High Temperature Superconducting Magnets

Revolutionizing Next Generation Accelerators and Other Applications

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Superconducting Magnet Division

466th Brookhaven Lecture

February 16th, 2011

Overview

- **Conventional Superconducting Magnets**
  - The impact as we see today
- **High Temperature Superconducting (HTS) Magnets**
  - How they can revolutionize various applications
- **HTS Magnet R&D at BNL**
  - Unparalleled research program covering a wide range of possibilities

    (one of the focus of this presentation)
- **Future Outlook and Summary**

Superconductors

Superconductors

- ➢ Discovered 100 years ago
  - Last Brookhaven lecture by Qiang Li
- ➢ Essentially zero electrical resistance
- ➢ Facilitate electro-magnets with high fields while conserving energy

Conventional Superconductors

- ➢ Most applications require operation at ~4K (-452 F, *liquid helium*)
  - Thus also called Low Temperature Superconductors (LTS)

High Temperature Superconductors (HTS)

- ➢ Materials that are generally superconducting at ~77 K (-321 F, *liquid nitrogen*)

Superconducting Magnets
How They Revolutionized the Accelerators

- Without "energy saving" superconducting magnets, the power bill of RHIC would have been so large that it may not have been built
- Without "powerful" superconducting magnets, the size of RHIC would have been so large that it may hardly have fit inside the BNL campus
- Without "high gradient " superconducting magnets, the collision rate would have been so small that many RHIC experiments would not have been practical

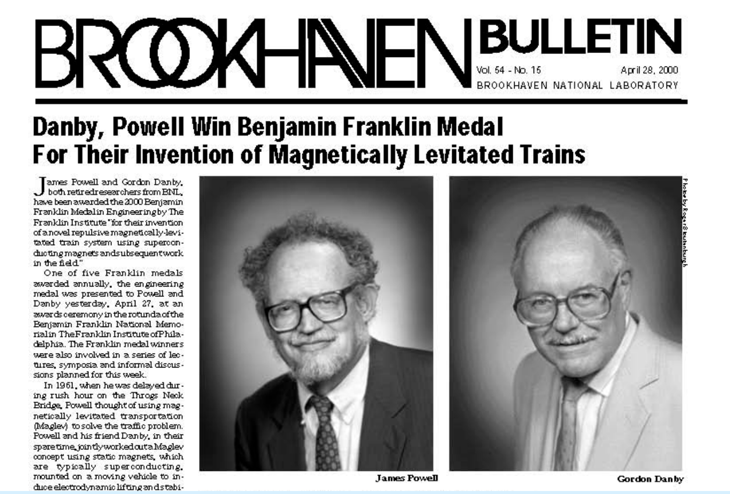
Relativistic Heavy Ion Collider (RHIC) at BNL

The same is true for other modern high energy accelerators such as Tevatron at Fermilab and LHC at CERN.

Superconducting Magnets
How They Revolutionized Other Fields

- Without superconducting magnets, the international experimental fusion reactor (ITER), now under construction, would not have been possible
- Without superconducting magnets, modern high resolution (high field) MRI would not have been possible, etc., etc., etc…

o Superconducting magnetically levitated train experiments



BROOKHAVEN BULLETIN
Vol. 54 - No. 15 April 28, 2000
BROOKHAVEN NATIONAL LABORATORY

Danby, Powell Win Benjamin Franklin Medal For Their Invention of Magnetically Levitated Trains

James Powell and Gordon Danby, both retired researchers from BNL, have been awarded the 2000 Benjamin Franklin Medal in Engineering by The Franklin Institute "for their invention of a novel repulsive magnetically-levitated train system using superconducting magnets and subsequent work in the field."

One of five Franklin medals awarded annually, the engineering medal was presented to Powell and Danby yesterday, April 27, at an awards ceremony in the rotunda of the Benjamin Franklin National Memorial in The Franklin Institute of Philadelphia. The Franklin medal winners were also involved in a series of lectures, symposia and informal discussions planned for this week.

In 1961, when he was delayed during rush hour on the Throgs Neck Bridge, Powell thought of using magnetically levitated transportation (Maglev) to solve the traffic problem. Powell and his friend Danby, in their spare time, jointly worked out a Maglev concept using static magnets, which are typically superconducting, mounted on a moving vehicle to induce electrodynamic lifting and stabi-

James Powell

Gordon Danby

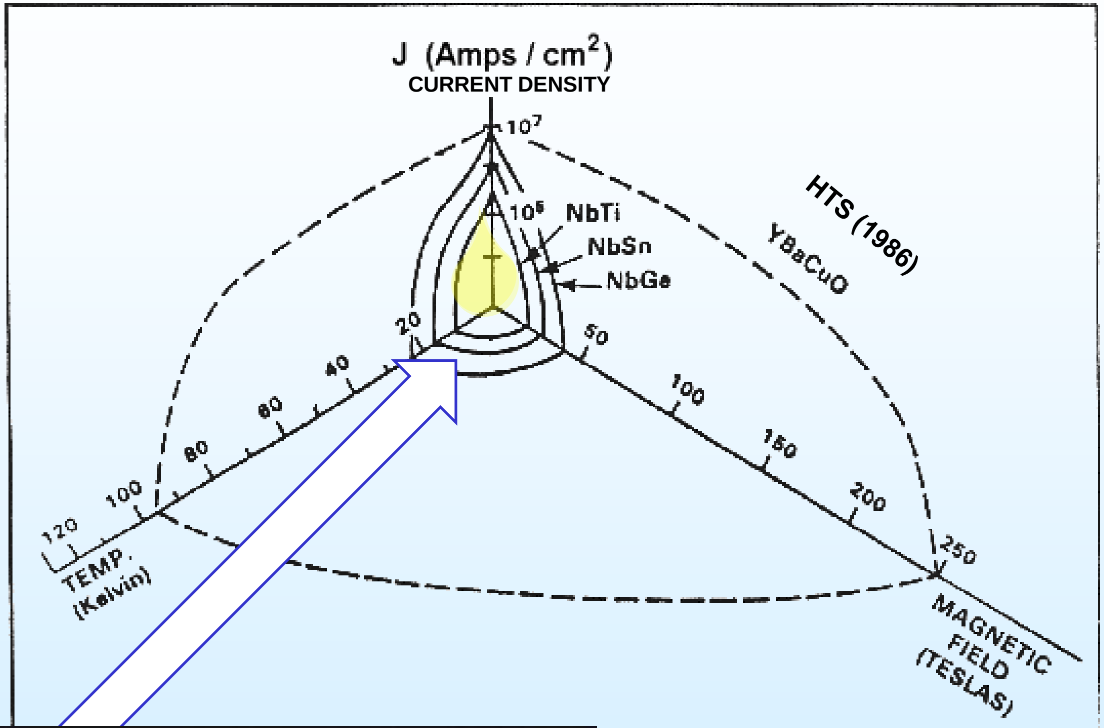
Photos by Roger Stoutenburgh

The development of conventional superconducting magnets a few decades ago revolutionized accelerator and other fields

Strong Power Forced to Remain in Captive Volume

Power kept

in captive volume



ity (New York: McGraw-Hill, 1975)

Diagram

Superconductor in magnets must remain in the captive volume of:

- Field
- Temperature
- Current (density)

Conventional superconductors (NbTi and Nb$_3$Sn) generally operate at 4 K and applications rely on liquid helium for cooling

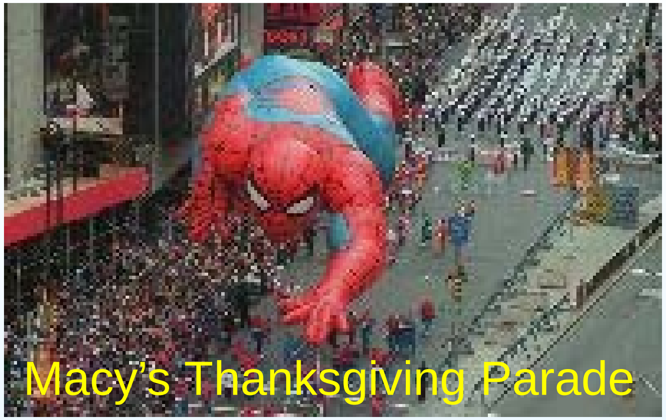
Dwindling Supply of Natural Resources
Where will we be in ~100 years?

No, we are not talking about oil …

NYSE

- **It is Helium ! ! !**
  - Essential for cooling practically all superconducting magnets now
  - Non renewable, escapes to upper atmosphere
- World Helium supply could be mostly exhausted in 30 years
  - CBS News, August 23, 2010
  - Prof. Robert Richardson, Cornell (1996 Physics Nobel Laureate)
- Price has increased ~3 times in last five years for many customers

Other Important and Bigger Users of Helium



LCDTV, rocket fuel and many experiments, etc ...

Need to look for alternative sources of cooling …

High Temperature Superconductor to Rescue

- HTS magnets can operate at higher temperatures where helium-free cooling schemes become attractive

Critical temperatures (T_c) of popular superconductors:

LTS

NbTi: ~ 9 K

Nb_3Sn: ~ 18 K

HTS

BSCCO2223: ~ 110 K

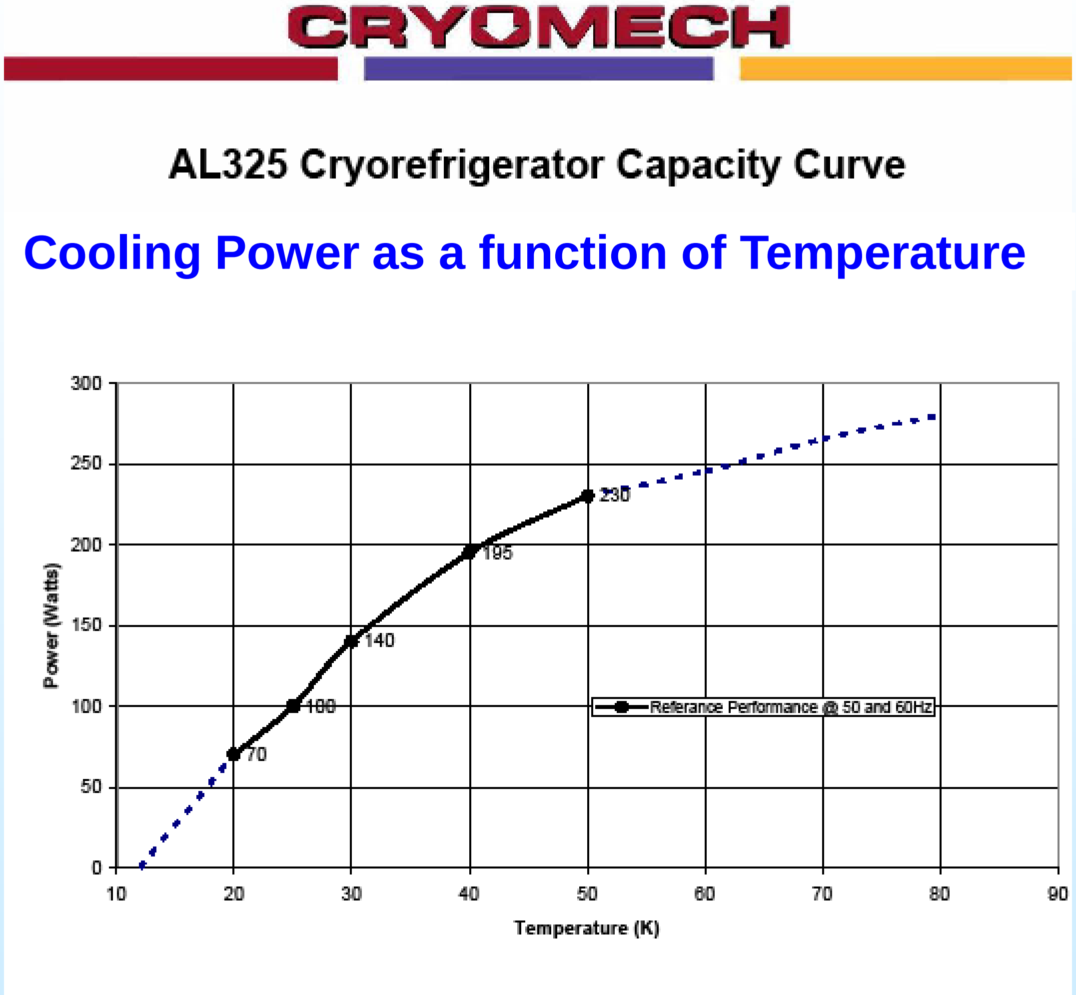
BSCCO2212: ~ 85 K

YBCO: ~ 90 K

MgB_2: ~39 K

Helium-free Cooling (with cryo-cooler)

- No helium refill needed
- Good for remote areas



Cooling Power as a function of Temperature

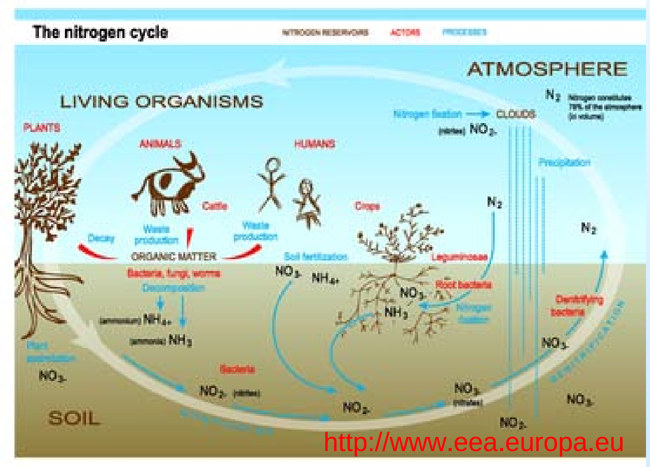
Capacity increases at higher temperature – HTS magnets, a good solution

Helium-free Cooling (with liquid nitrogen)

HTS magnets can operate with liquid nitrogen at ~77 K

- Liquid Nitrogen (LN2) is supplied in all quantities

- LN2 is ~100 times cheaper than liquid helium
  - ➢ @9 cents/liter, cheaper than milk or oil

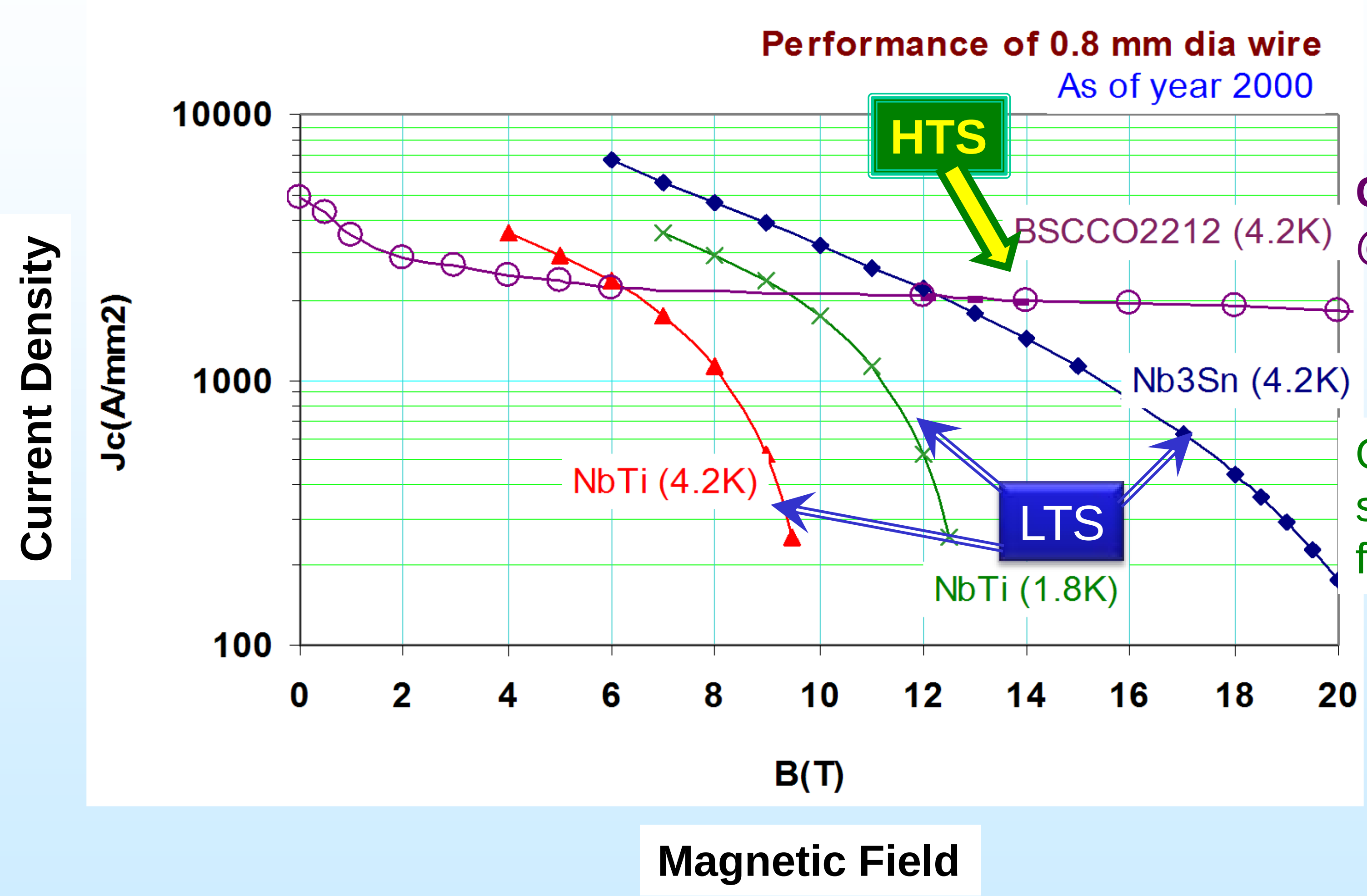


http://www.eea.europa.eu

HTS makes helium free superconducting magnets attractive

- ➢ Nitrogen is renewable
- ➢ Available in abundance (~78%)

Another Key Property of HTS (they can make high field magnets)



Carry current @ high fields

Only practical superconductor for fields >20 T

High Temperature Superconductors are also high field superconductors

New Possibilities with HTS in Superconducting Magnet Technology

HTS can function at high temperature

- That makes helium free superconducting magnets operating at high temperature possible as never before (> 20 K)

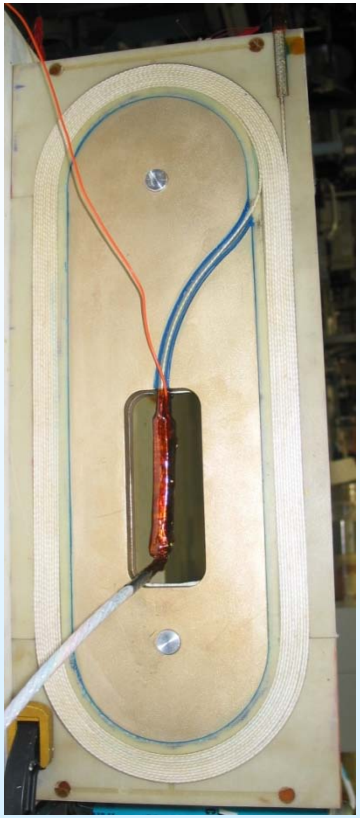
HTS can carry substantial currents at high fields

- That makes very high field superconducting magnets possible as never before (>20 T)

➢Even one of above is sufficient to revolutionize the field

- Here we have two ! !

Magnets Made with HTS
(offer a range of possibilities)



- ☐ High temperature, low field
  - ➢ Already in use in R&D programs at BNL
- ☐ Medium field, medium temperature
  - ➢ Potential for large scale cryogen-free applications
  - ➢ Solving critical problem of large heat loads
- ☐ Very high field magnets
  - ➢ Dipoles for energy upgrade (RHIC 7X, LHC 3X)
  - ➢ Quadrupoles for interaction region upgrade
  - ➢ Solenoids to make Muon Collider possible

✓ Possible only with HTS
✓ R&D @BNL in all 3 areas

Challenges with HTS Magnets

High Cost Conductor

- HTS is an order of magnitude more expensive than conventional superconductor

Challenging Conductor

- HTS is formed at very high temperatures (~850 C) within a narrow window
- HTS is brittle
- Properties of HTS tapes are anisotropic

High field Magnets

- Large stresses
- Slow quench (turning normal) velocities makes magnet protection challenging

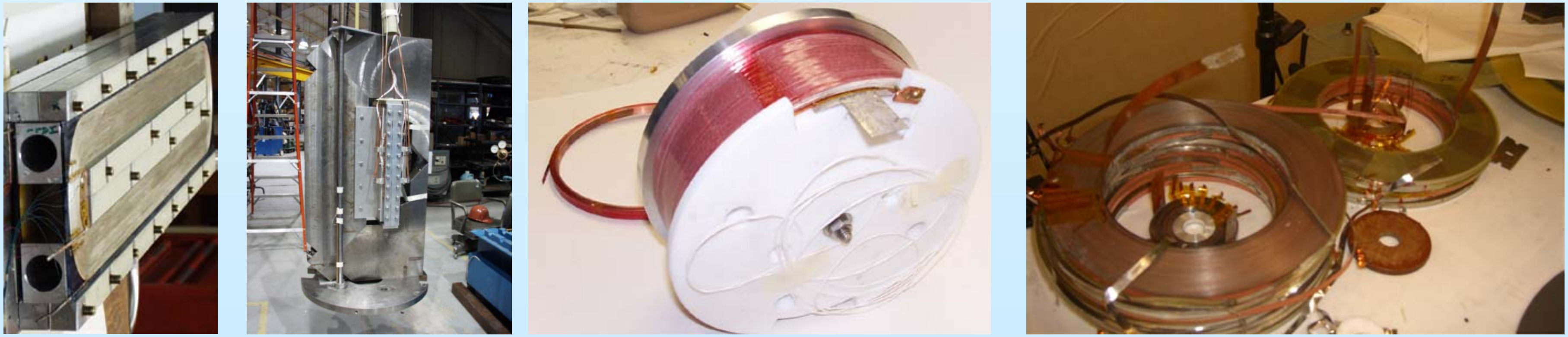
New Technology Syndrome

- First practical challenge: the “fear of unknown” :
  - Any “new technology” must be examined critically
  - Similar to what must have been in case of conventional LTS magnets

- Strategy to overcome the “New Technology Syndrome” :
  - ➢ Apply it first in smaller experiments
  - ➢ Develop it for applications with no other comparable solution
  - ➢ Demonstrate technology with as many coils and magnets as possible
  - ➢ Share the excitement with community about the potential benefits

HTS Magnet Programs at BNL

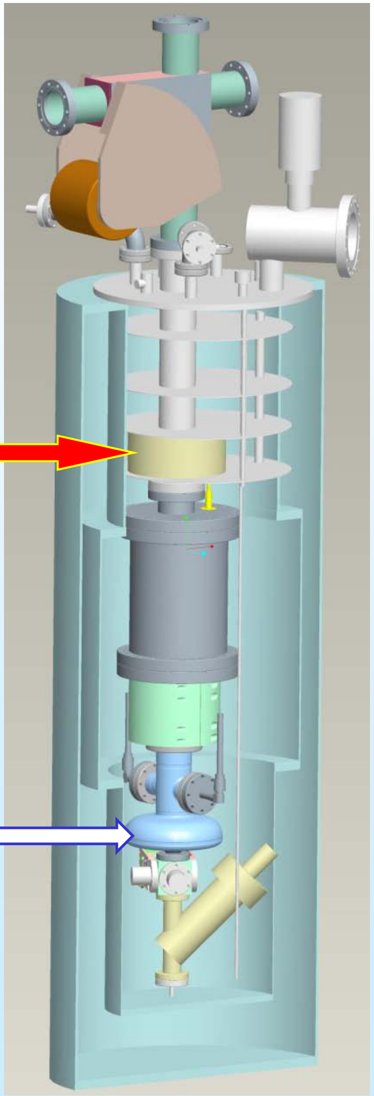
- **BNL has been the world leader on HTS accelerator magnet R&D for a decade**
  - **First national lab to design, build and test HTS coils & R&D magnets for accelerators**
- **The level of current activity is over an order of magnitude more than in any other accelerator or similar lab around the world**
- **It has funding, however limited (funding range ~10k$ to ~1.8M from DOE NP & HEP and stimulus package, research agreements with a small business and a university) for developing HTS magnets operating over a large range of temperature and field and having a variety of geometries**
- **Variety is the strength of our program. It helps us in fostering a wider understanding and makes the overall development more cost effective**



Low Field HTS R&D Magnets

(already being used in applications @ BNL)

HTS Solenoid for LDRD on Superconducting Electron Gun

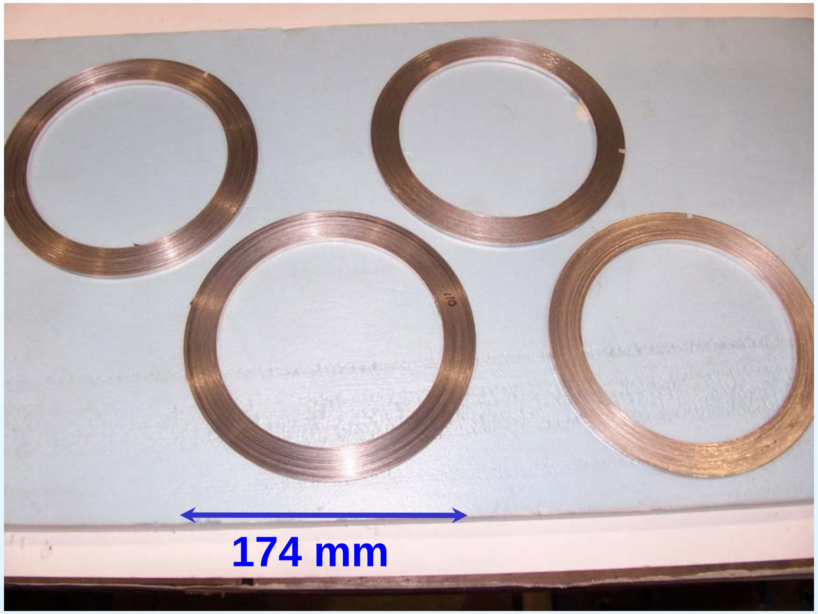


Courtesy:
Ben-Zvi, Kewisch

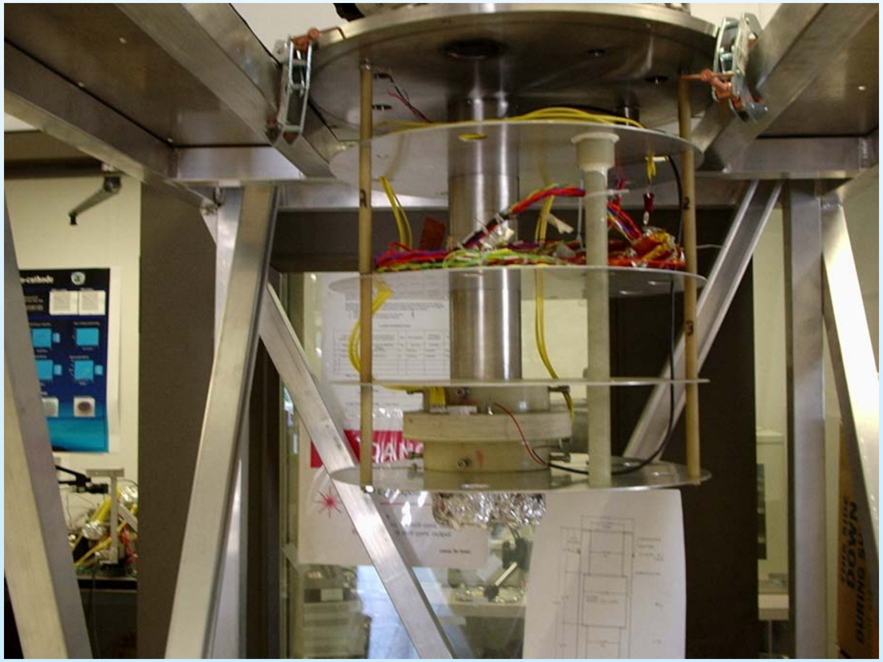
Produces intense electron beams with focusing from HTS solenoid

- No room for LTS solenoid in Liquid Helium
- Copper solenoid would generate ~500 W heat as against the ~5 W heat load of the entire cryostat
- Temperature between baffles ~20 K ***– NO LTS***
- **HTS solenoid provides a unique solution**

Hardware of HTS Solenoid Built as a Part of LDRD



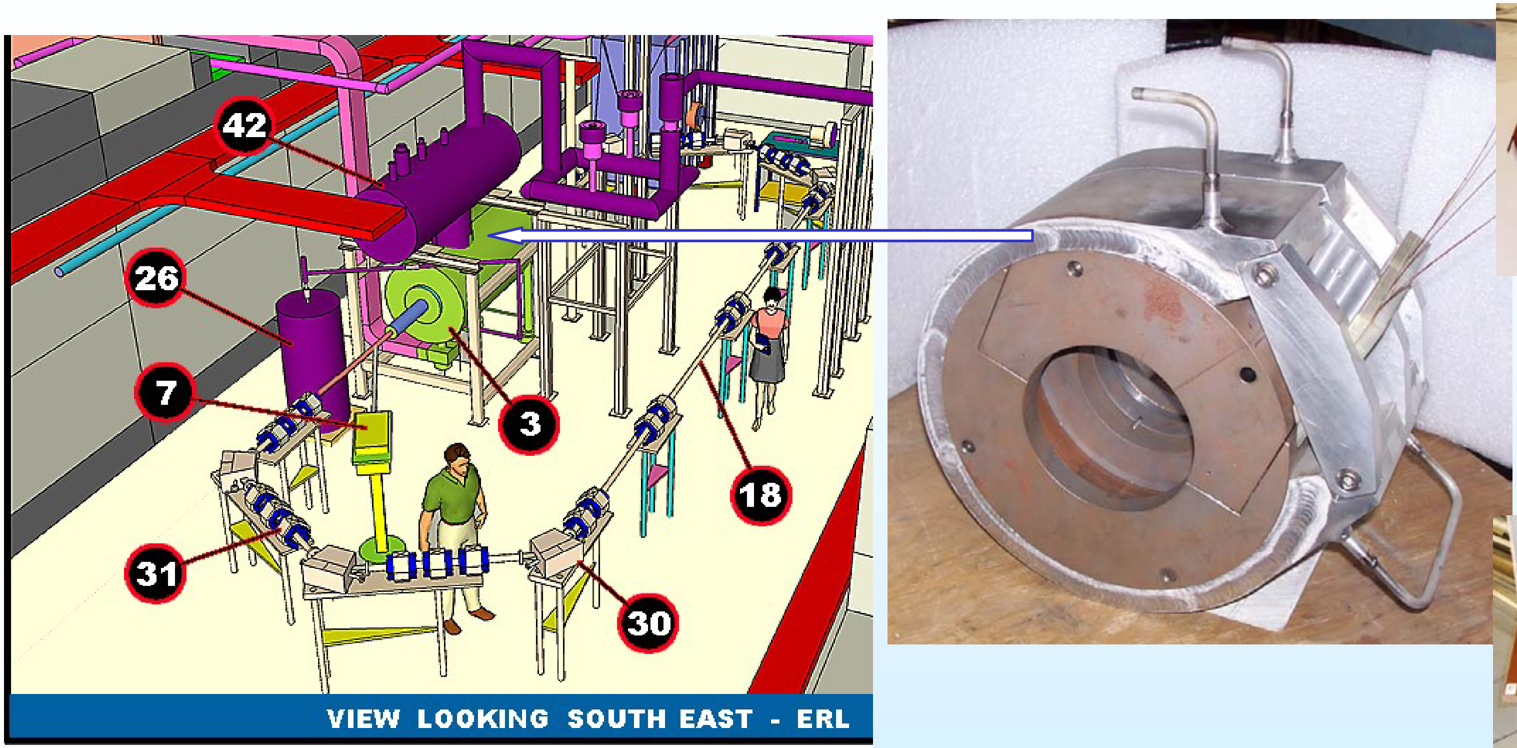
- Conductor cost: ~ a few k$
- Compact size
- Low current (<20 A) operation with household wiring



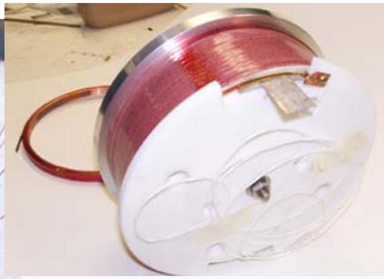
- Testing at ~77 K in LN_2 is much cheaper than testing at ~4 K in LHe
- **HTS provided an economically better (design + build + test) and technically superior solution**

Courtesy/Contributions: Dilgen, Ince

HTS Solenoid with Superconducting Cavity for the Energy Recovery Linac at BNL



http://www.bnl.gov/magnets/Staff/Gupta/Talks/erl-talks.htm

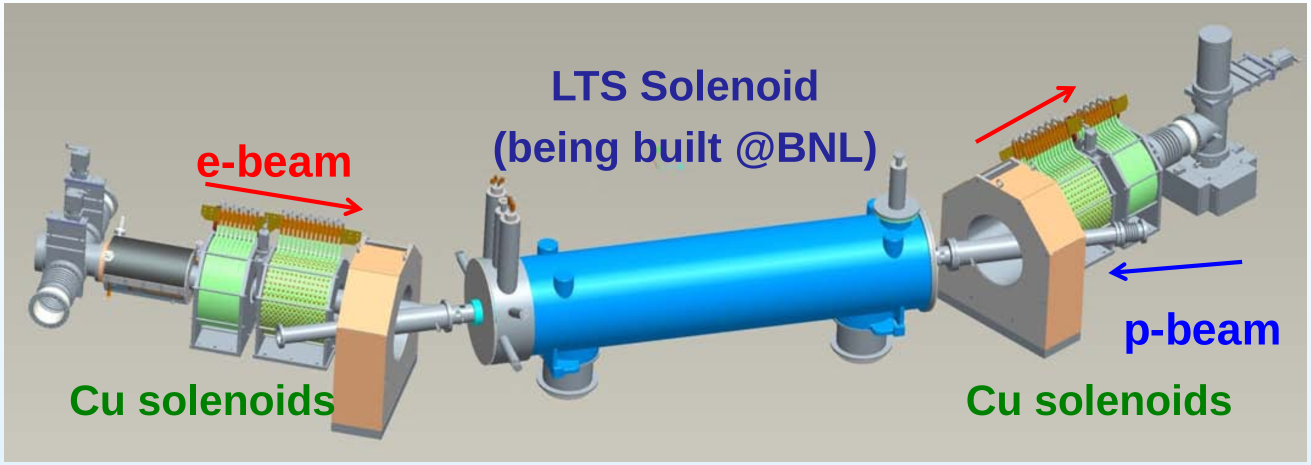


HTS solenoid is placed in cold to warm transition region after the superconducting cavity where neither LTS or copper solenoid would work

A unique BNL solution that other labs are adopting

Another Potential HTS Candidate for BNL

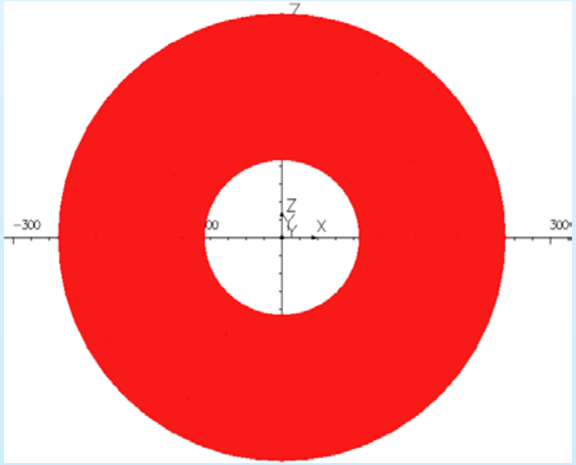
Electron lenses in RHIC – now under construction



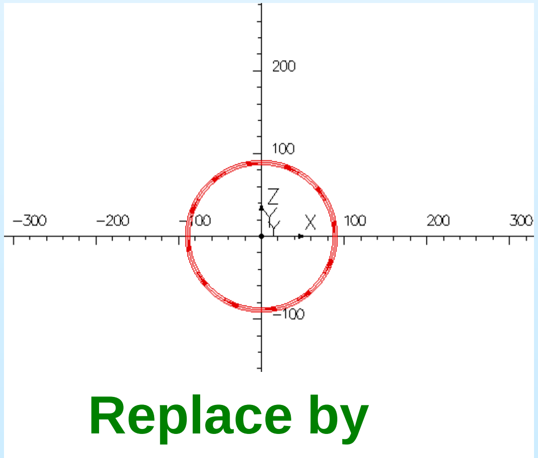
Cu solenoids consume significant power:

One of them consumes 58 kW to 114 kW

- ➢ **Issue not only of cost but of availability too**



Copper Solenoid



Replace by HTS solenoid

HTS solenoid cooled by return helium gas (no power needed)

(conductor cost: ~ 40 k$)

A good topic for LDRD for energy efficiency and to solve potential infrastructure problem

Medium Field HTS Magnet Programs

1. General Purpose (for accelerators & medical applications)

➢ Must compete with two established technologies:

- Magnets powered with water-cooled copper coils
- Super-ferric magnets with conventional superconductors (NbTi)

2. Special Purpose Magnets:

➢ **HTS magnets solve critical technical problems**

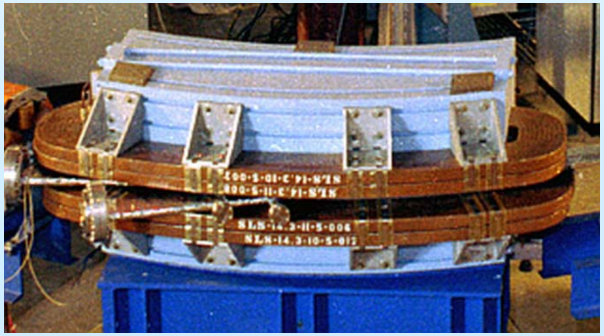
HTS Dipoles for Energy Efficiency (Example: Retrofit NSLS Dipole)

- Room temperature Cu coil magnets: Cheaper to build, expensive to operate (2M$/y)
- Cryo-cooled HTS magnets: Expensive to build, cheaper to operate

Compare the cost of ownership (capital + operation):

➢ ***GOAL:*** *Cost-effective technology to offer saving in cost of ownership after a number of years. Also take advantage of unique situation (upgrade?)*

Wider application: accelerators, medical facilities

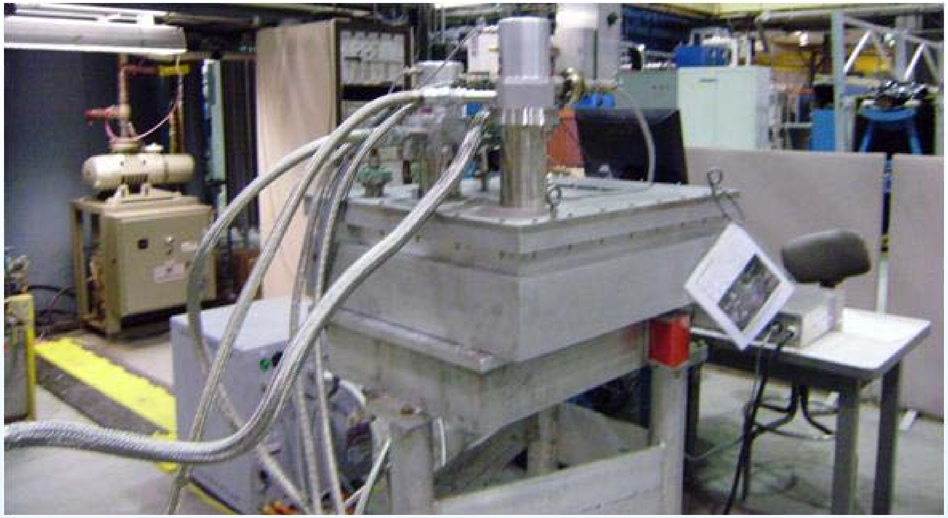


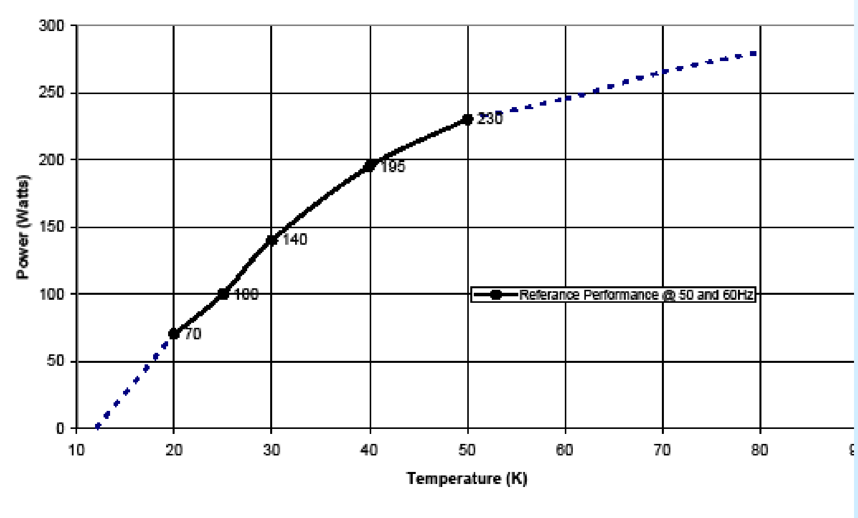
Original NSLS 1.55 T Dipoles with Copper Coils (~3 MW)

Cu coils replaced by cryo-cooled HTS coils by HTS-110

Cryo-cooled HTS coils with technology developed at BNL

HTS and Cryo-coolers
(a promising marriage)





Evening: Switch ON; Morning: Fully COLD

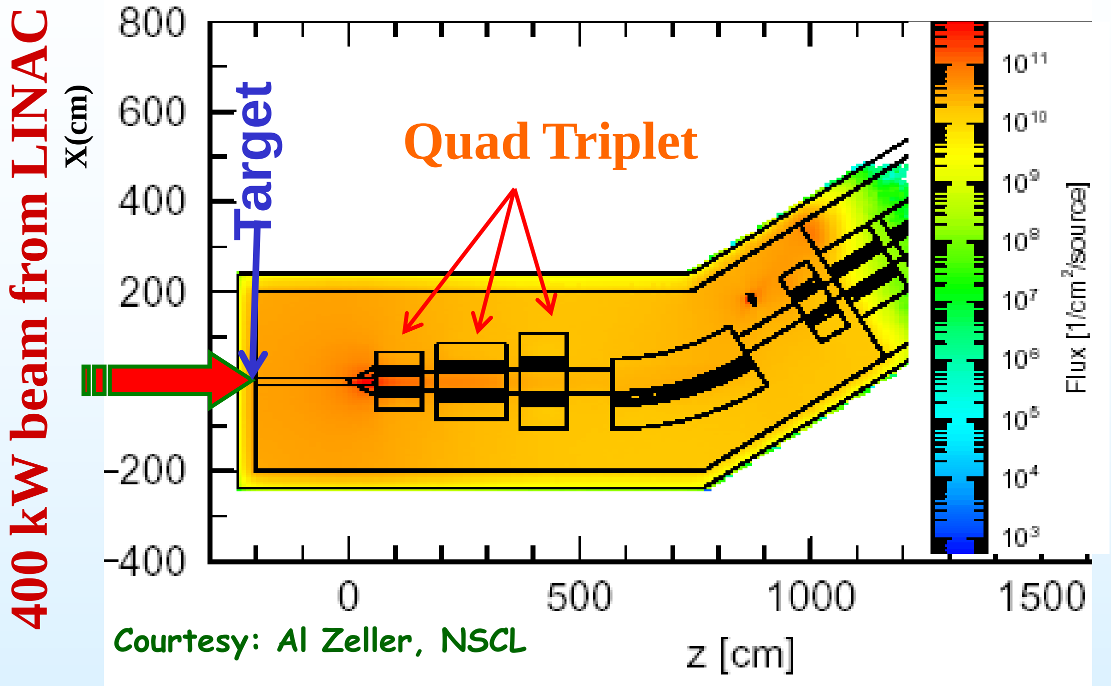
HTS Magnet Development Program for Facility for Rare Isotope Beams (FRIB)

Will create rare isotopes in quantities not available anywhere

- Site: Michigan State University

- Major source of funding for HTS magnet R&D at BNL
- Comprehensive program to solve a critical problem

Technical Advantage of HTS Magnets

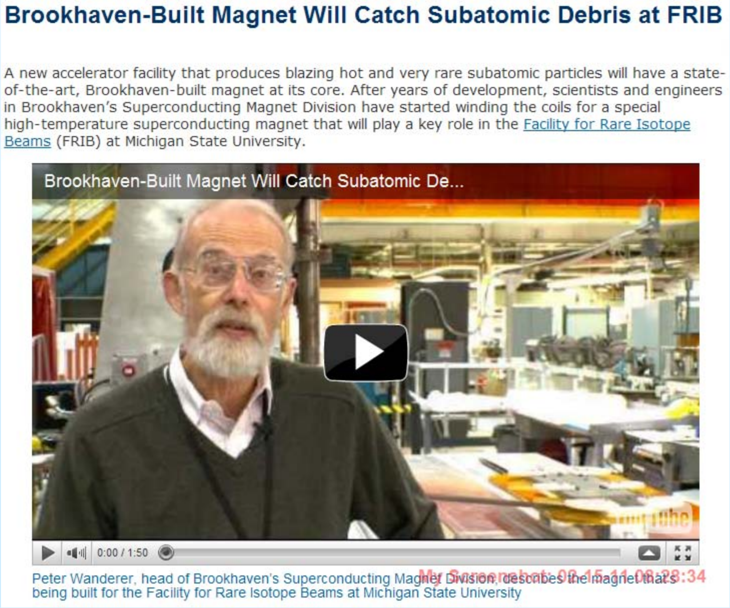


Courtesy: Al Zeller, NSCL

- ➢ High power beam (~400 kW) hits the target to create intense rare isotope beams
- ➢ Magnets are exposed to very high radiation and heat loads (~15 kW in the first)
- ➢ HTS magnets remove this heat more efficiently at 30-50 K than LTS at ~4 K
- ➢ HTS magnets have a large temperature margin, can tolerate a large local increase in temperature and allow a robust cryogenic operation in presence of large heat loads

HTS Coil Winding

Manual winding (earlier coils)



Brookhaven-Built Magnet Will Catch Subatomic Debris at FRIB

A new accelerator facility that produces blazing hot and very rare subatomic particles will have a state-of-the-art, Brookhaven-built magnet at its core. After years of development, scientists and engineers in Brookhaven's Superconducting Magnet Division have started winding the coils for a special high-temperature superconducting magnet that will play a key role in the Facility for Rare Isotope Beams (FRIB) at Michigan State University.

Peter Wanderer, head of Brookhaven's Superconducting Magnet Division, describes the magnet that's being built for the Facility for Rare Isotope Beams at Michigan State University

http://www.bnl.gov/today/story.asp?ITEM_NO=2147

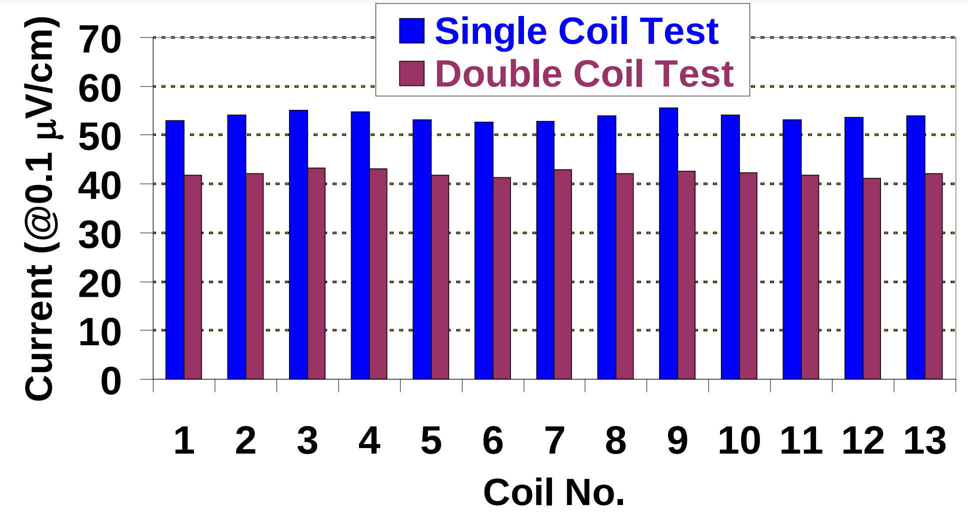
Modern computer controlled coil winding machine @BNL

Series Production of HTS Coils

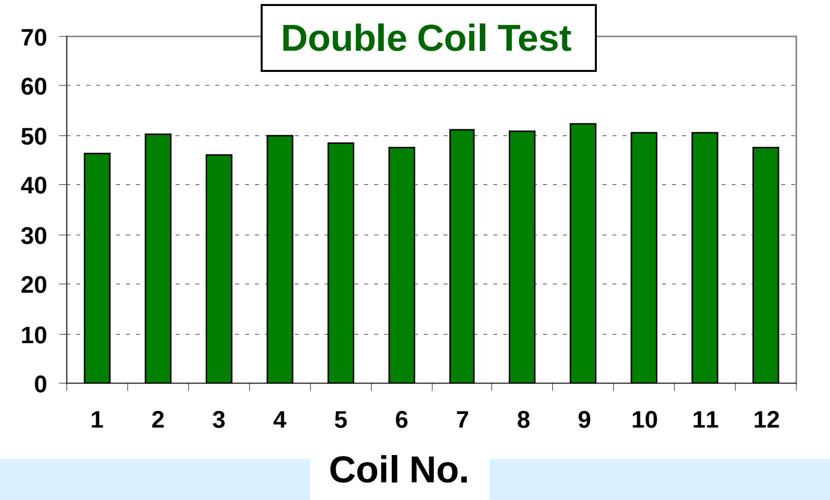
- Magnet consists of 24 coils; each coil is made with ~200 meter of HTS
- A good opportunity to examine the reproducibility of large number of coils

Performance of a Large Number of HTS Coils with LN_2

13 Coils made with earlier tape
(HTS ~220 meters)



12 Coils made with newer tape
(HTS ~180 meters)

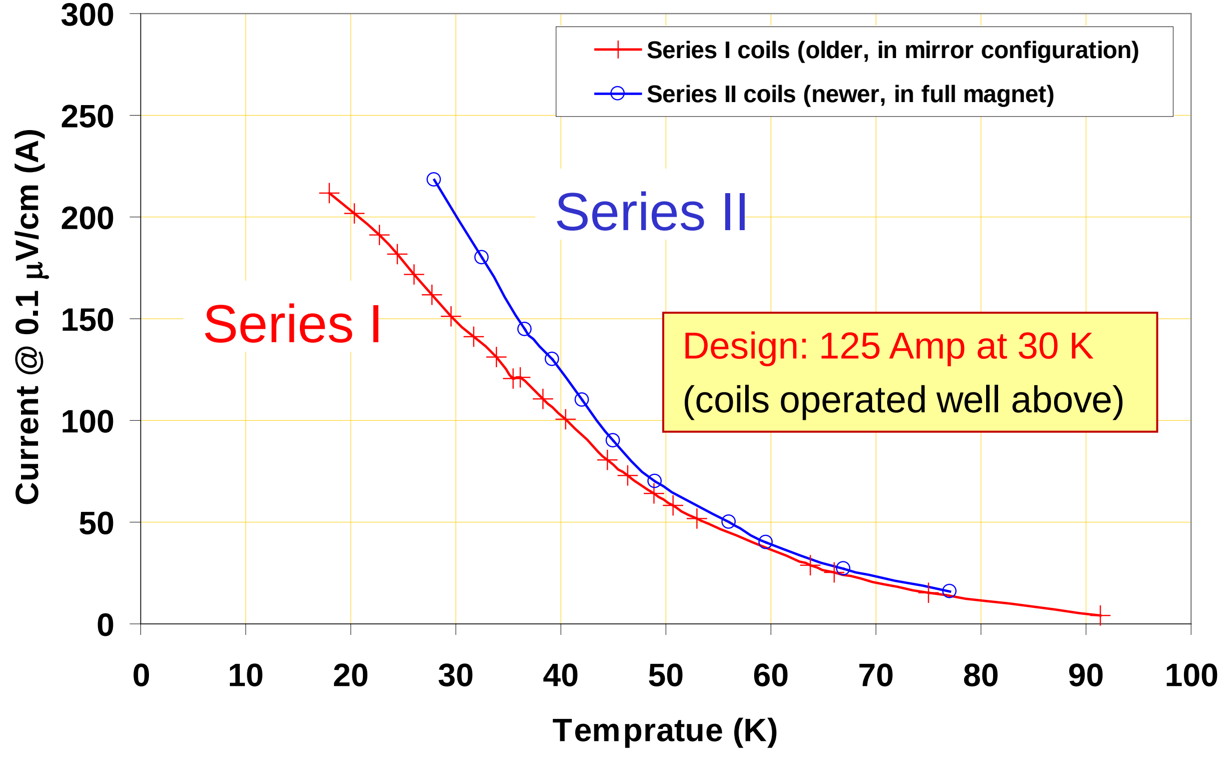


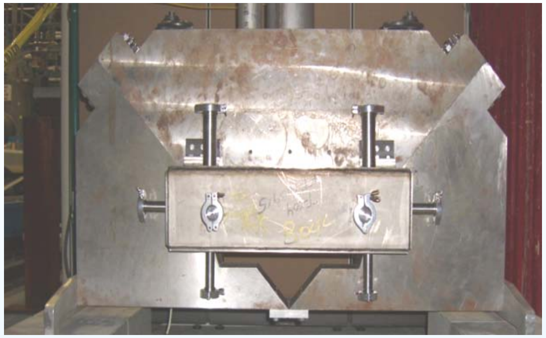
Note: Uniformity in performance of a large number of HTS coils.

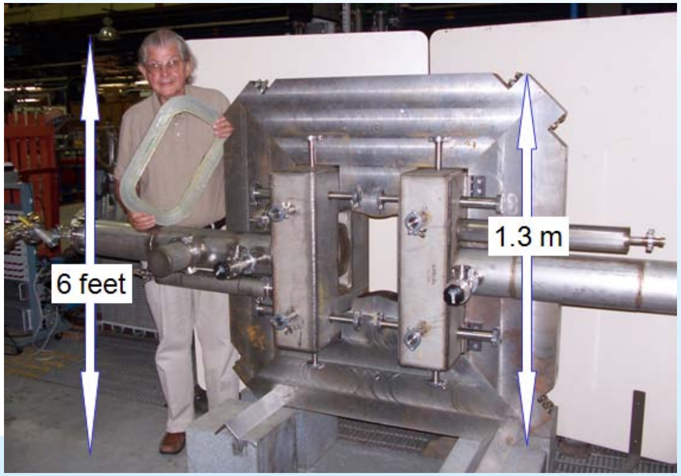
Shows that HTS technology is now maturing !

Summary of Test Results

(operation over a large temperature range)







<u>Benefits of HTS over conventional LTS demonstrated:</u>

- Large change in temperature causes only a small change in critical current
- To obtain significantly higher performance, just lower the operating temperature

the Bulletin

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Roger Stoutenburgh D1400810

William Sampson Honored With IEEE Award For Applied Superconductivity Research

(IEEE Award 2010)

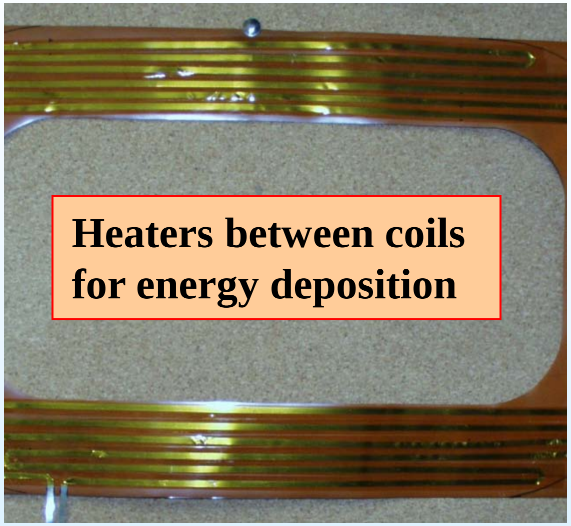
Masaki Suenaga
(IEEE Award 2008)

Eric Forsyth
(IEEE Award 2006)

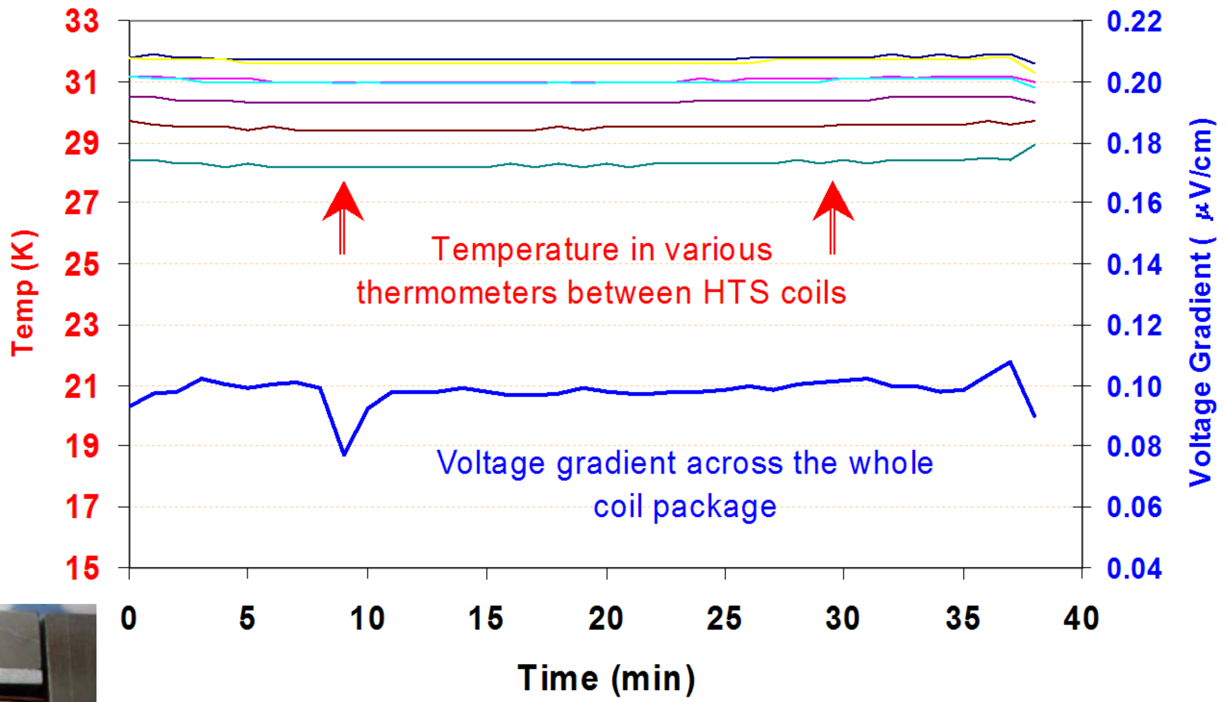
Demonstration of Large Energy Deposition and Radiation Tolerance of HTS Magnets

Energy Deposition Experiment

Large heat loads (25 W, 5kW/m^3) on coils to simulate energy deposition

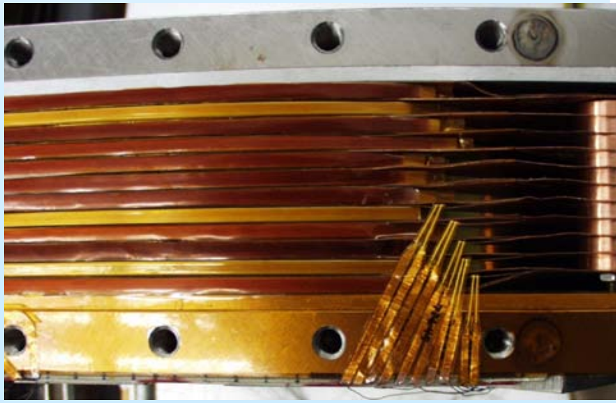


Heaters between coils for energy deposition



Temperature in various thermometers between HTS coils

Voltage gradient across the whole coil package

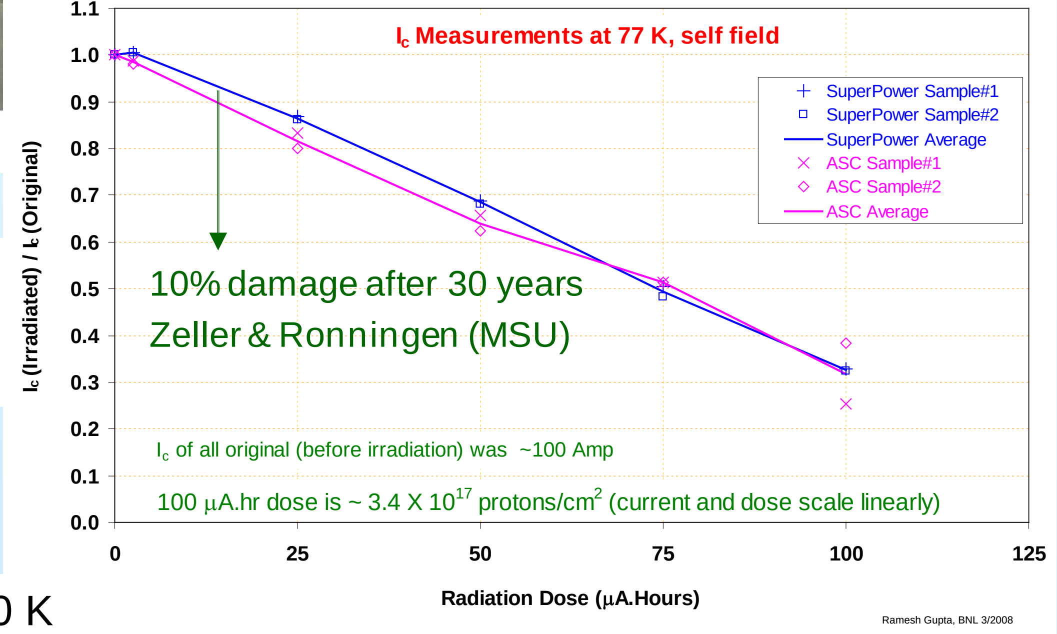


✓Stable fashion over a long period

HTS Radiation Damage Studies at BNL

Figure 2. The BLIP facility.

Brookhaven Linac Isotope Producer (BLIP)



10% damage after 30 years
Zeller & Ronningen (MSU)

I_c of all original (before irradiation) was ~100 Amp

100 μA.hr dose is ~ 3.4 X 10^{17} protons/cm^2 (current and dose scale linearly)

Ramesh Gupta, BNL 3/2008

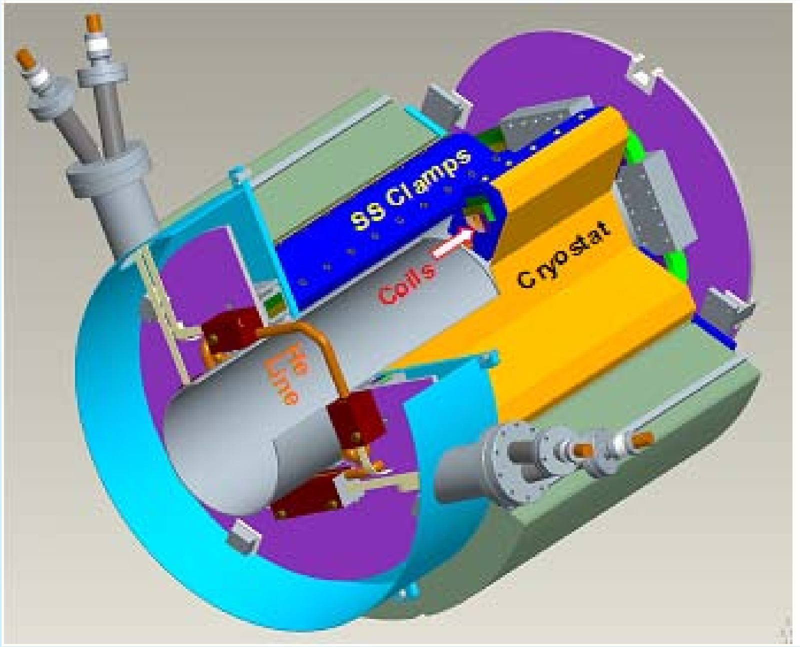
- ✓ **HTS acceptable for FRIB doses (Zeller, MSU)**

Next step: In field measurements at 40-50 K

2nd Generation Program

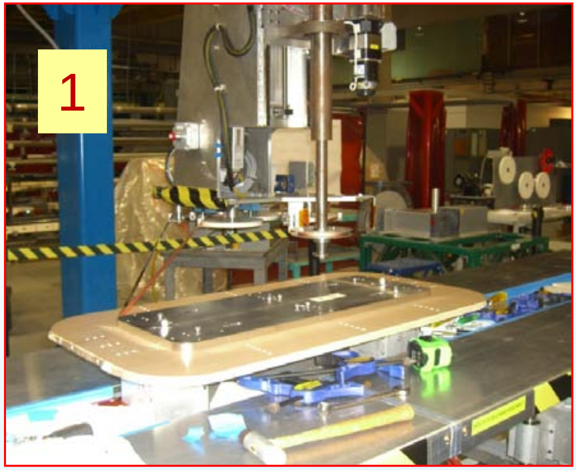
Positive outcome of the 1st generation HTS magnet R&D encouraged a more ambitious 2nd generation program:

- Higher operating temperature: ~50 K rather than ~30 K
- Second generation HTS available from two US vendors
  - ✓ American Superconductor
  - ✓ SuperPower
- Higher field gradient
- Full size prototype



Activities on the Floor

(snapshots around noon hour on January 20, 2010)



1. An HTS coil being wound on automatic winder
2. Another HTS coil being prepared for test in liquid nitrogen (notice a fancy cryostat!)
3. Advance magnet protection system being developed
4. Three coils in storage (next best to being in magnet)

HTS coil construction ahead of schedule – an interesting problem

Impact of FRIB HTS Magnet Program

- A successful R&D program that not only addresses a critical issue but also builds a good foundation for other
- Could be the first significant application of HTS magnets in an accelerator

Very High Field Magnets
(made possible only with HTS)

- **Several different geometries**
- **Several different applications**
- **Several different sources of funding**

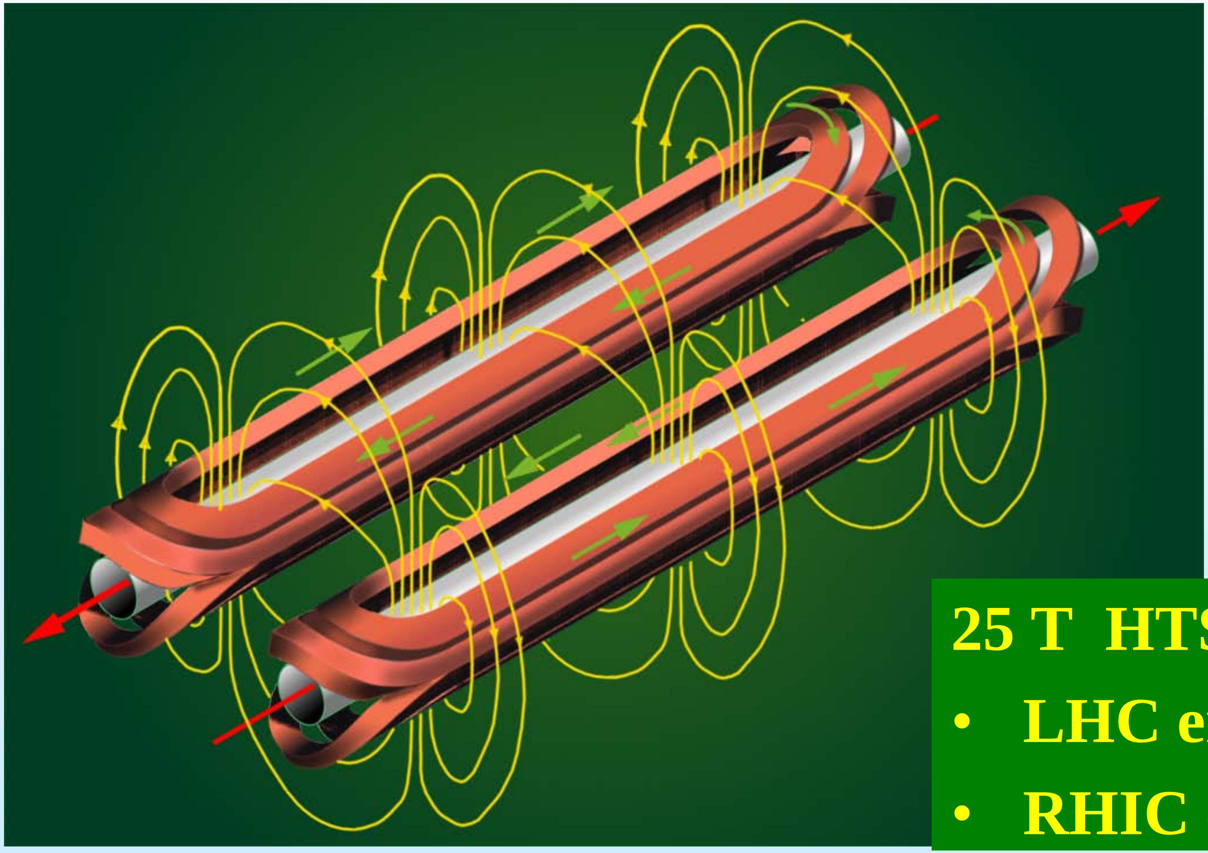
They Should All Help Each Other:

IN CREATING THE MOST POWERFUL SUPERCONDUCTING MAGNET, EVER!

High Field Dipoles for Energy Upgrade of Existing Accelerators

Conventional design with complex ends

- **Not best suited for high fields**
- **Not best suited for brittle materials (HTS, Nb_3Sn)**

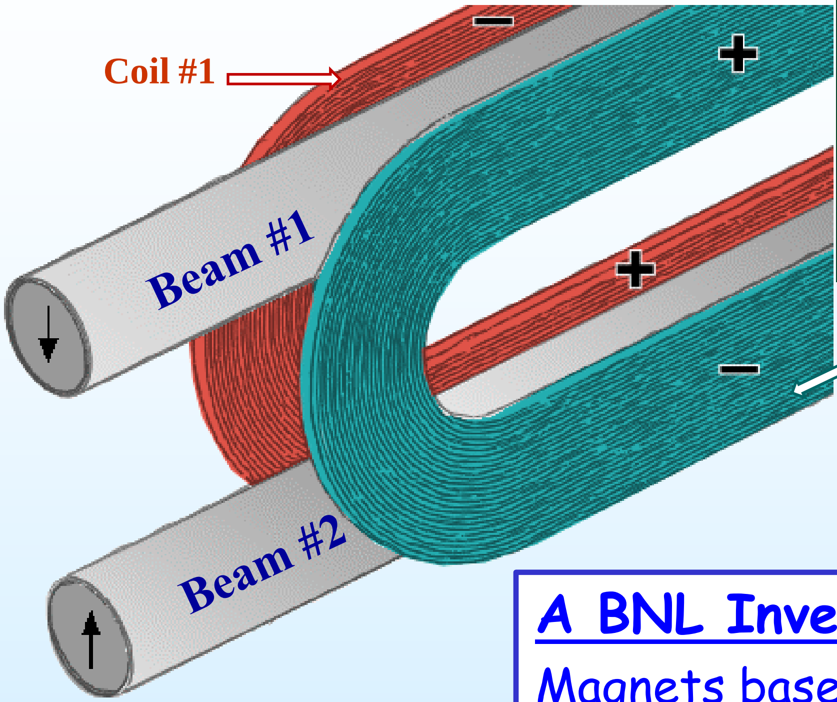


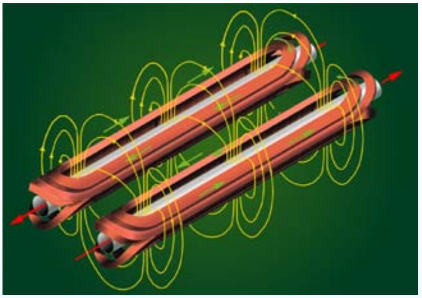
25 T HTS magnet will increase

- **LHC energy > 3 times**
- **RHIC energy > 7 times**

LHC collider dipole concept rendering from CERN

High Field 2-in-1 Common Coil Dipole Design for Colliders



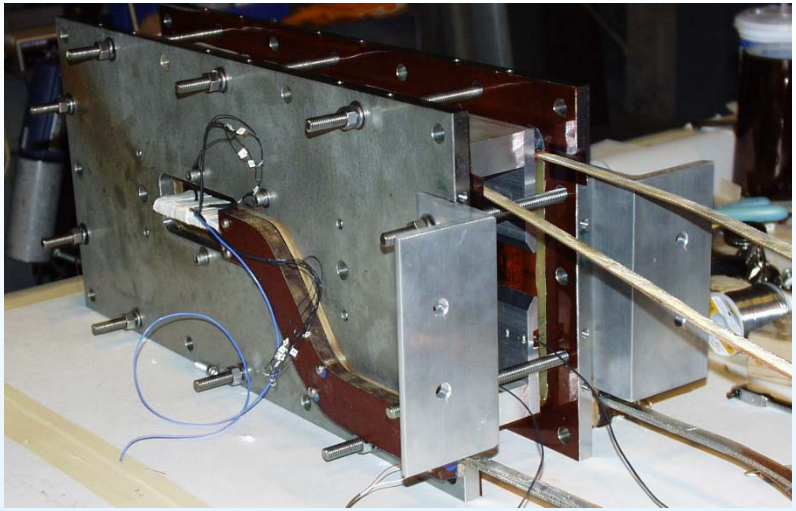


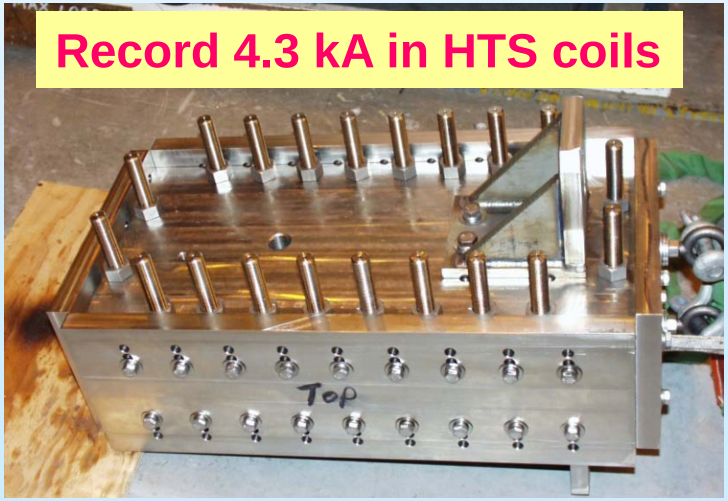
A BNL Invention:

Magnets based on this design built at LBL and Fermilab also

- **A conductor friendly design with simple racetrack Coils**
- **No complex ends**
- **Large bend radius**
- **Suitable for coils made with brittle conductors (HTS)**

BNL Common Coil Structures

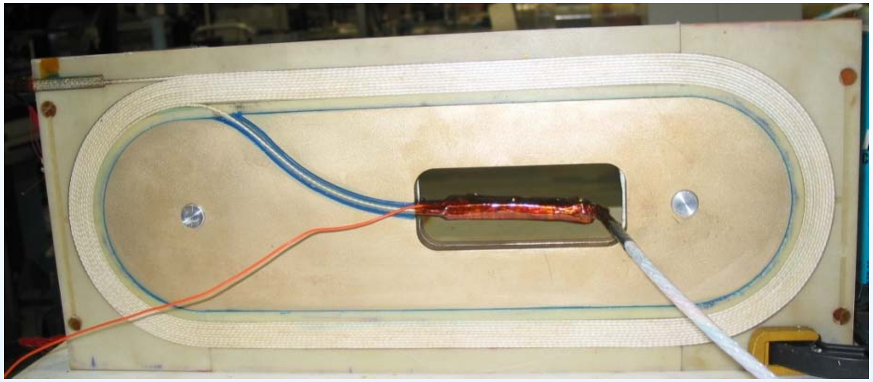




Record 4.3 kA in HTS coils

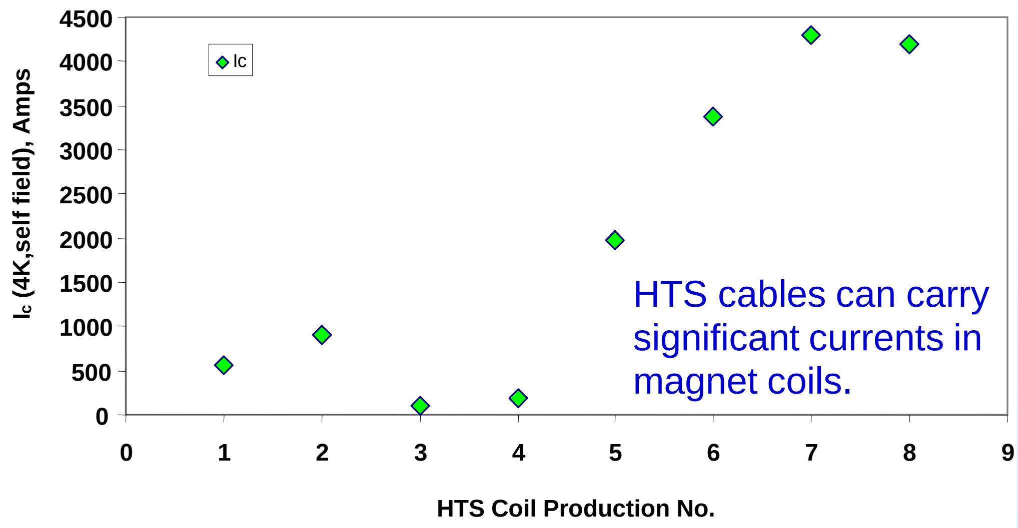
Record 10.4 T in R&W Nb_3Sn Magnet

HTS Common Coil with Bi2212 Cable



Earlier coils
<1 kA (~2001)

Later coils
4.3 kA (2003)



HTS cables can carry significant currents in magnet coils.

World Record:

- **Reached 4.3 kA ==>> the highest current HTS coils ever built.**
- **Program terminated for the lack of funding. Others are still trying.**

➢ **Our 2003 record still holds!**

Very High Field HTS Solenoids

- **The most demanding program yet**
- **High fields create large forces, large stored energy, etc., etc., etc.**
- **New conductor and limited budget makes it even more challenging**
- **Systematic, step by step approach**
- **Will test the limit of the conductor and of structure**

Two ambitious programs:

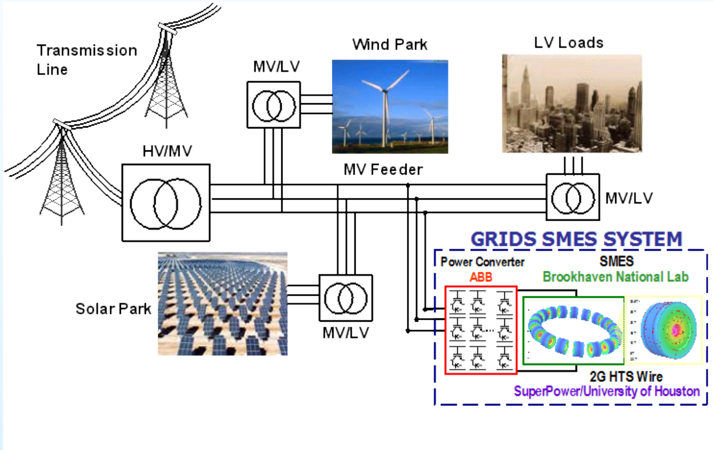
- **20-22 T HTS solenoid for cooling in muon colliders**
- **24-30 T HTS solenoid for magnetic energy storage**

Both would be the highest field HTS magnets ever built!

Superconducting Magnetic Energy Storage (SMES)

Magnetic field stores energy

- It's a "purpose" here not a "problem"



Overall Project Leader: V. Ramanan, ABB

- BNL PI: Qiang Li
- SMES Coil PI: Ramesh Gupta

BNL Departments:

CMPMSD: Condensed Material Physics & Material Science Dept.

SMD: Superconducting Magnet Division

ARPA-E to Power Superconducting Magnet Energy Storage Project

Lab Director Sam Aronson joined elected officials and representatives from DOE and several collaborating institutions for the August 31 announcement of a $4.25 million grant from the American Recovery and Reinvestment Act to fund superconducting magnet energy storage (SMES) research. The grant was awarded through DOE's Advanced Research Projects Agency-Energy (ARPA-E), and will be matched with $1 million from the collaborating institutions for a total of $5.25 million.

The Brookhaven team, headed by Principal Investigator Qiang Li and including Ramesh Gupta and Vyacheslav (Slowa) Solovyov, joined Aronson at the press event held August 31 at SuperPower, Inc. in Schenectady, NY. Also attending were ARPA-E Program Manager Mark Johnson, New York Congressman Paul Tonko, and Schenectady Mayor Brian Stratton.

The grant funds work on an advanced su-

Celebrating the announcement of an important new energy storage collaboration are (from left) BNL Director Sam Aronson, Congressman Paul Tonko, SuperPower General Manager Art Kazanjian, ARPA-E Program Manager Mark Johnson, ABB Inc. Global Project Manager V.R. Ramanan, and Allan Jacobson, director of the Texas Center of Superconductivity at the University of Houston.

wire. The fourth partner in the collaboration

Advanced Research Projects Agency – Energy (ARPA-E)

test the magnet system. BNL's multi-disciplinary team includes scientists the Superconducting Magnet Division and from the Advanced Energy Materials group in the Condensed Matter Physics & Materials Science Department. In addition, BNL, SuperPower, and the University of Houston, where SuperPower conducts its research and development, will develop a new-generation HTS

Developing affordable, large-scale energy storage systems would be a game-changing advance for the U.S. electrical grid. In particular, energy storage will be crucial in enabling the widespread use of two key renewable energy sources: wind and solar power. SMES systems use magnetic fields in superconducting coils to store energy with...

See ARPA-E on p.2

Roger Stoutenburgh

Superconducting magnetic energy storage systems will be built using the second generation high-temperature superconducting wire used in the R&D magnet in the background. The team members are: (from left) Principal Investigator Qiang Li, Condensed Matter Physics & Materials Science Department (CMPMSD) Peter Wanderer, Superconducting Magnet Division (SMD), Vyacheslav (Slowa) Solovyov, CMPMSD, and Ramesh Gupta, Principal Investigator for SMD.

Superconducting Magnetic Energy Storage (SMES) Options with HTS

High T (~65 K) Option: Saves on cryogenics (Field ~2.5 T)

High B (~25 T) Option: Saves on Conductor (Temperature ~4 K)

Previous attempts:

LTS: up to 5 T

HTS: few Tesla; high temp. to save on cryo

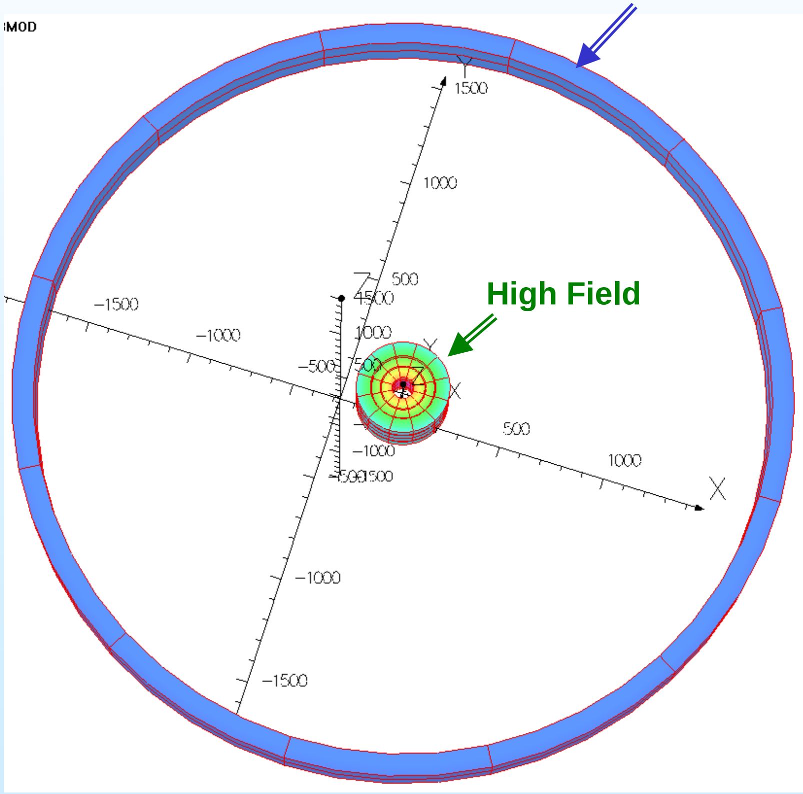
Our analysis on HTS option:

Conductor cost dominates the cryogenic cost by an order of magnitude

An aggressive option:

- Go for ultra high fields 24 – 30 T
  - ✓ Only possible with HTS

High Temperature



High Field

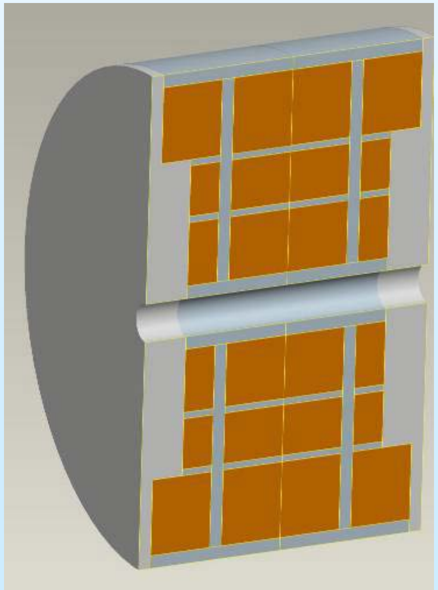
Superconducting Magnetic Energy Storage (SMES) Proposal

- HTS with high field and high energy density (E α B^2) was proposed to reduce the system cost
- Need to overcome many technical challenges (including those associated with 24 – 30 T)

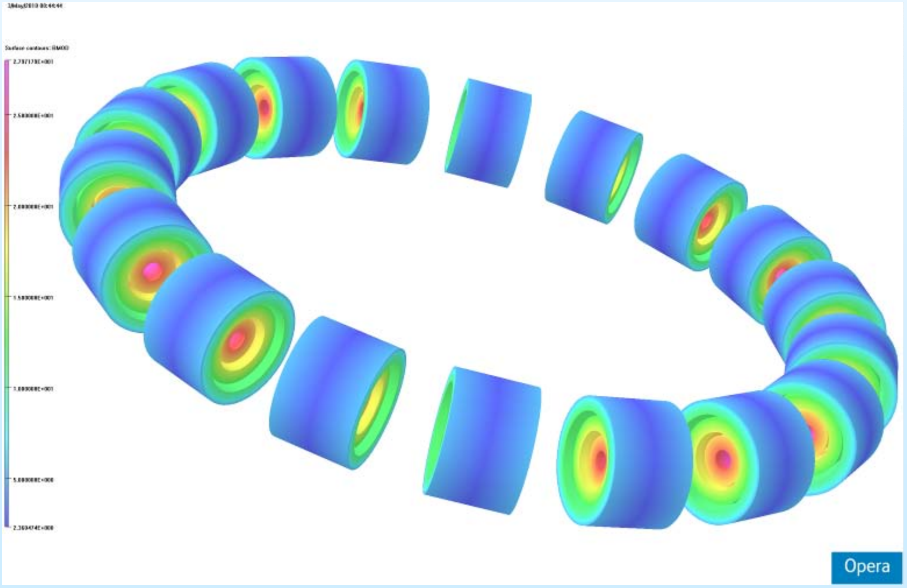
arpa-e specifically asked for “high risk high reward” proposals!

➢ **37 were selected out of ~3,700 proposals submitted !!!**

this one was the third largest in this announcement with 5.25M$



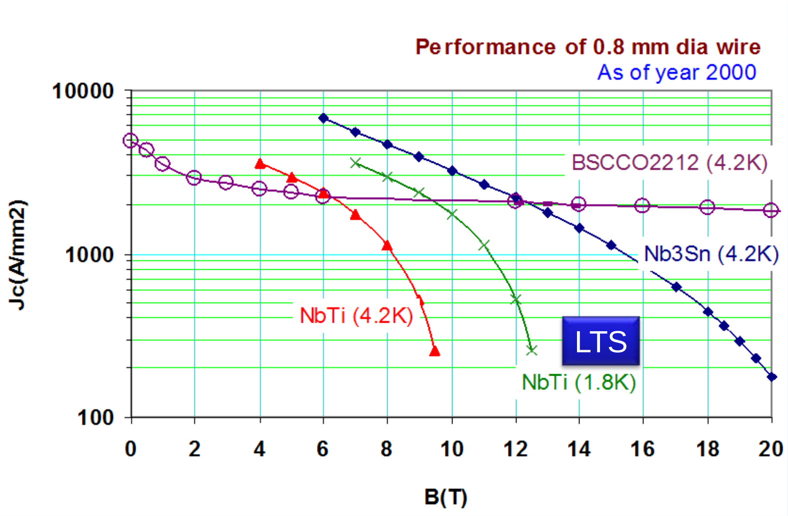
Basic structure of a single Unit



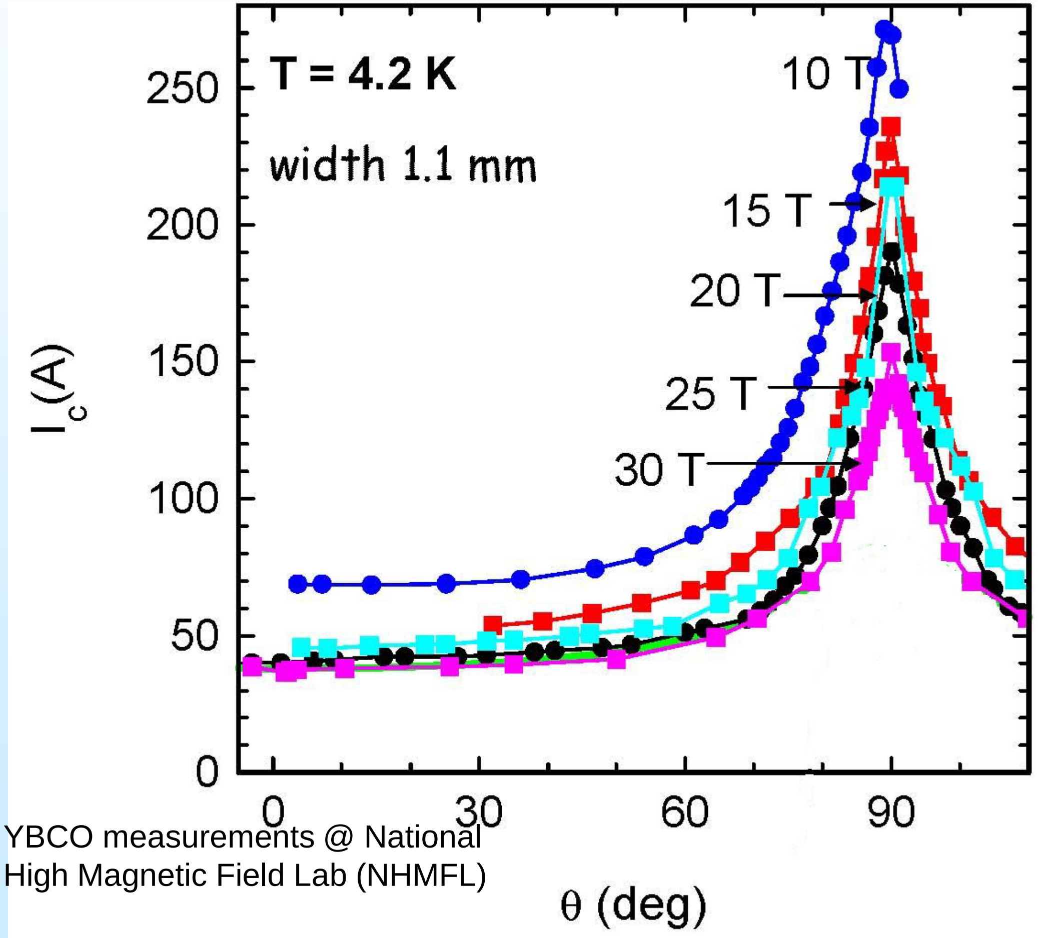
Number of units in a SMES system

Anisotropic Property of HTS Tape

Round wire: Isotropic



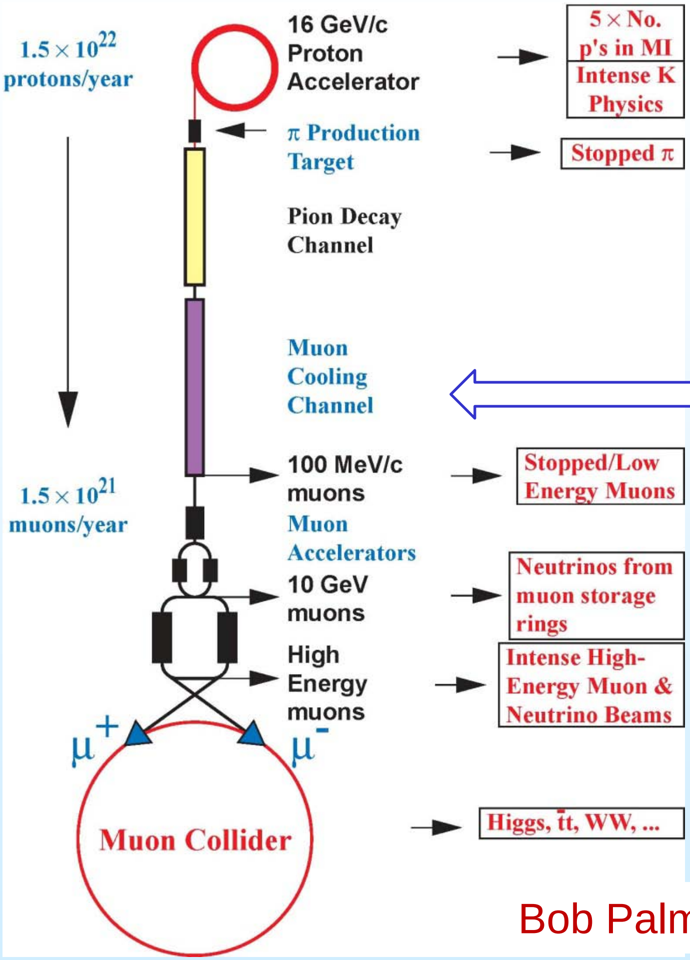
HTS tape: angular dependence



YBCO measurements @ National High Magnetic Field Lab (NHMFL)

However, energy storage solenoid will be made with HTS tapes. Tapes have anisotropic properties.

High Field Solenoid for Proposed Muon Collider



Bob Palmer

Muon collider:

- An exciting and challenging machine

One key challenge:

- High field (~40 T) solenoid for cooling
  - ➢ Resistive insert would use **hundreds of MW**

✓ **Crying need for High field HTS solenoid**

Next: Small Business Innovative Research (SBIR) experimental program with Particle Beam Lasers (PBL)

High Field Muon Collider Solenoid

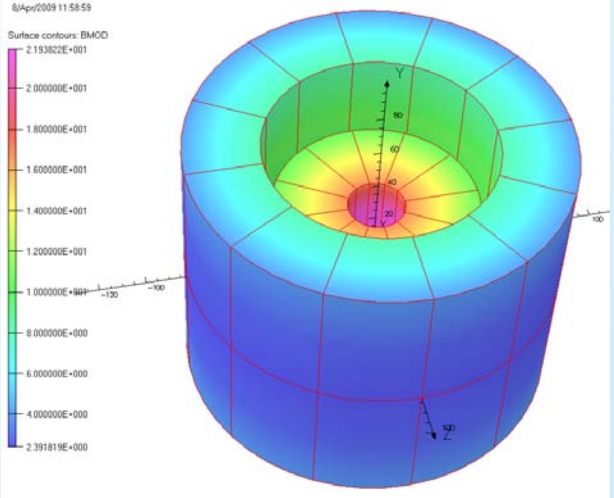
Overall strategy:

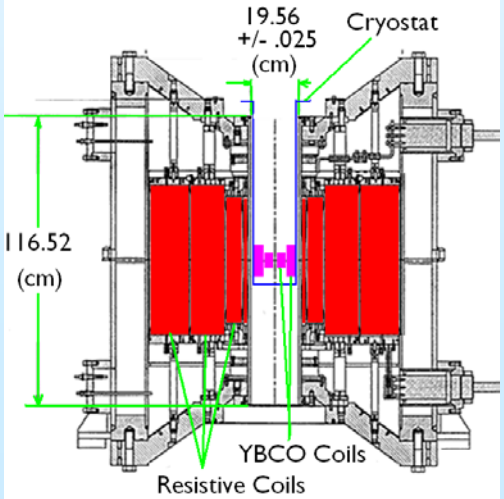
- A series of SBIR proposals with PBL, each attractive on its own.
  1. ~10 T outsert HTS Solenoid
  2. ~12 T insert HTS Solenoid
  3. Combine two for 20-22 T HTS solenoid (would be a record)
  4. Test at High Field Magnet Lab in ~20 T resistive solenoid to approach 40 T
  5. Outermost LTS solenoid to make a ~30 T superconducting solenoid (record)
- Segmentation needed, anyway, to reduce build-up of large stresses at high fields

High Field HTS R&D Solenoid for Muon Collider

R. Gupta, M. Anerella, G. Ganetis, A. Ghosh, H. Kirk, R. Palmer, S. Plate, W. Sampson, Y. Shiroyanagi, P. Wanderer
Brookhaven National Laboratory

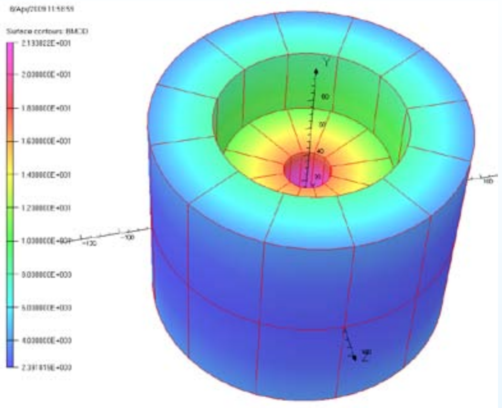
B. Brandt, D. Cline, A. Garren, J. Kolonko, R. Scanlan, R. Weggel
Particle Beam Lasers





Status of the BNL/PBL High Field HTS Solenoid

- All 24+5 coils (each using 100 m conductor) for outsert solenoid (100 mm aperture) have been built and individually tested at 77 K.
- Coils are being wound for insert solenoid.
- Advance magnet protection system and related R&D is under way.
- Should test 10 T in a few months and 20+ T by the end of this year.



Potential LDRD: Outer NbTi solenoid (similar to e-lens) to create the highest field superconducting magnet ever

Summary of HTS Magnet R&D at BNL

- **BNL has made devices with all varieties of HTS**
  - **BSCCO2212, BSCCO2223, YBCO, MgB_2**
- **Major HTS R&D program at BNL**

  Amount of wire procured (normalized to common 4 mm tape):
  - **~20 km so far; ~35 km in next two years**
- **Successfully designed, built and tested a large number of HTS coils and magnets:**
  - **Number of HTS coils built: ~100**
  - **Number of magnet structures built and tested: ~10**
- **High current cable and conductor test facility**
- **Material research (last Brookhaven lecture by Qiang Li)**
- **Also promising: wiggler and other magnets for photon source**

Papers on HTS Magnet Program at 2011 Particle Accelerator Conference

Wide range of HTS R&D activities at BNL to be presented:

1. Engineering Design of HTS Quadrupole for FRIB – Cozzolino, et al.
2. Design, Construction and test of Cryogen-free HTS Coil Structure – Hocker, et al.
3. Influence of Proton Irradiation on Second Generation HTS in Presence of Magnetic Field – Shiroyanagi, et al.
4. Measurements of the Effect of Axial Stress on YBCO Coils – Sampson, et al.
5. Open Midplane Dipole for Muon Collider – Weggel, et al.
6. Design Construction and Test Results of HTS Solenoid for ERL – Gupta, et al.
7. HTS Magnets for Accelerator and Other Applications – Gupta
8. Quench Protection Studies in HTS with Small Coils – Joshi, et al.

Cryogen-free HTS Magnets for Future (non-accelerator applications)

- High speed levitated train
  - ➢ Highest speed manned train (581 km/h)
- Superconducting Magnetic Energy Storage
  - ➢ High temperatures or high fields
- Propulsion Motors
  - ➢ Light weight (defense applications)
- Cryogen-free MRI and beam lines for cancer therapy
  - ➢ A potential area for BNL contribution, a multi-disciplinary lab

Japan Railways

Some of above were recently discussed at

Acknowledgement

Magnet division key support staff: D. Votruba, R. Felter, D. McChesney and R. Prwivo

Magnet division technicians (including): R. Ceruti, J. D'Ambra, J. Cintorino, S. Dimaiuta, J. Gormley, D. Ince, G. Jochen, P. Ribaudo, T. Levine, R. Meier, W. McKeon, A. Sauerwald, E. Sperry, D. Sullivan, F. Teich, T. Van Winckel and E. Weigand

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BNL collaborators from other divisions/departments: I. Ben-Zvi, G. Greene, H. Kirk, J. Kewisch, Q. Li, R. Palmer and S. Solovyov

Michigan State University: R. Ronningen and A. Zeller

Particle Beam Lasers: D. Cline, A. Garren, J. Kolonko, R. Scanlan and R. Weggel

Advanced Energy System: M. Cole and D. Holmes

HTS Wire Manufacturers: ASC and SuperPower

SUMMARY

HTS magnets are poised to revolutionize the field the same way the conventional superconducting magnets did a few decades ago.

- **Cryogen (helium) free HTS magnets**
  - ➢ **Energy efficiency**
  - ➢ **Remote areas**
- **Very high field superconducting magnets (only possible with HTS)**
  - ➢ **Major upgrade in existing facilities (e.g., LHC)**
  - ➢ **New facilities (e.g., muon colliders)**
- **Other fields (Superconducting Magnetic Energy Storage, medical)**

BNL leads the way with

- ➢ **A wide range of HTS magnet R&D programs**
- ➢ **Many positive test results in magnets using large amount of HTS**

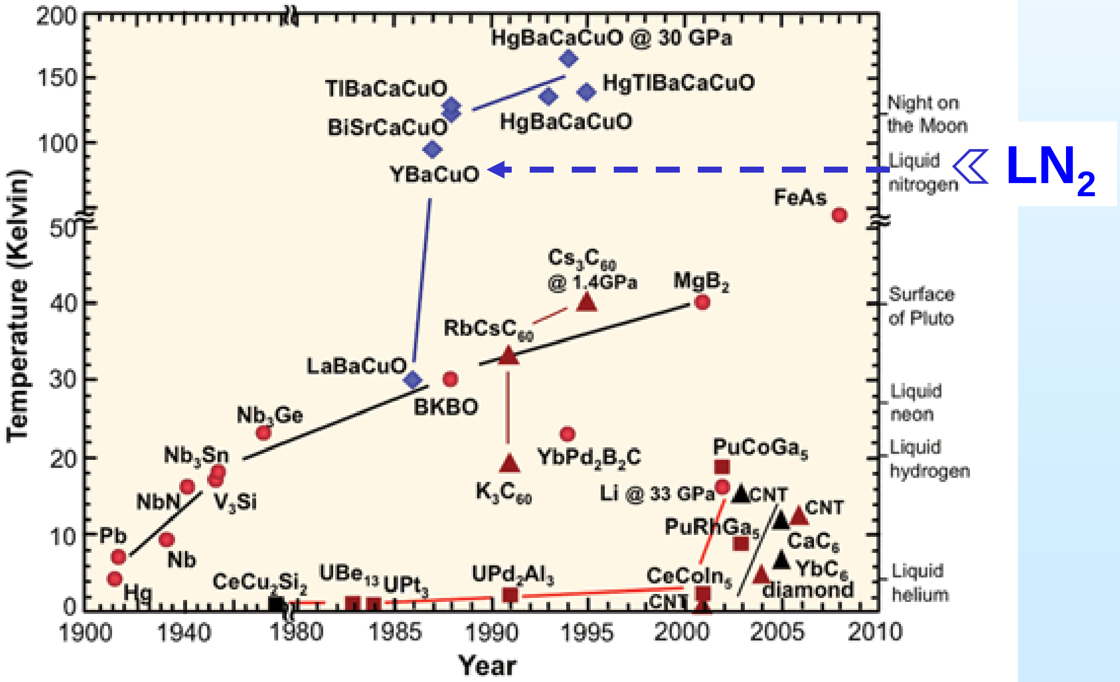
Backup Slides

Race for Higher Critical Temperature

Current status and future perspective

1) The mechanism of high temperature superconductivity: <u>not known</u> (a lot of theories)

2) A lot of superconducting materials, including iron-based ones (2008)



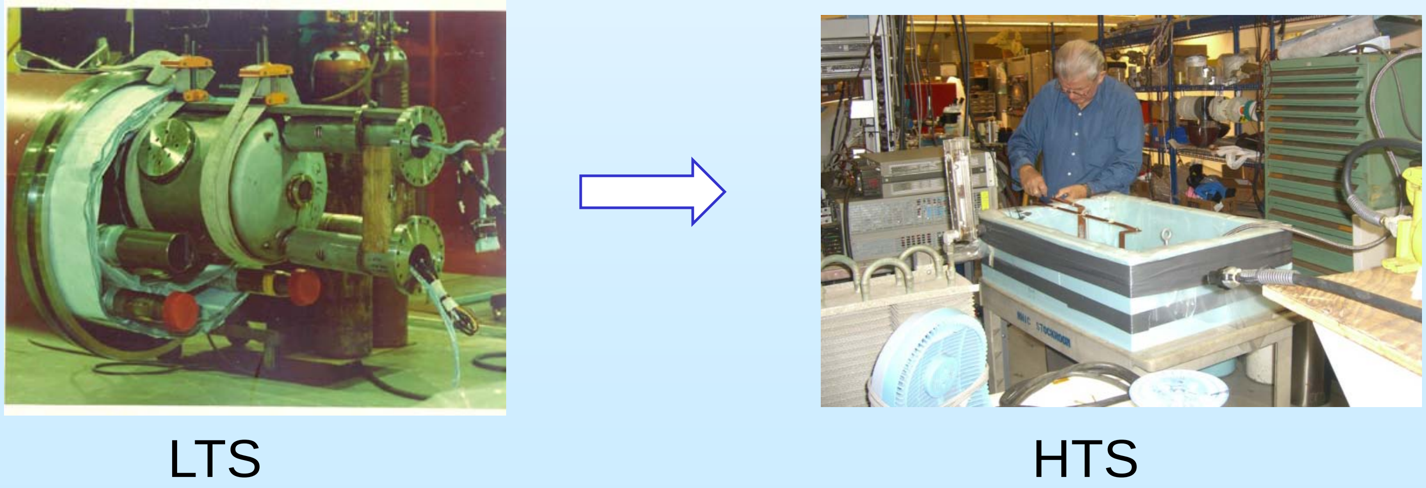
Qiang Li, January 2011
465th Brookhaven Lecture

Practical Advantage of HTS Magnets
Simplified and Robust Cryogenic Operation

- In conventional superconducting magnets (such as those for RHIC), the operating temperature must be controlled to within a few tenths of degree.

- In HTS magnets, this control can be relaxed by over an order of magnitude. HTS can tolerate a few degrees without significant loss in critical current.

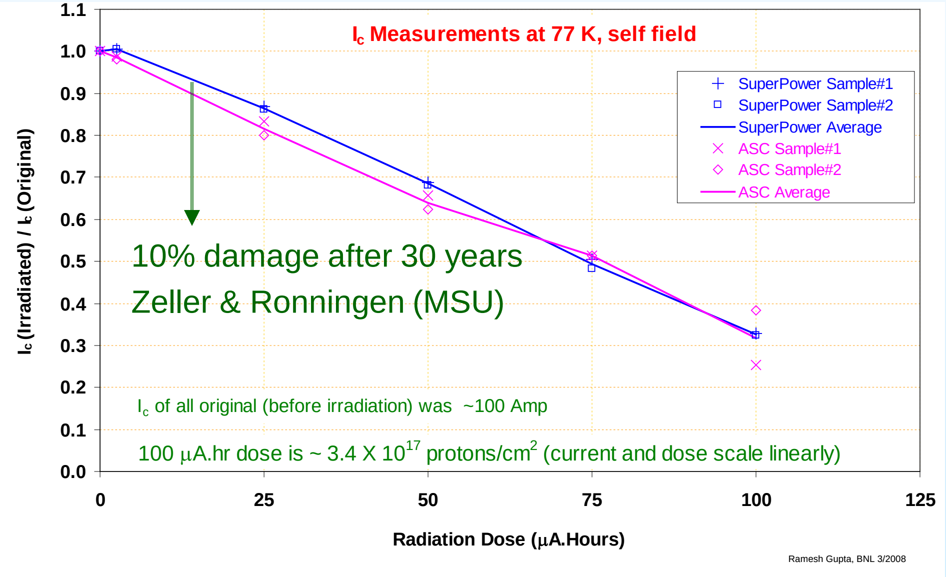
- **This makes cryogenic system very simple, inexpensive and robust.**



Radiation Damage Studies
2G HTS from SuperPower and ASC

- Radiation damage studies in self-field at 77 K
- Radiation damage studies in applied field at 77 K

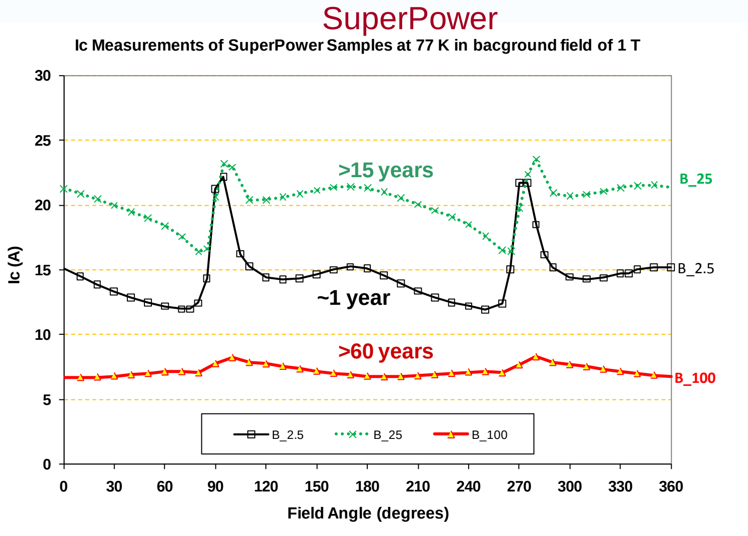
✓ HTS acceptable for FRIB radiation (Zeller, MSU)

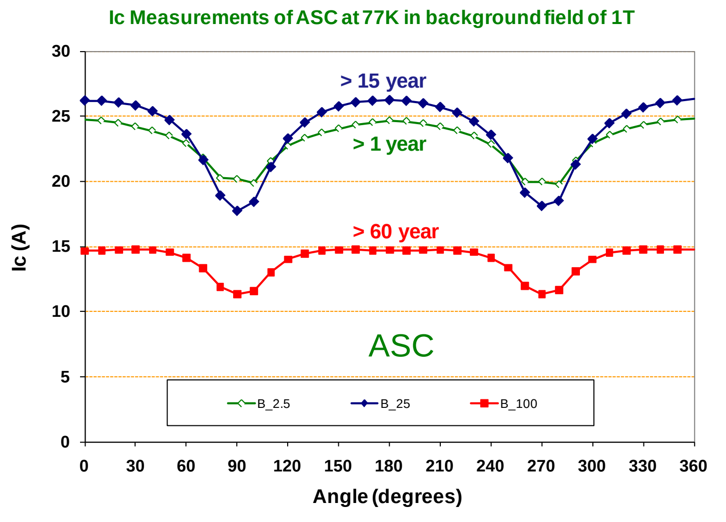


10% damage after 30 years
Zeller & Ronningen (MSU)

I$_c$ of all original (before irradiation) was ~100 Amp

100 μA.hr dose is ~ 3.4 X 10^{17} protons/cm^2 (current and dose scale linearly)





Next step: Measurements at 40-50 K

Challenges with HTS Magnets (and our strategy to overcome them)

High Cost Conductor

- HTS is an order of magnitude more expensive than conventional superconductor
  - Cost decreasing but likely to remain higher than conventional superconductors.
  - Simpler cryogenic and cryogen free operation must offset the higher conductor cost.

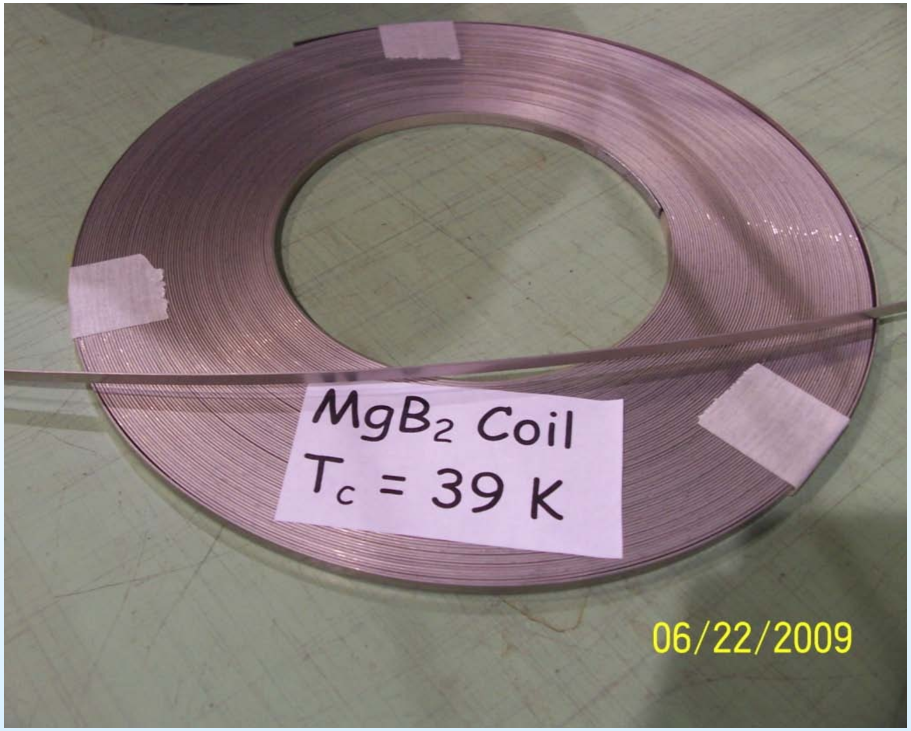
Magnet Protection

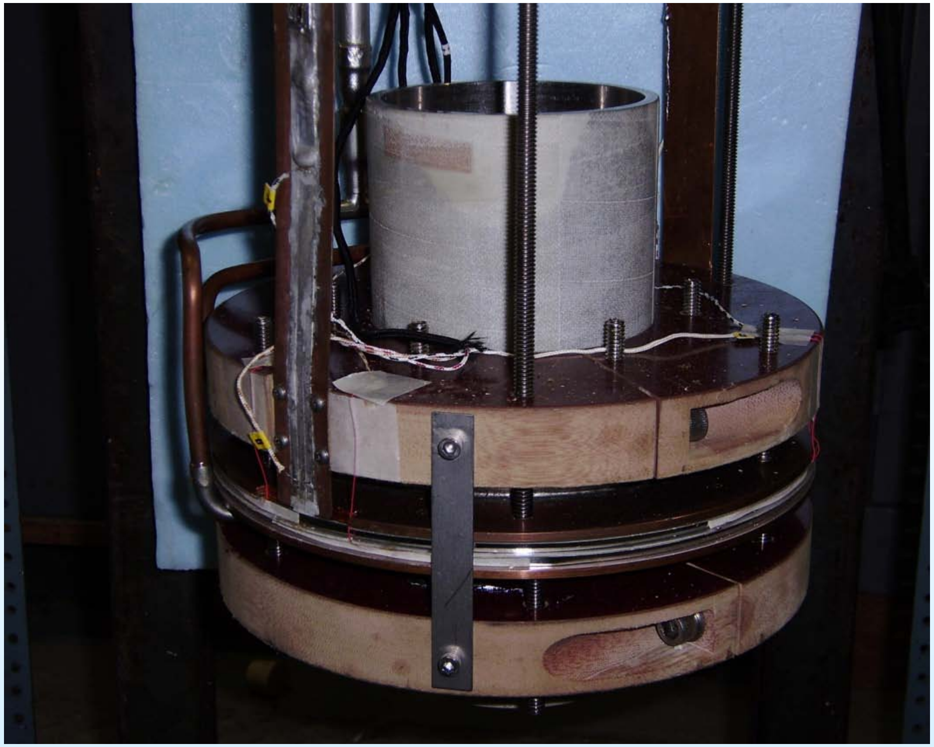
- Magnets must be protected when superconductor turn normal (resistive). Slow propagation of signal makes HTS magnets more challenging
  - Significant ongoing R&D at BNL and elsewhere.
  - Large temperature margin in HTS helps in many cases.

Challenging Conductor

- HTS is brittle
  - Design “conductor friendly” magnets.

MgB_2 Solenoid made with Conductor from COLUMBUS SUPERCONDUCTORS SpA





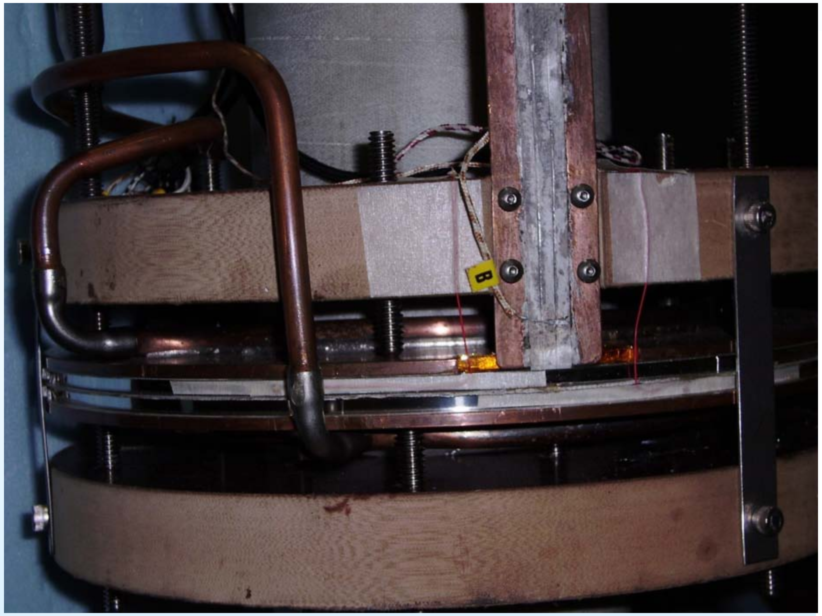
Coil i.d. = 100 mm

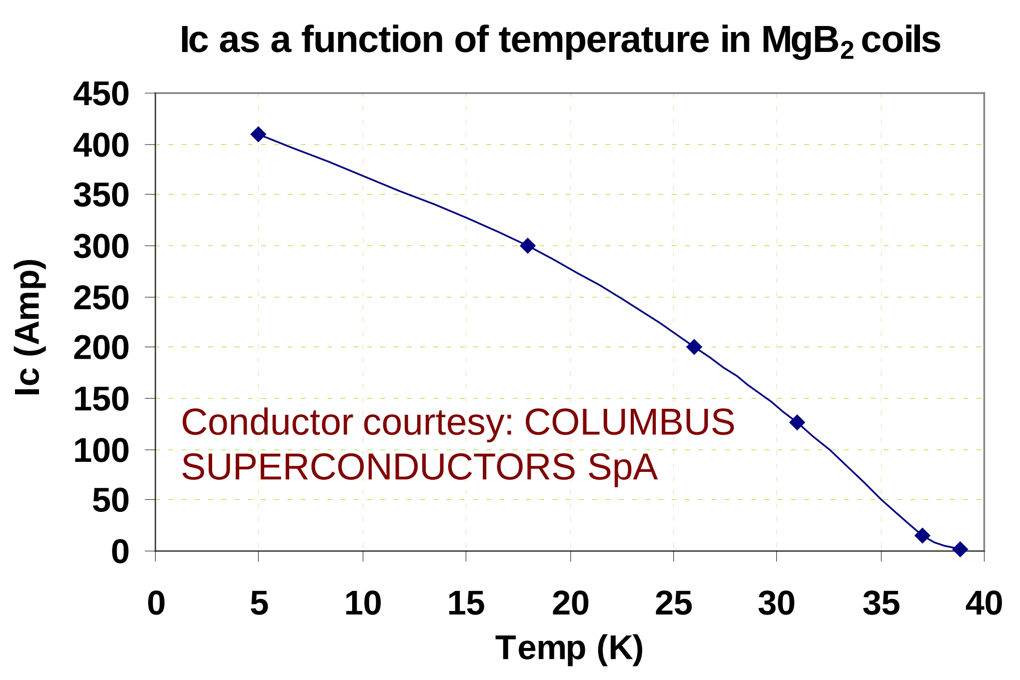
Coil o.d. = 200 mm

# of Turns = 80

MgB_2 Solenoid with a double pancake coil

MgB_2 Solenoid
Critical Current as a Function of Temperature





- **Top and bottom plates are conduction cooled with helium gas**
- **Helium flow is adjusted to vary the temperature.**

~1.3 T peak field

100 A => ~0.31 T