043

Construction and test of the NHMFL 32 T superconducting magnet


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Background

The 32 T project aims to combine a 15 T LTS magnet with two REBCO double pancake coils generating 17 T to create a 32 T / 34 mm cold bore user magnet for the MilliKelvin facility at the NHMFL. Both coil sets operate at 4.2 K using two separate power supplies. Oxford Instruments provided the NbTi & Nb_3Sn LTS magnet, which features both passive and active quench protection. The HTS coil technology was developed at the NHMFL, based on SuperPower coated conductor. A key feature is the active quench protection system that relies on powerful quench heaters to protect the HTS coils, in case of a quench in either the HTS or LTS coils, from excessive hoop stress, peak hot-spot temperatures and voltage-to ground.

Relevance

- The first all superconducting user magnet that aims to substantially exceed the limits of Nb-based LTS superconductors is constructed
- Quench detection, Quench protection and long lifetime (fatigue) are an integral part of the magnet technology development
- NI promises higher current density & more compact magnets but has unresolved issues requiring development before practical & reliable high field user magnets, especially those with ramp rate requirements, can be expected.

Summary

- The 32 T superconducting magnet is in the 4.2 K test phase
- All supporting electronic systems are qualified
  - After extensive stand-alone and in-system testing
  - Two redesigns of the battery bank switch system
- Site for user operations has been built and is being fitted out.
- The 32 T magnet has been tested to 5 T in HTS-only mode
  - Quench detection needs adjustment
- Deliberate quenches at moderate field/coil energy levels are next
  - 12 T HTS-alone and 16 T HTS + LTS
- Design of HTS magnets with insulated anisotropic conductor requires careful design of the I_c / temperature margin: both minimum and maximum
  - To limit quench heater power and voltage to ground during quench
  - Conductor grading highly desirable

32 T at test site (Cell 4)

Site of future User Operations (Millikelvin Building Expansion
1) Magnet pit (with cover)
2) Room for pumps, battery racks

Magnet

Target

- 32 T, 34 mm cold bore, $5x10^{-4}$ uniformity/1cm DSV
- 1 hour to full field
- 20 year life time

Choices

- 4 mm wide REBCO Coated Conductor tapes
- Double pancake construction
- Insulated stainless steel co-wind
- Wax impregnation
- Quench heaters between double pancakes
- 15 T / 250 mm bore 7 MJ LTS magnet

Design Constraints

- Operating current ≤ 70% of I_c
- $J_{copper} \leq$ 450 A/mm^2
- Max stress/strain : 400 MPa / 0.4 % (≤ 70% $\sigma_{critical}$)
- Target $T_{hot\ spot} \leq$ 200 K
- Voltage to ground ≤ 1.0 kV

Consequences

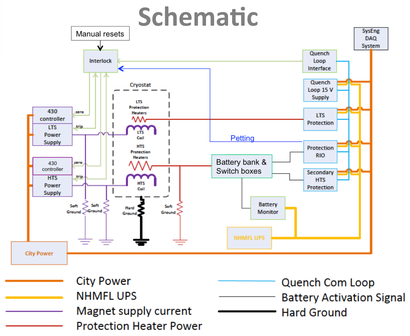
- 8.3 MJ, 2.6 ton system
- 50,000 lifetime cycles
- Integrated HTS & LTS magnet design & quench management
- New technology requires testing and prototypes
- Screening currents in HTS

	Coil 1	Coil 2
IR, OR, height [mm]	20, 70, 178	82, 116, 318
Double pancakes	20	36
$I_{operation}$ [A]	174	174
$J_{average}$ [A/mm^2]	200	170
Conductor length [km]	2.9	6.8
Inductance [H]	2.6	9.9
Field contribution [T]	10.7	6.3
Co-wind thickness [μm]	25	50

Construction

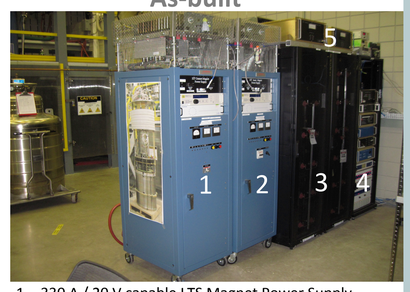
Supporting Systems

Schematic



- Voltage-based quench detection
- Redundant power sources for critical equipment
- Redundant HTS quench detection: one analog, one FPGA based
- Redundant quench heater switching
- Noyes@magnet.fsu.edu

As-built

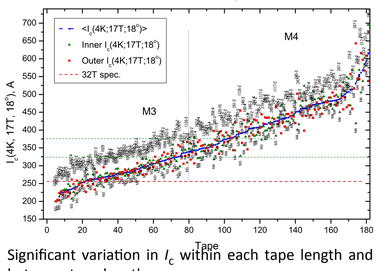


1. 330 A / 20 V capable LTS Magnet Power Supply
2. 200 A / 8 V capable HTS Magnet Power Supply
3. 31 Lead-acid batteries in two racks
   390 V open circuit, ~300 V at 500$^+$ A
4. 3 × Quench detection, High-voltage Isolation, Interlock and instrumentation
5. Quench heater switch boxes

Results

Conductor as-received

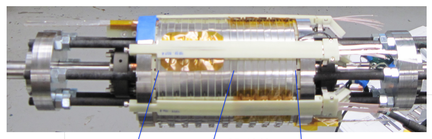
Late 2013-early 2015

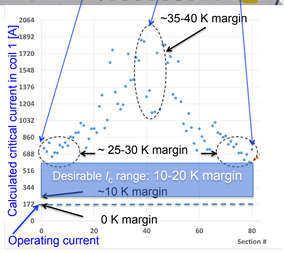


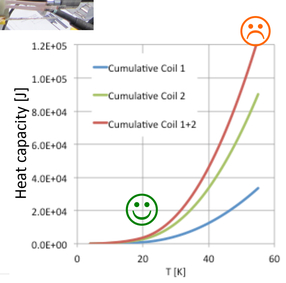
Significant variation in I_c within each tape length and between tape lengths
Most tapes well exceed I_c specification

Specifications:
- I_c(4.2K, 17 T, 18°) ≥ 256 A
- *n*-value > 25
- 4.10±0.05 mm wide
- <0.170 mm thick
- 50 ≤ RRR ≤ 60
- 0.39±0.02 mm^2 Cu
- < 160 nΩ-cm^2 joint resistance
- 60-110 m piece lengths
- 12.3 km ordered, 9.6 km in coils

Margins as-built and consequences





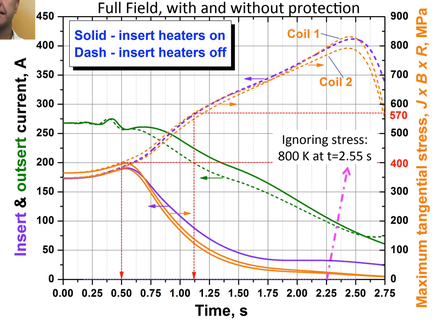


Operating at ≤ 70% of I_c would give > 10 K initial temperature margin: OK

32 T operates at 33-10% of I_c with conductor as received
- The price for this *high margin* is in the heater power required: 0.16 MW
- The price of the *variation in margin* is 1 kV to ground during quench

Quench simulations

Full Field, with and without protection

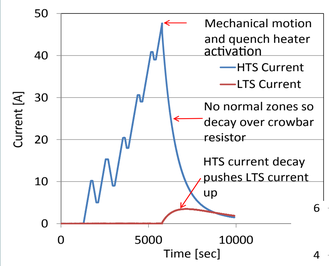


Quench modeling has advanced much and many scenarios have been simulated (gavrilin@magnet.fsu.edu and collaborators)
- No quench heaters: > critical strain in 1.1 sec
  - If strain could be ignored: burn out in 2.55 sec
- Too much heater power: voltage to ground > 1 kV, T hot spot T↑

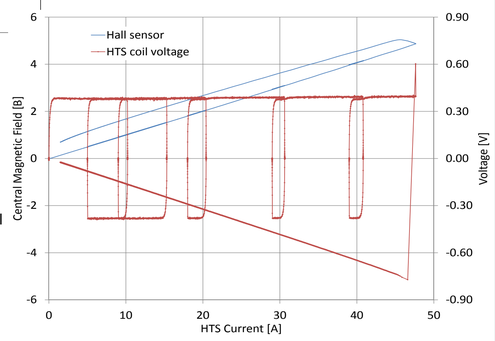
Quench modeling quite sensitive to input parameters
- Within margins of error of available data

Deliberate quenches at moderate field are required to benchmark quench code and update the quench protection

First 4.2 K data



- Ramping HTS coils only
- LTS current actively held at zero
- Mechanical motion induced false trips of quench detection at 4.8 and 5.0 T
- Quench heaters ineffective in creating normal zones at 4.8 T
- Quench heaters cause sufficient normal zones at 5.0 T



- Coil voltages are very smooth
- Very little hysteresis in Hall voltage

Until mechanical motion in top 1/3 of Coil 2 triggers the quench protection
- 32 T magnet seems unaffected