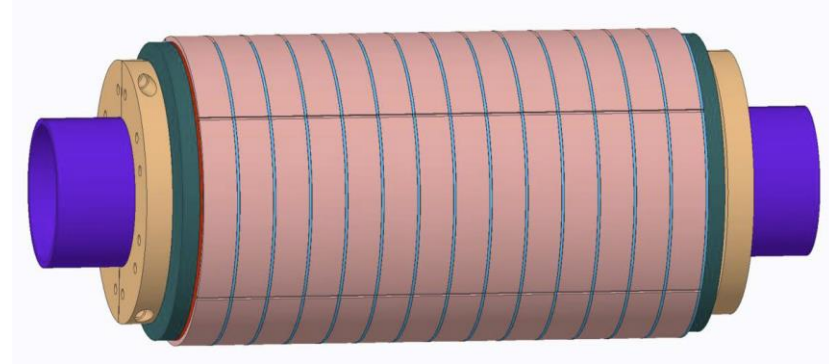
- High performance needed at high fields @ 4 K

❑ Stress/strain margin : ~50%

- Multi-width option increases maximum stress (NOT acceptable here)

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/mm²
- Stored Energy: ~1.6 MJ
- Max. Hoop Stress: ~500 MPa

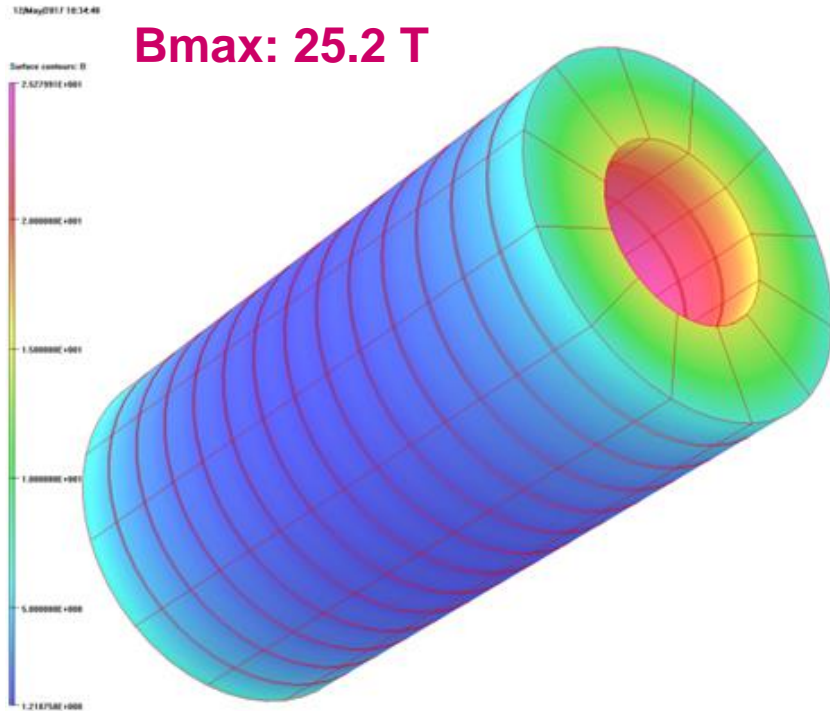


Key Conductor Specifications

- 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

Basic Magnetic Analysis



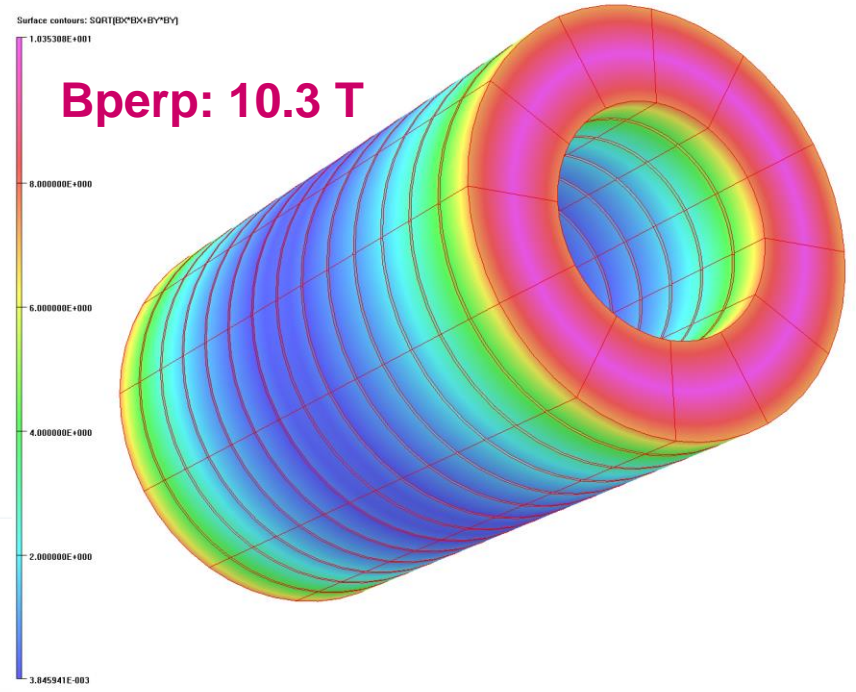
UNIT: m
Length: m
High-Pure Density: 7
High-Pure: 6.4e7
High-Pure-Flux: 6.4e7
High-Pure-Density: 6.4e7
Low-Pure Density: 2.4e7
Low-Pure: 6.4e7
Low-Pure-Flux: 6.4e7
Current Density: 6.4e7
Phase: 0
Force: 0
Phase: 2
Phase: 0

FIELD DATA
HT Conductors

Field Point Local Coordinates
Local = Global

FIELD EVALUATION
Line Line (magnetic), Curve
x=0.0 y=0.0 z=0.0

12Jun2017 16:35:52



Opera

Ope

Simple constant J_e model
(in reality J_e may vary across the tape width)

Mechanical Analysis

Orthogonal Coil Strains @ 4 K, 25 T

D: Static Structural

Coil Radial Strain

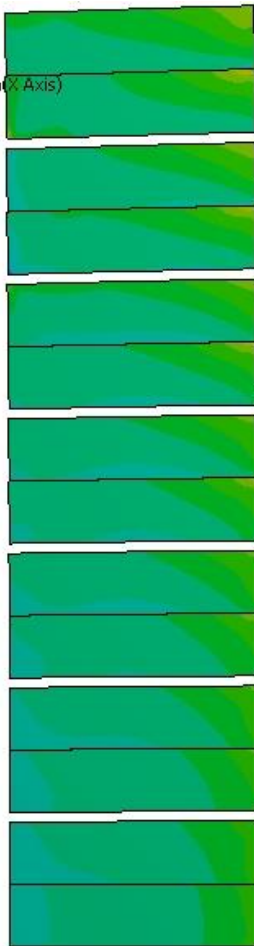
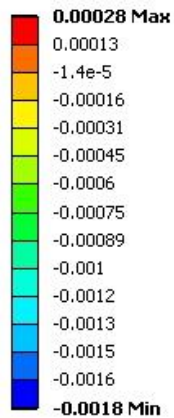
Type: Normal Elastic Strain(Z Axis)

Unit: in/in

Global Coordinate System

Time: 1

6/20/2017 1:26 PM



D: Static Structural

Coil Axial Strain

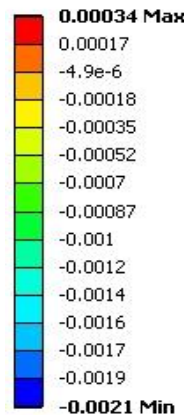
Type: Normal Elastic Strain(Y Axis)

Unit: in/in

Global Coordinate System

Time: 1

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D: Static Structural

Coil Azimuthal Strain

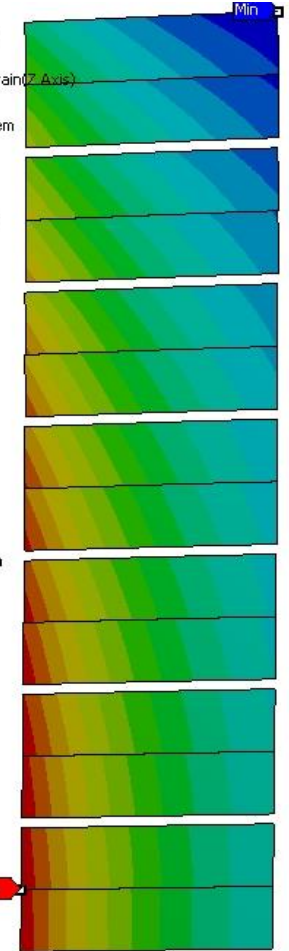
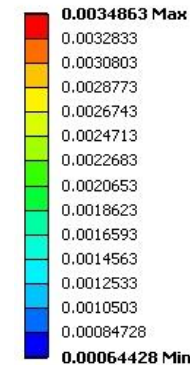
Type: Normal Elastic Strain(Z Axis)

Unit: in/in

Global Coordinate System

Time: 1

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.35% Max Strain

-.10% Max Strain

-.21% Max Strain

Radial



Axial



+

Azimuthal

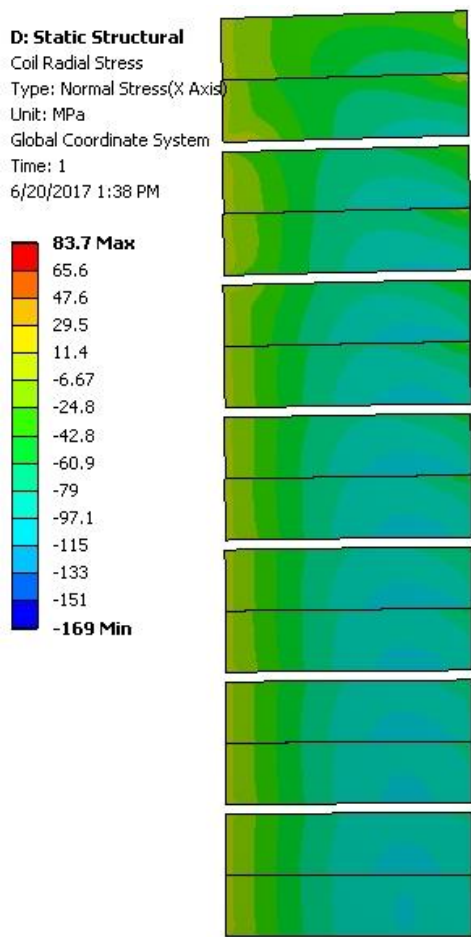
70 YEARS OF DISCOVERY

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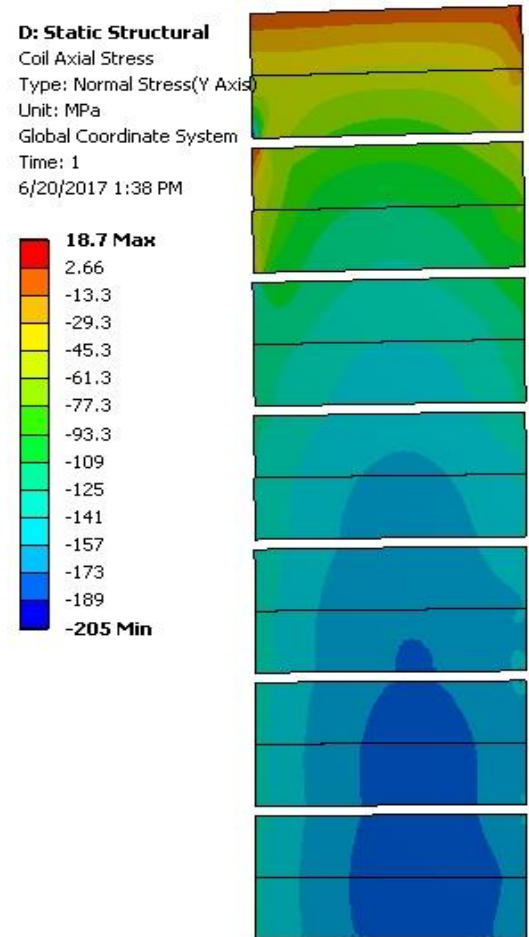
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Orthogonal Coil Stresses (MPa) @ 4 K, 25 T



-100 MPa Max Stress

Radial

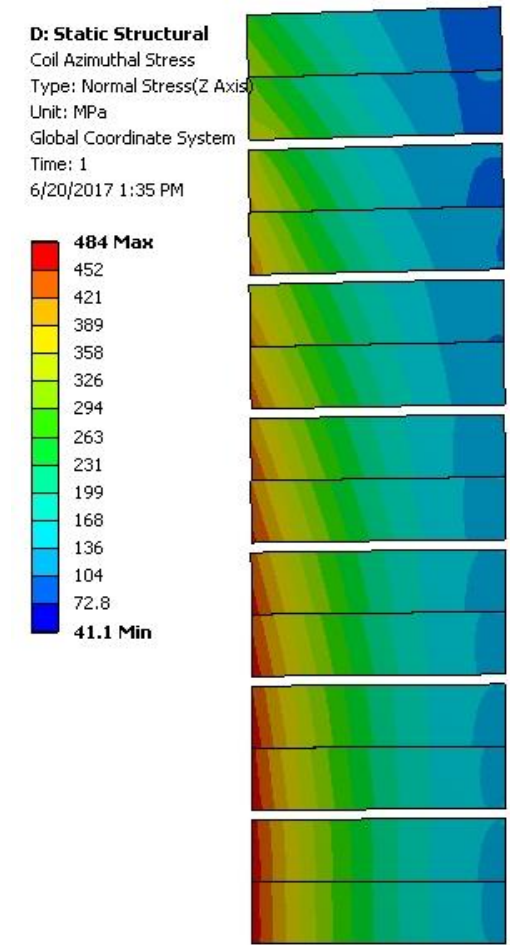


-205 MPa Max Stress

Axial



+



Azimuthal

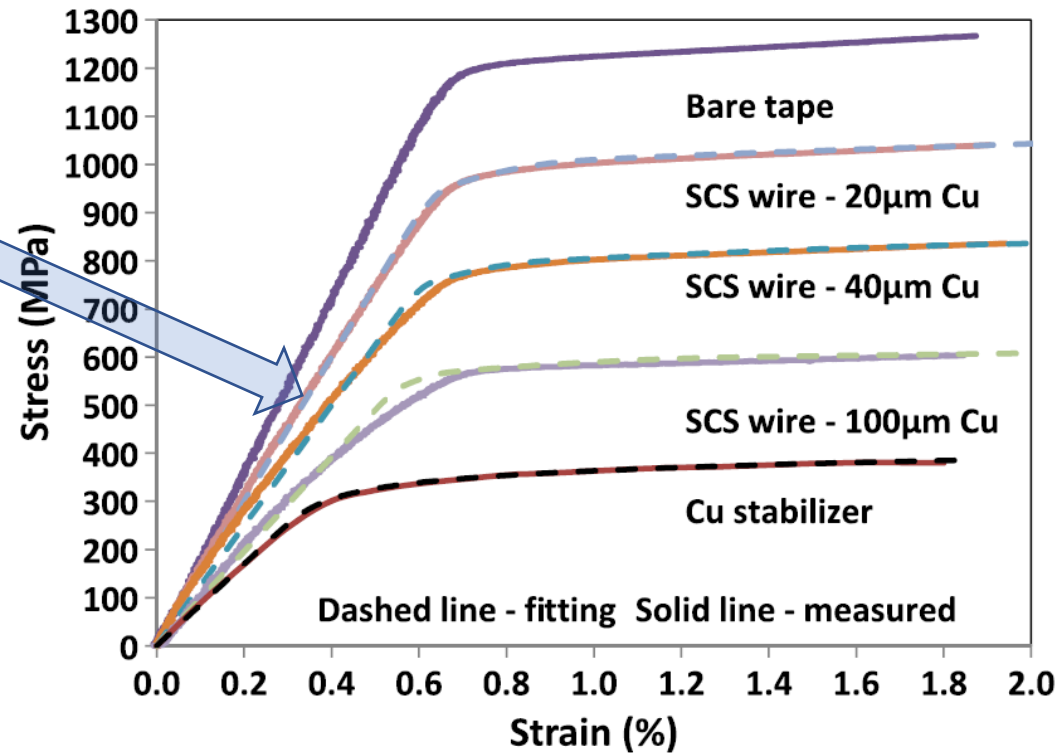
484 MPa Max Stress

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

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

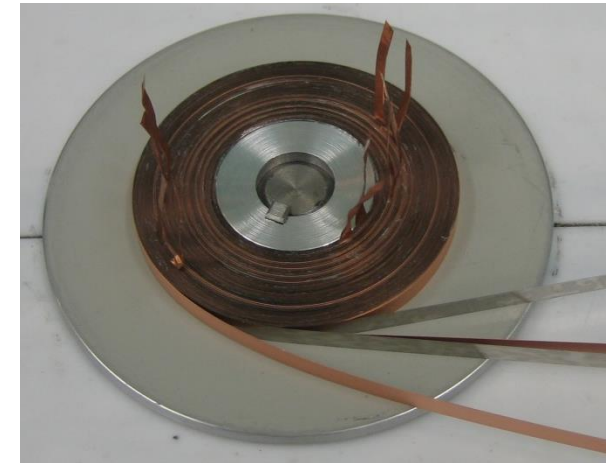


Meeting requirement of ~200 MPa on the narrow side of the tape needs to be checked as no such data is available

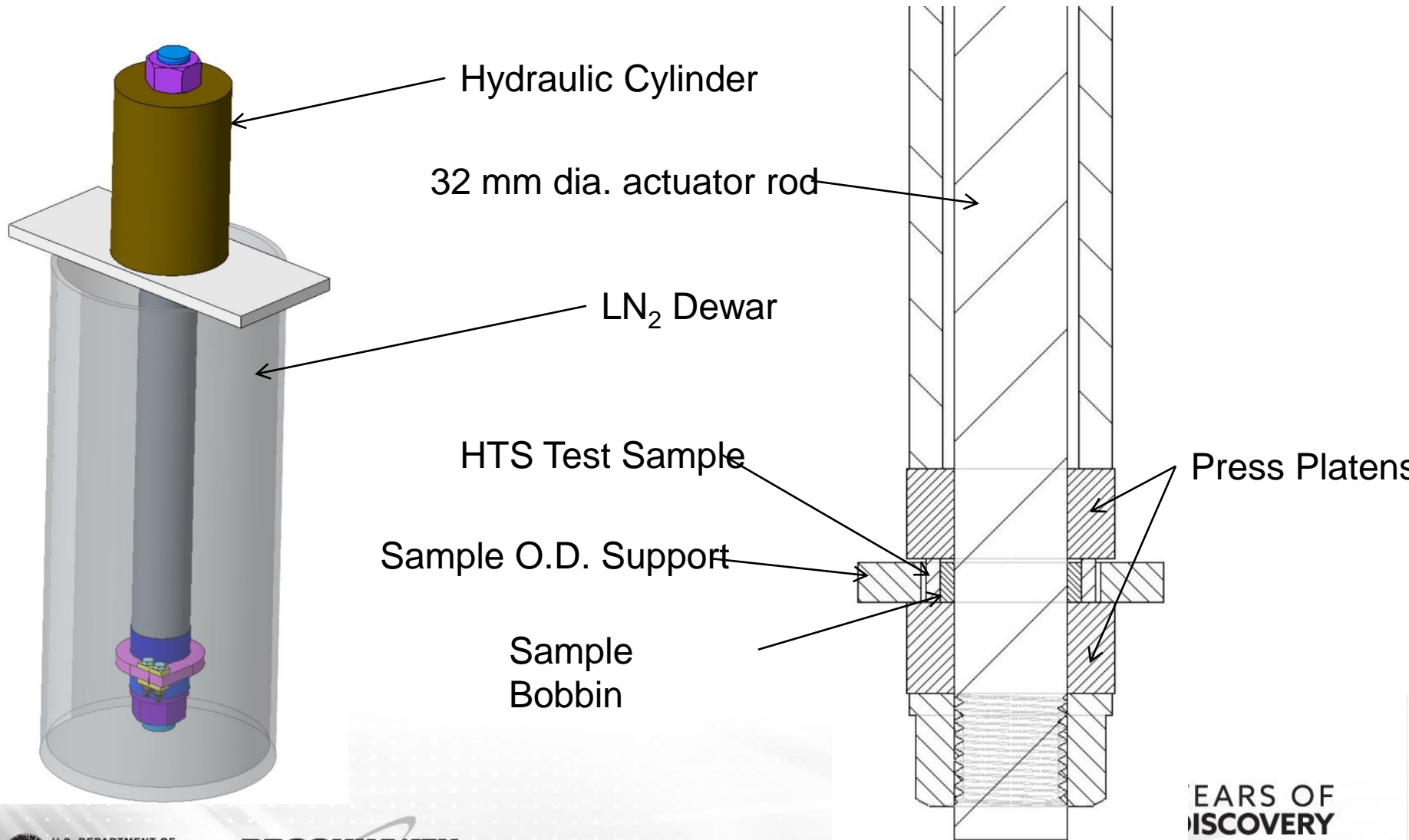
Courtesy: SuperPower

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

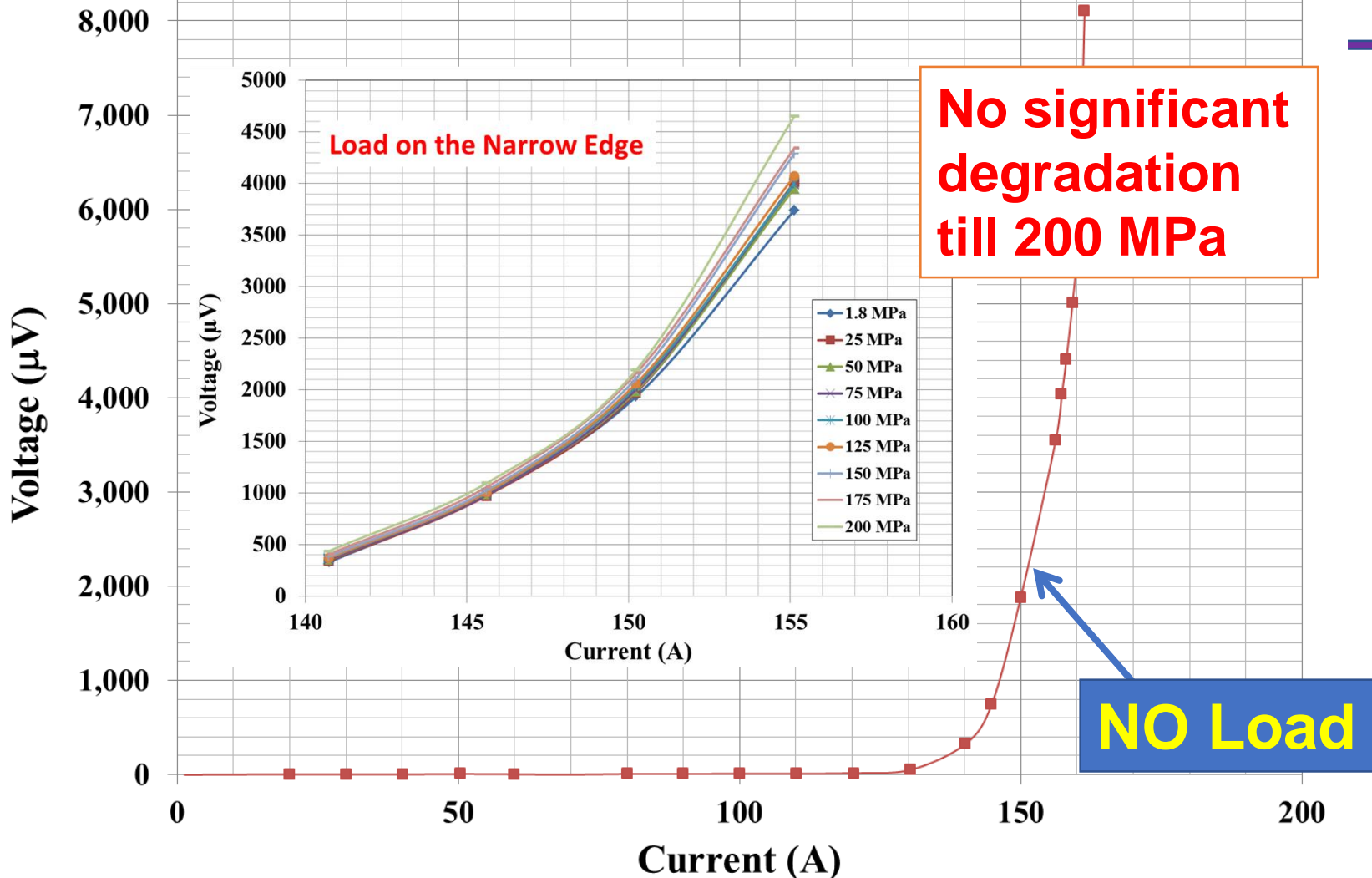
Works well to 100 MPa
(criterion used in many designs)



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



Impact of Load on the Narrow face of the Conductor



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



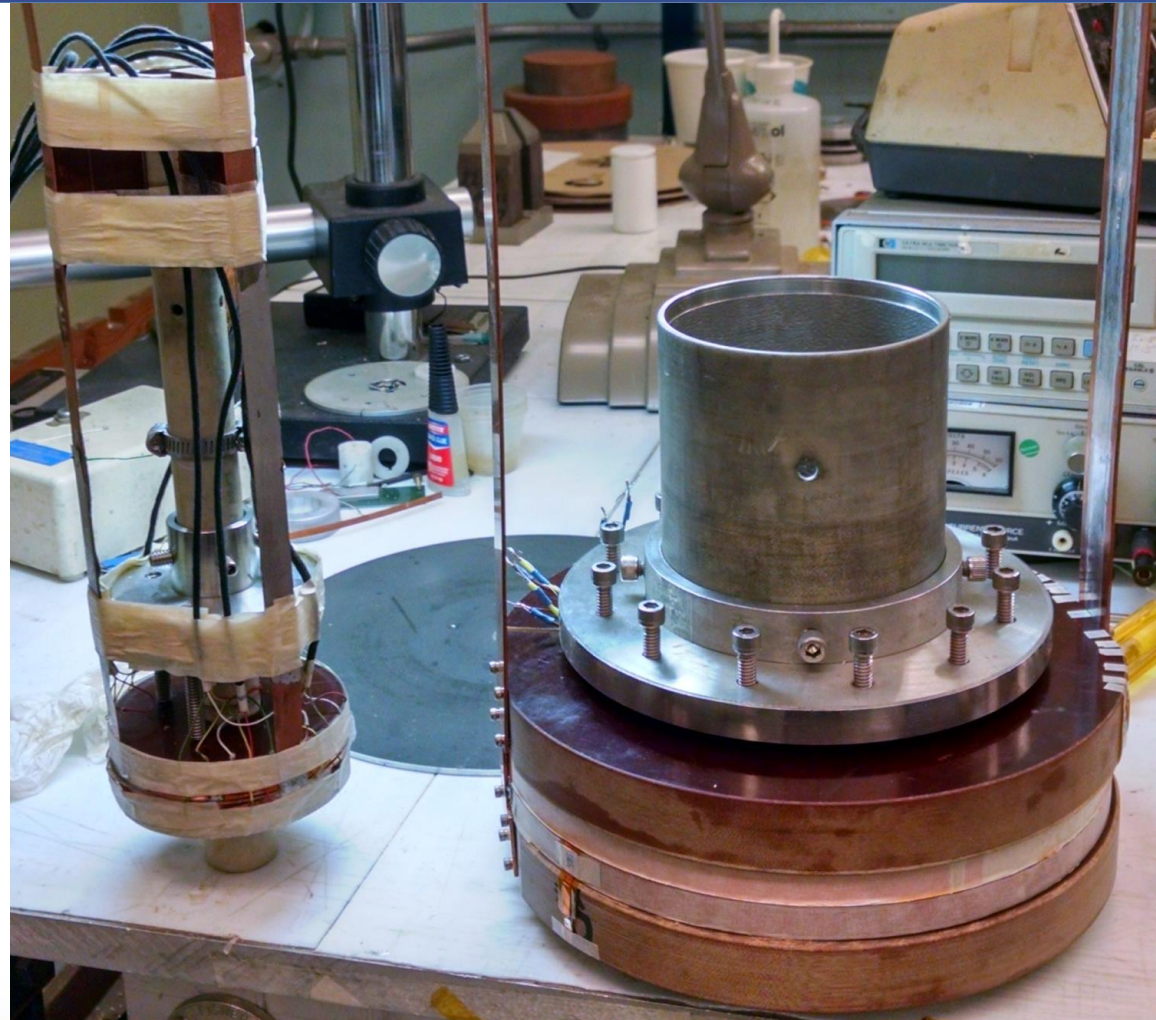
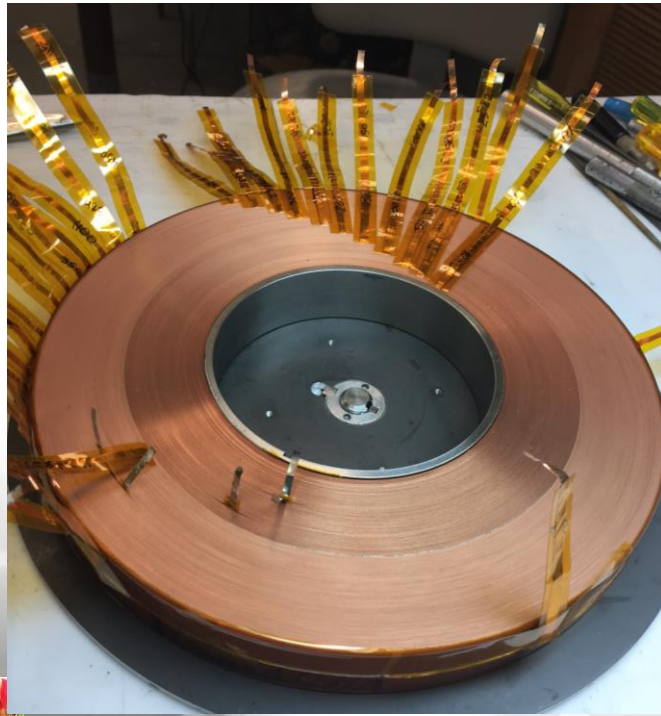
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No Insulation Double Pancake Coils

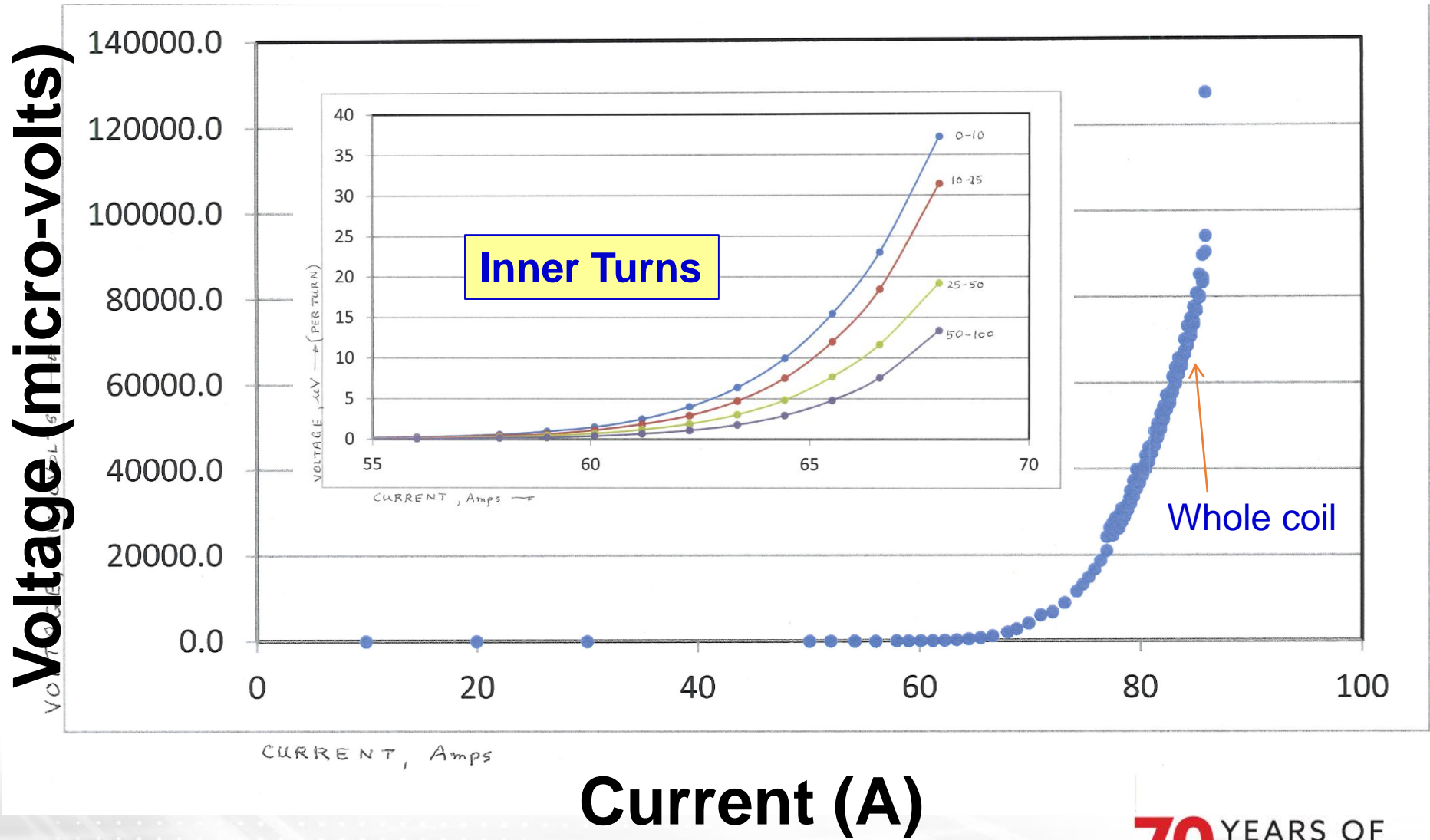
To obtain data and 4 K test experience with large “NI” coil early on, a coil wound with ~550 m of 12 mm wide ReBCO tape

- 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

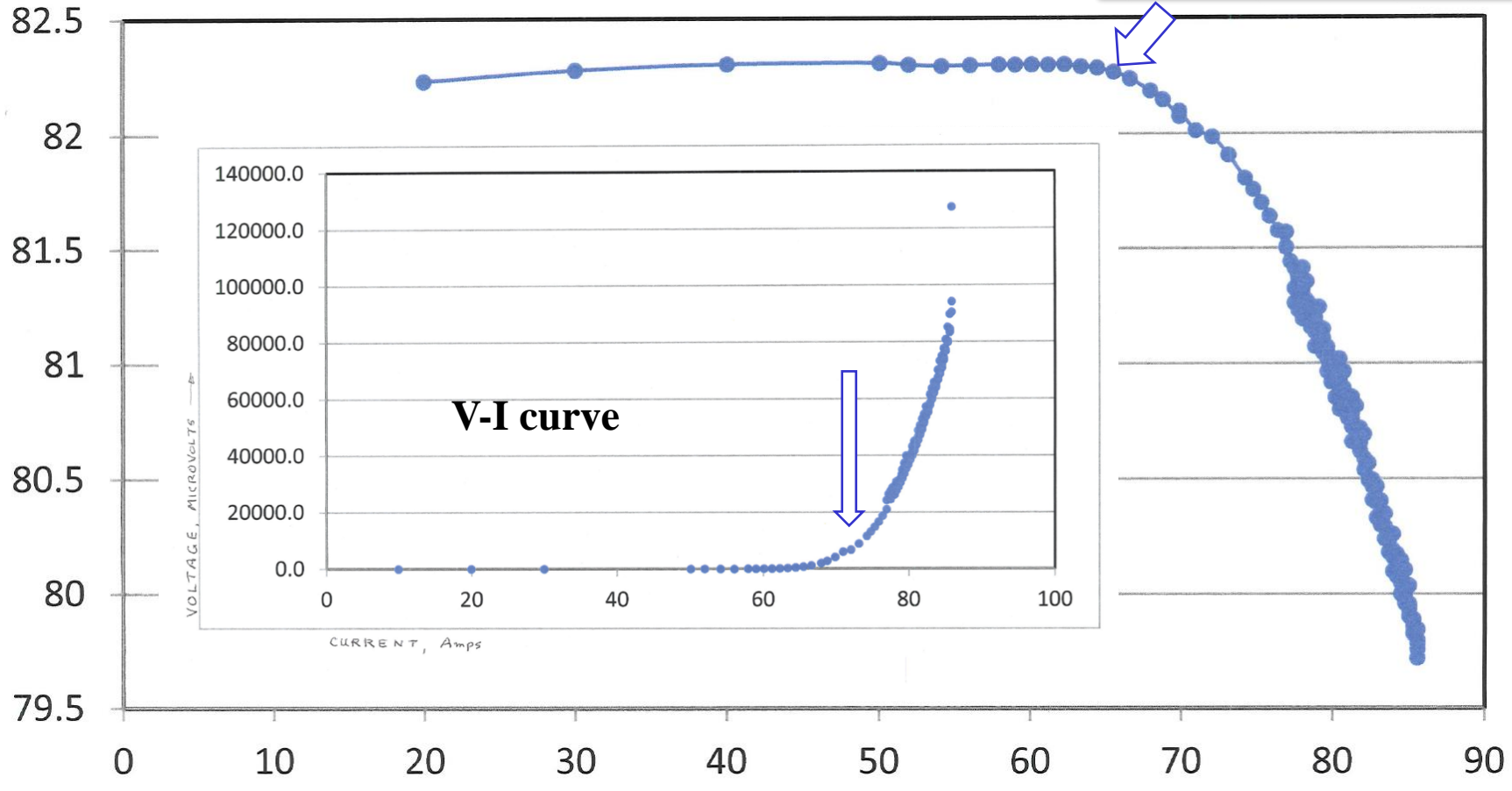


Current (A)

Transfer Function Vs. Current in No Insulation Coils

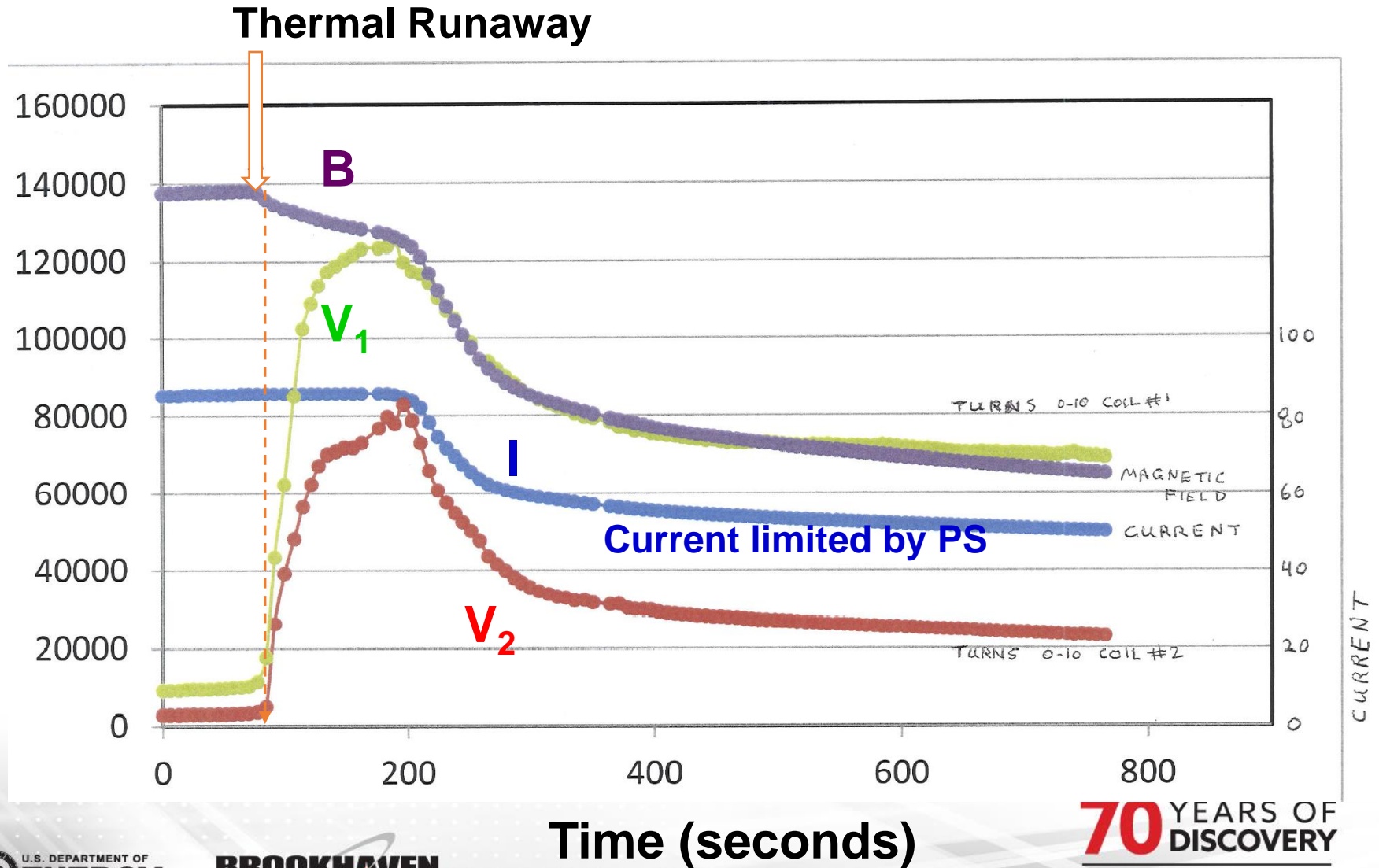
Voltage (micro-volts)

Over Current

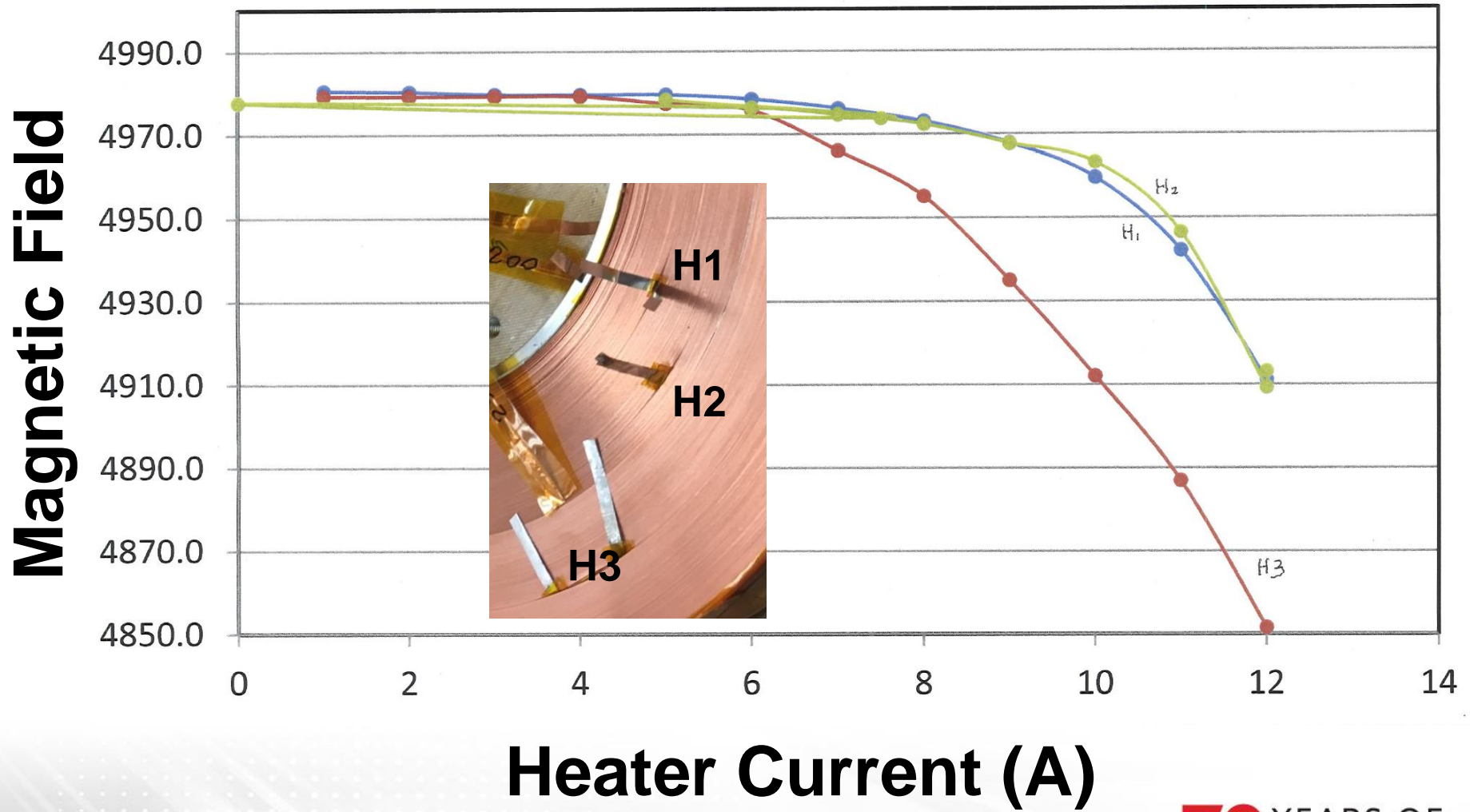


Current (A)

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



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



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)

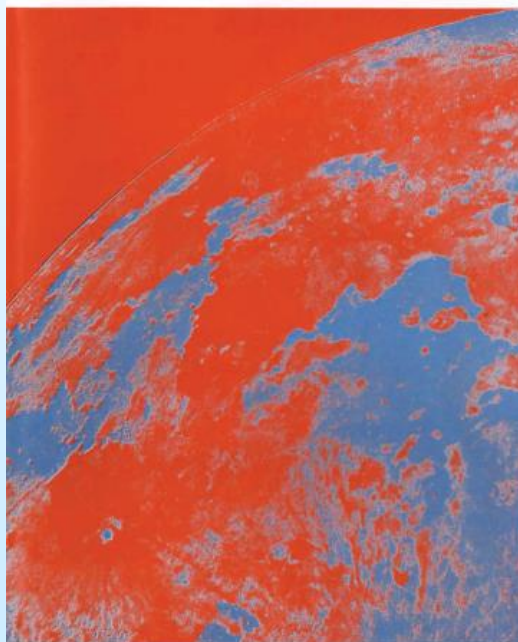
Next: 4K tests

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

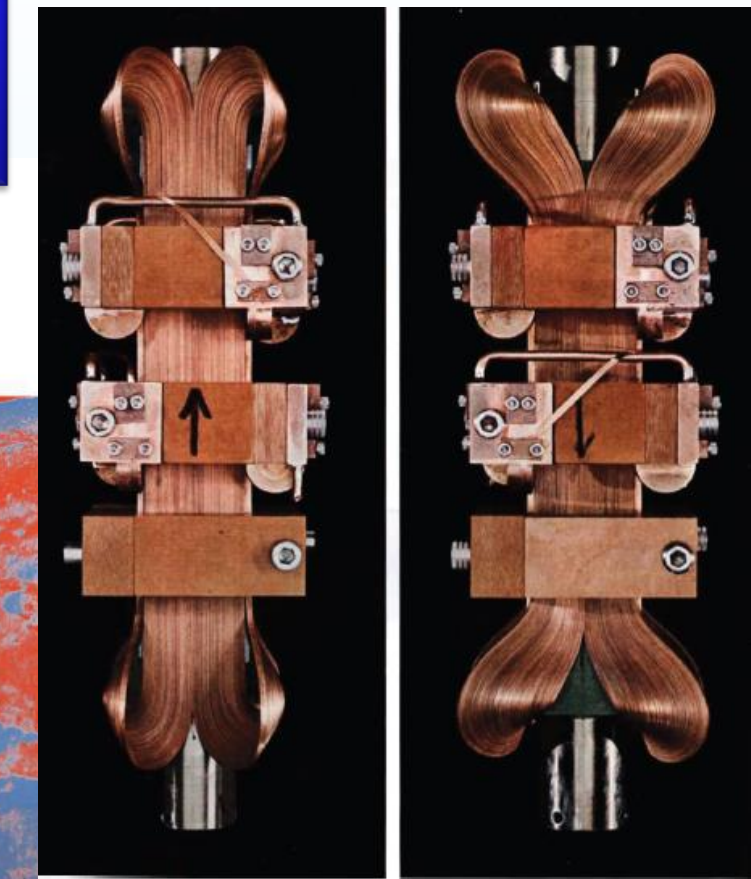
Fifty Years of "No-Insulation" Superconducting Tape Magnets

**Bill Sampson
1967**

**SCIENTIFIC
AMERICAN**



SURFACE OF THE MOON



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 beams of protons from the 350-million-electron-volt accelerator at the Brookhaven National Laboratory. The device, called a rectangular quadrupole magnet, consists of four normally

perpendicular current sheets made of superconducting niobium-tin ribbon encased in copper. The direction of the current (pointed black arrow) 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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**Nb₃Sn Tape Quadrupole
(still available to touch)**

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 R. Sampson, Paul P. Craig and Myron Strongin

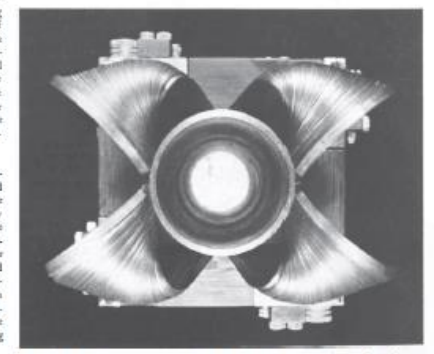
Five years ago superconducting magnets were a laboratory curiosity. An adequate supply of superconducting wire was available, and experimental magnets capable of generating fields as high as 70,000 gauss had been built and operated successfully [see "Superconducting Magnets," by J. E. Kuzler and Morris Tansbaum; SCIENTIFIC AMERICAN, June, 1962]. Nevertheless, numerous technical difficulties remained, and in spite of their widely recognized potential such magnets were held to be economically impractical for most purposes in competition with conventional electromagnets.

Today this situation has changed dramatically. Considerable progress has been achieved in the past few years in the design and fabrication of superconducting magnets. For a substantial number of applications superconducting magnets now perform better and more economically than comparable conventional magnets. Moreover, it seems probable that in the not too distant future the growing need for stronger and cheaper magnetic fields in many areas of science and technology will be filled by superconducting magnets.

The most important property of superconducting materials is their complete lack of resistance to an electric current at temperatures near absolute zero. This property, discovered by the Dutch physicist Heike Kamerlingh Onnes in 1911, makes it possible in principle to build an extremely strong magnet that requires no input of power. (Permanent iron magnets also produce magnetic fields with no power input, but the strongest fields they can attain are only about 20,000 gauss.) The vast amount of power consumed by a conventional high-field electromagnet appears in the form of heat as a result of electrical resistance in the current-carrying coils. This power input produces no useful work and must be carried away by some cooling agent, usually large quantities of water. At the National Magnet Laboratory in Cambridge, Mass., continuous fields as strong as 250,000 gauss have been achieved with a conventional electromagnet, but the electric power consumed by the magnet is about 10 million watts—approximately the power requirement for a town of 15,000 inhabitants [see "Intense Magnetic Fields," by Henry H. Kallen and Arthur J. Freeman; SCIENTIFIC AMERICAN, April, 1965].

Since there is no electrical resistance in the current-carrying coils of a superconducting magnet, no power is dissipated as heat, and strong fields can be

At the Brookhaven National Laboratory we are engaged in building and testing superconducting magnets for use primarily in the fields of high-energy physics and solid-state physics. We have also begun to use such magnets for specific experiments in these fields. Other investigators have recently speculated on some potential uses of superconducting magnets in space research. Although the space applications seem much further in the future, they do not require any unreasonable extension of existing knowledge.



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.

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**However, no-insulation coils
were made for different reasons**

The most important property of superconducting materials is their

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**