The NHMFL 32 T all-superconductor magnet project

An update

Nov 9, 2012, UC meeting

H.W. Weijers
Contributions by W.D. Markiewicz, J. Lu,
J.J. Jaroszynski, D.V. Abraimov, and D.C. Larbalestier
(all NHMFL)
Acknowledge: REBCO vendors, particularly SuperPower

Project Scope

- Provide 32 T at NHMFL in an all-superconductor user magnet
  - Unprecedented ~ 10 T increase in magnetic field
  - At a fraction of the power use of a resistive magnet

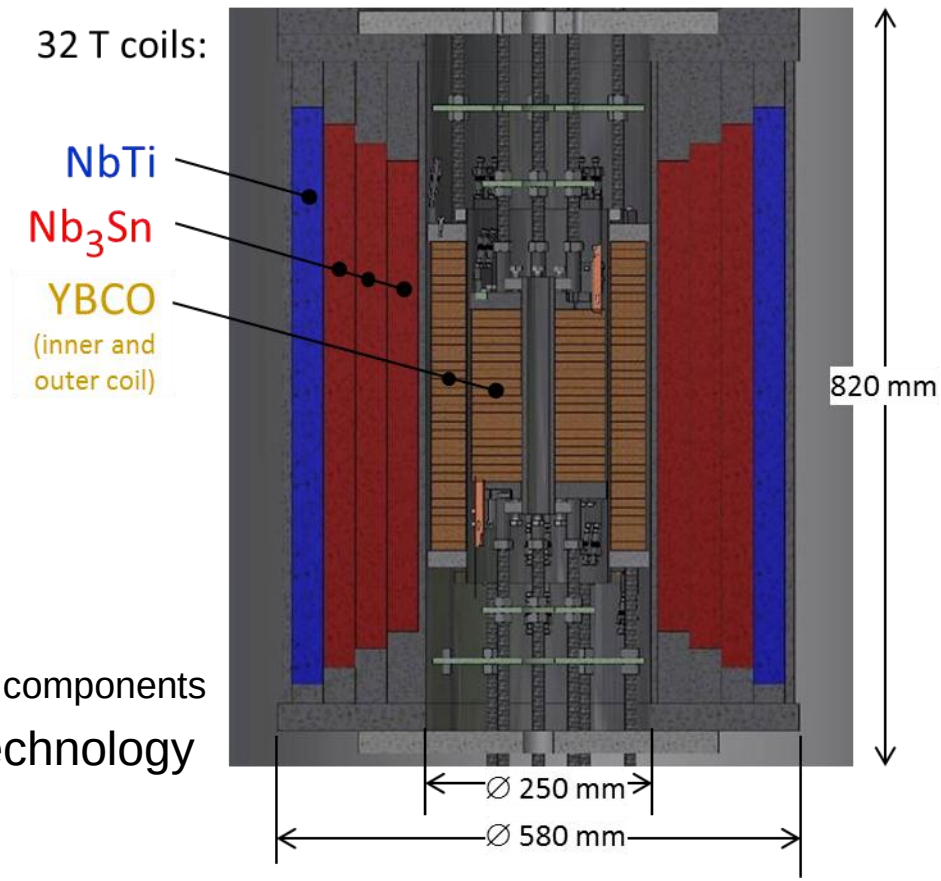
- Transform high-field magnet design by developing and integrating LTS and HTS technologies
  - 32 T technology won't be the last word, but should represent a break-through

  - HTS won't be a small add-on but ~ equal footing in ΔB in user magnet

    >> replacing inefficient Nb_3Sn coils>> more compact system

32 T User magnet

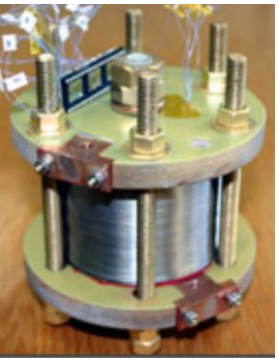
- Goal:
  - 32 T, 4.2 K, 32 mm cold bore
  - 500 ppm in 10 mm DSV
  - 1 hour to full field
  - dilution refrigerator <20 mK
  - 20 years of operation at NHMFL
- Funding:
  - $2M grant from NSF
    - for LTS coils, cryostat, YBCO tape & other components
  - Core grant for development of new technology
    - Cover grant shortfall
    - $8+M 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, potentially the first user

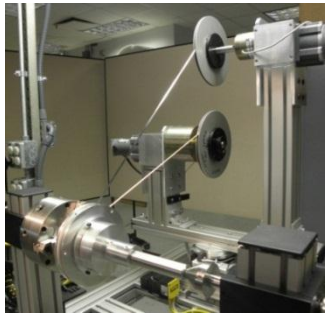


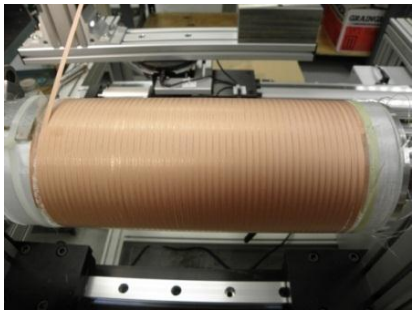
~600 H, 9 MJ

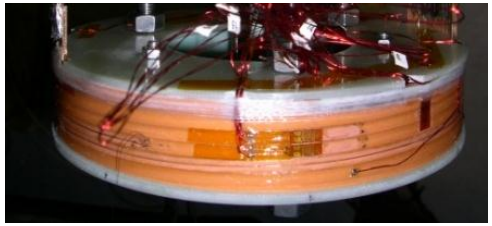
Timeline

2007	NHMFL test of SuperPower YBCO coil 19+8.6=27.8 T, J_{ave}= 259 A/mm^2
2008	NHMFL YBCO coil: 31+2.8T=33.8 T, J_{ave}= 460 A/mm^2
2009	Project awarded 2 M$ by NSF
2010	Technology exploration: layer winding, pancakes, insulation, quench analysis
2011	Test coils (1 and 6 modules), technology choices
2012	Rebuild test coil, detailed 32 T design, inner coil prototype (Test in December)







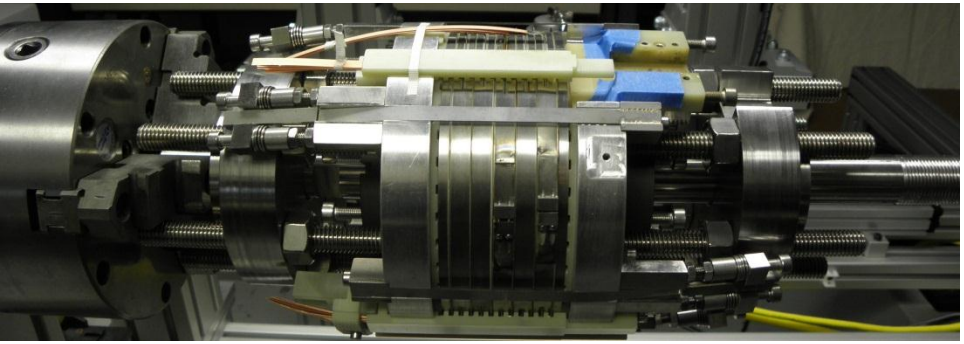


2007 2008 2009 2010 2011 2012

Timeline

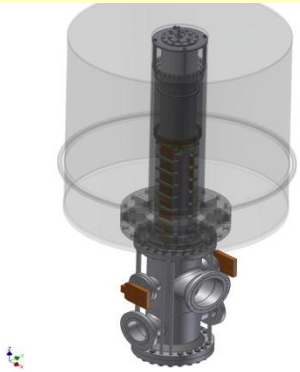
2007	NHMFL test of SuperPower YBCO coil 19+8.6=27.8 T, J_{ave}= 400 A/mm^2
2008	NHMFL YBCO coil: 31+3.4T=34.xT
2009	Project awarded 2 M$ by NSF
2010	Technology exploration: layer winding, pancakes, insulation, quench analysis
2011	Test coils (1 and 6 modules), technology choices
2012	Rebuild test coil, inner HTS coil prototype (test in December), ordered LTS outsert (OI)
2013	Outer HTS coil prototype, retest inner prototype, order HTS tape (SP), design review
2014	Build HTS coil set, LTS outsert arrives, system integration, test, user ops (best case)
2015	Completion in case of > 4 months delay

Inner prototype coil



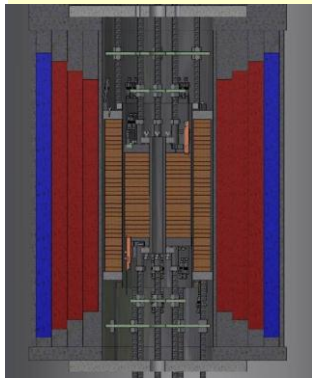
2012

Both prototype coils tested in 45 T outsert



2013

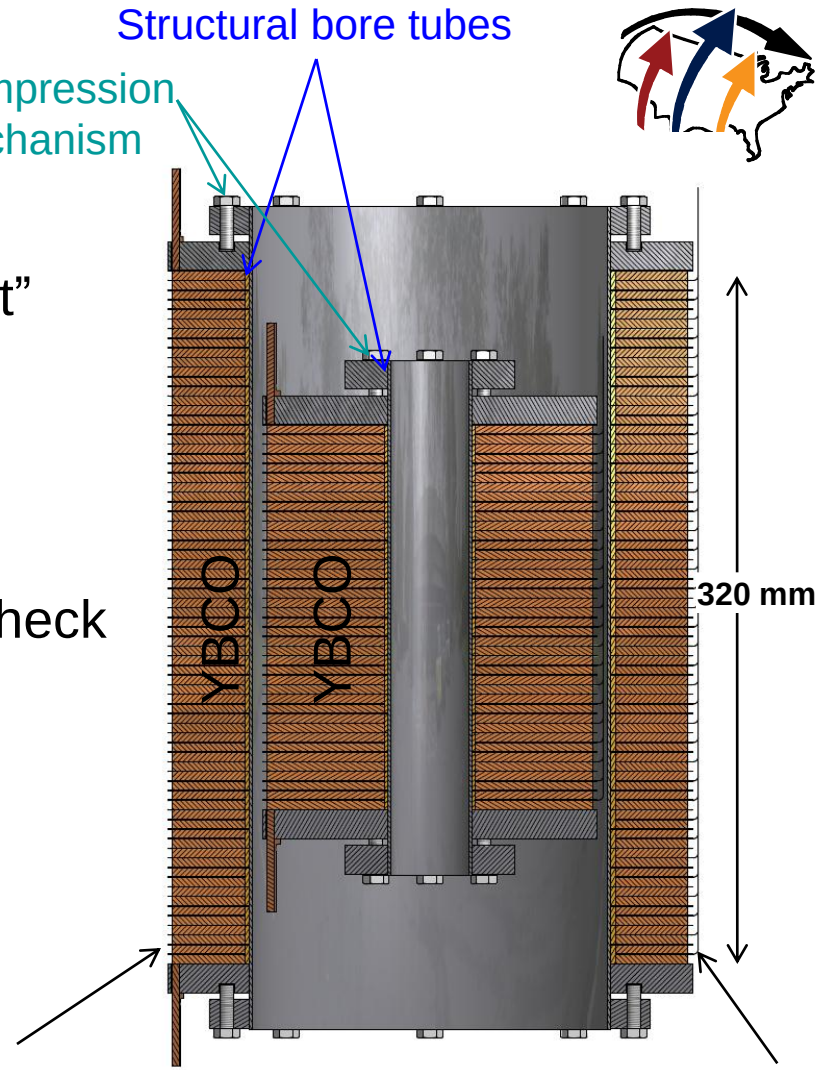
LTS+HTS assembly



2014

32 T Approach

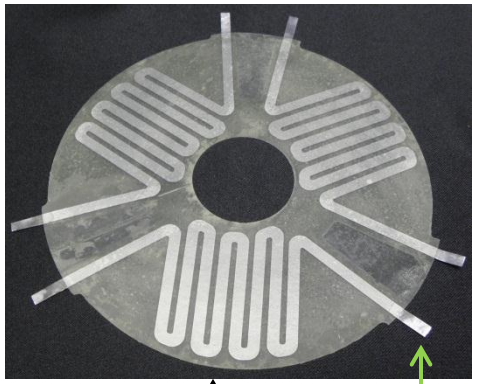
- Commercial Supply:
  - 15 T, 250 mm bore Nb_3Sn/NbTi “outsert”
  - cryostat
- In-House development:
  - 17 T, 32 mm cold bore YBCO coils
  - YBCO tape characterization & quality check
  - Insulation technology
  - Coil winding technology
  - Joint technology
  - Quench analysis & protection
- Choices 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

HTS Quench management

- Active quench protection heaters (NZP is slow but not zero, κ_{axial} a factor)
- Voltage based quench detection
  - 10 mV normal zones recover
- Refinement ongoing

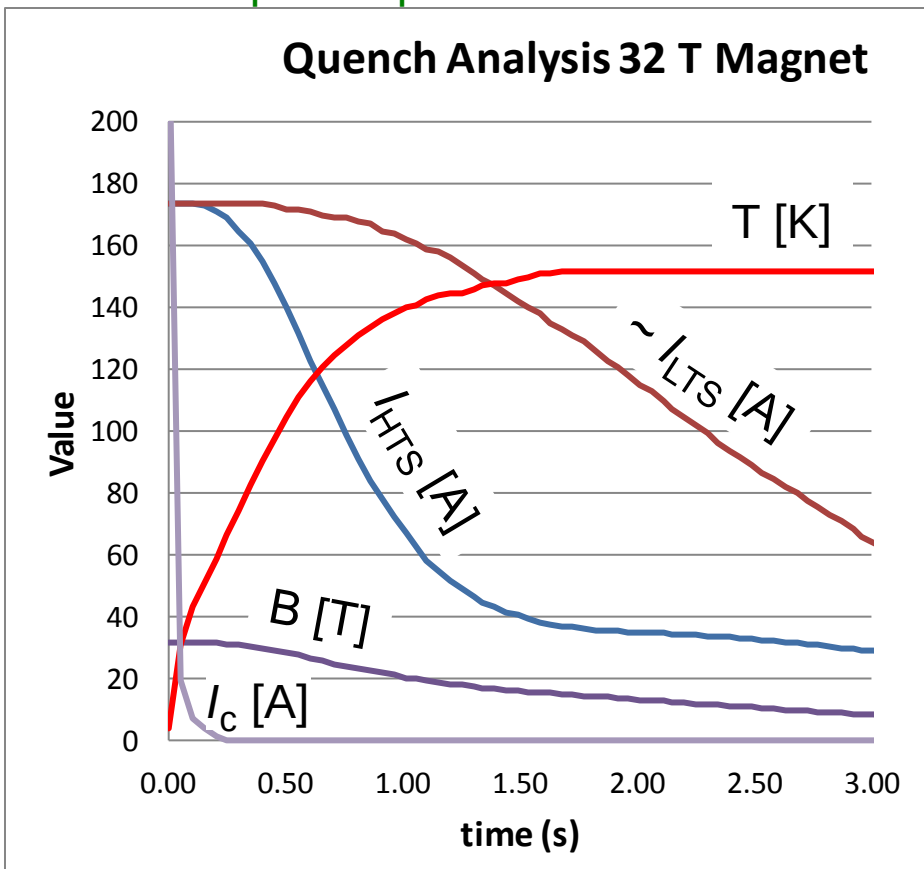


Heater element

Heater terminal tabs

Model for assembly practice

Example of quench code run result



Status

- Design is stable,
  - $I_{op} \leq 0.7 \cdot I_c$, $\sigma_{hoop} \leq 400$ MPa, J_{ave}=188 A/mm^2, J_{Cu} = 420 A/mm^2
- Coil winding, joint, cross-over, termination procedures well developed (updating and formal documentation ongoing)
- Insulation development complete
  - Commercial sol-gel Silica with added Alumina on co-wound stainless steel reinforcement tape (2-3 μm layer)
- Conductor characterization transitioning into Quality Assurance: (4 K I_c specifications, 14 parameters total)
- Repeated tests on sc. test coils in 20 T background
  - >100 dumps after quench initiation and quenches
- AC (ramp-) loss and Quench codes in use (underway)
- Outsert +cryostat is on order (OI, 21-30 months for delivery)
- Working on first of two prototype coils
  - (full-featured, radially full size, limited height)

Organization chart

Project leader
Huub Weijers

Meets every 4 weeks

Advisory board
Eric Palm, Denis Markiewicz (PI), Mark Bird, David Larbalestier (co-PI), Sheryl Zavion

Meets every 2 weeks

Operational board
Sheryl Zavion (Schedule oversight and budget tracking)
Denis Markiewicz (Fabrication)

4711
Conductor specification and purchase
Huub Weijers
- Denis Markiewicz
- Dima Abraimov

4712
Outer magnet
Huub Weijers
- D. Markiewicz
- Tim Murphy

4713, 4714, 4715
YBCO coil design & fabrication
4713: Prototype coils;
4714: 32 T coil fabrication;
4715: System integration;
Denis Markiewicz
- **Insulation** — Jun Lu
  - Hom Kandel
- **Drawings** — Scott Bole
- **20/70 schedule** — Zach Johnson
- **82/116 Test** — Patrick Noyes
- Adam Voran, Bill Sheppard, Brent Jarvis, Scott Gundlach, Zach Johnson, Michael White

4716
Conductor quality assurance, other characterization
Dima Abraimov
- Michael Santos?
- John Sinclair?

4718
Magnet power supplies
Scott Hannahs

4719
Cryogenic aspects
Hongyu Bai

tentative
Site prep
Ju-Hyun Park
- *Tim Murphy*

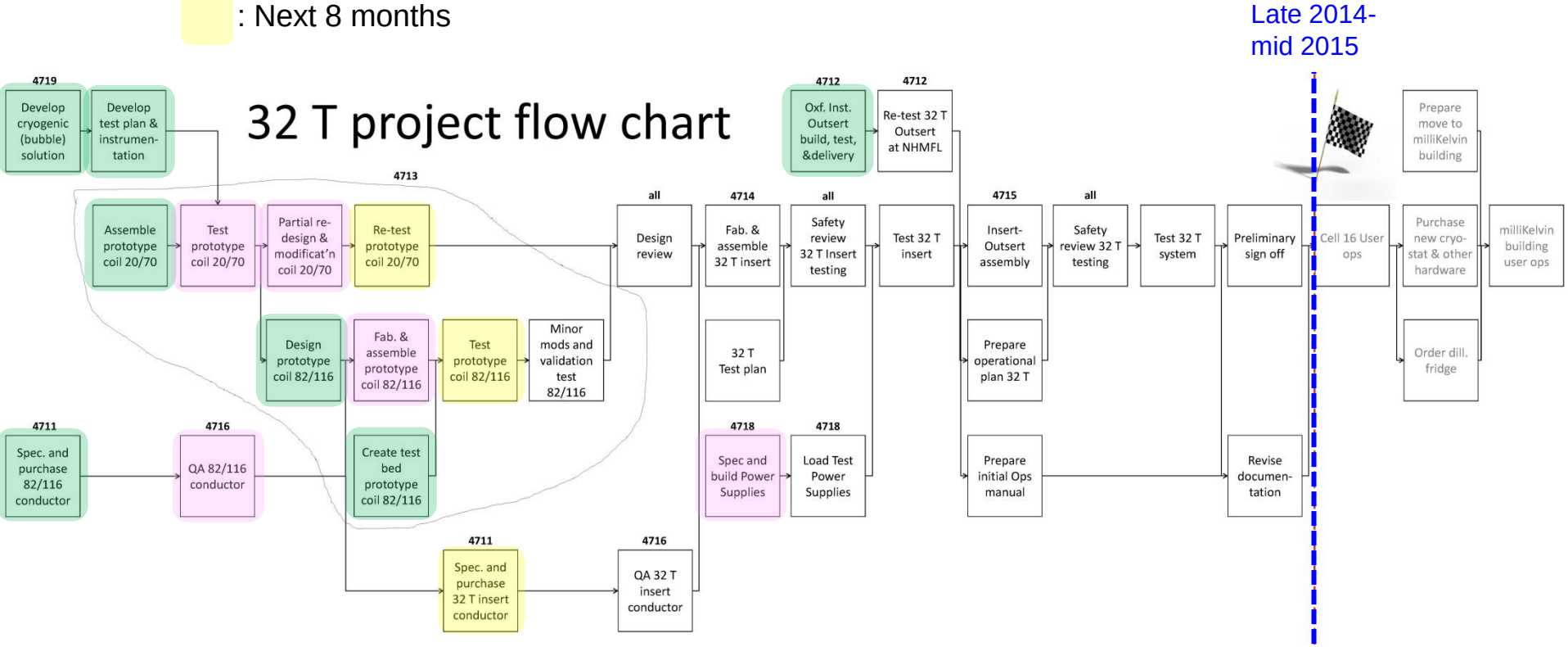
General resource pool
Dima Abraimov, Hongyu Bai, Matthieu Dalban-Canassy, Andy Gavrilin, Robert Goddard, Scott Gundlach, Ke Han, Scott Hannahs, David Hilton, Brent Jarvis, Jan Jaroszynskyi, Zach Johnson, Hom Kandel, David Larbalestier, Jun Lu, James Maddox, Denis Markiewicz, Lee Marks, Tim Murphy, Dustin McRae, Sarah Napier, Patrick Noyes, Eric Palm, Donny Richardson, Edward Rubes, Michael Santos, Bill Sheppard, John Sinclair, Ulf Trociewitz, Youri Viouchkov, Adam Voran, Bob Walsh, Huub Weijers, Michael White, Vaughan Williams, Carl Windham, Yan Xin, Sheryl Zavion, machine shop

Project flow chart
(August 2012 start date)

: Currently underway

: Next 4 months

: Next 8 months



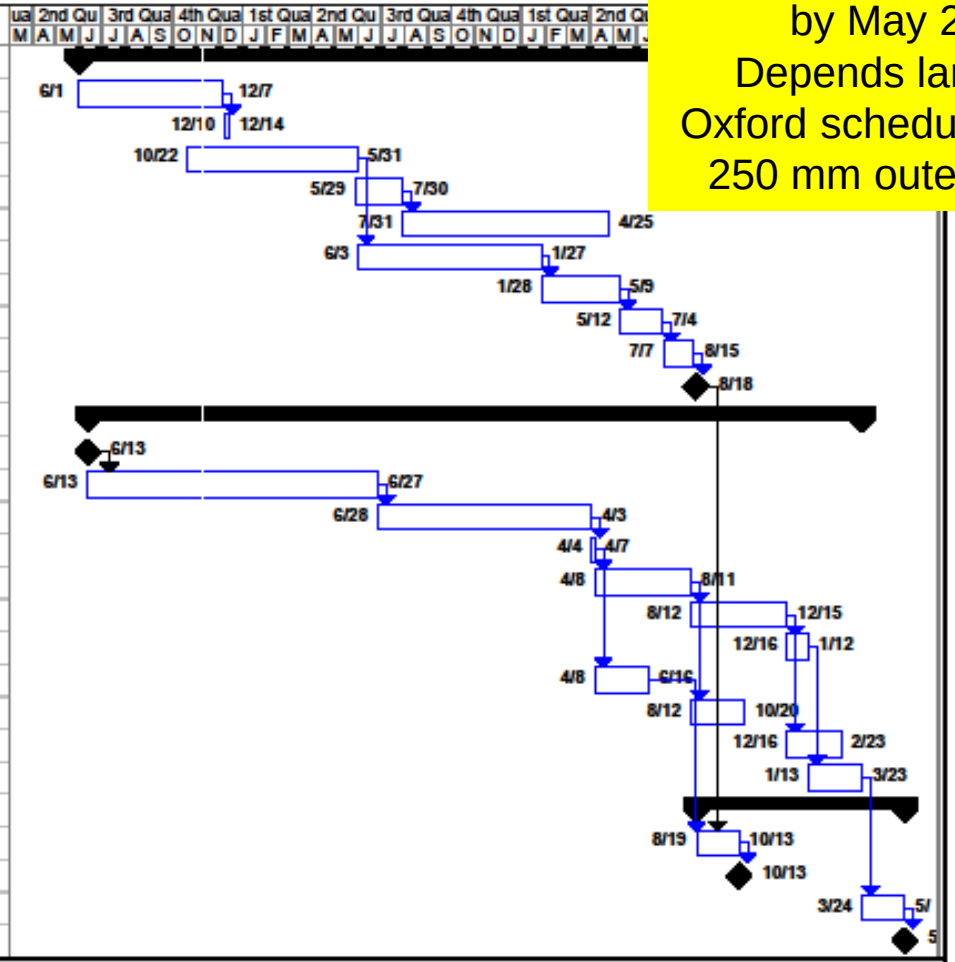
Each box represents a task
Workload per tasks varies

32 T Schedule

User Operation Expected by May 2015.
Depends largely on Oxford schedule for 15 T, 250 mm outer coil set.

32T HTS MAGNET PROJECT SCHEDULE

ID	Task Name
1	**HTS insert (Magnet Lab)**
2	Inner prototype (20/70) design and fab
3	Inner prototype (20/70) test
4	Outer Prototype Design, fab, Test
5	Finalize Tape spec and order
6	Fabricate REBCO tape
7	Review, detailed design & parts fab.
8	Winding of modules
9	Insert assembly
10	stand-alone test
11	Insert ready
12	**LTS Outsert**
13	Issue PO
14	Design outsert
15	Fabrication outsert
16	First factory test
17	1st replacement coil
18	2nd replacement coil
19	Negotiations if spec is not met
20	Earliest delivery and MagLab test
21	Delivery and MagLab test, one rebuild
22	Delivery and MagLab test, two rebuilds
23	Delivery after negotiations
24	**System integration**
25	Earliest possible assembly
26	Earliest possible test
27	Latest assembly
28	Latest test



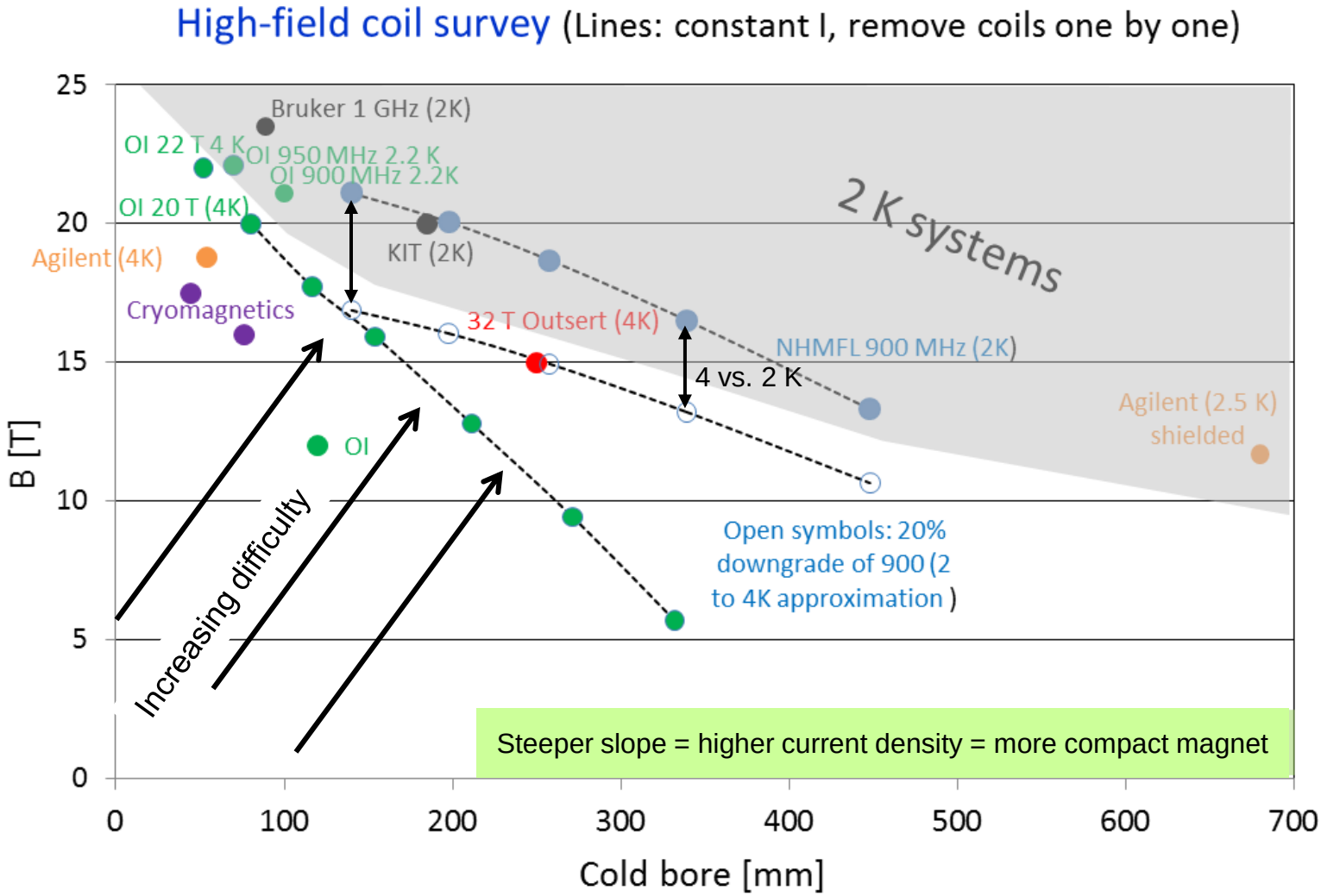
Project: 32T HTS COIL Plan_update_
Date: Fri 11/9/12

Task		Rolled Up Task		External Tasks	
Progress		Rolled Up Milestone		Project Summary	
Milestone		Rolled Up Progress		Group By Summary	
Summary		Split		Deadline	

Page 1

LTS magnet (i.e. outsert)

- 15 T in 250 mm is at boundary of previous 4 K systems



LTS magnet (i.e. outsert)

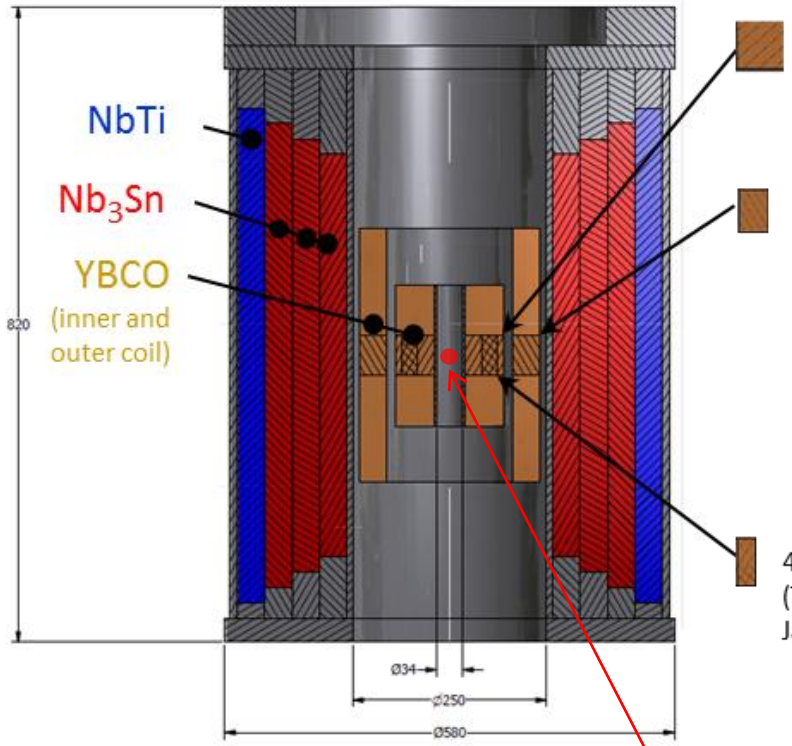
- 15 T in 250 mm is at boundary of previous 4 K systems
  - Challenging LTS technology as well
- Nb_3Sn conductor delivery is dominant factor in schedule
- HTS and LTS coils are coupled
  - Quench analysis on combined coil set needed
  - Quench field decay time constant > 3 sec for LTS
  - Quench field decay time constant ~ 0.5 sec for HTS
- Collaborative interaction with vendor (OI) required
  - Is starting up

Relative size of HTS coils

32 T coils

Prototype coils

10 km of
4 x 0.15 mm
REBCO tape



20/70 Inner prototype coil (under construction, 1st test in December 2012 — 0.9 km

82/116 Outer prototype coil (1st test scheduled for April 2013) — 1.5 km

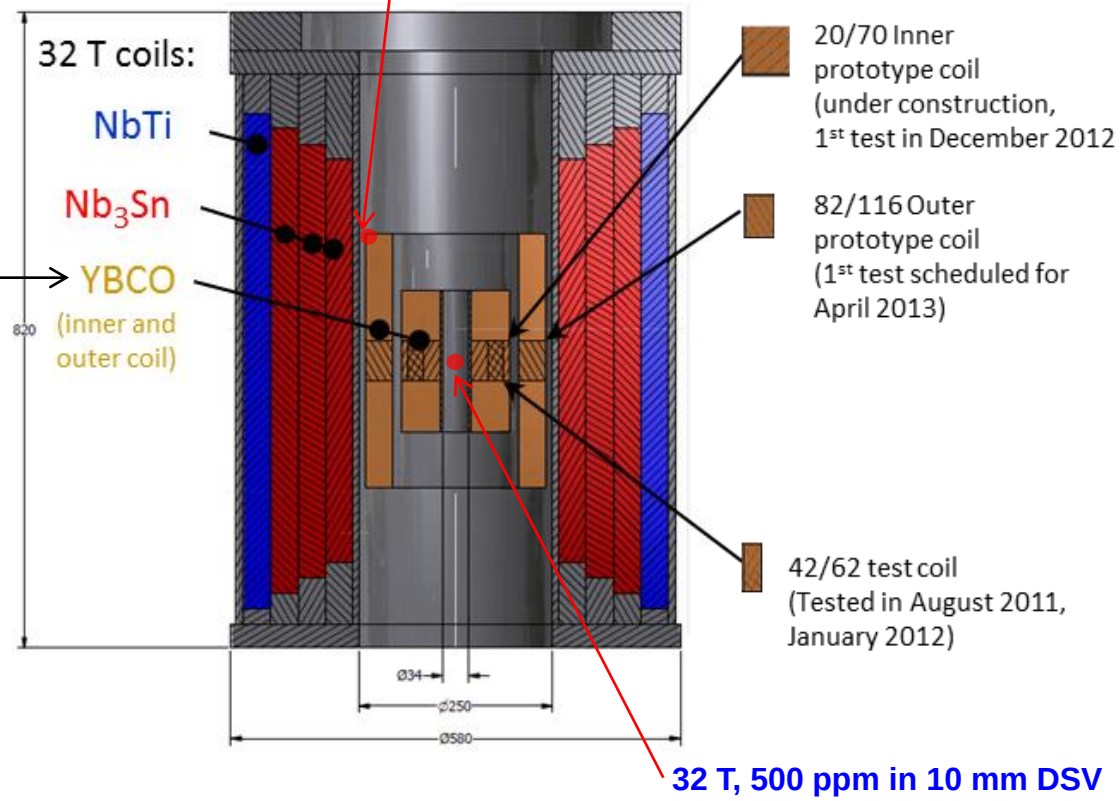
42/62 test coil (Tested in August 2011, January 2012) — 0.4 km

32 T, 500 ppm in 10 mm DSV

Critical aspects

Most restrictive condition: B = 16 T, angle ϕ = 18°

10 km of
4 x 0.15 mm
REBCO tape



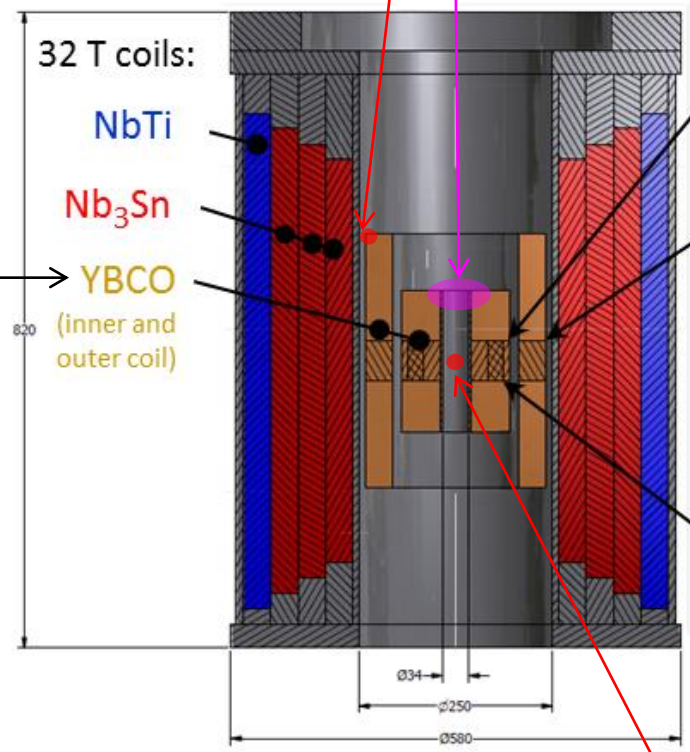
Critical aspects

Most restrictive condition: B = 16 T, angle ϕ = 18°

$-B_z{*}dB_z/dz_{max}$= ~5000 T^2/m: windings may be **poorly cooled** in area where $-B_z{*}dB_z/dz_{max}$ exceeds 2100 T^2/m

(gas bubbles get trapped)

10 km of
4 x 0.15 mm
REBCO tape



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32 T, 500 ppm in 10 mm DSV

Translation of these aspects to conductor specification follows

Conductor specification categories

- Geometrical properties
- Mechanical properties
- Electrical properties
  - Normal state properties
  - Superconducting properties
- Magnetic properties

→ + tolerances (uniformity)

- Environmental
- Traceability and records
  - Materials and production procedures
- Quality Control, Quality Assurance
  - Measurement techniques, procedures, standards
- Handling Non-conformity

Routine for LTS, breaking new ground for HTS conductors

Mind set

- Measurements cost real money
  - Balance cost of QA with cost of missing imperfections and potential repair
- Specifications must match vendors ability
  - And project needs
- Goal of specifications and QA measurements is
  - Not to drive vendors to new heights in I_c, or get "the best"
  - Obtain what is routinely proven possible and adequate (in test coils)
    - In large quantity
    - Predictable and uniform properties

Vendor task

Project task

Mind set

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    - In large quantity
    - Predictable and uniform properties

Vendor task

Project task

In most cases "typical" is good enough, but weeding out "non-typical" is critical

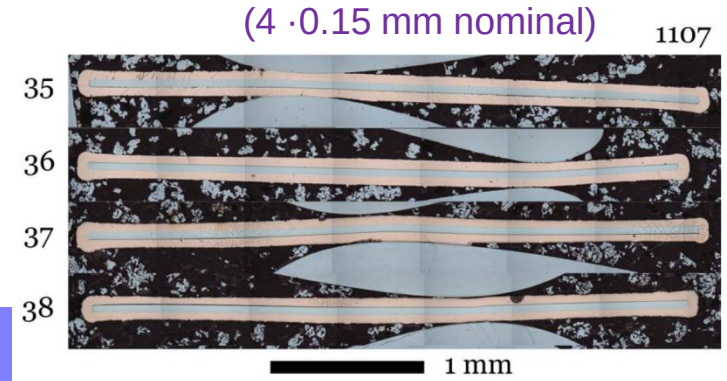
Geometrical spec

- Trapped He gas leads locally to poor surface cooling
  >> maximize thermal conductivity of windings
  >> Need good radial contact between turns
  >> Need good axial contact between pancakes
- Specify "flatness" of conductor (0 to +15 μm)
- Consistent width (±50 μm) over 10 km important for
  - Axial thermal conductivity
  - Transfer of axial loads in windings
  - Packing factor

Unprecedented precision for HTS conductors

Extensive interaction with vendor lead to
- Reduced burr and dogboning
- Much reduced variability in width
- Vendor ability now matches 32 T design values

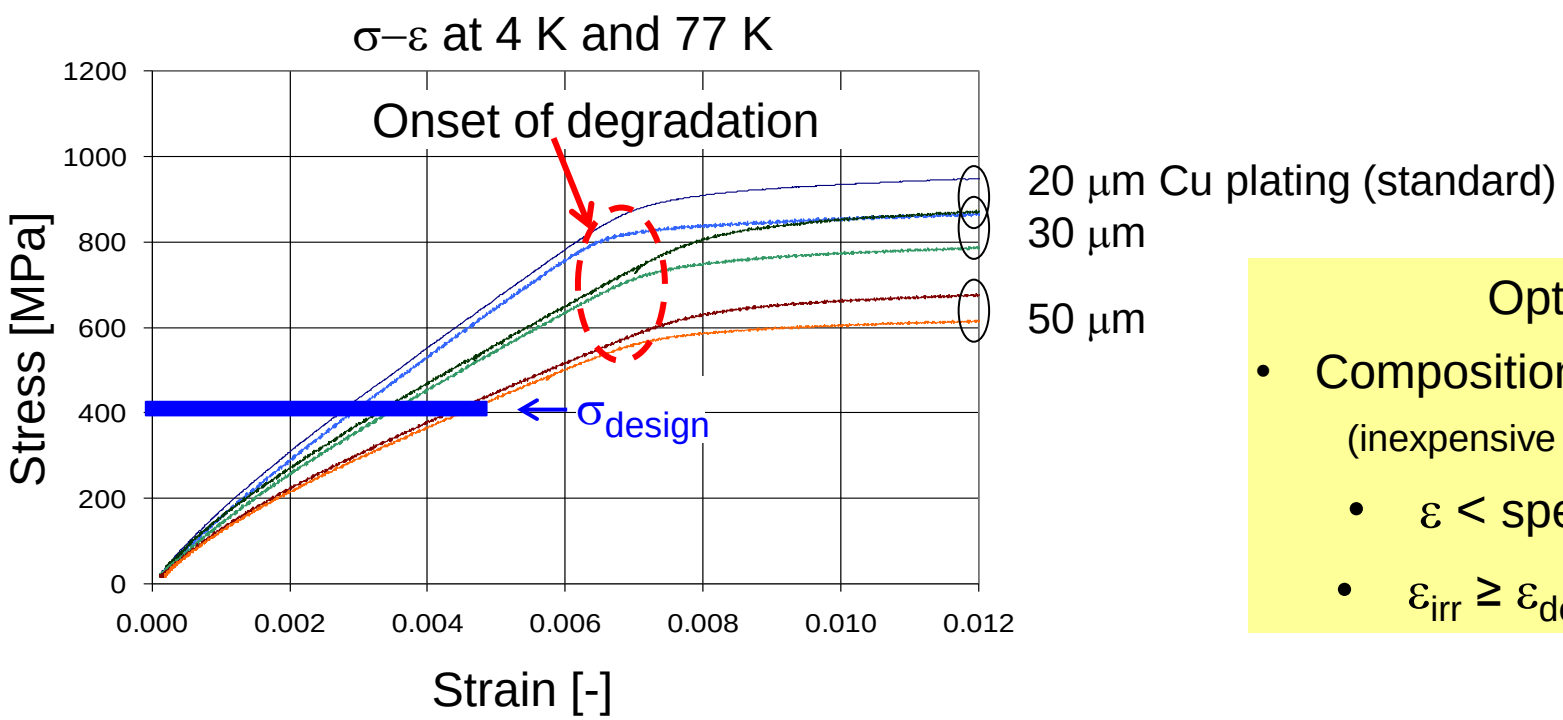
Conductors have varying dog-bone shape
(4 ·0.15 mm nominal)



Pancakes need to be firm, flat and consistent in width

Mechanical

- Mechanical properties
  - Tensile stress-strain-(I_c), √
  - Reversibility range, √
  - Transverse compression, (can't test on individual conductor > no spec)
  - Transverse tension (delamination), (bypass problem with dry coil, no spec)
  - Tolerance to bending√, twisting, etc.



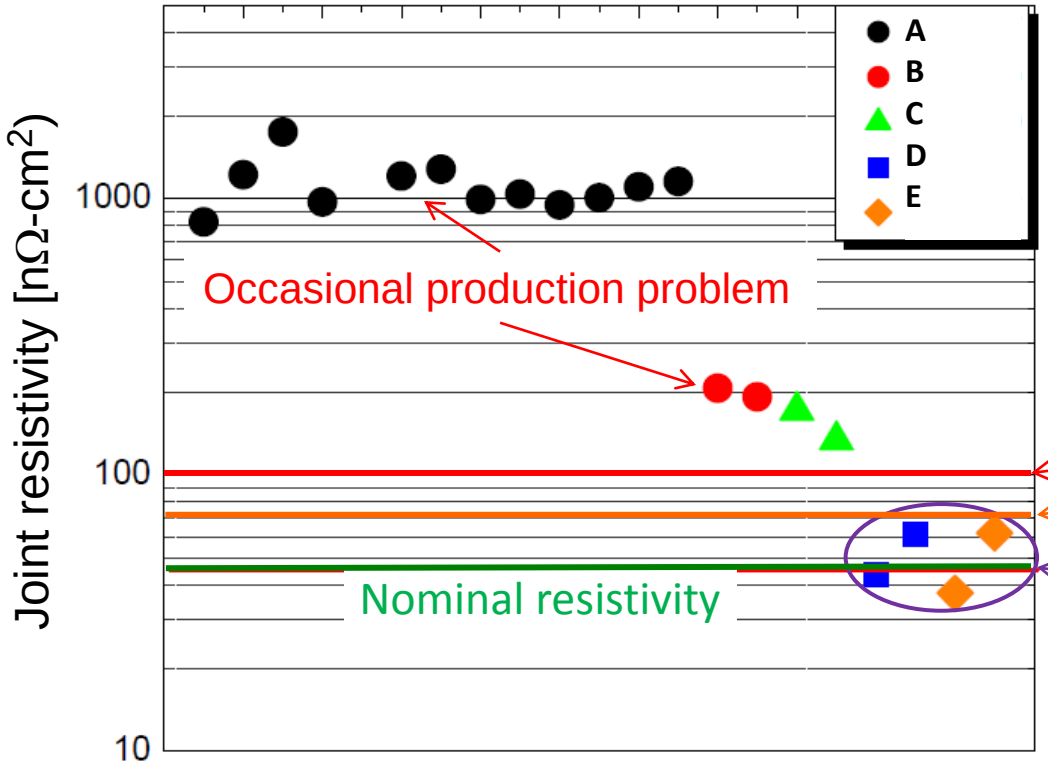
Options:

- Composition and hardness (inexpensive and adequate)
  - ε < spec at σ_{design}
  - $\varepsilon_{irr} \geq \varepsilon_{design}$+margin

Rather than measure stress-strain on each piece length, we rely on material composition certification and "half-hard"

Electrical -Normal state

77 K, self-field data



32 T will have 170 joints:

- 112 joints internal to DP module
- 54 cross-over joints between modules
- 4 terminal joints

170 joints at 70 nΩ-cm^2 >> 0.1 Watt

32 T Specification:

Maximum for *single* joint

Maximum for *average* of all joints

(test joints for every piece length)

Most conductors we tested

77 K joint testing is relatively easy, inexpensive and adequate predictor

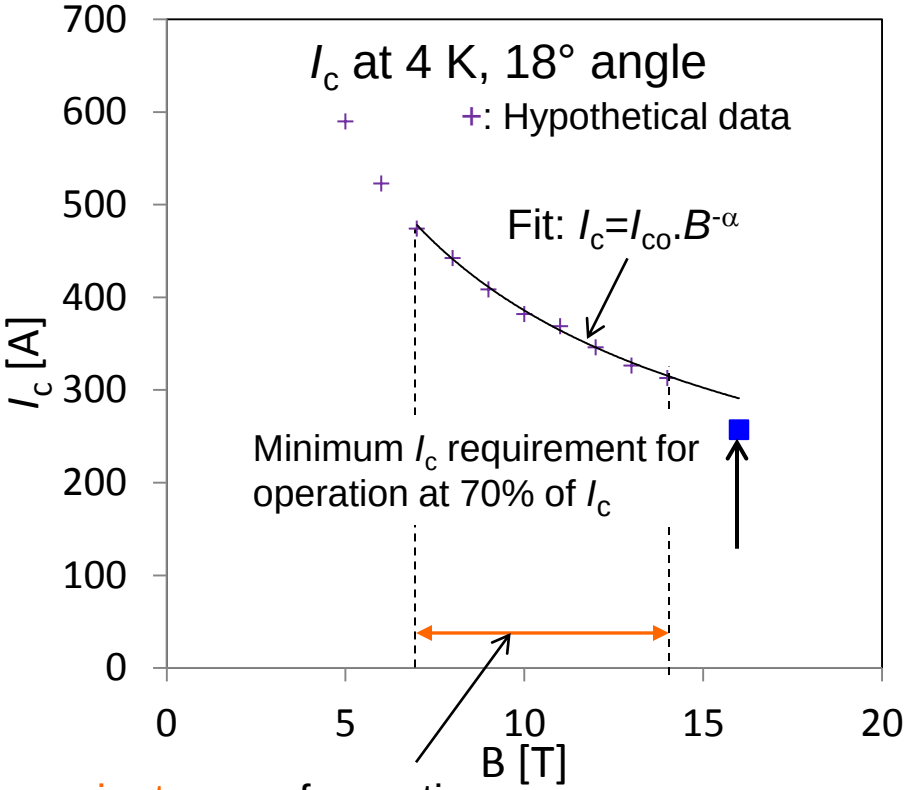
Electrical - Superconducting

- Superconducting properties
  - $I_c(B,T,\varepsilon,\phi)$, n-value
  - AC–loss (B-H curve, ramp rate loss): not independently variable >> **no spec**
  - ab-plane inclination

↓

Helium boil off

Electrical -Superconducting
I_c specification



Convenient range for routine measurements at NHMFL

77 K Self-field data (provided) is a weak indicator of 4 K, high-field performance

>> 4 K I_c specification

QA: no reel-reel capability >> sampling only,

Vendor can **not** do routinely 4 K sampling
- We do with dedicated setup
- Unusual but effective arrangement

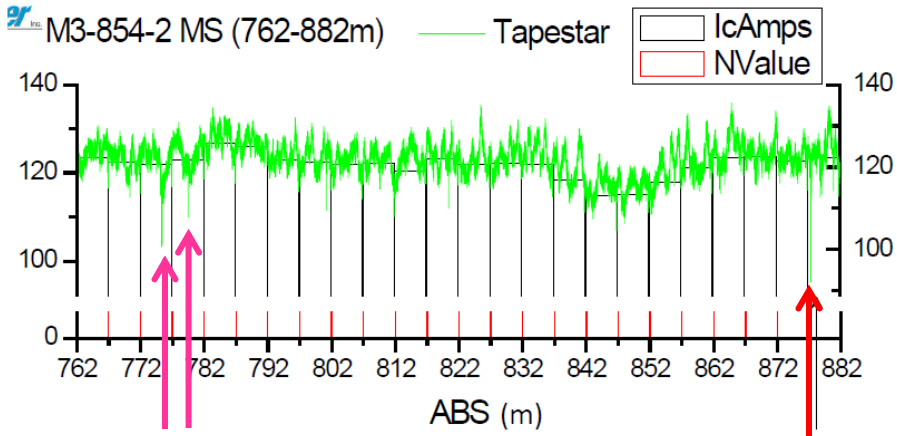
Most restrictive condition in 32 T magnet

Extrapolation of measured I_c between 7 and 14 T at **4 K**, **18°**, to **16 T** must exceed target
(2 samples per piece length)

Most of conductor in 32 T in less severe conditions: grading

Electrical –Superconducting Uniformity

Data courtesy of SuperPower



Not detected with LANL device ("Yatestar")

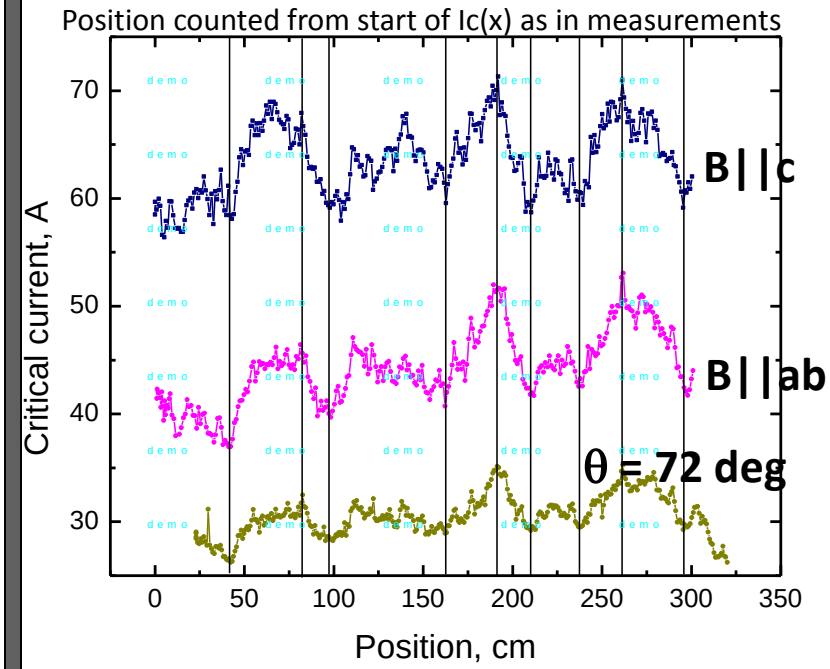
Used in section of coil where quenches originate

Tapestar:

- Magnetization-I_c corresponds well to transport I_c over 5 meters at 77 K
- High through-put
- Spikes may or may not correlate to physical realities

"Yatestar"

- Transport I_c per 2 cm
- T = 75 K (LN_2) B = 0.5 T, …..variable angle
- Low throughput



System constructed at LANL – Yates Coulter

Comparison of reel-reel data on single 3-m conductor piece at 77 K:

- Similar size oscillations, differ in "spikes" (and B)
- Correlation to absolute 4 K in-field I_c is weak, but *does uniformity correlate*??>**no spec**

Specification for 32 T prototype

Represents > 2 years of negotiations and collaborations

SOP: Standard Operating Procedure.

Item	Requirement	Measurement Method	Sampling frequency	Report	By
Superconductor type	YBCO coated conductor				
Total amount	1.54 km				
Minimum piece length	14 pieces of ≥110 meters	Vendor SOP	Each piece	Actual values	Vendor
Minimum I_c at 4.2 K, 17 T and 18°	256 A	Extrapolation of data at 4.2 K, 7-14 T, 18°	2 samples per piece	Actual values	NHMFL
Resistive transition index for above	> 25	Linear fit to log-log data	2 samples per piece	Actual values	NHMFL
Final conductor width	4.10±0.05 mm		2 samples per piece	Pass / fail	Vendor, NHMFL
Final conductor thickness	154 μm nominal, 180 μm max per tape, 170 μm mean overall	Needs specifying, NHMFL: Image analysis	N samples per piece	Pass / fail	Vendor, NHMFL
YBCO *ab*-plane orientation	Indicate orientation of *ab*-planes	SEM visualization. (Cu, Ag chemically etched)	1 sample each, first 6 tapes	Confirm	NHMFL, Vendor
Substrate cross-sectional area	0.200 ± 0.01 mm^2 (nominal 4 by 0.05 mm)	Image analysis	≥10% of pieces	Pass /fail	NHMFL
Substrate material	Hastelloy C276, half hard	Composition certificate	Each piece	Pass /fail	Vendor
Ag cap layer thickness	2.0±0.5 μm on YBCO side, seal all YBCO	Image analysis	≥10% of pieces	Pass /fail	NHMFL
Cu Stabilizer cross-sectional area	0.41 (-0%, +5%) mm^2 (nominal 50 μm per side)	Image analysis	≥10% of pieces	Pass /fail	NHMFL
RRR of stabilizer	> 50	RRR_procedure_Abraimov	≥10% of pieces	Actual values	NMHFL
Surface condition	No surface penetrating scratches, grease-free	Vendor SOP	Each piece	Pass /fail	Vendor
Joint resistivity	100 nΩ.cm^2 max per joint, average 70 overall	Vendor & NHMFL SOP Default 80 mm lap joint.	1 sample per piece	Actual values	Vendor, NHMFL

Summary for HTS Specification

- 4 K magnet conductor specifications come in many categories and relate to many features
- Consistent width and thickness are important for thermal conductivity of winding pack of 32 T magnet
  - Tight specifications
  - Interaction with vendor required to reach acceptable levels
- For I_c, 4 K spec is necessary
  - At most demanding field angle in design
  - NHMFL to measure
- For joint resistance, 77 K spec is fine
- For strength rely on composition certificates
- 32 T project will use an unprecedented 14-parameter specification
- How to address 4 K uniformity in I_c?
  - 4 K sampling plus 77 K reel-reel data
  - Better understanding desirable

32 T Project Summary

- 32 T all-sc user magnet project is transformational in scope
- Design is stable, technologies largely developed, choices made
- Critical HTS technology test via inner prototype coil is imminent
- Milestones reached:
  - Committed to the design
  - LTS Outsert ordered
  - Agreement with vendor on REBCO conductor specification
- Risks (technical and schedule)
  - Helium bubble solution not proven yet
  - Scale-up of quench protection heater system
  - Lack of 4 K reel-reel characterization, link with 77 K properties unclear
  - LTS magnet may need Nb_3Sn coil rebuilds before meeting spec
  - Unknown unknowns
- Schedule
  - Both LTS outsert and HTS insert on critical path
  - Best case late 2014 completion, foreseeable potential issues: mid-2015