NATIONAL HIGH MAGNETIC FIELD LABORATORY

State of the Art and Challenges in Ultrahigh Field Magnet Technology

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Ultrahigh Field NMR and MRI: Science at the Crossroads

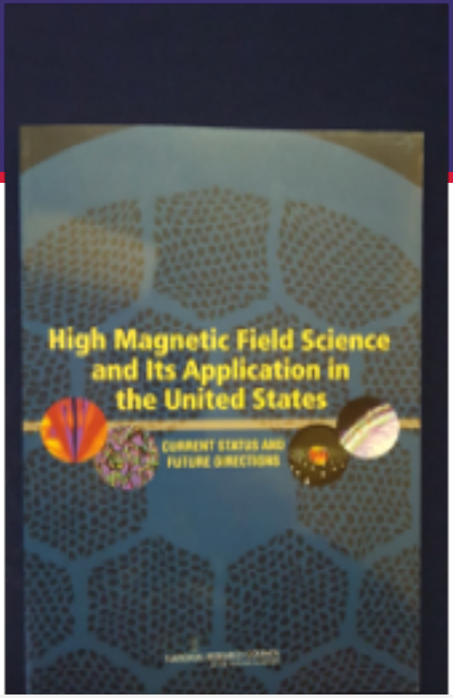
November 12-13, 2015

*Support by NSF core grant, DOE-High Energy Physics (HEP) , CERN and NIH and DOE-SBIR pass through awards

Material shown here drawn from a wide variety of internal MagLab staff and students in the Applied Superconductivity Center, Magnet Science and technology and the NMR program and collaborations with FNAL, LBNL, BNL in the BSCCo partnership, SuperPower (REBCO) , Oxford Superconductor Technology (2212) and Solid Materials Solutions (2212)

MagLab Viewpoint

- MagLab has worked >10 years in framework of 2003 and 2013 NRC reports on High Magnetic Field Science and Technology
- MagSci (2013) set aggressive NMR challenges
- We started with the simpler magnets (also addressing COHMAG and MagSci challenges)
- Great progress has been made
  - First on the conductor technology
  - Recently on the magnet technology



New mechanisms should be devised for funding and siting high-field NMR systems in the United States. To satisfy the likely demand for measurement time in a 1.2 GHz system, at least three such systems should be installed over a 2-year period. These instruments should be located at geographically separated sites, determined through careful consultation with the scientific community based on the estimated costs and the anticipated total and regional demand for such instruments, among other factors, and managed in a manner that maximizes their utility for the broad community. **Moreover, planning for the next-generation instruments, likely a 1.5 or 1.6 GHz class system, should be under**. **way now** to allow for steady progress in instrument development

Key messages:

1. We are confident that 30-37 T (1.3-1.6 GHz) NMR is feasible and that the time to start is now
2. Present and former DOE programs have supported extensive HTS conductor development

Multiple MagSci Goals

- **Consider regional 32 T superconducting magnets at 3-4 locations optimized for easy user access.**
- **Establish at least 3 US 1.2 GHz NMR instruments (likely commercially sources) for broad access and plan for ~1.5 GHz class system development**
- Establish high field (~30 T) facilities at neutron and photon scattering facilities
- **Construct a 20 T MRI instrument (for R&D with Na, P etc)**
- Design and build a 40 T all-superconducting magnet,
- Design and build a 60 T DC hybrid magnet that will capitalize on the success of the current 45 T hybrid magnet in Tallahassee

Very strong synergy with HEP goals (future 100 TeV circular hadron collider) and fusion goals (Tokamaks beyond ITER e.g. DEMO or small compact machines)

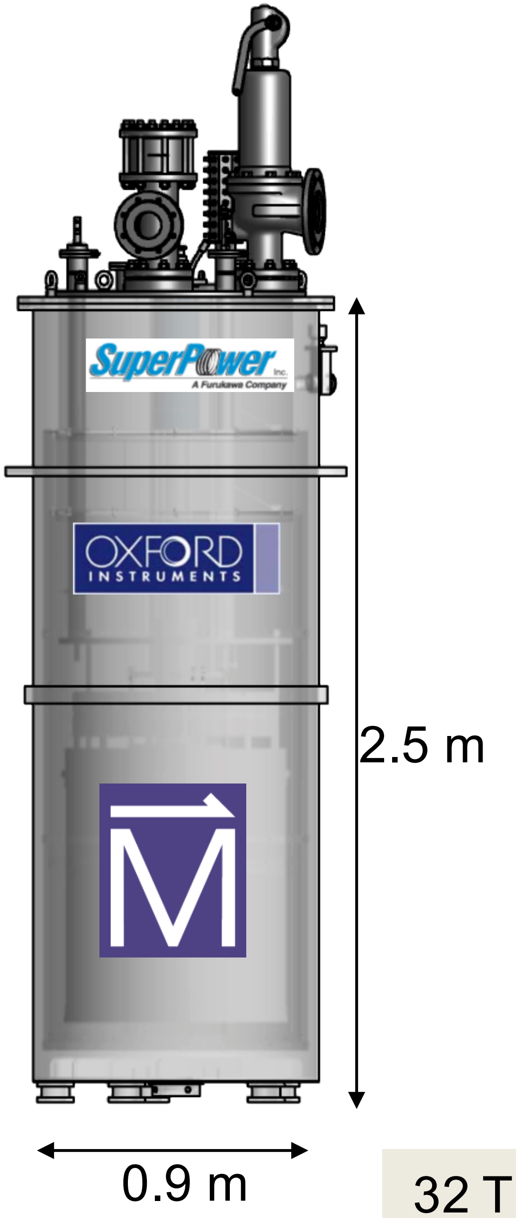
Recent UHF Magnet Successes

- **MagLab – insert magnets: 2007-2012**
  - Mostly REBCO – all insert coils, 27, 34, 35 T in 2012
  - FM 2212 34 T in 2012 – insert coil in 31 T resistive magnet
- **Standalone, all superconducting magnets**
  - Matsumoto *et al*. (NIMS/JASTECH/RIKEN LTS/HTS) – 24 T in 2012 (not quenched)
  - Weijers *et al*. MagLab 27 T (32 T prototype LTS/HTS) June 2015
    - All windings of the full 32 T magnet are now complete
    - Release to MagLab users expected in mid-2016
  - Moon, Hahn et al. **No Insulation (NI)** all-REBCO 26 T (March 2015), quenched safely twice August 2015) (SuNAM/MIT/MagLab collaboration)

Key messages:

1. Much of the last decade concentrated on HTS conductor development – finally real user coils are imminent
2. Most HTS coils have lacked quench protection – the 32 T user magnet and the NI approach build quench protection into REBCO pancake-wound coils

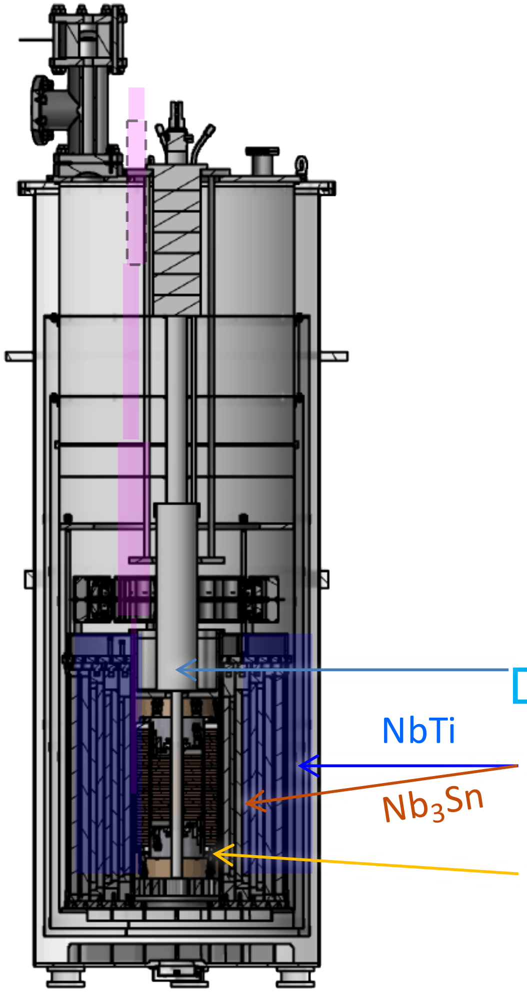
The 32 T User Magnet – 2016 operation



Chief designer: Denis Markiewicz

Cold Bore	34 mm
Uniformity $^{1\ \mathrm{cm\ DSV}}$	$5 \cdot 10^{-4}$
Total inductance	254 H
Stored energy	8.1 MJ
Ramp to 32 T	1 hour
Lifetime cycles	50,000

Mass (total) 2.3 ton



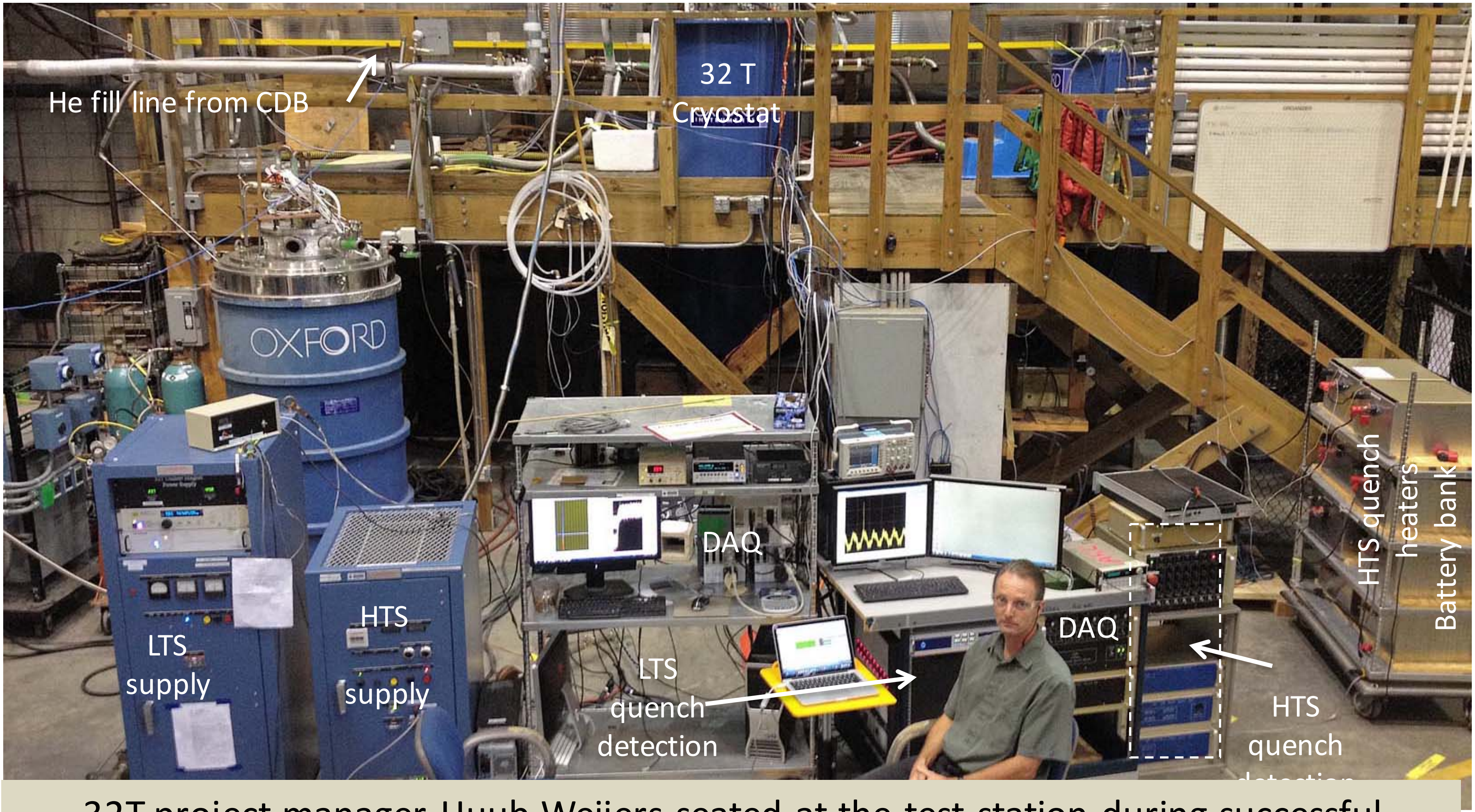
Dilution refrigerator or VTI

15 T / 250 mm bore LTS magnet

17 T REBCO coils (9.4 km of 4 mm wide tape)

32 T will spend most of its life *ramping up and down at 4.2 K*

Prototype 32 T test with 15 T Outsert – June 5, 2015 – 15 T LTS + 12 T REBCO = 27 T (1/6 height)



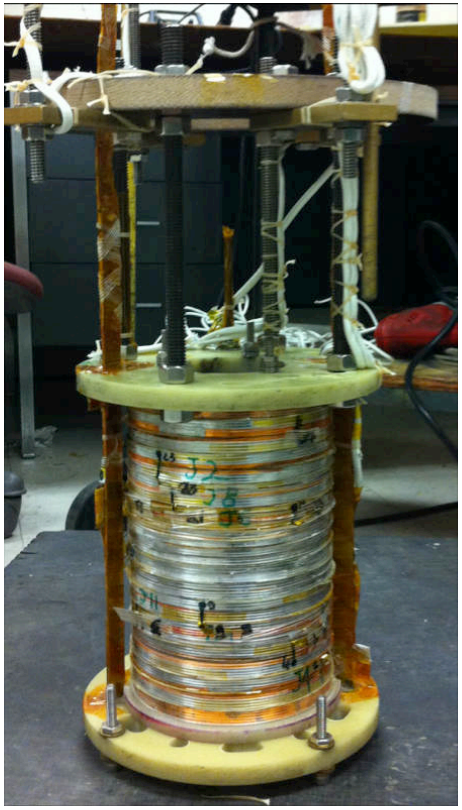
32T project manager Huub Weijers seated at the test station during successful testing of insert coil and outsert coil quenches – extensive tests of operation of LTS and HTS quench performance and cyclic testing to 25 T – full 32 T coil winding completed last week (November 2015)

26 T very compact NI (No Insulation) REBCO magnet recently quench tested at NHMFL

New faculty ME-NHMFL Seungyong Hahn formerly of Iwasa group at MIT

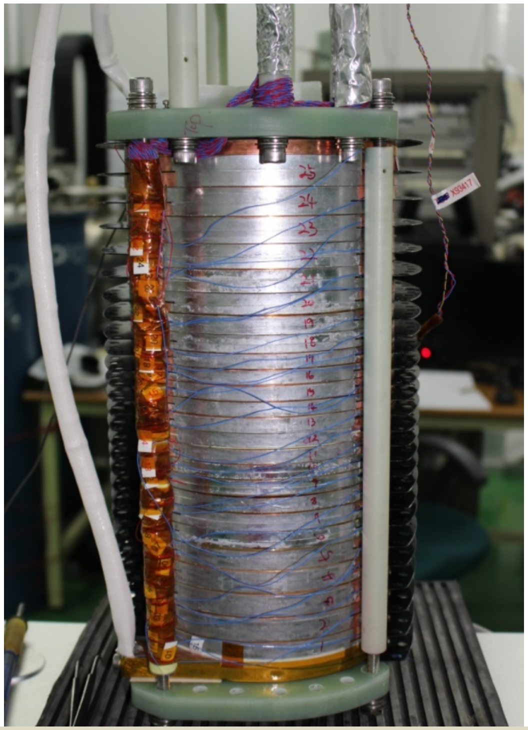
- Pros of NI magnets
  - Self-protecting by turn-to-turn "bypass" of quench current
  - Strong: >50 % enhanced winding mechanical strength
  - Compact: 3x J_W means 1/3 coil radial build
- Cons
  - Charging delay: 0.5-hour for 9 T/78-mm; 3-hour for 26T/35-mm
  - Limited operational experience so far
- Challenges
  - Charging delay may be improved by Partial-Insulation (PI)
  - Unbalanced forces during a quench at high fields

9 T/78-mm REBCO-NI
(2014, MIT)



- Coil OD: 101 mm
- Self-protecting at J_e of 870 A/mm^2

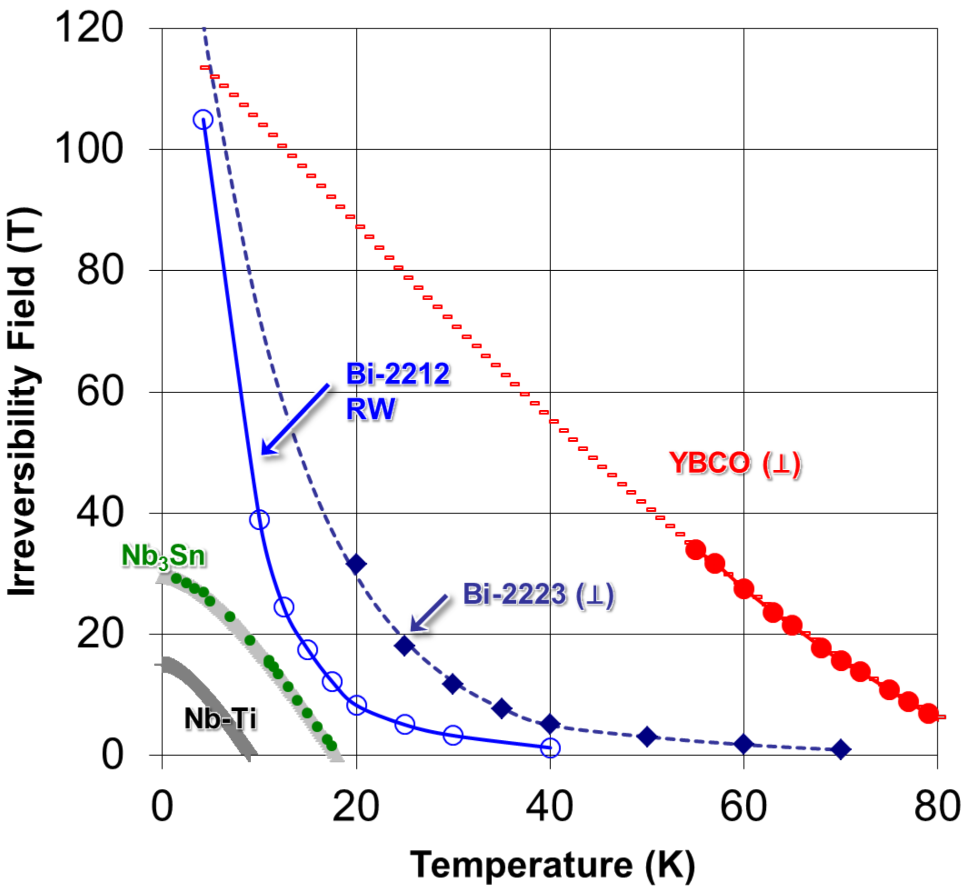
26 T/35-mm bore REBCO
(2015, SuNAM/MIT/FSU)



Design by Hahn, mfr. by SuNAM

- Coil OD/ID: 172/35 mm
- World record all-REBCO magnet quenched safely twice 9/15

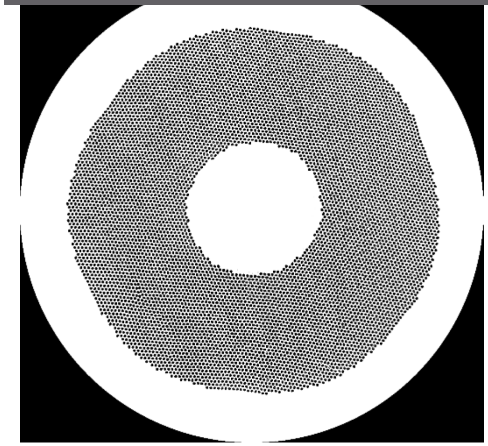
HTS supplies 3-4x higher H_{c2} or H_{irr}



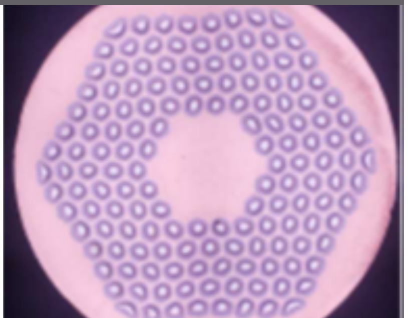
Higher fields require HTS – unlike LTS (Nb-Ti and Nb_3Sn) there are 3 choices of conductor and 4 magnet construction choices

State of the art 1 GHz Nb_3Sn NMR magnet in Lyon. France in persistent state at 23T

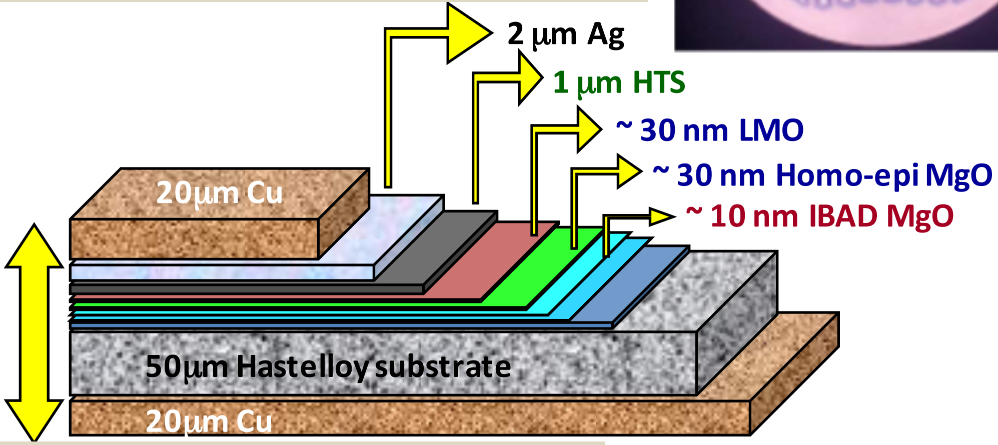
Magnet Conductor Choices



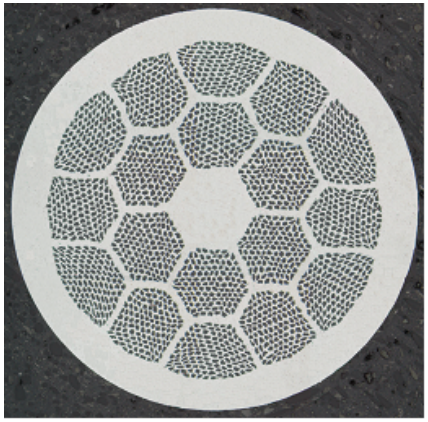
2. RRP (150/169 design) very high J_c Nb_3Sn conductor- thousands of few μm dia. Nb filaments in pure Cu converted to ~ 40 μm filaments after reaction with Sn cores, easily cabled to make 10-20 kA conductors



1. Nb47Ti conductor- thousands of 8 μm dia. Nb47Ti filaments in pure Cu, easily cabled to operate at 10-100 kA



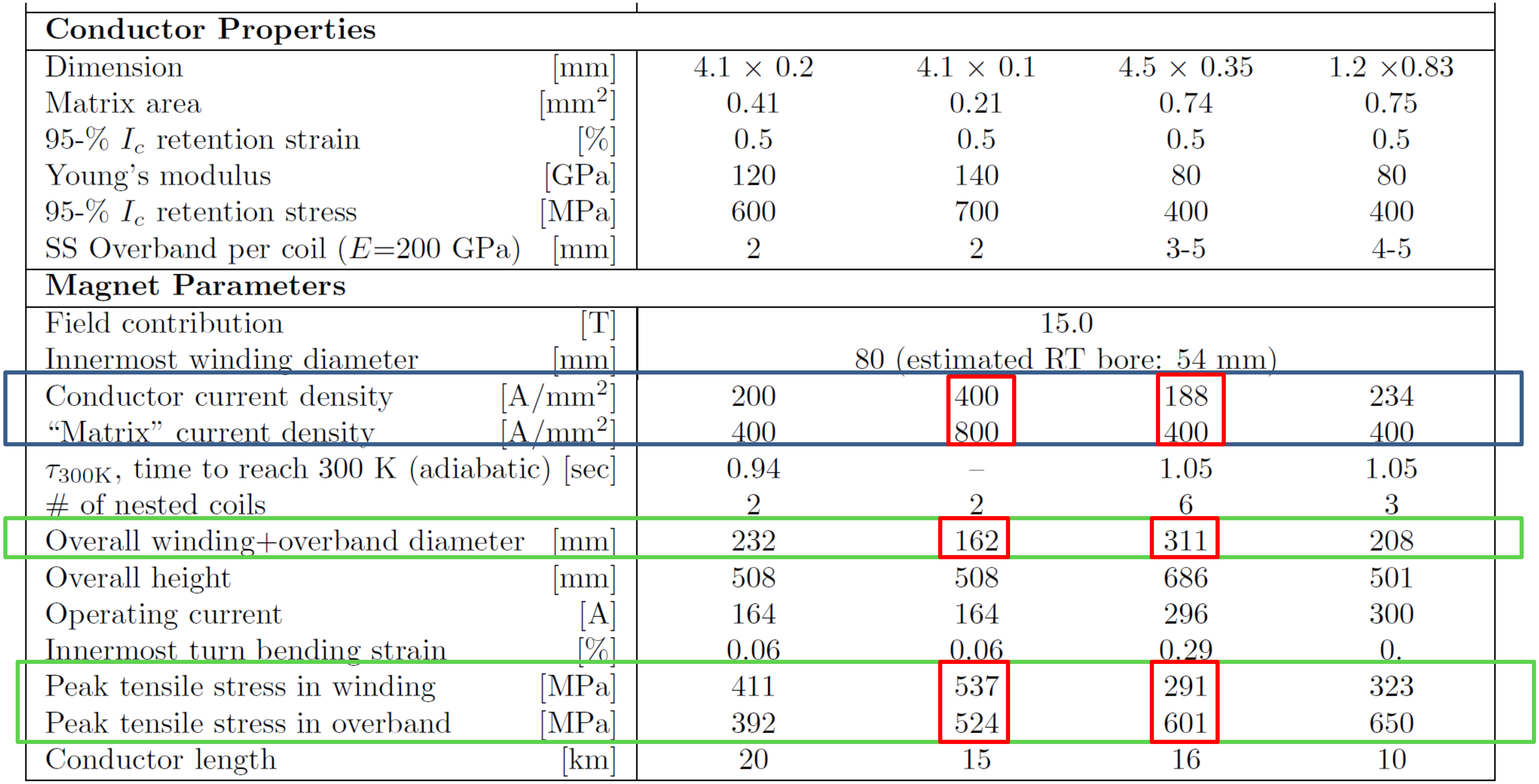
4. REBCO coated conductor – highest J_c obtained by biaxial texture developed by epitaxial multilayer growth



5. Bi-2212 – high J_c in isotropic form without macroscopic texture! The first HTS conductor like an LTS conductor.

3. Bi-2223 – the first HTS conductor – high J_c requires uniaxial texture developed by deformation and reaction

Straw designs with REBCO, 2223 and 2212 (30 T designs:15 T LTS and HTS)



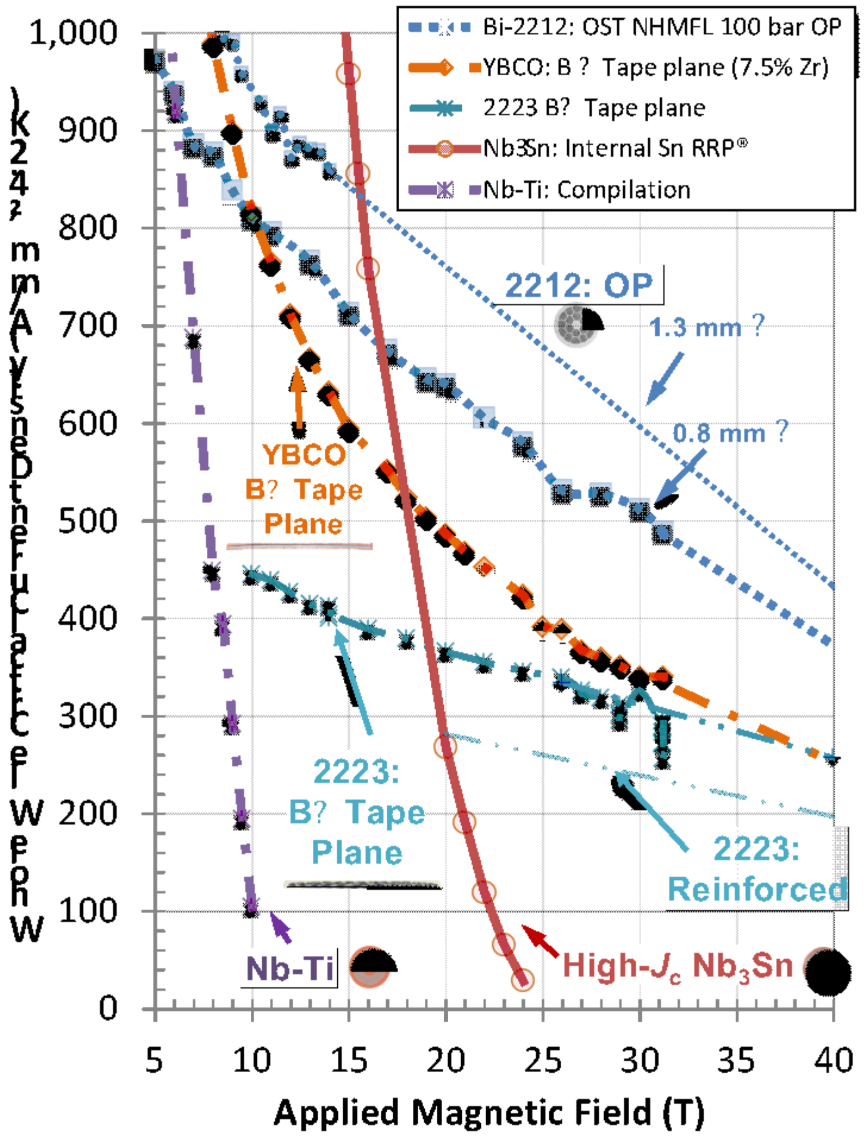
Conductor Properties					
Dimension	[mm]	4.1 × 0.2	4.1 × 0.1	4.5 × 0.35	1.2 ×0.83
Matrix area	[mm^2]	0.41	0.21	0.74	0.75
95-% I_c retention strain	[%]	0.5	0.5	0.5	0.5
Young's modulus	[GPa]	120	140	80	80
95-% I_c retention stress	[MPa]	600	700	400	400
SS Overband per coil (E=200 GPa)	[mm]	2	2	3-5	4-5
Magnet Parameters					
Field contribution	[T]	15.0			
Innermost winding diameter	[mm]	80 (estimated RT bore: 54 mm)			
Conductor current density	[A/mm^2]	200	400	188	234
"Matrix" current density	[A/mm^2]	400	800	400	400
$\tau_{300\mathrm{K}}$, time to reach 300 K (adiabatic)	[sec]	0.94	–	1.05	1.05
# of nested coils		2	2	6	3
Overall winding+overband diameter	[mm]	232	162	311	208
Overall height	[mm]	508	508	686	501
Operating current	[A]	164	164	296	300
Innermost turn bending strain	[%]	0.06	0.06	0.29	0.
Peak tensile stress in winding	[MPa]	411	537	291	323
Peak tensile stress in overband	[MPa]	392	524	601	650
Conductor length	[km]	20	15	16	10

Huge value in being able to operate at high stress, high Cu/Ag current densities – much smaller LTS and HTS coil (designs by Hahn – further iterations expected)

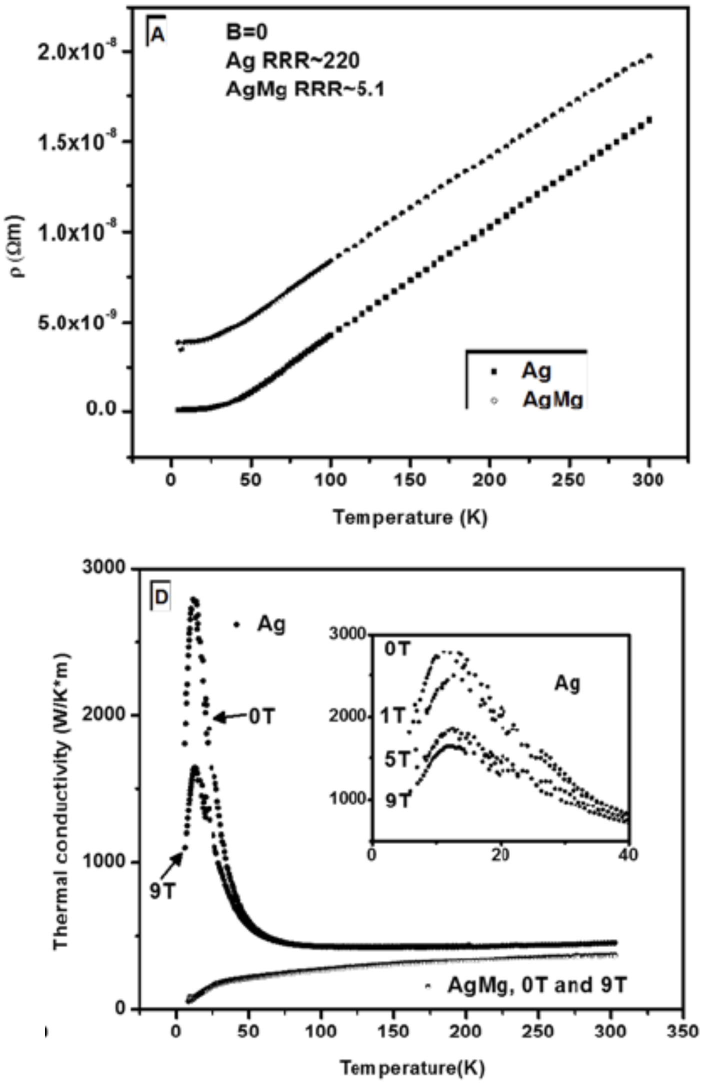
Key conductor challenges

- Operate at high engineering and winding current density (J_E and J_W) – demonstrated for all conductors now
- Have low normal state resistivity ρ to minimize $\int J^2\rho(T).dt$ during any transition to normal state (32 T Cu ~ 3 x 10^{-10} Ωm, 2212 Ag ~ 4-8 x 10^{-11} Ωm)
- Have high strain/stress tolerance (Both REBCO and strengthened 2223 (2223NX) can sustain >400 MPa at $\varepsilon < 0.4\%$)
- Have good insulation capability (unless NI) – hardest for 2212 but now demonstrated
- Have low magnetization to minimize field errors and allow good shimming (Much smaller for 2212 than 2223 or REBCO)
    - Also to minimize large imbalance between transport current and induced screening currents that occur in superconductors
    - Safety under all operational and magnet quench conditions
    - Most HTS magnets so far have not been protected against spontaneous quenches………………
    - Although HTS magnets are unlikely to quench under many conditions, many have burned in unplanned quenches!
- Persistent joint technologies - claims but no coil level demo yet

Excellent engineering current densities and normal stabilizer conductivity



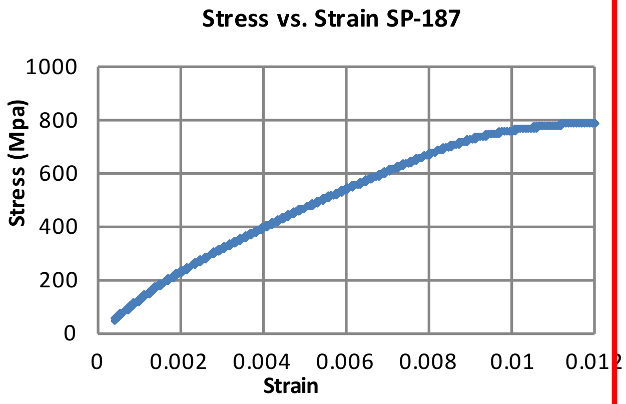
Master plot kept up by Peter Lee (ASC-NHMFL-FSU)



Excellent ρ and κ for reacted 2212 (Li, Ye, Jiang, Shen FNAL/MagLab collab. ICMC 2015, to appear in J Phys Conf Series 2016)

Good stress/strain tolerance

REBCO Coated Conductor

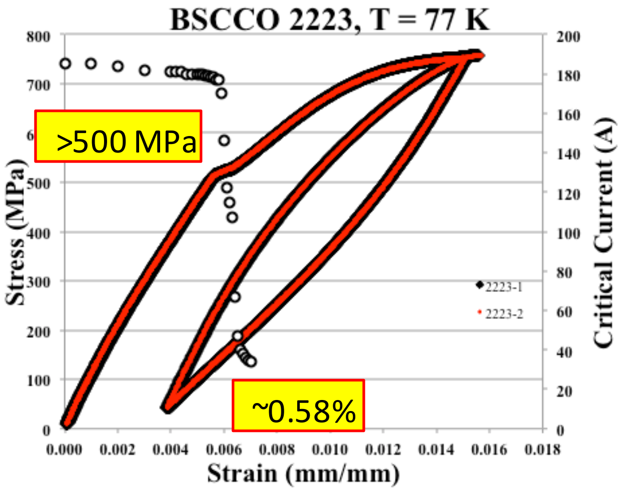


σ(ε) for 32 T REBCO

32 T operates at ~400 MPa at ε = 0.4%

Weijers et al. MT24 IEEE TAS subm.

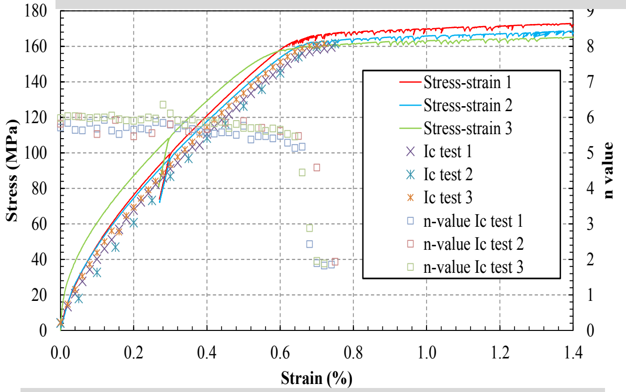
Strong 2223 (2223NX)



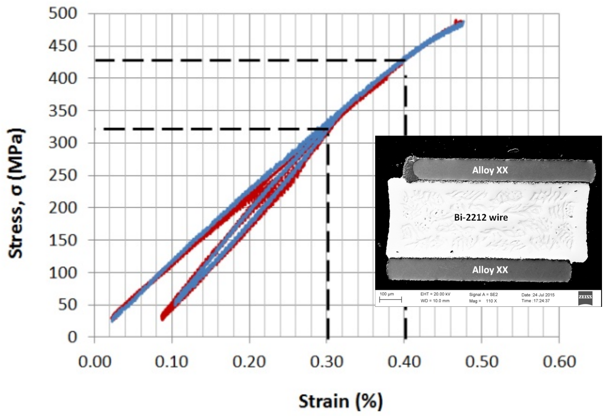
Excellent high field performance by Godeke *et al.* (MagLab 10/15 and Yanigisawa *et al.* SuST 2015

2212

Round, unstrengthened 2212 wire



Bjoerstad and Scheuerlein, *SuST (2015)*



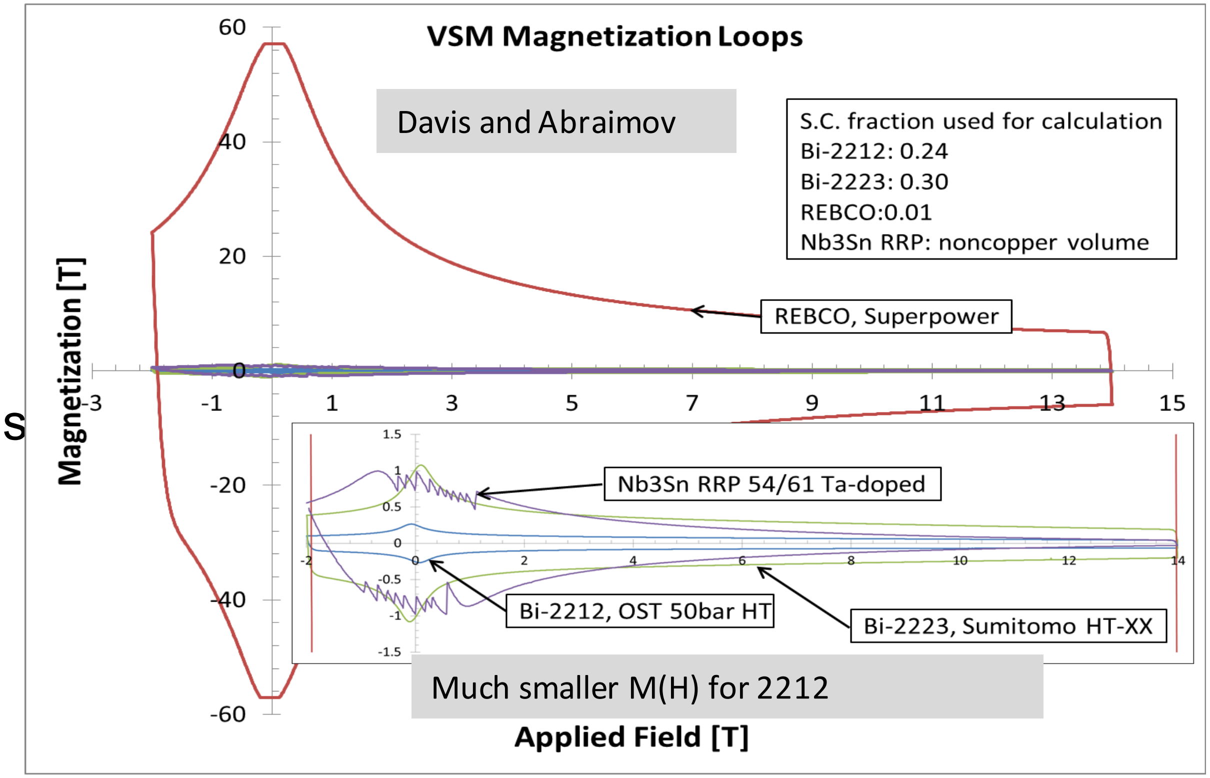
Stress for ε = 0.4% raised from 120 to 425 MPa

Key message: REBCO is inherently very strong, 2223 has recently been greatly strengthened, 2212 strengthening now being prototyped by similar lamination to 2223 (Alex Otto, Solid Materials Solutions)

M. Boebinger,
R. Walsh

Conductor magnetization varies strongly

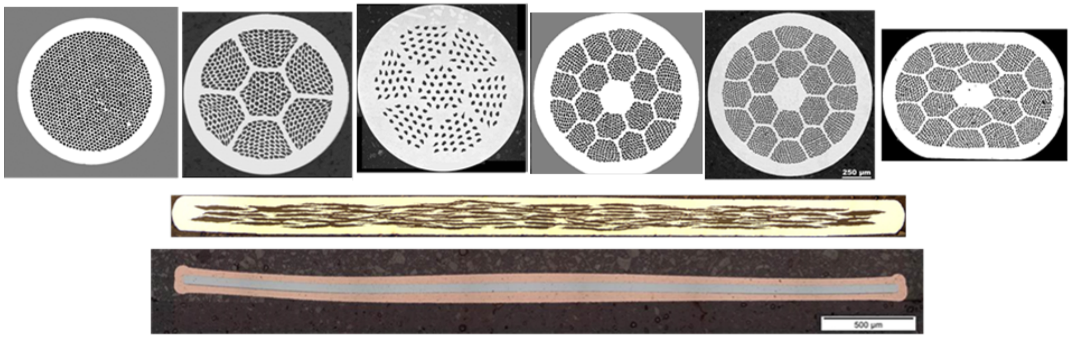
- Two anisotropic conductors:
  - REBCO – fully coupled across the 3-6 mm tape width
  - 2223 – strongly coupled across the 4 mm width of the conductor
  - Much larger magnetizations
- One isotropic conductor (2212)
  - Most closely correlates to Nb-Ti and Nb_3Sn
  - Smallest magnetization

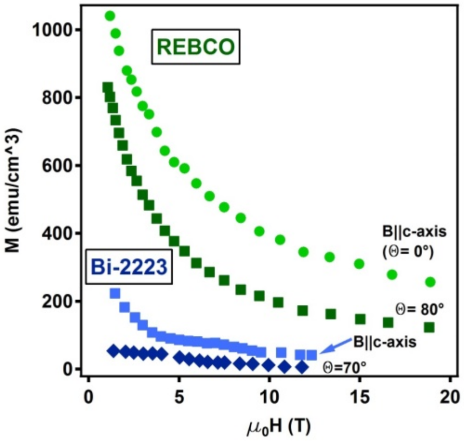


Davis and Abraimov

S.C. fraction used for calculation
Bi-2212: 0.24
Bi-2223: 0.30
REBCO:0.01
Nb3Sn RRP: noncopper volume

Much smaller M(H) for 2212





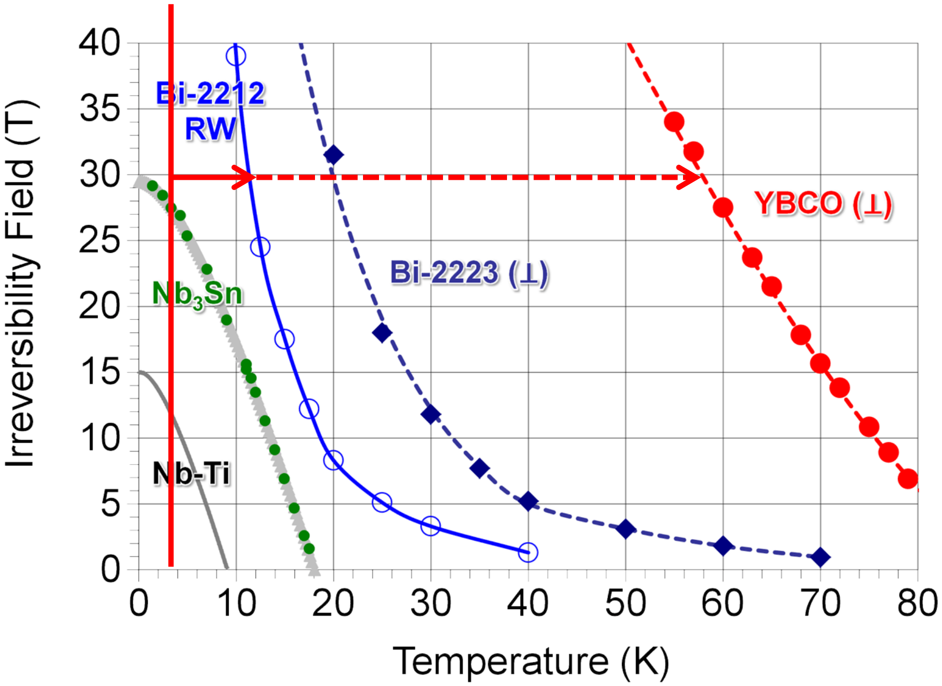
Parallel H measurements show reduced (M(H) – Constantinescu and Jaroszynski

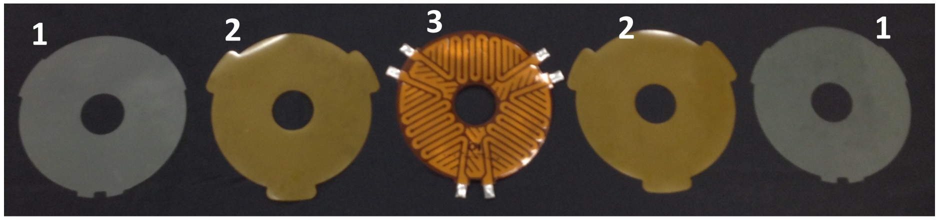
Quench issues

- If normal zones go undetected, conductors can burn out.
- HTS has favorable high stability but very undesirable slow normal zone propagation velocity.
    - m/s for Nb-Ti and Nb_3Sn.
    - <10 cm/s for 2223 and YBCO.
    - **40-100 cm/s for 2212 at 20-30 T (like Nb_3Sn at 15 T)***
- Quench is being addressed with:
    - The NI approach (SuNAM 26 T magnet)
    - Thin TiO_2 insulation (MagLab/nGimat) promotes 3D propagation in 2212 - proximity to H_{irr} good!.
    - Quench heaters protect 32 T REBCO.
    - New idea CLIQ (Coupling-Loss Induced Quench) now introduced in US at LBL (Emanuele Ravaili -Touhig Fellow)

*Ye et al., FNAL-NCSU-NHMFL collaboration

4 K operation





32 T quench heater: 1. G10, 2. Kapton, 3 the SS heaters

Principal conductor pros and cons

Conductor	Advantages	Disadvantages
REBCO	- Very strong substrate - Highest sc J_c, but small fraction dilutes J_E - Cu fraction easily varied - Supplied in sc state - Supported by hope for electric utility use at 30-77K - Persistent joints reported	- Single filament - ~40:1 aspect ratio - Electric anisotropy ~5 - Ic variation by varying conductor width (~2-12 mm) - Lengths and defect densities still improving
Bi-2223	- The most mature HTS conductor now laminated with strong substrate with high strain tolerance – multifilament, untwisted - Has delivered good NMR signals in NIMS (1 GHz) and RIKEN (400 MHz) (LTS has supplied main field) - Is supplied in SC state in lengths of ~ 500 m unlaminated and 100-300 m laminated	- One size and current rating makes coil grading infeasible - ~20:1 aspect ratio - Electric anisotropy ~ 2
Bi-2212	- **Round, twisted, multifilament** - Manufactured in many architectures so as to make grading feasible as for Nb-Ti and Nb_3Sn - Single lengths of 1-2 km now available - Has smallest magnetization and promises best field quality (coil in mfr. for RIKEN in early 2016) - **Persistent joints being obtained in small coils**	- High Jc requires overpressure (50-100 bar) reaction at 900 C forcing wind and react magnet construction (like Nb_3Sn) - The least developed magnet technology - Needs industrial lamination development

Each conductor offers an interesting mix of positive features

"Platypus" : A Bi-2212 NMR Demo-Magnet

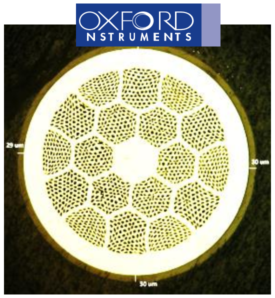
Goals:

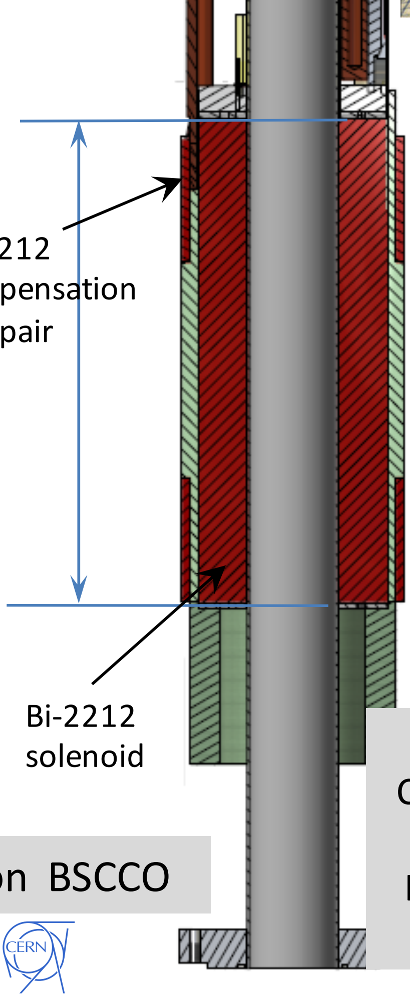
- Establish 2212 technology
- NMR demo magnet of ~ 1 GHz (24 T) with ppm field homogeneity and stability
- Hybrid LTS/HTS coil with all conductors twisted, round and multifilament (16 T Nb-Ti/Nb_3Sn + 8 T Bi2212)

Status:

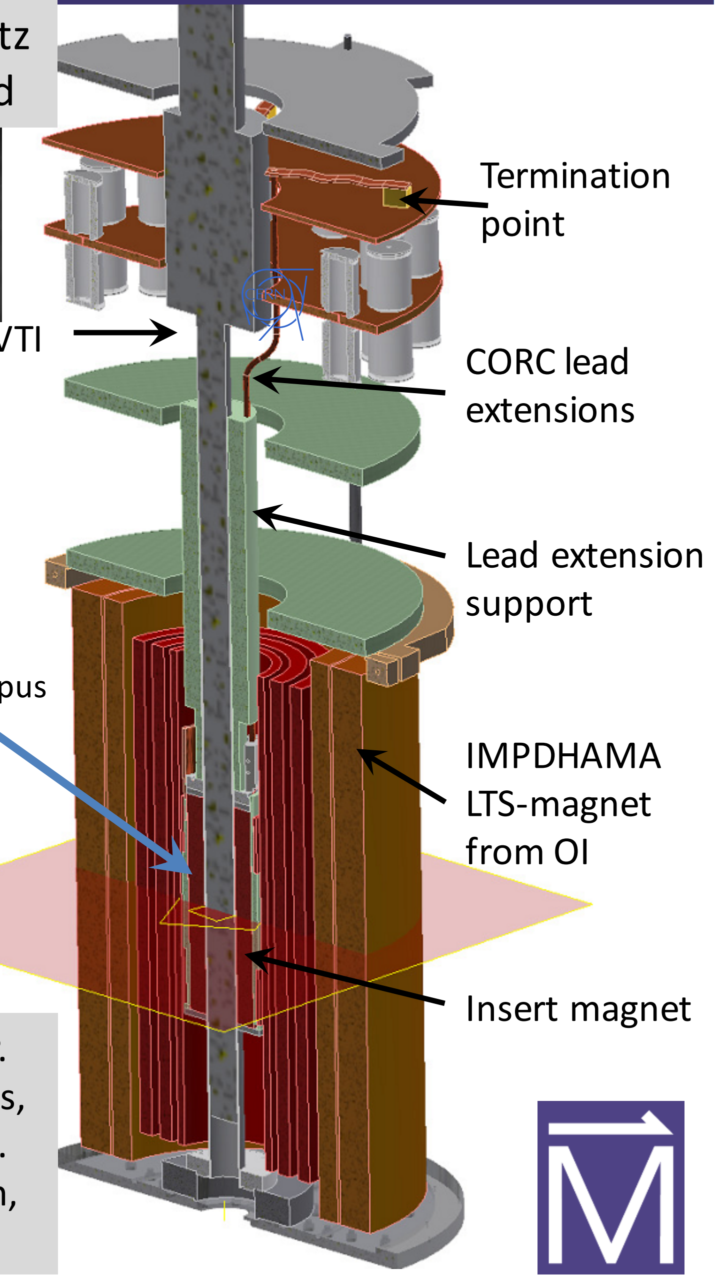
- Novel 2212 HTS technology has been led by NHMFL
- All sub-systems demonstrated
- Platypus coils being wound with new tests planned in 2016
- Strong DOE-HEP and CERN support for conductor development with industrial partner OST (E. Hellstrom, F. Kametani, J. Jiang and DCL)

Bismuth Strand and Cable Collaboration BSCCO





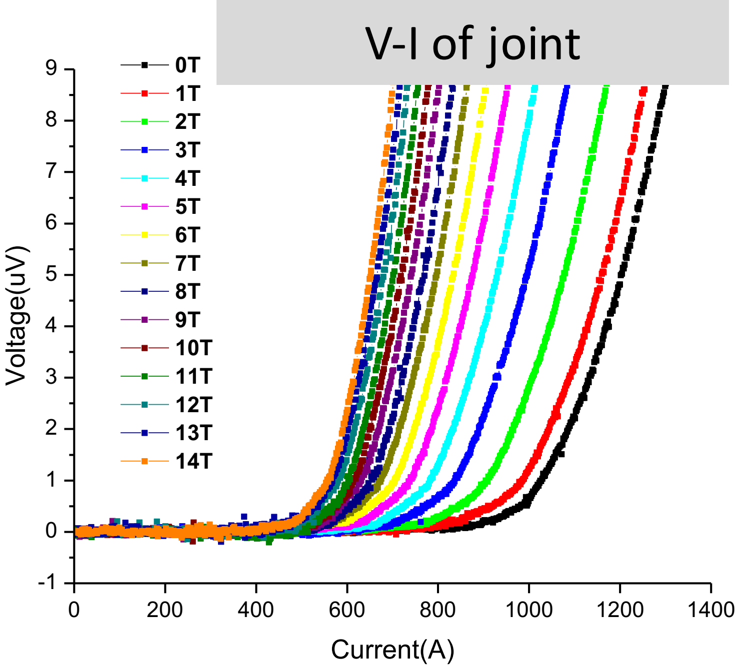
Ulf Trociewitz
Project lead

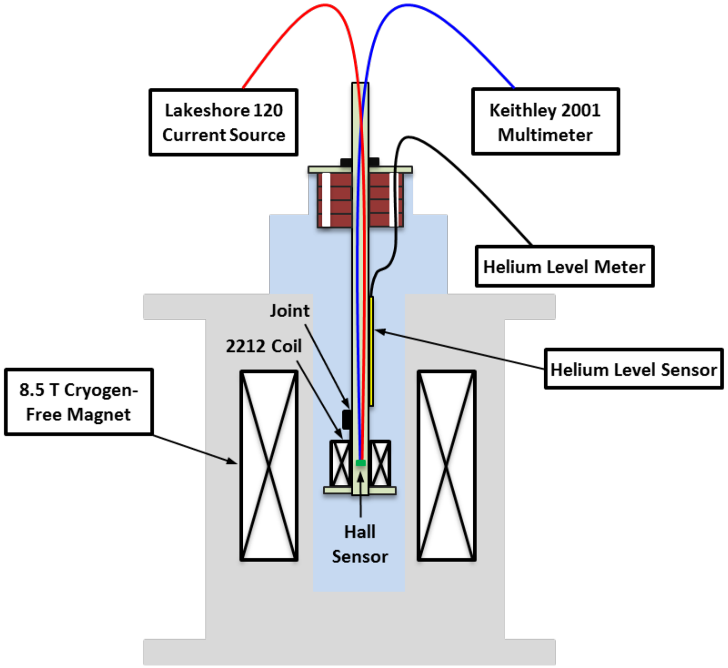


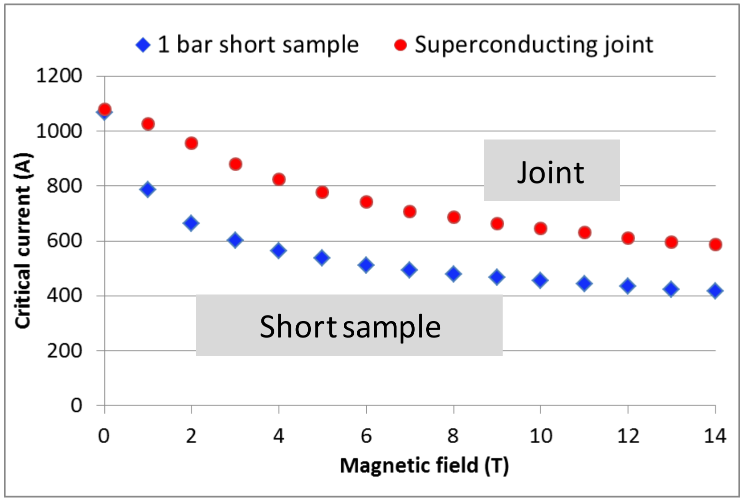
E. Bosque, P. Chen, D. Davis, L. English, D. Hilton, Y. Kim, G. Miller

Persistent joints seem feasible with 2212

- Joints being evaluated by direct transport and by induced field and its decay
- Long term decay consistent with logarithmic creep of short samples measured in SQUID
- For 100 H magnet τ = 100/5 x 10^{-12} Ω ~ 5 x 10^{9} hrs.

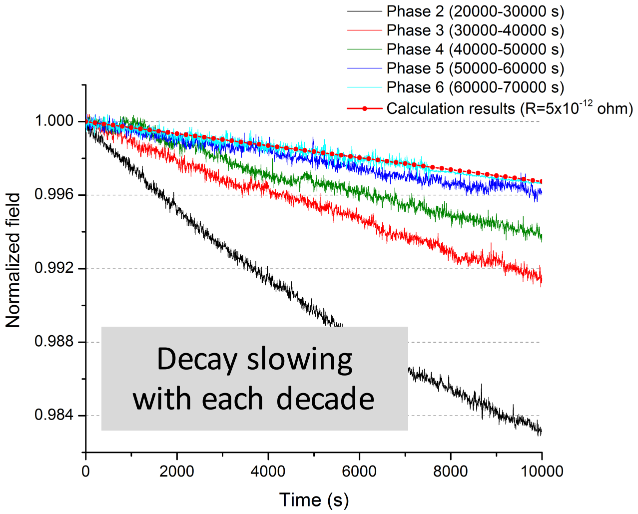

V-I of joint





Joint

Short sample



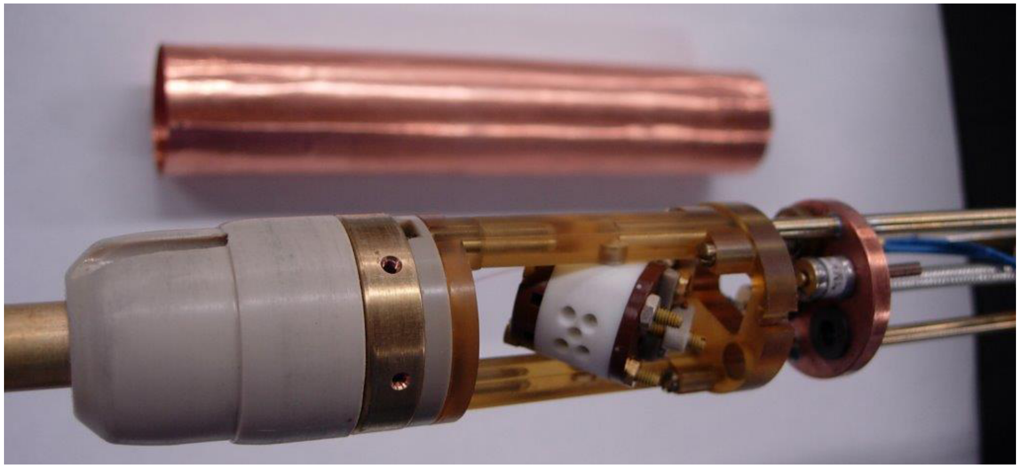
Decay slowing with each decade

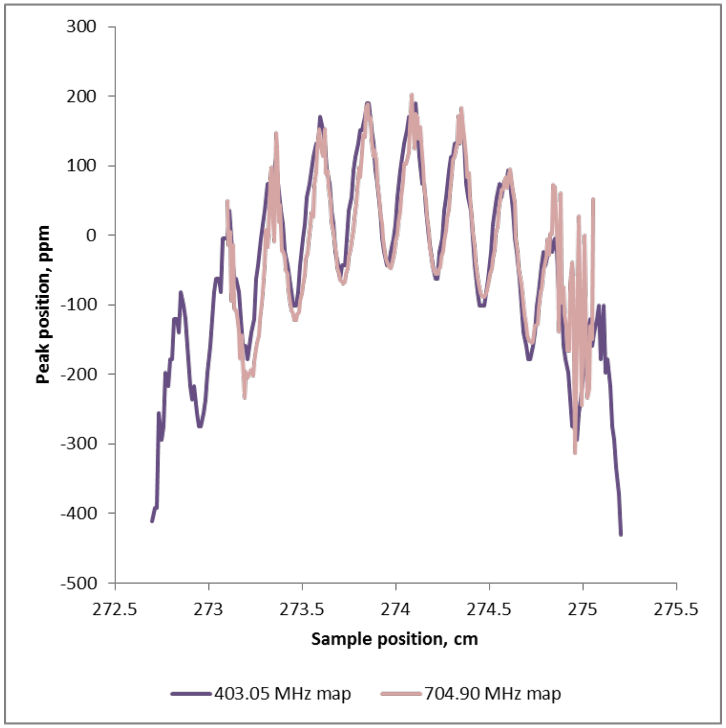
Peng Chen and Dan Davis

A high field (~1 GHz) NMR test bed

- IMPDHAMA is a reasonably homogeneous 17 T magnet
- Now fitted with VTI and MAS for NMR signal and field quality evaluation
- Plans for 2212, 2223 and REBCO coils (with Z2 compensators) to extend field quality issues so far studied by RIKEN at ~400 MHz

	9.4T	16.4T	
Gradient Z2	-239.74	-224.55	**ppm/cm2**
Gradient Z4	15.33	97.60	**ppm/cm4**
radial ($\sqrt{(x^2+y^2)}$)	213.54	213.91	**ppm/cm**
Gradient ZX	5.47	0.14	**ppm/cm2**
Gradient ZY	1.51	-40.94	**ppm/cm2**





Ilya Litvak, Zhehong Gan, Ivan Hung, Peter Gor'kov, Steve Ranner, and Bill Brey

On track for 1.3-1.6 GHz NMR challenge?

Yes!

Thank You!

David Larbalestier

larbalestier@asc.magnet.fsu.edu

Great thanks to the following :

- 32 T team led by Huub Weijers and Denis Markiewicz
- Platypus team led by Ulf Trociewitz with Ernesto Bosque, David Hilton, Youngjae Kim, George Miller and Lamar English and PhD students Peng Chen and Daniel Davis and the NMR effort led by Bill Brey
- Magnet design led by Seungyong Hahn, Ernesto Bosque and David Hilton
- Conductor design and evaluations led by Peter Lee and Chiara Tarantini
- The 2212 conductor effort led by DCL, Eric Hellstrom, Jianyi Jiang and Fumitake Kametani with PhD students Maxime Matras and Yavuz Oz and UG Matt Boebinger
- The 2223 team led by Arno Godeke with Scott Marshall and Dima Abraimov
- The Vibrating Coil Magnetometer development led by Jan Jaroszynski and Anca-Monia Constantinescu
- The BSCCo and OST team led by Tengming Shen (FNAL, now LBL), Arup Ghosh (BNL) and Yibing Huang (OST) and Alex Otto at SMS
- Great support from Greg Boebinger, Lucio Frydman, Tim Cross and Mark Bird