High field magnets with coated conductors
A viewpoint emerging from projects at the NHMFL

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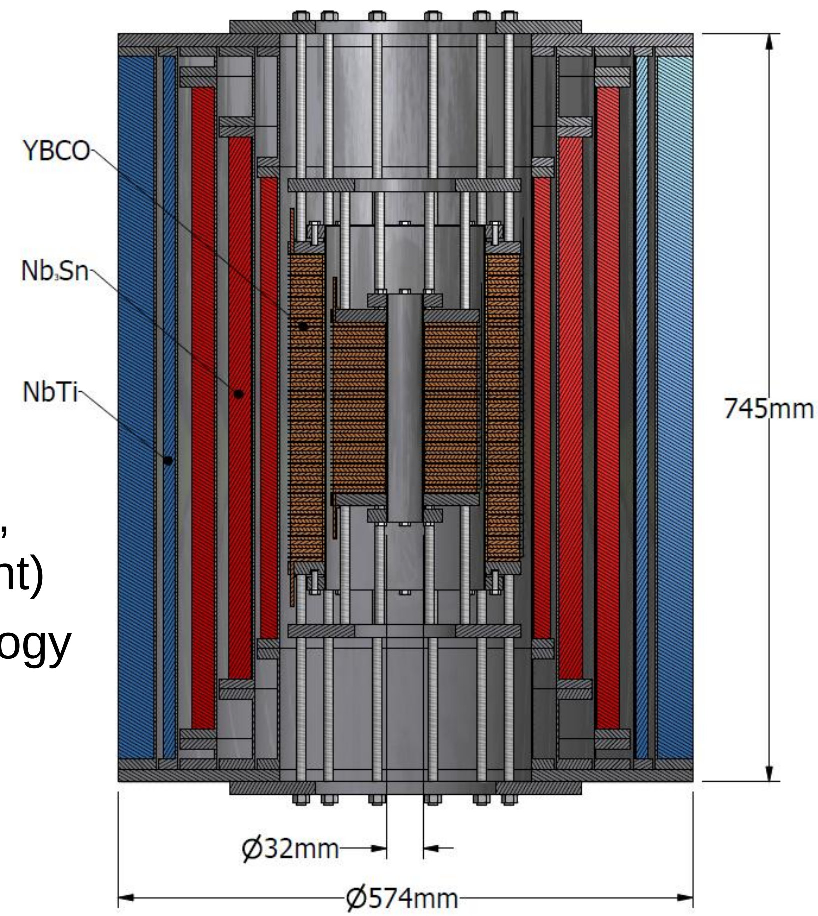
Outline

- Pancake style coated conductor magnet technology
  - Introduction to the 32 T project
  - Quench
  - Project status
  - Areas of concern
  - Key points
- Layer-wound coated conductor technology

32 T Magnet Project: User magnet

- Goal:
  - 32 T, 4.2 K, 32 mm bore
  - 500 ppm in 10 mm DSV
  - 1 hour to full field
  - dilution refrigerator <20 mK
  - 20 years of operation at NHMFL
- Funding:
  - $2M grant from NSF for LTS coils, cryostat, YBCO tape & other components (insufficient)
  - Core grant for development of new technology
    - ~ $8M total expected, ~ $4M to date
- Key Personnel
  - Huub Weijers, NHMFL, Project lead
  - Denis Markiewicz, NHMFL: Magnet Design
  - David Larbalestier, NHMFL: co-PI, SC Materials
  - Stephen Julian, Univ. of Toronto: co-PI, Science

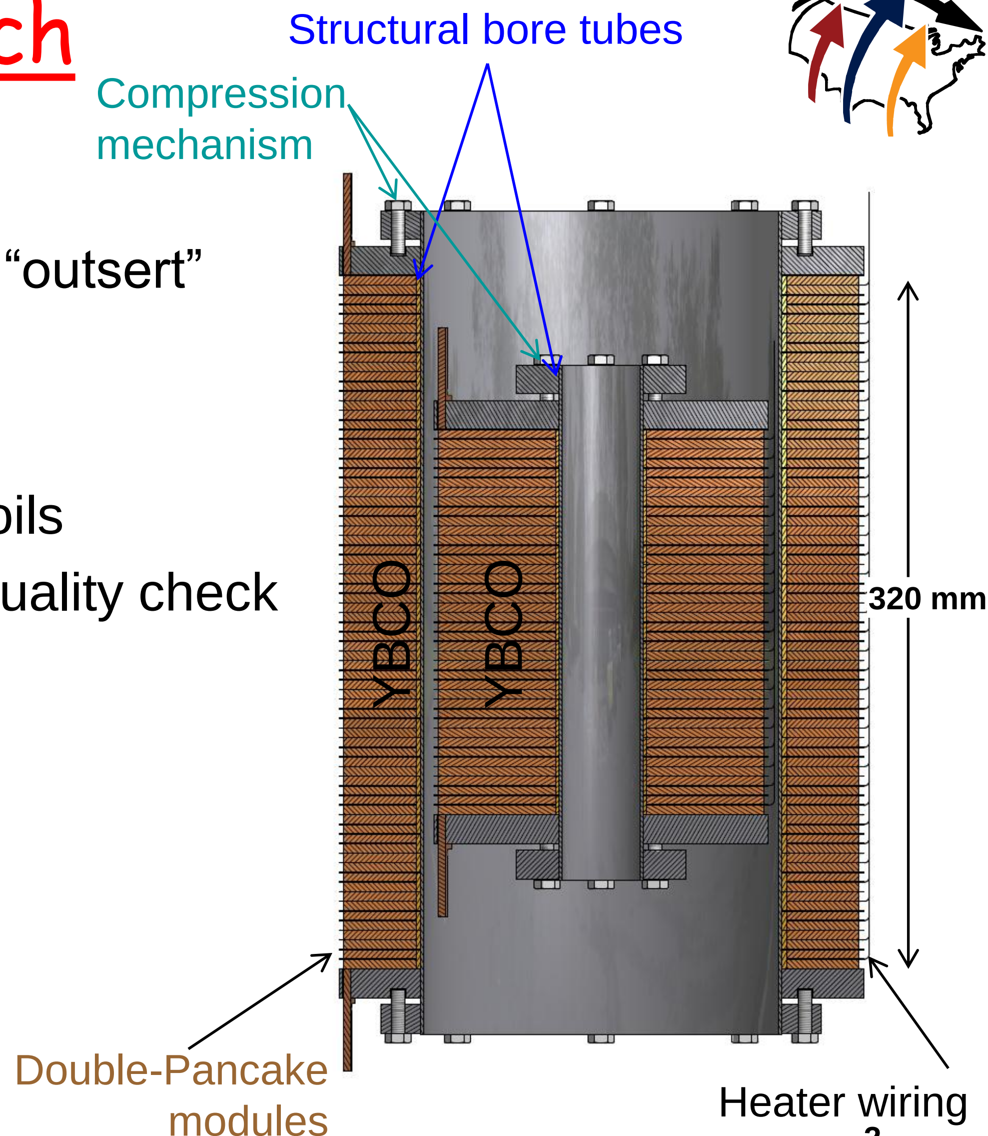
32 TESLA SUPERCONDUCTING MAGNET



HTS Current	**172 A**
Total Inductance	**619 H**
Stored Energy	**9.15 MJ**

32 T Approach

- Commercial Supply:
  - 15 T, 250 mm bore Nb_3Sn/NbTi “outsert”
  - cryostat
- In-House development:
  - 17 T, 34 mm cold bore YBCO coils
  - YBCO tape characterization & quality check
  - Insulation technology
  - Coil winding technology
  - Joint technology
  - Quench analysis & protection
- Choices so far
  - Pancakes, not layer-winding
  - Dry, i.e. no epoxy
  - 4 mm wide tape, 50 μm Cu plating
  - Insulation on co-wound steel strip
  - Quench heaters for protection



J_{ave}	188 A/mm^2
Inductance	18 H
DP Modules	20+36
Turns	10,255+11,368
Conductor	2.9+7.0 km

Status

- Repeated tests on sc. test coils in 20 T background
  - >100 dumps after quench initiation and quenches
- Conductor characterization transitioning into Quality Assurance
- Insulation development complete
  - Commercial sol-gel Silica with added Alumina on co-wound stainless steel reinforcement tape
- Coil winding, joint, cross-over, terminal development well developed
- AC (ramp-) loss and Quench codes in use
- Design is stable,
  - $I_{op} \leq 0.7\, I_c$, $\sigma_{hoop} \leq 400$ MPa, $J_{Cu} = 420$ A/mm^2
- Outsert +cryostat is on order (21-30 mo.)
- Working on first of two prototype coils
  - (full-featured, radially full size, limited height)

Categories of concern
with relevance to MAP

- Conductor
- Quench
- Cryogenics

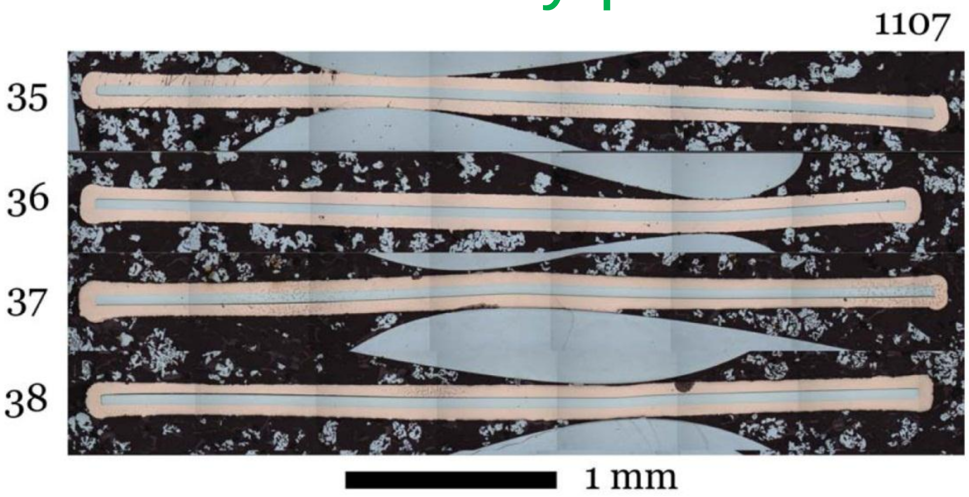
Coated Conductor

- Drop-outs in I_c or local variation in any property?
  - Coated conductors are not fully developed yet as commercial, user-magnet proven product
  - Continuous QA is at ≥295 K or 77 K at manufacturer
    - Is Tapestar data fully understood?
  - High-field magnet applications are at ~ 4K
  - Correlation between sc. properties at 77 K and 4 K is not strong
- For 32 T:
  - Conductor I_c specification and QA at 4 K, 14 T
  - Modular approach (pancakes)
- Observation
  - I_c drop-outs not observed so far in 32 T test coils and BNL insert coils
  - Conductor shape (thickness and width) are neither as uniform nor as reproducible as desirable
    - Affects quench behavior: **reduced** axial and radial **thermal conductivity** κ plus **increased uncertainty** in thermal conductivity

Coated Conductor

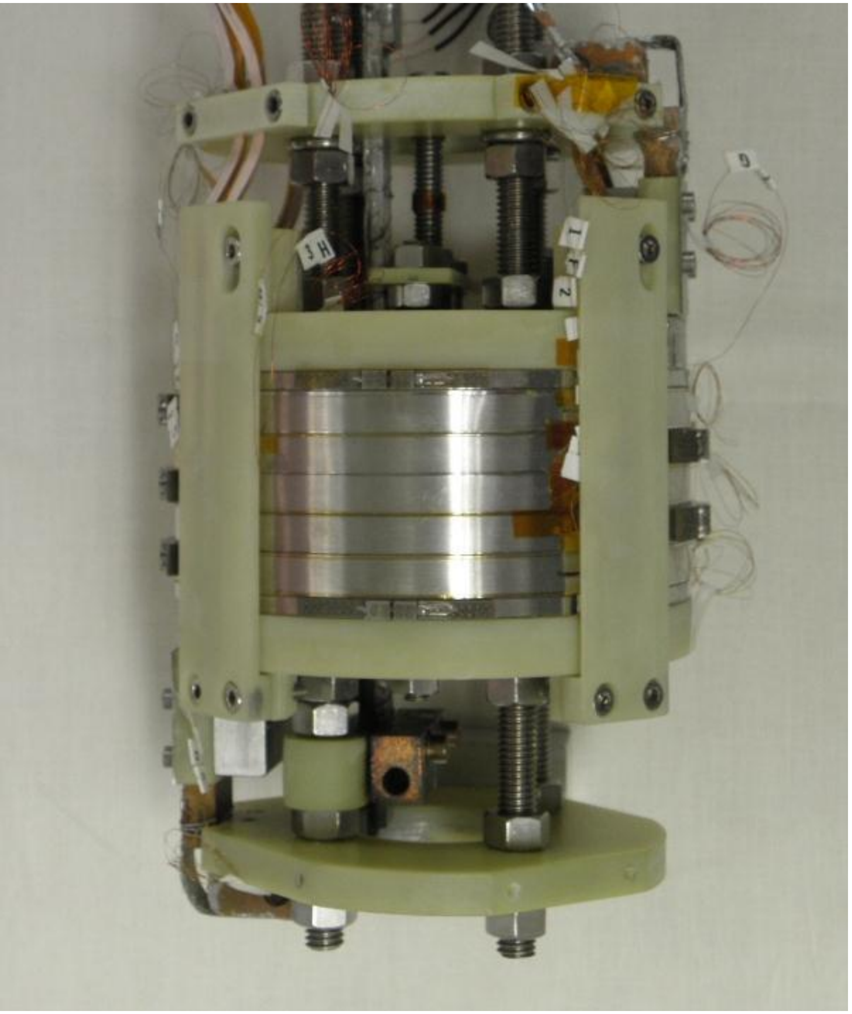
< Older material (> 2-3 years)

More recently purchased

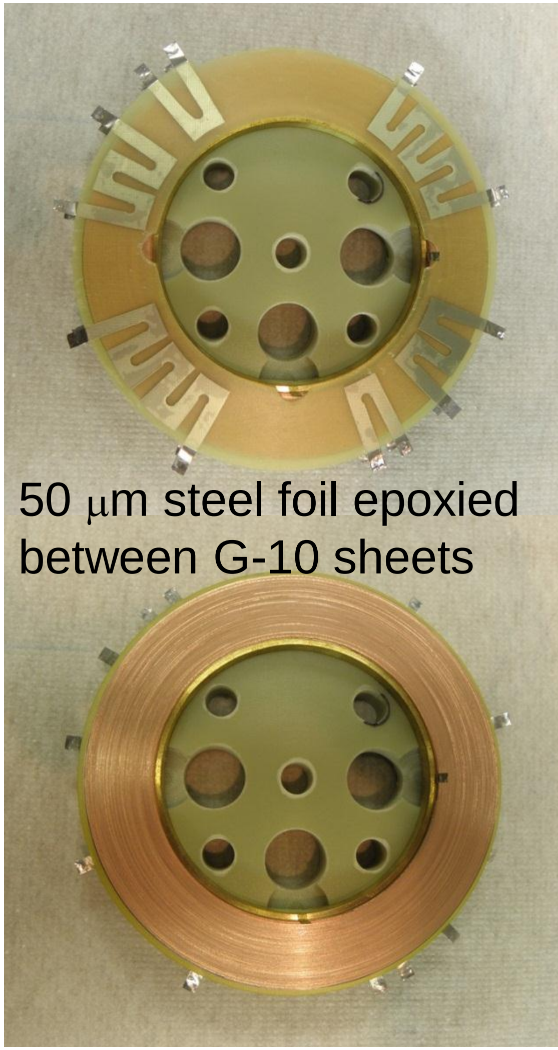


Reduced dog-bone
Slight bulge in middle
Some are narrow <4.0 mm
Overall: better shape for winding
But not as reproducible as desired

Quench Protection of YBCO Coils



Test coil: IR 42 mm, OR 62 mm
6 DP modules

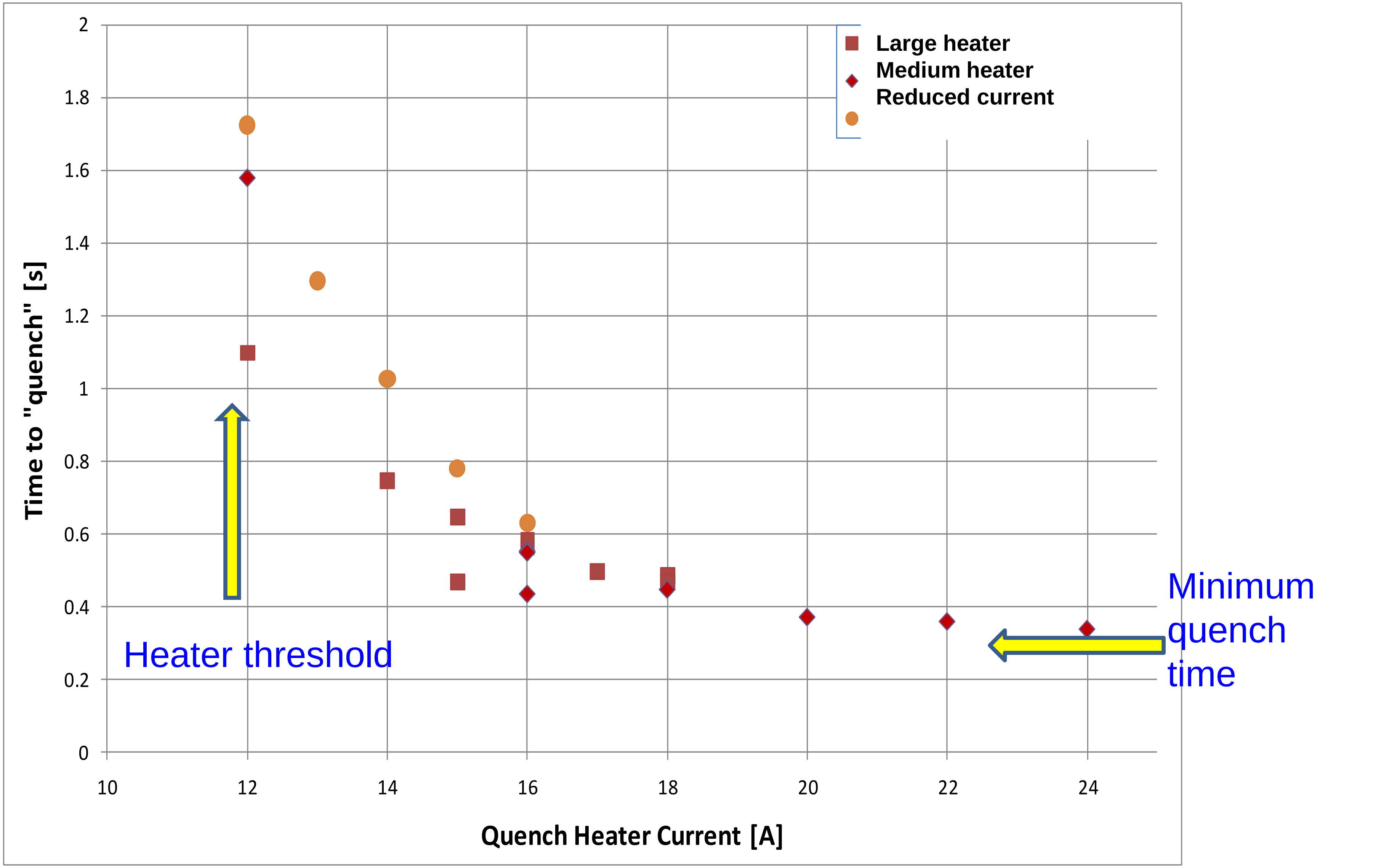


Quench protection heater elements shown on YBCO test coil.

Quench testing

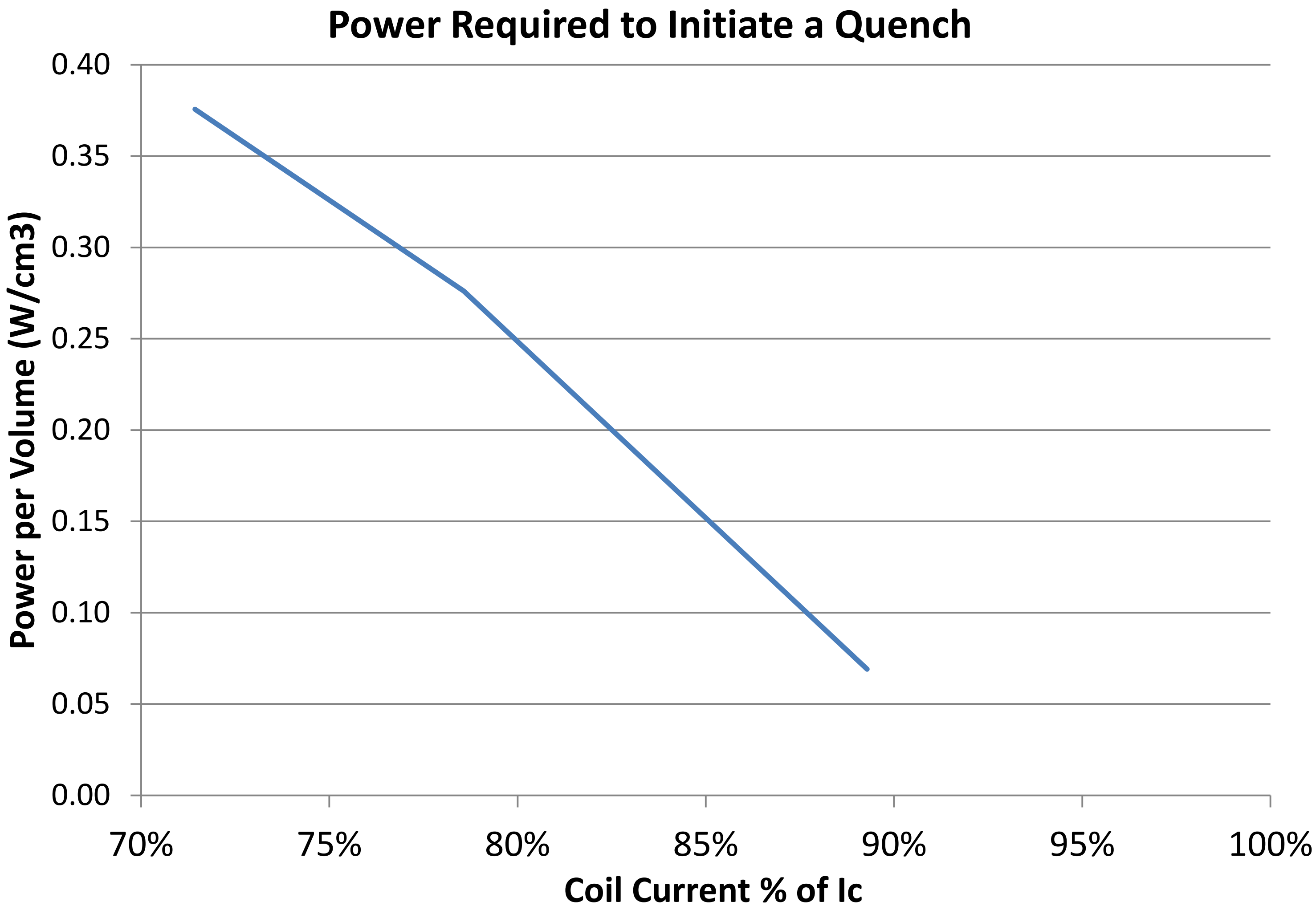
- In 42-62(2)
  - Fire heaters for 0.5 sec to initiate quench
  - Module voltage spikes up to ~ 10 mV recover
  - 12-13 mV leads to runaway
  - Protection typically with contactors and dump resistor
  - Detection criteria for whole coil (6 modules) ≥ 50 mV,
    - ≥ 20 mV per 3 modules
    - Balance voltage (top 3 minus bottom 3) much more sensitive, balances out induced voltages during ramps
- For full 32 T
  - Voltage based quench detection seems OK
    - Balance voltage quite sensitive
  - ~14 kW, 6 kJ energy dump in quench heaters

Quench Heater performance curves (time to ≥10 mV, 180 A, in 20 T)



Typically 0.5 sec pulse, single heater, resistor dump after quench initiation

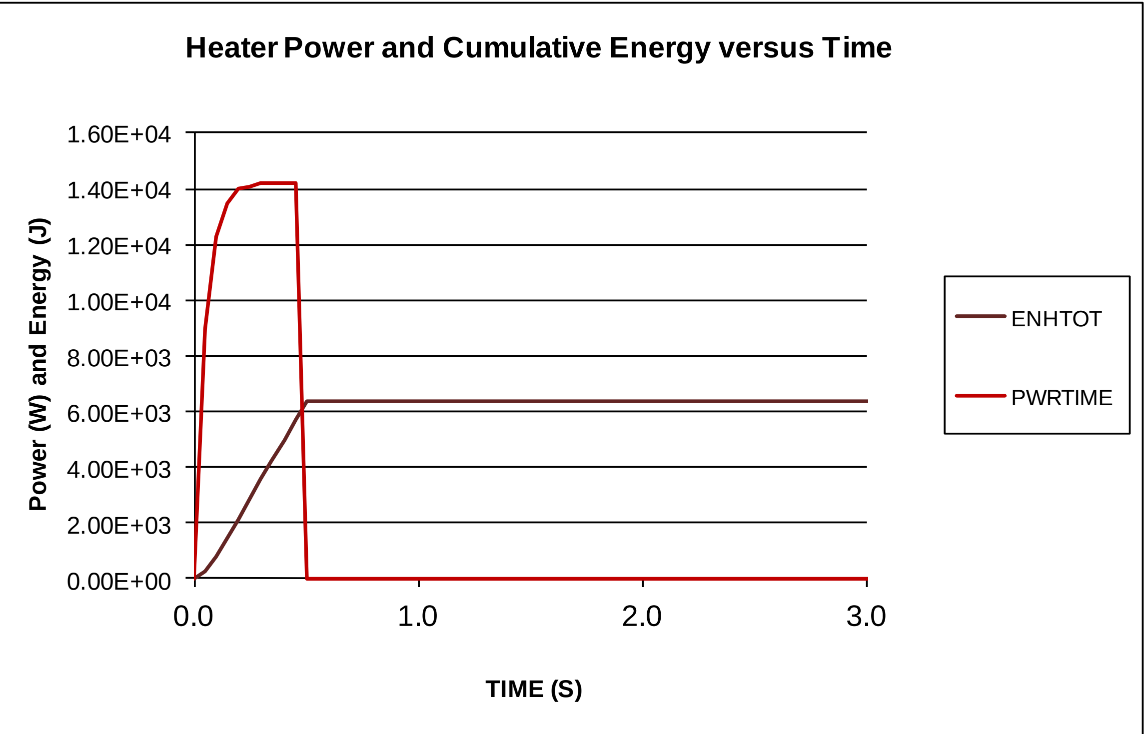
Quench
Induced via low power continuous heating



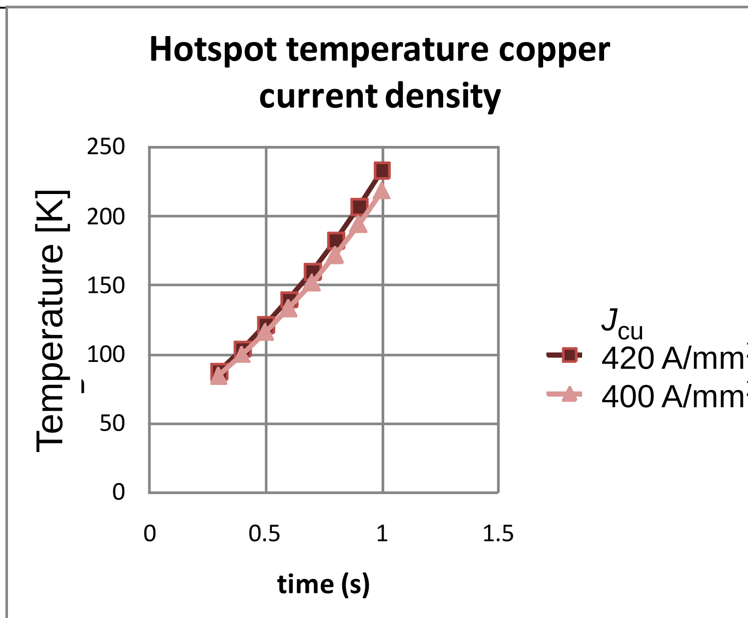
Mimicking AC loss ramp heating using quench heaters

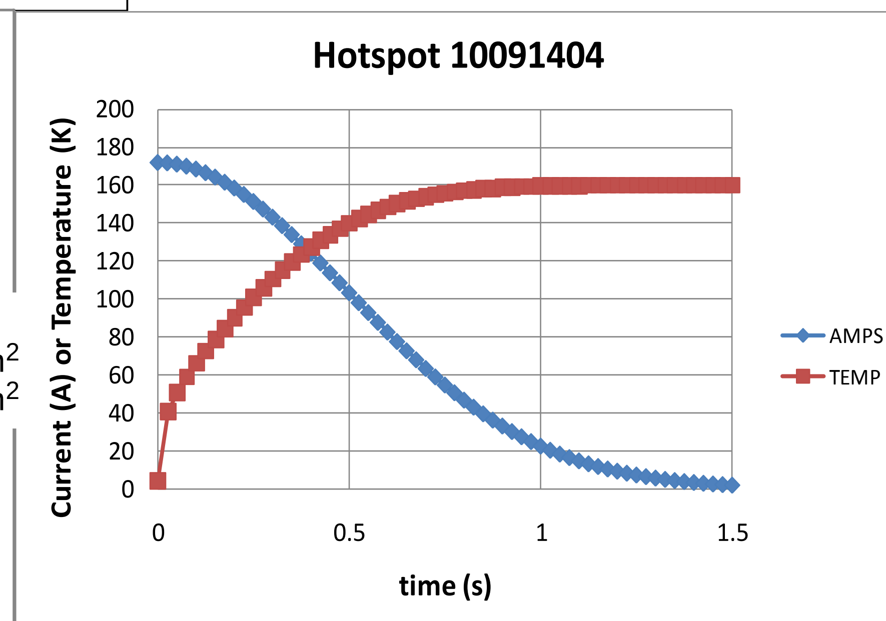
4K, 20 T background

Quench codes



The required heater power and accumulated energy are calculated and form the basis for heater power supply design.





The “HOTSPOT” calculation gives an indication of the allowable time for coil discharge.

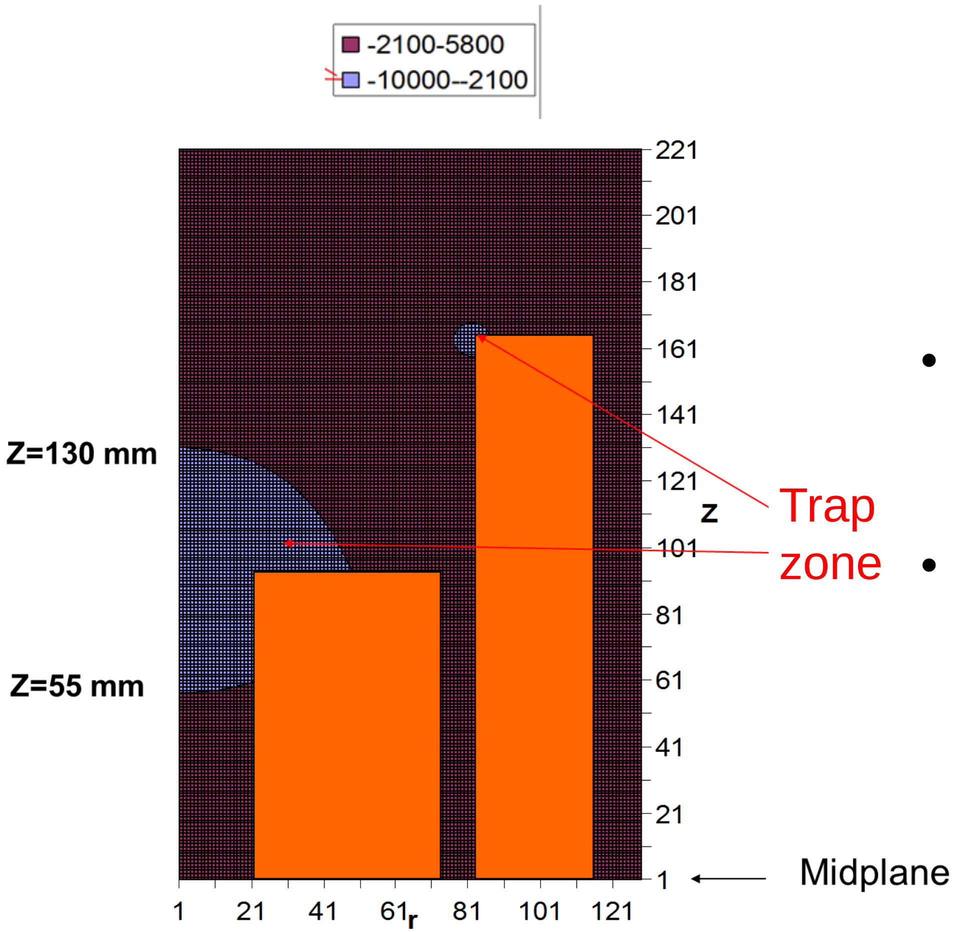
Quench

- At J_{ave} < 200 A/mm^2 one needs a current decay time constant τ after quench of ~0.5 to 1 seconds to limit hot-spot temperature using quench heaters
- 0.4 sec seem achievable for 32 T, but not much faster
  - J_{cu} at 420 A/mm^2 via 50 μm Cu over standard 20 μm helps
- τ is ~inversely proportional to $j^2.\rho$
- Quench protection at J_{ave} ~ 400 A/mm^2 and τ ~ 0.1 sec does not seem feasible using single-strand, pancake approach with distributed active heaters

Cryogenics

– "Helium bubble problem":
  - If B*dB/dz > 21 T2/cm, magnetic forces exceed buoyancy and gas bubbles no longer rise to surface but form a stationary bubble with correspondingly poor heat exchange: one has to rely on conduction through magnet windings and structure
  - Joint and AC (ramp-rate) losses can and DO cause this in narrow-bore high-field magnets
  - Again, low and unpredictable thermal conductivity of the winding pack is problematic
    – May need dedicated Cu cooling channels

B*dB/dz at full field



Quarter cross-section of HTS part of 32 T magnet

Layer wound insert coil

- Technology demonstration, not user magnet
- Main features
  - One-piece, 96 m of 4 mm wide AP tape from SuperPower
  - Insulated with shrink-tube
  - Wet-wound with unfilled epoxy
  - 14 mm ID, 38 mm OD, 80 mm tall
  - Tested in 31 T resistive magnet
- No delamination problems, thermal shock resistant
- I_{max} = 196 A, J_{ave}= ~290 A/mm^2 at 35.4 T and 340 MPa
- Affected by helium bubble problem at 4K, stable at 1.8 K
- Quench protection proven effective using simple voltage detection, contactors and external dump resistor: $\tau < 0.1$ s
  - Protection scheme doesn't scale to large L

Key points

- The 32 T magnet seems feasible as user magnet with
  - Single strand double-pancake coated conductor modules
    - 25 cm OD, 32 cm tall, 10 km HTS tape for 17 T field increment in 15 T LTS
  - Insulated co-wound reinforcement
  - Active quench heaters in spacers between modules
  - At J_{ave} just below 200 A/mm^2,
  - J_{cu} just above 400 A/mm^2
  - τ~0.5 seconds
  - Which seems not far from limits of this approach
  - Operation foreseen in 2014
- For (even) more substantial magnets
  - All three areas of concern
    - Variability in properties, quench protection and cooling (low κ)

plead for application of multi-strand, multi-kA cable with built-in cooling channel for cryogen (forced flow, supercritical helium)

Operating current large enough to use a dump resistor with acceptable voltages