IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), June 2023. Presentation given at Coated Conductors for Applications Workshop, Houston, TX, USA, April 2023.

Ultra High Field Magnet Applications of Coated Conductors

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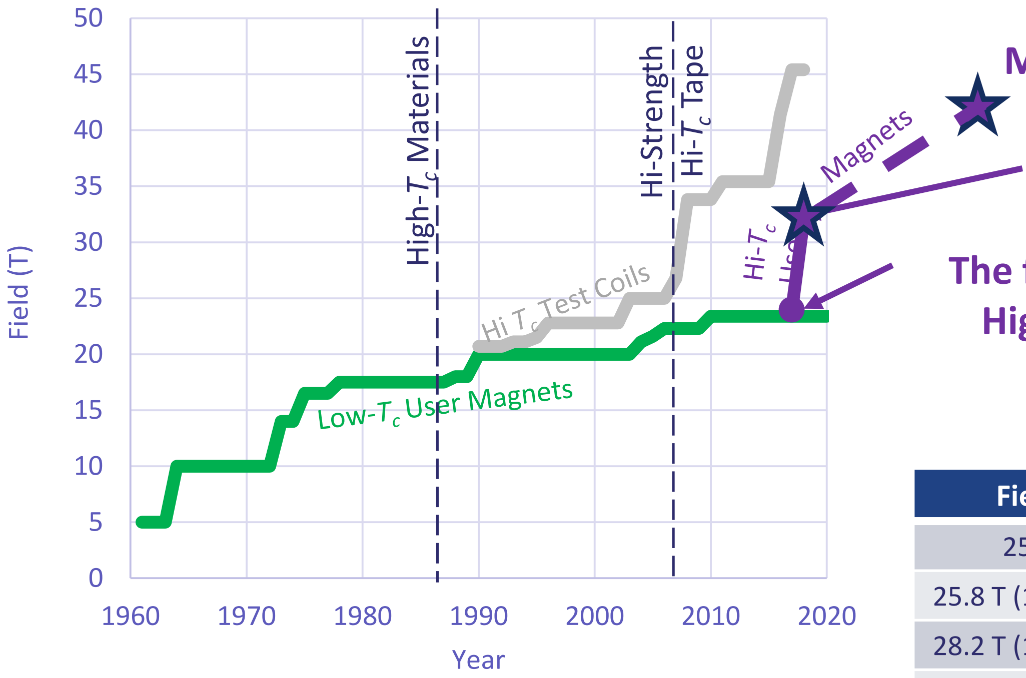
National High Magnetic Field Laboratory
Florida State University, Tallahassee, Florida, USA

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

The Development of Superconducting Solenoids

Ultra-High Field (UHF) solenoids means >23.5 T



MagLab 40 T

MagLab 32 T

The first Ultra-High Field High-T_c user magnet.

Many UHF test coils have been built but only a few magnets are in service.

Existing User Magnets > 23.5 T Worldwide

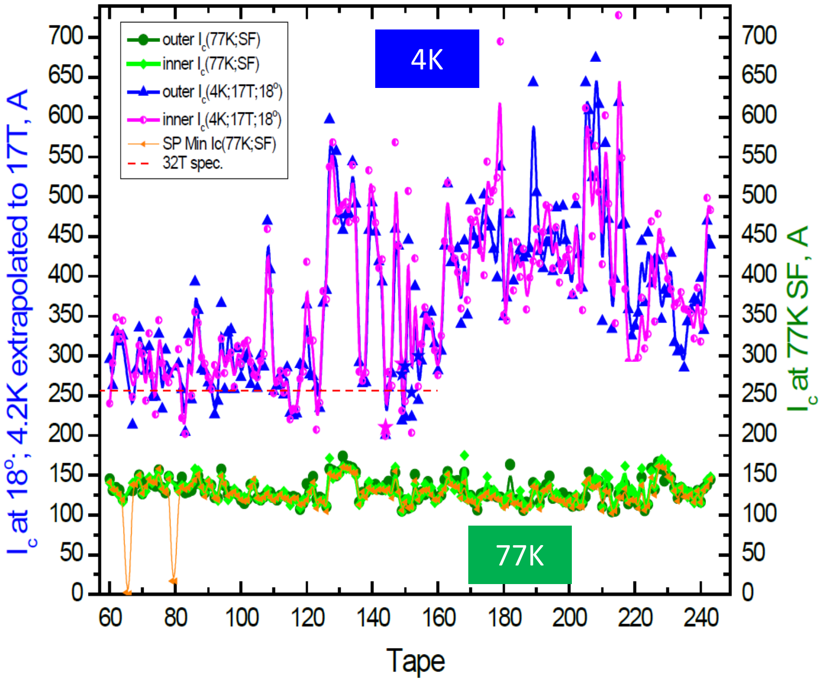
Field	Conductors	Maker	Location	Year
25 T	Bi-2223 + LTS	Toshiba	Sendai	2017
25.8 T (1.1 GHz)	REBCO + LTS	Bruker	Nashville	2019
28.2 T (1.2 GHz)	REBCO + LTS	Bruker	Florence (+6)	2020
32.1 T	REBCO + LTS	MagLab	Tallahassee	2017

Several Other Projects Underway at labs Worldwide!

Some UHF REBCO Magnet Concepts

Unpredictability of REBCO I_c Tape-to-Tape

32 T Magnet: 2012 – 2014
SuperPower tape



Temp	Ave	St. Dev.	St. Dev.	Min	Max	Ratio
4.2 K	393 A	94 A	24%	200 A	725 A	3.6
77 K	130 A	15 A	12%	100 A	175 A	1.8

There is significant variation in I_c at 4 K between tapes.

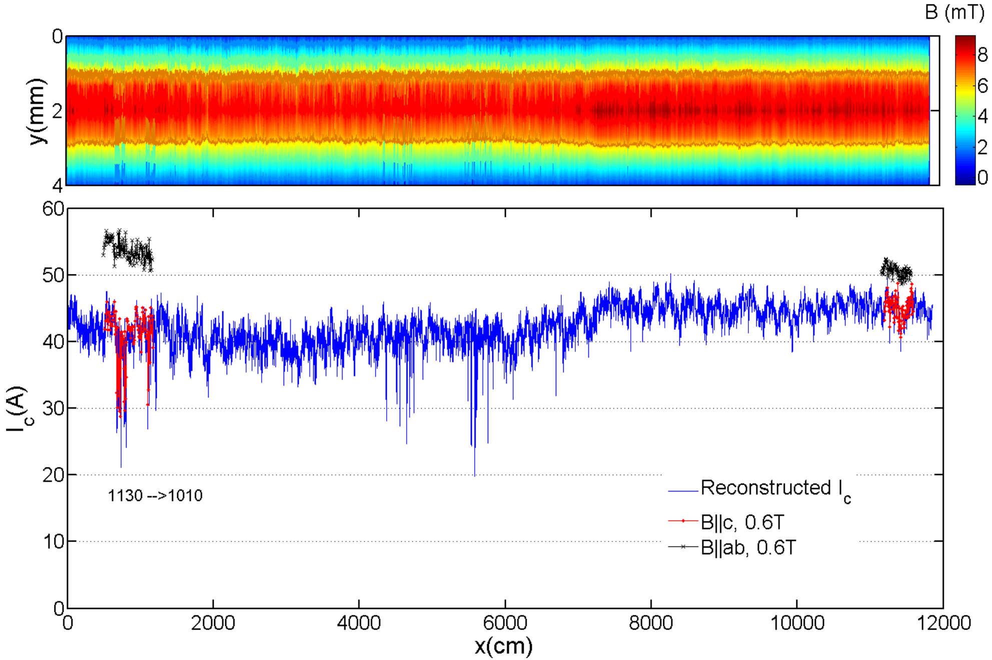
It cannot be predicted from a 77 K measurement.

(Present variation seems to be less than in the past.)

Dima Abraimov

Unpredictability of REBCO I_c Dropouts

YateStar measurement of critical current at 77K of SuperPower tape M4-352-5 0912

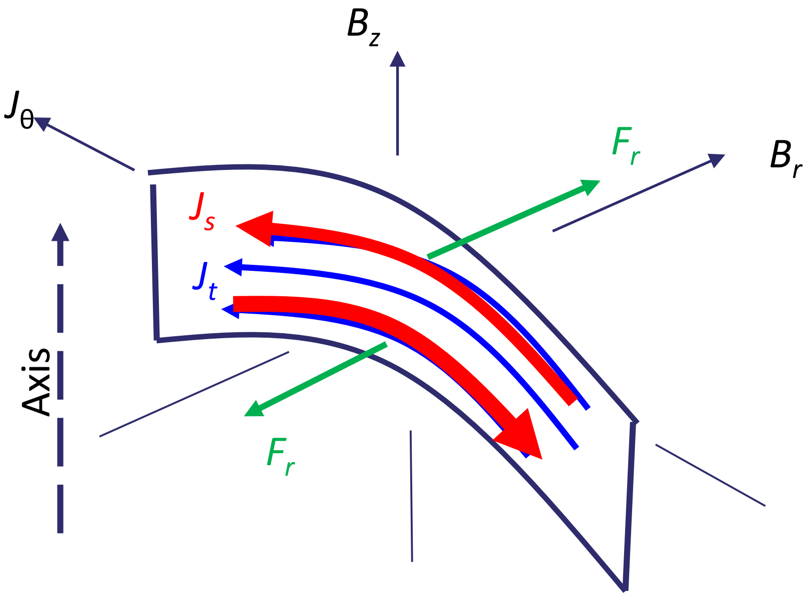


77 K measurements with TapeStar & YateStar indicate there can be spots along a conductor with low critical current.

Similar measurements at 4K have not been made.

Variation at 4K is unknown.

Screening Currents: Tape Conductors



J_t = transport current in θ direction.

- During charging of the magnet, B_r creates screening currents, J_s, in the tape.
  - J_s reacts with B_z to give radial forces F_r, in addition to those created by the transport current.
  - This gives rise to a Diamagnetic Torque and Twist and strain that is not uniform across the width of the tape.
  - Tape removed from test coils can display plastic deformation!

D. Kolb-Bond, M.D. Bird, I.R. Dixon, T.A. Painter, J. Lu, K.L. Kim, K. Kim, R.P. Walsh, F. Grilli, *SuST,* 34, 095004 (2021).

Y. Yan, P. Song, C. Xin, M. Guan, Y. Li, H. Liu, and T. Qu, *SuST.* **34** (2021) 085012 (13pp)

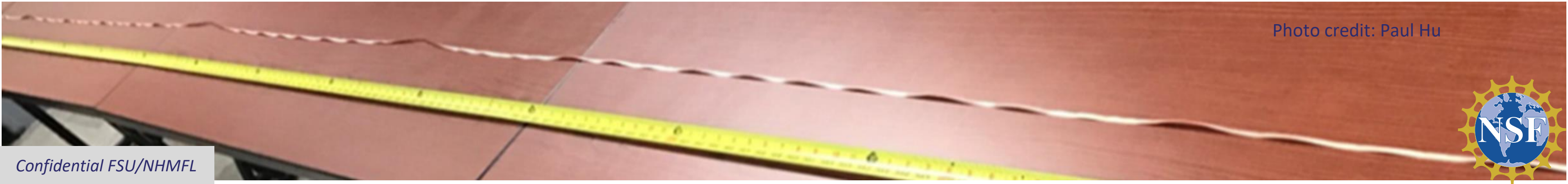
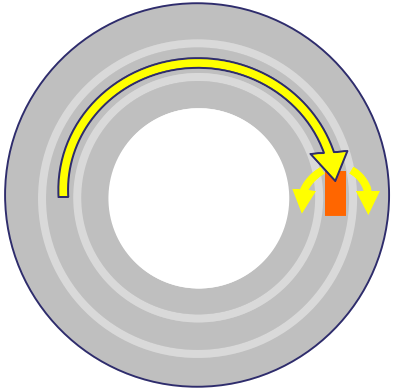


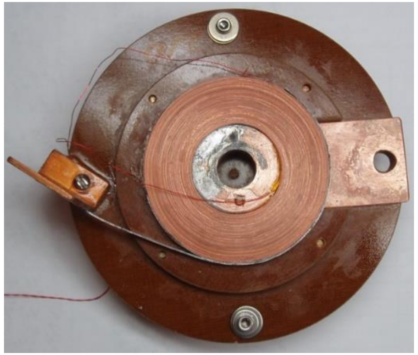
Photo credit: Paul Hu

Insulated vs No-Insulation REBCO

Insulated REBCO
- MagLab 32 T, 2017
- Bruker 28.2 T (1.2 GHz), 2019
- RIKEN 30.5 T (1.3 GHz)
- Sendai 33 T

No-Insulation REBCO
- Resistive (Metal) Insulation
- Partial Insulation
- MIT 30.5 T NMR
- Grenoble/CEA 30 T
- IEE-Beijing: 30 T CMP + 27 T CM NMR





Current Bypasses Quench reducing hotspot temperature.

Less Cu is Required → Smaller Coils [3, 4].

Less Reinforcement Required → Smaller Coils.

- ☐ Coil quench at I_{op}=412 A (1580 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

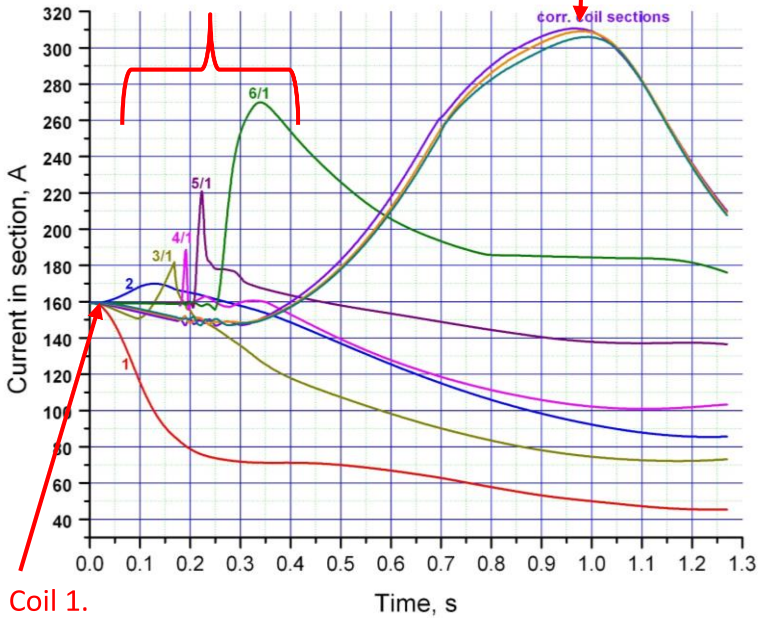
S. Hahn, D.K. Park, J. Voccio, J. Bascunan, and Y. Iwasa, IEEE Trans. On Appl. SC, **22**, 3, (2012) 4302405

Quench

	LTS
Energy Margin	Small (mJ)
Small coils	Self protect Quench propagates quickly Energy distributed uniformly
Large Coils	Require protection system
	1. Diodes allow current to bypass quench
	2. Heaters can accelerate quench
	3. External dump resistor extracts energy

Quench Wave (Tsunami) propagates through magnet.

Coil 7 experiences excessive current (over-stressed, redesigned).

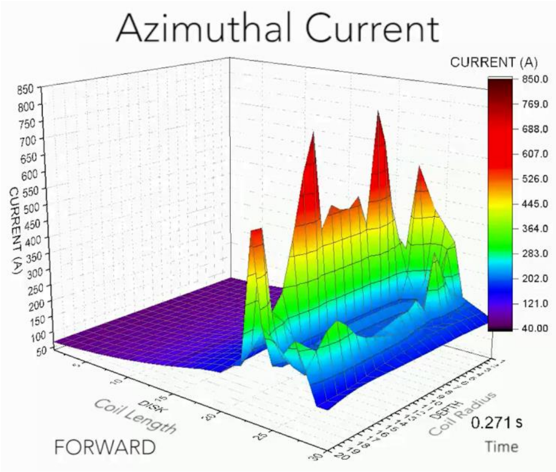


Quench starts in Coil 1.
Diode breaks down.
Coil current Decays.

Andy Gavrilin

Quench

	LTS	HTS (REBCO, high field, operating at 4 K)
Energy Margin	Small (mJ)	Large (kJ)
Small coils	Self protect Quench propagates quickly Energy distributed uniformly	Frequently burn Quench propagates slowly Energy concentrated in a small volume
		NI-REBCO magnets allow current to bypass quench.
Large Coils	Require protection system	
	1. Diodes allow current to bypass quench	
	2. Heaters can accelerate quench	
	3. External dump resistor extracts energy	



NI-REBCO shows similar current spikes to those of diode-protection.

Many more degrees of freedom.

Denis Markiewicz

Quench

	LTS	HTS (REBCO, high field, operating at 4 K)
Energy Margin	Small (mJ)	Large (kJ)
Small coils	Self protect Quench propagates quickly Energy distributed uniformly	Frequently burn Quench propagates slowly Energy concentrated in a small volume
		NI-REBCO magnets allow current to bypass quench (with potentially high induced currents and strains)
Large Coils	Require protection system	Require protection system
	1. Diodes allow current to bypass quench (with potentially high induced currents and strains).	1. NI might require controlled inter-turn resistance to control quench dynamics (Metal Insulation, Resistive Insulation, Partial Insulation) [1, 2].
	2. Heaters can accelerate quench	2. Heaters can accelerate quench
	3. External dump resistor extracts energy	3. External dump resistor extracts energy

[1] P.C. Michael, et al., *IEEE-TAS* **29**, 5, Aug 2019, 4300706
[2] D. Park, et al., IEEE-TAS 29, 5, Aug 2019, 4300804

Operational UHF REBCO Magnets

32 T SC: I-REBCO

NATIONAL HIGH MAGNETIC FIELD LABORATORY · SuperPower Inc. A Furukawa Company · OXFORD INSTRUMENTS

REBCO Unpredictability

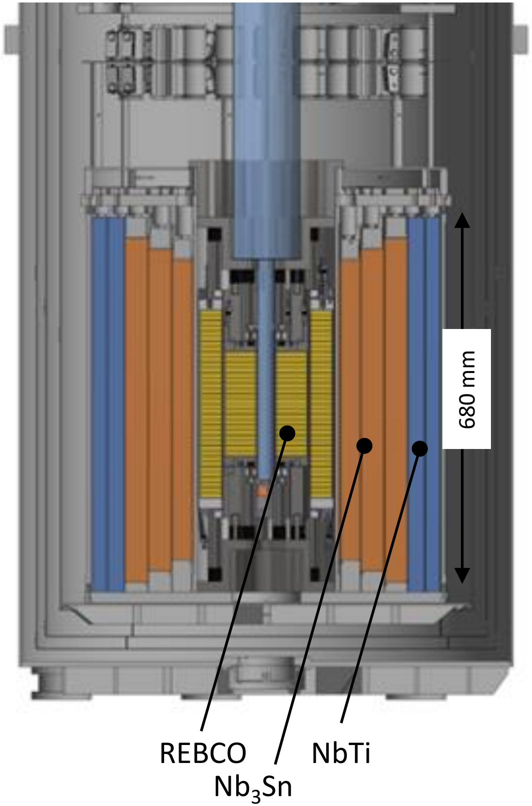
I_c of all tapes was measured at 4K, 18° from *ab*-plane, 14 T. Magnet operates between 20% and 30% of I_c.

Screening Currents

Not fully appreciated at the time.

Quench

Heaters between REBCO double-pancakes (~100 kJ).

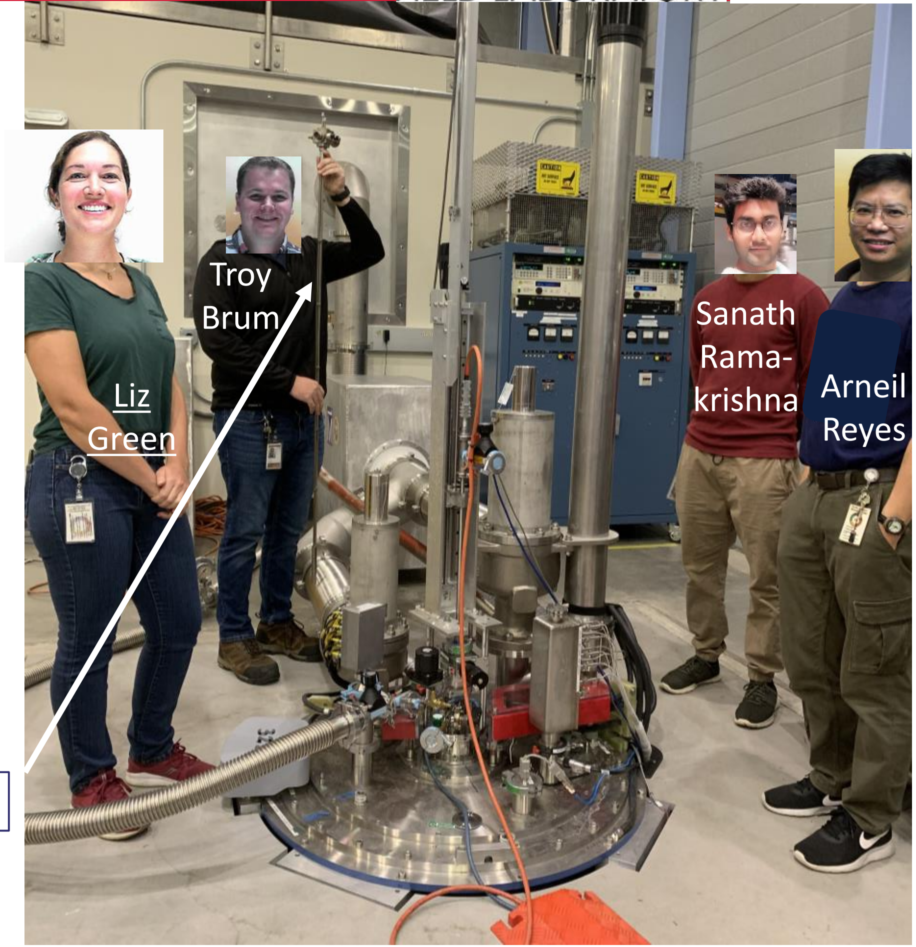


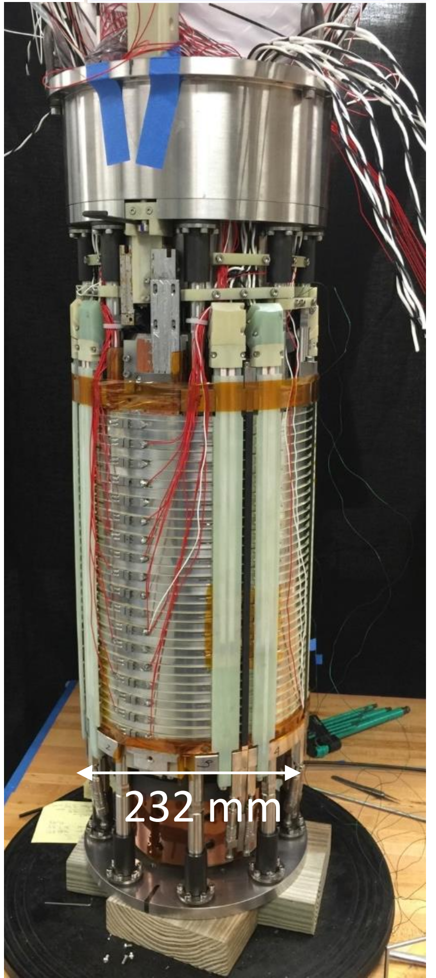
Total field	32 T
Field YBCO coils	17 T
Field LTS coils	15 T
Cold inner bore	32 mm
Current	172 A
Inductance	619 H
Stored Energy	9.15 MJ
Uniformity	5×10^{-4} 1 cm DSV

- Commercial Supply:
  - 15 T, 250 mm bore LTS coils
  - Cryostat (Oxford Instruments)
  - REBCO tape (SuperPower)
- 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).

32 T magnet: User Service





Liz Green, a Research Faculty member at the MagLab, leads the 1st User Experiment in the 32 T magnet performing NMR measurements of a frustrated magnet system.

NMR probe

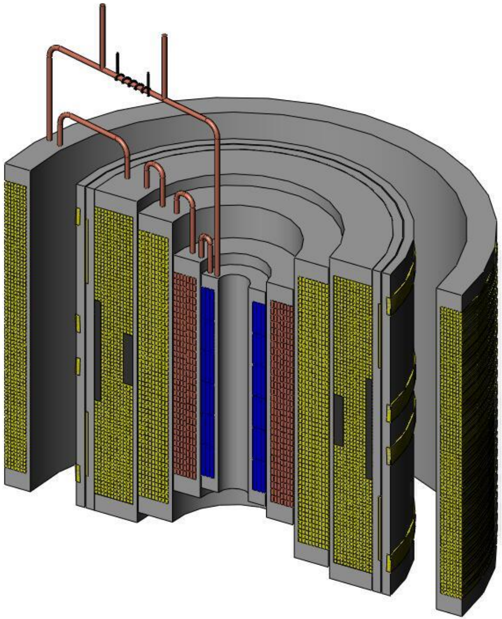
NMR Magnets Beyond 1.0 GHz
High Temperature Superconductors (I-REBCO)

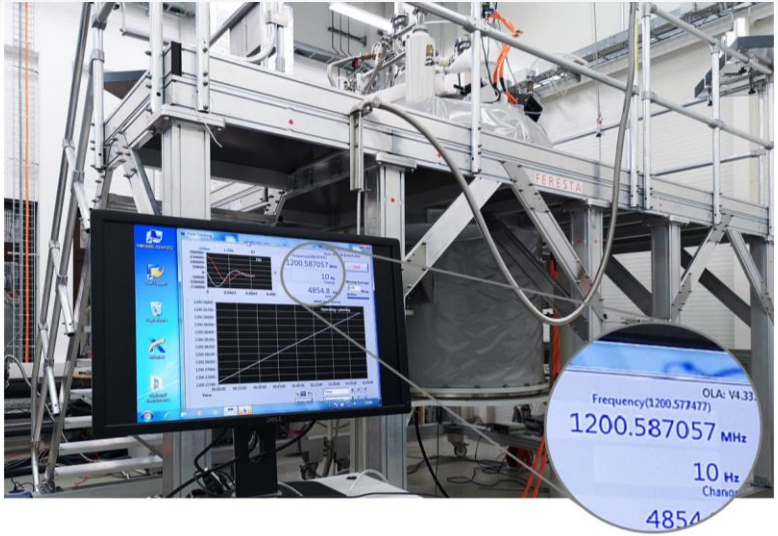
Nuclear Magnetic Resonance is the largest steady market for SC magnets with fields > 3 T.

It requires field uniformity & stability <10 ppb.

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

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

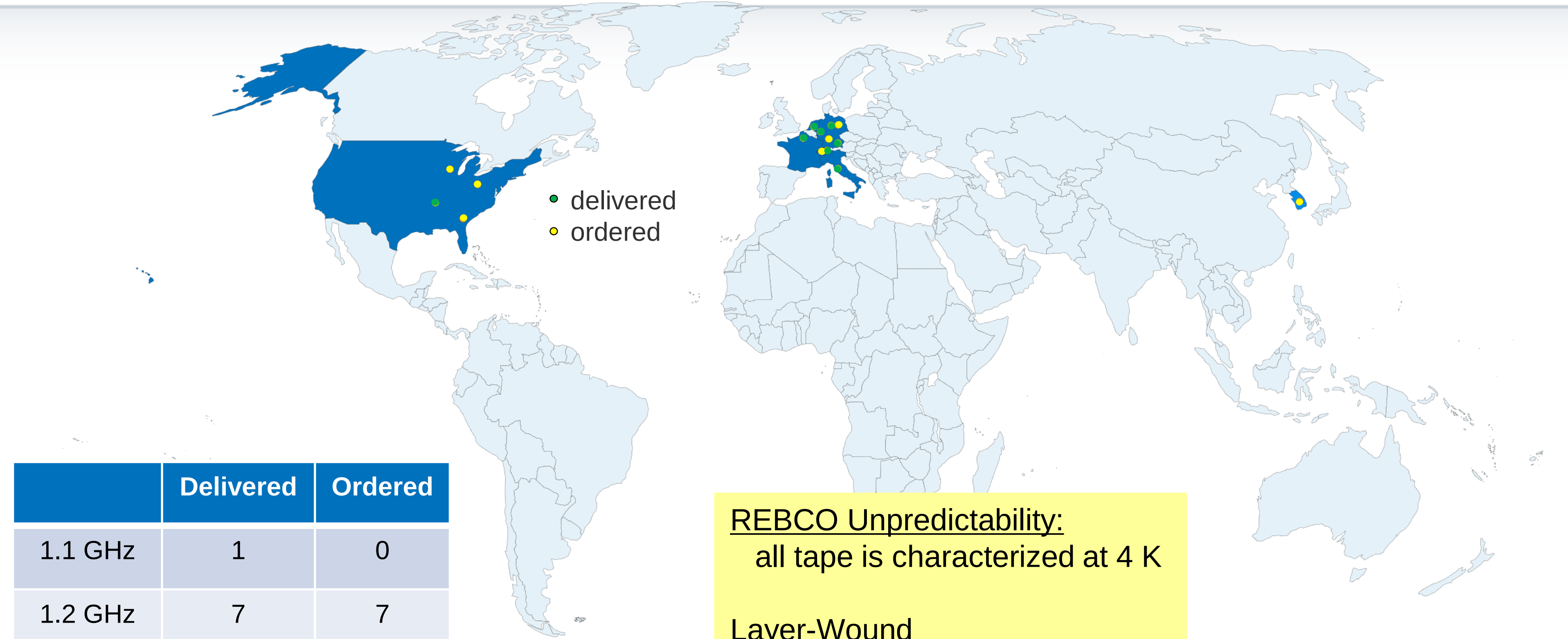




The First 1.2 GHz (28.2 T) NMR Magnet Reached Full Field in 2019

Slide courtesy of Patrick Wikus

1.1 and 1.2 GHz NMR systems using ReBCO coated conductors ordered and delivered worldwide (Q4 2022)



	Delivered	Ordered
1.1 GHz	1	0
1.2 GHz	7	7

REBCO Unpredictability:
all tape is characterized at 4 K

Layer-Wound

UHF REBCO Magnets Underway

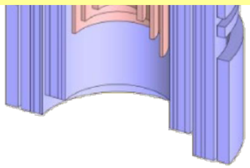
REBCO Insert for MIT 1.3-GHz NMR Magnet

- ❑ **H835:** 19.7-T REBCO insert into a 10.93 T LTS NMR coil (L500)
- ❑ Towards an NMR quality 30.5T magnet – the MIT 1.3G
- ❑ **H835** Design Features
  - No-insulation (NI) double-pancake (DP) winding
- ❑ High mechanical strength/stiffness
  - 304 stainless steel co-winding for DPs in strongest axial fields
  - 316 stainless steel overband for all DPs
- ❑ Learned from **H800** Quench
  - Single solenoid to avoid magnetic coupling between nested coils
  - Metallic insulation to accelerate relaxation of bypass current
- ❑ Screening-Current Effect Considered in the Design
  - Associated field reduction and stress/strain modification analyzed

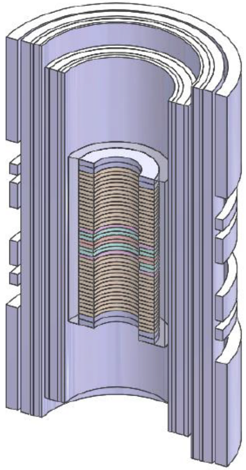
REBCO Unpredictability
- MI-REBCO
- <70% I_c

Screening Currents
- Narrower tape than earlier version.
- Strain <0.7% including SCS.

Quench
- MI-REBCO self-protection.
- Dump resistor.
- Heaters.



Precedent H800
3-Nested-Coils Design
NI-REBCO
Quenched & Damaged in standalone test (March 2018)



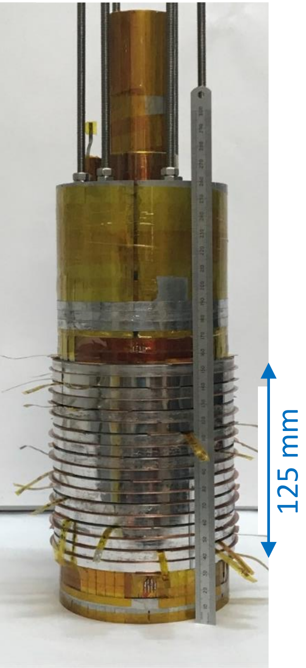
New H835
Single Solenoidal Design
MI-REBCO

12 of 40 Double-Pancakes have been wound.
Due 2024

Y. Li, D. Park, W. Lee, Y. Choi, H. Tanaka, J. Bascuñàn, Y. Iwasa, *Applied Supercond. Conf.*, Oct. 26 – Nov. 6, 2020, Wk1LOr4D_06

Grenoble Magnet Lab + CEA, Metal Insulation

LNCMI



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

- March 2019
  - System reached 30.1 T (12.1 T HTS + 18 T Resistive).
  - System reached 29 T (10 T HTS + 19 T Resistive) when resistive magnet tripped off, inducing large current in HTS coil.
  - HTS coil worked well despite discharge of resistive background magnet.
  - HTS coils re-energized in self-field successfully.
  - System reached 32.5 T (14.5 T HTS + 18 T resistive) when Quench occurred.
- Significant damage seen in HTS coil.
- All 9 double-pancakes were repaired.
- System reached 28.2 T (10.2 T HTS + 18 T Resistive), Oct. 2021.
- Install HTS coil in LTS outsert @ Dresden to provide 30 T SC user magnet.

REBCO Unpredictability
  MI-REBCO.
  60% of I_c.
Screening Currents
  Not included in strain calculations.
Quench
  MI-REBCO.
  HTS shield between LTS & HTS coils.

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

Philippe Fazilleau, Xavier Chaud, Francois Debray, Thibault Lecrevisse, Jung-Bin Song, *Cryogenics*, 106, March 2020, 103053.
Jungbin Song, Xavier Chaud, Francois Debray, Steffen Kramer, Phillippe Fazileau, & Thibault Lecrevisse,
Thibault Lecrevisse, Xavier Chaud, Philippe Fazilleau, Clement Genot, Jung-Bin Song, *SuST*, **35** (2022) 074004 (18pp).

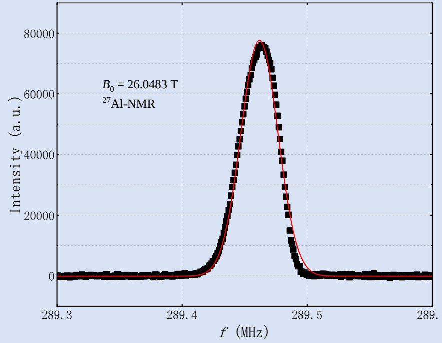
Progress of SC Magnets at IEECAS

INSTITUTE OF ELECTRICAL ENGINEERING, CHINESE ACADEMY OF SCIENCES

☐ 30T/Φ35mm user magnet at the IEE CAS for SECUF Project : quantum oscillation

Total field	**30 T**
Insert coils	**10.05 T (inner coil)** **4.95 T (outer coil)**
Background coil	**15 T**
Cold inner bore	**35 mm**
Operating current	**140.1 A**
Superconducting tape	**YBCO**
Co-wound tape	**stainless steel tape**
Coil structure	**Double pancake**
HTS conductor length	**9290 m**
Homogeneity	**8 ppm @30 mm**

- **Preliminary test to 26 T was achieved for SECUF, at Huairou, Beijing, on Jul. 8,2022**



NMR magnet reached 25T, with a homogeneity of 13ppm@10mm DSV, and a field drift of ~0.83ppm/hour (62 hours later);

<u>REBCO Unpredictability</u>

MI-REBCO

<u>Quench</u>

MI-REBCO self-protection.

"Coupling coils" slow dB/dt.

Slide courtesy of Jianhua Liu

33 T I-REBCO Magnet Development in Sendai

HFLSM Sendai

TOSHIBA Leading Innovation >>>

REBCO Unpredictability

Measure I_c of each pancake at 77 K.

Wind 2 conductors in parallel.

50% I_c.

Screening Currents

Epoxy bonds turns to G10 spacers to eliminate strain due to screening currents.

Quench

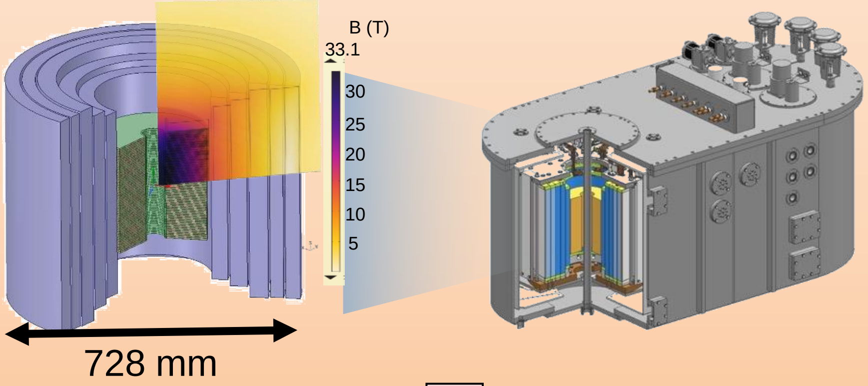
Assume HTS will not quench.

If LTS quenches, use external resistor to prevent current increase in HTS coil.

2022-

NEW 33T Cryogen–Free

- High strength Nb_3Sn Rutherford Cable
- Robust REBCO conductors



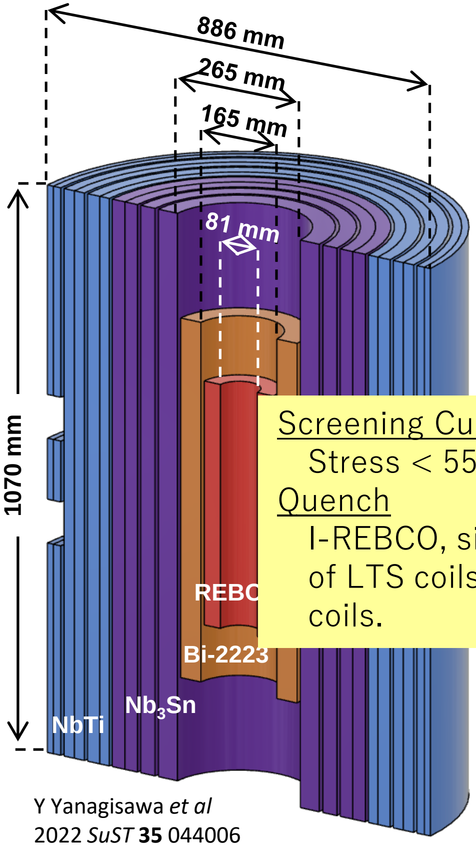
Superconducting magnet technology beyond 40 T.

50 T Superconducting magnet

Recent test coil w/ 20 pancakes generated 11 T HTS + 14 T LTS = 25 T total.

Slide courtesy of Satoshi Awaji

Development of a 1.3 GHz (30.5 T) NMR magnet in the JST-Mirai Program



Y Yanagisawa *et al* 2022 *SuST* **35** 044006

30.5 T series-connected LTS/HTS coils in the persistent-mode with superconducting joints for HTS

Operating temperature (K)		4.2 (LHe)
Operating current (A)		231
Self-inductance (H)		988
Stored energy (MJ)		26.4
Weight of superconductors (ton)		3.9
)		9.9
		HTS+LTS series
	Layer-winding	REBO / Bi-2223
n²)	REBCO / Bi-2223	205 / 137
Field contribution (T)	HTS (REBCO+Bi-2223) LTS	15.7 (8.7+7.0) 15.1
Conductor length for winding (km)	REBCO / Bi-2223 / LTS	5.2 / 11.0 / 154
Number of joints	RR / BB RL / BL R: REBCO B: Bi-2223 L: LTS	16-32 / 30-45 several / several

Screening Currents
Stress < 550 MPa (~0.33%) including SCS.
Quench
I-REBCO, single power supply, resistance of LTS coils extracts energy from HTS coils.

The 40 T SC Magnet at MagLab

- Developed software to compute screening currents, strains, and field distributions that is being adopted by other labs worldwide.
- Developed quench modelling software for both MTI and RI coils.
- Introduced critical-current graded coils.
- Demonstrated coils survive
  - <u>50,000 cycles with 125 MPa axial pressure</u>
  - <u>>23,000 cycles at 0.4% strain; >200 cycles at 0.5% strain.</u>
- Increase in copper current density, J_{cu}, compared with 32 T.
- Introduced Reinforcement grading.
- Demonstrated numerous improvements to quench protection
- <u>Tested 19 different REBCO coils</u>.

<u>REBCO Unpredictability</u>
Measure each REBCO tape at 4K.
$I_{op}/I_c \sim 0.6$.
I-REBCO = 2-in-hand
RI-REBCO
<u>Screening Currents</u>
Strain <0.45% including SCS.
<u>Quench</u>
I-REBCO version uses heaters between modules.
NI-REBCO version has controlled inter-turn resistance and fast quench heaters.

TC2
(August 2022)

RI-NC
(Sep. 2022)

Two recent REBCO test coils from the 40 T magnet project.

Tsinghua U + ASIPP: 35 T

Institute Of Plasma Physics
Chinese Academy Of Sciences

Tsinghua University

1. 20-T HTS Magnet Configuration

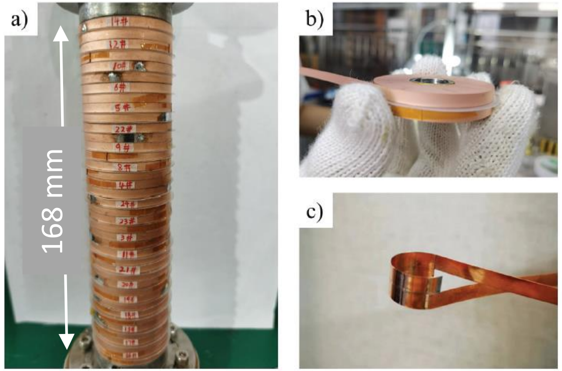


Fig.1 Fabrication process of Coil 1 (a: Stack of 20 NI DPs; b: One individual DP; c: REBCO inner joint.)

Table.1 Key Parameters of 20 T HTS Magnet

Parameter	Unit	Coil 1 (NI)	Coil 2 (MI)
Inner radius	mm	8.5	46.2
Outer radius	mm	22.2	67.3
Turns per DP	-	210	90
Number of DP	-	20	28
Height	mm	168	280
Length per DP	m	40	65
Over-Banding Thickness	mm	11	3.7
Co-winding Thickness	μm	-	50
Operation Current	A	244	
Copper Current Density	A/mm^2	938.5	274.8*
Center Field Contribution	T	15	5
Inductance	H	0.352	0.562

Fig.2 Photo of fabricated 20-T magnet before liquid-helium test.

Coil 1 winding configuration:

- ◆65-μm REBCO tapes, with 38-μm Has substrate.
- ◆Superconducting inner-joint, soldering on 8-mm transitional tape.
- ◆Optimize the stack order of DPs according to the critical current, DP on the edge has larger I_c.

*The thickness of co-winding Hastelloy tapes was not considered.

<u>REBCO Unpredictability</u>

65% of I_c at end of coil.

<u>Screening Currents</u>

Strain 0.68% max including SCS w/o coupling.

<u>Quench</u>

NI-REBCO for inner coil

MI-REBCO for 2nd coil

<u>35 T All-SC Test Coil</u>

20 T HTS coils quenched 5 times in stand-alone testing.

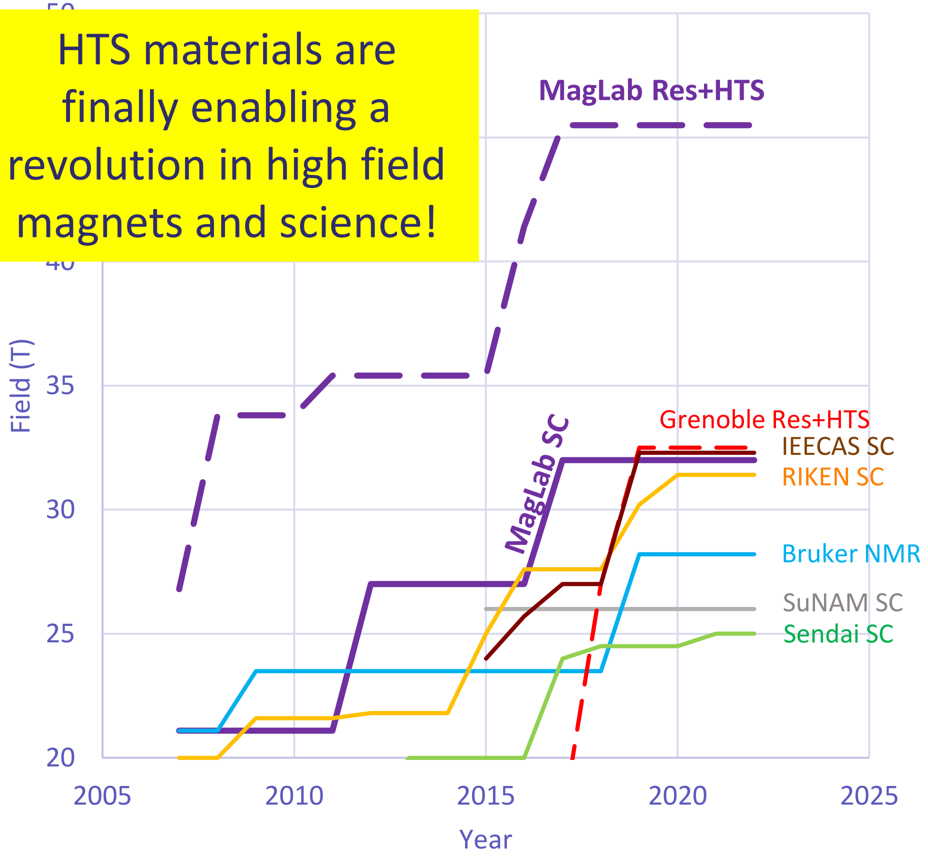
Each quench caused damage to Coil 1 DP 3.

HTS coils repaired & charged again to 23.2 T with no background field

Liangjun Shao, Xintao Zhang, Zhirong Yang, Yubin Yue, Yufan Yan, Peng Song, Yi Li, Huajun Liu, & Timing Qu, *ASC 2022*.

Summary

HTS materials are finally enabling a revolution in high field magnets and science!



NMR = Nuclear Magnetic Resonance.

There are now > 7 organizations worldwide developing HTS coils for service at Ultra-High Fields.

- All SC magnets >25 T use REBCO.
  - SC magnets are presently available at 28 – 32 T for condensed matter physics.
  - NMR magnets are operating at 28.2 T (1.2 GHz).
  - >4 groups are pursuing 30 – 35 T SC.
  - 2 groups are pursuing 30.5 T (1.3 GHz) NMR.
  - ~4 labs are pursuing 40 T SC.
- Variability of properties, effects of screening currents, and quench protection remain important challenges.

Thank You!

NATIONAL HIGH MAGNETIC FIELD LABORATORY