HTS Wire for Ultra-High Field Superconductor Magnets

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A Breakthrough Opportunity in All-SC Ultra-High-Field Magnet Systems

amsc

- Highest all-LTS-superconductor magnet: Bruker **23.5 T** (1 GHz) NMR magnet
  - Near asymptotic limit for low temperature superconductors (NbTi/Nb_3Sn)
- HTS materials like YBCO have enormous (~**100 T**) upper critical field in low-T limit
  - Opens up a potentially huge new range of fields for science and NMR, using all-superconductor magnets
- HTS wires are now commercially available, enabling such magnet systems

All-SC magnet systems from 23.5 up to 50 T?

Towards a 50 T All-Superconductor DC Magnet System

- Exceed present highest DC field magnet: the 45 T hybrid at the National High Magnetic Field Lab (NHMFL)
- Reduce operational cost (typical Bitter magnets cost $2000/hr. to run, or, for a year of continuous running $17.5 M!
  - All-superconducting magnets would eliminate this dominating cost, expanding use dramatically
- Avoid noise from forced water cooling of Bitter magnets
- Enable revolutionary new science
  - Far more sensitive physics experiments probing quantum oscillations, decoherence, quantum computation, etc.
  - Far higher resolution in NMR for bioscience

An impossible dream or credible opportunity?

Could 50 T All-SC Magnets be Possible?

- Hoop stress σ_h = JxBxr
- Assume σ_h = 500 MPa
- Extrapolation to 50 T gives 4 cm bore, requires ~500 A/mm^2 under 50 T axial field

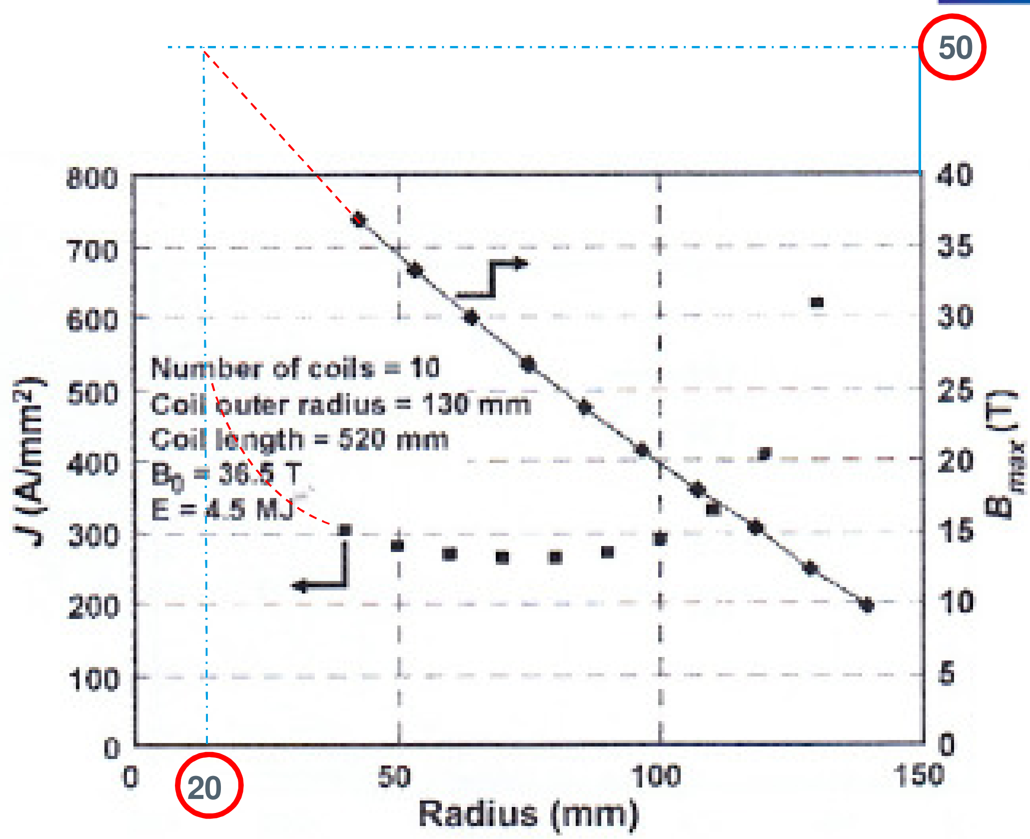


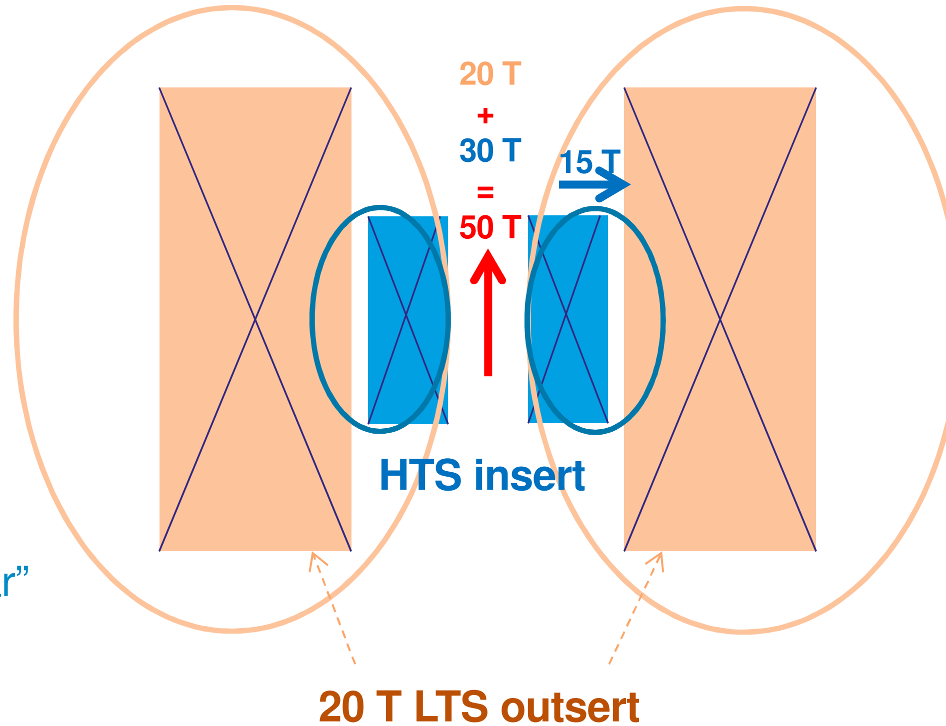
Fig. 3. A calculation example of the current densities and peak field in the case of σ_h = 500 MPa.

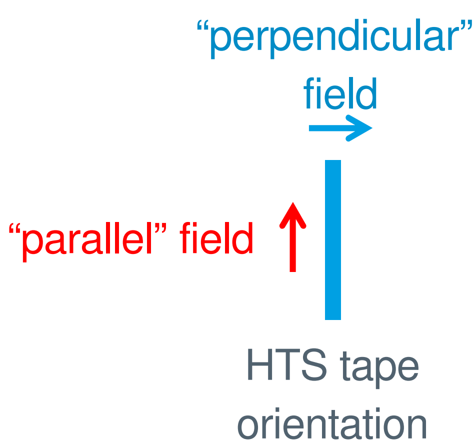
Otsuka & Kiyoshi, High Field Magnet Design Under Constant Hoop Stress, IEEE TAS, 2008

Could 50 T All-SC Magnets be Possible?

- HTS wires tape-shaped, with anisotropic field-dependence

- Possible design will have
  - 50 T axial field parallel to tape at inner bore,
  - 15 T field perpendicular to tape at HTS coil ends





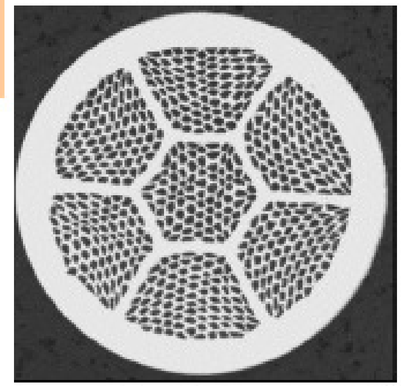
The HTS conductor choices

Bi-2223 multifilament tapes

Bi-2223 tapes exhaustively studied for power applications
30-77K: Now mature – lower Je than 2212 and YBCO

AMSC

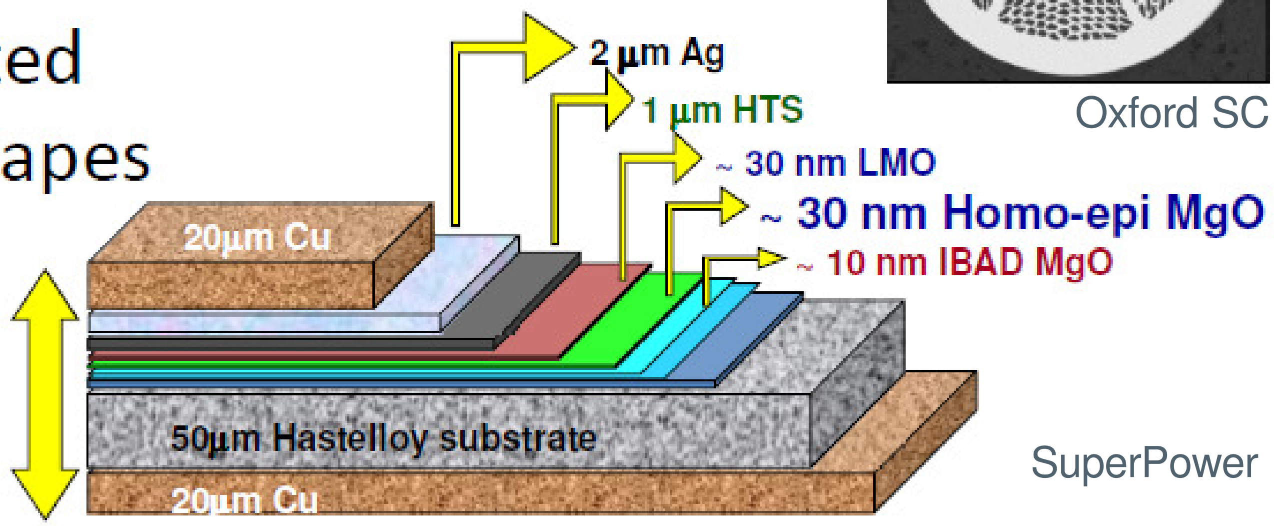
Bi-2212 round wire ~ 1mm dia.



Oxford SC

- REBCO coated conductor tapes

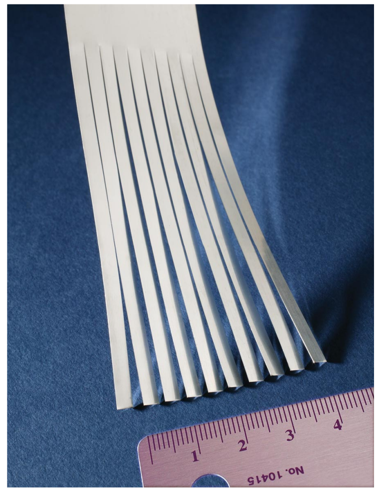
4-12 mm wide by ~ 0.1 mm thick

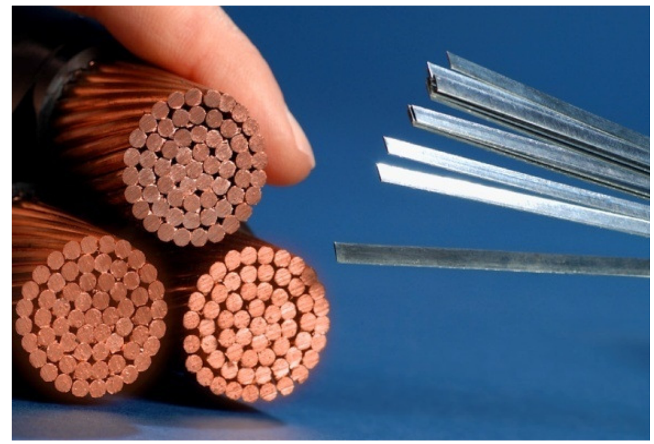


SuperPower

Example: AMSC Amperium™ 2G Wire

- Processed wide, then slit to desired width
- Laminated with copper, stainless… for strength, electrical stabilization





Cu, HTS 1000 A equivalents

Copper laminates

HTS – 1 µm YBCO layer

200 µm

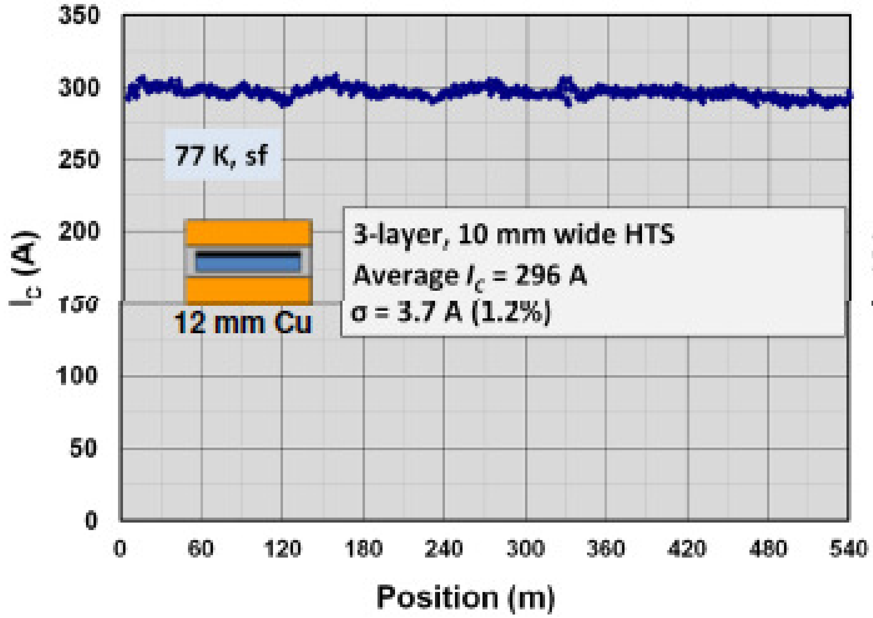
Substrate – Ni-5W

AMSC "Amperium™" wire cross-section

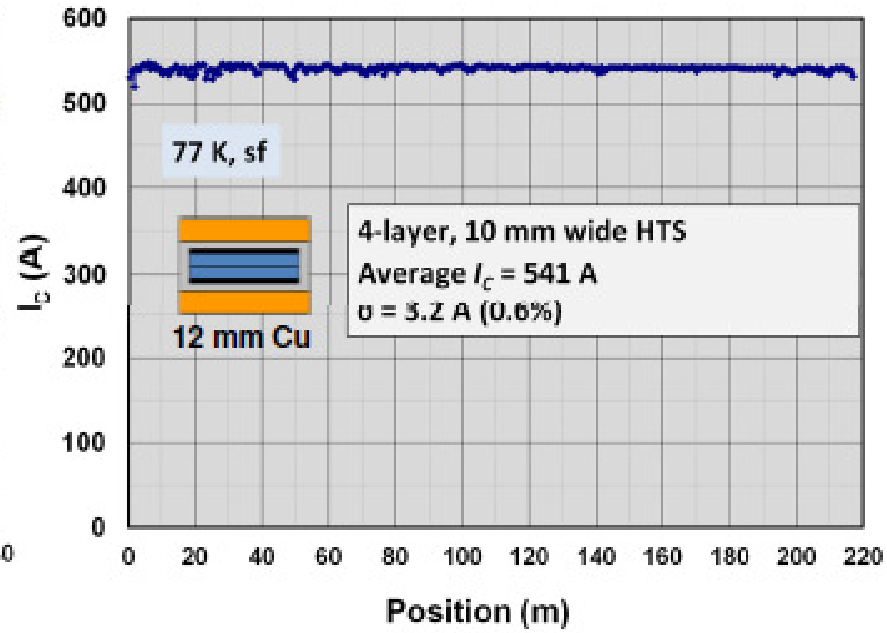
Well-established process producing 100's km wire yearly

2G HTS Wire Available in Long Length with High Uniformity

Amperium™ Copper Laminated 12
~300 A/cm-width



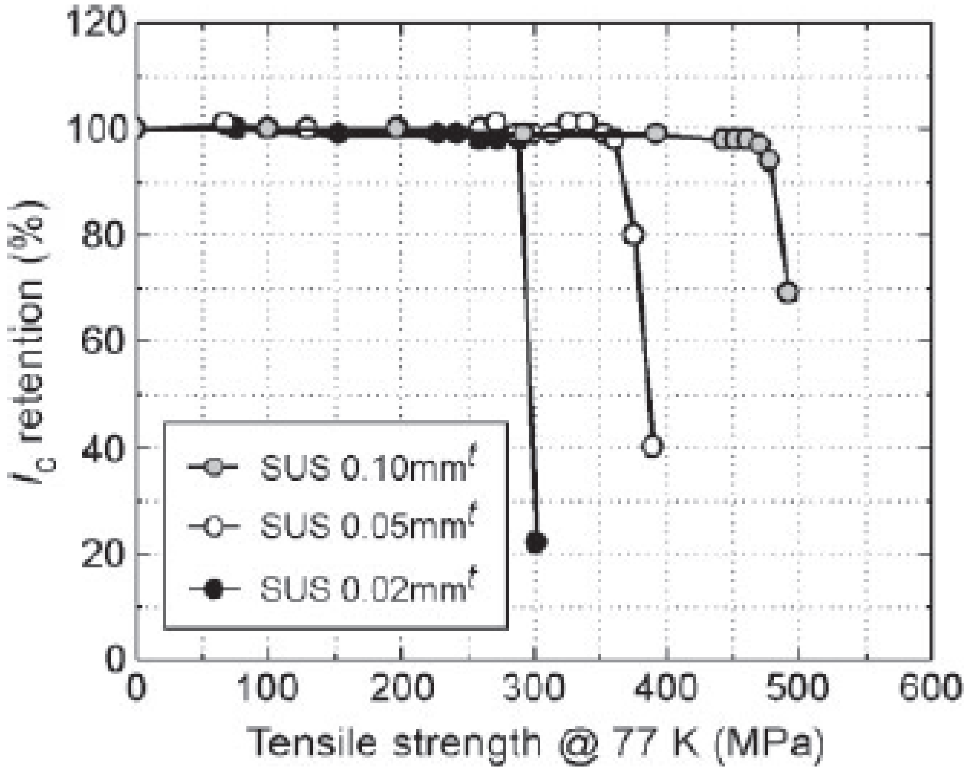
Beta Wire – Double Insert
~550 A/cm-width effective



High uniformity essential for stable operation

Can HTS Wire Meet Hoop Stress Requirement for a 50 T Magnet? YES!

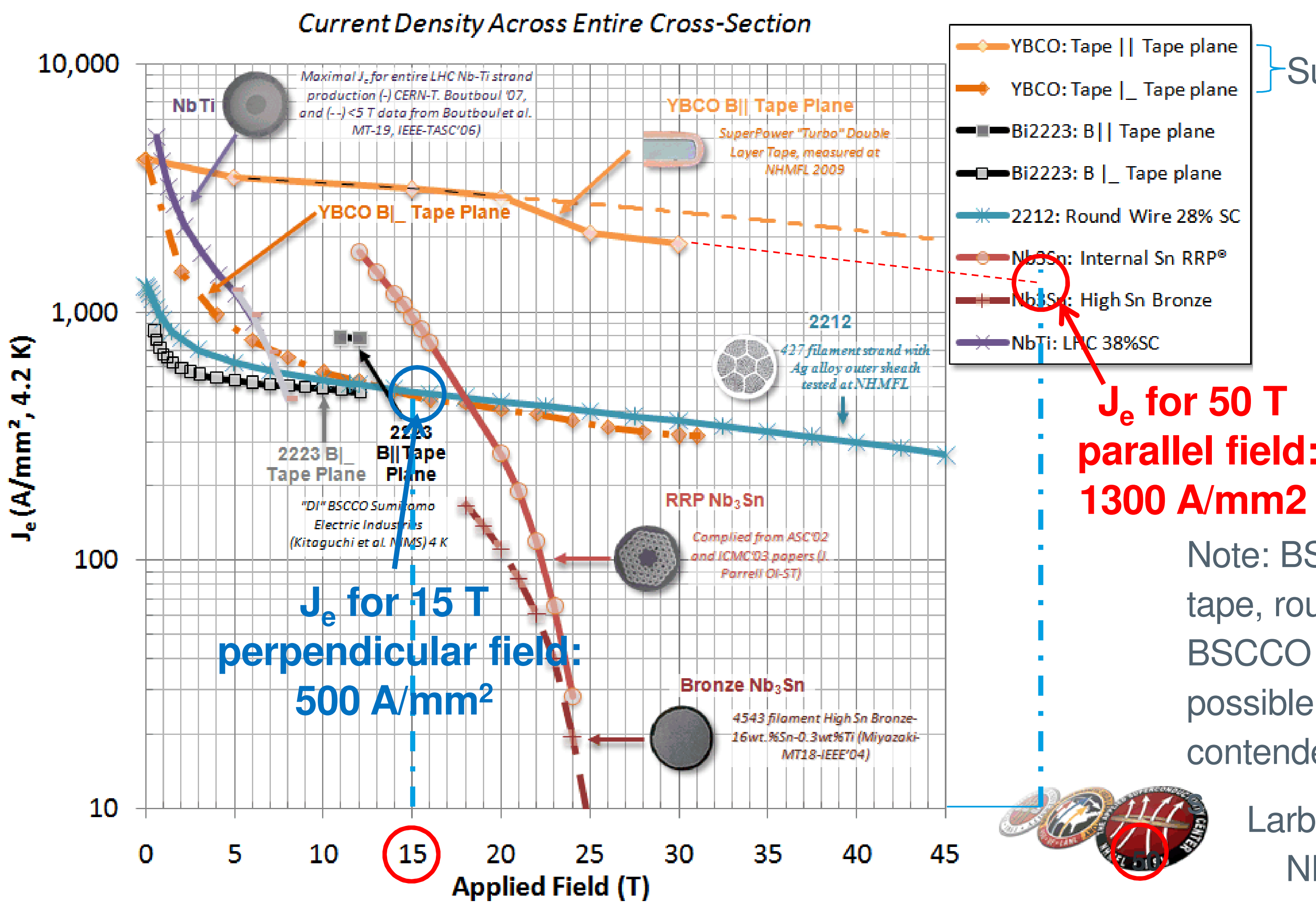
e. g. SEI 1G (BSCCO) wire reinforced with 0.02-0.1 mm stainless steel



K. Sato et al.
JJAP 51, 2012

K. Sato, SEI: "500 MPa of tensile stress will be feasible"

Does Existing 2G HTS Wire Have Enough $J_c(H)$ for a 50 T Magnet? YES! (just)



Note: BSCCO 2223 tape, round BSCCO 2212 wire possible future contenders

Larbalestier, NHMFL

Principal Commercial HTS Wire Producers Today

- AMSC – 2G wire
  Ni-W substrate, MOD REBCO, laminated stabilizer
- Bruker – 2G wire
  Stainless steel substrate, PLD REBCO, laminated or electrodeposited stabilizer
- Fujikura – 2G wire
  Hastelloy substrate, PLD REBCO, electrodeposited stabilizer
- Sumitomo Electric (SEI) – 1G wire
  BSCCO/Ag composite, laminated stabilizer
- SuperPower-Furukawa – 2G wire
  Hastelloy substrate, MOCVD REBCO, electrodeposited stabilizer

A growing HTS wire industry, but no standardization yet

Remaining Hurdles for 50 T HTS Magnet Wire

- Wire for ultra-high-field magnet systems still requires development
  - Optimization still needs to be done to further enhance J_e at 4.2 K and ultra-high-field beyond today's marginal values
  - Even higher strength tapes could be developed, e. g. by laminating to a thin tape of CuNb with yield strength > 1 GPa
  - No wire producer yet combines all the wire characteristics needed for a 50 T magnet
  - Cabling may be needed for some designs; industrial Roebel cabling still rudimentary
- Are HTS wire producers interested in such a relatively small market, in comparison to the huge wire-volume opportunities in power cables, wind generators and fault current limiters?
  - Would they be willing to pursue the necessary development work under government contract?

HTS wire already meets intermediate field requirements

How about Industrial Producers of Magnet Systems? (excluding MRI)

- Agilent (former Varian) – NMR systems
- AMSC – all HTS magnet systems (e. g. 7 T research magnet) – now focused on coils for rotating machinery
- Bruker – NMR systems with world's highest field all-LTS system; also has BEST as HTS wire source; planning 28 T HTS NMR
- Cryomagnetics – cryofree SC magnet systems
- HTS-110 – so far mostly lower field HTS coils
- Kobe Steel and JASTEC – cryofree SC magnet systems, NMR
- Oxford Instruments – cryofree SC magnet systems, has worked with NHMFL on ultra-high-field HTS coil tests using Bi-2212 round wire
- SEI – all HTS magnet systems (7 T research magnet)
- Toshiba – cryofree LTS magnet systems, today focused on ITER, Maglev

Are any of these ready to address hi-field HTS systems?

NIMS/JASTEC(Kobe Steel) 24 T All-SC Magnet System Demo: Tsukuba

S. Matsumoto et al., SUST, 2012

- 515 m of Fujikura GdBCO 2G wire in layer wound coil w/5 cm i. d.

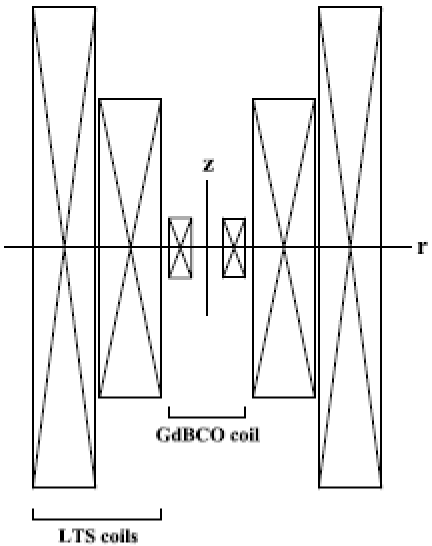


Figure 4. Configuration of the GdBCO insert, Nb_3Sn and Nb–Ti coils.

Figure 3. Fabricated GdBCO coil installed in the 17.2 T low-temperature superconducting magnet.

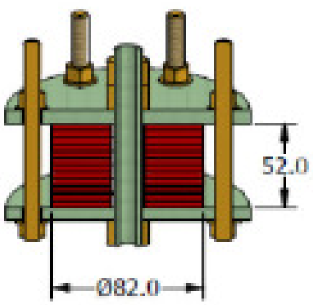
Highest all-superconductor field to date

UNIVERSITY of HOUSTON

SuperPower Inc.

Ultra high-field magnets demonstrated at 4.2 K with Zr-doped MOCVD conductors

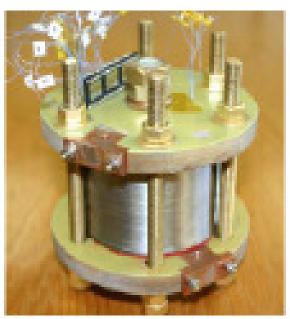
- Je ~ 300 A/mm²
- Stress levels 300 – 400 MPa

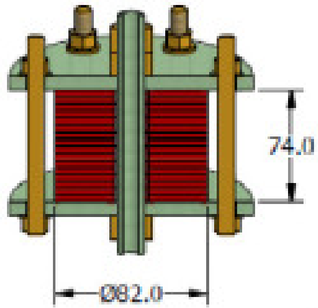


SuperPower I.

Bmax = 26.8 T

ΔB = 7.8 T

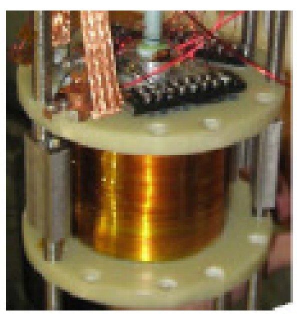


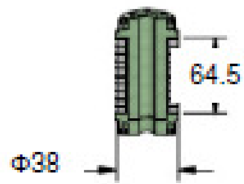


SuperPower II.

Bmax = 27 T

ΔB = 7 T





NHMFL II.
Bmax = 35.4 T
ΔB = 4.2 T

SEI 7T All-HTS Magnet System: 1G DI-BSCCO Wire, 20 K Operation

K. Sato et al., JJAP 51, 2012

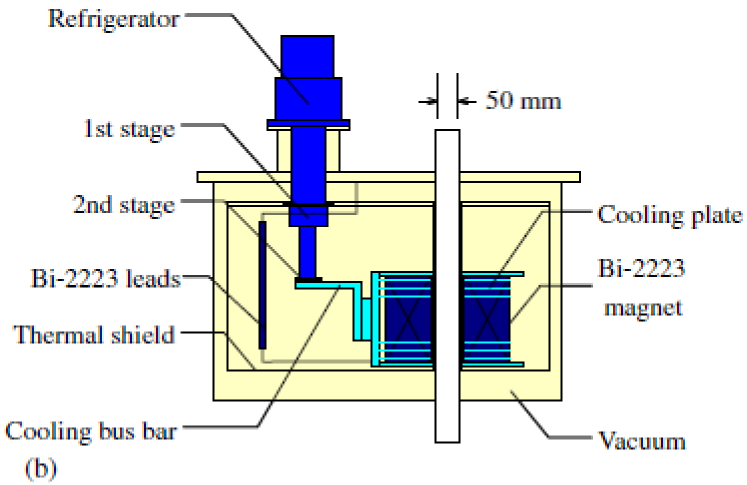


Fig. 13. (Color online) Image (a) and structure (b) of Bi-2223 magnet cooled with refrigerator.

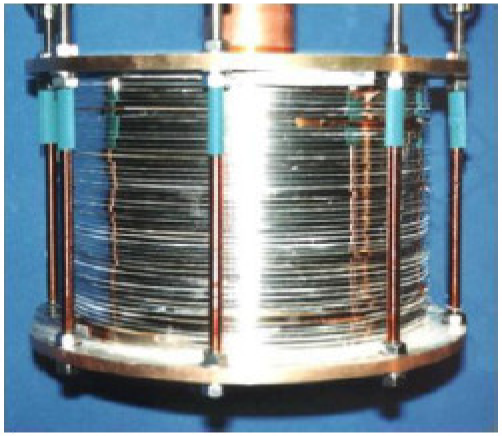


Fig. 12. (Color online) Double pancake coils wound with Bi-2223 wires.

SEI a leader in both HTS wire and its applications

NIMS, Kobe Steel, JASTEC 24.2 T NMR Magnet System – in progress

Kiyoshi et al., IEEE TAS 2010

Uses SEI 1G "DI-BSCCO" wire

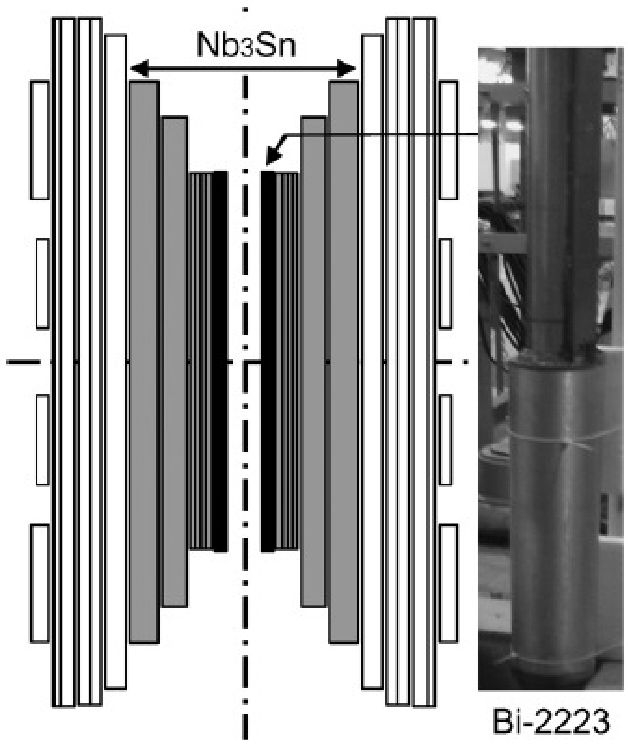


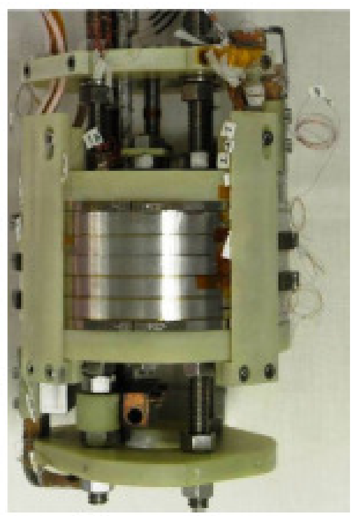
Fig. 6. Coil configuration of the 1.03 GHz NMR magnet and a photograph of the fabricated Bi-2223 coil for 1.03 GHz.

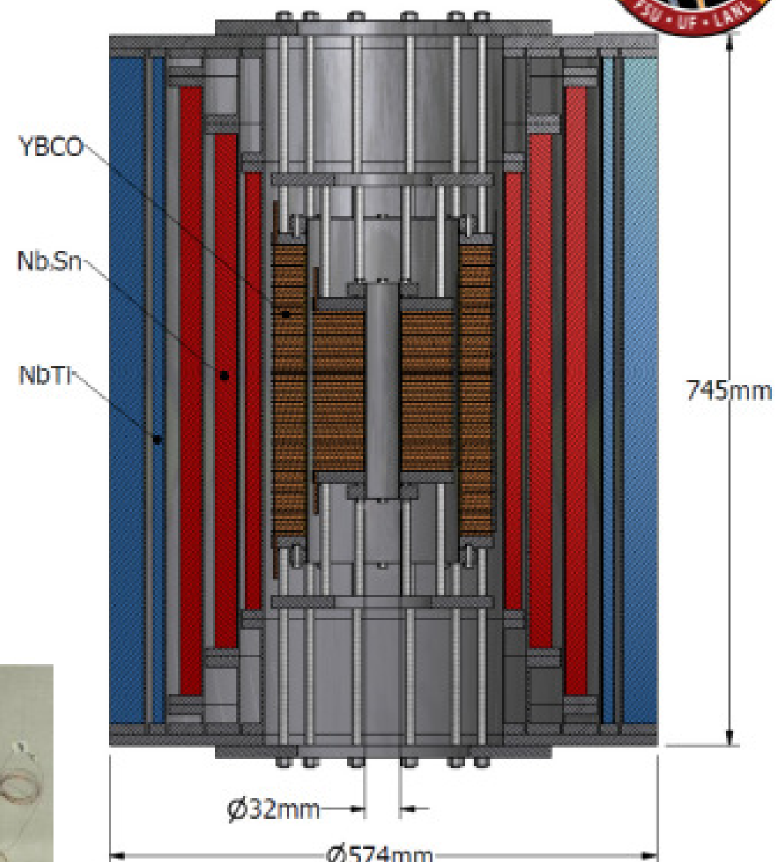
First operating NMR system w/HTS insert – target 2012

NHMFL 32 T: The first HTS user magnet

- High field 24/7 use
  - Low operating cost
  - Breakthrough from current 18/20 T level
- HTS Technology choices
  - REBCO Coated conductor, single strand
  - Conservative design with margin
- Focused project team
  - Reliability is key
  - Supported by broader, aggressive R&D program
- Close interaction with conductor vendor
- The first ever all superconducting magnet with B >24T

Key technological choices made
Now: full-featured test coils
2013: User operations →





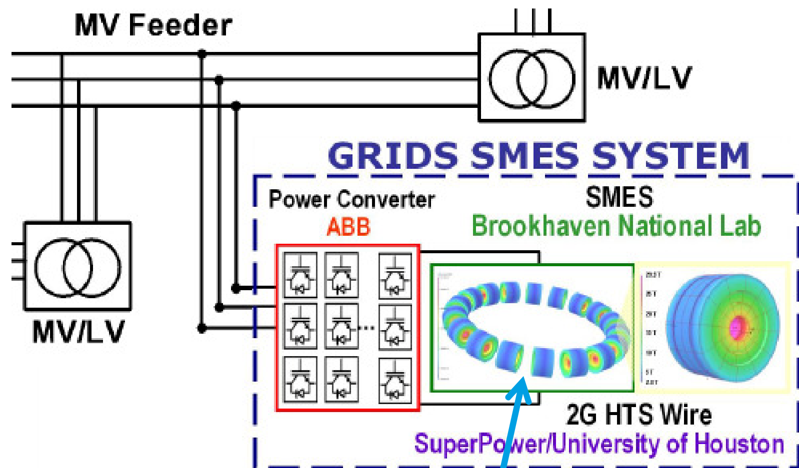
HTS/LTS hybrid (LTS outsert from industry)
- 32 T, 4.2 K, 32 mm bore
- Standard "physics" homogeneity
- Dilution refrigerator : <20 mK

Other HTS magnet projects and plans

- Brookhaven National Lab HTS Magnet Program plans:
  - 24-30 T torus for ARPA-E SMES project
  - 40 T HTS solenoid test in 19 T resistive magnet background field: muon accelerator program (MAP) with Fermilab muon collider proposal

- Grenoble High Magnetic Field Laboratory
  - Interest in HTS for high fields, but no funded program yet
  - European funding for 5 kA HTS cables

- LHC energy upgrade – CERN
  - Goal ~20 T dipoles



Plan: torus with 24-30 T field

Summary: HTS-Based All-SC Ultra-High Fields – a Revolutionary Opportunity

- HTS opens up the entire field range from 23.5 T to ~50 T for all-superconductor magnets

- Multiple companies producing commercial HTS wire
  - Wire quality and quantity has matured to the point of enabling all-SC magnets >24 T, though more optimization required to achieve full range

- Multiple companies have high field magnet systems expertise
  - Several already involved in initial ultra-high-field all-SC magnet systems

- Government funding and co-operation with high field magnet labs like NHMFL or Tsukuba are likely needed

International race is on to capitalize on this opportunity