Advances in Ultra-High Field Magnet Technology

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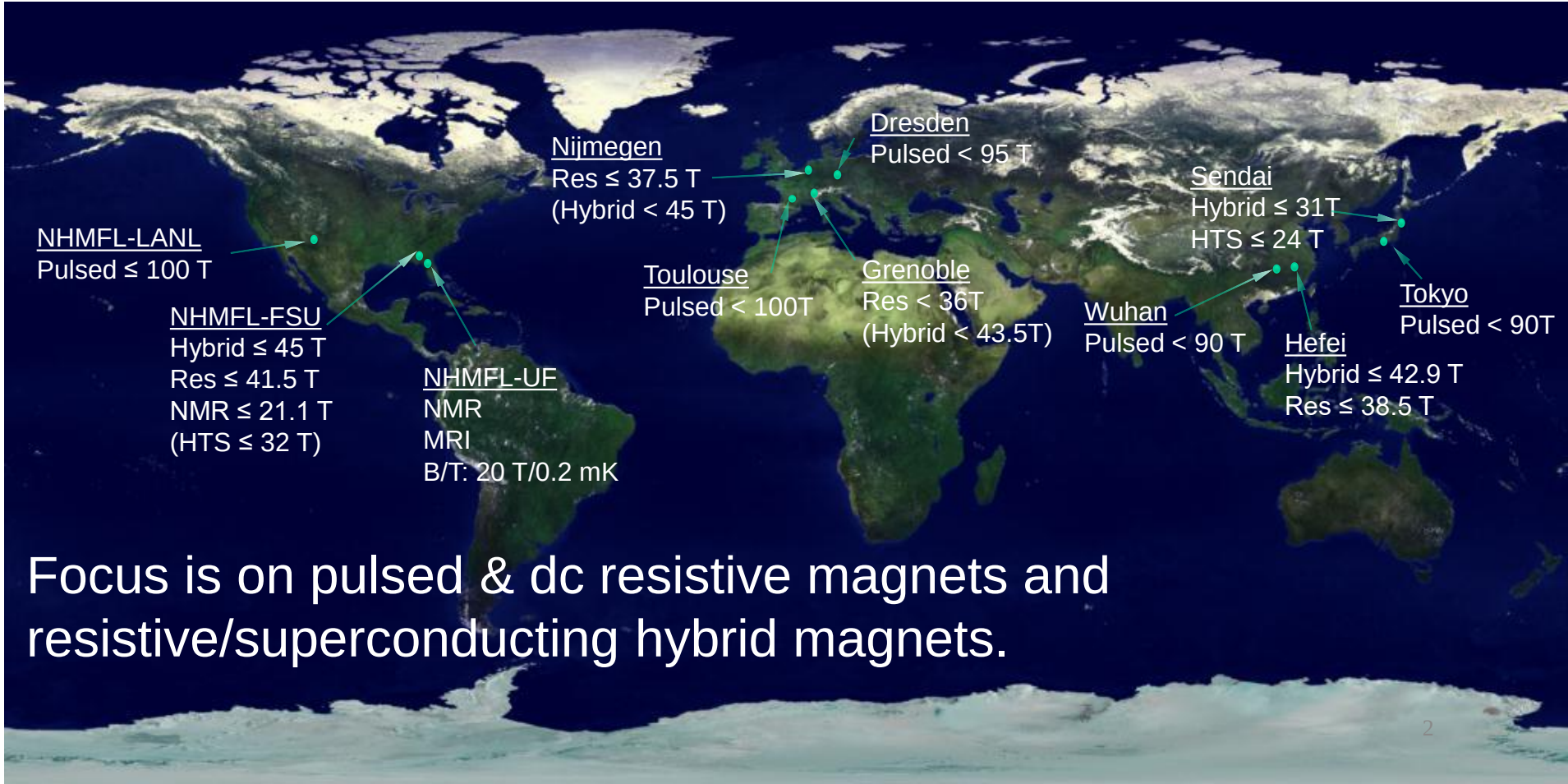
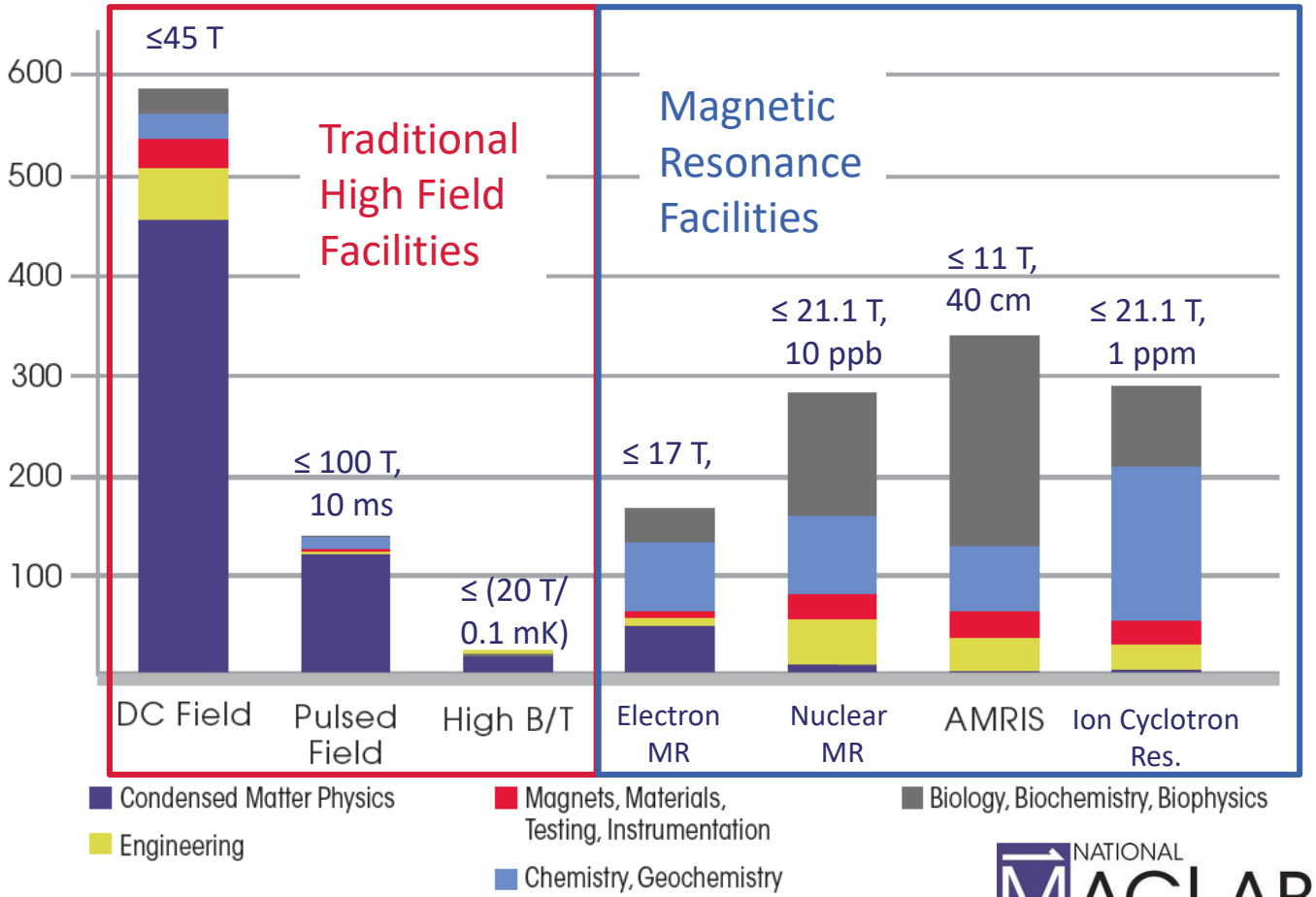
High Field Magnet Labs



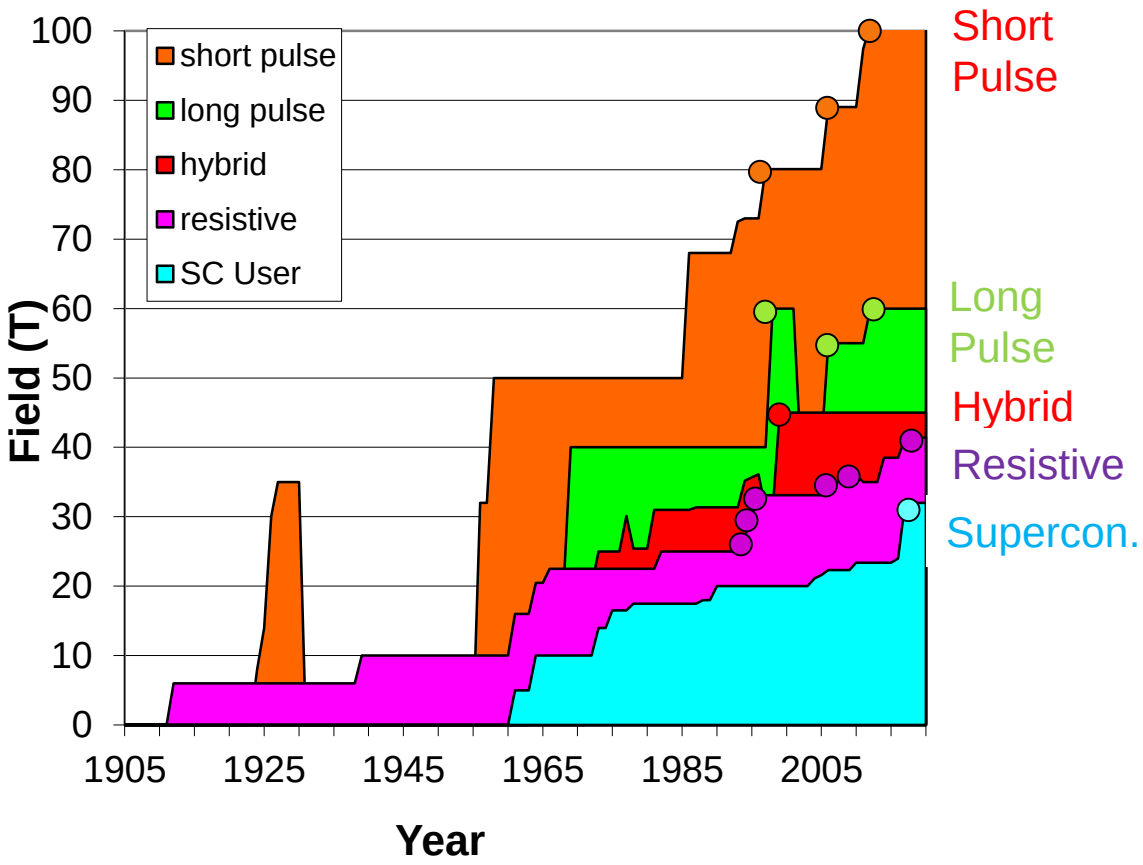
Focus is on pulsed & dc resistive magnets and resistive/superconducting hybrid magnets.

2017 MagLab USERS by Discipline



NATIONAL MAGLAB

Non-Destructive User Magnets:



○ MagLab record magnet

Planned to discuss all these Magnet Technologies.

My background is in Resistive, Pulsed, NbTi, & Nb_3Sn magnets.

Far more progress in recent years in Supercon (HTS) than in others.

While the NHMFL has completed a 32 T SC magnet, my role in it was small.

An Alternate Title:

A Novice's View on Recent Developments in HTS Magnet Technology

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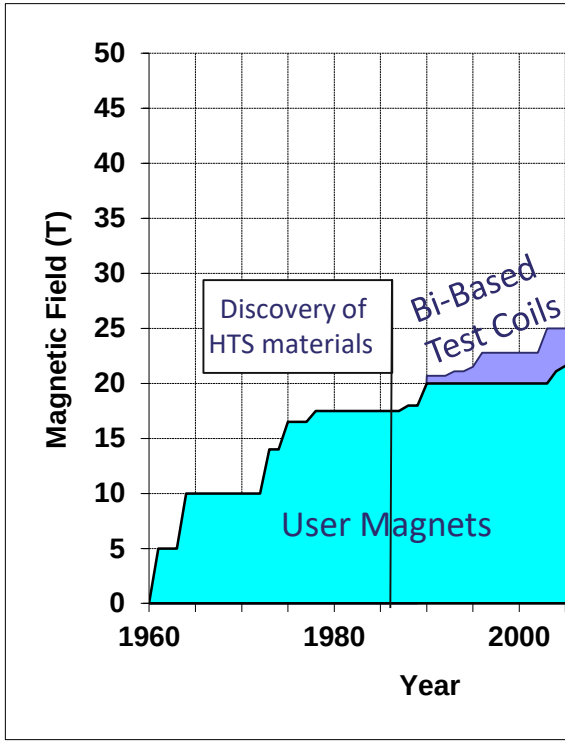
Disclaimer: There has been a tremendous amount of development in recent years, I cannot mention everything. I apologize to those I've left out.

HTS Magnets > 23.5 T: Bi-2223

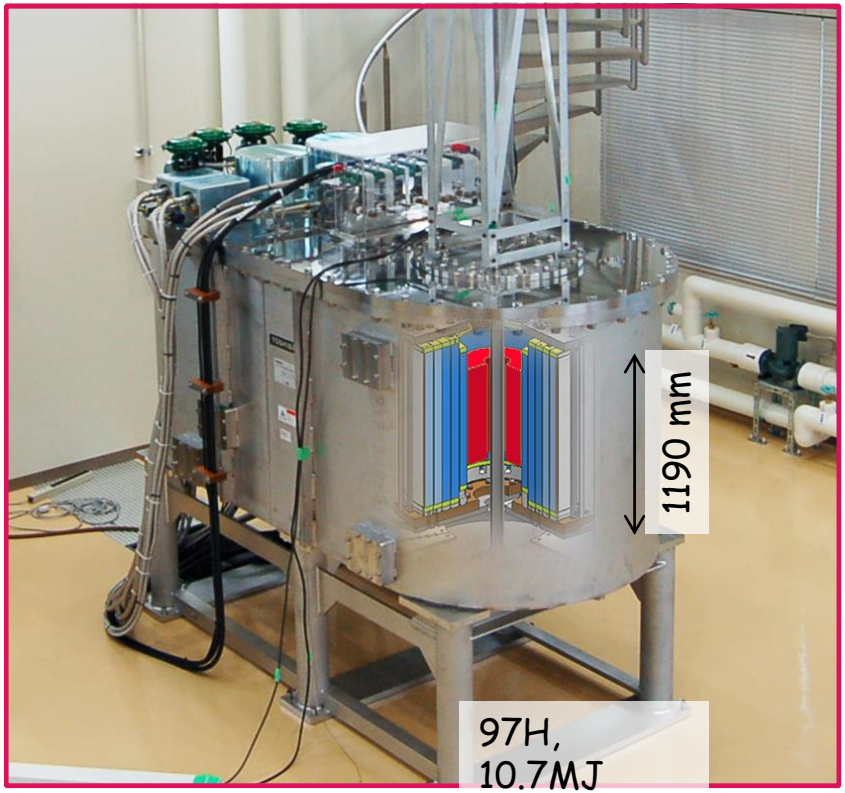


2010- 2015

1.02 GHz (24 T)
LTS/HTS (Bi-2223)
NMR Driven mode

Kenjiro Hashi, Shinobu Ohki, Shinji Matsumoto, Gen Nishijima, Atsushi Goto, Kenzo Deguchi, Kazuhiko Yamada, Takashi Noguchi, Shuji Sakai, Masato Takahashi, Yoshinori Yanagisawa, Seiya Iguchi, Toshio Yamazaki, Hideaki Maeda, Ryoji Tanaka, Takahiro Nemoto, Hiroto Suematsu , Takashi Miki, Kazuyoshi Saito, Tadashi Shimizu, *JMR*, **256**, 30-33 (2015)

Bi-2223: 25T User Magnet in Sendai



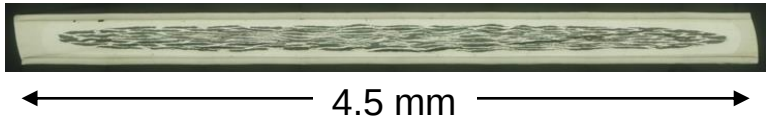
LTS: 14T@854A

3 CuNb/Nb_3Sn Rutherford solenoids
Ø300 mm x Ø539 mm x h628 mm
Max. hoop stress 251MPa
Pre-bent R&W Nb_3Sn cable.

3 NbTi Rutherford solenoids
Ø545 mm x Ø712 mm x h628 mm
Max. hoop stress 138 MPa

HTS: 10.6T@188A

38 Ni-alloy/Bi2223 double pancakes
Ø96mm x Ø280 mm x h390 mm
Max. hoop stress 323 MPa via Partial Turn Separation.



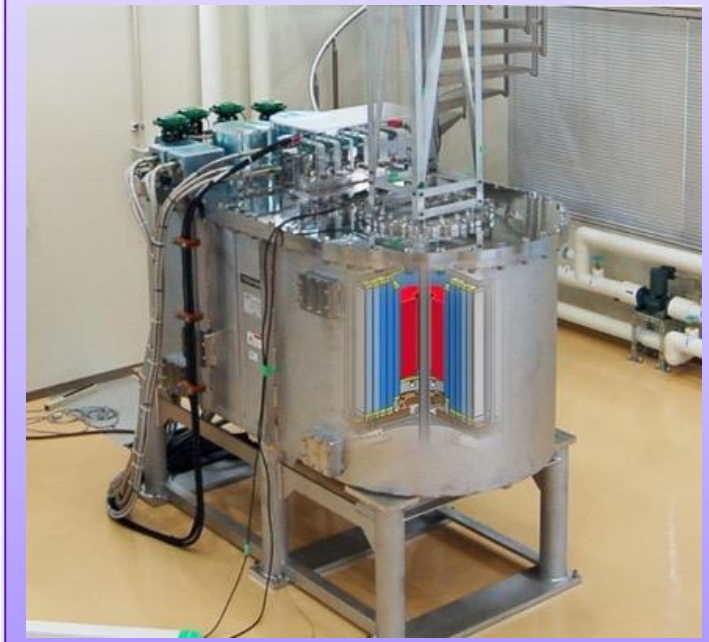
Satoshi Awaji, Kazuo Watanabe, Hidetoshi Oguro, Hiroshi Miyazaki, Satoshi Hanai, Taizo Tosaka, and Shigeru Ioka, *SuST*. **30** (2017) 065001

H. Oguro, S. Awaji, K. Watanabe, M. Sugimoto, and H. Tsubouch, *IEEE TAS*, **24**, 3, (2014) 8401004

Slide courtesy of Satoshi Awaji

Bi-2223: 25T User Magnet in Sendai

25 T cryogen-free
Superconducting Magnet
(25T-CSM)



- 24.6 T in 52 mm RT bore with 1 hour ramping
- Advanced high strength Nb_3Sn technologies and high strength Bi2223 (Type H-Nx (SEI))
- World highest field Cryo-Free SM
- Open for users since 2016

  (250 days operation in 2018),

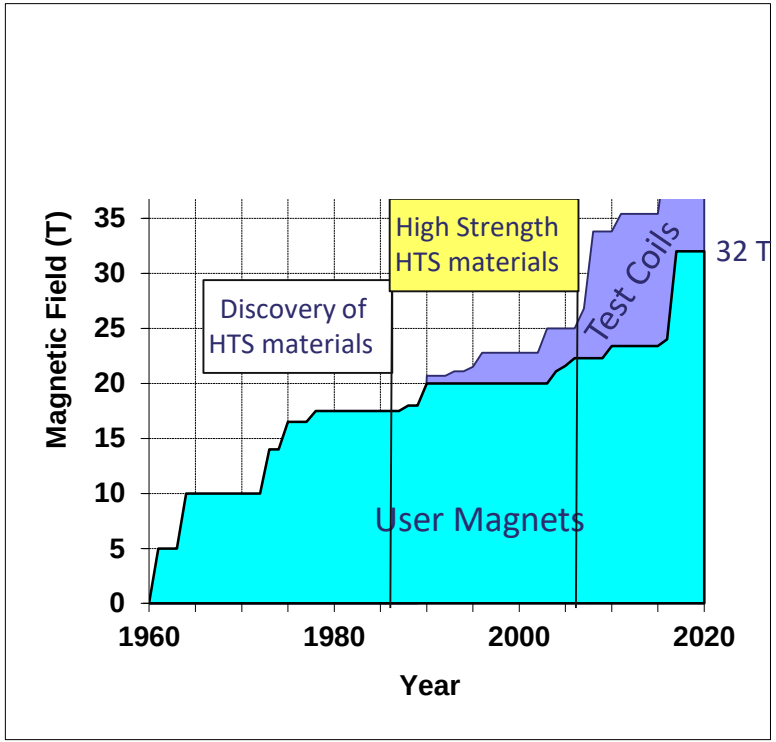
  >450 high stress cycles
- Long time, high precision experiments
- J_c-B-T-q of HTS, transport, NMR, high pressure, etc.

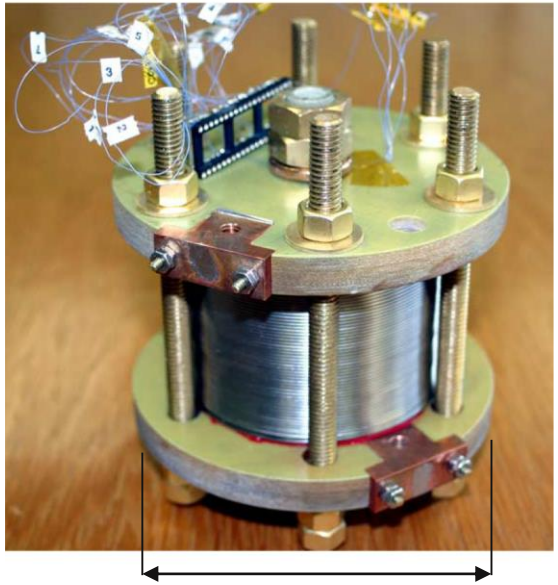
Slide courtesy of Satoshi Awaji

Insulated REBCO

I-REBCO

Insulated REBCO Coils

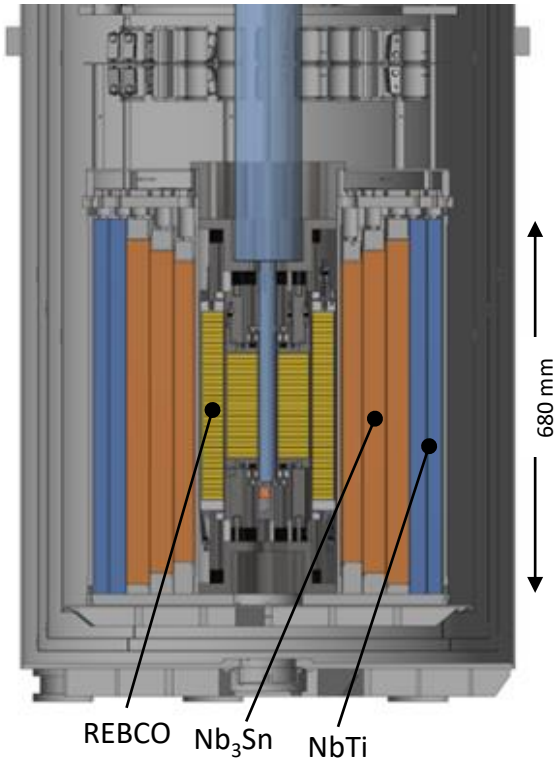




High Strength REBCO coil built at SuperPower.
9.8 T HTS + 19 T Res = 26.8 T Total.
2007

Drew W. Hazelton, Venkat Selvamanickam, Jason M. Duval, David C. Larbalestier, William Denis Markiewicz, Hubertus W. Weijers, and Ronald L. Holtz, *IEEE Trans. On Appl. SC.* **19**, 3, June 2009.

I-REBCO: 32 T SC R&D



Total field	32 T
Field inner YBCO coils	17 T
Field outer LTS coils	15 T
Cold inner bore	32 mm
Current	172 A
Inductance	619 H
Stored Energy	9.15 MJ
Uniformity	5×10^{-4} 1 cm DSV

- Commercial Supply:
  - 15 T, 250 mm bore LTS coils
  - Cryostat
  - (Dilution Refrigerator)
- In-House development:
  - 17 T, 34 mm bore YBCO coils

W. Denis Markiewicz, David C. Larbalestier, Hubertus W. Weijers, Adam J. Voran, Ken W. Pickard, William R. Sheppard, Jan J. Jaroszynski, Aixia Xu, Robert P. Walsh, Jun Lu, Andy V. Gavrilin, Patrick D. Noyes, *IEEE TAS*, **22**, 3, 4300704 (2012).

I-REBCO Quench Protection Concept

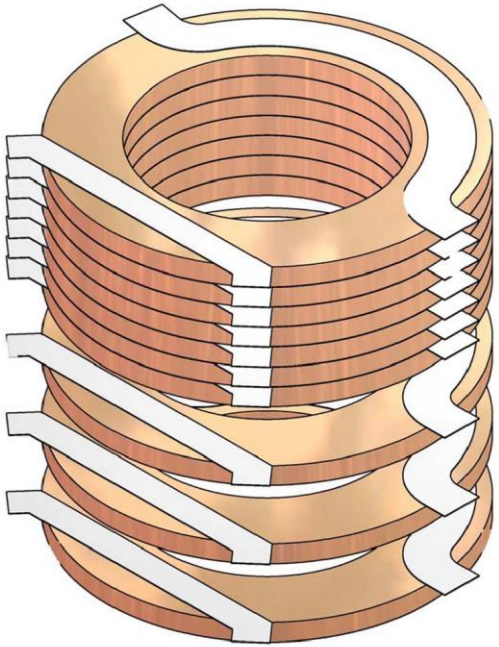


Fig. 2. Exploded view of pancake coil windings, showing concept of distributed heaters as heater strips on each pancake, with different heater configurations and degree of coverage of the pancake area.

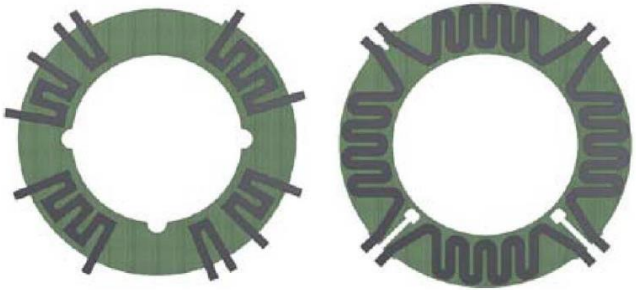
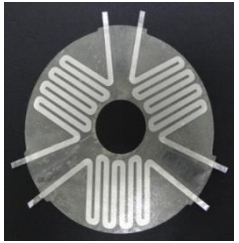
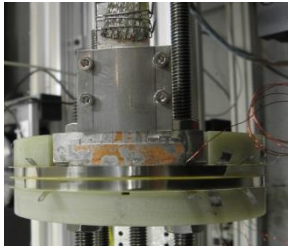
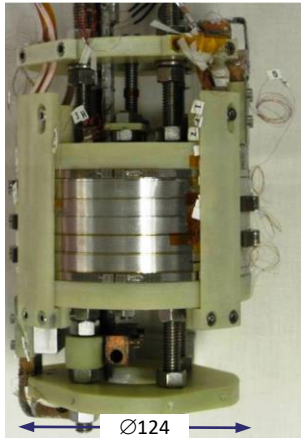


Fig. 2. One of two heater disks for Coil 1 (left). One of five heater disks for Coil 2 (right).



Quench heater



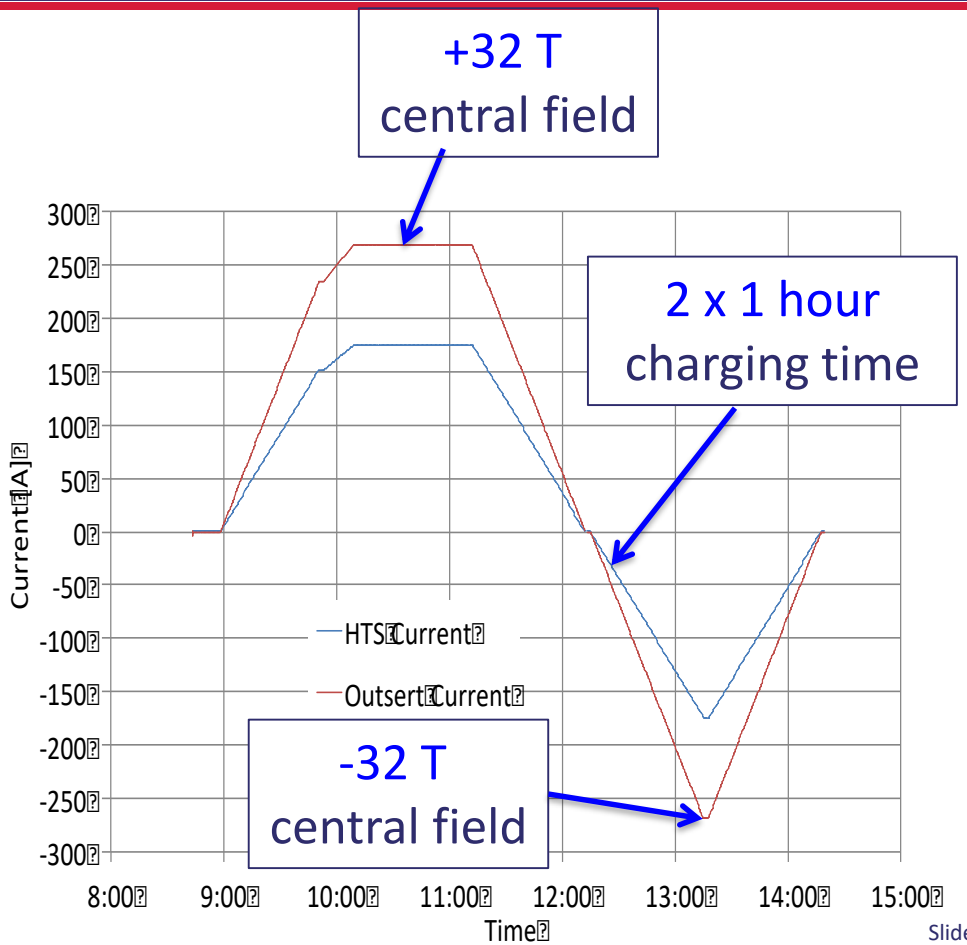


42-62 Mark 2:
2nd test coil

W. Denis Markiewicz, *IEEE TAS,* **18**, 2, June 2008, pp. 1333- 1336.

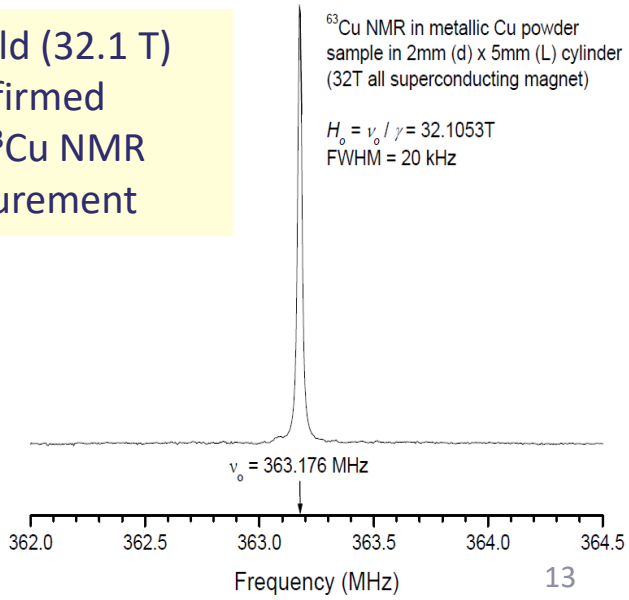
P. D. Noyes, W. D. Markiewicz, A. J. Voran, W. R. Sheppard, K. W. Pickard, J. B. Jarvis, H. W. Weijers, and A. V. Gavrilin, *IEEE TAS,* **22**, 3, (2012), 4704204.

32 T Test Data



Clear bore	34 mm
Uniformity 1 cm DSV	5×10^{-4}
Operating temperature	4.2 K
Helium Consumption	32 liters for this run
Projected He Consump.	40 liter/day at steady field

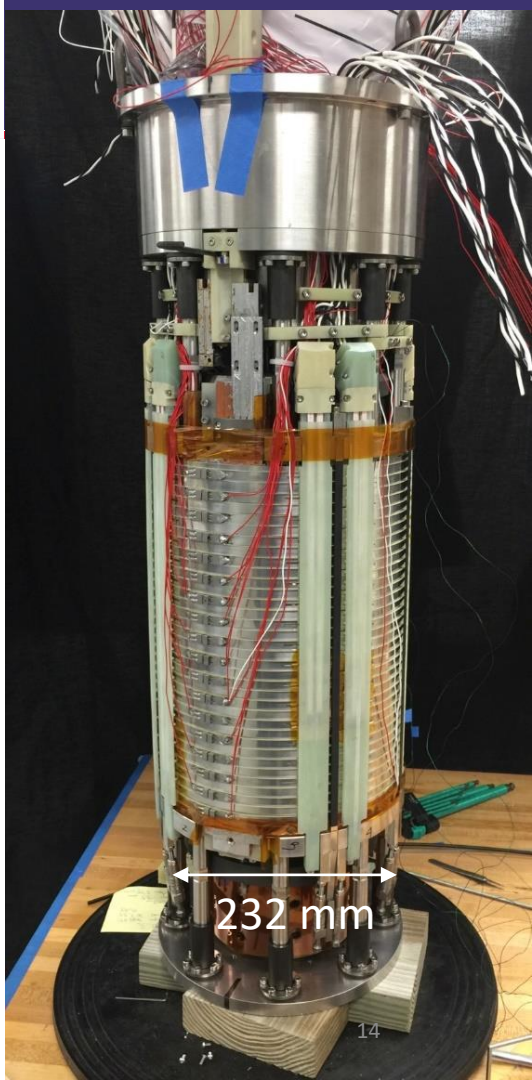
Peak field (32.1 T) confirmed with ^{63}Cu NMR measurement



Slide courtesy of Huub Weijers

I-REBCO: 32 T Fully Assembled

Normal Operations
expected 1st quarter 2020.

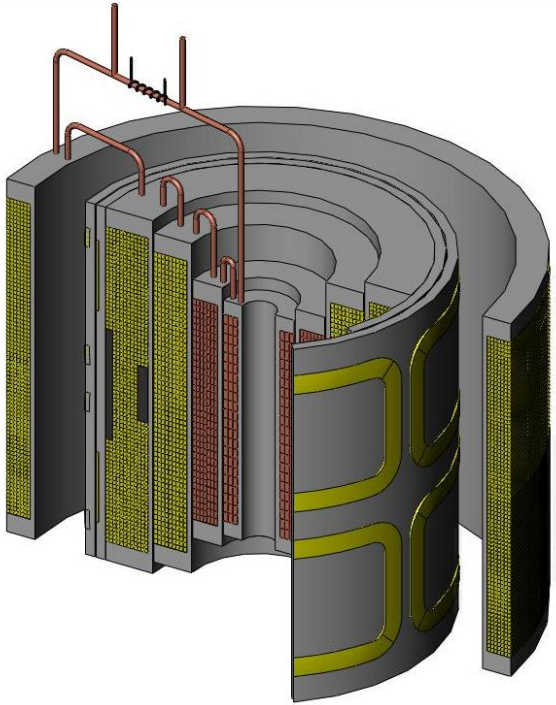


Superconducting NMR Magnets
Typical Layout

Nuclear Magnetic Resonance is the largest steady market for SC magnets with fields > 3 T.

It requires field uniformity & stability <10 ppb.

Standard magnets are superconducting with compensation, shielding, persistence, and shimming.

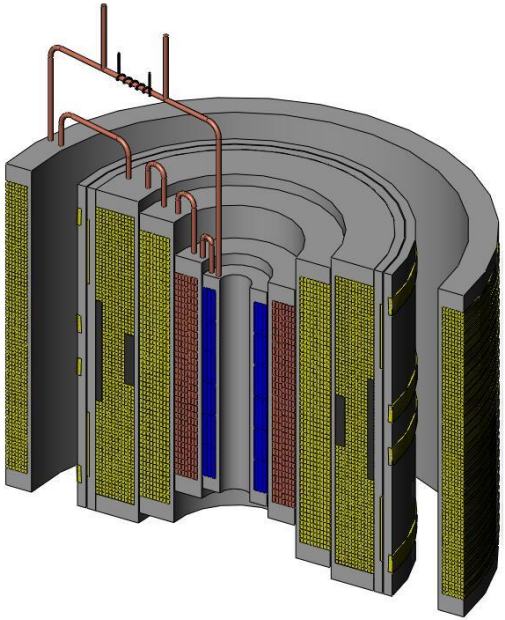


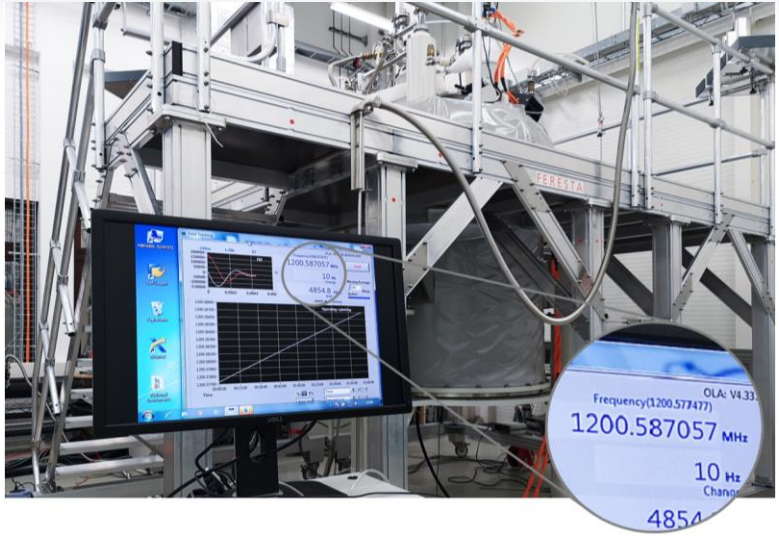
In 2009 Bruker delivered the first 1.0 GHz (23.5 T) NMR magnet using LTS materials.

Slide courtesy of Patrick Wikus

NMR Magnets Beyond 1.0 GHz
High Temperature Superconductors (I-REBCO)

To go beyond 1.0 GHz, HTS coil(s) replace inner Nb_3Sn coil(s) and stronger shim coils are needed.

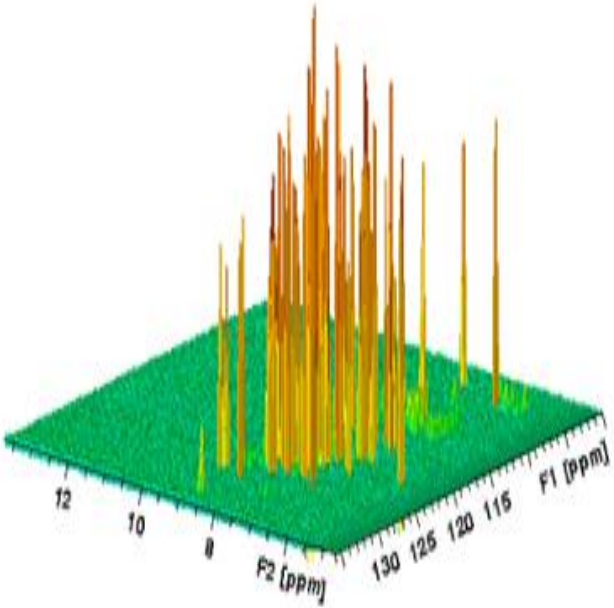




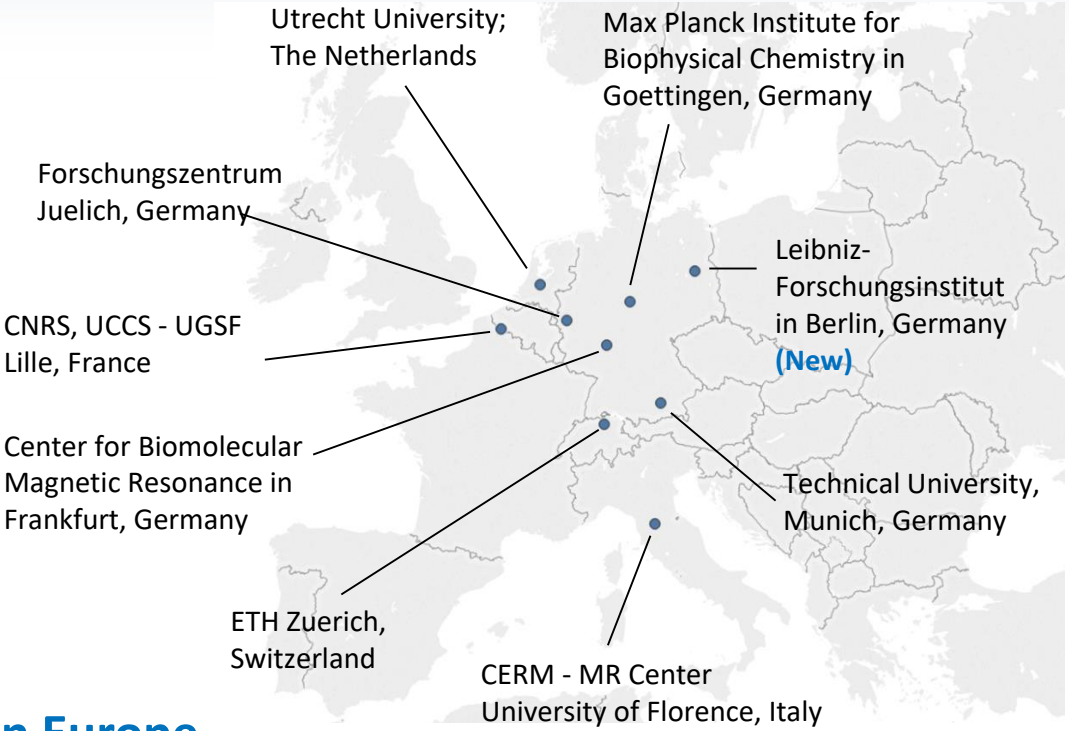
The First 1.2 GHz (28.2 T) NMR Magnet Reached Full Field in 2019

Slide courtesy of Patrick Wikus

Protein NMR at 1.2 GHz I-REBCO (Ubiquitin)



^{1}H-^{15}N 2D BEST-TROSY of a 500 µM ubiquitin sample, $^{13}C/^{15}N$ labeled in H_2O:D_2O 90:10, recorded with a 3 mm TCI CryoProbe.

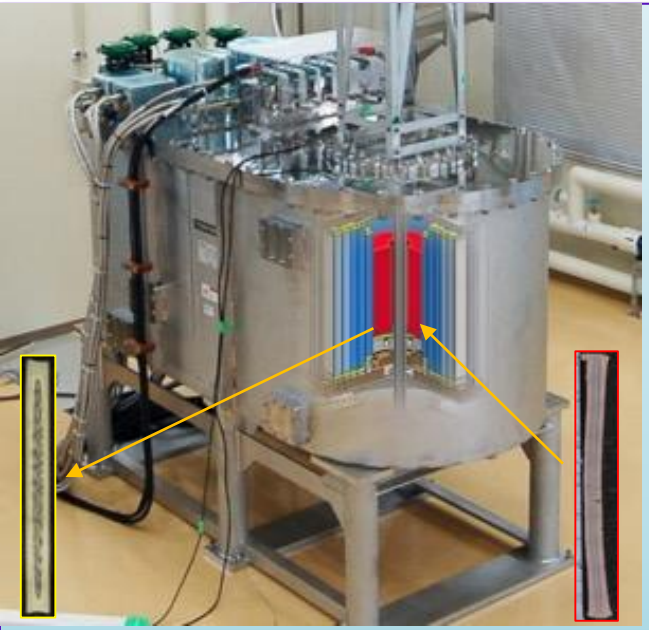


Nine 1.2 GHz Customer Orders in Europe

Slide courtesy of Patrick Wikus

I-REBCO Magnet Development in Sendai

2018-2021



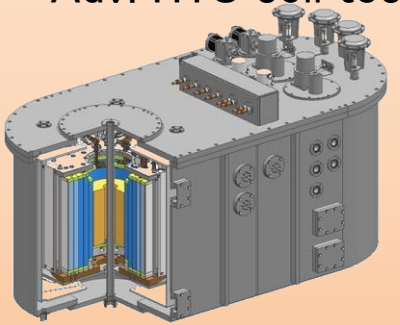
Upgrade to
30T Cryogen-Free
(JSPS project)

- Replace Bi2223 with REBCO.
- R&D toward to 33T

2021-

NEW 33T Cryogen-Free
Under the High Field Collaboratory
Japan project

- High strength Nb_3Sn
- REBCO conductors
- Adv. HTS coil technol.



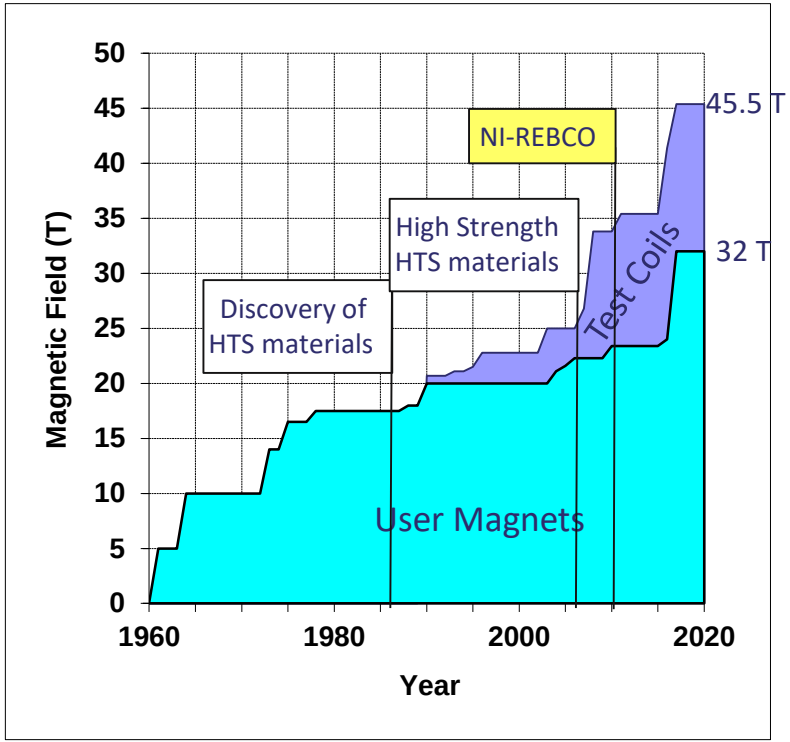
Superconducting magnet technology beyond 40 T

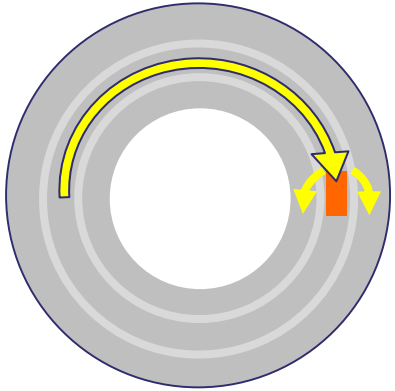
Slide courtesy of Satoshi Awaji

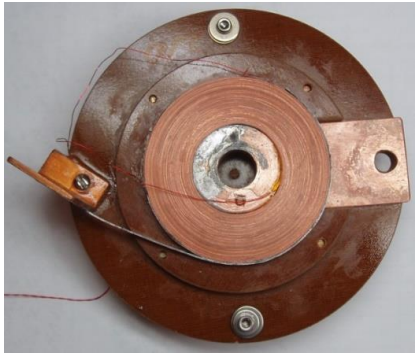
No-Insulation REBCO

NI-REBCO

No-Insulation-REBCO Coils







Current Bypasses Quench reducing hotspot temperature.

Less Cu is Required → Smaller Coils.

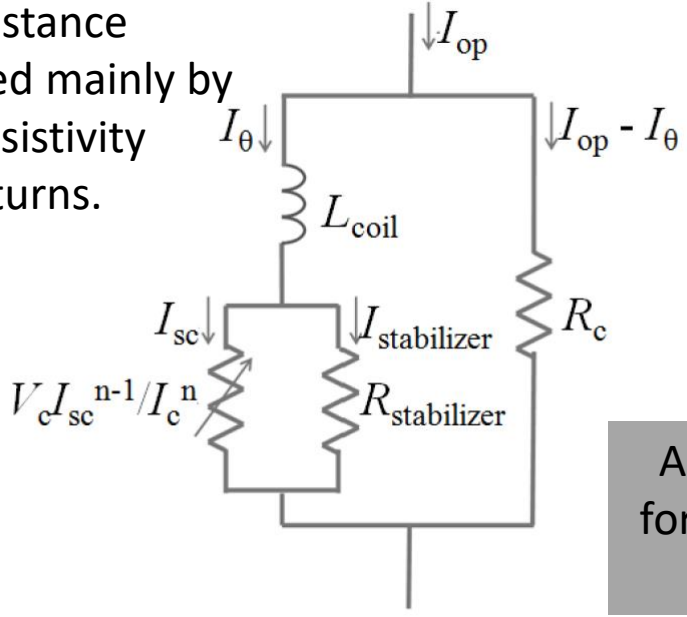
Less Reinforcement Required → Smaller Coils.

- Coil quench at I_{op}=412 A (1580 A/mm^2).
- 32 T ~ 200 A/mm^2.
- No coil damage in 20-s "over-current" operation.

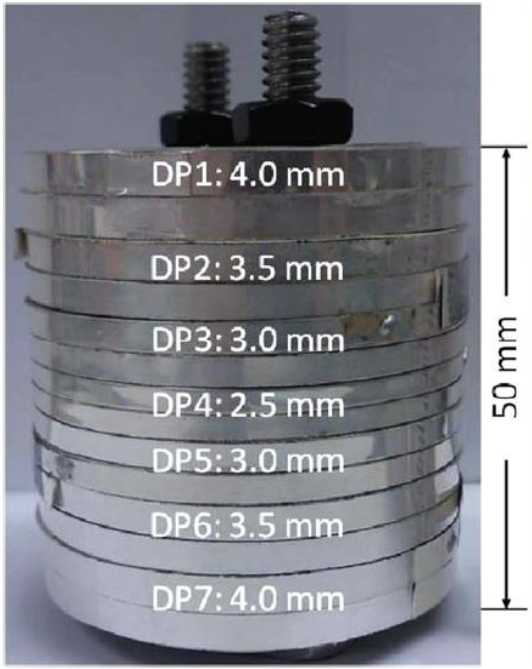
S. Hahn, D.K. Park, J. Bascunan, and Y. Iwasa, *IEEE Trans. On Appl. SC*, **21**, 3, (2011) pp. 1592 – 1595
S. Hahn, D.K. Park, J. Voccio, J. Bascunan, and Y. Iwasa, IEEE Trans. On Appl. SC, **22**, 3, (2012) 4302405

NI-REBCO Test Coils: Bypass Resistance and Multi-Width

Showed coils as having a Coil Resistance determined mainly by contact resistivity between turns.



Built coils using different width tape to maintain I_{op}/I_c.



Approach chosen for 1.3 GHz (30.5 T) NMR magnet

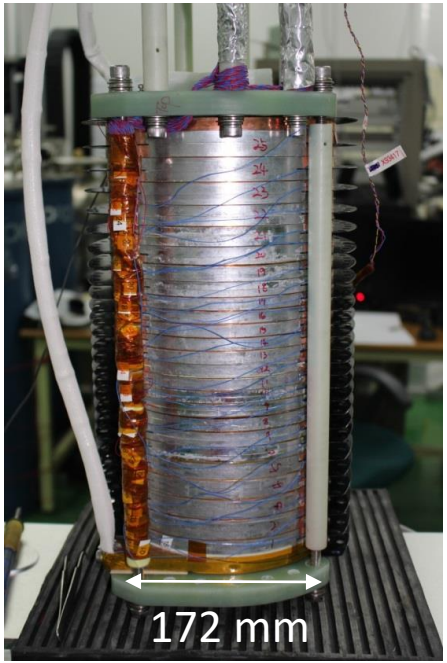
Xudong Wang, Seungyong Hahn, Youngjae Kim, Juan Bascunan, John Voccio, Haigun Lee, and Yukikazu Iwasa, *SuST*, **26** (2013) 035012

Seungyong Hahn, Youngjae Kim,. Dong Keun Park, Kwangmin Kim, John P. Voccio, Juan Bascunan, and Yukikazu Iwasa, *Appl. Phys. Let.*, **103**, 173511 (2013).

21

NI-REBCO Test Coils: 26 T & Defect-Irrelevant

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



- *Self-protecting* at J_e of 392 A/mm^2

Sangwon Yoon, Jaemin Kim, Kyekun Cheon, Hunju Lee, Seungyong Hahn, and Seung-Hyun Moon, SuST **29** (2016) 04LT04 (6pp)

Defect Irrelevance

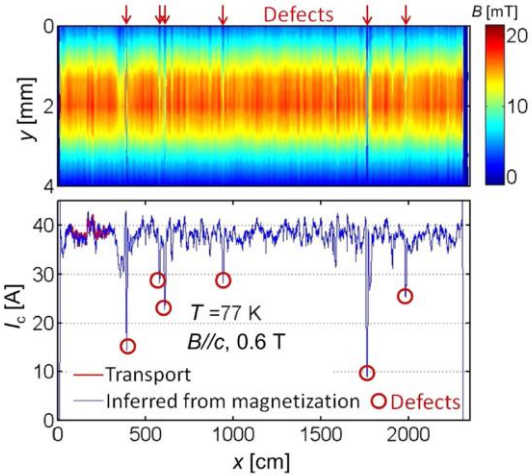


Figure 3. Lengthwise I_c test results of the 23 m long REBCO tape using the YateStar in a bath of liquid nitrogen at 77 K: (a) magnetization method; (b) transport current method. Six 'major' defects were identified, at which the local critical current is <80% of the coil's average, ~38 A, at a 0.6 T *c*-axis parallel field.

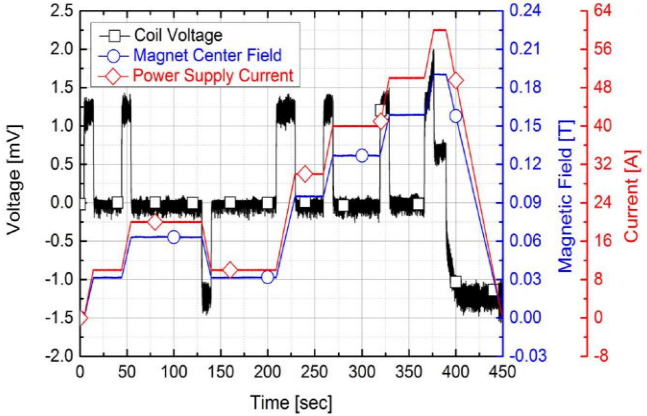
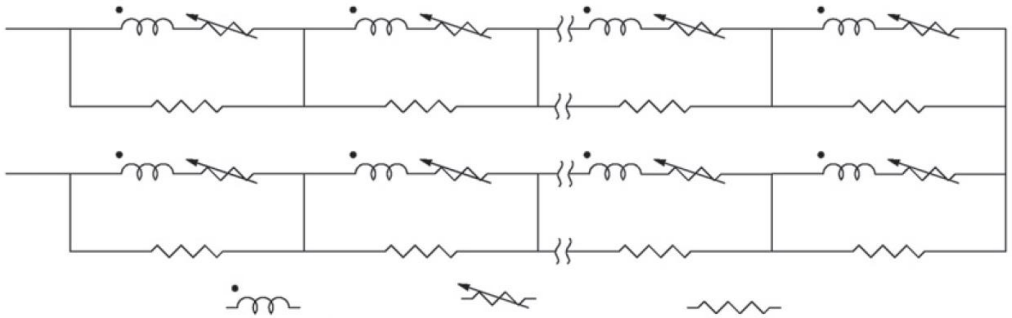
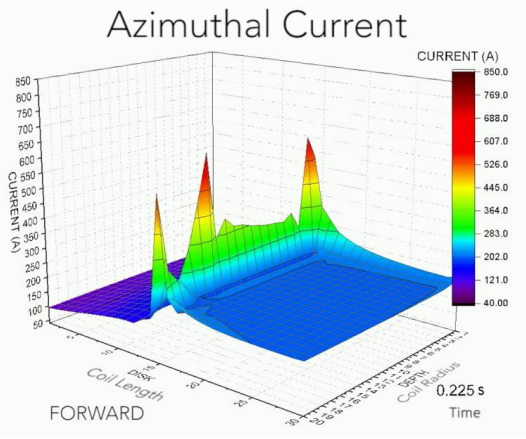


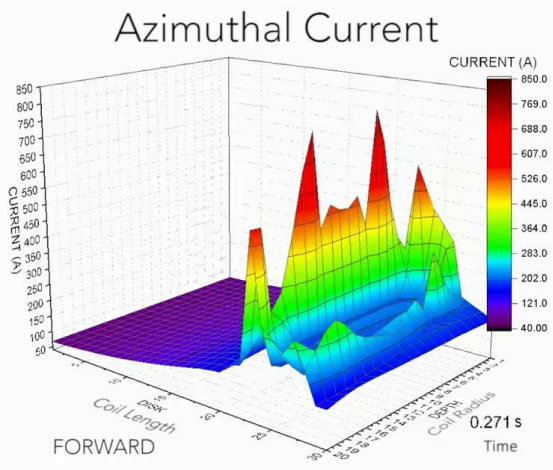
Figure 5. Charging test results up to 60 A.

Seungyong Hahn, Kyle Radcliff, Kwanglok Kim, Seokho Kim1, Xinbo Hu, Kwangmin Kim, Dmytro V Abraimov and Jan Jaroszynski, SuST, **29** (2016) 105017 (5pp).

NI-REBCO coils: Quench Propagation







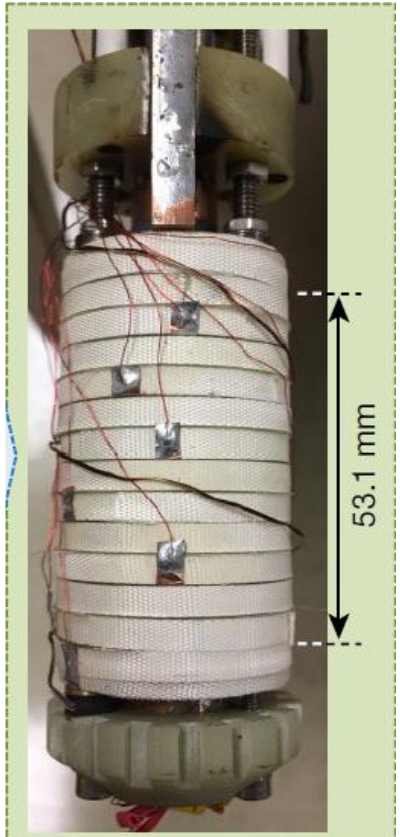
Quenches propagate in NI-REBCO similar to in commercial LTS magnets, except each turn is a separate inductive/resistive element instead of each coil section.

Large currents can be induced.

Assymmetric modes with large fault forces are common.

W. Denis Markiewicz, Jan J. Jaroszynski, Dymtro V. Abraimov, Rachel E Joyner, & Amanatullah Khan, SuST, **29**, (2016) 025001

NI-REBCO Test Coil: 45.5 T



LBC3 after 45.5-T test

45 T = 31T + 14T
(Aug. 2017, MagLab)

Coil	Current Density
32 T Ins-YBCO all SC User Magnet	200 A/mm^2
26 T NI-YBCO all SC test coil	392 A/mm^2
45 T NI-YBCO + Resistive test coil	1420 A/mm^2
NI Module	1580 A/mm^2

YatesStar indicates tape was damaged at high field:

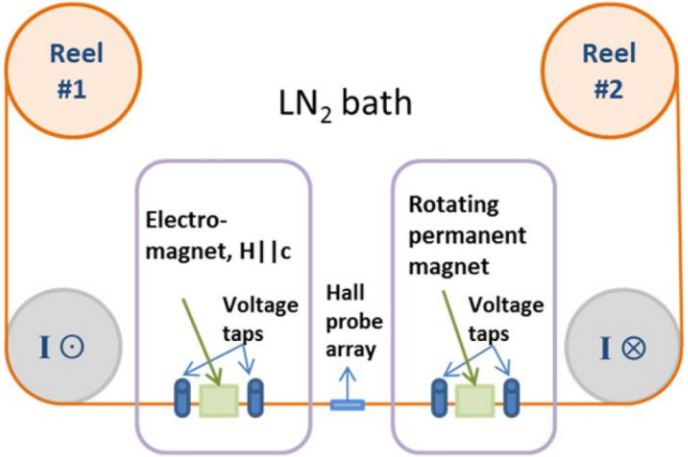
1) Screening Current Strain.
2) Current Spikes during Quench.
3) Crack due to edge slitting propagating.

Seungyong Hahn, Kwanglok Kim, Kwangmin Kim, Xinbo Hu, Thomas Painter, Iain Dixon, Seokho Kim, Kabindra R. Bhattarai, So Noguchi, Jan Jaroszynski, & David C. Larbalestier, *Nature*, 570, (2019) pp 496 – 499.

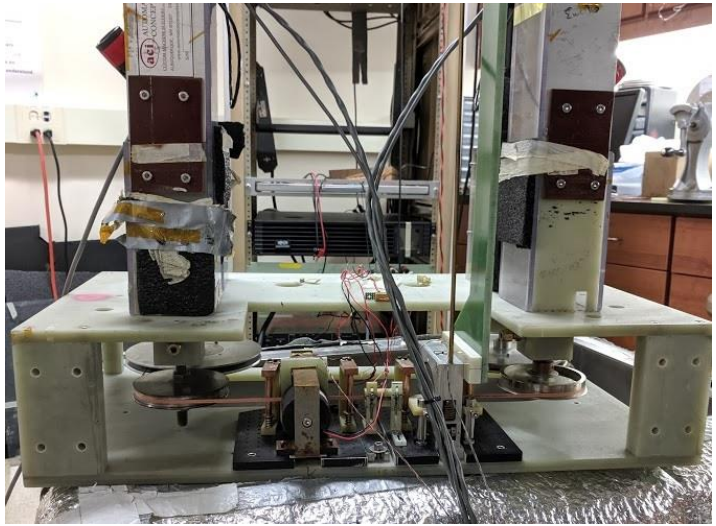
Yatestar: A Unique Diagnostic Tool in Tallahassee

Tool for end-end characterization in LN_2 of REBCO tapes, more capable than Tapestar of vendors

- Magnetization via Hall probe array gives 2D uniformity information on J_c and self-field I_c
- Direct measurement of transport I_c up to 0.6 T for both $B//$ and $B\perp$ to tape gives insight in uniformity of flux pinning (microstructure) and I_c values scale better to I_c at low temperature high field



Used extensively in 32 T project to find dropouts & help SuperPower improve quality of tape.



L Rossi, X Hu, F Kametani, D Abraimov, A Polyanskii, J Jaroszynski and D C Larbalestier, SuST **29** (2016) 054006 (9pp)

J. Yates Coulter, Jens Hänisch, Jeffrey O. Willis, Leonardo Civale, and Warren K. Pierce, IEEE TAS, **17**, 2, (2007) pp. 3394 – 3397.

YatesStar Examination of 45.5 T NI-REBCO Tape

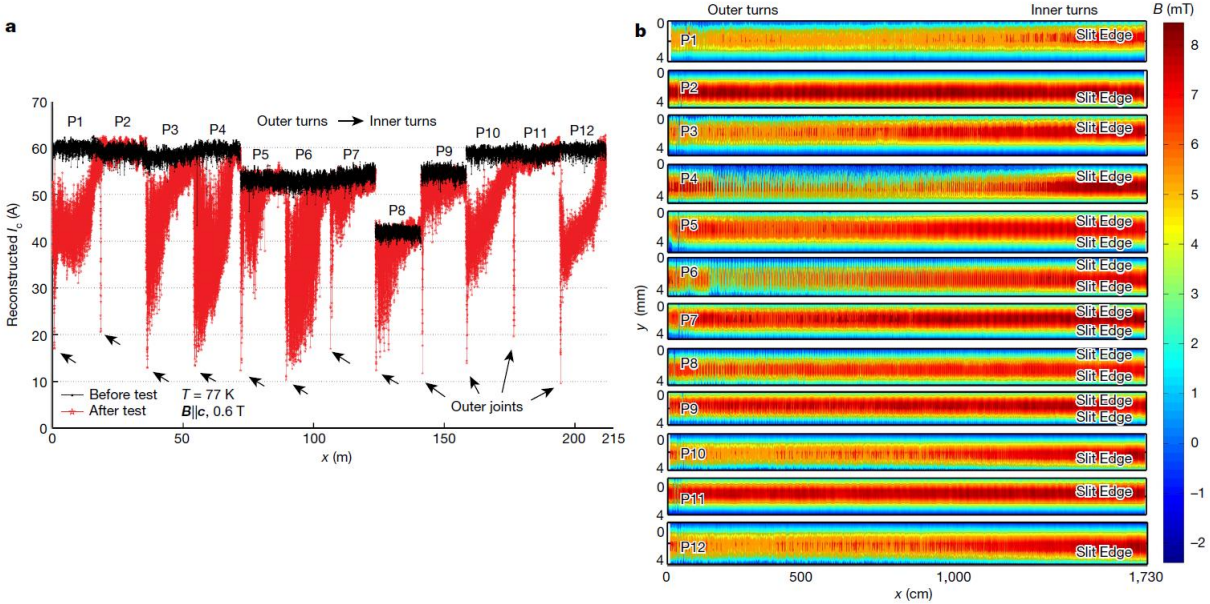


Fig. 4 | Post-mortem analysis of the superconducting tape. a, Transport critical current I_c versus position x of the 12 tape lengths before (black) and after (red) the test. $\boldsymbol{B}\|\boldsymbol{c}$ indicates that $\boldsymbol{B}$ is perpendicular to the tape plane. **b**, Two-dimensional remnant magnetization maps show the transverse tape uniformity; more uniform (red) tape indicates less damage. 10 of the 12 tapes in Fig. 4a show sharply reduced $I_c(x)$ as x increases, whereas the tapes of pancakes P2 and P11 are undamaged. The figure shows that the dominant damage pattern is one-sided, especially for end pancakes P1, P3, P4, P10 and P12. Pancakes P2 and P11, which have slit edges facing the magnet centre, exhibit essentially no longitudinal or transverse damage.

Damage to REBCO tape seems to initiate at microcracks formed during slitting of the tape from 12 mm to 4 mm wide.

Performance of tape appears to depend on the position of slit edges.

Seungyong Hahn, Kwanglok Kim, Kwangmin Kim, Xinbo Hu, Thomas Painter, Iain Dixon, Seokho Kim, Kabindra R. Bhattarai, So Noguchi, Jan Jaroszynski, & David C. Larbalestier, *Nature*, **570**, (2019) pp 496 – 499.

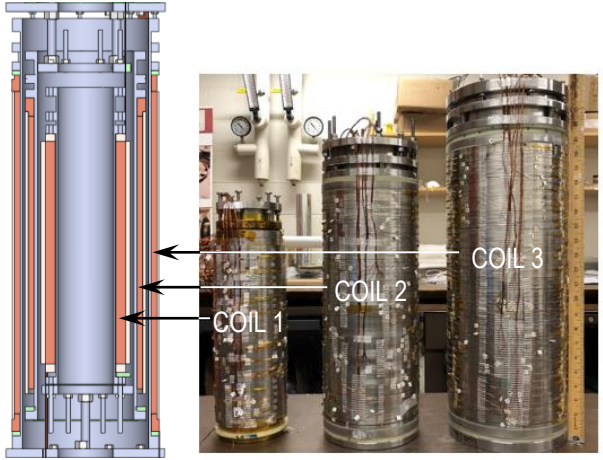
NI-REBCO: MIT 1.3-GHz High-Resolution LTS/HTS NMR Magnet

2016-2019 Specific Aims: 1) Complete H800; 2) Combine H800 and L500 to generate 30.5-T field

H800: 800-MHZ HTS insert of 3 nested coils, each a stack of No-Insulation REBCO DP coils

L500: 500-MHZ LTS NMR magnet available at FBML

- In 2018, H800 quenched at 243.5 A (design: 251.3 A), generating a center field of 17.93 T (18.50 T)
  - ➢ Quench initiated at a conductor defect in the cross-over turn of Coil 2 bottom DP coil



H800 housed in a cryostat for 2018 4.2-K test

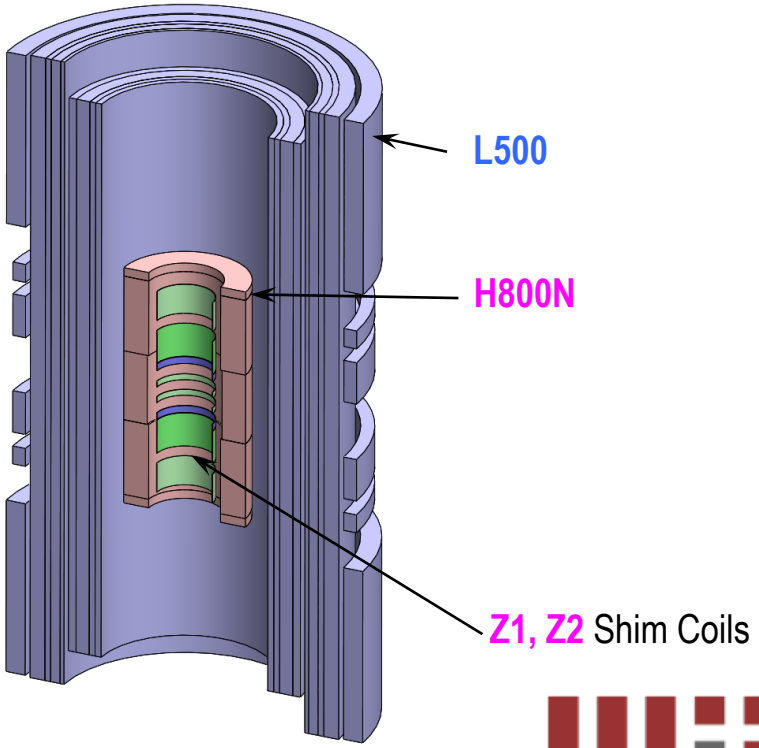
H800 quench

Slide courtesy of Yuki Iwasa

MI-REBCO: MIT 1.3GHz 2020-2023

Specific Aims: 1) Complete H800N; 2) Combine H800N and L500 to generate 30.5-T field; 3) Convert a 30.5-T field to a high-resolution NMR field

	Original	Proposal
# of HTS Coils	3	1
Insulation	None (Cu)	**Metal (SS)**



- Final phase of MIT 1.3G project currently under review by NIH

Slide courtesy of Yuki Iwasa

Metal-Insulated REBCO

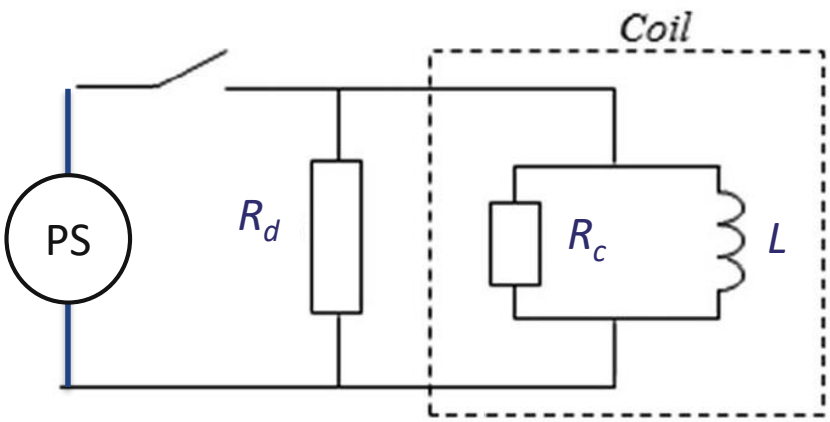
MI-REBCO

Metal Insulated (MI)-REBCO

NI-REBCO: R_c is very small, R_d is not able to extract much energy.

MI-REBCO: R_c becomes much larger, R_d can extract energy.

Variations: Partial-Insulation, Controlled Contact Resistance.



Ramesh Gupta, Mike Anerella, George Ganetis, Arup Ghosh, Harold Kirk, Robert Palmer, Steve Plate, William Sampson, Yuko Shiroyanagi, Peter Wanderer, Bruce Brandt, David Cline, Alper Garren, Jim Kolonko, Ronald Scanlan, and Robert Weggel, *IEEE TAS*, **21**, 3, (2011) pp 1884 – 1887.

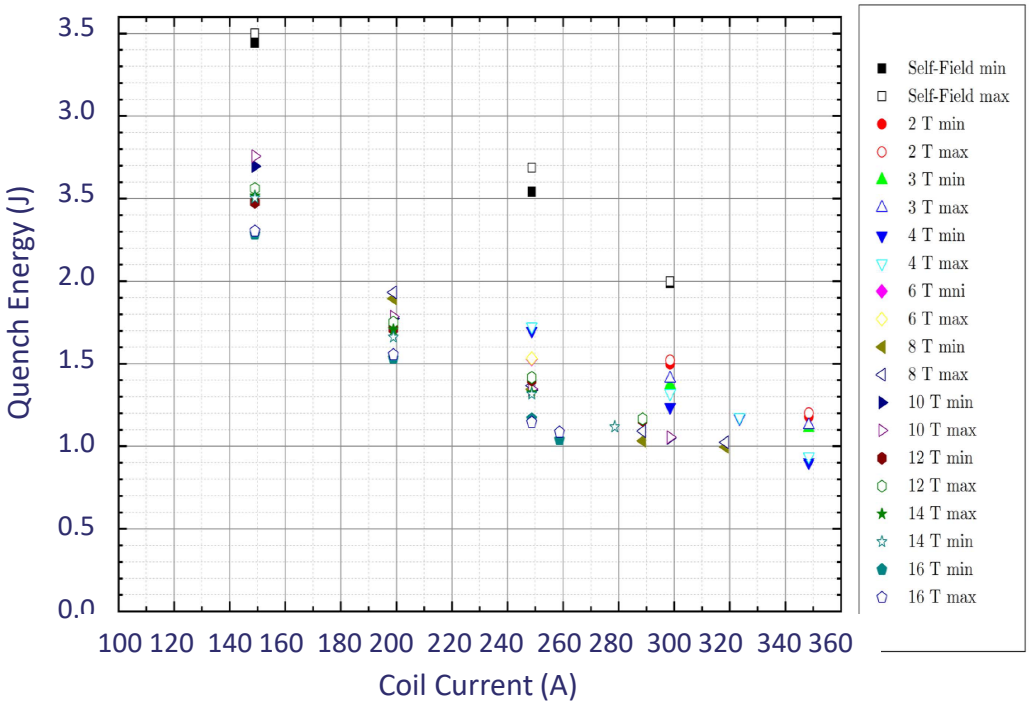
Grenoble/CEA: MI-REBCO

2015: Used model similar to Markewicz's. Calculated response of 10 T NI- & MI-REBCO coils in 20 T background to opening of breaker.

NI-REBCO: Slow onset (510 ms) but fast quench propagation (50 ms), most energy dissipated in the coil.

MI-REBCO: Fast discharge of coil, no quench, 96% of energy can be extracted.

2017: Demonstrated self-protection of MI-REBCO module from >100 heater-induced quenches.

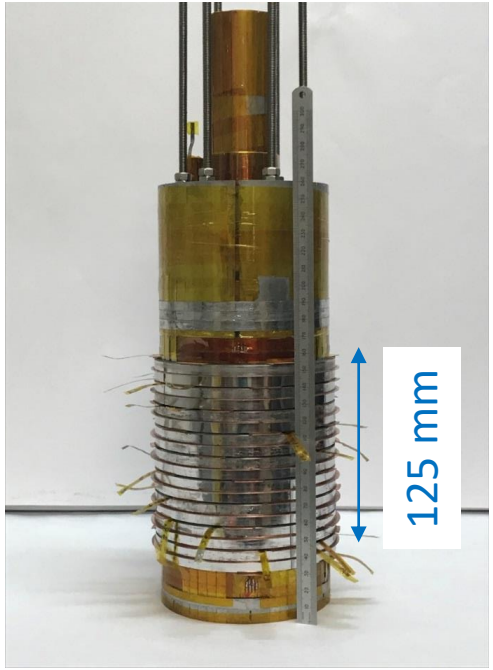


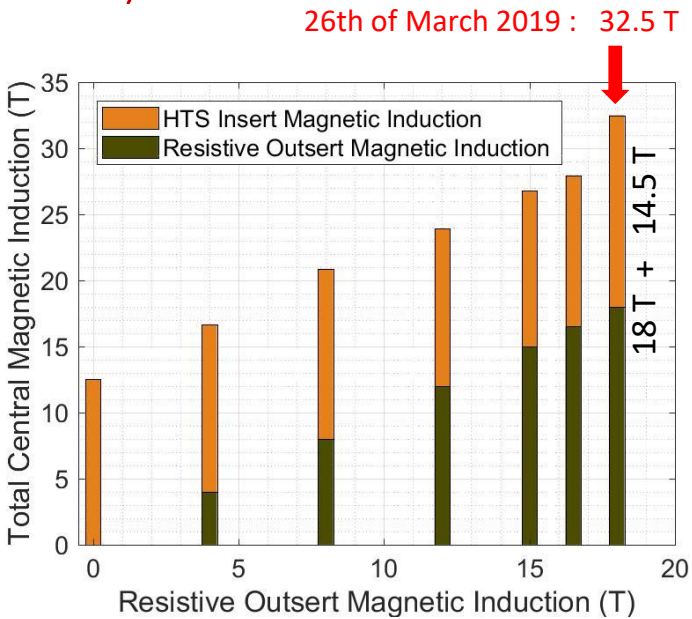
F. Borgnolutti, A. Badel, T. Benkel, X. Chaud, F. Debray, P. Fazilleau, T. Lecrevisse, and P. Tixador, *IEEE TAS*, **26** 4 (2016) 4600405.

T Lécrevisse, A Badel, T Benkel, X Chaud, P Fazilleau, and, P Tixador, *SuST*, **31** (2018) 055008.

MI-REBCO: Grenoble 14.5 T + 18 T Res = 32.5 T

Test of the 14 T NOUGAT HTS insert
(made of 9 "Metal Insulated" Double Pancakes)





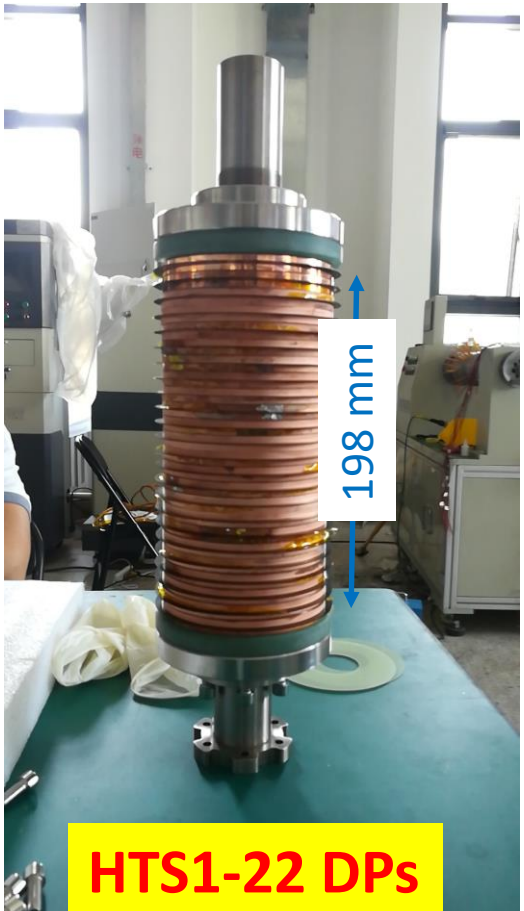
➔ **Perspectives H2020 study call** for the design of an All Superconducting Magnet (40 T), Studies for future hybrids

Xavier Chaud, JungBin Song, Benjamin Borgnic, Francois Debray, Thibaut Lecrevisse, Philippe Fazileau, Fri-Mo-Or27-04:
Jung Bin Song, Xavier Chaud, Benjamin Borgnic, Francois Debray, Philippe Fazlieau, Thibault Lecrevisse, Mon-Af-Po1.20-01:

32

30 T MI-REBCO Magnet

INSTITUTE OF ELECTRICAL ENGINEERING, CHINESE ACADEMY OF SCIENCES



Testing of 30 T Test Coils Planned Nov. 2019 using Multi-Width approach.

>30 T, 40 mm bore magnet for Quantum Oscillations due June 2021.

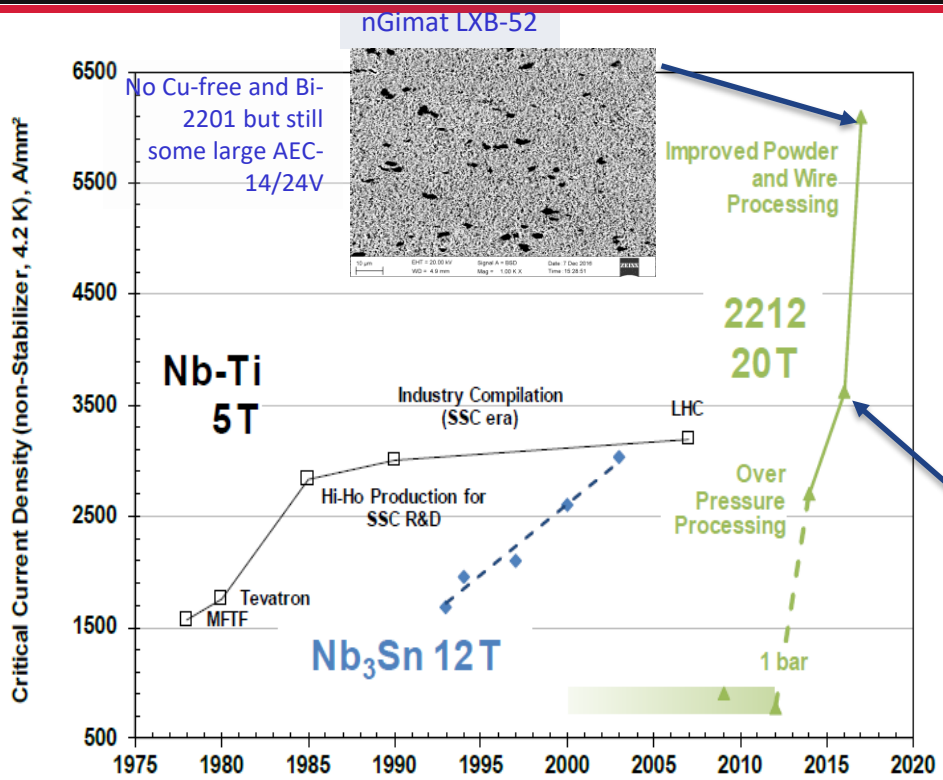
27 T, 50 mm bore, solid-state NMR magnet due June 2021.

25 - 28 T small animal MRI magnet also underway.

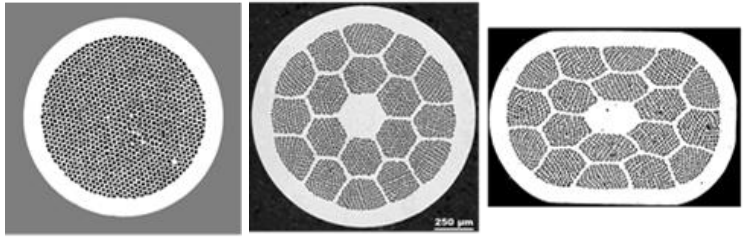
Qiuliang Wang, private communication, Aug. 13, 2019

Bi-2212

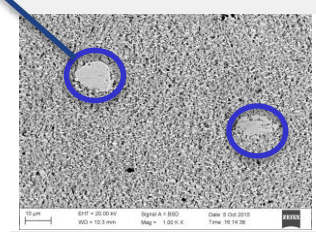
Bi-2212 Wire Development



Many architectures: single stack, double stack, aspected and sometimes laminated



Nexans lot 87C



Residual hard particles encourage filament merging.

Round, finely distributed twisted filaments and electromagnetic isotropy.

Architectural flexibility: can be cabled easily (Rutherford cable, 6-around-1).

Avoids single-point failure of single crystal with higher current density than Bi-2223.

U.S. DEPARTMENT OF ENERGY | Office of Science

U S MAGNET DEVELOPMENT PROGRAM

CERN

BRUKER

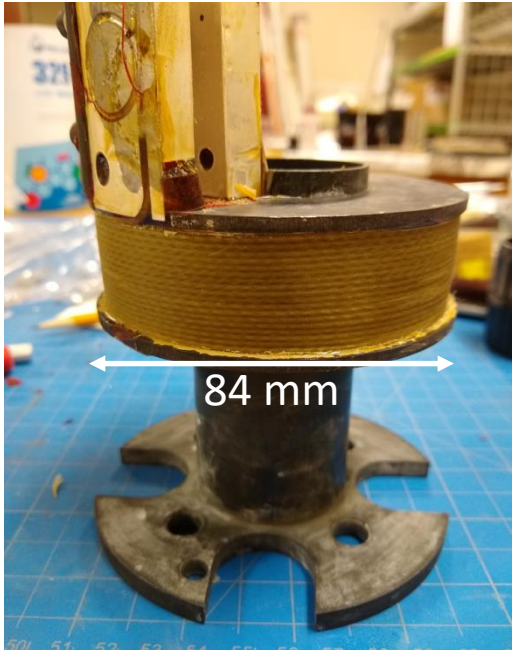
nGimat™ nanoEngineered Materials™

Content Courtesy of David Larbalastier

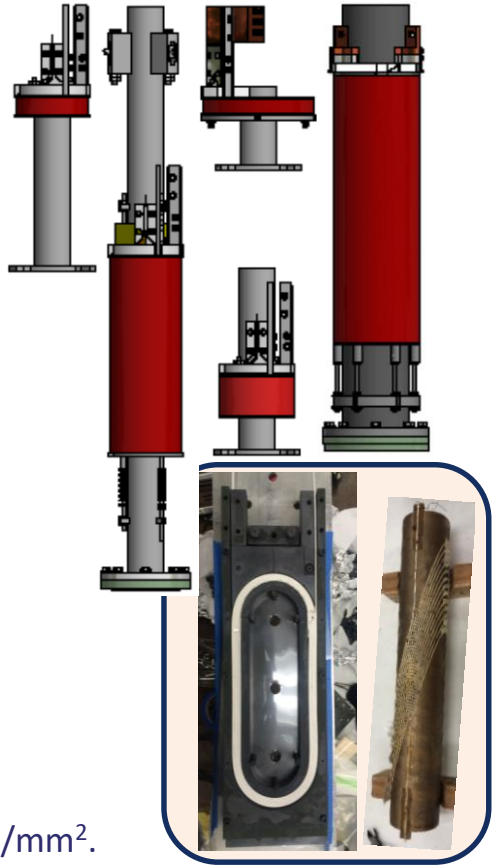
Bi-2212 Coil Development

6-zone 100 bar furnace with 16 thermocouples.

44 cm x 14 cm dia. Hot zone



B-OST wire & nGimat powder.
Internal co-wound reinforcement.
2.25 T HTS + 14 T LTS = 16.25 T @ 232 A/mm^2.
0.39% strain.

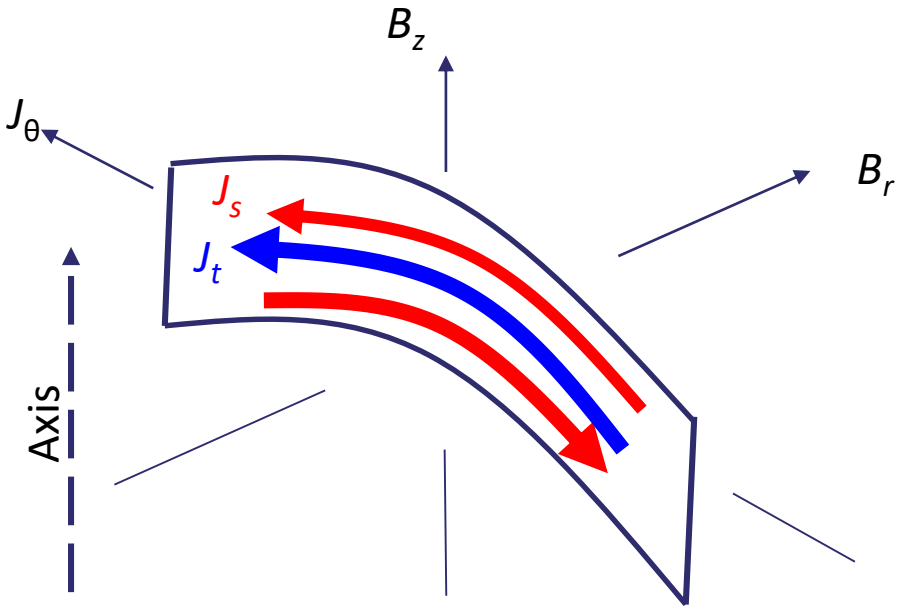


02/18/15	Pup1
02/23/15	Pup2
06/01/15	Pup3
06/23/15	Compression Coil
08/31/15	Platypus
04/01/16	Riky1
04/28/16	Riky2
06/09/16	LBNL RaceTrack1
07/26/16	LBNL RaceTrack2
10/25/16	RIKEN
01/07/17	CERN/Twente Rutherford Cable
01/12/17	OI Coil
02/27/17	Pup4
03/28/17	LBNL RaceTrack3
04/18/17	Riky3
04/26/17	Riky4
07/06/17	Platypus-II Dummy
08/14/17	LBNL RaceTrack4
08/17/17	LBNL RaceTrack5
12/05/17	Riky5 & Pup5
01/24/18	LBNL RaceTrack6
06/04/18	Riky6 & RikySRW2
09/10/18	Riky7 & Riky8
01/15/19	Pup6 & Cryomagnetics1
01/22/19	Cryomagnetics2
01/29/19	LBNL RaceTrack7
02/07/19	LBNL RaceTrack8
05/14/19	Pup7
05/22/19	LBNL CCT1
05/26/19	LBNL CCT2

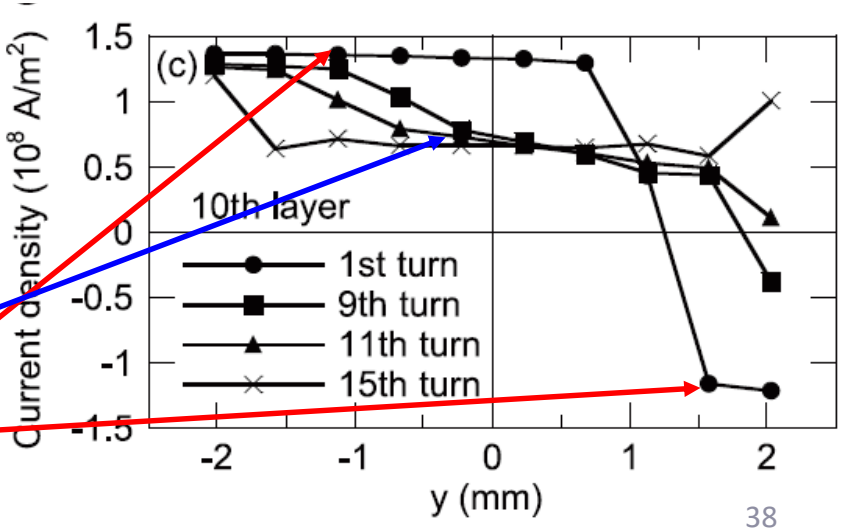
Slide courtesy of David Larbalestier

New Projects

Screening Currents: Tape Conductors



- J_t = transport current in θ direction. It creates B_z. At top of magnet B_r is positive.
- During charging of the magnet, B_r creates screening currents, J_s, in the tape.
- The Screening Current changes the field distribution.

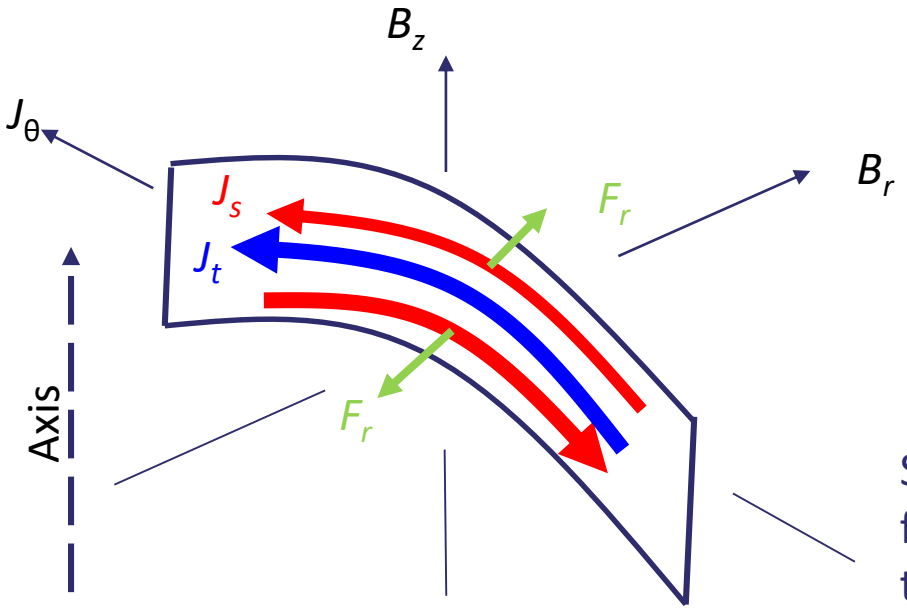


Transport Current = J_t

End pancakes have J_s = +/- J_c.

Naoyuki Amemiya & Ken Akachi, *SuST* (2008) 095001.

Screening Currents: Tape Conductors



- J_t = transport current in θ direction. It creates B_z. At top of magnet B_r is positive.
- During charging of the magnet, B_r creates screening currents, J_s, in the tape.
- The Screening Current changes the field distribution.

Screening currents also interact with the axial field to produce a "Diamagnetic Twist" on the tape.

Naoyuki Amemiya & Ken Akachi, *SuST* (2008) 095001.

Screening Currents: Strain

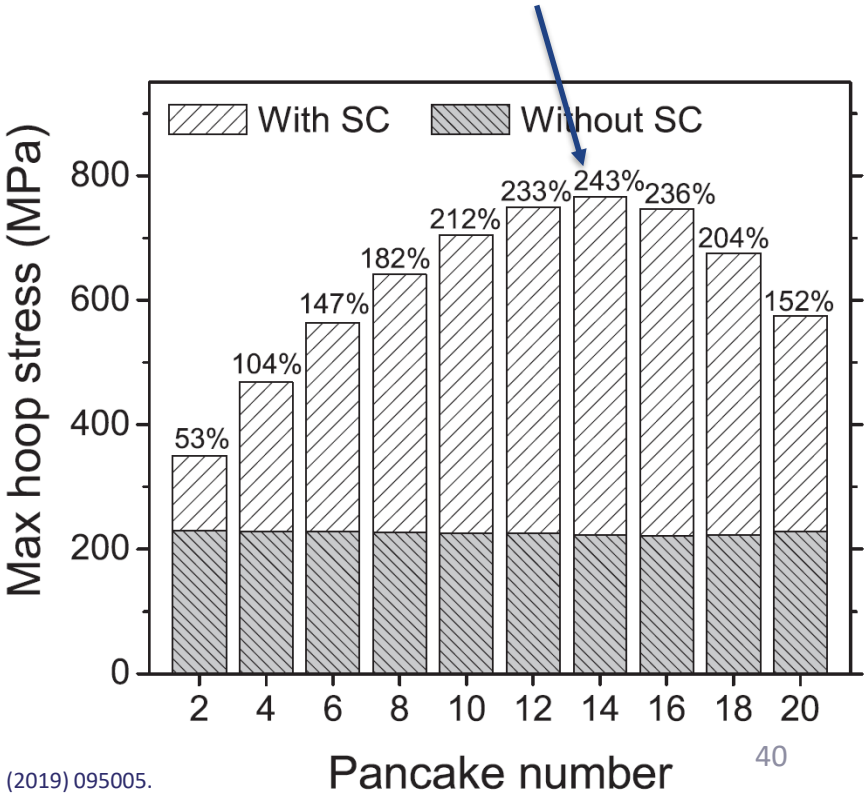
In the 1970s & 1980s, IGC built Nb_3Sn tape magnets.

Rippling of the edge of used tapes was observed.

In 2019 Jing Xia, et al., showed that if a coil was designed for uniform stress due to transport current only, actual stress including screening currents might be 2.4x higher.

Low screening currents at mid-plane due to low radial field.
High radial field at end of coil limits Jc.

Max. Torque and Strain for REBCO.



Jing Xia, Hongyu Bai, Huadong Yong, Hubertus W. Weijers, Thomas A. Painter, & Mark D. Bird, *SuST* **32** (2019) 095005.

Screening Currents: Strain

Li, et al., at MIT showed that computed stress might depend heavily on coefficient of friction assumed to exist between the tape and the spacers.

Coefficient of Friction	0.0	0.2
Stress (MPa)	940	680

38% difference in computed stress depending on coefficient of friction!

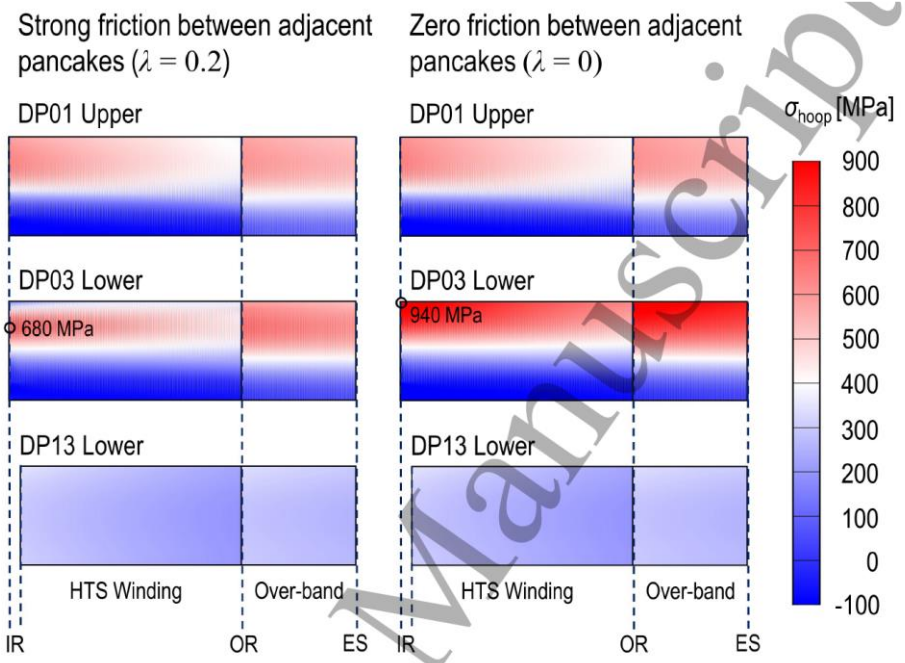
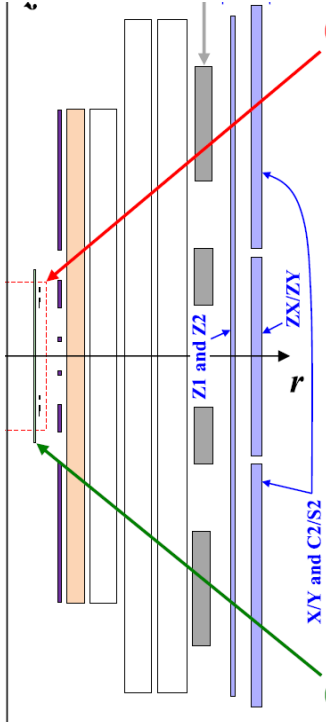


Figure 17. Hoop stress (σ_{hoop}) distribution with nonuniform current density considered and zero turn-to-turn friction, where "IR" and "OR" are the inner and outer radius of HTS winding, and "ES" the external surface of the over-band. 3 single pancakes are selected from Coil 1: one at the end of coil, one near the midplane, and one affected by maximum magnetic torque.

Yi Li, Dongkeun Park, Yufan Yan, Yoonhyuck Choi, Jiho Lee, Philip C. Michael, Siwei Chen, Timing Qu, Juan Bascunan, Yukikazu Iwasa, *SuST* (2019) in press.

History and future plans: ultra-high field NMR development in Japan

2013 - 2016



The high screening currents associated with REBCO coils require advanced shimming:

1) Ferroshims.
2) Superconducting Shims.
3) Higher order Resistive shims.
4) More space in the bore.

S. Iguchi, R. Piao, M. Hamada, S. Matsumoto, H. Suematsu, T. Takao, A .T. Saito, J. Li, H. Nakagome, X. Jin, M. Takahashi, H. Maeda and Y. Yanagisawa, *SuST* 29, (2016) 045013.

JST MIRAI Program 2017-2026

The magnet will be completed by 2024

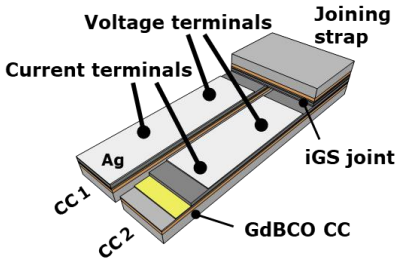
1.3 GHz (30.5 T) LTS/HTS NMR

Persistent current mode

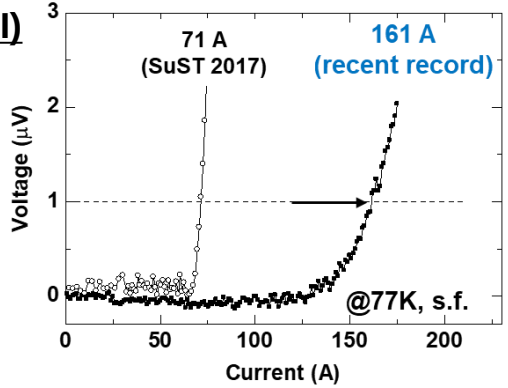
Maeda, Hideaki, et al. *IEEE Transactions on Applied Superconductivity* 29.5 (2019): 1-9.

Enhancement of the performance of superconducting Joints connecting HTS Tape

(a) REBCO Tape / REBCO Joint Layer / REBCO Tape (SEI)

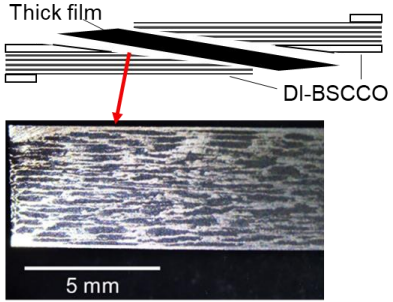


K. Ohki, *et al.*, *Supercond. Sci. Technol.*, 30 (2017) 115017

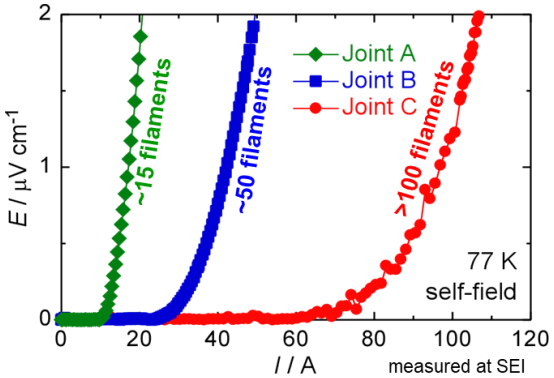


I_c > 700 A
(4.2 K, 1 T)

(b) Bi2223 Tape / Bi2223 Intermediate Layer / Bi2223 Tape (Aoyama Gakuin Univ.)



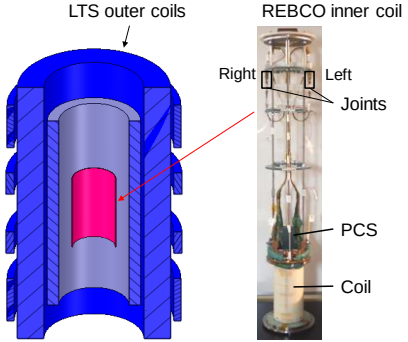
Y. Takeda *et al.*, *Appl. Phys. Express* 12 (2019) 023003

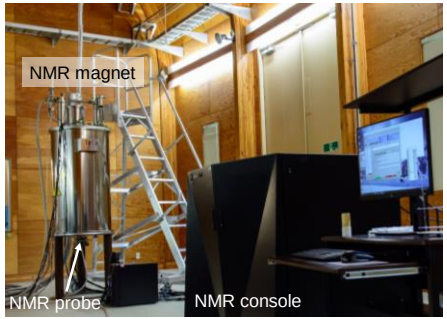


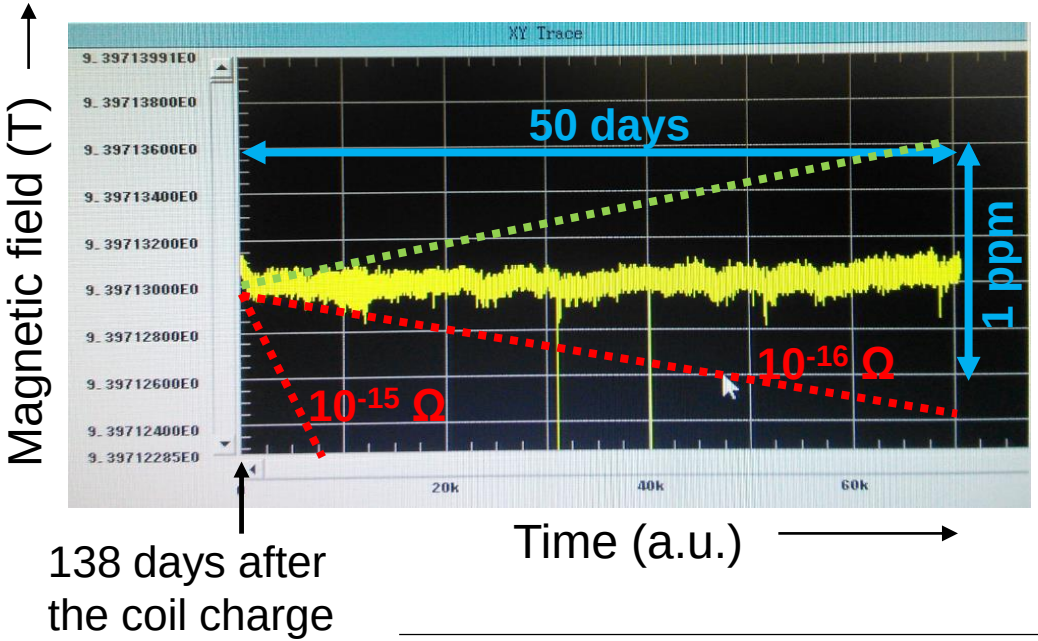
I_c > 300 A
(4.2 K, 1 T)

Long-term operation of the persistent 400 MHz NMR with superconducting joints between REBCO tape conductors

Gradual decrease in joint resistance with time, achieving < 10^{-16} Ω after half a year

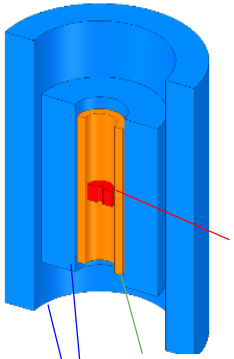


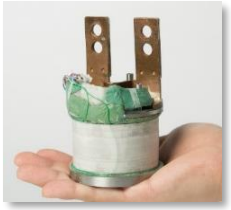




Y. Yamazaki et al., Towards 1.3 GHz NMR: A Persistent 400 MHz NMR with Superconducting Joints for High-Temperature Superconductors, ENC2019.

Achieving 30 T using an LTS / Bi-2223 / REBCO layer-wound magnet : a model coil of the 1.3 GHz (30.5 T) NMR

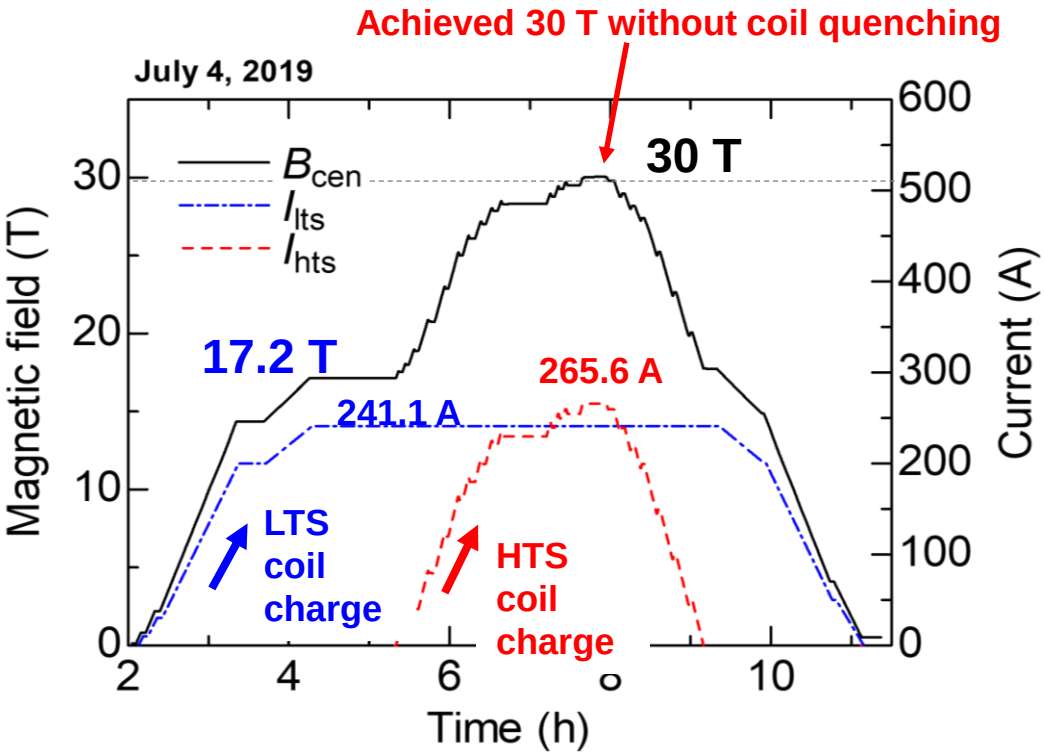




9.3 T Intra-layer no-insulation (LNI) REBCO coil

4.1 T Insulated Bi-2223 layer-wound coil

17.2 T Nb_3Sn / NbTi magnet



Y. Suetomi et al. presented at MT26, Fri-Mo-Or27-02, Sep. 27, 2019

40 T SC in Tallahassee: Considering 5 options

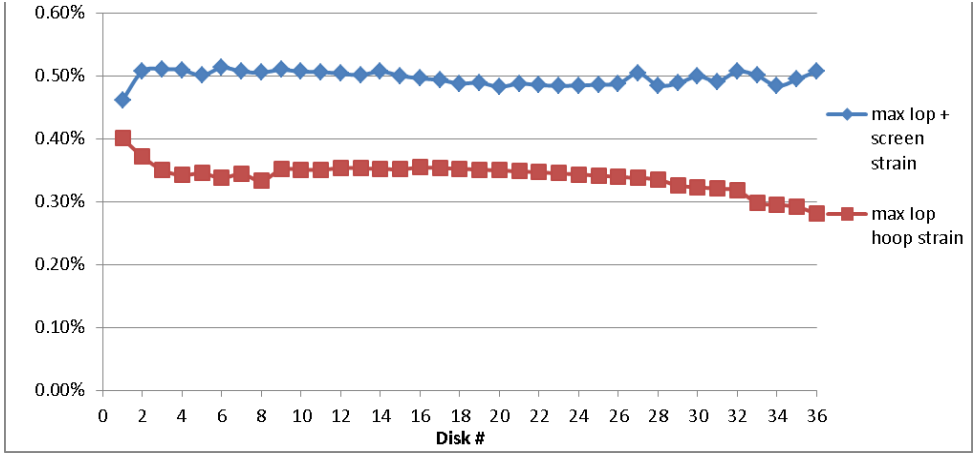
	Insulated REBCO	No-Insulation REBCO	Integrated Coil Form REBCO	Bi-2212	Bi-2223
Pros	Same technology as 32 T magnet: Extensive quench protection testing has been successfully completed (single coils >150 quenches).	Very compact → Lower cost. Has produced 26 T all-SC test coil & 45 T (31 + 14 HTS) test coil.	Very compact → Lower cost. Cables provide redundancy. Reinforcement system is better suited to screening currents.	Round, multi-filamentary wire facilitates coil construction and minimizes screening currents. Current density has recently surpassed I-REBCO.	Wire is produced in large quantities and length. Good quality control.
Cons	Concern about magnet life-time due to single-point failure of "single-crystal by the mile."	Quench protection not well developed.	No test coils to date.	No fatigue data. Coils built to date are very small. Reaction.	Wire has low current density, which results in larger magnets.

The goal of each test coil program is to reach a "Go/No Go" decision as soon as possible. This requires a dynamic process of weighing further risk reduction against time and cost of each test coil program.

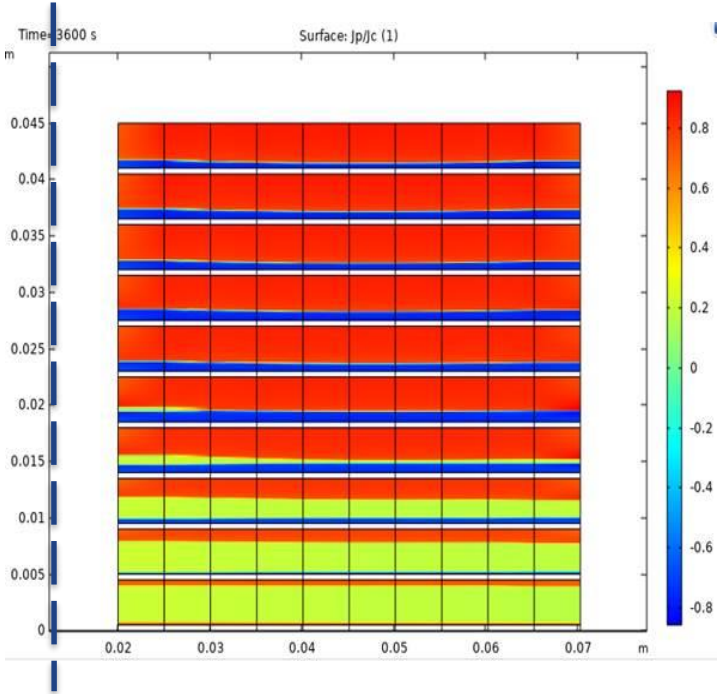
Screening Currents: Strain @ 40 T

For 40 T magnet project designs include strain due to screening currents.

By grading critical current and reinforcement one can obtain uniform strain throughout the coil.



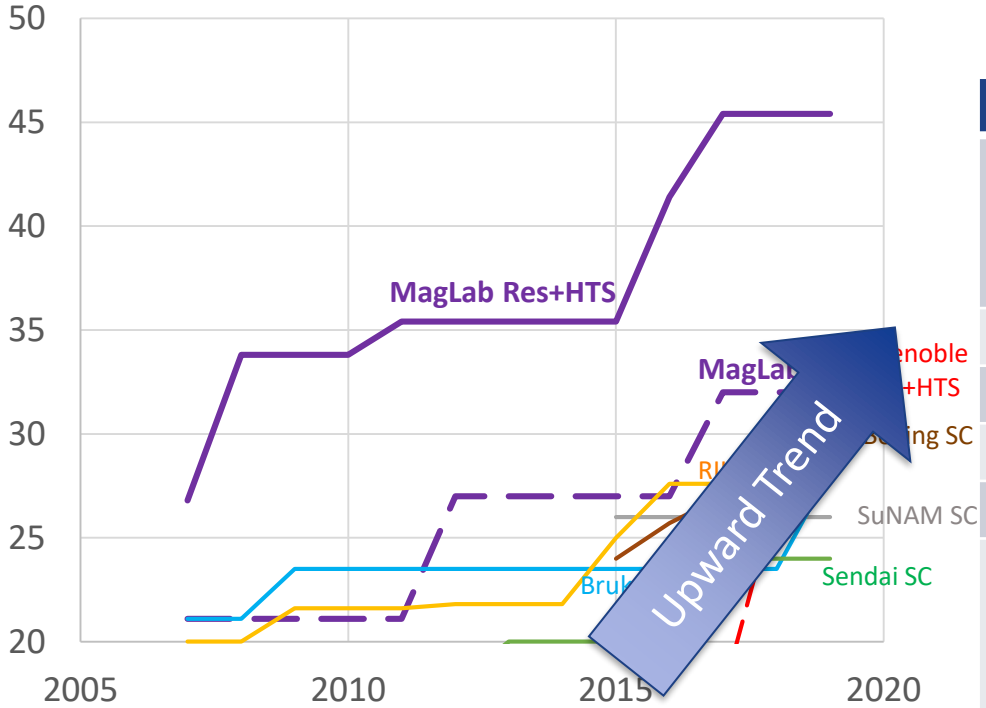
Current Density in Test Coil for 40 T Project



Stress increase due to Screening Currents reduced from factor of 2.4 to 1.3.

Dylan Kolb-Bond, Mark D. Bird, Iain R. Dixon, Hubertus W. Weijers, Edgar Berrospe-Juarez, Franchesco Gilli, Frederic Trillaud, & Victor M.R. Zermeno, Mon-Af-Po1.11-05.

Present Status > 23.5T SC



There are now at least 8 organizations worldwide developing HTS coils for service at Ultra-High Fields.

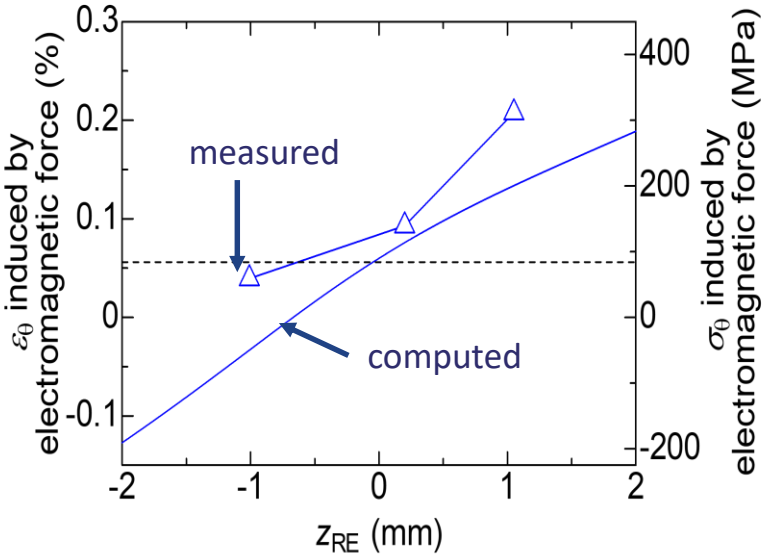
NMR = Nuclear Magnetic Resonance. MRI = Magnetic Resonance Imaging.

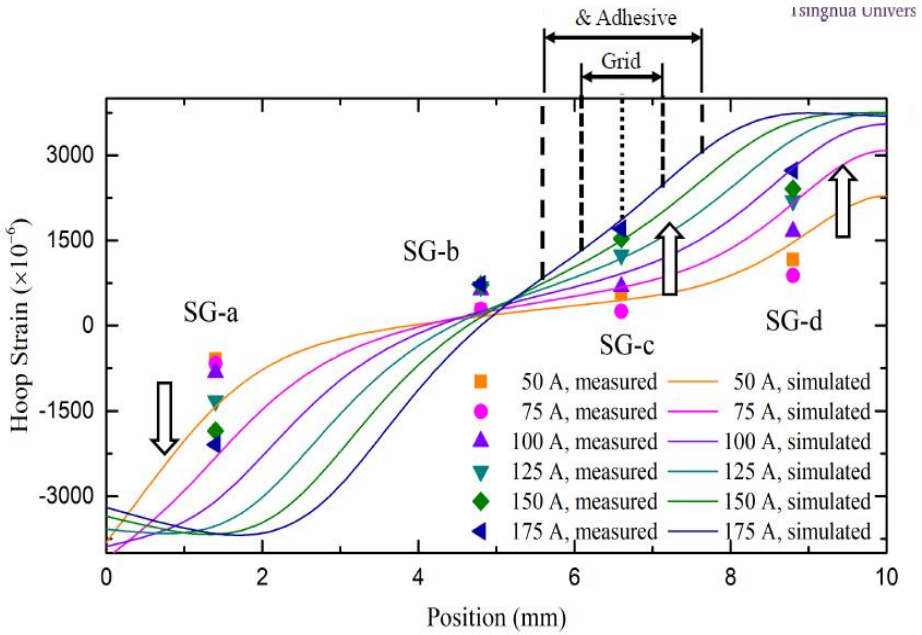
Publicly Stated Goals

Magnets are for Condensed Matter Physics unless stated otherwise.
Bold = Magnet in Service.

Organization	Present	Goal	Date
Sendai, Japan	**24 T**	30 T	2021
		33 T	funded
		40 T	
Tallahassee, Fl, USA	32 T	40 T	1st yr
Grenoble, France	32.5 T Res+	40 T	Study
Hefei, China		40 T	1st yr
KBSI, Korea	26 T	35 T	
Beijing, China	27 T test	30 T test	2019
		30 T	2021
		27 T ssNMR	2021
		28 T MRI	
Bruker	**25.8 T NMR**	**28.2 T NMR**	2019
RIKEN, Japan	27.6 T test	30.5 T NMR	2024

Screening Currents: Measured Strain





Agreement is not great. However, between these measurements, observation of plastic deformation, and observation of degradation of tape, it seems clear screening currents are causing strain. It was not clear what coefficient of friction was used in the calculations.

Tue-Mo-Or8-04, MT26, 24 Sep. 2019, Shunji Takahashi, et al., Sophia Univ. & RIKEN.

Fri-Mo-Or27-08, MT26, 27 Sep. 2019, Yufan Yan, et al., Tsinghua Univ. & Inst. Of Modern Phys. CAS.

Thank You!

NATIONAL HIGH MAGNETIC FIELD LABORATORY