NATIONAL HIGH MAGNETIC FIELD LABORATORY

30th Anniversary Symposium on the Discovery of Cuprate Superconductors

HTS conductors for high field magnets in the next 10 years

David Larbalestier*

March 17, 2017

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

The 63rd JSAP Spring Meeting 2016

Dates March 19 [Sat.] - 22 [Tue.], 2016

Venue Tokyo Inst. of Tech. Ookayama Campus

Material shown here drawn from a wide variety of MagLab staff and students in the Applied Superconductivity Center, Magnet Science and Technology Division 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)

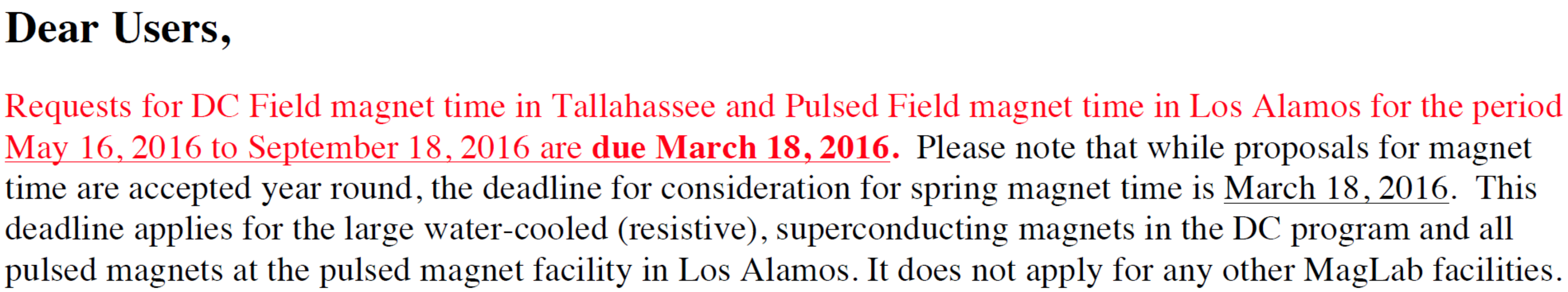
Outline of talk

- The rationale for HTS coils
- Some simple magnet design issues
- The MagLab program (2006-now)
  - Conductor driven – at first REBCO (2007 on)
  - HEP and NMR then drove a round, twisted, multifilament, arbitrary size conductor – Bi-2212 (2008 on)
  - High strength Bi-2223NX (2014 on)
- Cost and supply issues
  - Case for MgB_2 and Fe-base superconductors as affordable, round, multifilament, high-field wires to compete at least with Nb_3Sn

User demands, the power bill, and the NSF budget drive our program….

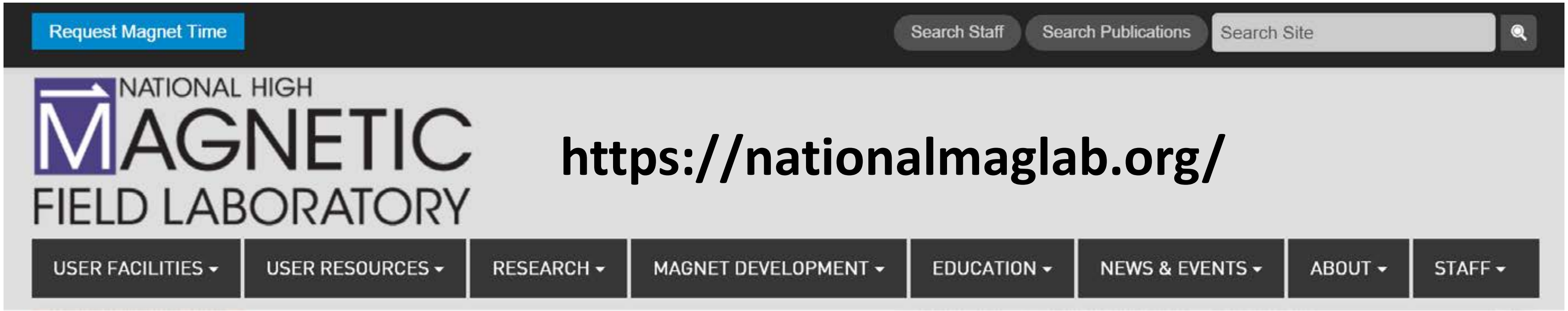
- The NHMFL provides the world's highest magnetic fields
  - 45T DC in hybrid, 32 mm warm bore
  - Purely resistive magnets: 35T in 32 mm warm bore, 31 T in 50 mm bore
- 20 MW resistive magnet ~$1500/hr at full power (7.5c/kWhr)
- Many specialized magnets for NMR and ICR

Interested in using the MagLab?



Dear Users,

Requests for DC Field magnet time in Tallahassee and Pulsed Field magnet time in Los Alamos for the period May 16, 2016 to September 18, 2016 are **due March 18, 2016.** Please note that while proposals for magnet time are accepted year round, the deadline for consideration for spring magnet time is March 18, 2016. This deadline applies for the large water-cooled (resistive), superconducting magnets in the DC program and all pulsed magnets at the pulsed magnet facility in Los Alamos. It does not apply for any other MagLab facilities.



https://nationalmaglab.org/

Access to facilities requires a proposal but new users are prioritized (Note March 18 deadline above)

Excellent user support scientists

He users benefit from 250 l free

Our long range vision is set by National Academy Panels

OPPORTUNITIES IN
HIGH MAGNETIC FIELD SCIENCE

NATIONAL RESEARCH COUNCIL

COHMAG - 2005

High Magnetic Field Science and Its Application in the United States

CURRENT STATUS AND FUTURE DIRECTIONS

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

MagSci - 2013

http://www.nap.edu/catalog/11211/opportunities-in-high-magnetic-field-science

http://www.nap.edu/catalog/18355/high-magnetic-field-science-and-its-application-in-the-united-states

Both are free downloads – they provide good descriptions of:

1. the science being done with high magnetic fields
2. the science that could be done with newer facilities
3. A description of the technology status
4. A rationale and list of desired new facilities

NRC reports do not provide money – only a hunting license!

The Global Context was first provided by COHMAG- Opportunities in High Magnetic Field Science – 2005

Grand magnet challenges:

- 30T NMR (All superconducting (SC))
- 60T Hybrid (Resistive (R) + SC)
- 100T Long Pulse (R)

All required materials *in conductor forms that were not available in 2005*

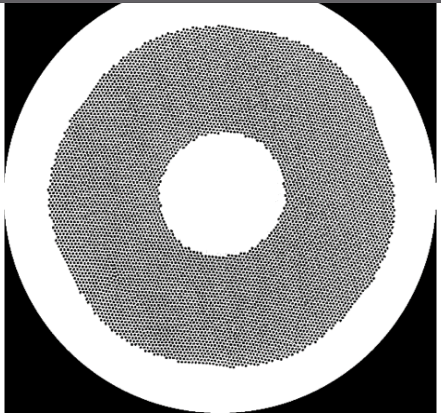
They now are!

Means:

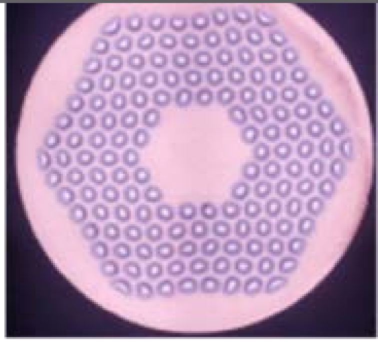
- ***….the involved communities [users and magnet builders] should cooperate to establish a consortium whose objective would be to address the fundamental materials science and engineering problems that will have to be solved…….. COHMAG report 2004***

Amplified in 2013 by a new NRC study MagSci – High Magnetic Field Science and technology

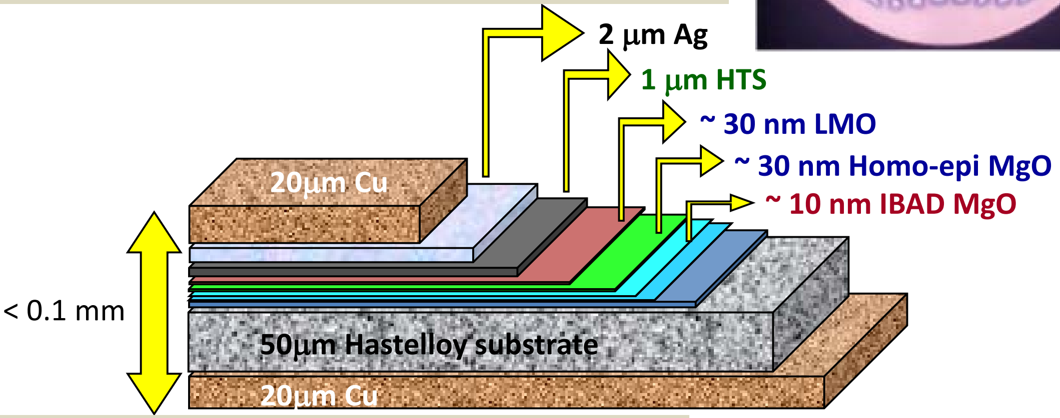
Magnet Conductor Choices



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



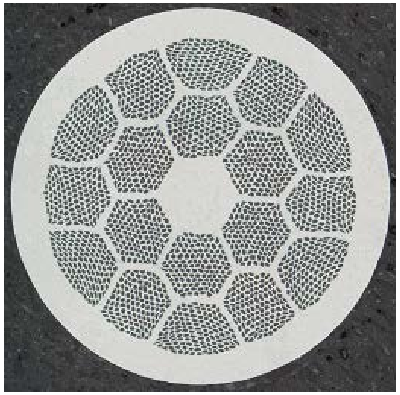
1. Nb47Ti conductor- thousands of 8 μm dia. Nb47Ti filaments in pure Cu, easily cabled to operate at 10-100 kA



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



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 (planned commercial) 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 – both need HTS strand AND cable development

Simple magnet design criteria

- $B \approx \mu_0 J d = 4\pi\ 10^{-7}.\ 10^{9}\ \mathrm{A/m^2}.\ 10^{-2}\ \mathrm{m} \sim 12\ \mathrm{T}$
  - Increase d, reduce J to what is available and tolerable in a quench and in stress

- $\sigma = J.\ B.\ r = 10^{9}\ \mathrm{A/m^2}\ .\ 10\ \mathrm{T}\ .\ 2.5\ \mathrm{x}10^{-2}\ \mathrm{m} \sim 250\ \mathrm{MPa}$!

- Assuming same cross-section of Cu as of superconductor gives dissipation of $J^2\rho\ \mathrm{J/m^3}$ per second – $10^{18}\ \mathrm{A^2/m^4}.\ 10^{-10}\ \Omega\mathrm{m} = 10^{8}$ watts!

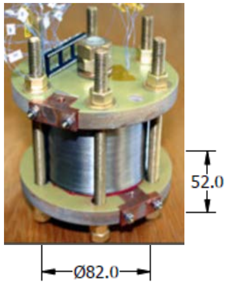
Danger! – a 20 or 30 T magnet deserves respect!

May have to reduce the current density J, both in the superconductor and in the Cu and above all get the energy out of the magnet fast or ensure that it is dissipated uniformly –

QUENCH and FORCE management are vital!

A long 32 T verification path

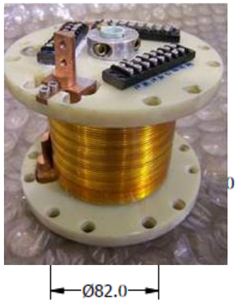
2007



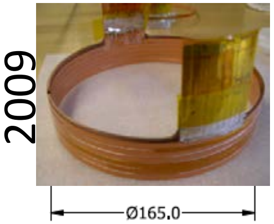
2008

High-B coils
31 T + ΔB

2008



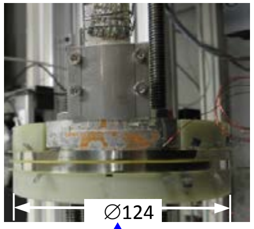
2009



Demonstration inserts
20 T+ ΔB

High Hoop-stress coils
>760 MPa

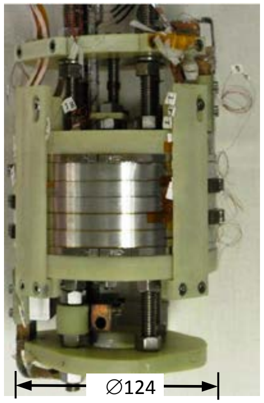
2011



First Quench Heaters

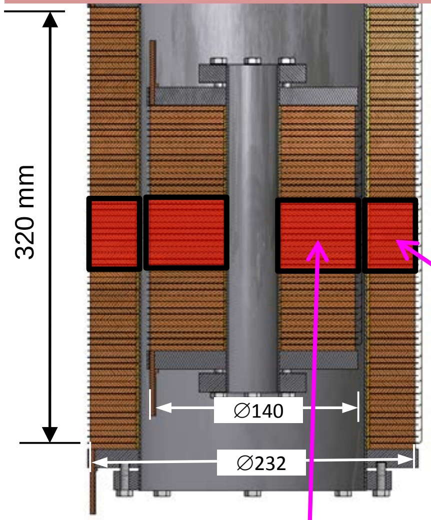
42-62 Mark 1:
1st test coil

2012



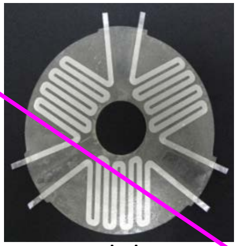
42-62 Mark 2:
2nd test coil

Prototype coils under test
20% of 32 T REBCO coils



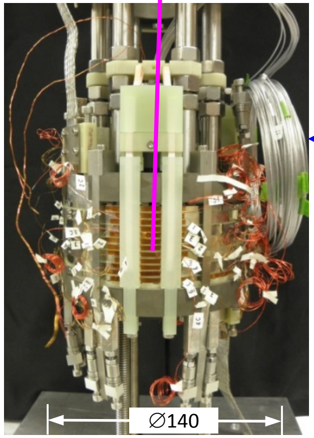
Development:

- YBCO tape characterization & QA
- Insulation technology
  - Ceramic on co-wound SS tape
- Coil winding technology
- Joint technology
- Quench protection analysis
- Extensive component testing



Quench heater

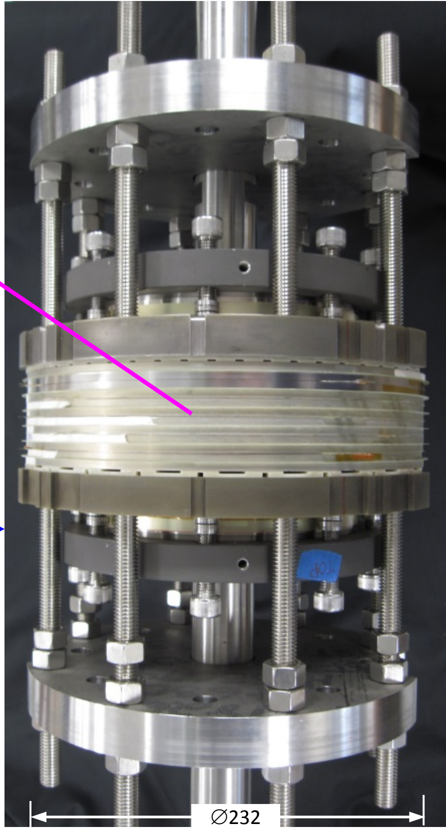
2013



20 - 70:
1st Full-featured Prototype

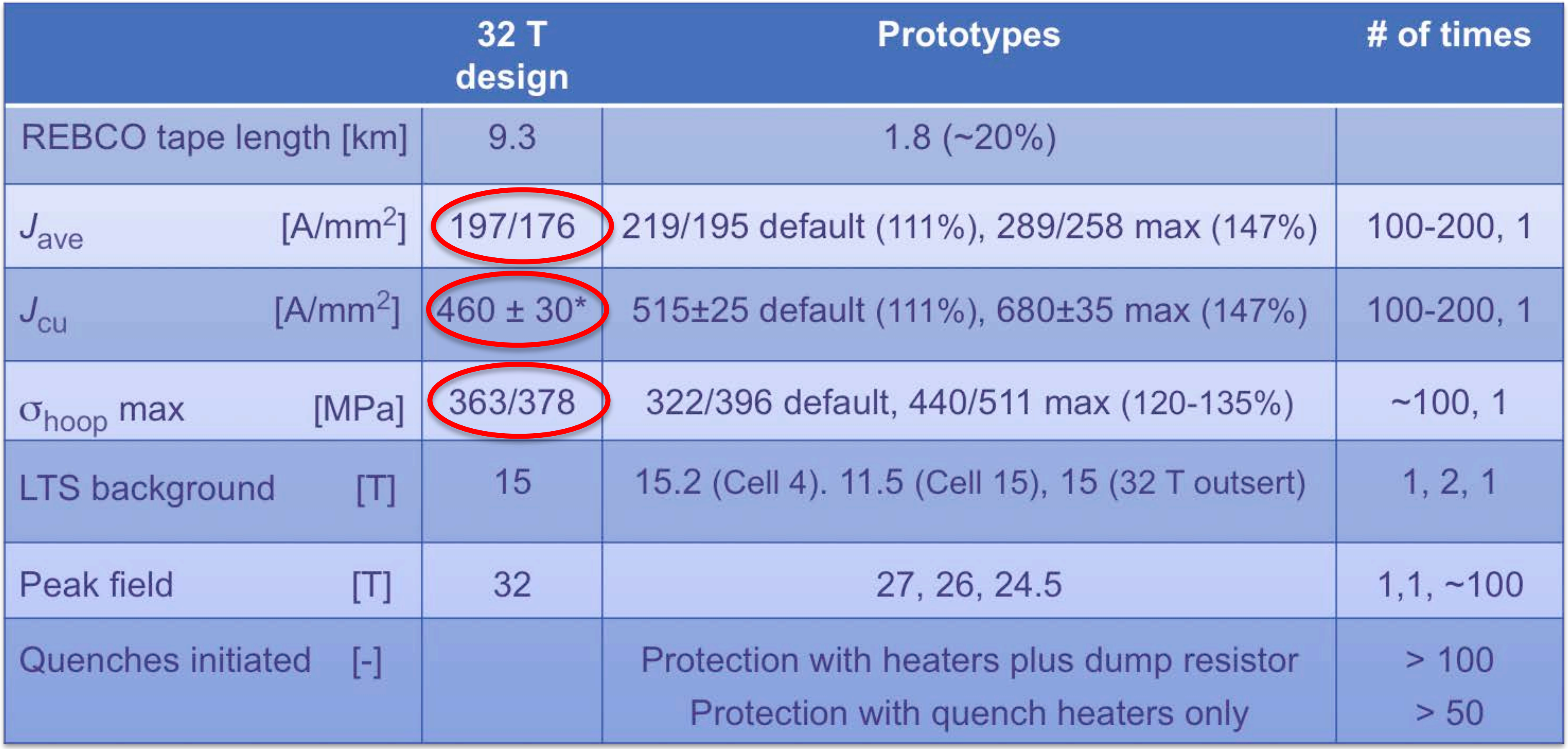
Heater-only
quench
protection

2014



82 - 116:
2nd Full-featured Prototype

32 T experiences so far

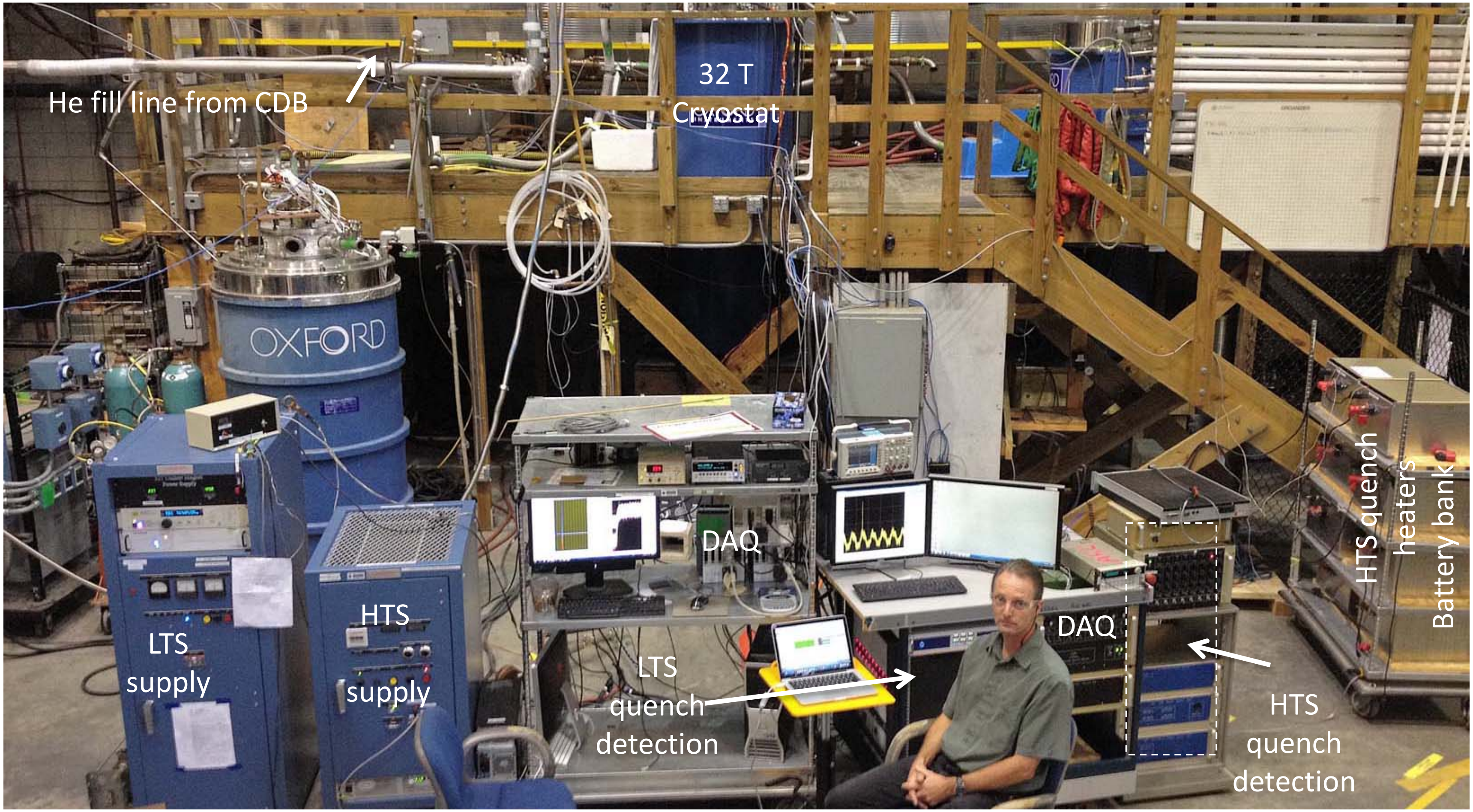


	32 T design	Prototypes	# of times
REBCO tape length [km]	9.3	1.8 (~20%)	
J_{ave} [A/mm^2]	197/176	219/195 default (111%), 289/258 max (147%)	100-200, 1
J_{cu} [A/mm^2]	460 ± 30*	515±25 default (111%), 680±35 max (147%)	100-200, 1
σ_{hoop} max [MPa]	363/378	322/396 default, 440/511 max (120-135%)	~100, 1
LTS background [T]	15	15.2 (Cell 4). 11.5 (Cell 15), 15 (32 T outsert)	1, 2, 1
Peak field [T]	32	27, 26, 24.5	1,1, ~100
Quenches initiated [-]		Protection with heaters plus dump resistor Protection with quench heaters only	> 100 > 50

*: Cu amount varies between conductor batches

As a user magnet it must work – choices not designed to be risky

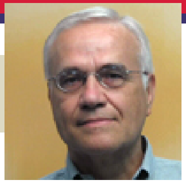
Prototype LTS/HTS integration test with 15 T OI Outsert: June 5, 2015 – 27.0 T achieved



32T project manager Huub Weijers seated at the test station during successful testing of many insert coil and outsert coil quenches

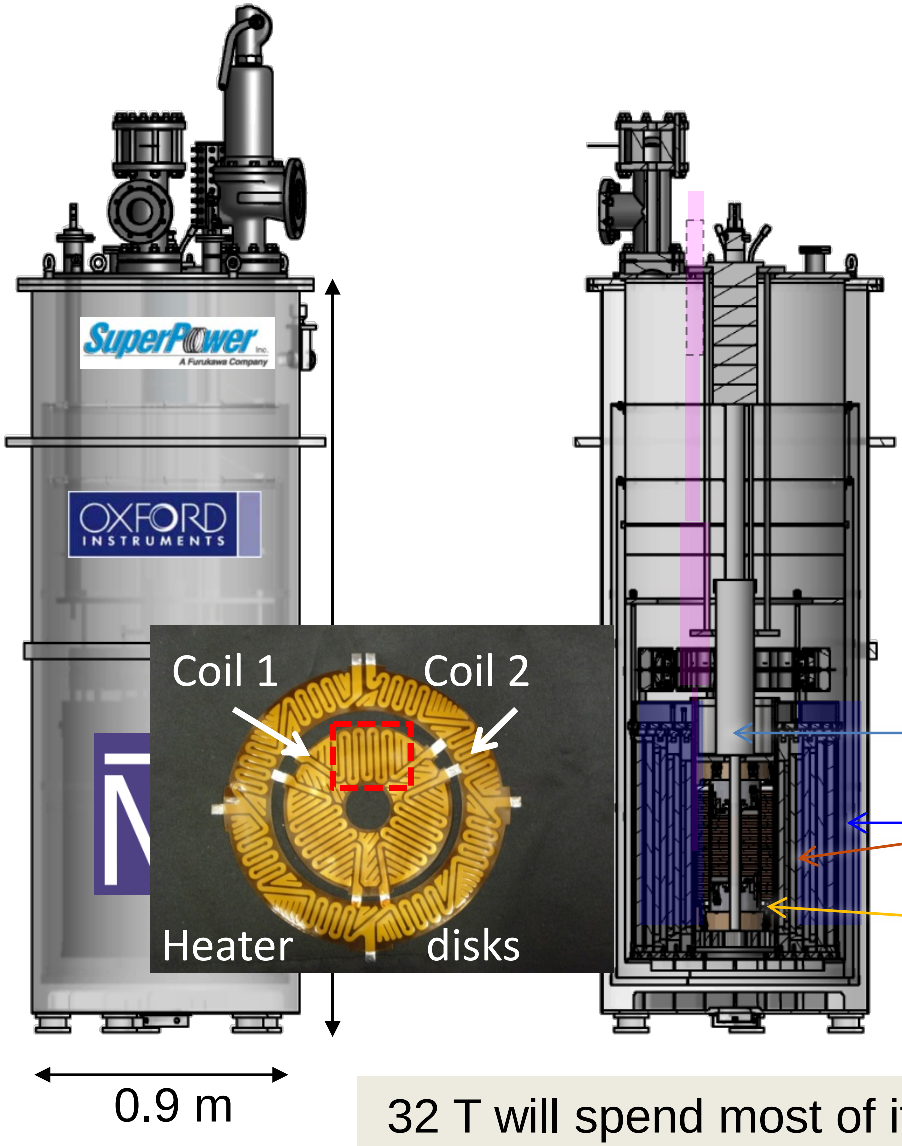
The 32 T User Magnet – 2016 operation

Chief designer: Denis Markiewicz



Cold Bore	34 mm
Uniformity $^{1\text{ cm DSV}}$	$5\cdot10^{-4}$
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

NbTi

Nb_3Sn

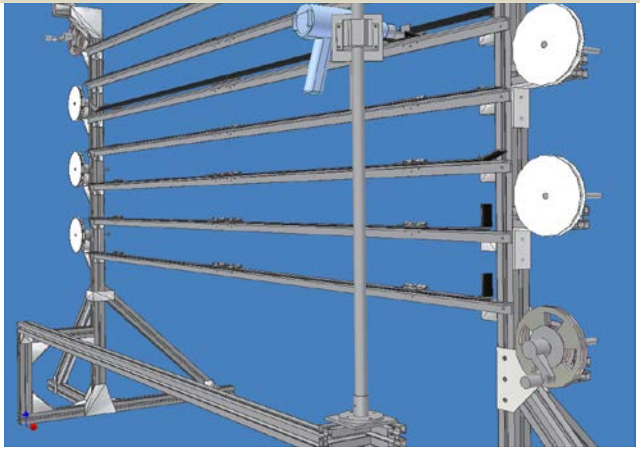
15 T / 250 mm bore LTS magnet

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

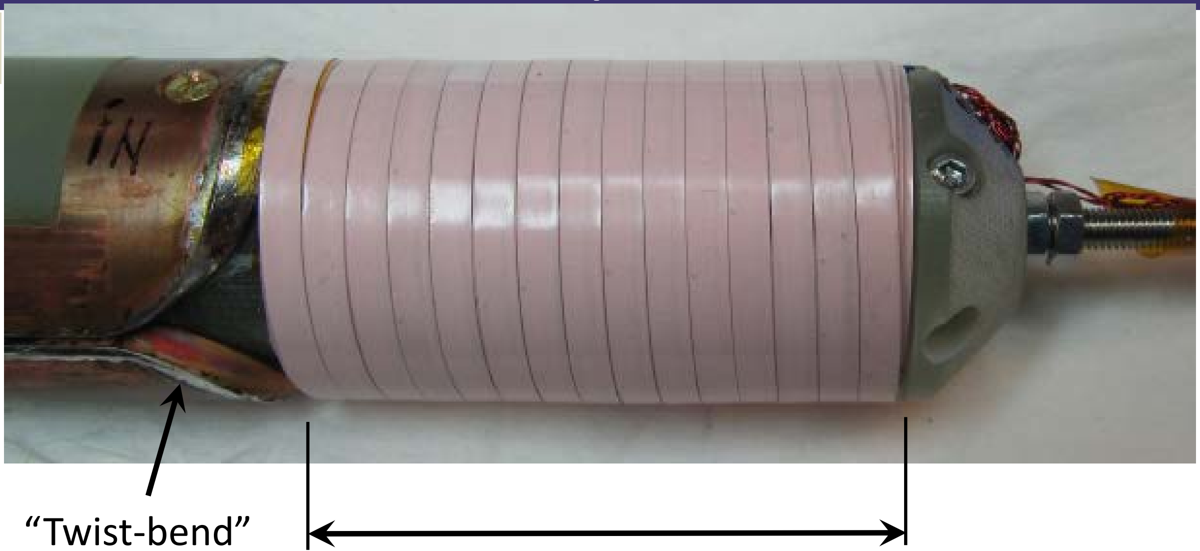
32 T will spend most of its life *ramping up and down at 4.2 K*

35 T REBCO Layer Wound Insert Coil in 2011 (present world record)

Andrew Whittington MS thesis 2014



200 m conductor insulation facility



“Twist-bend” coil termination

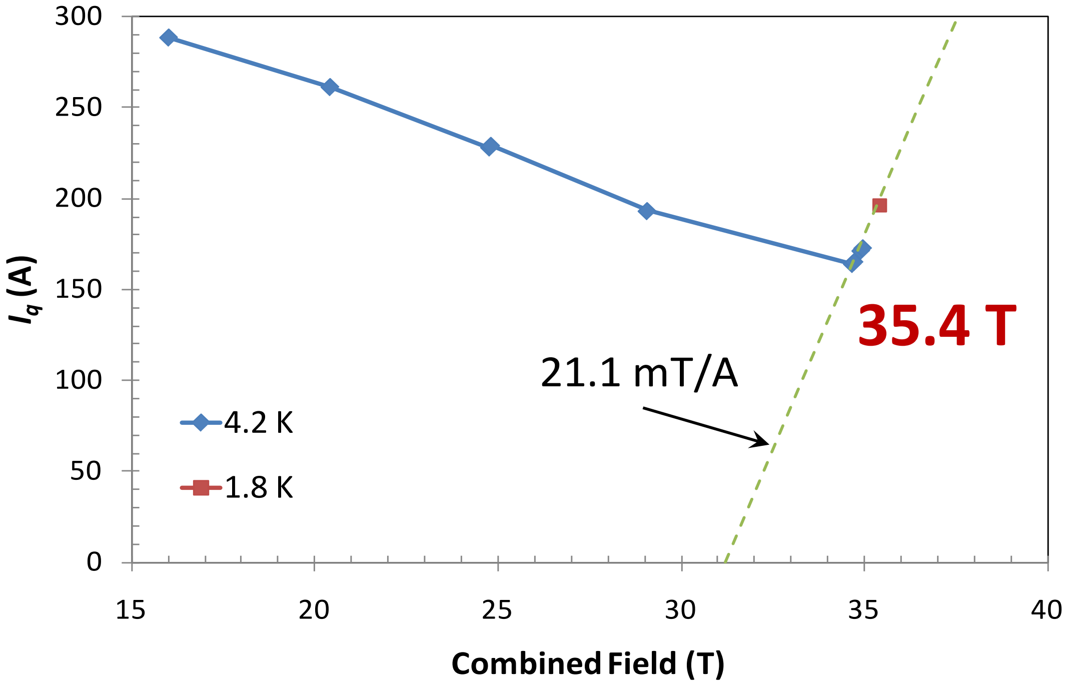
64.5 mm

- **Wet epoxy layer-wound without splices (SuperPower tape)**
- **thin walled polyester heat-shrink tube introduces zero-strength interface into winding, avoiding delamination issues**
- **Voltage taps every 5 – 10 layers**

Conductor & Coil			**EM Properties**	
Cond. Width [mm]:	4.02		Operating Current [A]:	200
Cond. Thickness [mm]:	0.096		Je (Engineering) [A/mm^2]:	518.24
			Jw (Winding) [A/mm^2]:	308.93
Inner Radius [mm]:	7.16		B(0,0) [mT]:	4221.01
Outer Radius [mm]:	18.92		Coil Constant (0,0) [mT/A]:	21.11
Height [mm]:	64.52		L [mH]:	8.90
Layers [-]:	80		Total Field Energy [J]:	187.92
turns/Layer [-]:	14.65			
turns total [-]:	1172			
Cond. Length [m]:	96.03			

Trociewitz *et al.*, APL 99 202506 (2011)

Testing in 38 mm cold bore 32 T magnet produces substantial He bubble and terminal heating – He II helps



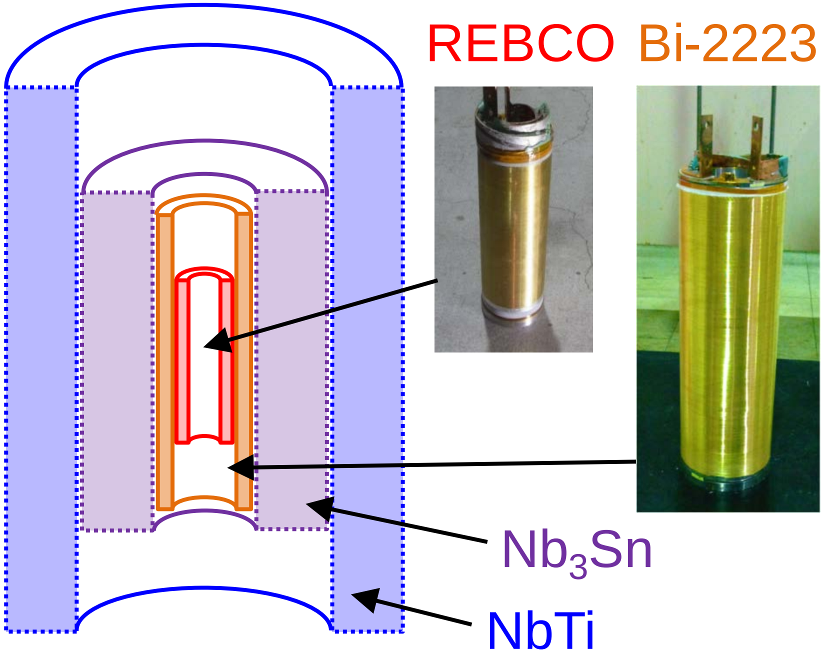
- Some signs of field limit by low Ic point in conductor – stimulated us to pursue length-dependent Ic apparatus (YateStar)
- Fully insulated and robust coil that could be thrown into liquid N_2

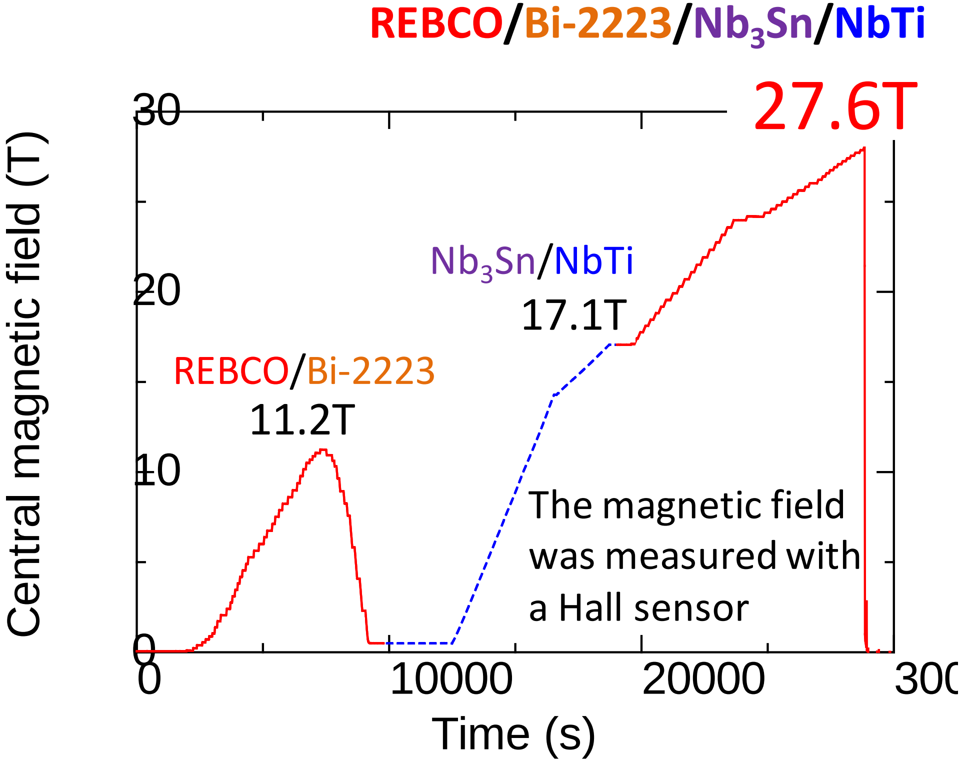
- 4.2 T Field increment achieved in 31.2 T background field
- Coil did not degrade even under repeated fast thermo-cycling
- Showed that stress levels >340 MPa and conductor current density J_e ~500 A/mm^2 are possible
- Introducing insulation layer decoupling during coil manufacturing negates low delamination stress weakness

Trociewitz, Dalban-Canassy et al. APL 99, 202506 (2011)

27.6 Tesla superconducting magnet; The combination of REBCO, Bi-2223, Nb$_3$Sn and NbTi

Supported by the JST under the S-INNOVATION program





The magnetic field was measured with a Hall sensor

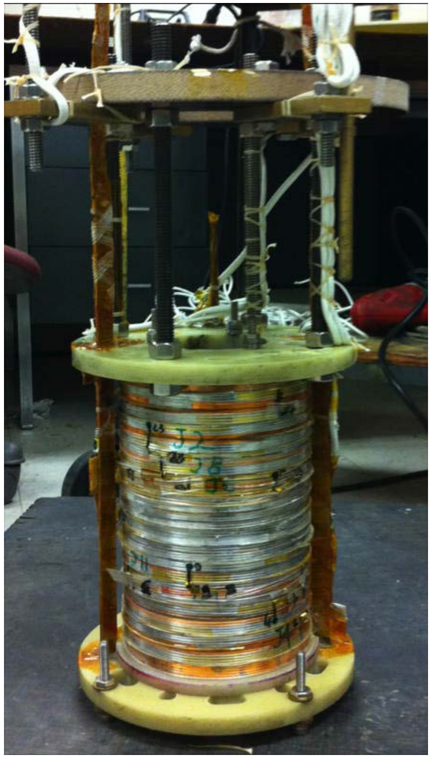
An increment of the world record of a magnetic field intensity for fully superconducting magnets operated at 4.2K

Very compact, very high field NI (No Insulation) REBCO magnets now at NHMFL

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

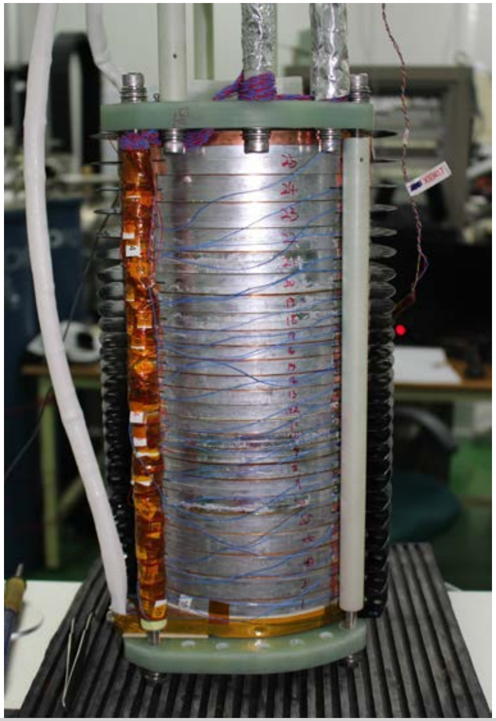
- Pros of NI magnets
  - Self-protecting by turn-to-turn "bypass" of quench current
  - Strong: >50 % enhanced winding mechanical strength
  - Compact: 3x J_W means 1/3 coil radial build
- Cons
  - Charging delay: 0.5-hour for 9 T/78-mm; 3-hour for 26T/35-mm
  - Limited operational experience so far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

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



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

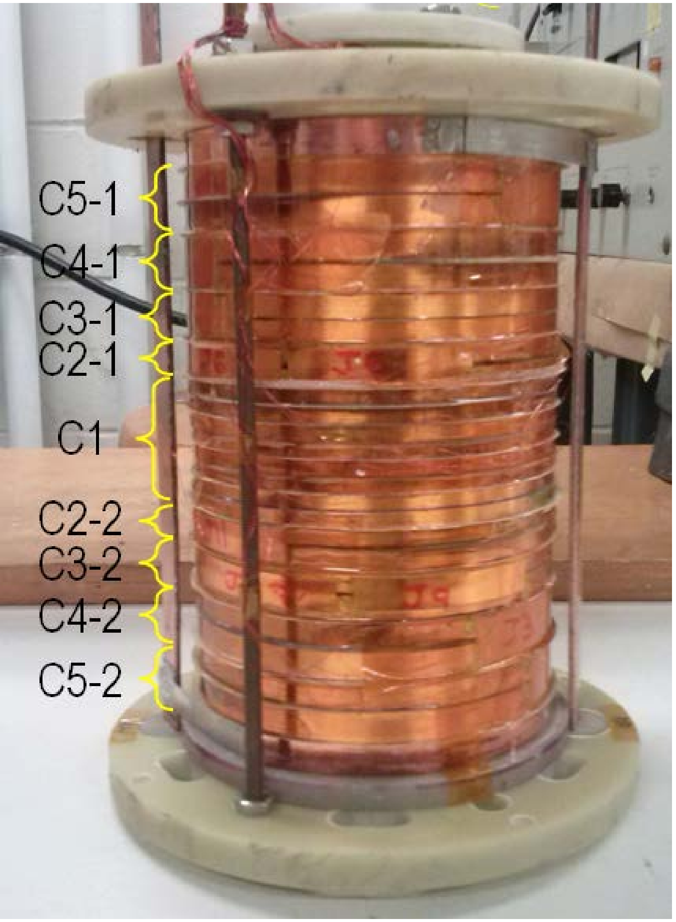
26 T/35-mm REBCO (2015, SuNAM/MIT/FSU)



Design by Hahn, mfr by SuNAM

- Coil OD: 172 mm
- World record all-REBCO magnet

Multi-width NI magnet: extremely high current density operation, yet self protecting

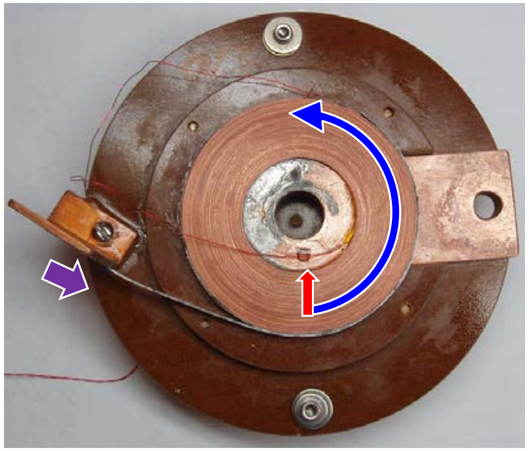


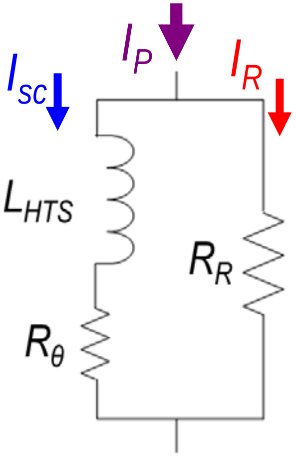
Parameter	C1	C2	C3	C4	C5
Tape width [mm]	4.1	5.1	6.1	7.1	8.1
ID; OD [mm]	78.0; 101.8				
Height [mm]	158				
Number of DP	5x1	1x2	1x2	1x2	1x2
Turn per pancake	140				
I_{op} at 9 T [A]	312				
T_{op} [K]	4.2				
Inductance	0.52				
J_e at I_{op} [A/mm^2]	870	703	590	508	447
Peak B_{perp} at I_{op} [T]	1.4	1.7	1.8	1.9	2.7

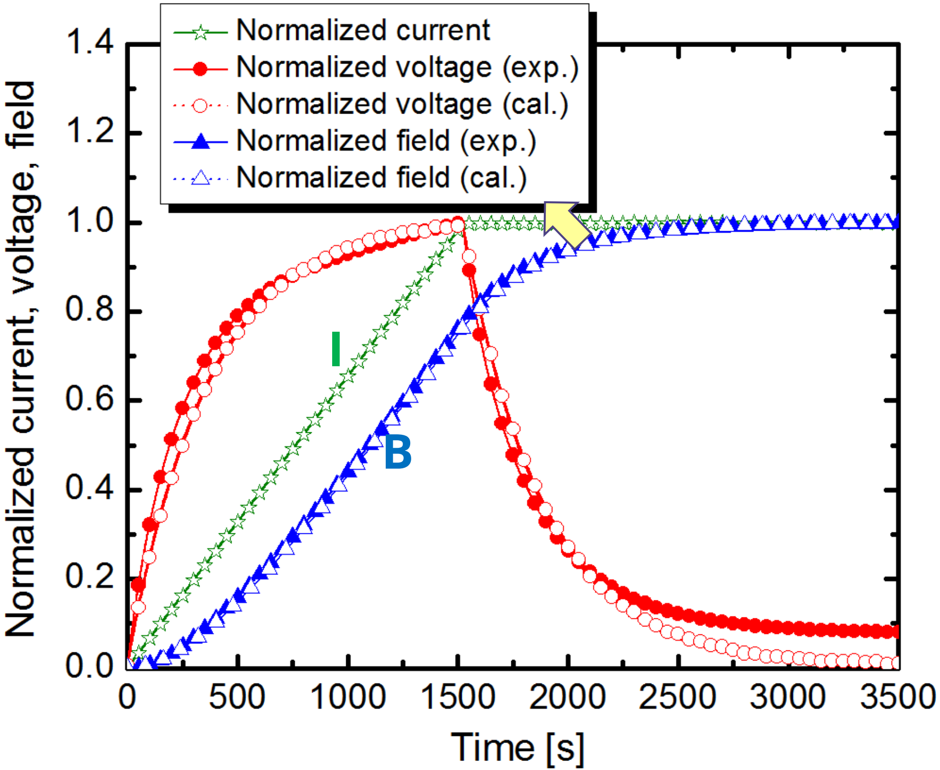
- First tests Hahn and Iwasa at MIT, thenat ASC-NHMFL
- Note the **very high winding current density - ~900 A/mm^2**

NI coil drawbacks

- Charging time constants:
  40 minutes for 26-T/35-mm;
  15 hours for 60-T/40-mm







☐ Partial Insulation: ~5 times faster charging than that of NI, measured at 77 K[1].

☐ Metallic cladding insulation: ~12 times faster charging than that of NI, measured at 77 K[2].

☐ Self-protecting of PI and MCI demonstrated in LN2 at 77 K but *not in LHe at 4.2 K*

REF 1: Y. H. Choi, et al., "Partial insulation of GdBCO single pancake coils for protection-free HTS power applications," *Supercond. Sci. Technol.*, 24, 2011 (125013).

REF 2: SuNAM, a report on test results of REBCO coils wound with stainless steel coating tapes, July 2015.

NI REBCO magnet summary

- The MW-NI technique enables REBCO magnets to be *compact, self-protecting, and mechanically robust* to a level never before achieved.
  - 40 T designs under consideration
- Challenges: 1) slow charging; 2) limited user experience so far; 3) unknown unknowns.
- Partial insulation or metallic cladding insulation may enable faster charging.

Seungyong Hahn designs

REBCO CC – key positives

- Multiple vendors in US, J, K, RU, EU vying to supply
- Many are made on very strong Hastelloy substrate (yield ~1 GPa)
- Winding diameters less than 15 mm
- Very high J_c in REBCO layer
- In superconducting state as delivered – winding is simple if appropriate restrictions observed

REBCO CC – key challenges

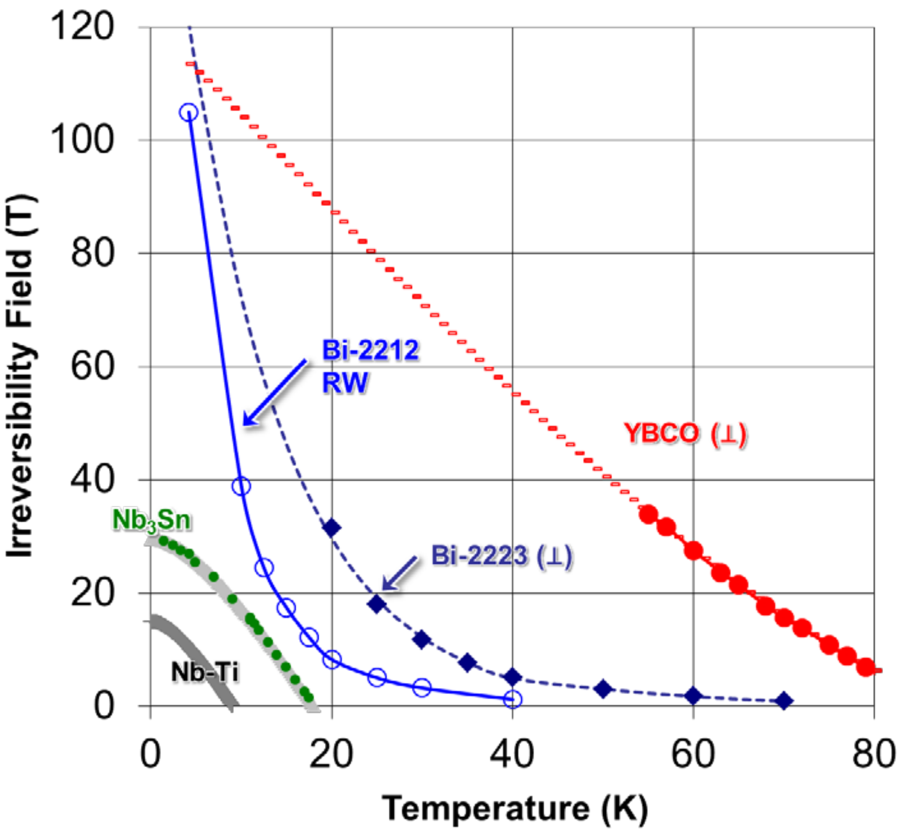
- “Single crystal by the kilometer” implies perfection
  - Conductors are not yet perfect
  - As single filaments they are subject to any defect that interrupts current
- Single filaments ~4 mm wide develop large screening currents in perpendicular fields – error fields (Questionable for NMR use?)
- Like all HTS, electromagnetic anisotropy is large ~ 5
- 32 T has been a wonderful test bed for working through many issues
- Weak adhesion of REBCO to buffer layer and substrate means that weak adhesion planes must be built in to impregnated magnets

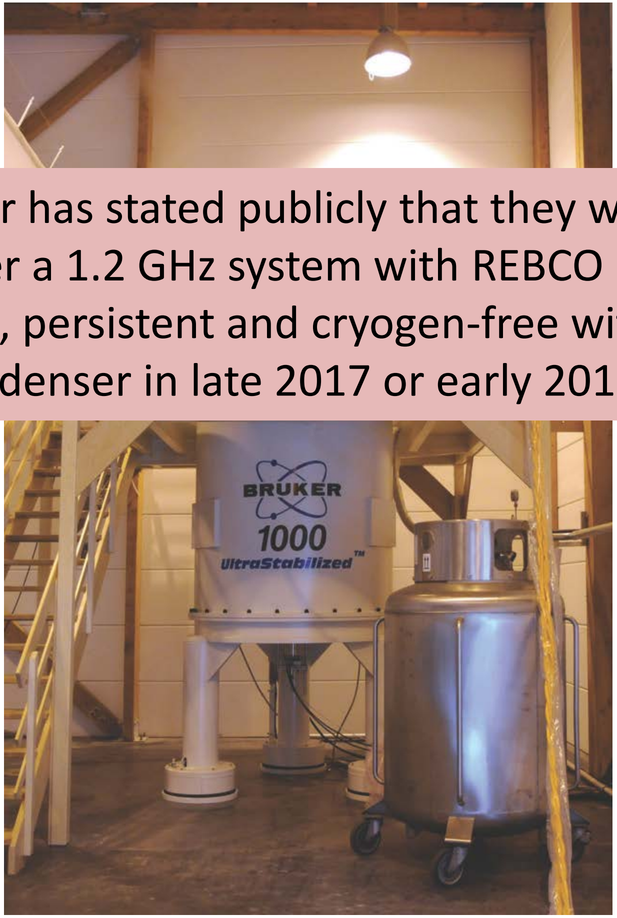
Multiple MagSci Goals (2013)

- **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

The high field NMR goal has 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)

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



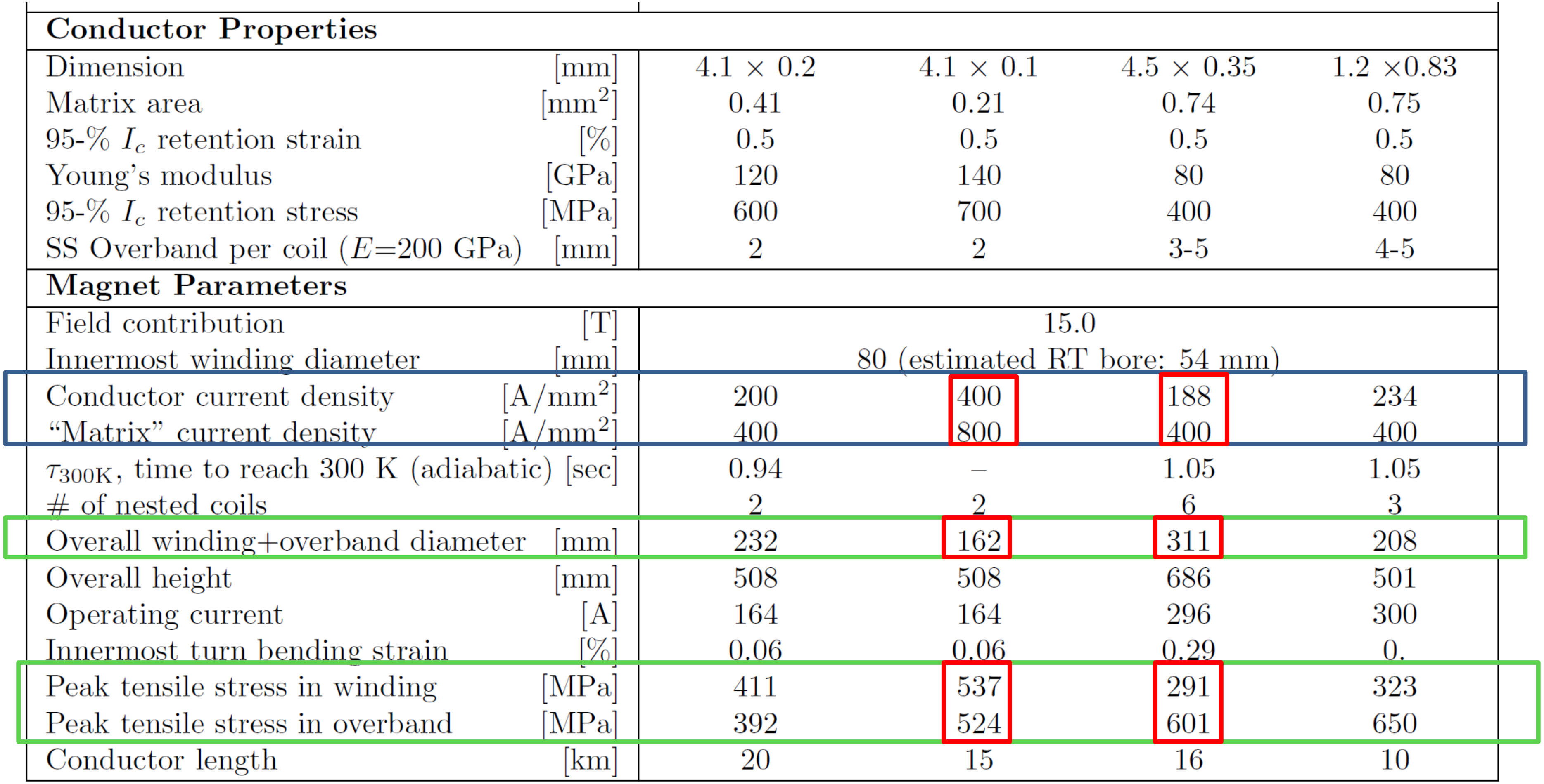


Bruker has stated publicly that they will deliver a 1.2 GHz system with REBCO insert, persistent and cryogen-free with recondenser in late 2017 or early 2018.

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

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
$\tau_{300\text{K}}$, 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

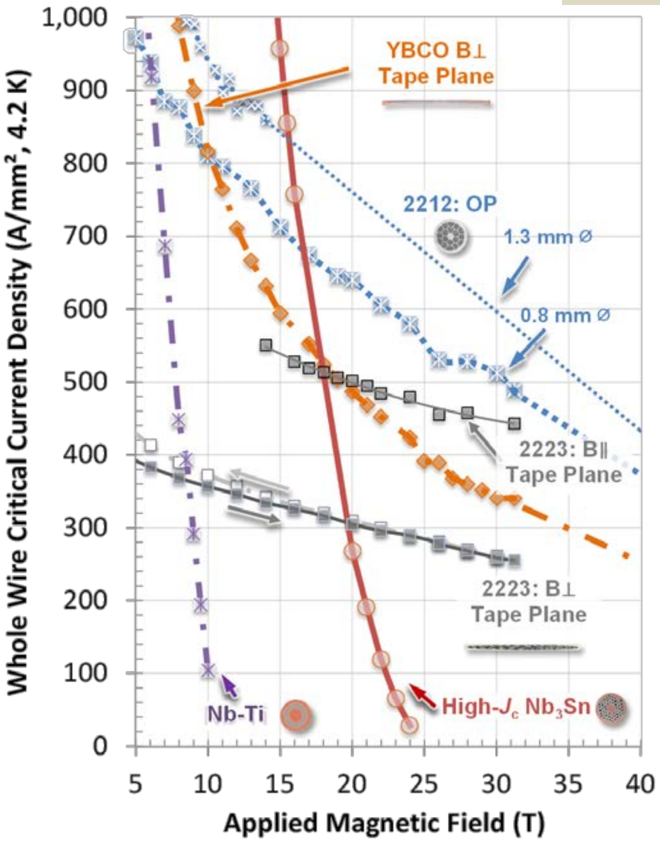
Huge value in being able to operate at high stress, high Cu/Ag current densities – much smaller LTS and HTS coil (designs by Hahn – further iterations expected)

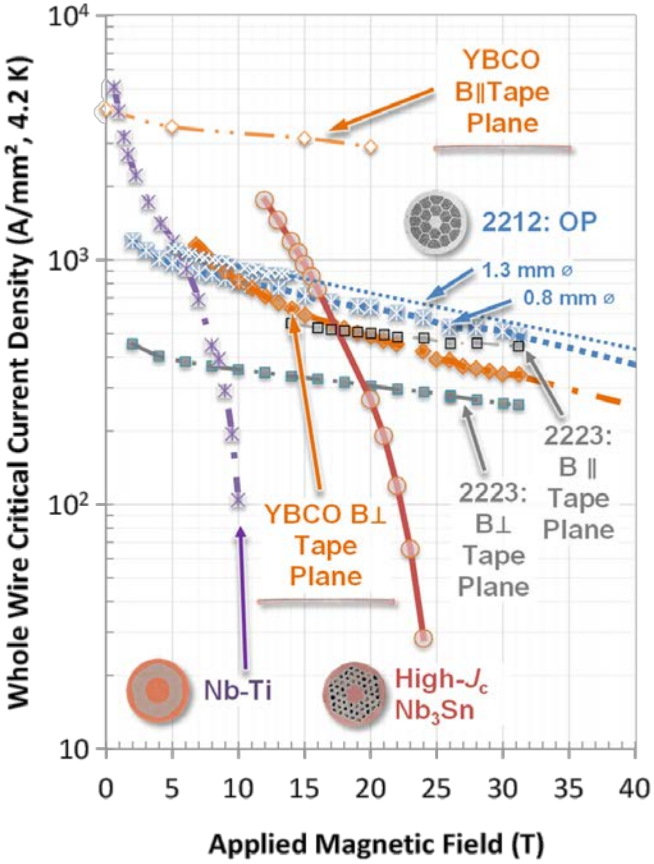
Key conductor challenges

- 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

What Current density is feasible?

Whole wire Jc values below

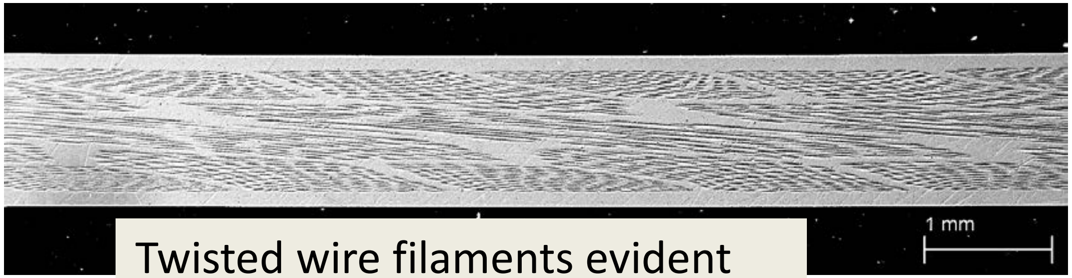




- Isotropic round wire conductors like Bi-2212 are in principle much preferred – but if anisotropic conductors like REBCO or 2223 are to be used, can their much higher H||ab plane properties be used?
- Remember that High Jc also brings quench and force problems too!

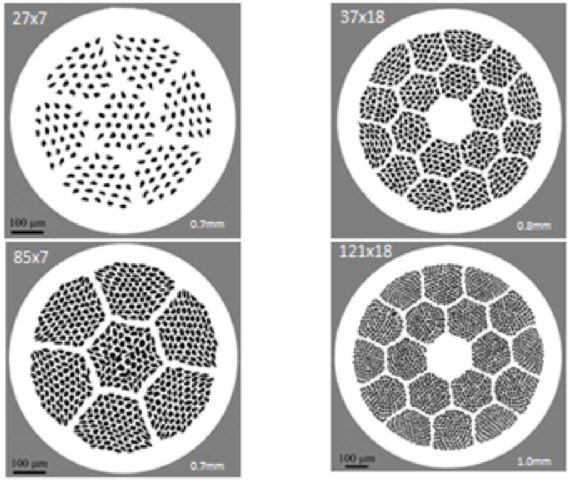
Bi-2212 – key positives

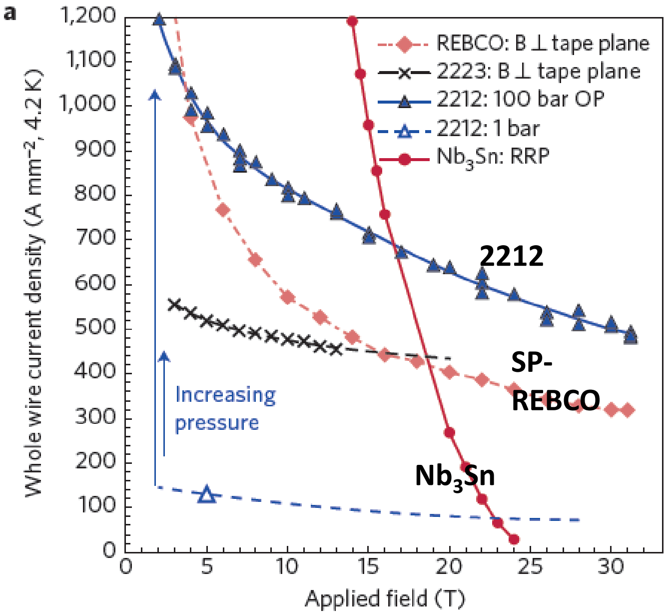
- Round, fine filament (~15 μm), twisted
- Available in multiple architectures
- Made on the same fabrication lines as Nb-Ti and Nb_3Sn
- OST is making single billet piece lengths in multiple architectures
- Does not depend (like REBCO and Bi-2223) on electric utility demand
- After loss of Nexans powder production, domestic SBIR companies appear able to supply equal or better powder
- Has the highest J_E of any HTS conductor and crosses over with Nb_3Sn at ~ 16 T (but with much bigger ΔT)
- Small coils being fabricated at FSU, FNAL and LBNL under BSCCo partnership



Twisted wire filaments evident

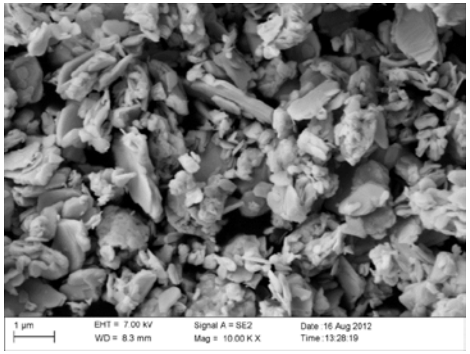
Unreacted Wire Cross Sections



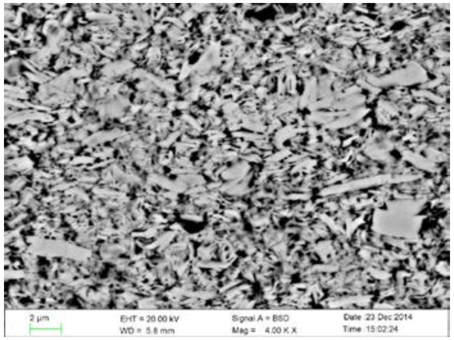


Bi-2212 – key challenges

- 50-100 bar overpressure required (now) for optimum properties
- Ag has low E (70GPa) and conductors have low filament fracture stress (~150 MPa)
- Powder supply has been a challenge – but 3 US vendors active (MetaMateria, nGimat, Solid Materials Solutions (SMS) – two now equal Nexans



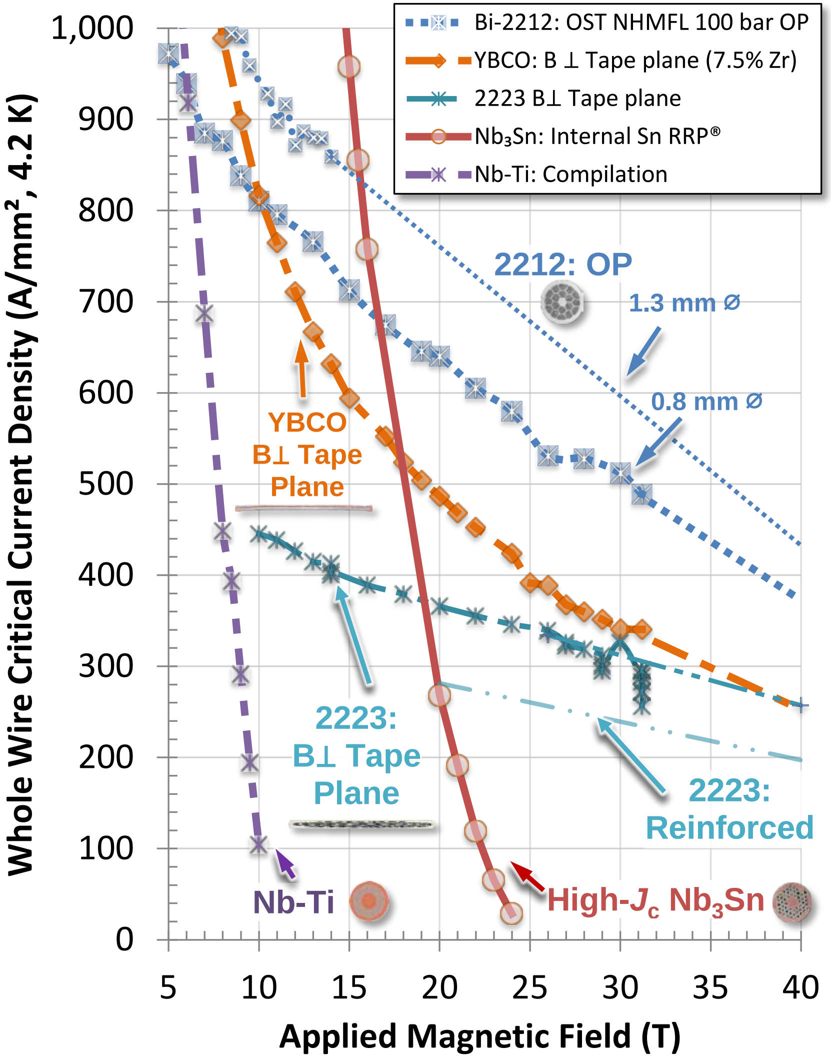
Nexans granulate



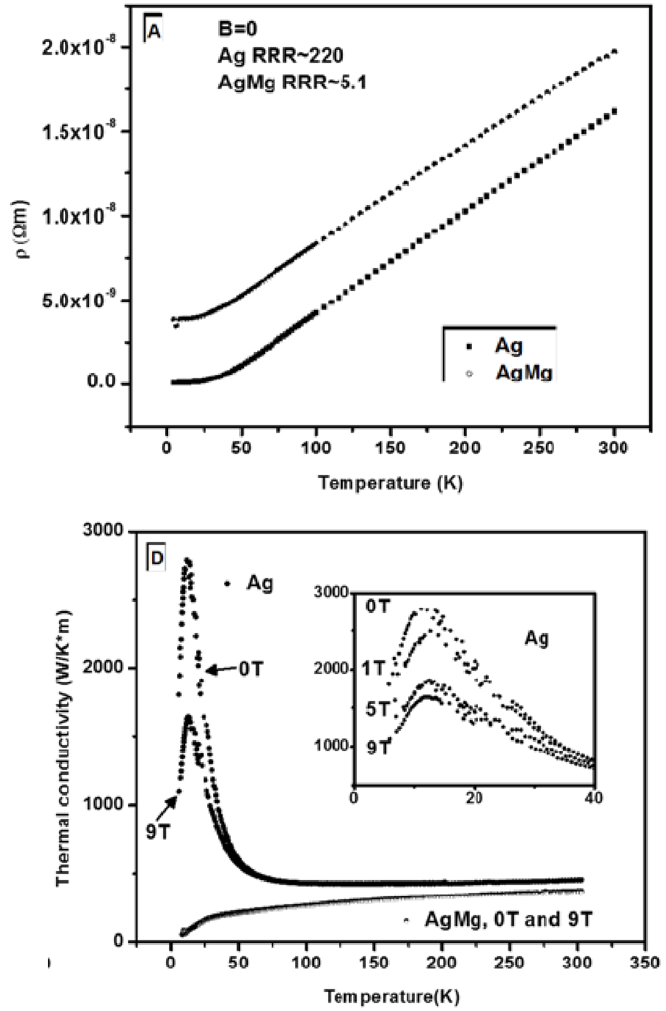
MetaMateria

The MagLab 100 bar OP furnace with 6 zone, 14 cm dia x 50 cm high uniform hot zone – open for collaborative reactions

Excellent engineering current densities and normal stabilizer conductivity in 2212



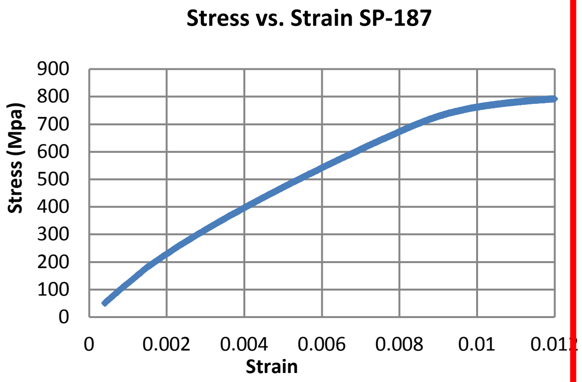
Master plot kept up by Peter Lee (ASC-NHMFL-FSU)



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 now available in REBCO and 2223 – 2212 in development

REBCO Coated Conductor

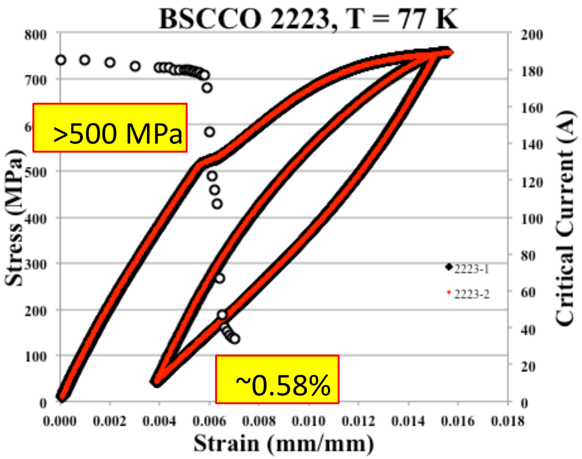


$\sigma(\varepsilon)$ for 32 T REBCO

32 T operates at ~400 MPa at $\varepsilon = 0.4\%$

Weijers et al. MT24 IEEE TAS subm.

Strong 2223 (2223NX)



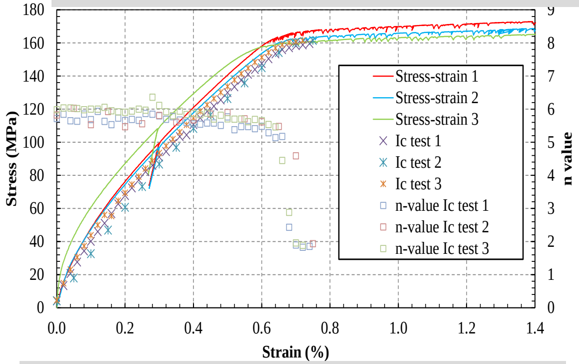
>500 MPa

~0.58%

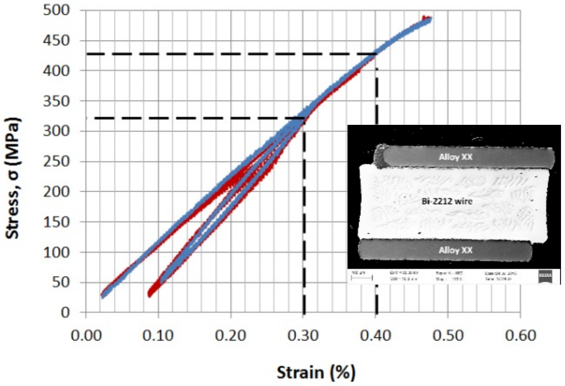
Excellent high field performance by Godeke *et al.* (MagLab 10/15 and Yanagisawa *et al.* SuST 2015

2212

Round, unstrengthened 2212 wire



Bjoerstad and Scheuerlein, *SuST* (2015)



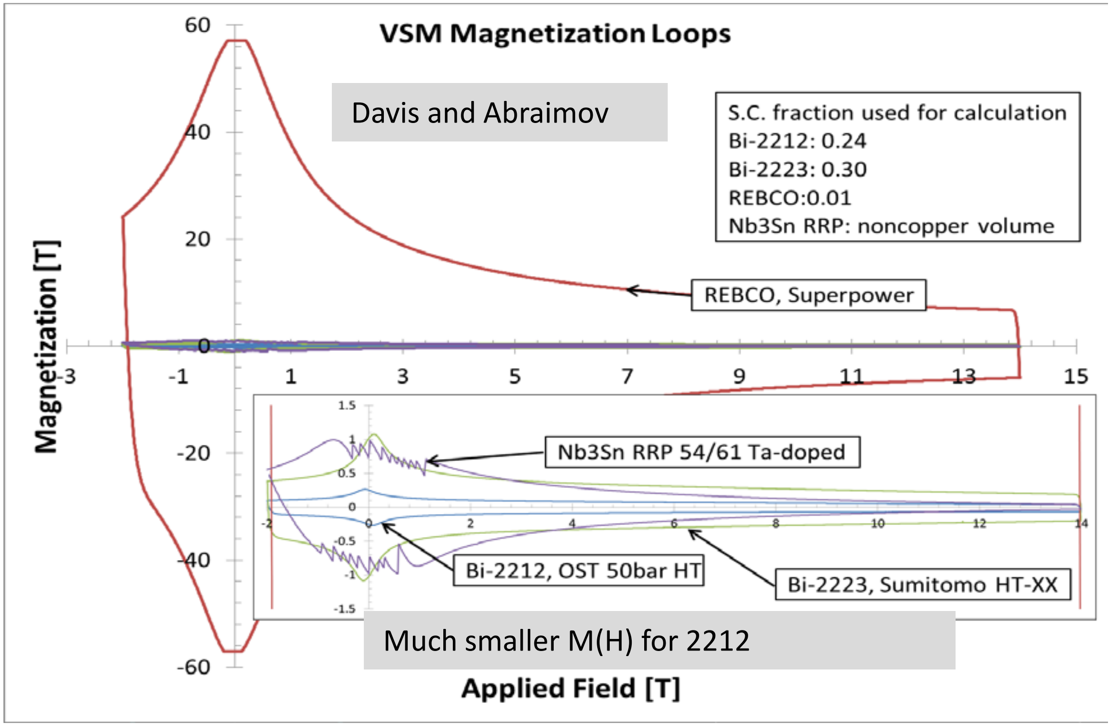
Stress for $\varepsilon = 0.4\%$ raised from 120 to 425 MPa

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

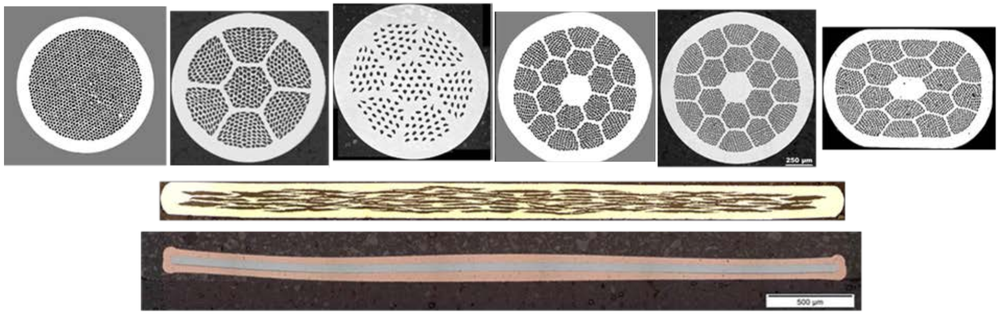
- Two anisotropic conductors:
  - REBCO – fully coupled across the 3-6 mm tape width
  - 2223 – strongly coupled across the 4 mm width of the conductor
  - Much larger magnetizations
- One isotropic conductor (2212)
  - Most closely correlates to Nb-Ti and Nb_3Sn
  - Smallest magnetization

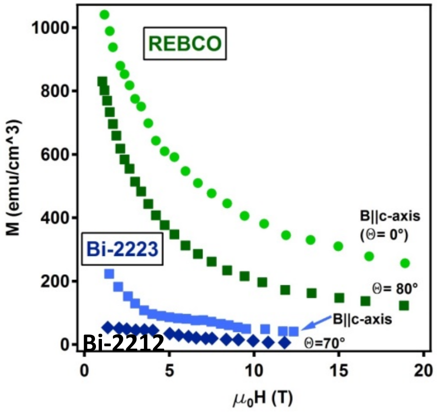


Davis and Abraimov

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

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 - Round wire cable CORC emerging	- 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

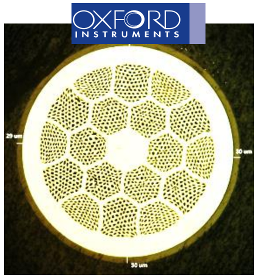
“Platypus” : A Bi-2212 NMR Demo-Magnet

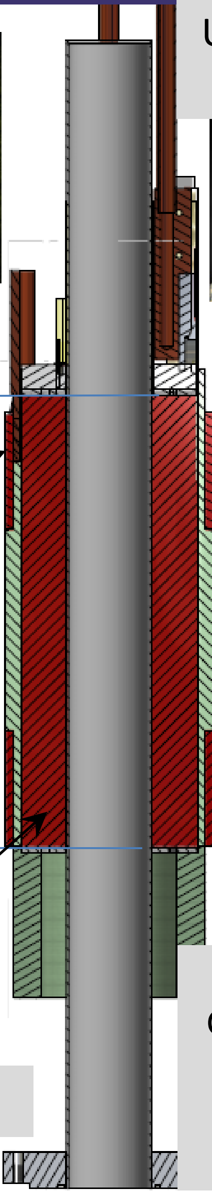
Goals:

- 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)

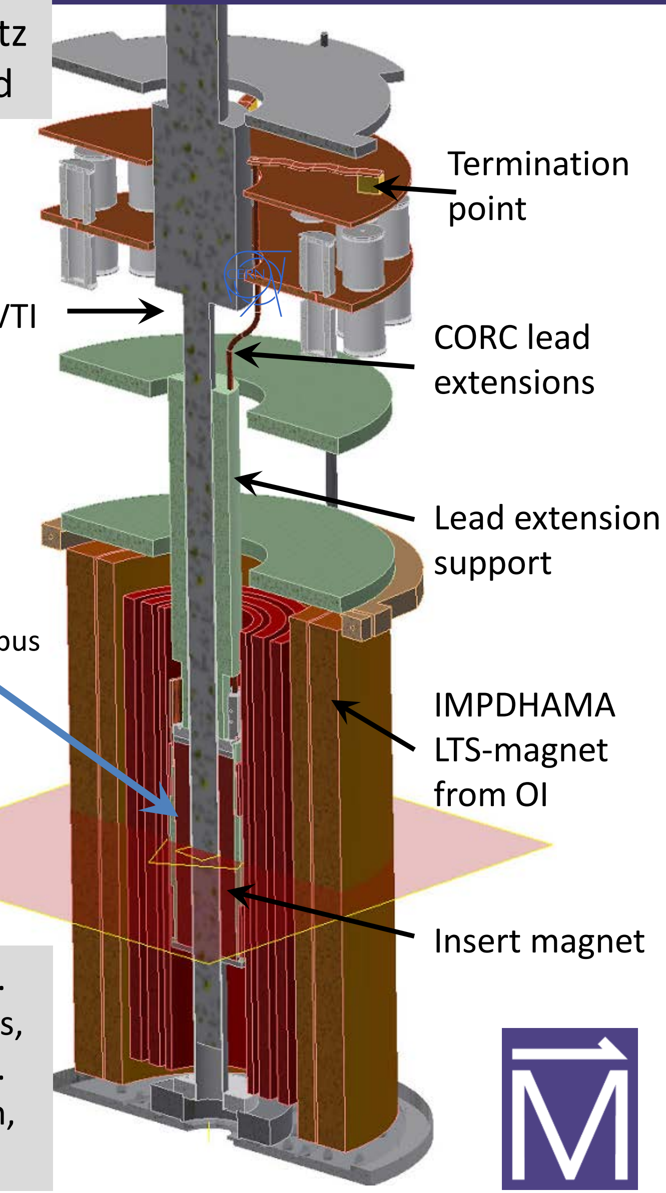
Status:

- 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)





Ulf Trociewitz
Project lead



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

Bismuth Strand and Cable Collaboration BSCCO

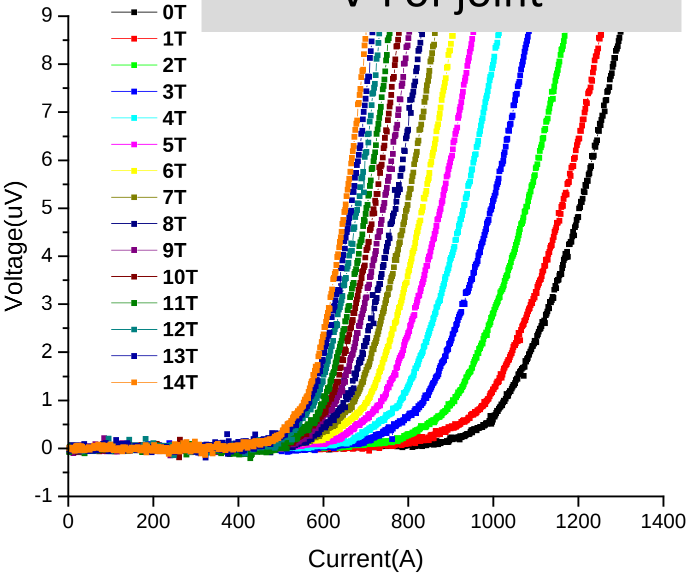
Fermilab BROOKHAVEN NATIONAL LABORATORY CERN

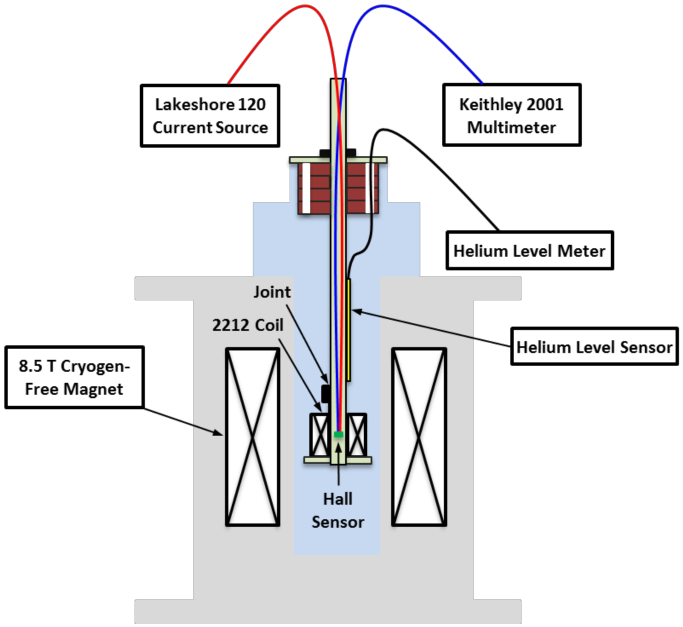
Persistent joints seem feasible with 2212

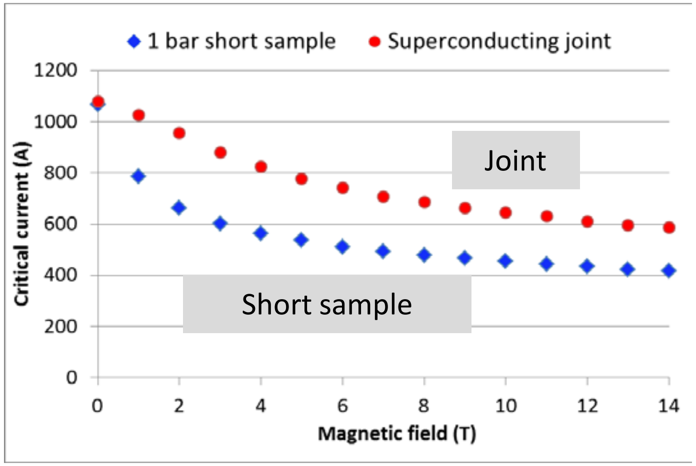
- Joints being evaluated by direct transport and by induced field and its decay
- Long term decay consistent with logarithmic creep of short samples measured in SQUID
- For 100 H magnet τ = 100/5 x 10^{-12} Ω ~ 5 x 10^{9} hrs.

Peng Chen and Dan Davis

V-I of joint

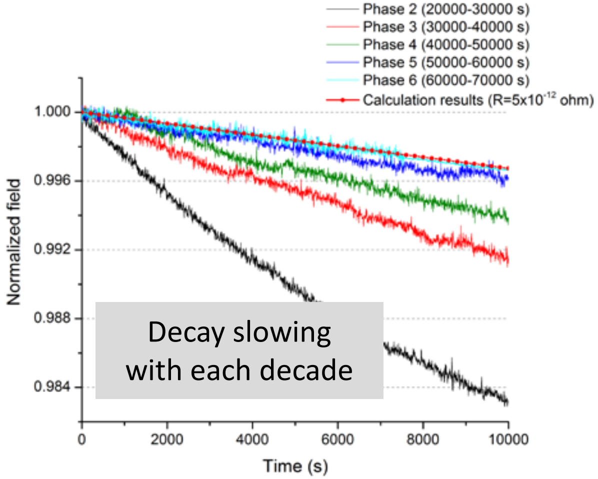






Joint

Short sample

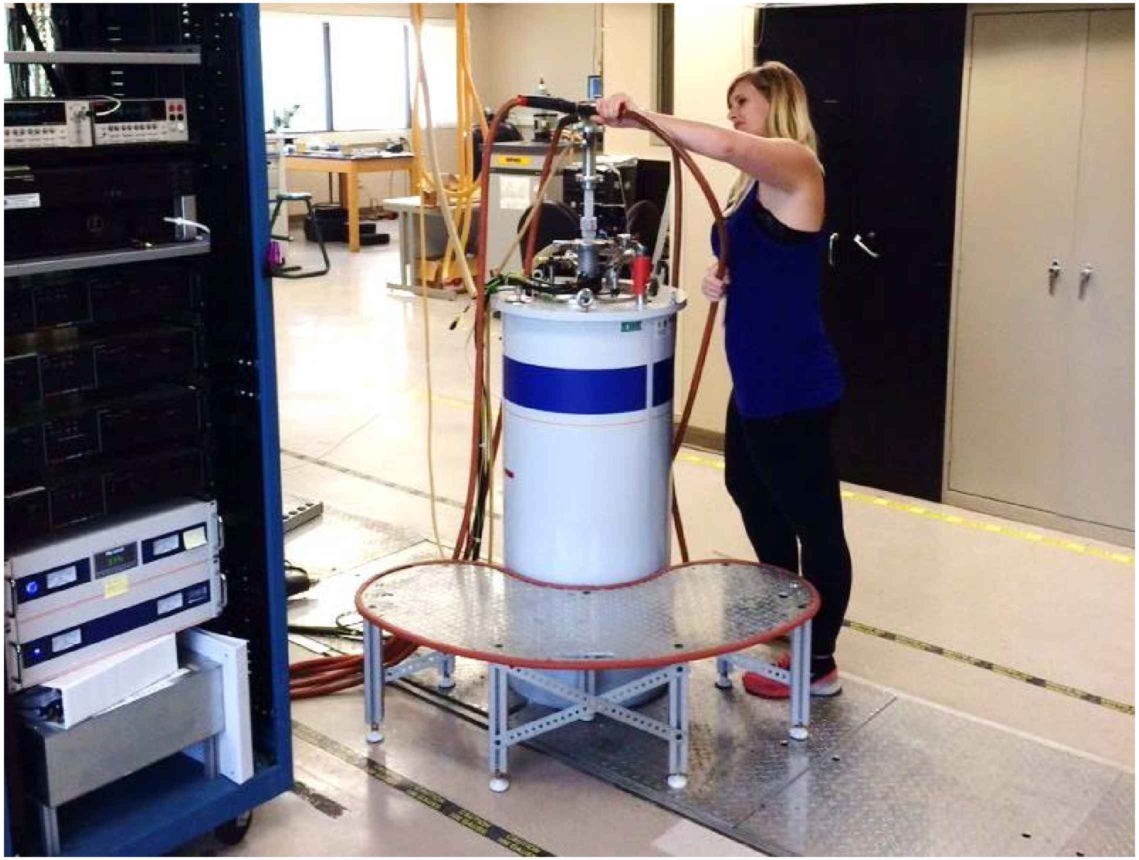


Decay slowing with each decade

Outlook

- Technical feasibility of HTS magnets appears imminent
  - **32 T and 25 T user magnets at NHMFL and Tohoku U are almost delivered for users**
  - **3 all superconducting magnets have generated >26 T (SuNAM (26.4T) , MagLab (27.0T) and RIKEN (27.6T))**
- But the high cost of present HTS conductors makes prototype magnets expensive……
- On a volumetric basis, HTS is 5-10 times cost of Nb_3Sn
- Can HTS conductor costs really come down in the foreseeable future?
- There could be a place for both MgB_2 and K-(Ba/Sr)Fe_2As_2 since both allow round, twisted, multifilament conductors

Standard Oxford 15/17 T 52 mm bore magnet – 2014 total system cost $125K ($Nb_3Sn$ insert = 1 liter)



Conclusion – even R&D magnets pose major budget challenges!

Nb_3Sn insert of 20 year old system failed (60 mm ID/108 mm OD/180 mm height = 1.13 l ~ $20k)

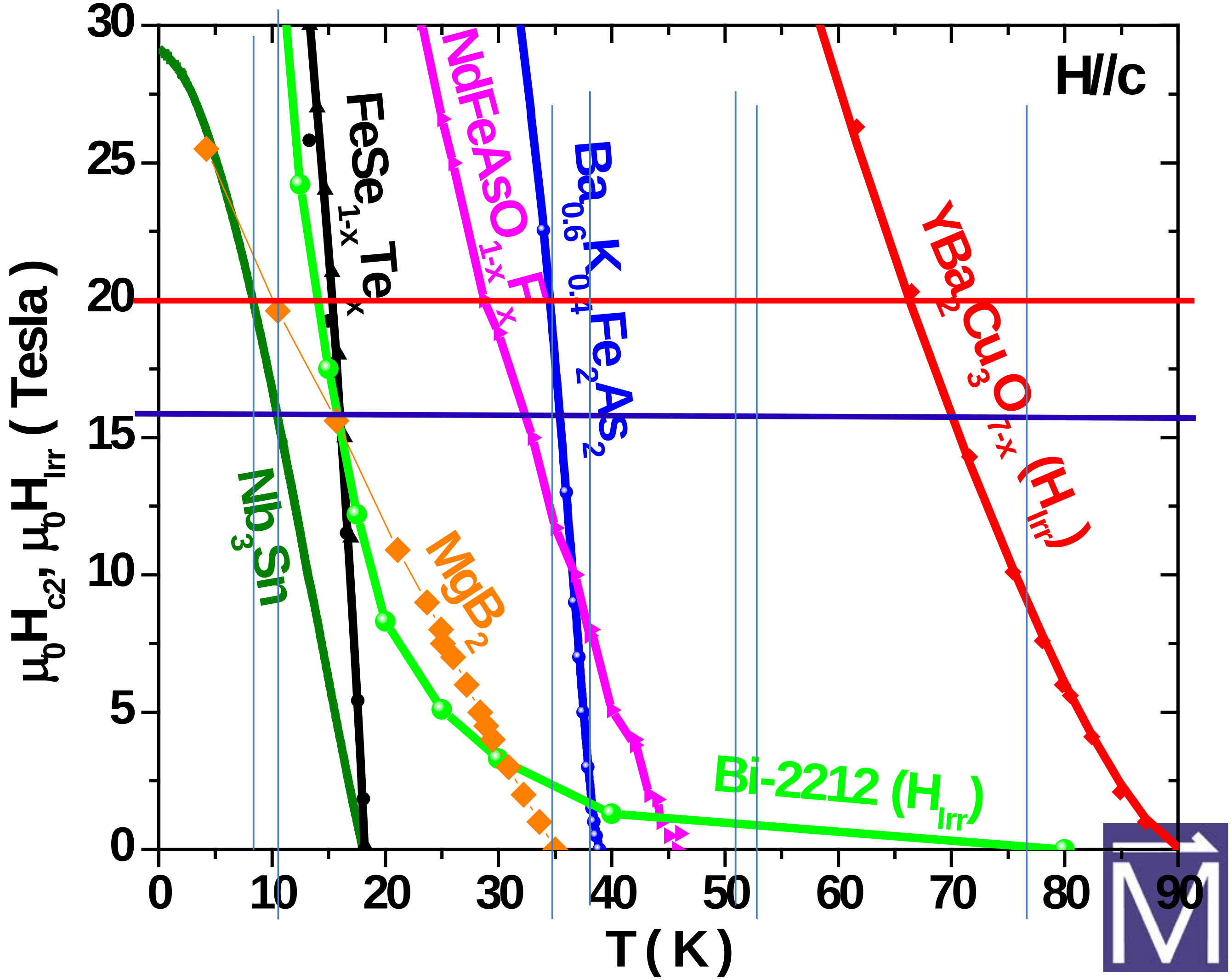
No Insulation REBCO coil replacement for the Nb_3Sn coil has been designed

But – cost of REBCO conductor alone is about $100-200K (1 liter of superconductor)

However – this may give us a compact 20-22 T 4.2 K 52 mm bore magnet for user access

A closer look at <30 T range

- The best reason for choosing a new superconductor may be to get more stability margin
- Quench management remains an unresolved issue for many HTS magnets

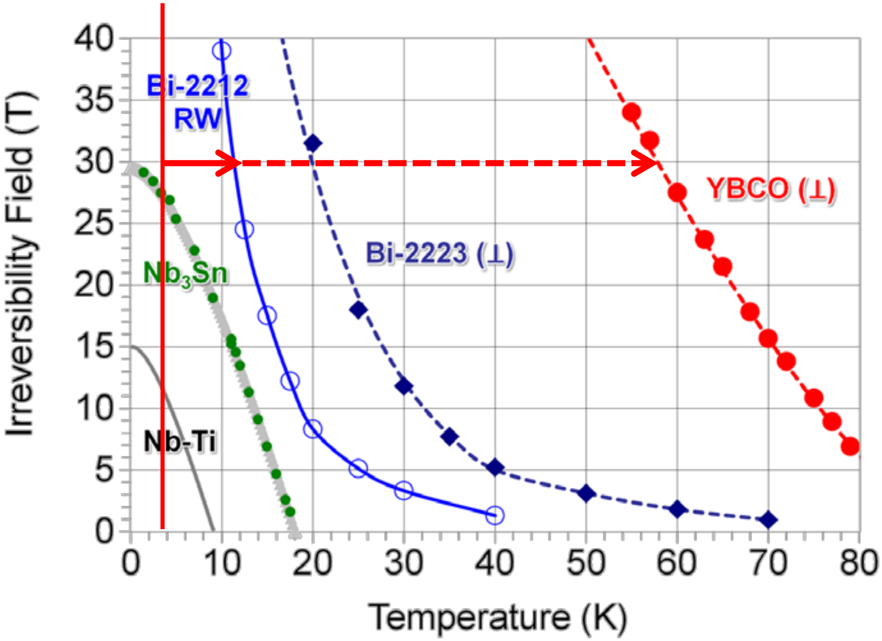


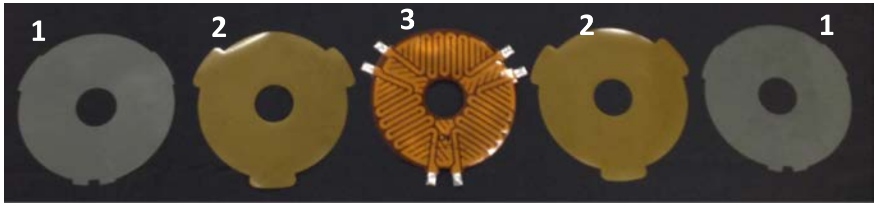
Quench issues

- 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 Ravaioli -Toohig Fellow LBNL)

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

4 K operation





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

Some summary points:

- We have 3 good HTS conductors today – we should use all 3 to understand their tradeoffs, merits and drawbacks
- No magnet is ever better than its conductor!
- No HTS conductor is yet as mature as Nb-Ti or Nb_3Sn (length, uniformity, cost)
- HTS blasts through the H_{c2} limit of Nb_3Sn – more subtle but real limits of stress, quench and cost remain and will challenge us!
- UHF NMR cannot support a major HTS conductor market by itself! (Risk of losing REBCO and 2223? We really need more electric utility demand to assure coated conductor production)

A bright future for high field HTS magnets?

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, Daniel Davis, Peng Chen, Yavuz Oz, Michael Brown 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