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Advances in HTS Magnets for Accelerators and Other Applications

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105th Topical Symposium on Superconductivity and Applications

SUNY at Oneonta, October 7th, 2011





- Conventional Superconducting Magnets
 - The impact as we see today
- High Temperature Superconducting (HTS) Magnets
 - How they can revolutionize various applications
- Advances in HTS Magnets for Practical Applications
 - Discussion limited to HTS R&D at BNL and mostly related to accelerator magnets. However, it has relevance everywhere
- Summary

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Advances in HTS Magnets ...



Superconductors

- Discovered 100 years ago
- Essentially zero electrical resistance



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*)



Superconductors



Superconducting Magnets How They Revolutionized Accelerators

- Without "energy saving" superconducting magnets, the electric power bill of major accelerators would have been so large that they would not have been built
- Without "high gradient" superconducting magnets, the collision rate would have been so small that many physics discovery would not have been possible
- Without "powerful" superconducting magnets, the size of Relativistic Heavy Ion Collider would have been so large that it may hardly have fit inside the BNL campus



Relativistic Heavy Ion Collider at BNL

The same is true for other modern accelerators such as Tevatron at Fermilab and Large Hadron Collider at CERN

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Strong Power Forced to Remain in Captive Volume

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Superconducting

Power kept



in captive volume

Superconductor in magnets must remain in the captive volume of:

• Field

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- Temperature
- Current (density)

J (Amps / cm²) CURRENT DENSITY HTS (1986) NbTi NbSn 100 200 320 1250 Kelvin MAGNETIC Michael Tinkham, Introduction to Superconductivity (New York: McGraw-Hill, 1975)

Phase Diagram

Conventional superconductors (NbTi and Nb₃Sn) generally operate at 4 K and applications rely on liquid helium for cooling

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

- No, we are not talking about oil ...
- > It is Helium !!!



NYSE

- Essential for cooling practically all
 - conventional superconducting magnets operating at ~4 K
- Non renewable, escapes to atmosphere
- According to some estimates, the world supply of Helium could be significantly depleted a few decades

• Price has increased ~3 times in last five years for many customers

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 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 Nb₃Sn: ~ 18 K HTS BSCCO2223: ~ 110 K BSCCO2212: ~ 85 K YBCO: ~ 90 K

MgB₂: ~39 K

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Helium-free Cooling (with liquid nitrogen)

HTS magnets can operate with liquid nitrogen at ~77 K (can reach even lower temperature by pumping)

Liquid Nitrogen (LN2) is supplied in all quantities

 LN2 is ~100 times cheaper than liquid helium

 \geq @9 cents/liter, cheaper than milk or oil







Nitrogen is renewable Available in abundance (~78%)

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No helium refill needed

Good for remote areas

Helium-free Cooling (with cryo-cooler)

CRYOMECH

AL325 Cryorefrigerator Capacity Curve



Cooling Power as a function of Temperature



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Cryogen-free HTS Magnets for Future

- 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



Japan Railways

- > A potential area for BNL contribution, a multi-disciplinary lab
- And Magnets for Particle Accelerators

Several possibilities discussed in this presentation

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High Temperature Superconductors NKH*r*ven NATIONAL LABORATORY are also High Field Superconductors Superconducting



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Large Current Carrying Capacity of HTS at High Fields at 4 K



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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 !!

> So why HTS magnets are still not a major player?

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- First practical challenge the "fear of unknown":
 - There is a natural hesitation against using any "new technology"
 - Similar to what was in early days of conventional LTS magnets
- Strategy to overcome the "New Technology Syndrome":
 Demonstrate it
 - \checkmark (a) first in smaller applications where it is safer to work
 - \checkmark and/or (b) applications where no other solution is possible
 - Prove reliable operation in as many R&D magnets as possible

> Share the excitement with community about the potential benefits

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A few examples in the slides to follow

• Not intended as an comprehensive overview of HTS magnets around the world but limited to a few handy examples at BNL

• The intend is to show of a variety of unique possibilities that HTS offer for accelerator magnets

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Low Field HTS Solenoid for Superconducting Electron Gun



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

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BROOKHAVEN NATIONAL LABORATORY Superconducting Magnet Division HTS Solenoid with Superconducting Cavity for the Energy Recovery Linac



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

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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 cryocooled HTS coils by HTS-110



Cryo-cooled HTS coils with technology developed at BNL

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BROOKHAVEN NATIONAL LABORATOR Superconducting Magnet Division HTS Magnet Development Program for Facility for Rare Isotope Beams (FRIB)



Will create rare isotopes in quantities not available anywhereSite: Michigan State University

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Technical Advantage of HTS Magnets

Superconducting Magnet Division

NATIONAL LABORATORY



High power beam (~400 kW) hits the target to create intense rare isotope beams

- Magnets are exposed to very high <u>radiation</u> and <u>heat</u> 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

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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

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Performance of a Large Number of HTS Coils with LN₂

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 !

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HTS Magnet Test Results (operation over a large temperature range)



Benefits of HTS over conventional LTS demonstrated:

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

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2nd Generation HTS Program

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

- Higher field (50% more) and operating temperature (~50 K instead of ~30 K
- Second generation HTS available from two US vendors
 - ✓ SuperPower
 - ✓ American Superconductor



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Very High Field Magnets (made possible only with HTS)

PROGRESS TOWARD CREATING THE MOST POWERFUL SUPERCONDUCTING MAGNET, EVER!

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High Field Muon Collider Solenoid

A National Lab and Private Industry (PBL) Collaboration:

- 1. ~10 T outsert HTS Solenoid
- 2. ~12 T insert HTS Solenoid
 - Combine two for 20-22 T HTS solenoid (would be a record)
 - Test at Florida Lab in ~20 T resistive solenoid to approach 40 T
- 3. Outer LTS coil to make a ~35 T superconducting solenoid (would be a record)
- Segmentation needed, anyway, to reduce build-up of large stresses at high fields



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Status of the BNL/PBL High Field HTS Solenoid

- All 29 coils (each using 100 m SuperPower HTS) 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.



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High Field HTS Coil Test in the Background Field at NHMFL



Four HTS coils built for inner solenoid were used for insert coil test at NHMFL



4 T @4K self field, and 23 T in 20 T background field

First demonstration of technology for 20-22 T HTS solenoid, as targeted in SBIR.

Current in HTS Coils (A)

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High Field Dipoles for Energy Upgrade NATIONAL LABORATORY of Existing Accelerators



LHC collider dipole concept rendering from CERN

25 T HTS magnet will increase

- LHC (Europe) energy > 3 times
- **RHIC (NY) energy > 7 times**

Dream => Reality:

KH/KVEN

Superconducting **Magnet Division**

> We have successfully completed a series of HTS magnet R&D programs for accelerators others are being built and proposed

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Magnet Structures for HTS Coils at BNL









Record 10.4 T in R&W Nb₃Sn Magnet

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HTS Racetrack Coil with 2212 Cable



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• Reached 4.3 kA ==>> the highest current HTS coils ever built.

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Superconducting Magnetic Energy Storage (SMES) at GRID Level

- There is significant interest in large energy storage system at GRID level capable of storing several GJ of energy.
- Electromagnetic coils can be charged to store energy. However, coils made with copper wire suffer significant resistive losses and hence are not suitable for long term energy storage.
- Superconducting coils with zero theoretical resistance offers an interesting possibility as Superconducting Magnetic Energy Storage System (SMES) for long term energy storage.
- SMES with conventional superconductors have been built earlier but have found only limited use.
- HTS offers new possibilities which could revolutionize the field.



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 with arpa-e funding:

- ➤ Ultra high fields: 24 30 T
 - ✓ Only possible with HTS



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Superconducting Magnetic Energy Storage (SMES) A Collaboration between A National Lab & Industries

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Team members and their roles:

ABB: Power electronics and system integration BNL: Magnet design, construction and joints

SP: 2G HTS manufacture and cost reduction

UH: Wire manufacturing process definition



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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 Vvacheslav (Slowa) Solovvov, 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.



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.

vire. The fourth nartner in the

Advanced Research Projects Agency – Energy (ARPA-E)

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

test the magnet system. BNL's multi-disciplinary 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 Superconducting magnetic energy

storage systems will be built using

the second generation high-tem-

perature superconducting wire used in the R&D magnet in the

background. The team members

are: (from left) Principal Investi-

gator Qiang Li, Condensed Matter Physics & Materials Science

Department (CMPMSD) Peter

Wanderer, Superconducting Mag-

net Division (SMD), Vyacheslav (Slowa) Solovyov, CMPMSD, and

Ramesh Gupta, Principal Investi-

gator for SMD.



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SMES R&D Test Coils

Superconducting Magnet Division









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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 accelerators and other facilities
 - New facilities and devices
- A large area of applications:

> Accelerator, medical, energy storage, national defense, etc.

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