Conductor Requirements for IBS HTS Solenoid for Axion Search

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BNL

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Schenectady, NY

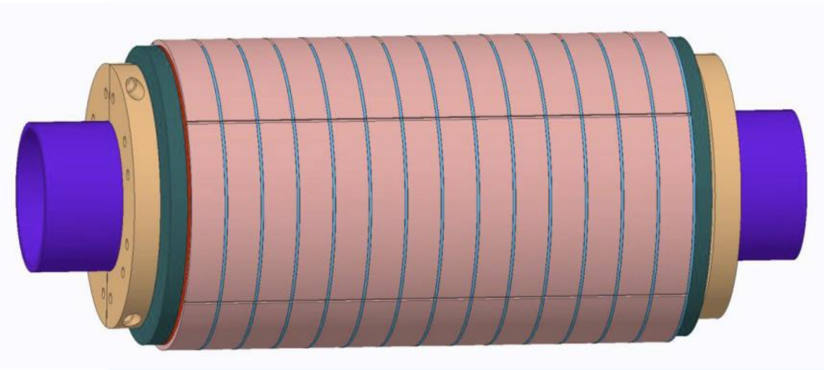
Institute Funding the Construction of High Field, Large Aperture Solenoid

- Center for Axion and Precision Physics Research (CAPP), Institute for Basic Science (IBS), Daejeon, South Korea
- Targeted science goals receive significant funding from Korean government to become major player internationally

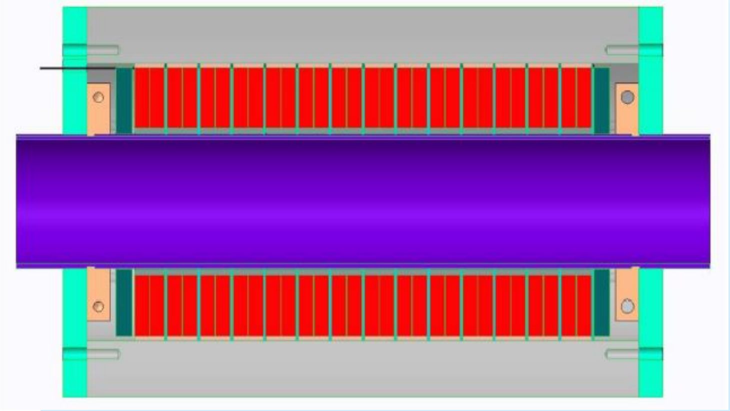
Relevance to HTS Magnet Technology

- This is a high visibility project. Even though it is funded by the Korean agency, US DOE is keenly interested.
- Positive outcome is likely to attract more applications worldwide - already a few on the horizon.
- It is in the best interest of both BNL and SuperPower that we do the best we can and work together to bring a positive outcome to this and other challenging projects.

Major Parameters of the IBS/BNL HTS Solenoid



- Field: 25 T@4 K
- Single Layer
- Cold Bore: 100 mm
- Coil i.d.: ~118 mm
- Coil o.d.: ~200 mm
- Conductor: 12 mm wide ReBCO
- Current: ~500 A
- Current Density: ~550 A/mm^2
- Stored Energy: ~1.6 MJ
- Max. Hoop Stress: ~500 MPa



Comparison between the SMES and IBS Solenoids

Key Similarities:

- Both are designed for 25 T, 100 mm using 2G HTS

Key Differences:

- SMES was part of a high risk high reward project. IBS solenoid must be reliable as it is for user.
- SMES had no design margin at 25 T. IBS has both electrical (I_c) and mechanical design margins.
- SMES was a two-layer design. IBS is single-layer.
- SMES used SS insulation. IBS is no insulation (NI).
- SMES required an advanced quench protection system. IBS may have a relaxed one due to NI.

Conductor for IBS Solenoid

- IBS solenoid needs a significant quantity of ReBCO tape
  - ~12 mm wide, 8-10 km (actual amount depends on the design margin, performance and extra desired)
- Minimum I_c(8T,4K) > 675A (no limit on maximum)
  - Limited specifications on the critical current (I_c)
  - Design is limited by the mechanical properties (large hoop/axial stresses) and not by the electrical/magnetic properties
  - Higher I_c, however, gives higher margin and is welcome
  - Performance limited by coils in the end region - sorting helps
- An order of 5 km tape has been placed with SuperPower

Important Issues

- **Delivery schedule**
- **Mechanical properties of conductor**
- **Copper plating**
- **Conductor free of defects**

SuperPower can easily meet the I_c specifications. However, it doesn't mean that conductor with defects can be accepted. Tapestar and other contractual data must be sent to BNL prior to delivery. After receiving the conductor, BNL will perform on-site reel-to-reel inspection before the conductor can be accepted.

Please let us know if there is anything unusual in the conductor (whether in the contract or not). We may still be able to use it at a non-critical location. Let's work to succeed.

Technical Specifications (geometry and copper plating)

- **Nominal thickness of the conductor: 75 microns**
- **Maximum variation from the nominal thickness of conductor in the entire shipment: +/- 5 microns**
- **Nominal conductor width: 12 mm**
- **Maximum variation from the nominal width of conductor in the entire shipment: +/- 0.10 mm**

Variation in the thickness of wire across the width is an important issue. It should be minimized. It has an impact on the quality of the coil (moisture and how it behaves under high Lorentz forces). Our understanding is that it is primarily caused by the copper plating. Our expectation is that less copper (20 micron) and in-house plating should help.

- **Copper plating impacts the performance of coil in many ways. This is an area where SuperPower can improve as compared to its competitors.**

Technical Specifications (Ic)

Minimum Critical Current (Ic) specification of 675 A (4K, 8T) are to met based on the following measurements at SuperPower:

- **Ic (77K, self-field) : 300 A**
- **Ic (30K, 2T) : 289 A (based on 4 mm samples)**

- **Minimum piece length: 100 meters without splice**

  We can minimize both - the wastage at SuperPower and the number of splices at BNL. Please feel free to supply wire in piece length longer than 100 meter *"minimum"* (for example 289 meters ok) as long as it meets the specifications in the variation (see next slide)

Ic Uniformity Specifications

- The variation in transport currents (77 K) over 100 m sections is to be < 10%. The lowest value of I_c in each section must still meet the minimum requirement (300 A).
- Tapestar at an interval of 1 to 5 mm: <20% drop from the "*nominal*". (Any material which exhibits a 20% or greater drop from the "*nominal value*" will be flagged and reviewed by SuperPower and BNL personnel for the corresponding transport Ic and n-value for potential acceptance).

The specifications on the variation are meant to isolate the conductor with potential flaws that could limit the magnet performance under high stresses and/or repeated cycles. "*Nominal*" above should be understood as the "running average" for that lot.

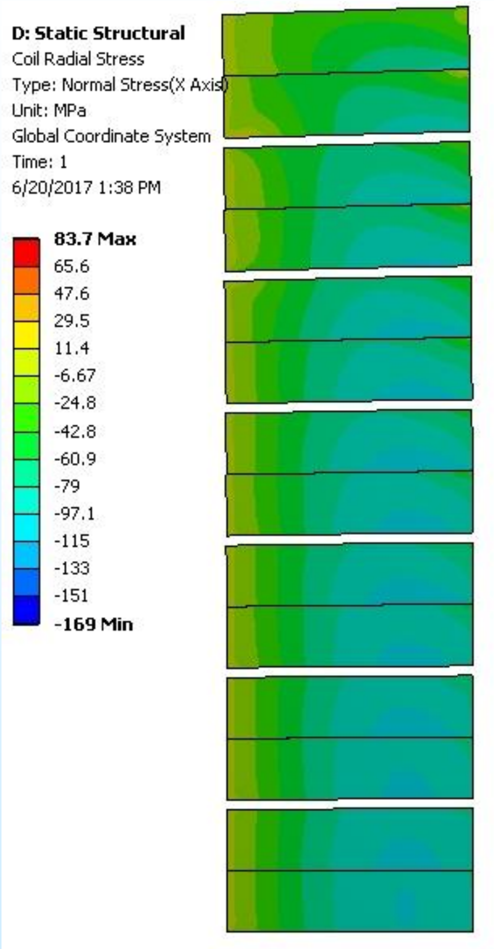
Mechanical Specifications

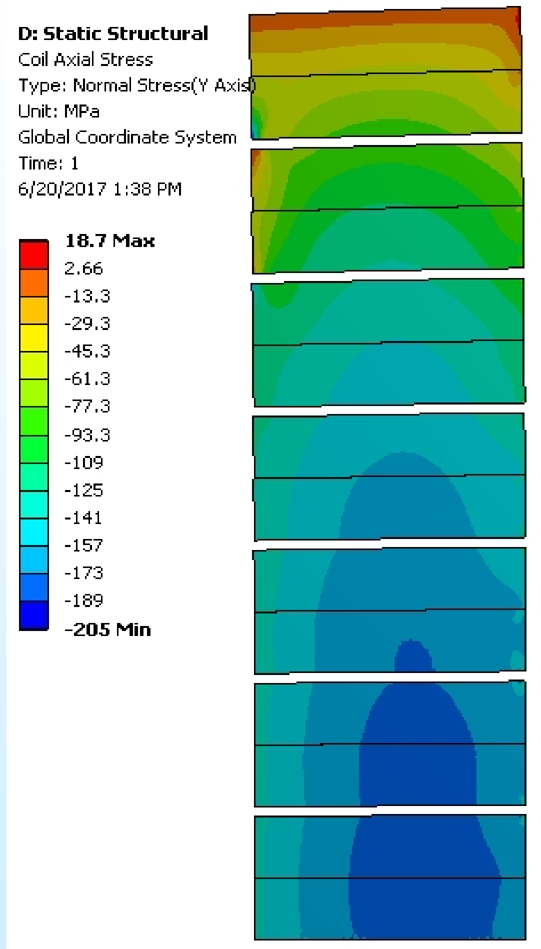
- Linear stress-strain relationship at 77 K (within 5%) up to 800 MPa
- Minimum critical stress for 5% drop in I_c (77K, self-field): 650 MPa
- Minimum critical strain for 5% drop in I_c (77K, self-field): 0.42%
- Minimum irreversible stress for 1% drop in I_c (77K, self-field): 900 MPa
- Minimum irreversible strain for 1% drop in I_c (77K, self-field): 0.7%

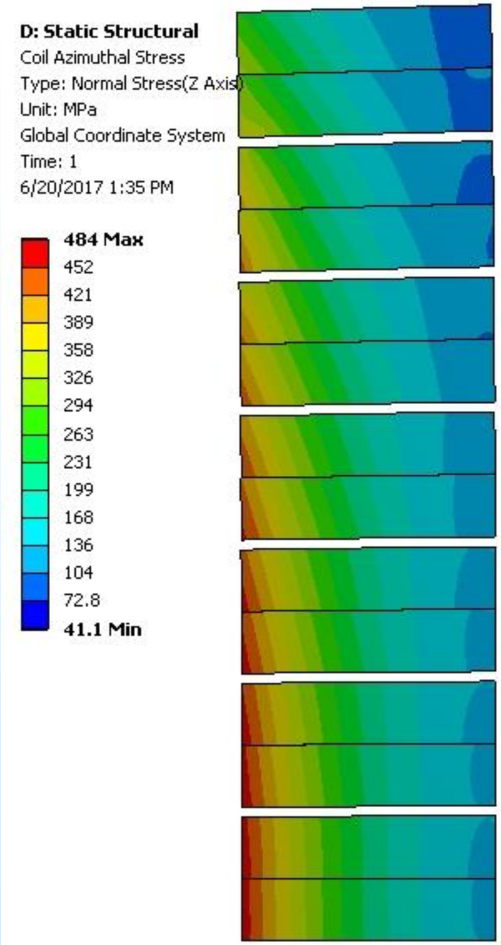
This is an application which takes full advantage of the favorable mechanical properties of 2G HTS. Mechanical properties are just as important (if not more) as the high field Ic.

Note specified directly: how robustly superconductor layer remains bonded to the substrate. Please pay attention to all aspects (copper plating, cleaning, etc.).

Coil Stresses (@4 K, 25 T)







~500 MPa Max Stress

-100 MPa Max Stress

-205 MPa Max Stress

Azimuthal

Radial

Axial +

+

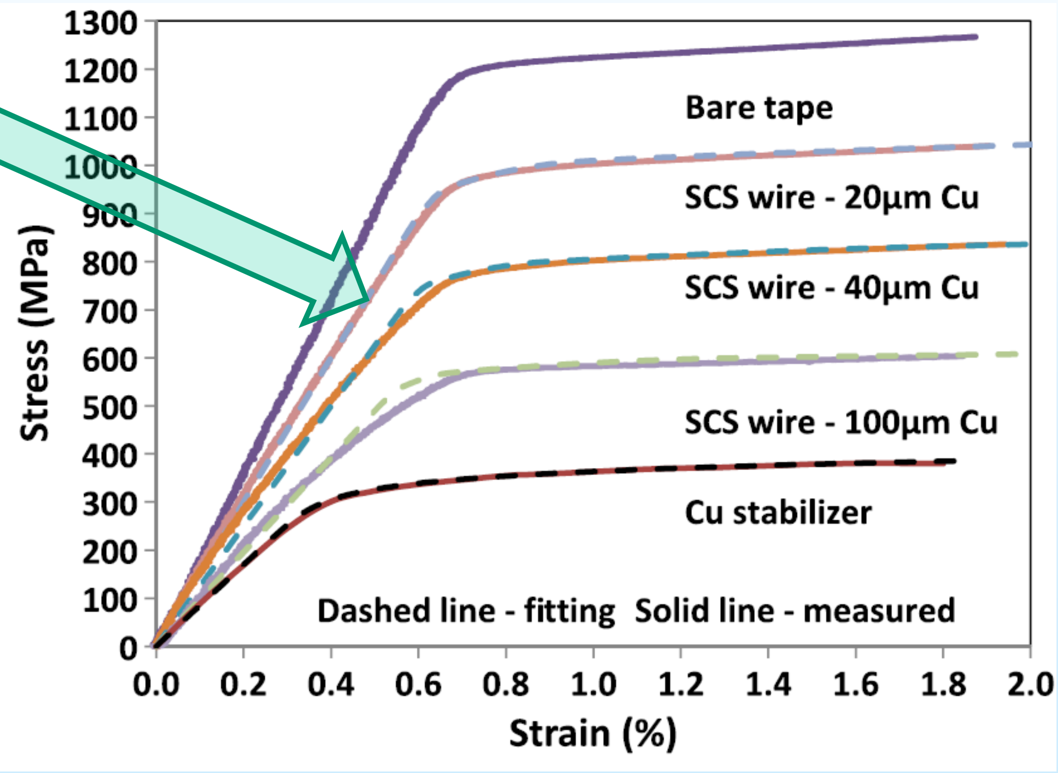
Mechanical Properties of the Conductor

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

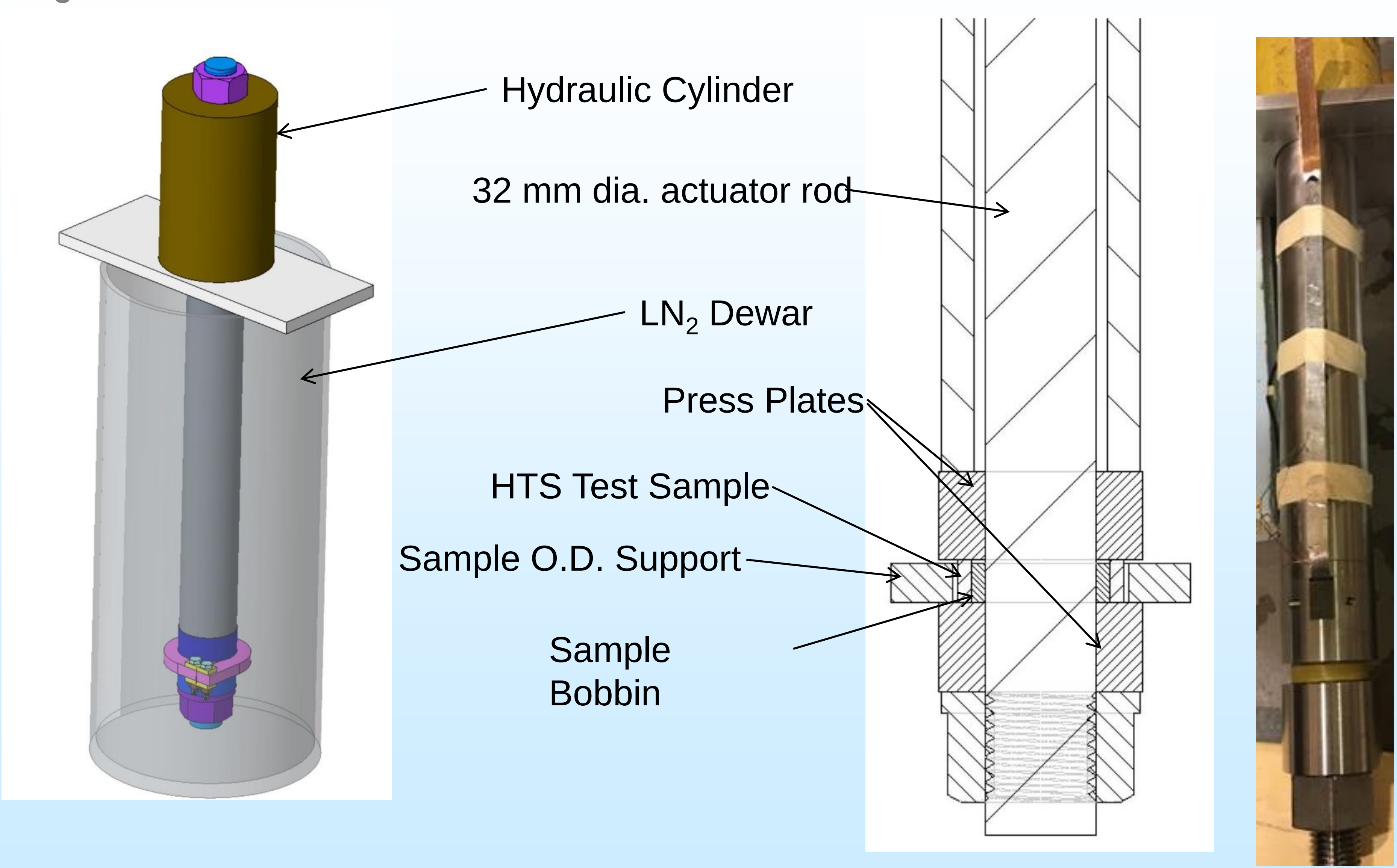
Y. Zhang, D. W. Hazelton, R. Kelley, M. Kasahara, R. Nakasaki, H. Sakamoto, and A. Polyanskii



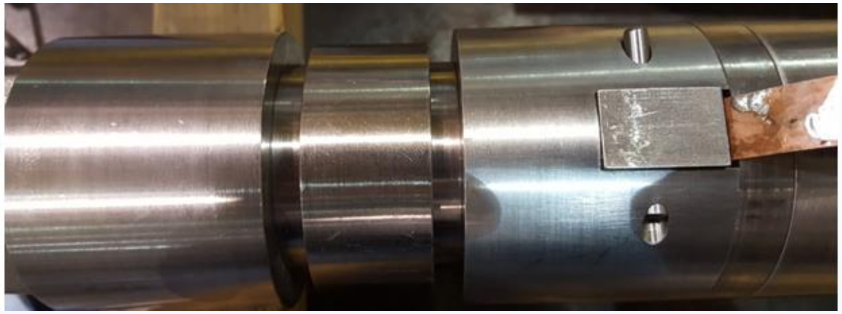
Courtesy: SuperPower

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

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



Apparatus to Measure High Pressure (300 MPa) on the Narrow Face of the Conductor and Coil



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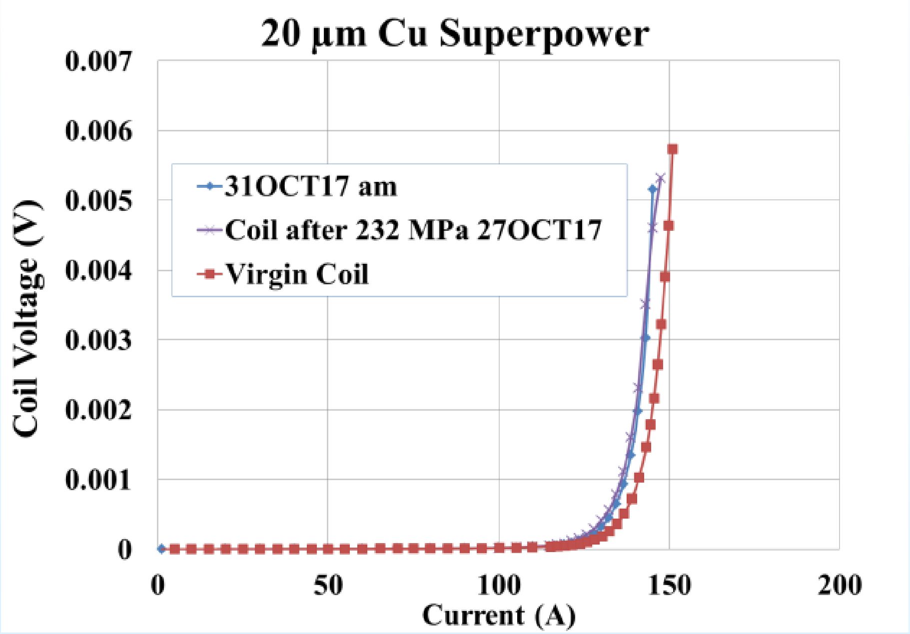
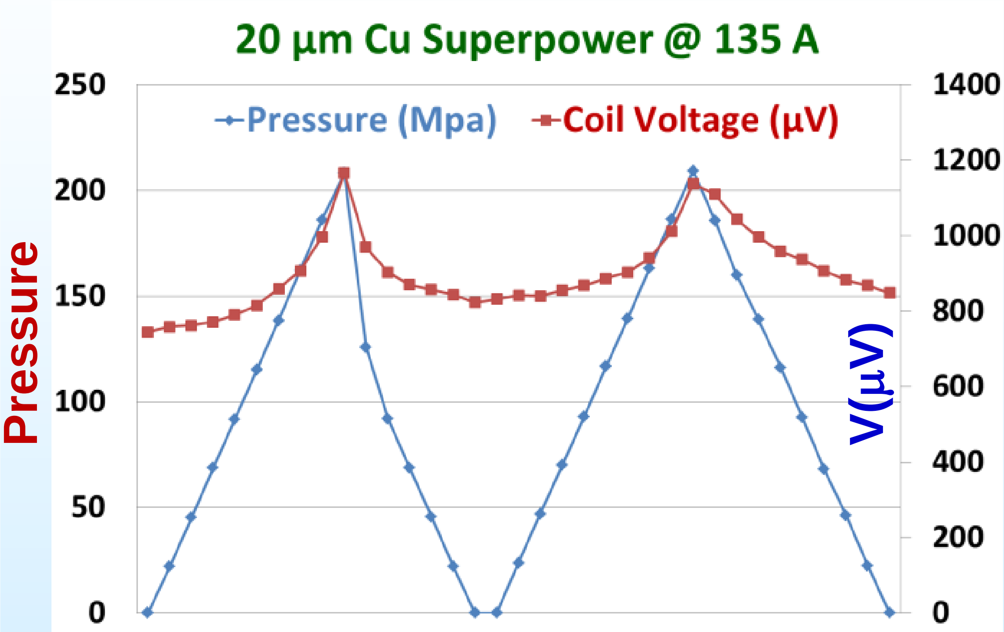
Superconducting Magnet Division

Measurement of the Load on the Narrow Face of HTS Tape

(50 µm Hastelloy, 20 µm Copper from SuperPower)





Meets the requirements of ~200 MPa on the narrow side

(we need a healthy margin)

Other Applications

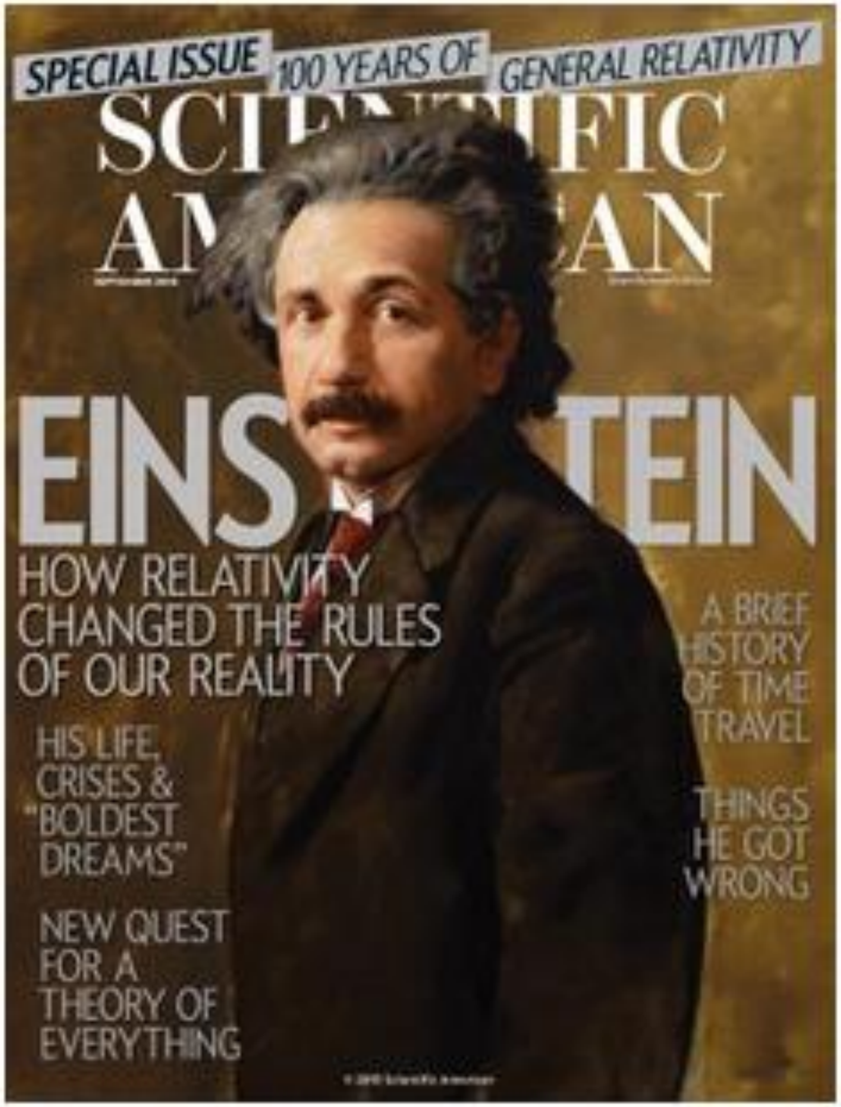
- **Accelerator Magnets**
- **NMR**
- **Fusion**
- **Axion search experiments in US (next few slides)**

US ADMX Experiment

The Axion Dark Matter eXperiment

http://depts.washington.edu/admx/index.shtml

Interest in ADMX Experiment



FUNDAMENTAL PHYSICS

CLEANING UP AFTER EINSTEIN

A new generation of physicists hope to succeed where Einstein failed

By Corey S. Powell

Leslie Rosenberg's attempt to understand the universe resembles a makeshift home hot-water heater tank, capped with some wires and shoved into a large, underground refrigerator. The experiment, housed in a laboratory adjacent to his office at the University of Washington, is a supercooled, magnetized vacuum chamber equipped with a sensitive detector that listens for the microwave "ping" of passing particles called axions. These particles are invisible and, so far, entirely hypothetical.

Rosenberg has been on the trail of this particle ever since he was a postdoctoral researcher at the University of Chicago in the early 1990s. In that time he has performed experiment after experiment, achieving ever greater precision and yet always the same old empty results, hoping for the positive detection that could rescue Albert Einstein's biggest—and most star-crossed—idea.

Physicists call it the unified field theory, but it is more popularly and evocatively known as the theory of everything. The idea has been to devise a single formulation that sums up the behavior of all the known forces of physics. Einstein started this quest nine decades ago. It bothered the great theorist that the two fundamental forces guiding the behavior of the universe—gravity and electromagnetism—appeared to play by different rules. He wanted to demonstrate that all types of matter and energy are governed by the same logic.

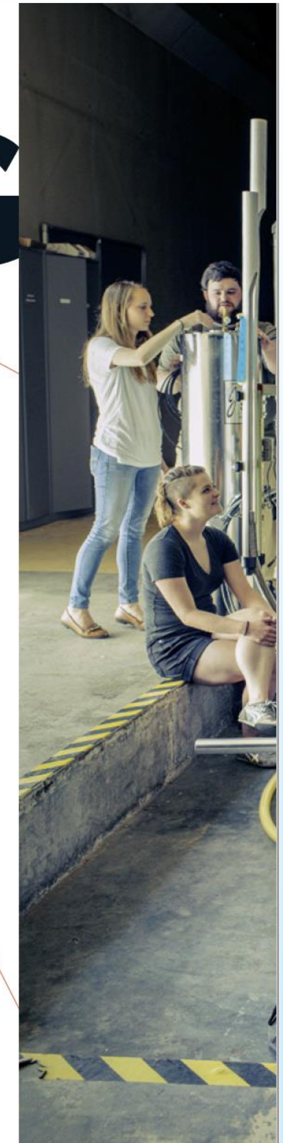
IN BRIEF

At the end of his life, Einstein tried to create a theory of everything, governing all forces in the cosmos.

He failed, in part because two of those forces, the weak and strong, had yet to be discovered.

Physicists are making the attempt again, starting with data on new types of particles and fields.

60 Scientific American, September 2015 *Photograph by Timothy Archibald*



ADMX and High Field Solenoid

DOE is likely to fund R&D on ADMX upgrade

Critical Parameters: High field & Large Volume

Similar to that as in the IBS HTS solenoid

ADMX should procure a new magnet to reach the goal of DFSZ sensitivity for halo axions up to 40 μeV mass (10 GHz).

Now: $B_0 = 8$ T; $V = 200\ \ell$.

Search up to 4 μeV (1 GHz) at DFSZ sensitivity.

$$P = 6 \cdot 10^{-23}\ \mathrm{Watt} \left(\frac{B_0}{8\ \mathrm{Tesla}}\right)^2 \left(\frac{V}{200\ \ell}\right) \left(\frac{m_a}{1\ \mathrm{GHz}}\right) \left(\frac{Q_L}{10^5}\right)$$

Cavity volume is smaller at higher frequencies

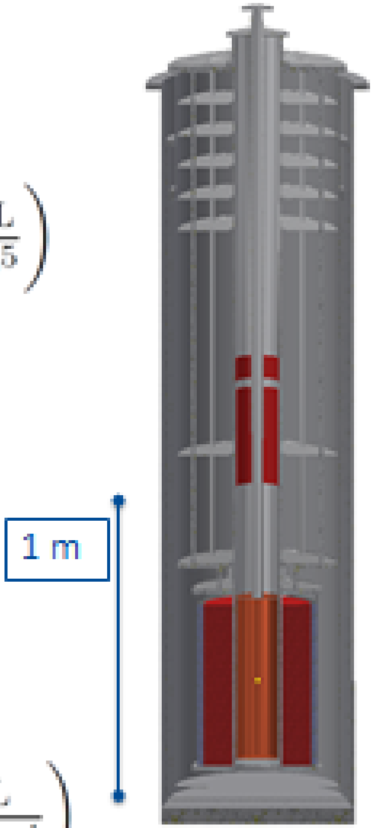
$V \sim 1/f^3$

and signal power decreases.

Signal power increases as B^2.

High temperature superconductors can provide 32 (or even 40 T) using proven technology.

$$P = 7 \cdot 10^{-23}\ \mathrm{Watt} \left(\frac{B_0}{32\ \mathrm{Tesla}}\right)^2 \left(\frac{V}{6\ \ell}\right) \left(\frac{m_a}{5\ \mathrm{GHz}}\right) \left(\frac{Q_L}{5 \cdot 10^4}\right)$$



Allows 5 GHz search with 4 cavity array, DFSZ sensitivity

Summary

- 100 mm, 25 T HTS solenoid will be a significant HTS magnet project for the next two years at BNL
- With required validation tests behind us and with the conductor delivery in a month or so, we expect to start construction and series of intermediate coil tests soon
- It is in the best interest of both BNL and SuperPower that we work together to achieve a successful outcome of this and other high visibility HTS projects.