Testing of prototype coils for the NHMFL 32 T superconducting user magnet

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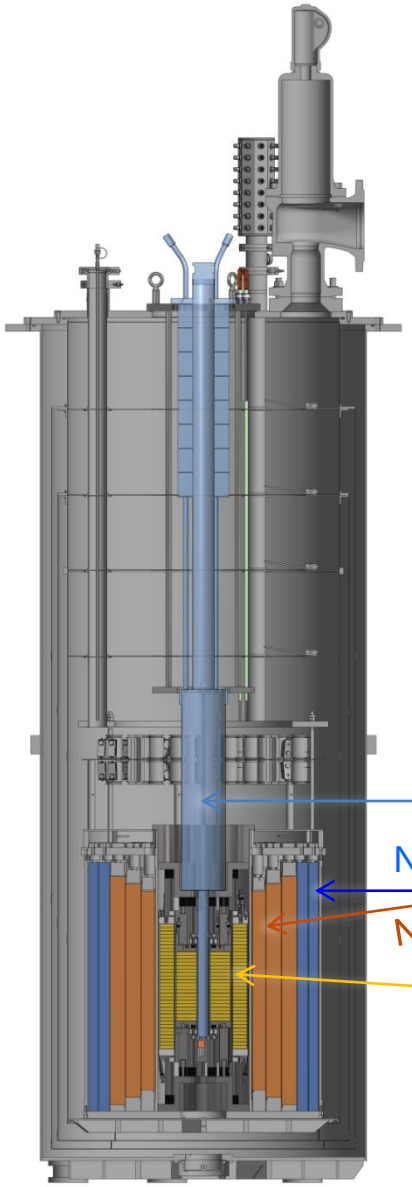
Outline

- Introduction to 32 T magnet & Prototypes
- Quench scenarios
- Goals for Prototype coils
- Combined prototype coil test runs
  - Sampling of data
- Summary

The 32 T magnet: a user magnet



Cold Bore	32 mm
Uniformity 1 cm DSV	$5 \cdot 10^{-4}$
Total inductance	254 H
Stored energy	8.6 MJ
Ramp to 32 T	1 hour
Lifetime cycles	50,000
Mass (total)	2.3 ton

32 T will spend most of its life
ramping up and down at 4.2 K

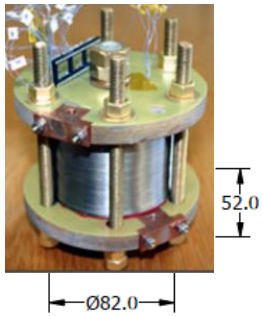
32 T Technology Development

Prototype coils represent 20% of 32 T REBCO coils

Development:

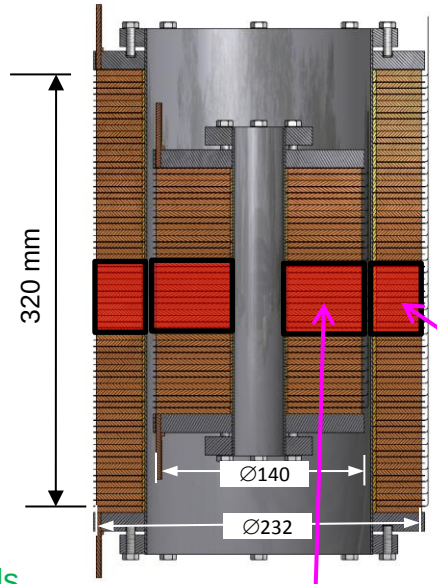
- YBCO tape characterization & QA
- Insulation technology
  - Ceramic on co-wound SS tape
- Coil winding technology
- Joint technology
- Quench analysis & protection
- Extensive testing of components

2007



2008

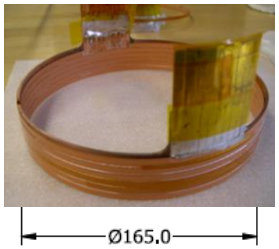
High-B coils
31 T + ΔB



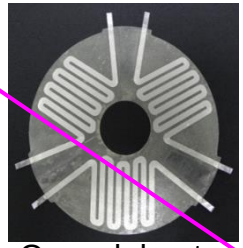
2008

Demonstration inserts
20 T+ ΔB

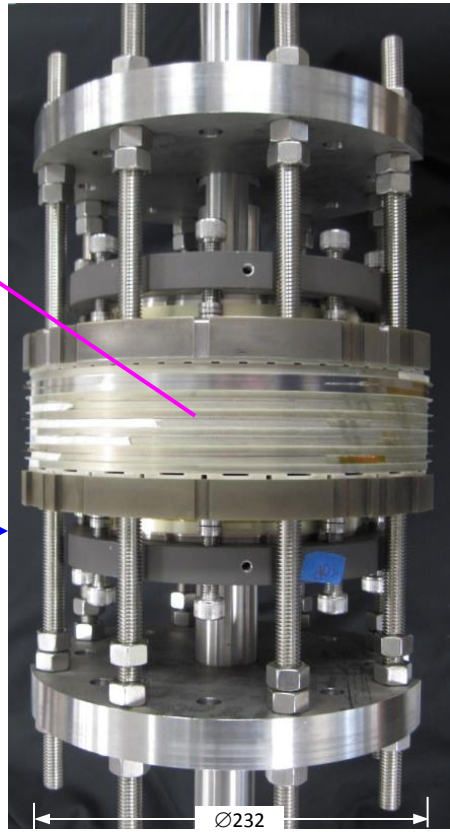
2009



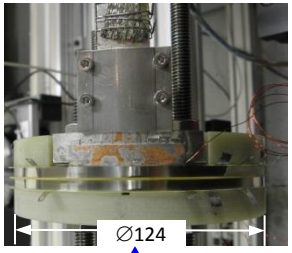
High Hoop-stress coils
>760 MPa



Quench heater



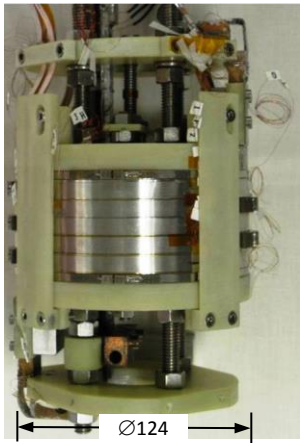
2011



First Quench Heaters

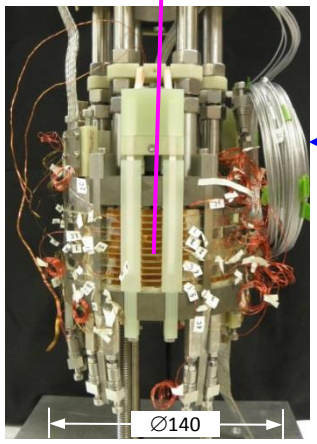
42-62 Mark 1:
1st test coil

2012



42-62 Mark 2:
2nd test coil

2013



20 - 70:
1st Full-featured Prototype

Heater-only quench protection

2014

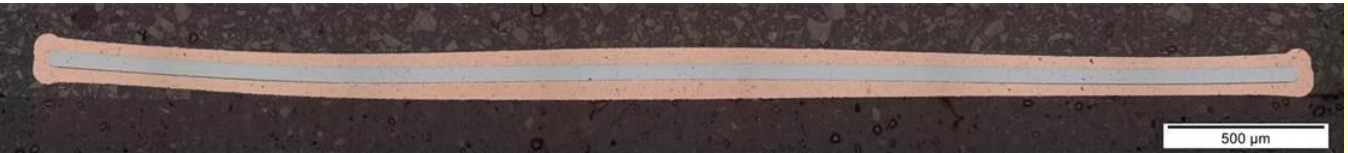
82 - 116:
2nd Full-featured Prototype

32 T design features

Parameter	Unit	ReBCO Coil 1 (inner)	ReBCO coil 2 (outer)
IR/OR/height	mm	20/70/178	82/116/320
Double Pancake modules	-	20	36
Total tape length	km	2.8	6.6
J_{ave}	A/mm^2	176	196
$I_{operating}$	A	180 (≤ 70% of I_c)	
J_{cu}	A/mm^2	440	
Hoop stress*	MPa	400	440

*: simple hoop stress versus 600$^+$ MPa critical stress,
actual strain reduced via insulated co-wound tape

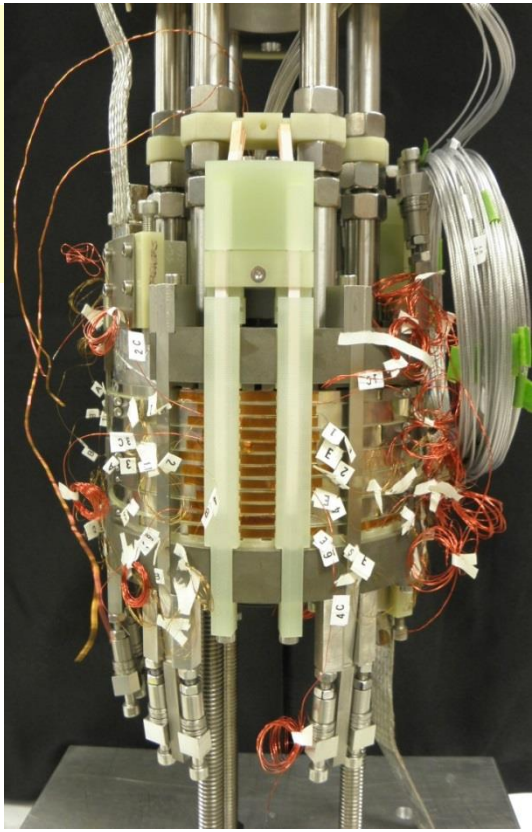
- 4 mm wide ReBCO tape with nominally 50 μm Cu plating (0.41 mm^2)
- Dry wound double pancake modules
- Focus on axial κ (as radial κ and radial NZP is very poor)
  - Narrow tolerance on conductor width → flat pancakes
  - Belleville washers & axial compression straps on flanges



Dogboning causes ~ 10% void fraction in windings, mechanical stability?

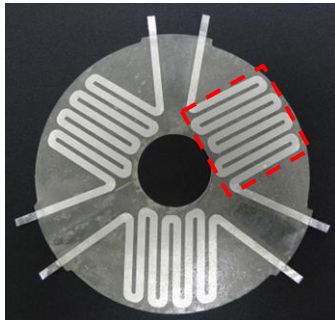
2013: Coil 1 prototype

Full featured
6 modules versus 20 in Coil 1 of 32 T
Much extra instrumentation
15 T background field



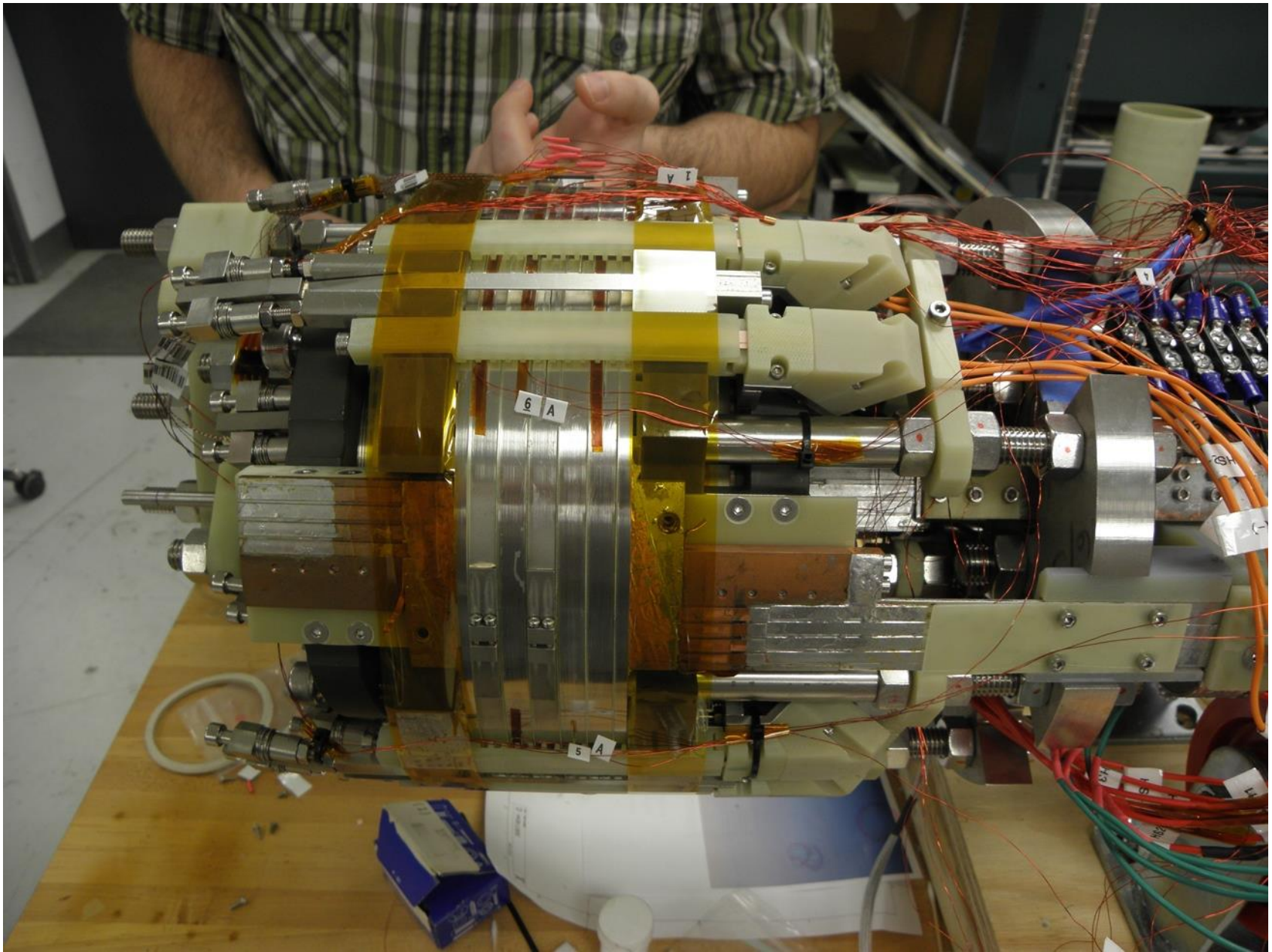
Complete Coil 1 prototype
with instrumentation and wiring

- Test results (MT-23)
  - Confirms concept viability: √ : build Coil 2 prototype
  - Identified detail areas that need rework (done)
  - "Helium gas bubble" (He diamagnetism) not a problem
    - Measures taken are effective √
  - Active quench protection with heaters:
    - Quench initiation study √
    - Quench protection test √
  - Lead to initial design of 32 T quench protection
    - Final design requires combined HTS-LTS analysis



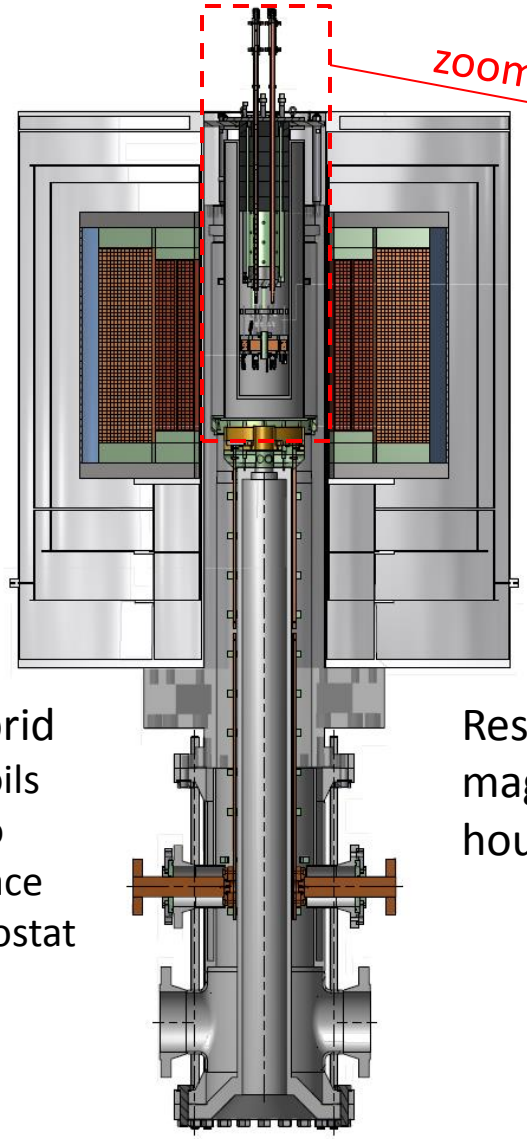
Heater disk with 3 sub-elements
(~ 1Ω / element)

2014: Coil 2 prototype



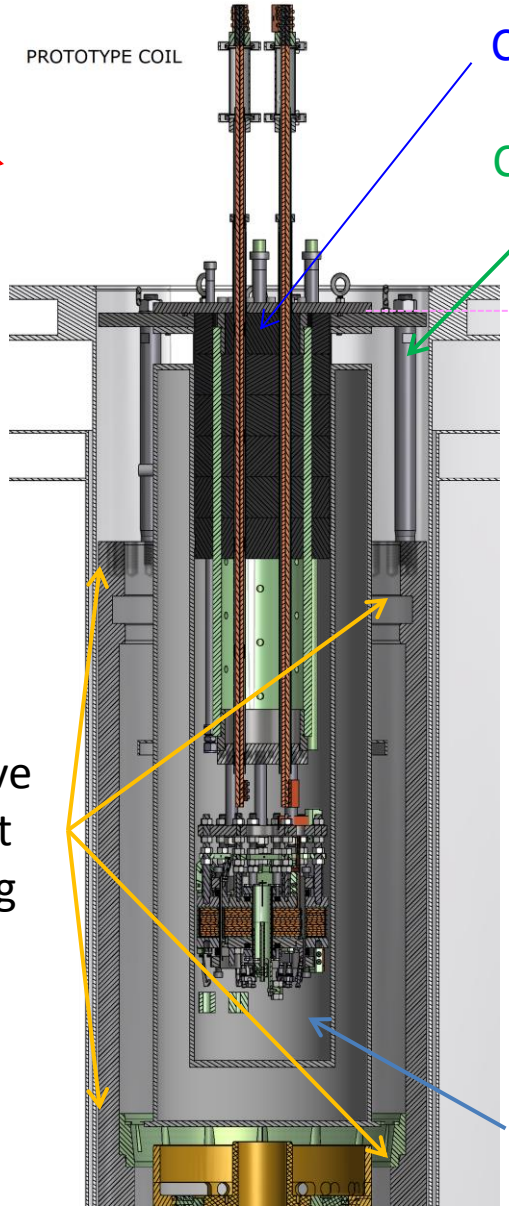
2014: Coil 1 and Coil 2 Prototype tests

in 45 T Hybrid Outsert (11.5 T)



45 T Hybrid
Resistive coils removed to provide space for test cryostat

Resistive magnet housing



Test cryostat

Proto-coils (6 modules each, 1.6 H)

32 T Quench scenarios

When would/should the quench protection fire

When operating at ≤ 70% of I_c, temperature margins are large (order of 25-40 K)

Event	Scenario	Trigger	Likelihood in 32 T
Quench in LTS Outer	Need to bring down I HTS coil ~ as fast as LTS coil.	TTL signal from LTS quench detection	Likely
Transient voltage spike (> 1 V, few msec)	Motion in HTS windings	*False* positive in HTS quench detection	? Observed many in 32 T prototype
Transient voltage spikes (>> msec)	Magnetic transients	*False* positive in HTS quench detection	Not observed in 32 T prototypes
Sudden permanent normal zone voltage (delamination, load cycling fatigue)	Degradation of HTS conductor below operating current	Proper positive in HTS quench detection	Not observed in 32 T prototypes (Would result in reduced field or coil repair)

Quench heaters can protect coils* even in the case of zero normal zone propagation

* W. D. Markiewicz, *Protection of HTS coils in the limit of zero quench propagation velocity*, IEEE Trans. Appl. Supercond., 18, pp. 1333-1336, 2008

Prototype coils test goals

Quench tests	Coil current	Active	Observe	Energy extraction
Quench initiation	0-200 A	Single heater element in one disk (1/35)	Heater efficiency vs. heater power & position	Dump resistor
Quench protection	0-200 A	2-3 heaters in all 10 heater disks (25/35)	NZ resistance growth & current decay vs. heater power	none

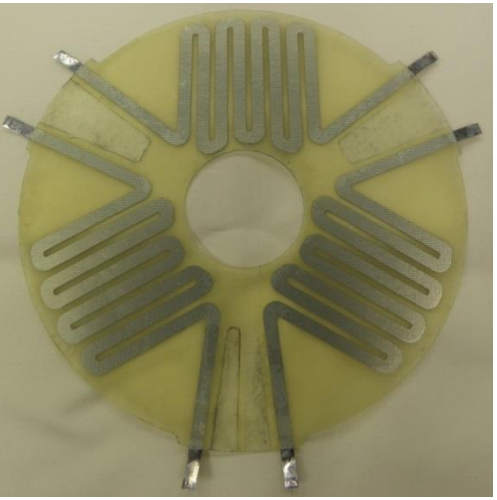
Stress tests	Coil current	Active	Observe	Comment
Peak stress	≤ 270 A	Design stress reached at 271 / 249 A resp.	All signals for signs of degradation	Avoid quench
Load cycling	≤ 270 A	Cycle from 25% to 100+% of design stress	All signals for signs of degradation	As many cycles as practical

AC-loss*	Coil current	Active	Observe	Comment
Ramp-rate loss	≤ 180 A	Current: steady, ramp ↑↓,steady: ---/_---	Helium boil-off, coil voltage	Avoid quench

*: Hongyu Bai and Jun Lu (4LPo2C-05), NHMFL

Combined prototypes test
initial setback

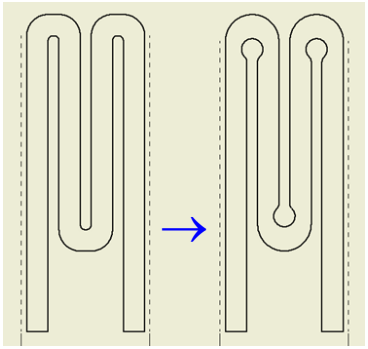
- Coils performed fine during quench initiation testing at 200 A
  - Dielectric around quench heaters failed (~300-400 V)
    - Properties of G-10 in thin (76 μm) sheets do not scale with bulk values
- Test aborted, rescheduled for August 2014
- Coils disassembled, failure analysis, test campaign with original and proposed new dielectric (sub-scale), construction/purchase of full-scale heaters, test of new heaters (done)
- Re-assemble prototype coils (done)
- Mounting & testing (done)



Original heaters

Sub-scale new

> 2 kV stand-off
Optimized electrical path
→ Higher power

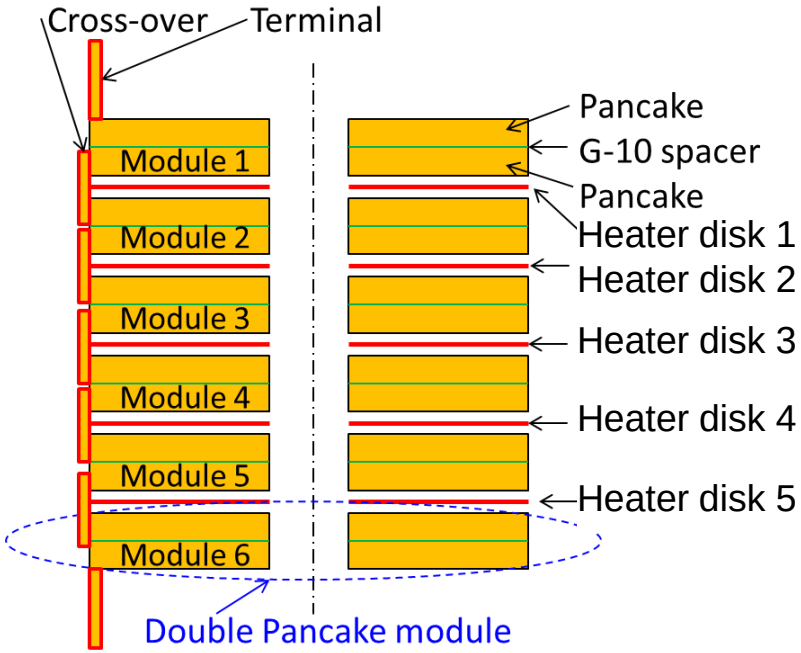


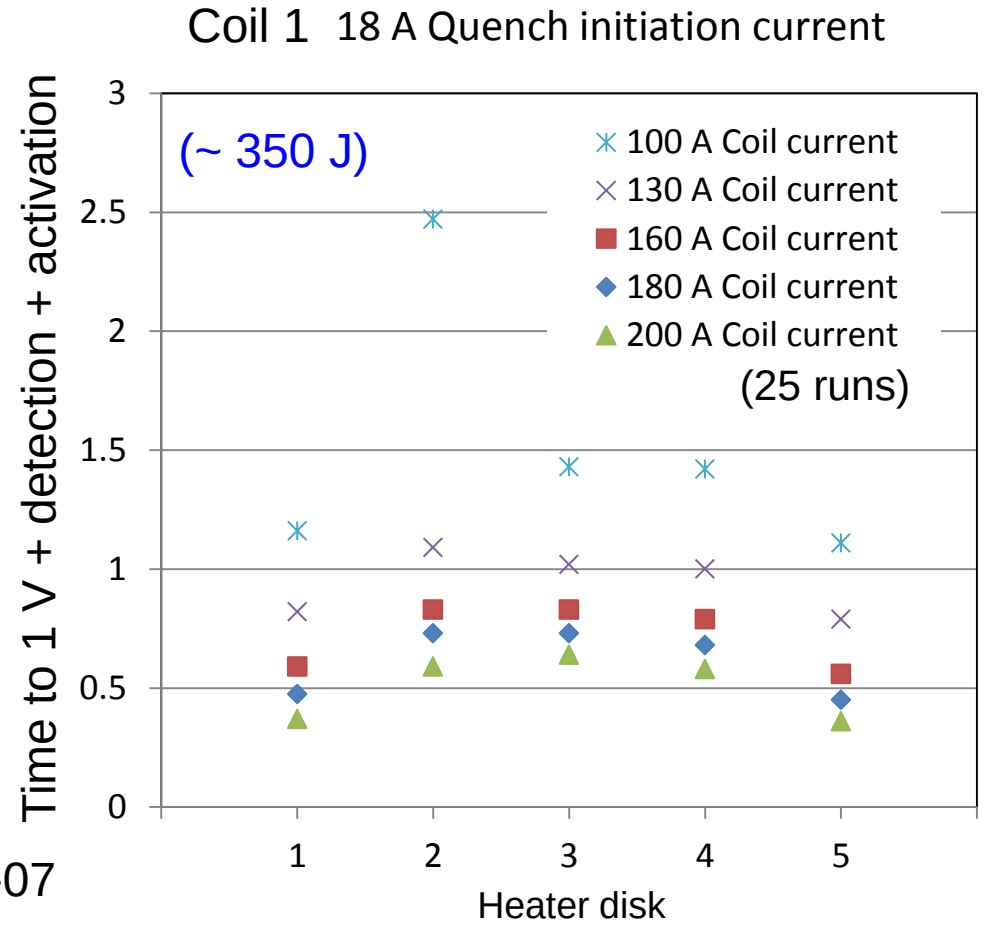
New quench protection heaters

Combined prototypes test runs

- Quench initiation runs (66) (with dump resistor)
- Quench protection runs (16)
  - Fire most heater elements (10+15) and observe current decay on NZ in coil
- Quench protection test runs (2)
  - Fire one heater element, let QD observe NZ and then fire quench heaters
- Load cycling in Coil 2 (Outer) prototype
  - 20 cycles to design stress: no ill effect observed
  - 40 cycles to 110% of design stress: no ill effect observed
  - 2 cycles to 120% of design stress: no ill effect observed
  - Modules remain superconducting at 270 A (so: quench testing < 74% of $I_{c,\,min}$)
- Very repeatable hysteresis in central magnetic field
- AC-loss run

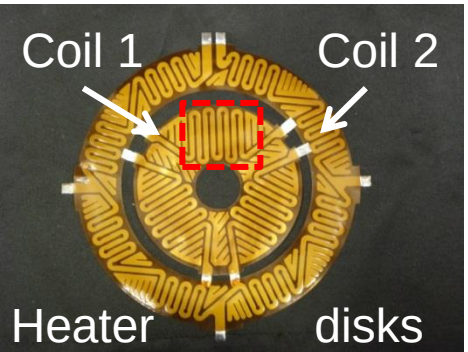
Combined prototypes test: example data





Quench detection at 1 V across coil

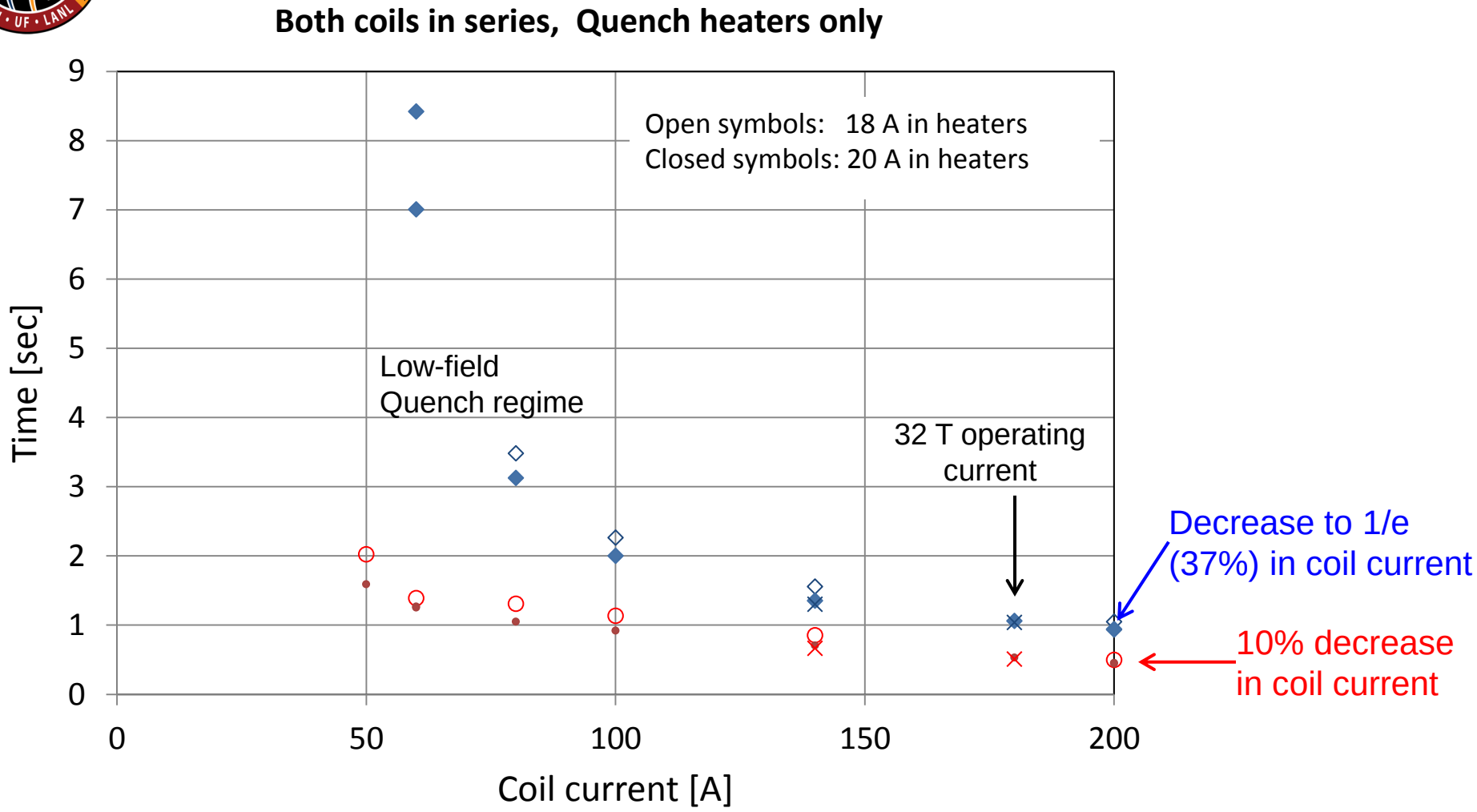
32 T quench detection: Noyes 4LPO1D-07



- Quench time scales with local I_c
- Module 5 was damaged* between February and August
- Modules 4 and 6 quench faster
- Below 100 A in coil, 18 A in heater insufficient to quench
- With 20 A in heater, good normal zones down to 60 A

*10 mV at 200 A (2 W dissipation heating coil > 5K

Combined prototypes test: example data



- Around the 32 T operating current, the coil current can be brought down in 1 second
  - Significant decrease in < 0.5 sec
- Can be accelerated with higher heater current
- Need (expect) to confirm numerically that this scales to “fast enough” for 32 T protection

32 T Prototype testing summary

- Successfully completed in-field testing of combined prototypes
  - New dielectric for quench protection heaters
- Quench heaters can create large normal zones anywhere in coils
  - Even at low fractions of I_c
  - Sufficient to distribute stored energy and decrease coil current (protection)
- Coils are robust under
  - Load cycling (Coil 2)
  - Quench initiation (Both coils)
  - Quench protection (Both coils)
- No degradation from testing in joints, cross-overs, terminals, windings
  - One previously damaged module in Coil 1 unaffected by tests
    - Limiting stress range in Coil 1
- Field non-linearity is repeatable
- Helium bubble is non-issue*
- First predictions of numerical code match data**
- Have enough data to fully benchmark numerical quench code
  - Required for upcoming combined HTS-LTS quench analysis
- Plan to start building 32 T in 2015 after full analysis and review
  - Scheduled operation in 2016

* H. Bai, 2LPo2A-03

** A. Gavrilin, 1LOr2D-04