H.W. Weijers

Test and commissioning of the NHMFL 32 T superconducting magnet

MT 26
International Conference on Magnet Technology
Vancouver, Canada | 2019

Thu-Mo-Or17-03

Credits

NHMFL

Bangura, Ali
Abraimov, Dmytro
Adams, Nicholas
Arroyo, Erick
Baek, Hongwoo
Bai, Hongyu
Bole, Scott
Brehm, William
Cantrell, Kurtis
Carter, Richard
Carter, Steven
Cherisol, Daphnee
Choi, S.
Coniglio, William
Dalban-Canassy, M.
Deterding, Justin
Dixon, Iain
Dong, Xiaohan
English, Charles
Farrell, John
Gavrilin, Andrey
Goddard, Robert
Godeke, Arno
Guillory, Shawn
Gundlach, Scott
Green, Betram
Hallstrom, Benjamin
Han, Ke
Hannahs, Scott
Hartley, Heath
Hilton, David
Hu, Xinbo (Paul)
Jaroszynski, Jan
Jarvis, Brent
Jiang, Jianyi
Johnson, Zachary
Kandel, Hom
Kolb-Bond, Dylan
Levitan, Jeremy
Li, Tianlei
Lu, Jun
Lucia, Joseph
Maddox, James
Markiewicz, William
Marks, Emsley
Martin, Matthew
McGuire, David
McIntosh, Daniel
McRae, Dustin
Miller, George
Murphy, Tim
Napier, Sarah
Noyes, Patrick
Oliff, Morgan
Painter, Thomas
Park, Ju-Hyun
Pickard, Kenneth
Polyanskii, Anatolii
Powell, Andy
Reyes, Arneil
Richardson, Donald
Roberts, Dennice
Rubes, Edward
Sheppard, Greg
Sheppard, William
Sinclair, John
Slade, James
Sloan, David
Smith, Kevin
Stanton, Robert
Stiers, Eric
Toplosky, Vince
Toth, Jack
Trociewitz, Ulf
Trowell, Amy
Uppalapati, Sujana
Viouchkov, Youri
Voran, Adam
Walsh, Robert
Weijers, Hubertus
White, Gary
White, James
Wickery, Ryne
Williams, Joseph
Windham, Carl
Wood, Marshall
Xin, Yan
Zavion, Sheryl
Zhang, Guangchi

NHMFL reviewers and other contributors

Bird, Mark
Boebinger, Greg
Boenig, Heinrich
Brown, Alphie
Cordi, Tom
Davis, Dan
Diaz-Jimenez, Carlos
Grey, Laymon
Julian, Stephen
Larbalestier, David
Palm, Eric
Smith, Julia
Zeller, Al

External Reviewers

Joshi, Piyush (BNL)
Steurer, Mischa (CAPS/FSU)
Bogdan, Ferenc (CAPS/FSU)
Boenig, Heinrich

Collaborators

Berrospe-Juarez, Edgar
Cavallucci, Lorenzo
Grilli, Francesco
Hazelton, Drew and colleagues at SuperPower
Breschi, Marco
Melhem, Ziad and colleagues at Oxford Instruments
Ribani, Pier Luigi
Trillaud, Frederic
Zermeno, Victor M.R.

Students

Dickey, Jermaine
Francis, Ashleigh
Freeman, Stephen
Hu, Xinbo
McCallister, Jeremiah
Ramakrishna, Sanath Kumar
Santos, Michael
Xia, Jing
Xu, Axia

Administration, management at the NHMFL and FSU

Vendors

Many more

Supported in part by the NSF (U.S. National Science Foundation) under Grants DMR-1157490, DMR- 1644779 and the State of Florida

Outline

Introduction

- Specifications

First test

- Performance versus specifications

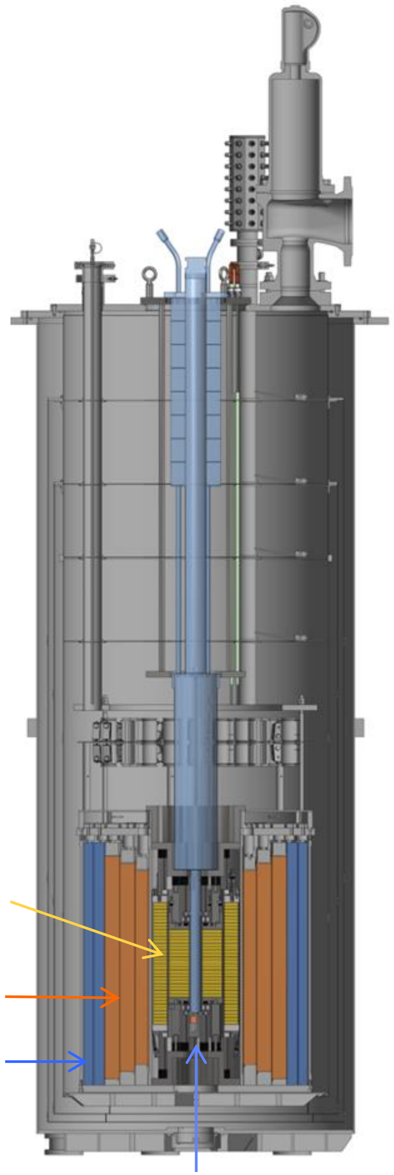
Commissioning

- Inspection
- MilliKelvin facilities
- Field-Current Non-linearities

Lessons learned

Summary

The 32 T magnet



Specifications:

Center field	32 T
Clear bore	34 mm
Ramp time	1 hour
Uniformity 1 cm DSV	<500 ppm
Operating temperature	4.2 K
Helium refill interval	> 20 h
Quench	Robust
Expected cycles/20 years	50,000

Features:

Stored energy	8.3 MJ
System weight	2.6 ton

15 T / 250 mm bore LTS magnet
17 T / 34 mm bore REBCO coils
Separately powered, simultaneously ramped

HTS & LTS Quench detection and *active protection with quench heaters*

Just before the union of HTS and LTS coils

The 32 T system during first test

Top of cryostat

Data Acquisition

The 32 T system during first test

Crowbar resistor (protects supply, not magnet)

Switch Box 1 & 2

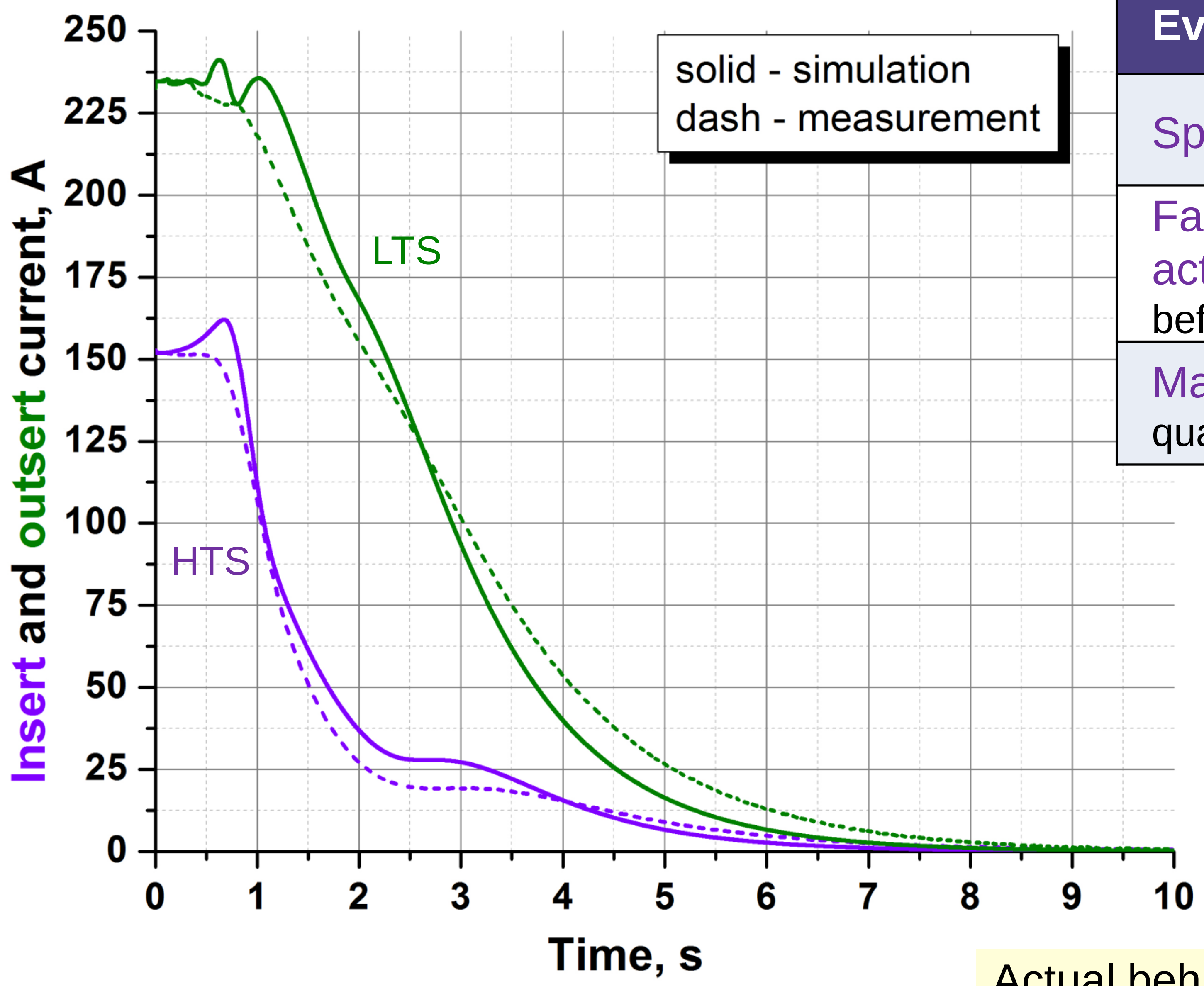
Interlock

HTS Quench management

LTS Quench management

Actual performance versus specifications: quench

28 T deliberate quench



43 runs ≥16 T, 9 to 32 T

Event	#
Spontaneous quenches	zero
False positive in quench detection, activating quench (protection) heaters before sensitivity adjustment	11
Manually induced quenches quarter, half and ¾ energy: 16, 22.5, 28 T	3

This is unique data:

- High-value high-field HTS coils
- The HTS and LTS coils survived
- Quench Robust √

Actual behavior slightly more favorable than simulation

Actual performance versus specifications: bore and temperature

Specifications:

Center field	32 T
Clear bore	34 mm √
Ramp time	1 hour
Uniformity 1 cm DSV	<500 ppm
Operating temperature	4.2 K √
Helium refill interval	> 20 h
Quench	Robust √
Expected cycles/20 years	50,000

Clear bore → Project started with 32 mm bore specification
Delivering 34.0 mm clear bore

Operating temperature → 4.28 K in bath-cooled areas
≤ 4.4 K in “helium bubble” zone*

* In parts of the windings and bore: $-B_z \cdot dB_z/dz > 2100\ T^2/m$
so downward force on helium gas bubbles exceeds buoyancy → gas is trapped →heat exchange (cooling) reduced

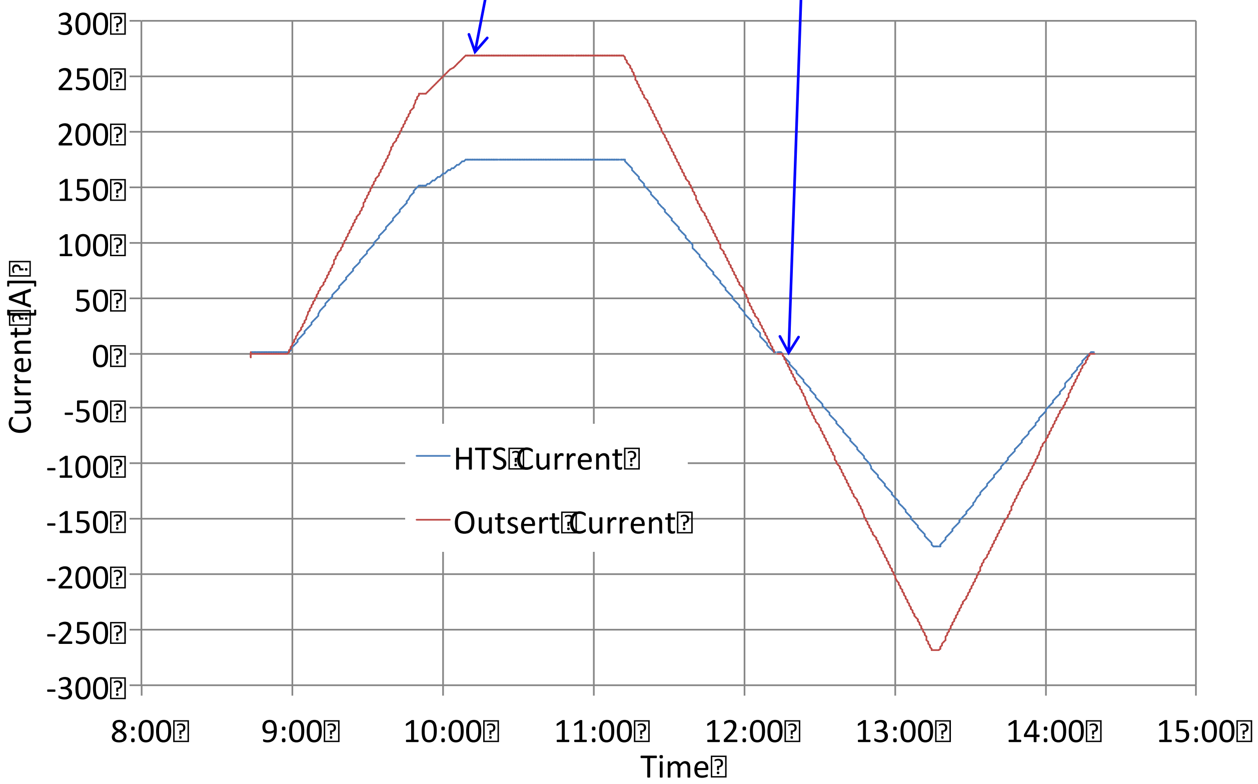
Specifications:

Center field	32 T √
Clear bore	34 mm √
Ramp time	1 hour √
Uniformity 1 cm DSV	<500 ppm
Operating temperature	4.2 K √
Helium refill interval	> 20 h √
Quench	Robust √
Expected cycles/20 years	50,000

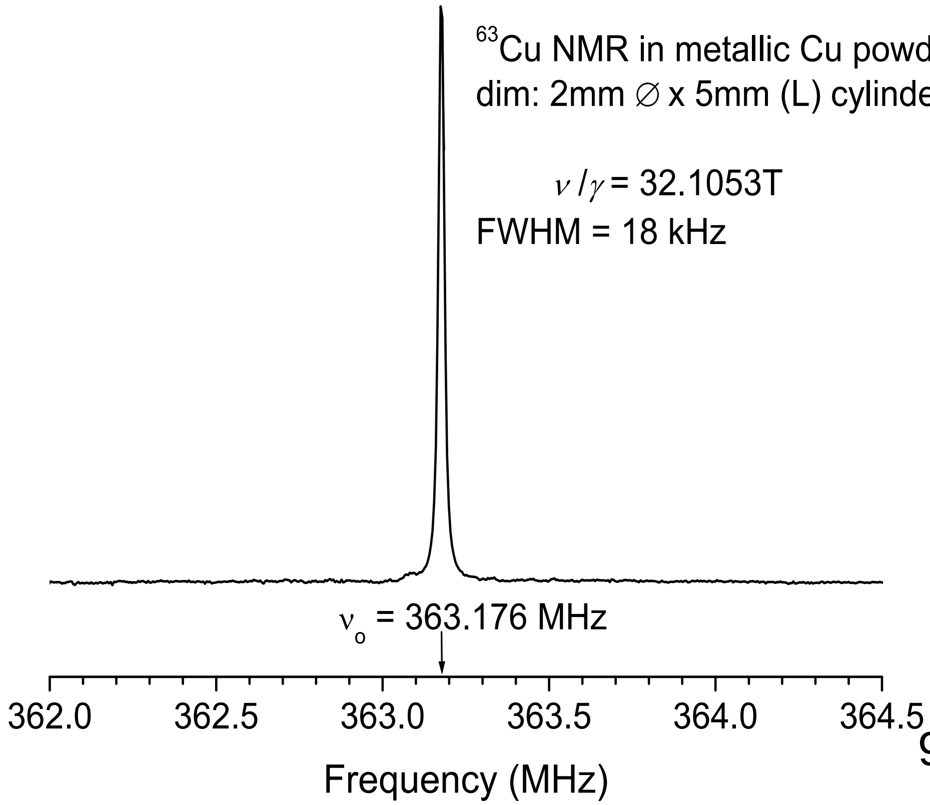
Used 32 liters helium for this run

- ~ 6 liter/hour versus 11.3 liter/hour max in heat load budget
- → 130 liter/day with 24/7 ramping operation
- ~ 60 l/day steady state at 32 T
- With 300 l useable helium → 2 to ~5 days between refill

Dec 8, 2017

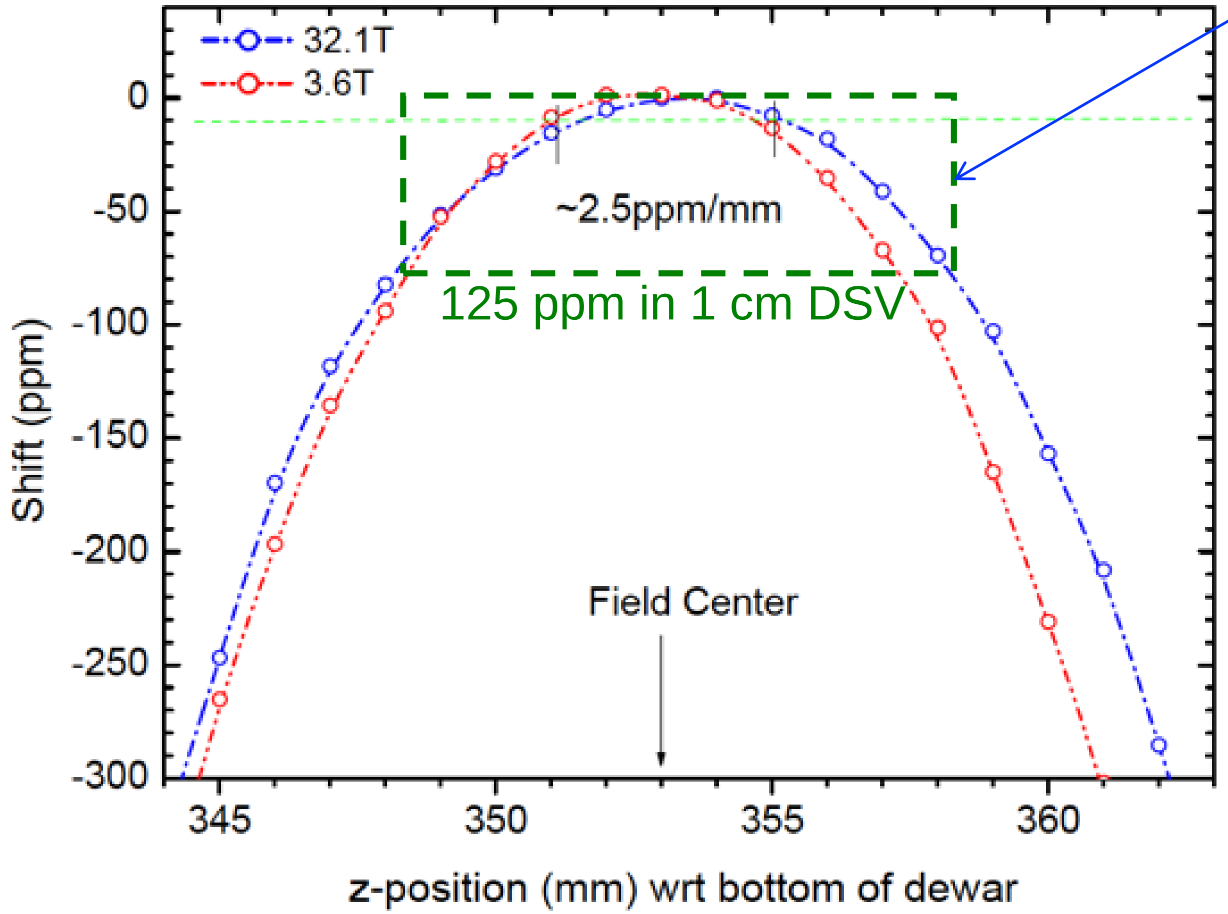


Peak field (32.1 T) later confirmed with ^{63}Cu NMR measurement



Uniformity is ~ 125 ppm in 1 cm DSV ~independent of *B*

- Well within spec of 500 PPM



Specifications:

Center field	32 T √
Clear bore	34 mm √
Ramp time	1 hour √
Uniformity 1 cm DSV	<500 ppm √
Operating temperature	4.2 K √
Helium refill interval	> 20 h √
Quench	Robust √
Expected cycles/20 years	50,000

All specifications met

- Except lifetime cycles

Commissioning

- Inspection of magnet

- Upgrade Interlock functionality for safe operation with users
  - Data recording upgrades

- New building, new layout
  - Rewire all electronics
  - Facilitate routine maintenance

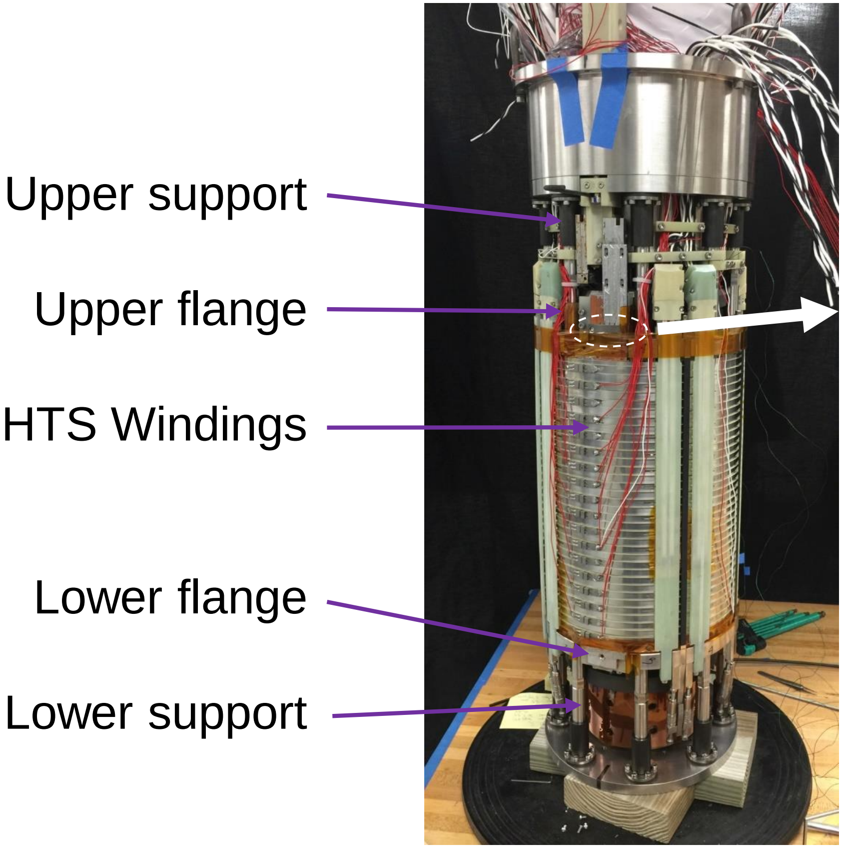
- User magnet infrastructure
  - Dilution refrigerator,
  - Variable Temperature Insert
  - Low noise environment

- Safety as user facility

Inspection after 42 runs in 16-32 T range

Data suggests: Coil flanges do not move freely, separate from windings

- HTS outer coil terminals affected, redundancy and terminal lifetime expectation reduced
- Modified flange suspension while maintaining pre-compression
    - Avoid disassembly to double pancake level
- Redesigned terminals, stand-alone fatigue testing to 200,000 cycles, re-assembled magnet
- Added optical displacement sensors to monitor relative motion of support, flanges, windings, terminals



Original terminals:
Two out of four parallel tapes compromised,
still functional, but longevity unclear

New terminals have added axial flexibility

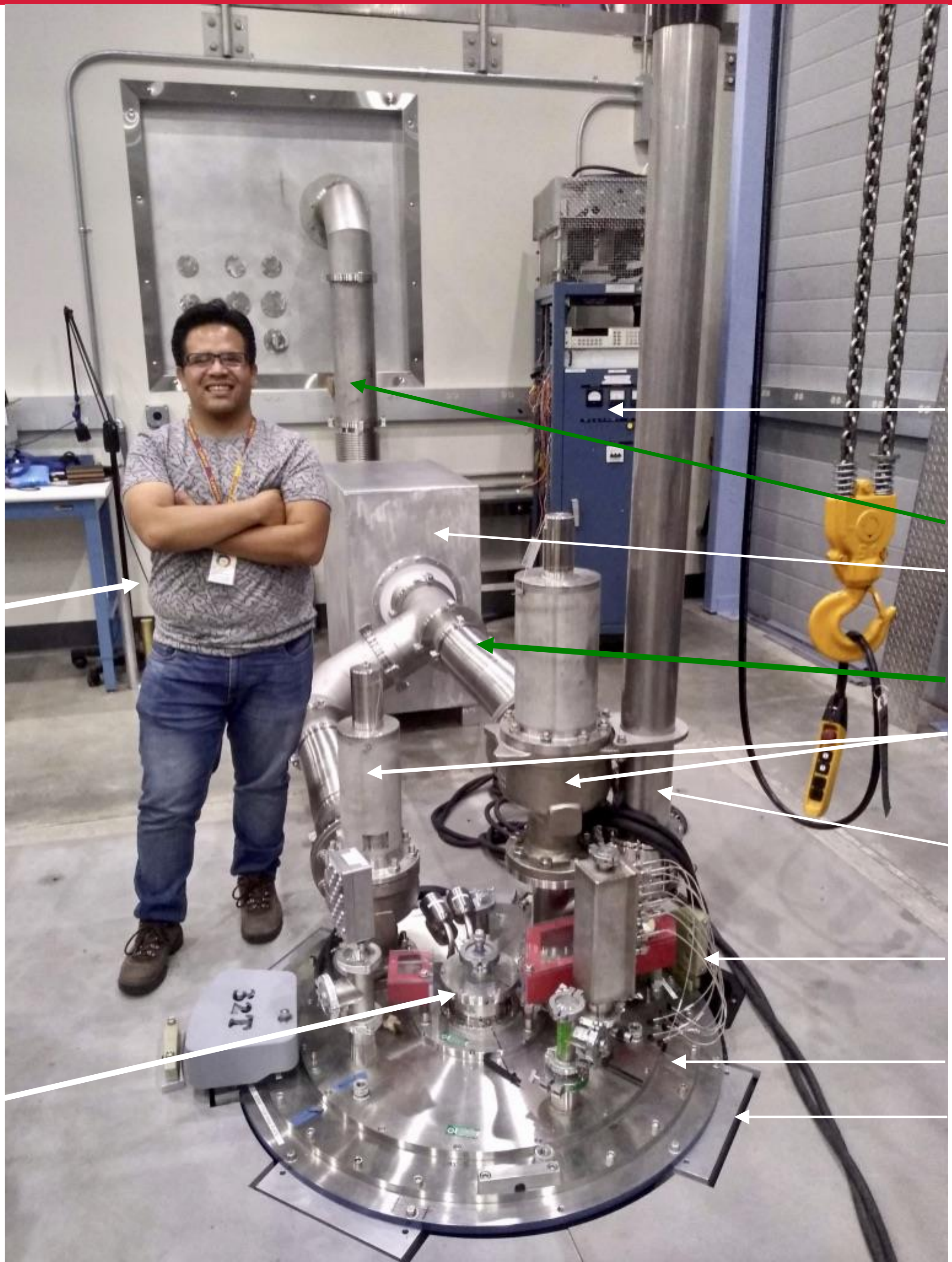
The MilliKelvin facility: home of the 32 T magnet

MilliKelvin facility houses three ≤ 20 T superconducting magnets

Extension with two pits: 32 T and future 40 T

Edgar Berrospe-Juarez of UNAM visiting the NHMFL (MT26-Fri-Mo-Or27-07)

Port for VTI and
Dilution Refrigerator



One (of 2) magnet power supplies

Quench valve plumbing

Vibration isolation sand box

Quench valve plumbing

Quench valves

Burst disk vent

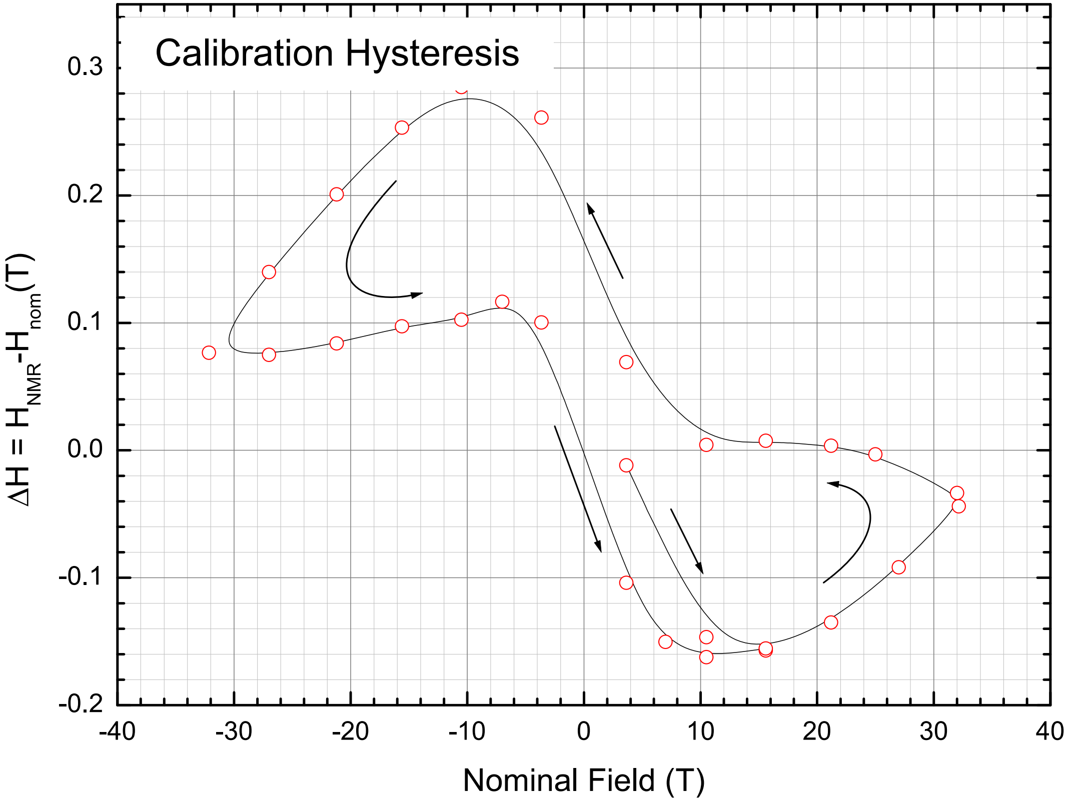
Optical fibers (displacement sensors)

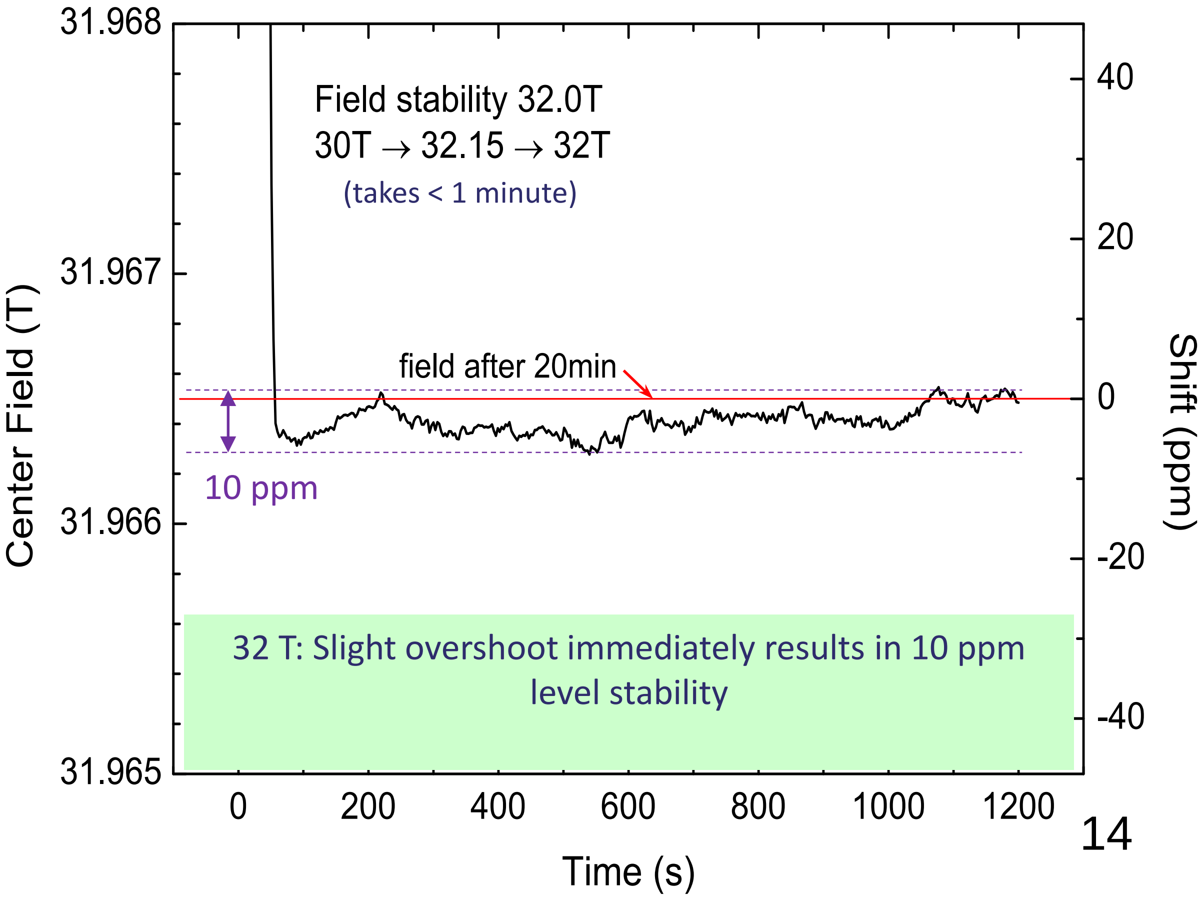
Cryostat top flange

Air-suspended supports

Commissioning: Dealing with non-linearity

- Slight overshoot in current mitigates field drift/relaxation to power supply level
- Screening currents cause non-linearity in field-current ratio (<1% field deviation)
  - Available data suggest this is reproducible
  - Plan to measure this further on 32 T to develop prediction algorithm based on *I*, d*I*/d*t* and history
    - Screening current simulations now run faster than real time
    - Augment with field measurement if needed





Lessons learned: Large I_c margins are undesirable

Conductor is at 10-33% of I_c at 32 T
→ margin is 25 to 40⁺ K
Higher at lower field → ☹

Quench protection

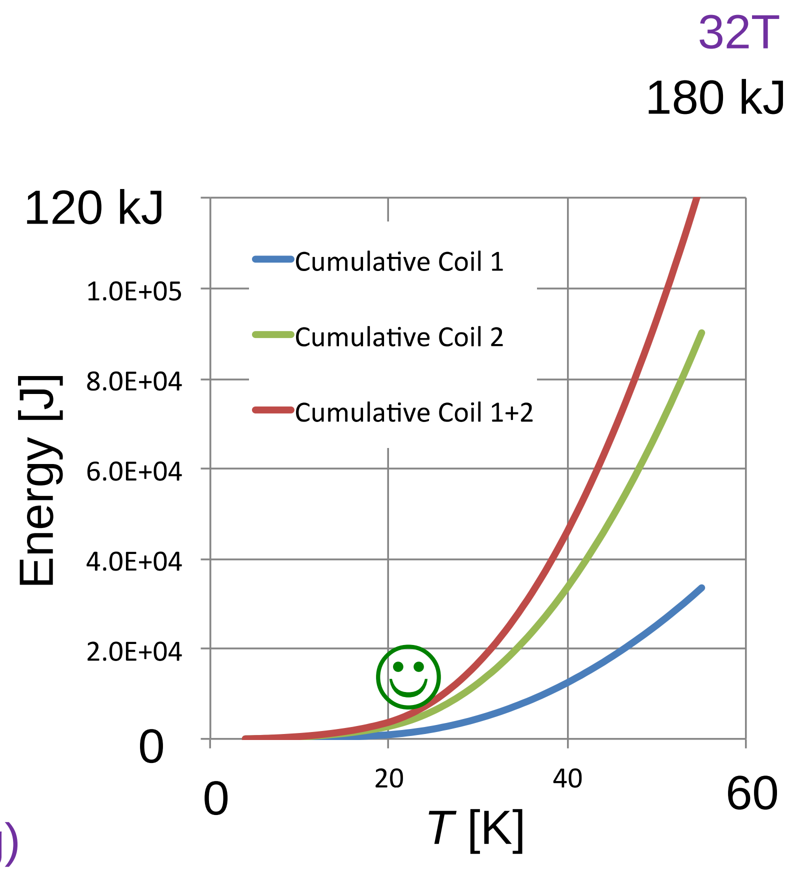
- High field REBCO coils do not self-protect against quench (incl. NI)
  - Either energy extraction or distribution is needed
- Distribution means creating normal zones by heating → T_{cs}: Order(kJ/kg)
  - Available time determined by J_{ave} in windings and quench dynamics
- High I_c margin → high power density
  - Manageable in 32 T with Battery bank energy source
  - Prefer going to capacitor based Pulse Forming Network

Screening currents*

- Cause hysteresis in *B* (SCIF) and additional strain (torque)
- High I_c margin → more screening currents
- 9 cycles (32 T) or > 100 cycles (prototypes) to ≥ design stress/strain: OK
  - Ability to reach 50,000 cycles unproven

Going forward

- Magnet designs with specified range and distribution of temperature margin
- Conductor specification with multiple minimums and maximums on I_c (grading)
- Re-use prototype coil conductor for new fatigue test coil, benchmark simulations



Energy needed to heat the 32 T HTS windings (~80 kg)

*: MT26-Fri-Mo-Or27-07 (Edgar Berrospe), also SuST 32 (2019) 065003
MT26-Mon-Af-Po1.11-05 (Dylan Kolb-Bond)

Summary

32 T magnet tested: reached field repeatedly and met all specifications

- In transition to be the first HTS-LTS superconducting user magnet > 30 T
- High-power quench heaters for quench protection
- Magnet is very stable: large I_c margin, no spontaneous quenches

Key design comments

- Quench management demonstrated effective
- Desirable to engineer I_c and temperature margins across coil via conductor grading

Commissioning as user magnet underway in new MilliKelvin facility expansion

Thank you

Questions?

NATIONAL HIGH MAGNETIC FIELD LABORATORY