The NHMFL 40 T All-SC Magnet Project

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NSF-funded User Program

1 Lab. 3 Sites. 7 User Facilities	Users
DC @ FSU**:** *continuous fields.*	631
Nuclear Magnetic Resonance @ FSU*: solution and solid-state NMR and animal MRI.*	341
Advanced Magnetic Resonance and Spectroscopy @ UF*: high-resolution and solid-state NMR, in-vivo imaging and spectroscopy, MRI microscopy, and diffusion.*	262
Ion Cyclotron Resonance @ FSU*: ultra-high resolution and high mass-accuracy Fourier transform ICR mass spectroscopy.*	246
Electron Magnetic Resonance @ FSU**:** *continuous & pulsed techniques associated with unpaired electron spins.*	173
Pulsed Field @ LANL*: short, ultra-intense field pulses.*	155
High B/T @ UF*: high fields combined with ultra-cold electron temperatures to 0.4 mK.*	18

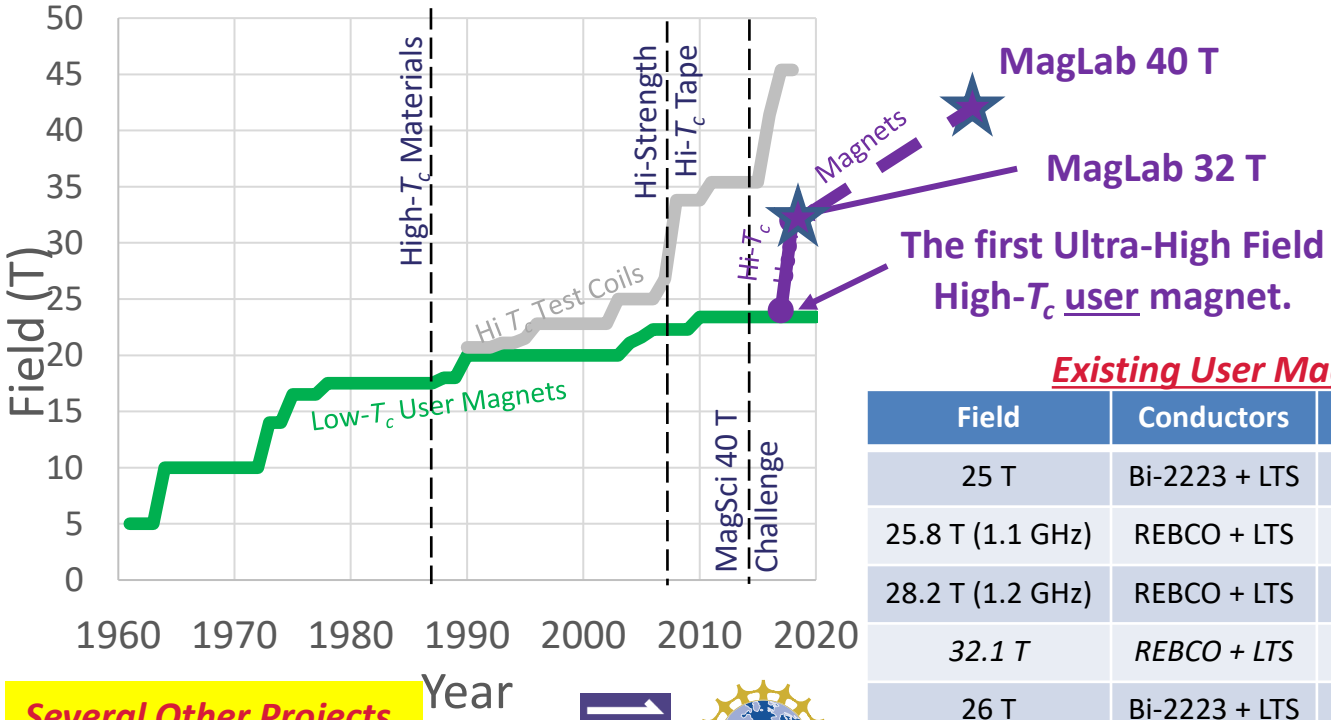
FSU | FLORIDA STATE UNIVERSITY UF | UNIVERSITY of FLORIDA Los Alamos NATIONAL LABORATORY

Total = 1826 users in 2023

The Development of Superconducting Solenoids

NATIONAL MAGLAB
Headquartered at Florida State University

"A 40 T all-superconducting magnet should be designed and constructed, building on recent advances in high-temperature superconducting magnet technology." – *MagSci Report*, 2013, pg. 17



There is only 1 commercial magnet supplier building magnets at 30 T, for NMR only.

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 + 12	2020
32.1 T	*REBCO + LTS*	*MagLab*	*Tallahassee*	*2017*
26 T	Bi-2223 + LTS	IEE-Beijing	Huairou	2023
30 T	REBCO + LTS	IEE-Beijing	Huairou	2023

Several Other Projects Underway Worldwide!

40 T All-SC Magnet Requirements

Key Performance Parameters:

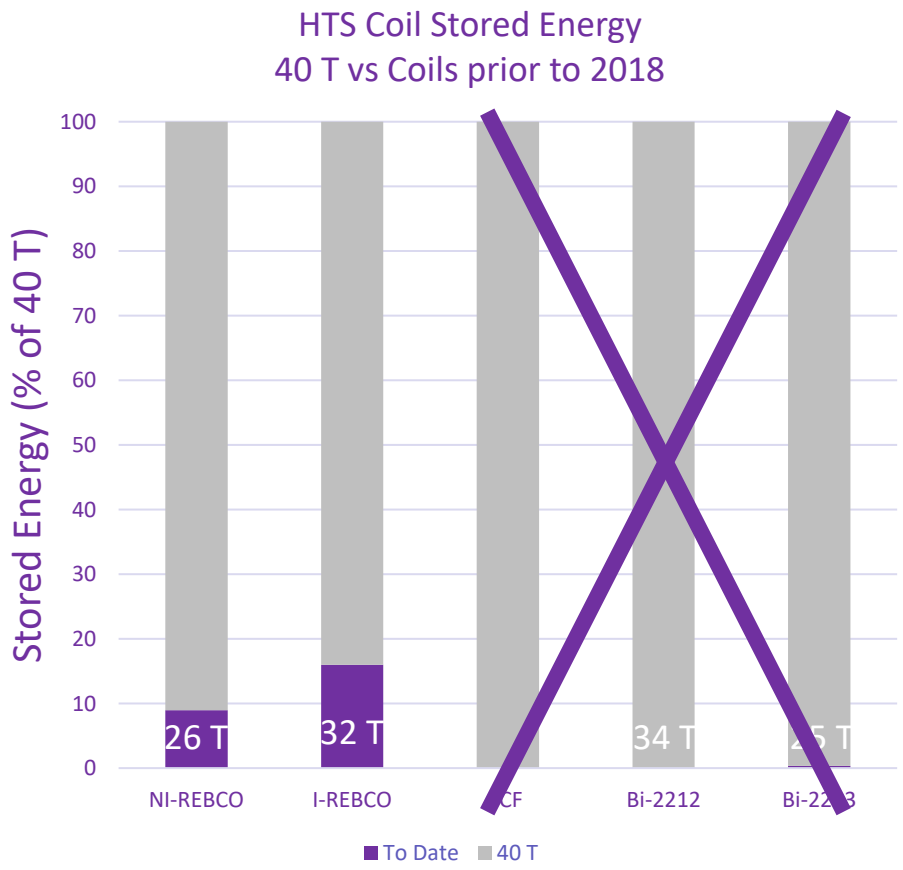
1. Central field: 40 T
2. Operating lifetime: 50,000 cycles or 20 years
3. Field set-ability: ≤ 10 mT across the range of field
4. Cycling repeatability: ≤ 10 mT
5. Operating temperature: 4.2 K in LHe
6. Cold bore diameter: ≥ 34 mm
7. Ramp rate: ≥ 0.5 T/min
8. Homogeneity: ≤ 500 ppm over a 1 cm DSV
9. Stabilization time: < 3 minutes to stabilize at a set point
10. 10 Gauss fringe field: < 5.4 m from the axis of the magnet at the mid-plane

SCS & fatigue testing are important

REBCO SCIF generates ~0.2T

NI-REBCO not likely

Stored Energy in HTS Coils



As magnets get larger, stored energy increases along with potential for damage during quench!

Quench Damage

- 1 MJ ~ 1 stick of dynamite.

Some coils destroyed during quench

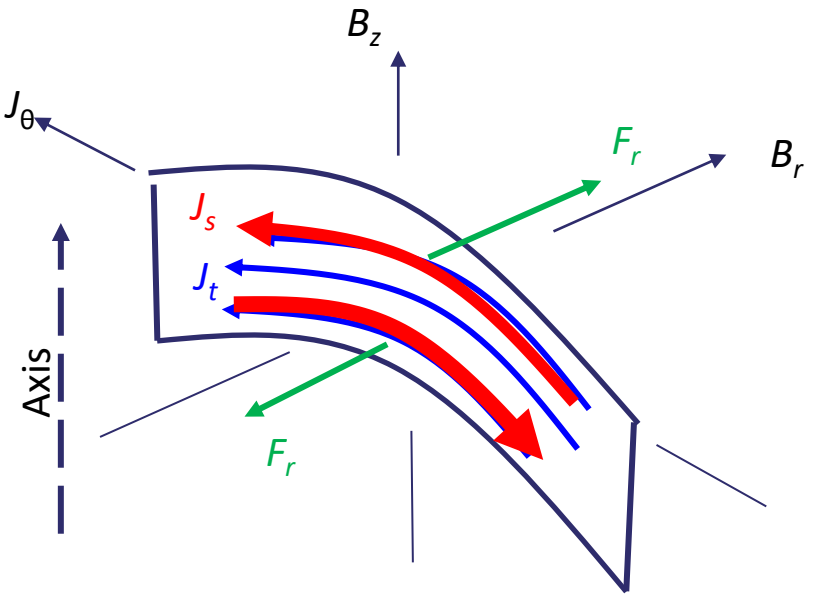
Org.	Field	Energy	Year
MIT	30.5 T	80 kJ NI-REBCO	2018
RIKEN	28 T	30 kJ I-REBCO x 2	2017
Tohoku U	25 T	350 kJ I-REBCO	2016

- ***Numerous*** **other HTS test coils around the world have destroyed themselves**.

We need more development to handle increase in stored energy.

Tape Magnets: Screening Currents

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)

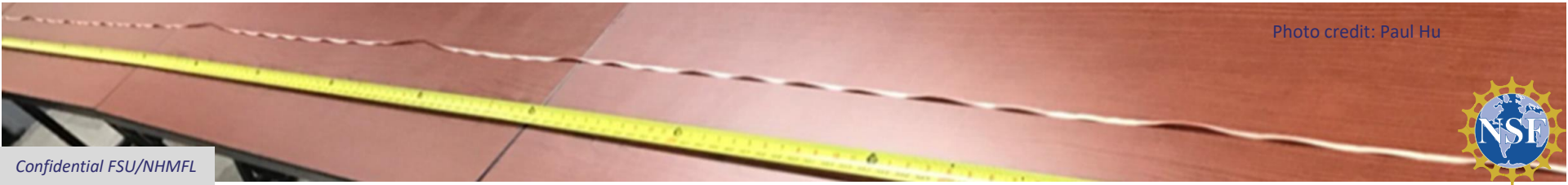
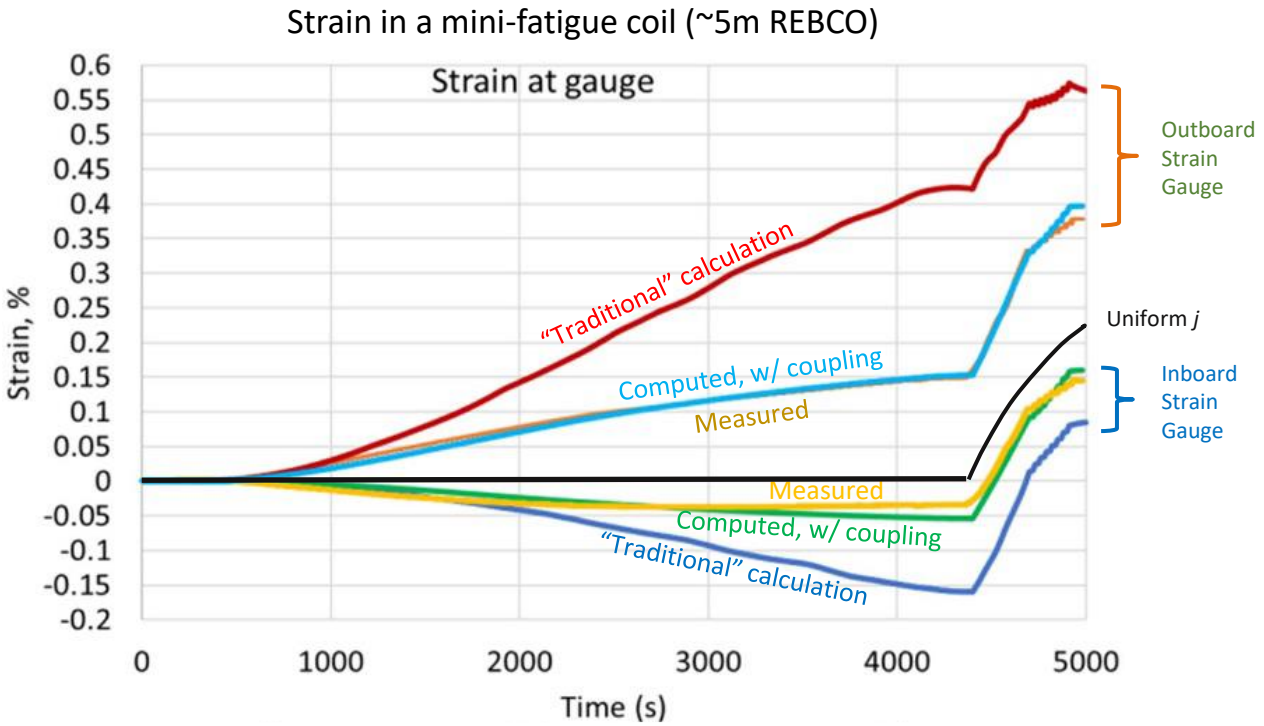


Photo credit: Paul Hu

Computed Screening Currents: With and Without Rotation (2020)



Tiny solenoid energized in a background field.

Strains due to screening currents now agree with measurements for small coils.

Screening current induced field calculations also now agree.

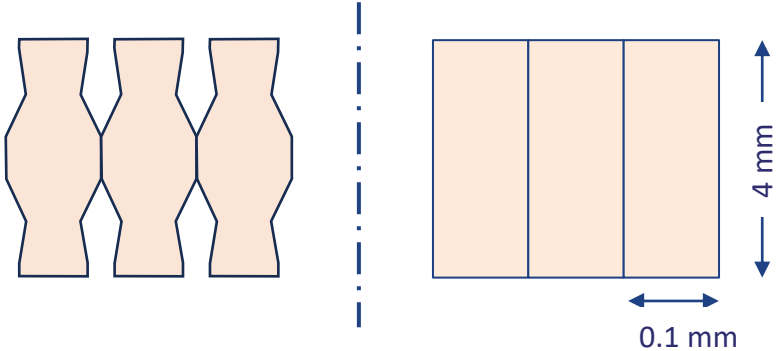
D. Kolb-Bond, M.D. Bird, I.R. Dixon, T.A. Painter, J. Lu, K.L. Kim, K. Kim, R.P. Walsh, F. Grilli, *SuST,* 34, 095004 (2021).

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

Impact of non-Uniform REBCO (Cu) Thickness

Exaggerated REBCO tape cross-section.

High radial compressibility.



- Traditional model = low radial compressibility
- Electroplated Cu results in a non-uniform cross-section in REBCO tape.
- We are adding additional co-wound steel.

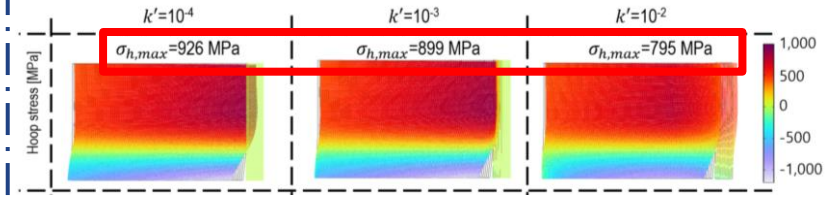


Fig. 8. Hoop stress and radial stress distributions with different k' values(number of overbanding is 10.). As the winding becomes compressible, compressive radial stress decreases in absolute value and peak hoop stress increases.

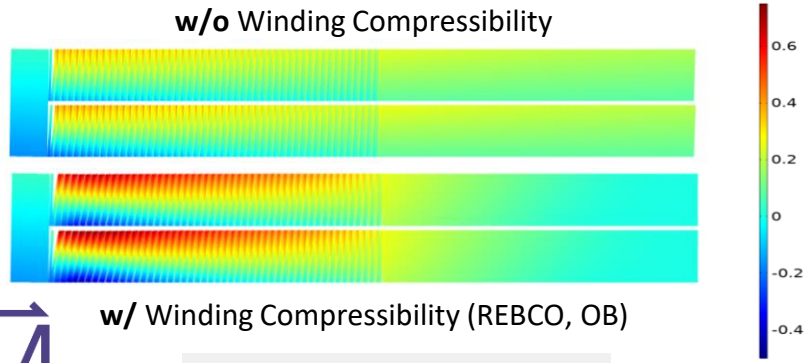
서 울 대 학 교
SEOUL NATIONAL UNIVERSITY

J. Park et al., *IEEE-TAS* **35**, 5, Aug. 2025, 4801805, doi: 10.1109/TASC.2025.3538680.

MagLab end module

Hoop strain [%]

w/o Winding Compressibility



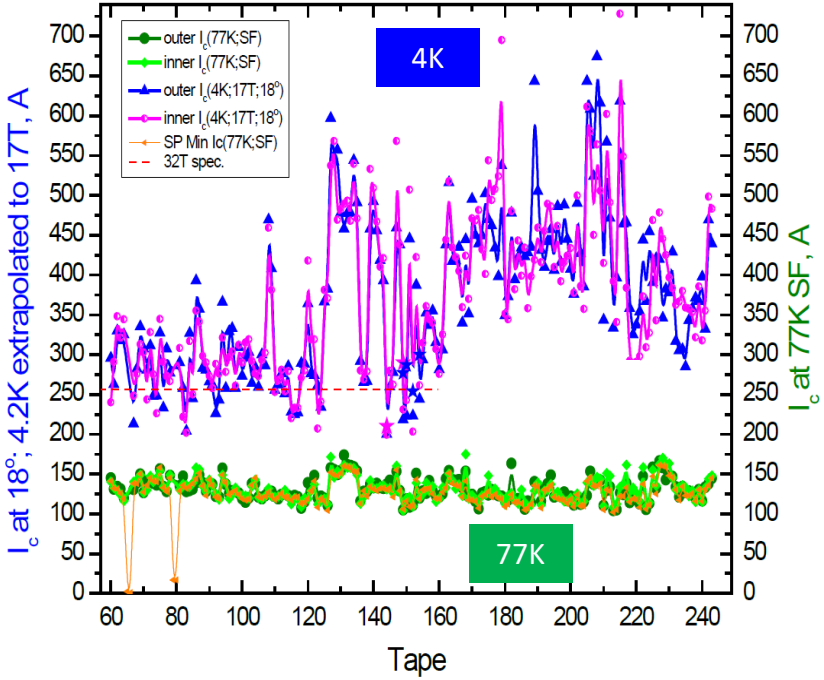
w/ Winding Compressibility (REBCO, OB)

Y. Suetomi, et al., Fri-Mo-Or2-02

REBCO Challenges

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.)

I_{op}/I_c of outer REBCO coil of 40 T all-SC

Axis of rotation

89%	93%	94%	92%	88%	82%	78%	74%
87%	89%	89%	87%	84%	80%	77%	74%
85%	86%	85%	84%	81%	78%	76%	73%
82%	83%	82%	81%	79%	76%	74%	72%
80%	80%	79%	78%	76%	75%	73%	71%
78%	78%	77%	76%	75%	73%	71%	70%
76%	76%	75%	74%	73%	72%	70%	69%
74%	74%	74%	73%	72%	71%	69%	68%
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32%	31%	30%	29%	27%	26%	25%	25%
32%	31%	30%	28%	27%	26%	25%	25%
32%	31%	30%	28%	27%	26%	25%	25%

I_c variation is helpful.

I_c	Min	Max
Uniform	25%	94%

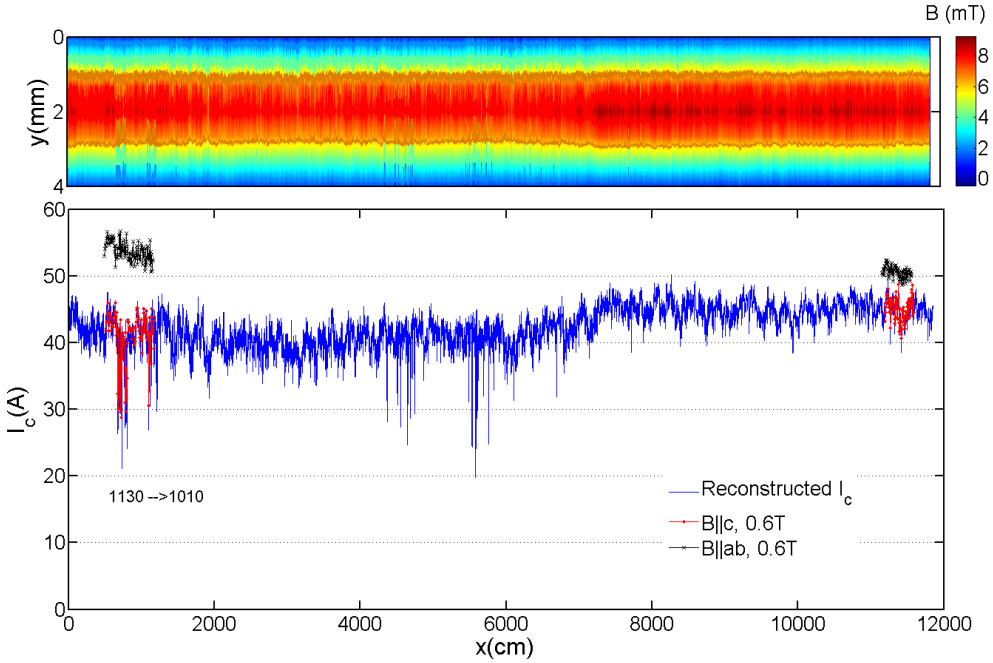
If I_{op}/I_c varies, quench protection is harder,

SCS can be excessive.

Mid-Plane

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.

MagLab (& others) are using multiple tapes in parallel.

I_c Variation at low angles

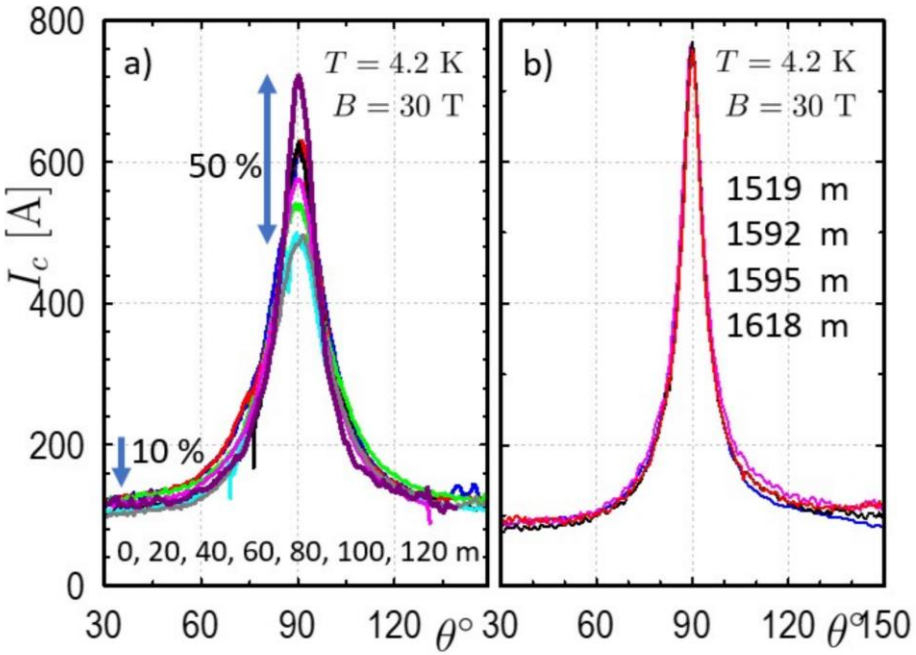


Figure 9. a) Angular I_c for several samples cut from the edge slit of a long tape every 20 m b) Angular critical current for four samples cut from the central slit of an another tape at positions between 1519 to 1618 m. $T = 4.2$K at $B = 30$ T

J. Jaroszynski, et al., *arXiv*:2502.02706v2, 11 Feb. 2025. Sat-Mo-Or3-05

It is difficult to measure I_c of REBCO tape at 4 K at angles close to the *ab*-plane.

For MagLab 32 T magnet we adopted measurements at 18° from the *ab*-plane, and extrapolation.

>1/2 of 32T & 40T operate at <5°.

There is typically a variation in microstructure along the edge of REBCO (12 mm) tape as it is fabricated.

Recent measurements suggest that this variation might contribute to significant variation in I_c along the length of 4 mm tapes cut from the edges as opposed to the center.

Transport measurements at appropriate angle, field, temperature are rare.

No-Insulation REBCO Challenges & Status

Quench

Each turn of an NI-REBCO coil includes:

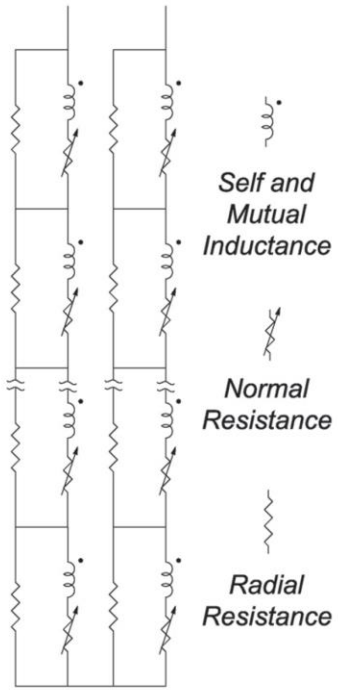


Figure 1. Equivalent circuit showing circuit element representation of a double pancake module.

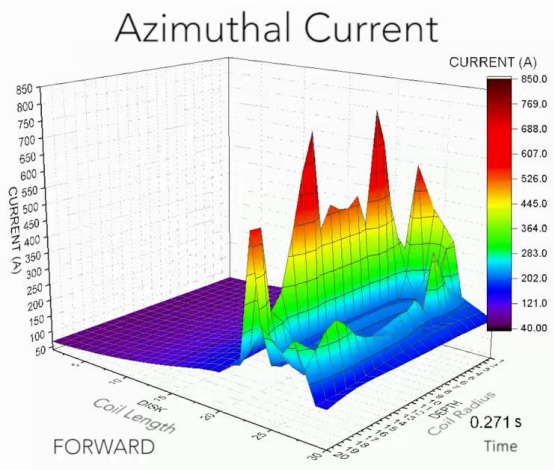
During quench, current can flow radially between turns.

Quench is inductively driven

As current drops in a turn, increased current will be induced in nearby turns, driving them normal.

This can result in large current spikes with large forces (concentration of stored energy).

Large NI-REBCO coils require controlled inter-turn resistance (and active protection?)

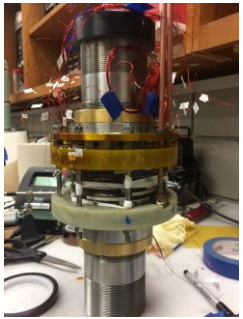


NI-REBCO shows similar current spikes to those of diode-protection.

Many more degrees of freedom.

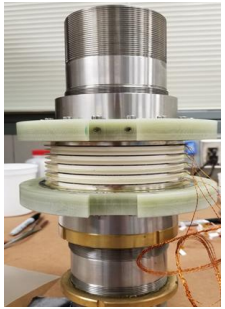
Markiewicz, et al., SuST, **29**, (2016) 025001. Markiewicz, et al., SuST, 32 (2019) 105010

RI-REBCO Test Coils at the MagLab



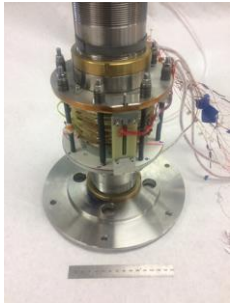
PTC1
(Apr 2019)

LBC-AR
(Apr 2019)

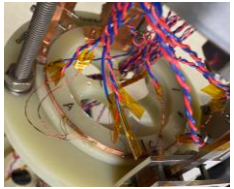


PTC2
(Jun 2019)

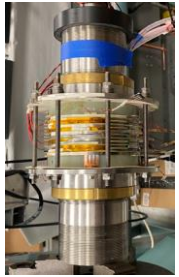
LBC-CO
(Aug 2019)



PTC1R
(Oct 2019)



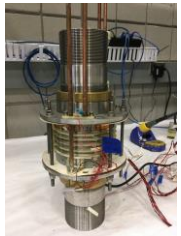
Mini fatigue coil
– Off centered
(Jun 2020)



PT3
(July 2020)

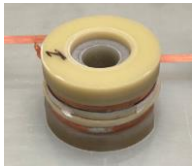
RI-NC (Sep. 2022)

2022: Were not able to consistently control the quench dynamics

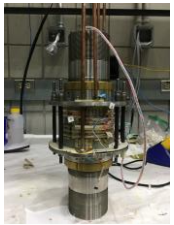


PTC4
(Dec 2020)

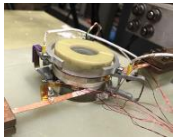
Mini fatigue coil
– centered
(Mar 2021)



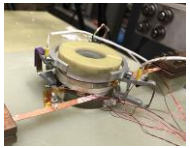
Axial pressure
test coils
(Mar 2021)



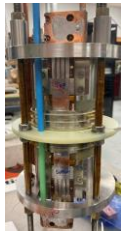
PTC5
(Mar 2021)



Axial pressure
test coil:
two in hand
(April 2021)



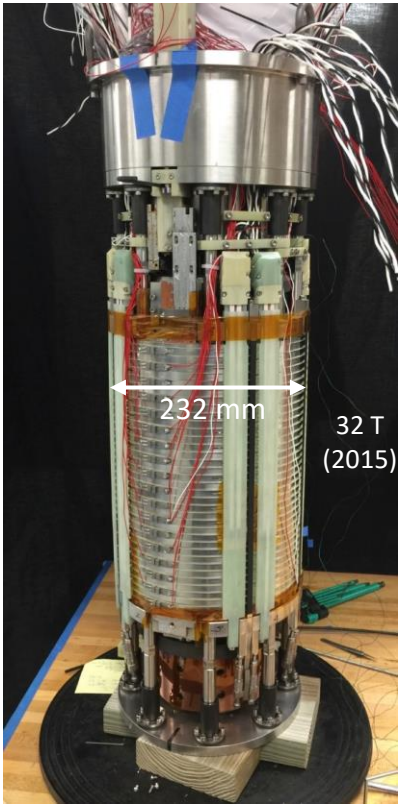
Axial pressure
test coil:
two in hand
(April 2021)



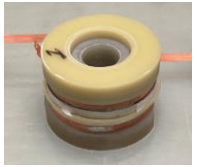
PT6
(June 2021)

I-REBCO Technology for 40 T SC

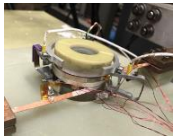
I-REBCO Coils at the NHMFL



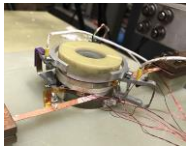
32 T
(2015)



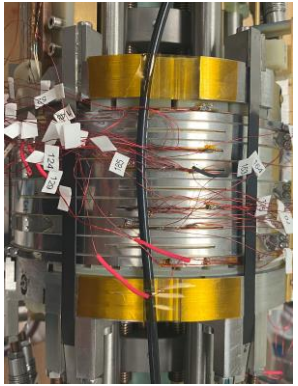
Axial pressure
test coils
(Mar 2021)



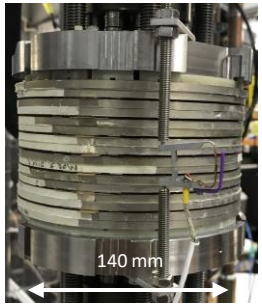
Axial pressure
test coil:
two in hand
(April 2021)



Axial pressure
test coil:
two in hand
(April 2021)

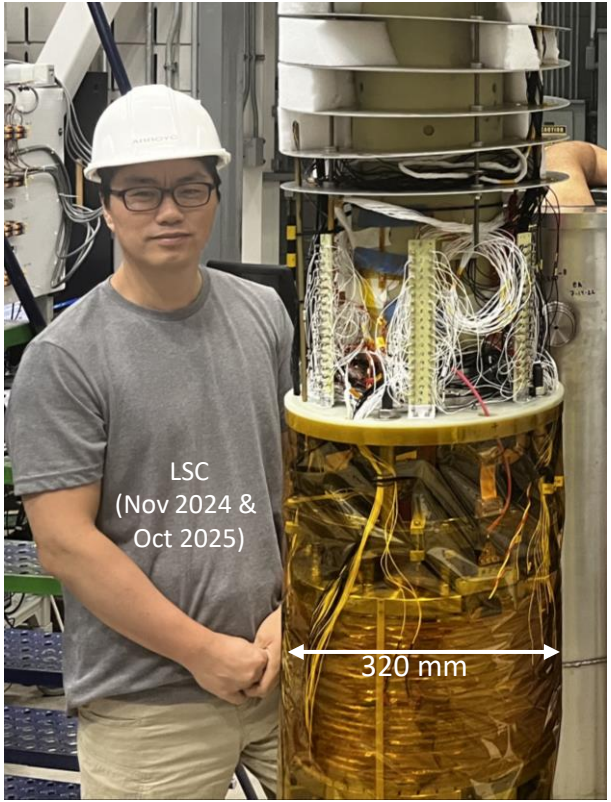


TC0
(October 2020)



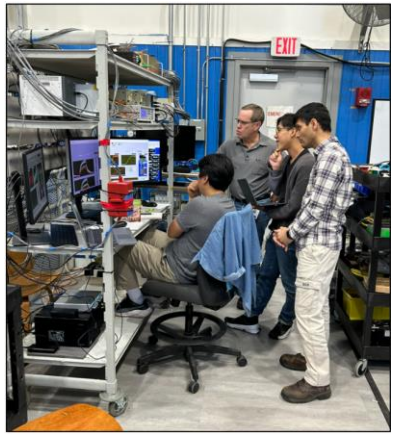
TC1
(May 2021)

TC2 (August 2022)



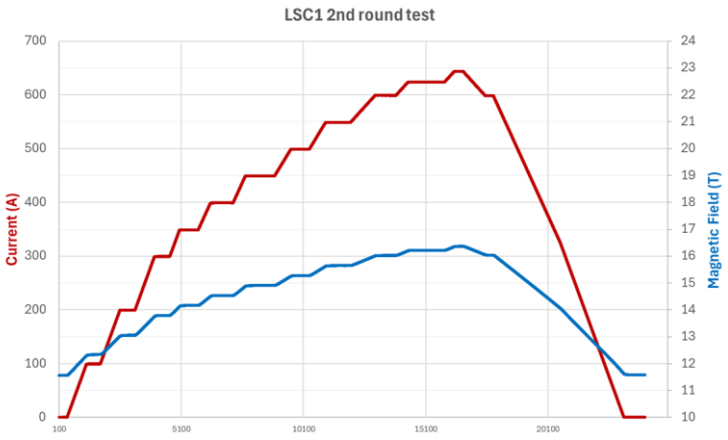
Axial pressure & TC are on same scale

Large Scale Coil Test Oct. 7 – 17, 2025

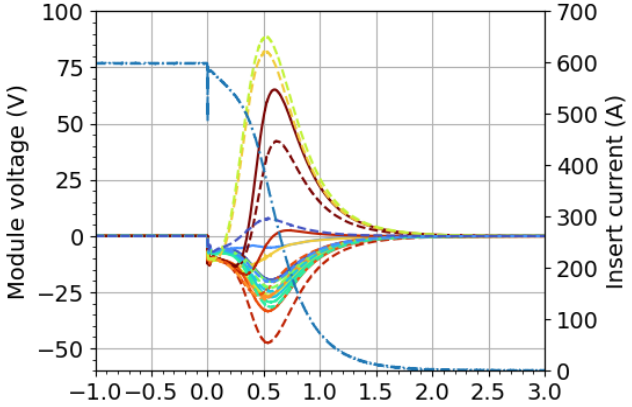


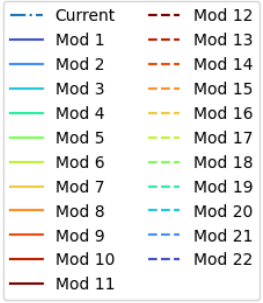
Kwangmin Kim, Iain Dixon, Yu Suetomi, and Dharmendra Shukla reviewing test data.

- The coil reached the full design current of 645 A in a background field of 11.4 T, corresponding to 70% of the coil's critical current.



3: 600 A / BM 11.2 T / PFN 500 V





7 intentional quenches were conducted with various combinations of background field, insert current, and PFN voltage.

No Degradation was observed!
Measured voltages agreed well with predictions!

Iain Dixon, Yu Suetomi, et al.

The 40 T SC Magnet at MagLab

- Developed software packages to compute screening currents, strains, and field distributions that are being adopted by other labs worldwide.
- Developed quench modelling software for both I-REBCO and RI-REBCO coils.
- Introduced critical-current graded coils.
- Demonstrated coils survive
  - 50,000 cycles with 125 MPa axial pressure
  - >23,000 cycles at 0.4% strain; >200 cycles at 0.5% strain.
  - Multiple quenches at high J_{Cu}, I_{op}/I_c, & strain.
- Increase in copper current density, J_{cu}, compared with 32 T.
- Introduced Reinforcement grading.
- Demonstrated numerous improvements to quench protection
- Tested >20 different REBCO coils.

Presently have funding for Preliminary & Final Design

Expect to submit proposal for Construction in 2026.

Anticipate Construction funding to arrive 2027.

Start placing orders for tape, etc. at that point.

Alex Downey, Scott Marshall, Robert Stanton, Kathleen Amm, Shannon Griffin, Dharmendra Shukla, Kwangmin Kim, Yu Suetomi, Lee Marks, Tom Painter, Justin Deterding, Erick Arroyo, Iain Dixon, John Rogers, Hongyu Bai, & Jun Lu celebrate the successful LSC test.

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Summary

- High Magnetic Fields play an important role in numerous types of basic research in physics, chemistry, biology, materials science, etc.
- The HTS materials have (finally) started to enable higher fields.
- There are several REBCO-based magnets in operation at 28 – 32 T around the world.
- There are still a number of challenges that require further development.

Some NI- & RI-REBCO High Field Magnets & Test Coils

Design	Site	Field	Bore	Year	Status	Protection
Magnets put into Service						
IEE-Beijing	Huairou, China	30 T	32 mm, 4 K	2023	Operational	Passive
IEE-Beijing	Huairou, China	27 T, 12 ppm/cm	50 mm, 4 K 30 mm, 1.4 K 27 mm, 20 mK	2023	Operational	Passive
Test Coils (Hahn's list is more comprehensive)						
MIT-SuNam	Daejeon, Korea	26 T	35 mm, 4 K	2015	Out of Service	Passive
MagLab	Tallahassee, FL, USA	45.5 T	14 mm, 4 K	2018	Test	Passive
LNCMI-CEA	Grenoble, France	32.5 T	38 mm, 4 K	2019	Test	Passive
Tsingua U.	Beijing, China	32.4 T		2024	Test	Passive
ETH	Zurich, Switzerland	45 T	4 mm, 4 K	2024	Test	Passive
Projects Underway						
CAS-IPP	Hefei, China	46 T?		2025		Passive?
MIT	Boston, MA, USA	30.5 T	NMR			Passive
CERN	CERN	40 T	50 mm, 4 K			**Active**
LNCMI-CEA	Grenoble, France	≥30 T				Passive

I-REBCO Magnets & Test Coils

Design	Site	Field	Bore	Year	Status	Protection
Magnets Put Into Service						
MagLab	Tallahassee	32 T	34 mm, 4.2 K	2017	Repair Underway	Heaters between modules.
Bruker	Nashville	25.8 T, 10 ppb	56 mm, 300 K	2018	Operational	?
Bruker	Florence + 12	28.2 T, 10 ppb	56 mm, 300 K	2019	Operational	?
Test Coils						
RIKEN	?	27.8 T	68 mm. 4.2 K	2018?	Test	?
Tohoku U	Sendai, Japan	25 T		2022	Test	?
Projects Underway						
MagLab	Tallahassee	40 T	34 mm, 4.2 K	2031?	Design nearing Completion.	Similar to 32 T.
Tohoku U	Sendai, Japan	33 T		2027	LTS fabrication complete, HTS underway.	External resistor to limit current-rise.
Bruker		32.9 T, 10 ppb				?
Bruker		35.2 T, 1 ppm				?

Options for 40 T all-SC Magnet