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Magnet technology in the NHMFL 32 T HTS-LTS solenoid

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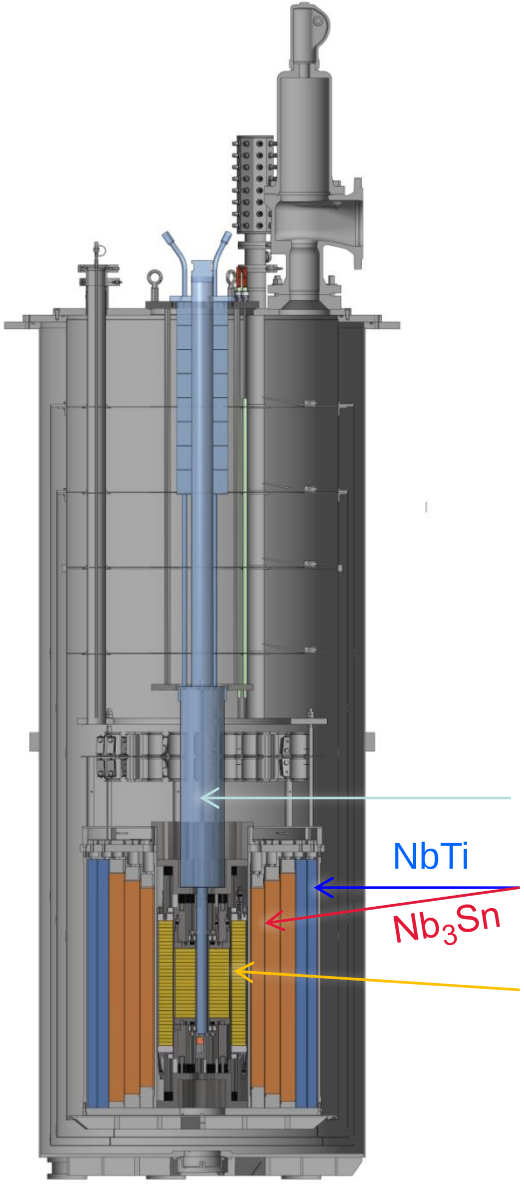
Outline

- Introduce the 32 T all-superconducting magnet
- Prototype testing
- REBCO CC Quench modeling

The 32 T magnet: a user magnet



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

Dilution refrigerator or VTI

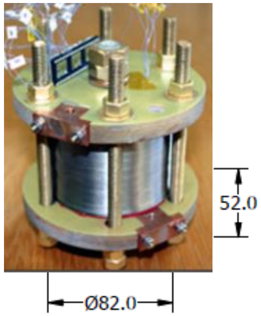
15 T / 250 mm bore LTS magnet

17 T REBCO coils (on separate power supply)

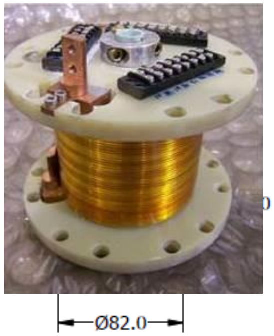
32 T will spend most of its life *ramping up and down at 4.2 K*

32 T Technology Development

2007



2008

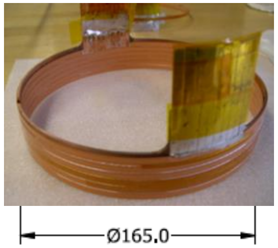


Demonstration inserts
20 T+ ΔB

2008

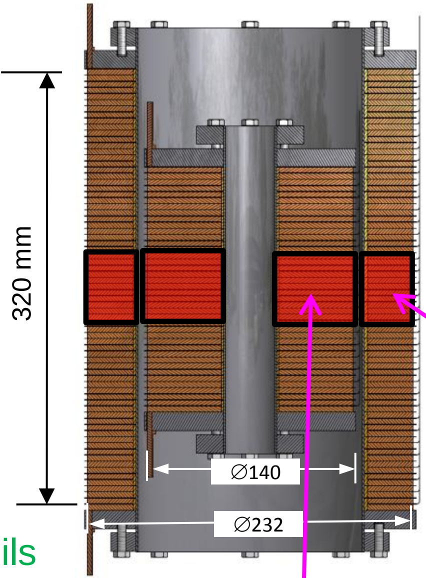
High-B coils
31 T + ΔB

2009



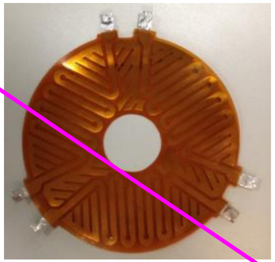
High Hoop-stress coils
>760 MPa

After prototype phase: TRL = 7, start of construction phase



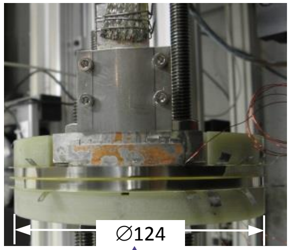
Development:

- YBCO tape characterization & QA
- Insulation technology
- Coil winding technology
- Joint technology
- Quench analysis & protection
- Extensive testing of components



2014 quench heater

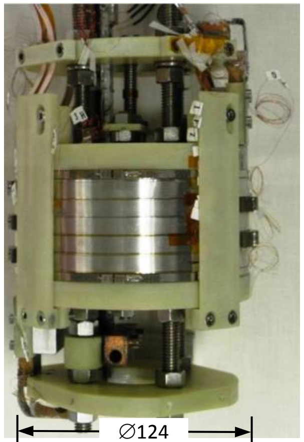
2011



First Quench Heaters

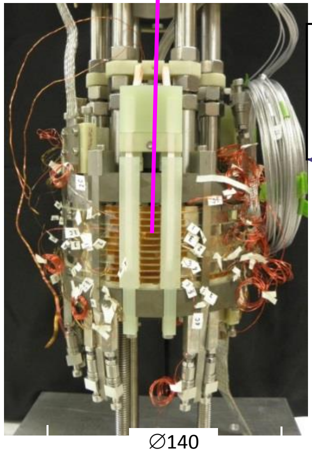
42-62 Mark 1:
1st test coil

2012



42-62 Mark 2:
2nd test coil

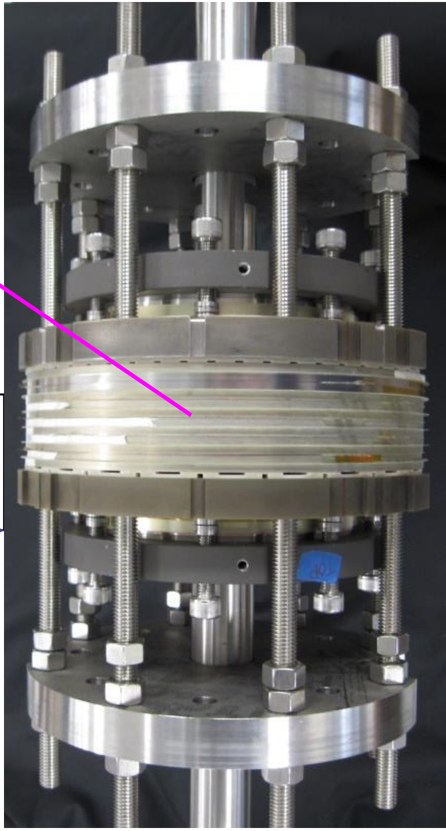
2013



20 - 70:
1st Full-featured Prototype

Heater-only quench protection

2014



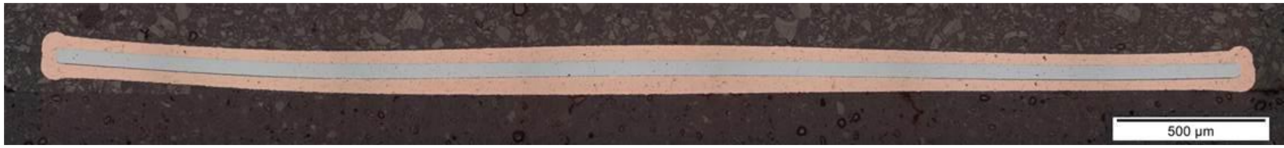
82 - 116:
2nd Full-featured Prototype

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
- Thin ceramic insulation on co-wound steel tape for turn-turn insulation
- Active quench heaters capable of heating ~ 50% of coil volume > T_{cs}
- Axial pre-load
- SuperPower tape



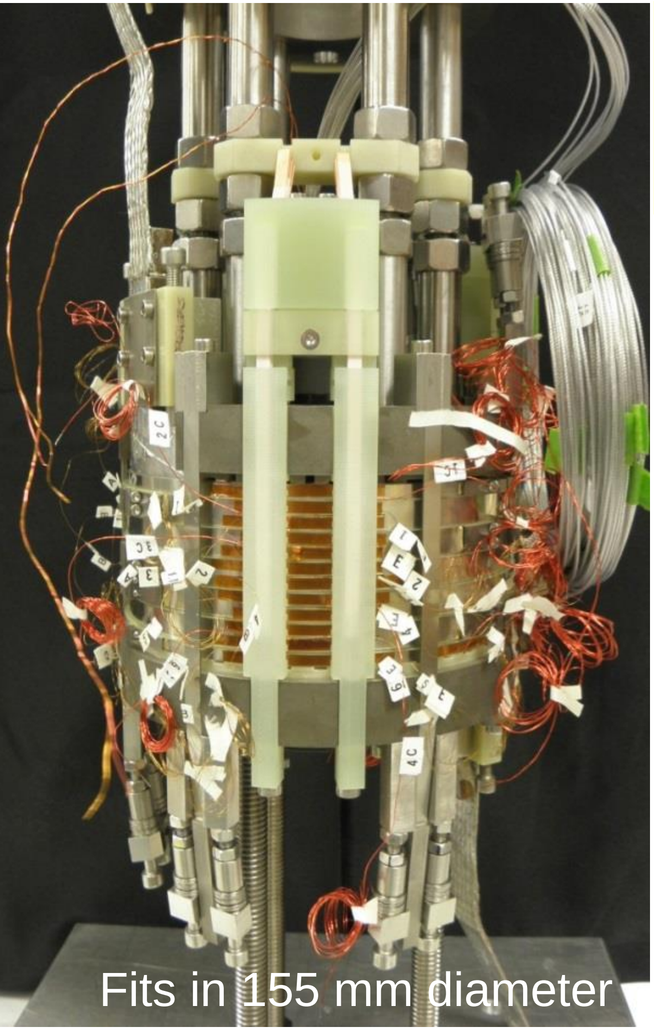
32 T design features

Feature	Reason	Long term Perspective
Dry-wound	Allows re-work & repairs, avoids delamination issue	Mechanical integrity of epoxy impregnated windings preferred
Cu-plated stabilizer	All 32 T magnet technology developed using SuperPower tape	Prefer a truly flat tape. Dog bone + dry wind → voids → mechanical instability? Helium in voids not needed for stability
Monolithic conductor	No cable option in 2009; allows series operation with LTS in future (not in 32 T)	Prefer cable (if $J_{ave} \geq 200$ A/mm^2) + dump resistor
Quench heaters to heat 50% coil > T_{cs}	Low NZPV	10-fold improvement of NZPV is still slow. Prefer cable + R_{dump}
Pancake coils	Modularity; large quench heater interface area; simpler insulation compared to layer winding	Prefer pancakes without internal joints, layer winding or cable windings
Internal joints	10 km worth of ≥150 m piece lengths not commercially viable (at the time)	
Axial pre-load	Keep terminals with coil, take out initial softness	Softness linked to dry winding; terminals always complex

Prototype coils

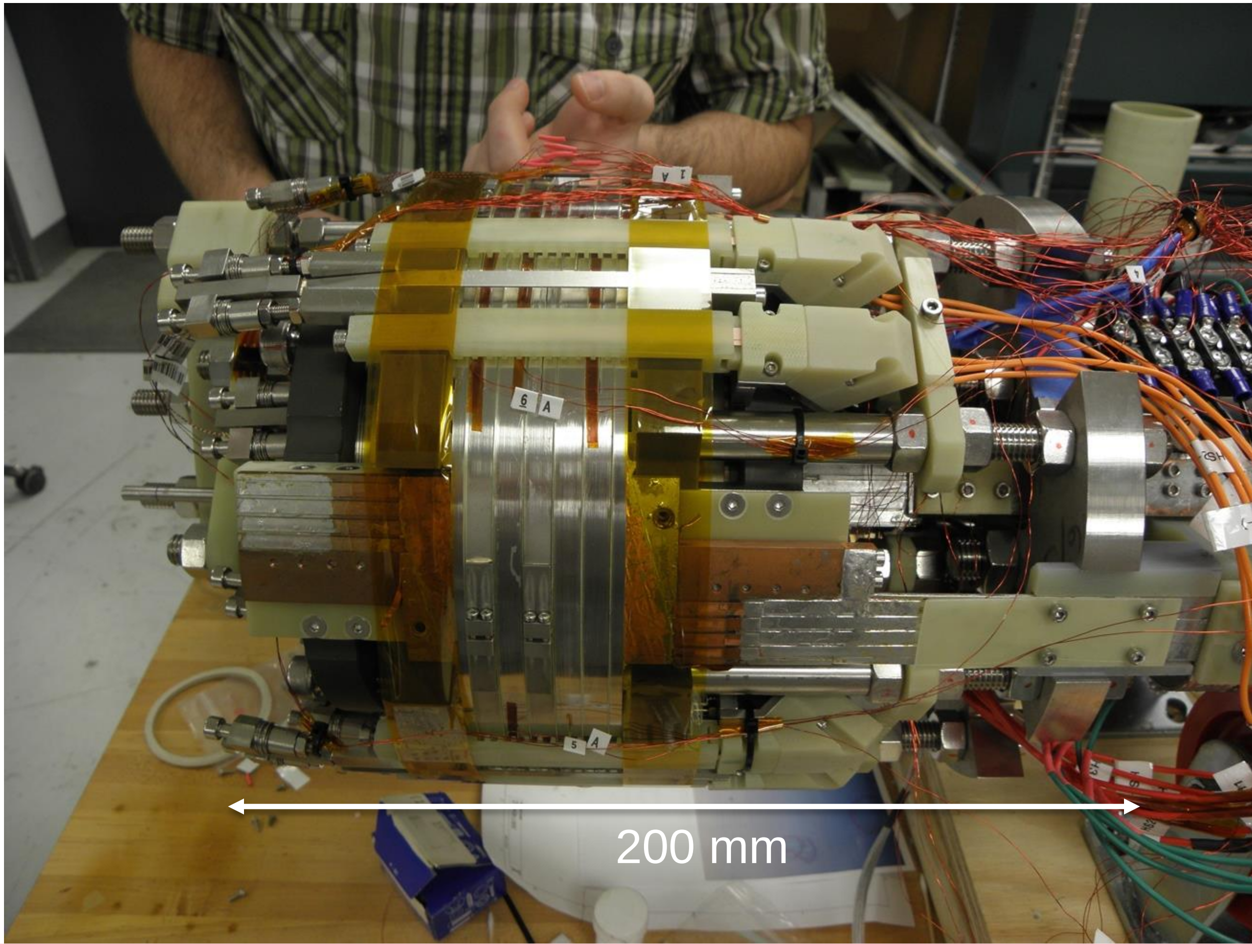
Full featured, only reduced height

- 6 modules versus 20 resp. 36 in 32 T
- Much extra instrumentation

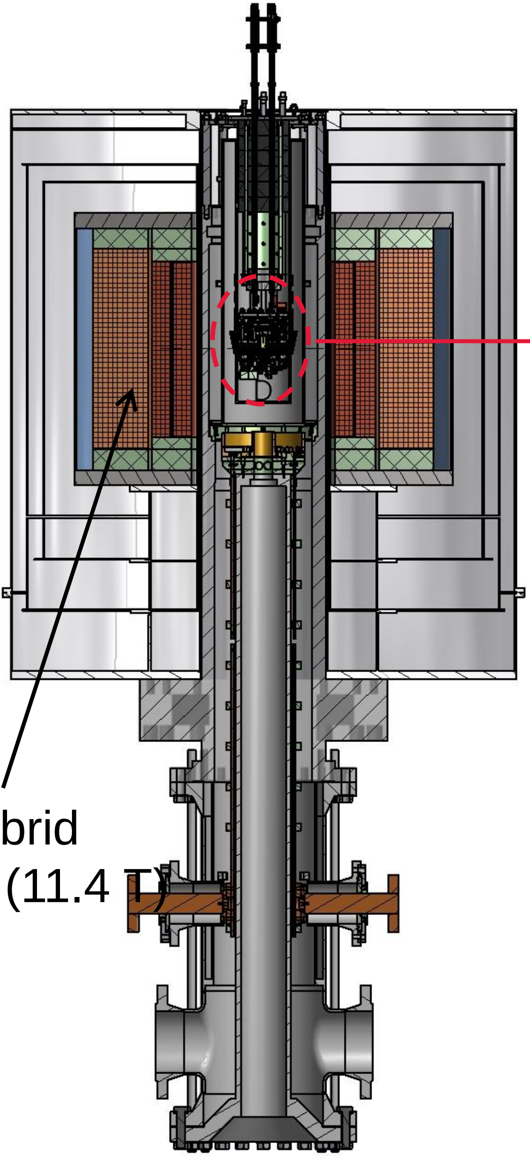


Coil 1 prototype with instrumentation and wiring

Coil 2 prototype

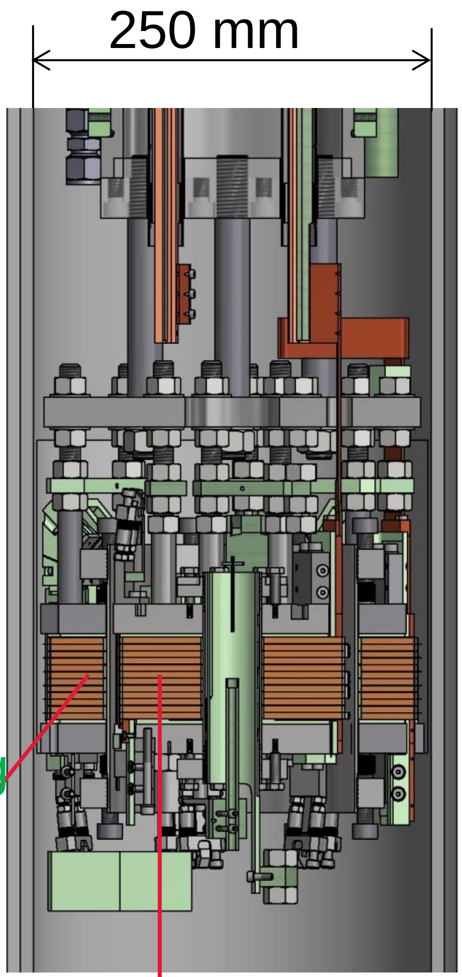


Combined prototype coil test in 45 T Hybrid Outsert



45 T Hybrid Outsert (11.4 T)

Cryostat with REBCO coils in cryostat inside Resistive Magnet housing



- 1.9 km of REBCO in
- 12 double pancakes
- Realistic stress levels
- Exceed current density
- Extensive Quench testing
- 21 T all-SC at 200 A

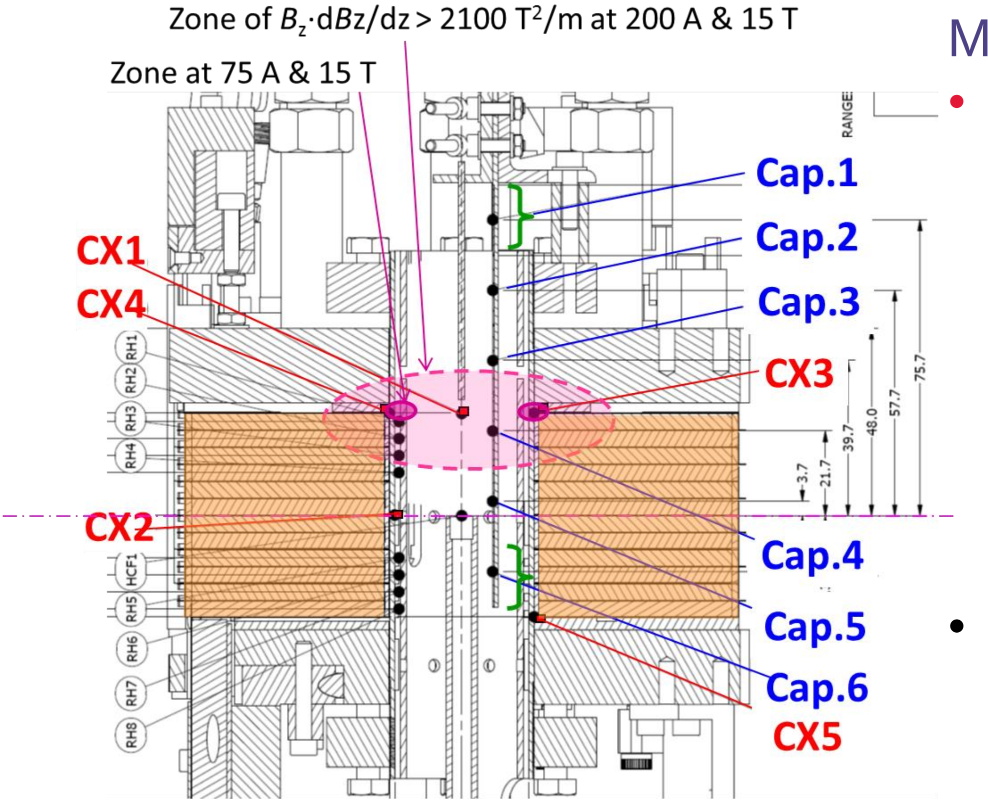
Coil 82/116 (2nd)

Coil 20/70 (1st)

(radii in mm)

Diamagnetic helium: stagnant helium "bubble" if B·dB/dz > 2100 T^2/m

Coil 1 prototype



CX= Cernox™ temperature sensor, Cap= capacitive gas/liquid sensor

- Bubble forms as calculated
- Size is ~ same in prototypes and 32 T
- Coil temperature remains stable with mitigation

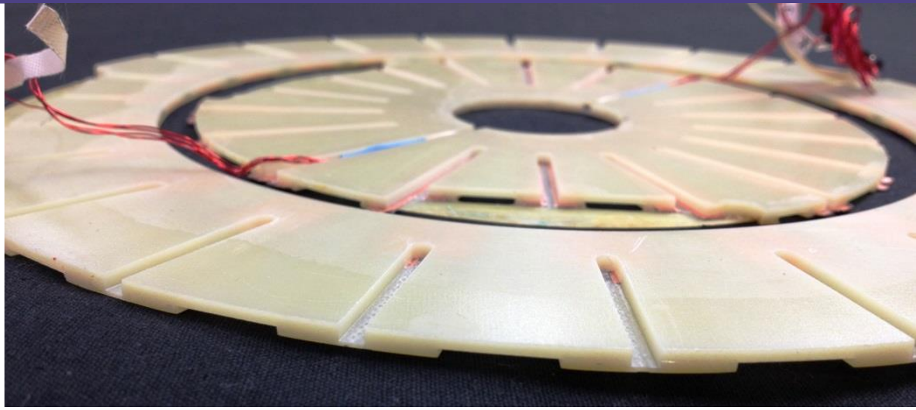
Mitigation:

- Maximize axial thermal conductivity
  - Circumferential κ is fixed, radial κ and NZP are poor given dry coil & dog bone
  - **Narrow tolerance on conductor width → flat pancakes**
  - **Axial pre-load via Belleville washers & axial compression straps on flanges**
  - **This is beneficial for heat exchange with bath and quench propagation**
- Cu strips and helium vent channels in "cooling spacer" at ends of coils

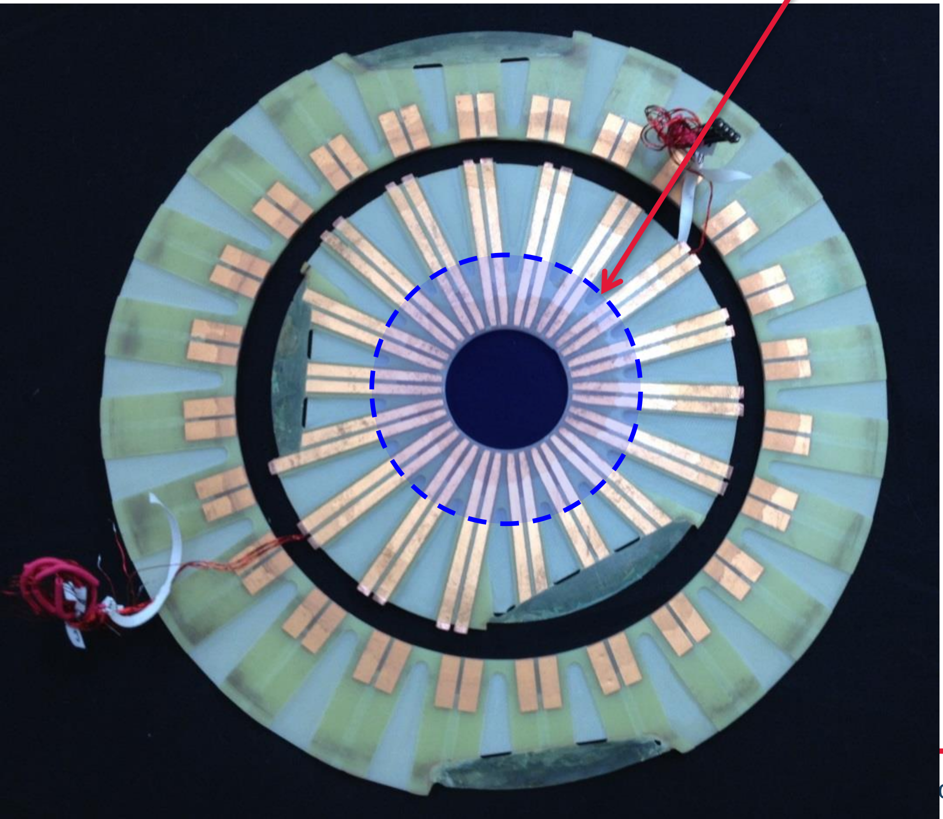
H. Bai, S.T. Hannahs, W.D.. Markiewicz, and H.W. Weijers, *Helium gas bubble trapped in liquid helium in high magnetic field*, Appl. Phys. Lett., 104, 133511 (2014)

The cooling spacers

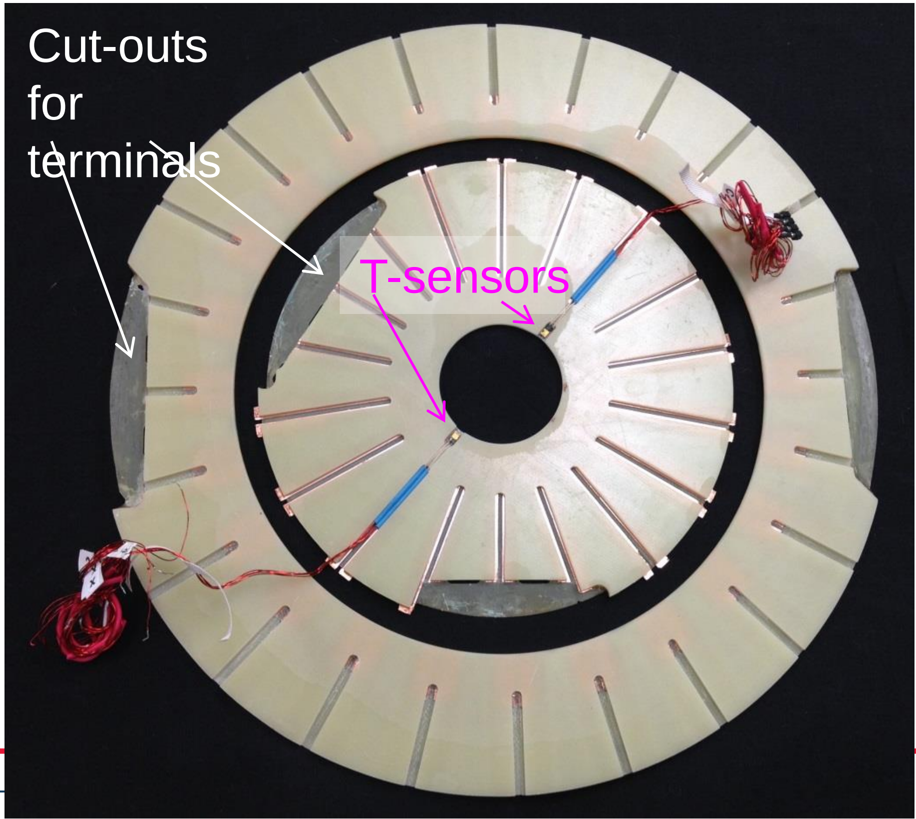
Provide electrical insulation, helium vent channels, cooling via recessed Cu strips for part of coil in helium gas bubble:



Coil-facing side



Flange-facing side



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 (Separate supply & protection)	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)

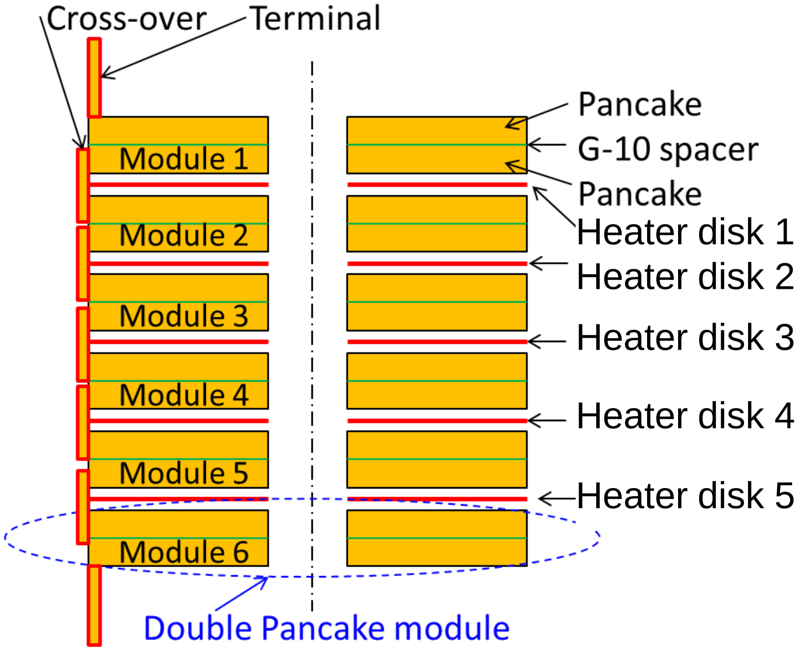
Quench heaters can protect coils* even in the case of **zero** normal zone propagation

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

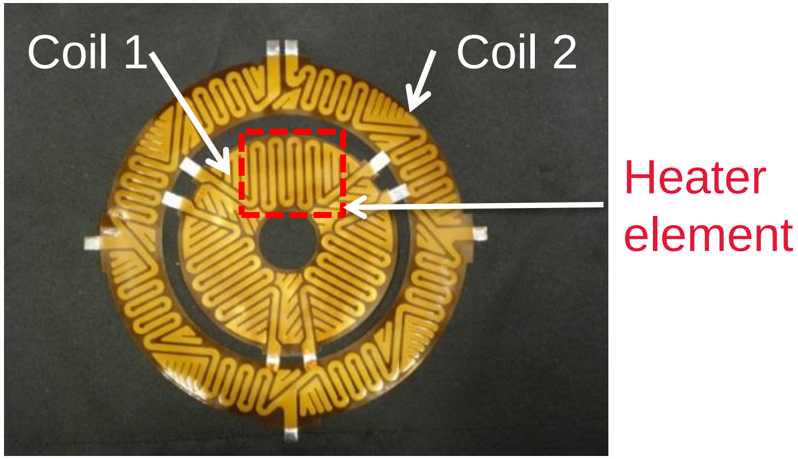
Prototype coils test goals

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

Coil 1 prototype schematic



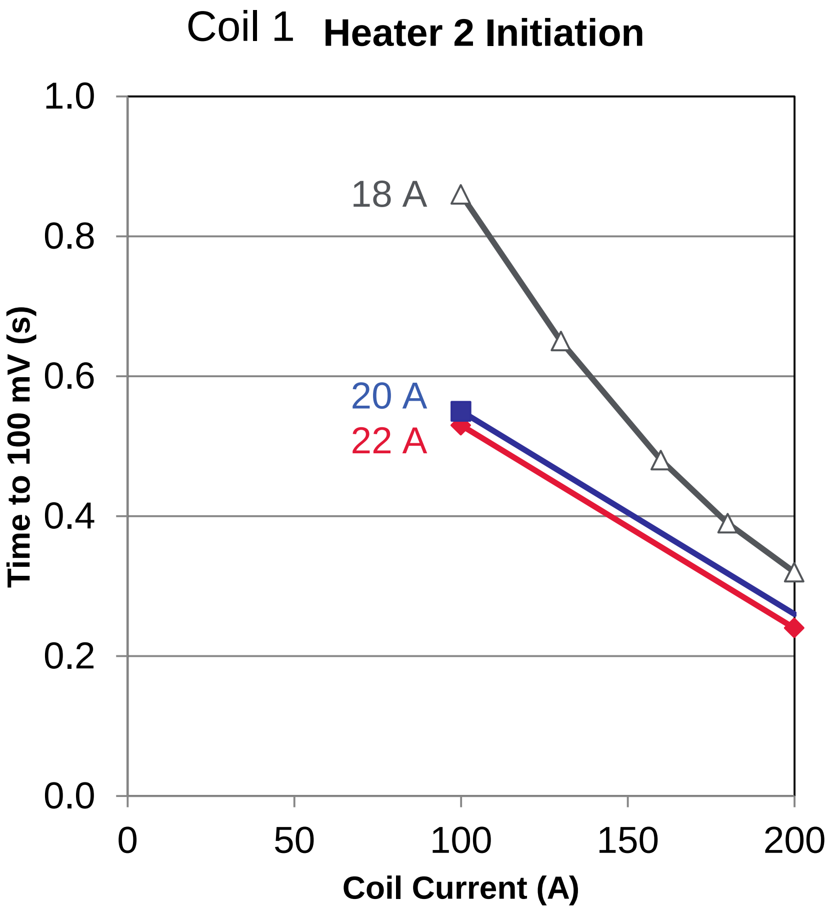
Coil 1 and Coil 2 Quench Heater disks

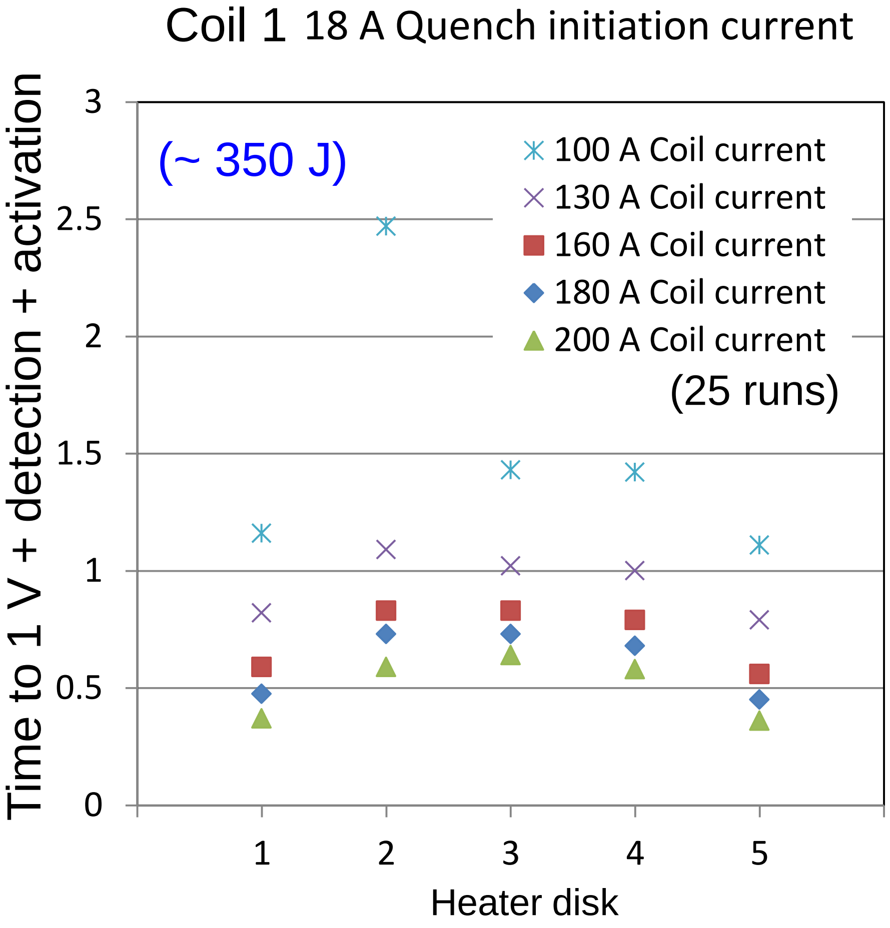


Quench detection at 1 V across coil

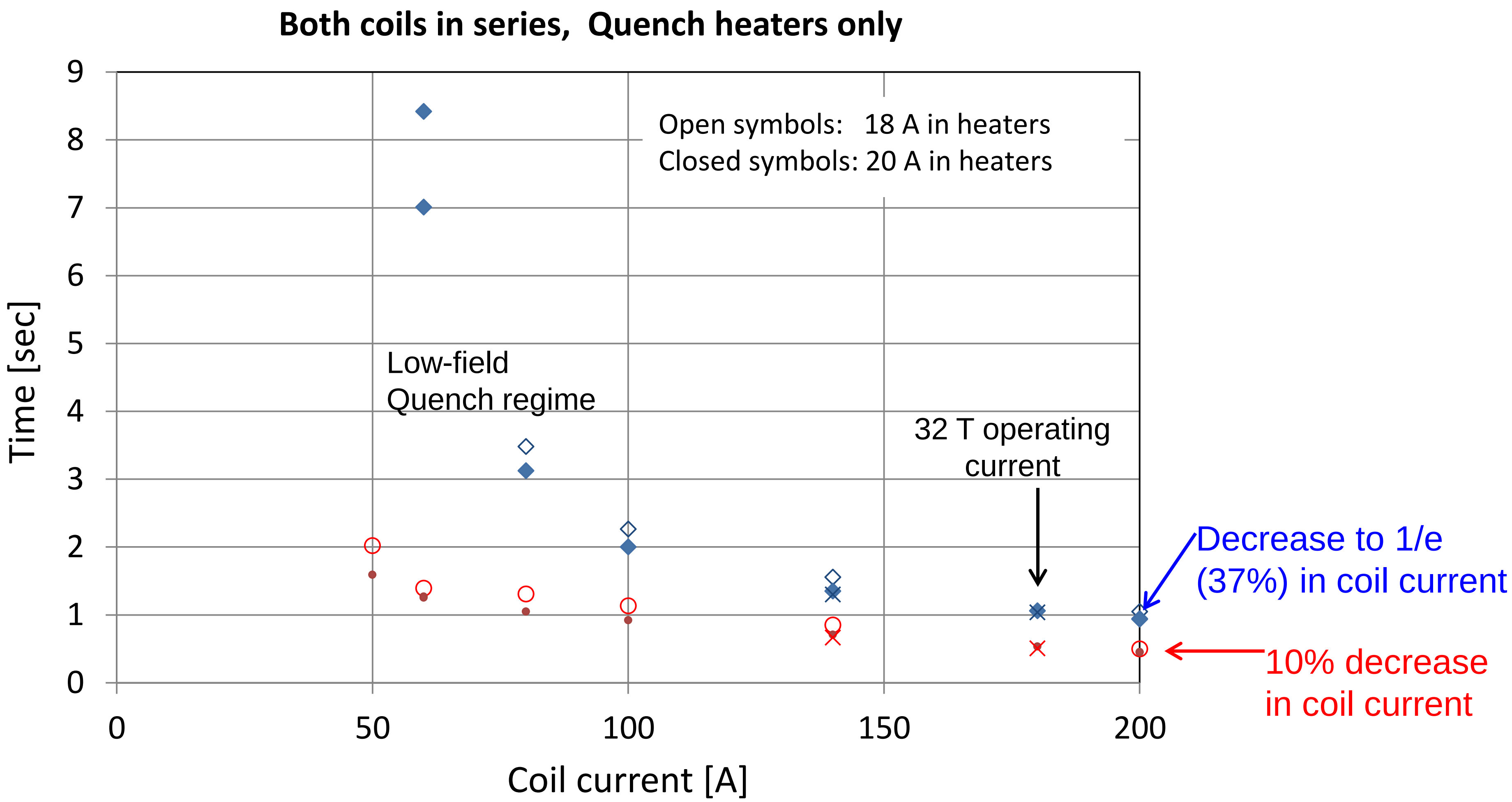
Quench initiation example data

- Quench time scales with local I_c
- Below 100 A in coil, need >18 A in heater to quench
- With 20 A heater current, good normal zones down to 60 A
  - Higher heater current possible





Quench protection 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

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

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

What have learned form prototypes?

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

Field non-linearity is repeatable

Helium bubble is non-issue

First predictions of numerical code match data

Have a lot of data to benchmark numerical quench code

- Difficult but required for upcoming combined HTS-LTS quench analysis

Next prototype run will be in actual LTS outsert: including quench run

Plan to start building 32 T in 2015 after full analysis and review

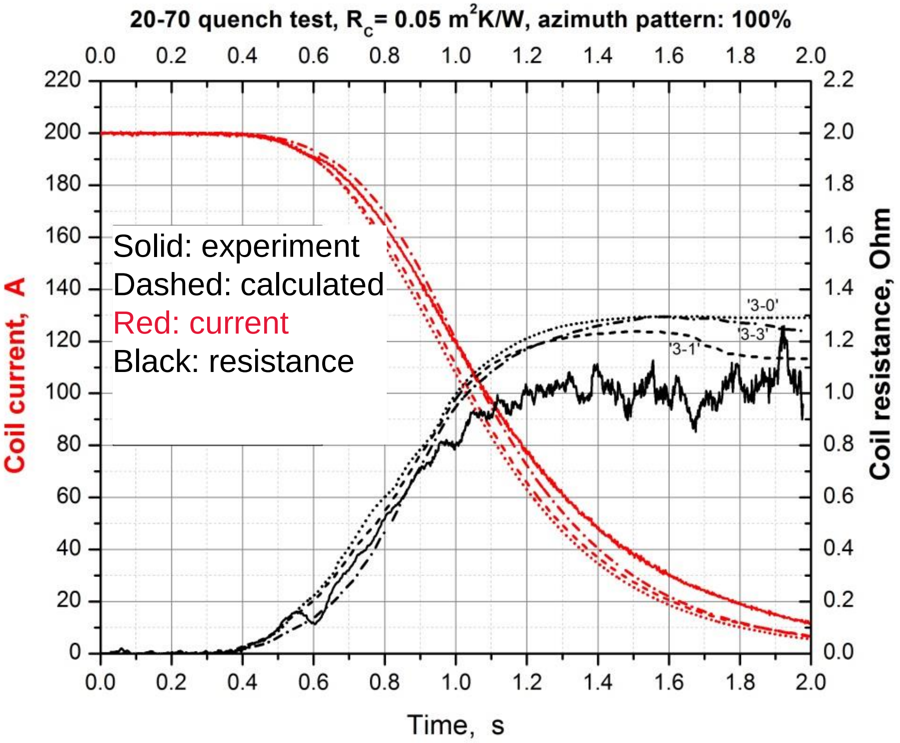
- Scheduled operation in 2016

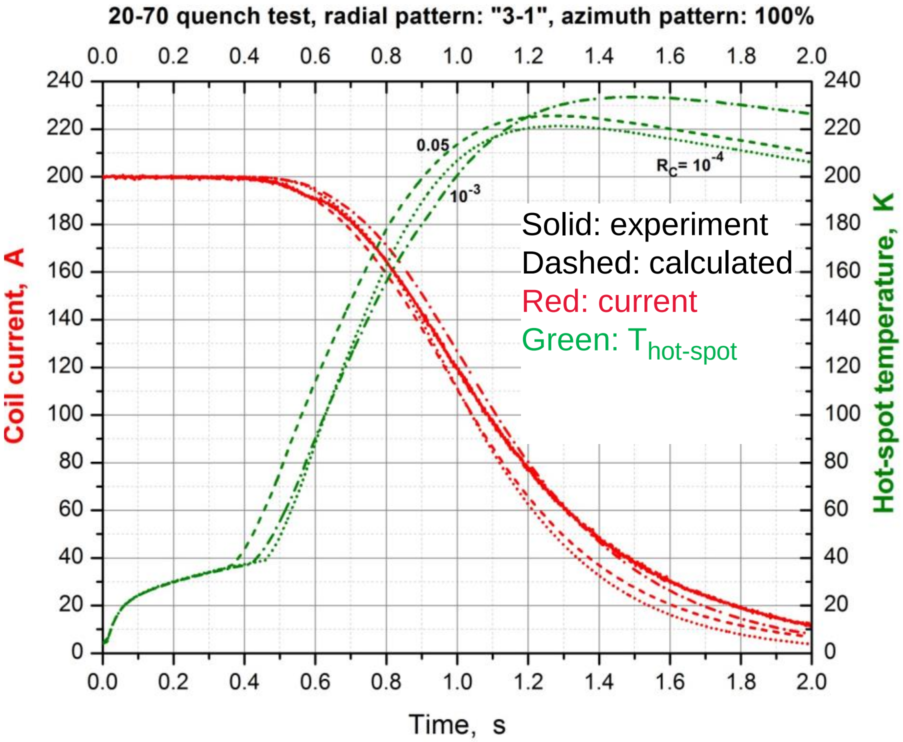
Quench model aspects

- Traditional model of LTS coils
- $c_p(T)$ of materials in HTS windings, including 10 vol% helium
- Our “standard” normalized $I_c(B, T, angle)$ 4.2-40 K
  - measured on “bridges” (narrowed samples, 2012)
  - T_{cs} at midplane & very small field angles >> 40 K: not realistic: corrected
  - I_c scaled to measured I_c(4K, 17T, 18°) for each tape in coil
- RRR and magneto-resistance of Cu
- % contact area between heaters and turns,
- Contact resistance between heaters and turns, turn-turn, pancake-pancake
- Radial, axial and circumferential κ in conductors
- Heat flux from heaters versus time and heater current from simulation
- Magnetic field depends on transport current
- Heat conductance equation with a source term solved
- include index heating, Ohmic heating AC-loss

Firing quench heaters at full coil current

Coil 1 prototype in 15 T background (2013)
Firing 40% of available heaters at a modest 16 A
No dump resistor



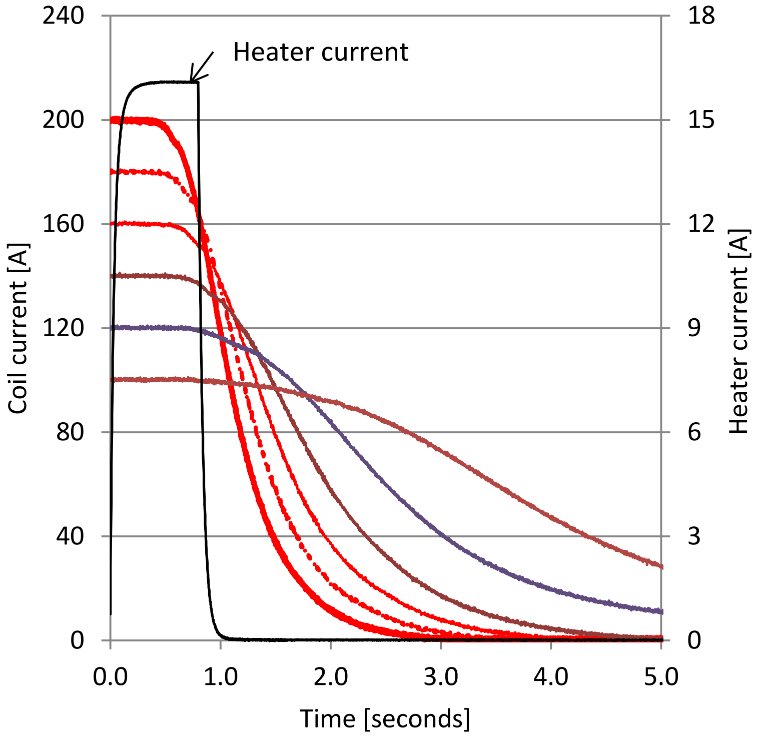


A range of contact resistance and %contact area parameters give reasonable fit for current decay and resistance rise

Firing quench heaters at reduced coil current

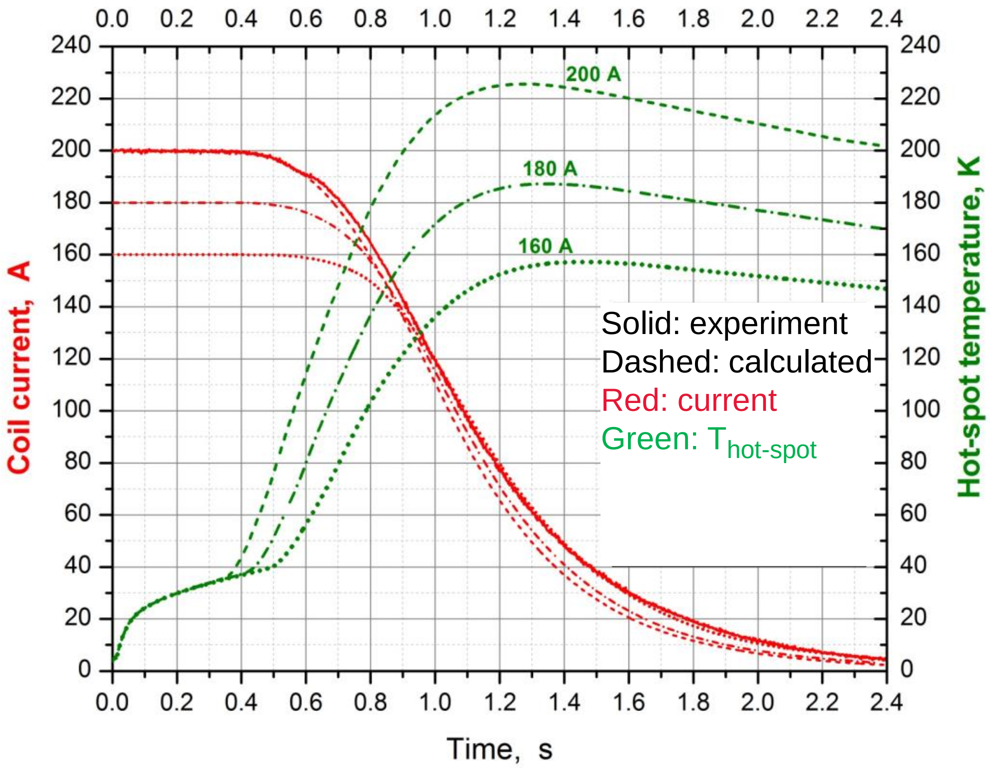
Coil 1 prototype in 15 T background
Firing 40% of available heaters at 16 A
No dump resistor

Measured



Model

Coil 20-70 quench test, R_C= 5 10^{-2} m^2K/W, heater current of 16A, radial pattern: "3-1"



Measurement: Current decay extends in time, I(t) curves cross over
Model: Current decays in same time, I(t) curves shift down

32 T Quench simulation discussion

- NZP in three directions (r, z, ϕ) not applicable as primary input parameters to HTS quench code
  - It is not a simple binary system with a moving normal zone front
  - Instead there is a wide partially superconducting zone with 1% < I_{Cu} <99 % of I
- Thermal contact resistances, *n*-value , current sharing temperature,

  I_c(*B, T, angle*) are important but poorly understood over *some* of the relevant range (> 4.2 K)
- Model parameters can be set to match measured resistance versus time for full current, nominal quench heater power case
  - At lower coil current and heater power the actual coil shows consistently a resistance rise well (> 1 sec) after the heaters are off
  - Numerical model has trouble matching that
    - Is variability of I_c along length a necessary input?
    - Correct modeling of AC-loss & shielding currents?
      - Models should be able to predict/explain shielding current effect on measured parameters like local magnetic field, induced voltages while ramping, helium boil-off

32 T Magnet technology summary

- Introduced the 32 T all-superconducting magnet
  - Design features
  - History and technology choices
  - Long term perspective
- Prototype testing
  - Implication of test results: REBCO coils are robust
  - Mitigation of “helium bubble issue”
  - Quench testing: Quench heaters can protect REBCO tape pancake coils
- REBCO CC Quench modeling
  - Early days: not a simple extension of LTS quench models
  - Benchmarking code against relevant experimental data is yielding results
  - Some physics or material properties not yet fully captured
- LTS+ HTS solenoid operation incl. quench in 2015

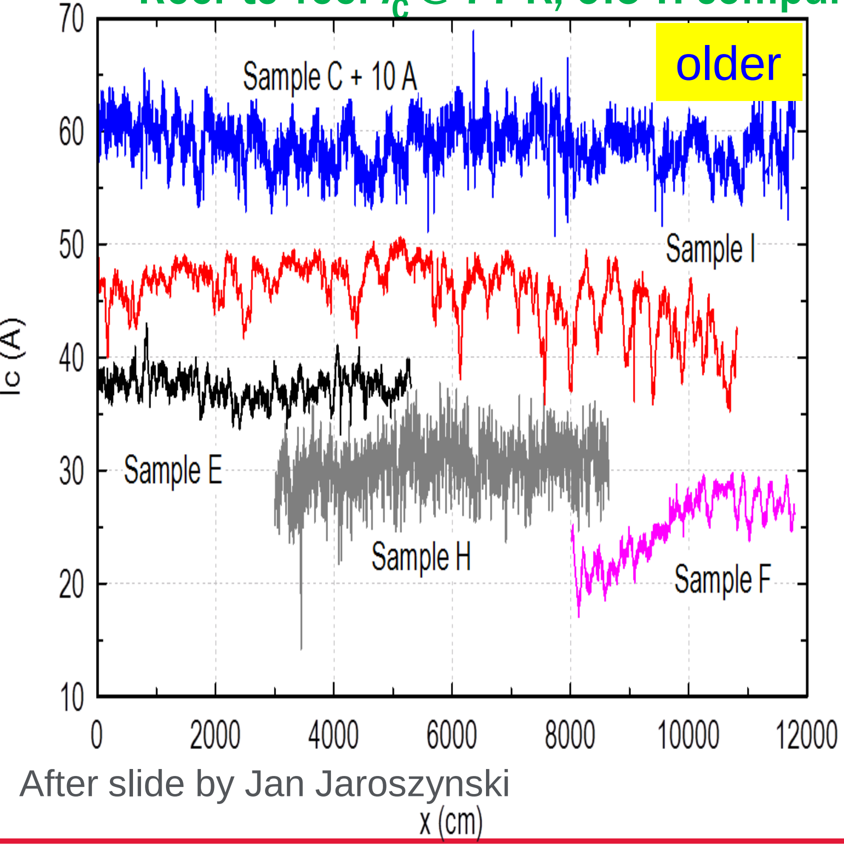
The REBCO Superconductor

Negotiated unprecedented 14 specifications

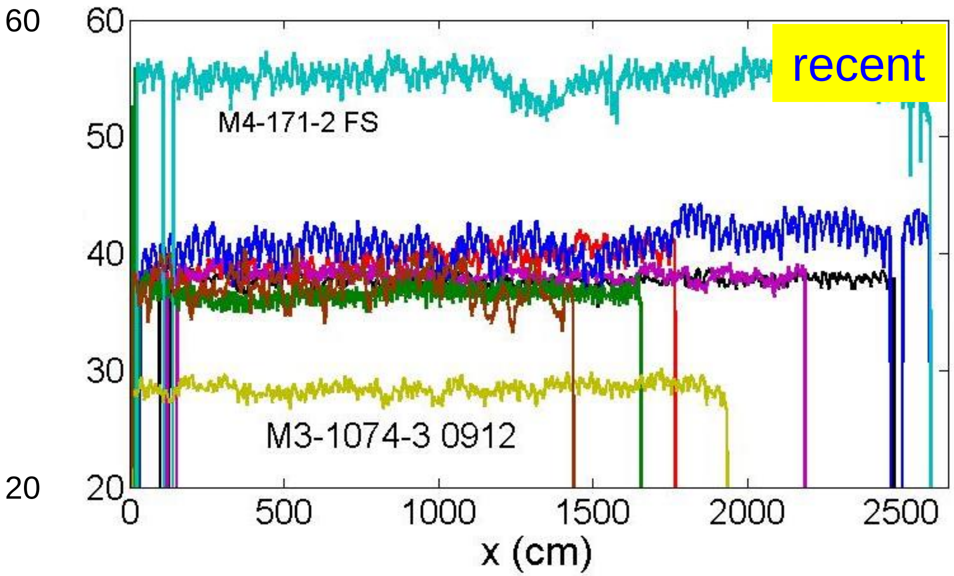
- Balance project needs and commercial viability
- QA program has pushed vendor to improved conductor geometry
  - Width, Cu area within thickness specification

Conductor is steadily getting better

- Reel-to-reel I_c @ 77 K, 0.5 T: comparison



After slide by Jan Jaroszynski



Much less variation along the tapes,
still substantial variation between different tapes