NATIONAL HIGH
MAGNETIC
FIELD LABORATORY

Construction and Test of the NHMFL 32 T Superconducting Magnet

Update for WAM-HTS Barcelona, February 15-17, 2017
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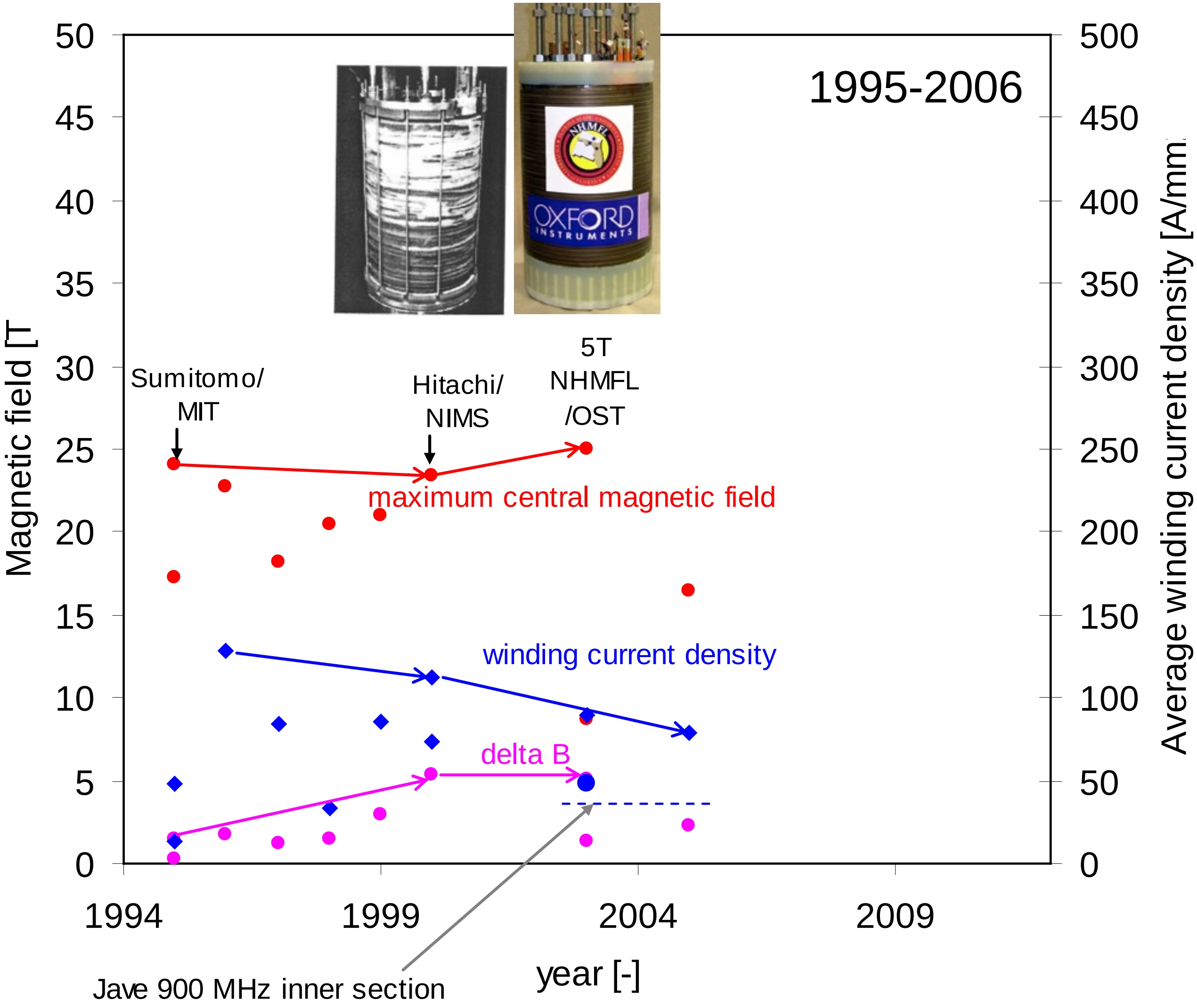
H.W. Weijers, December 12, 2016

H.W. Weijers, W.D. Markiewicz, A. J. Voran, S.R. Gundlach, Y.L. Viouchkov, A.V. Gavrilin, P.D. Noyes, T.A. Painter, B. Jarvis, W. R. Sheppard, G. Sheppard, D.V. Abraimov, D.K. Hilton, and T. P. Murphy, all NHMFL

Outline

- Introduction
  - Historical context
  - 32T Concept
  - Brief comparison with selected other projects
- Prototype phase
  - Goals and results
  - Key lessons and unfinished business
- Conductor
- Construction of the 32 T magnet
- Test
  - Results so far
  - Outlook
- Summary

Introduction – The first HTS insert coils (2006)



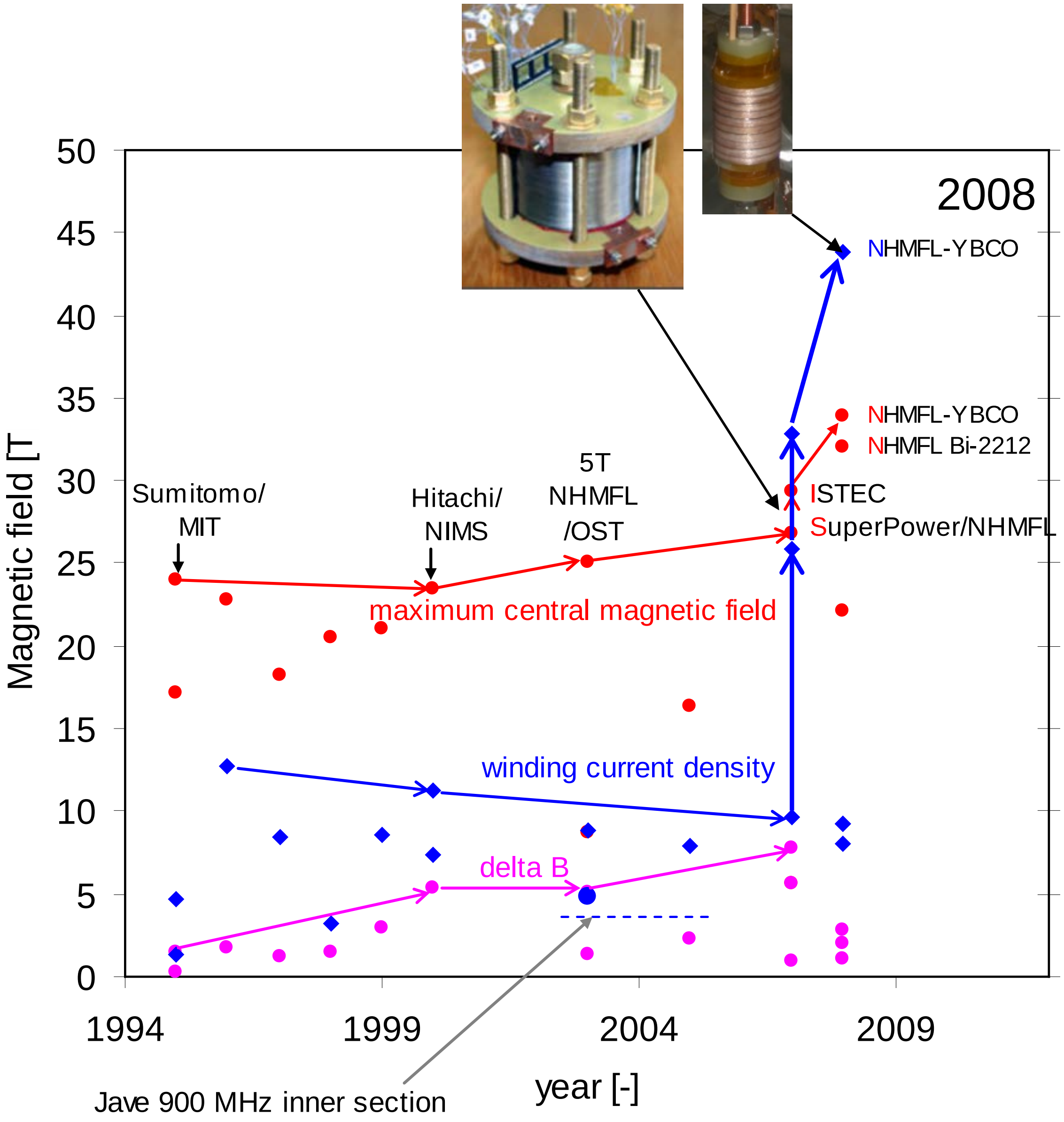
After a decade of BSCCO coil development

- Coil size and delta *B* ↗
- B_{peak} still ~ 24-25 T
- $\sigma_{peak} \leq$ 125 MPa
- J_{ave} ↘ <100 A/mm^2

- 22.3 T/ 950 MHz LTS NMR in operation
- 23.5 T / 1.0 GHz LTS NMR in development

- Little enthusiasm left for HTS insert coils at 100 A/mm^2 for 25 T
  - Except NIMS 1.02 GHz

Introduction – The first REBCO insert coils (2008)



After a decade of BSCCO coil development

- Coil size and delta B ↗
- B_{peak} ~ same
- $\sigma_{peak} \leq 125$ MPa
- J_{ave} ↘ <100 A/mm^2

First few REBCO coils

- Coil size ↓, delta B ↑
- B_{peak} ↑↑ 34 T
- J_{ave} ↑↑ $>>200$ A/mm^2
- $\sigma_{peak} > 200$ MPa

- 30 T HTS-LTS magnet now seems feasible
- Conductor immature

(Developed for power applications)

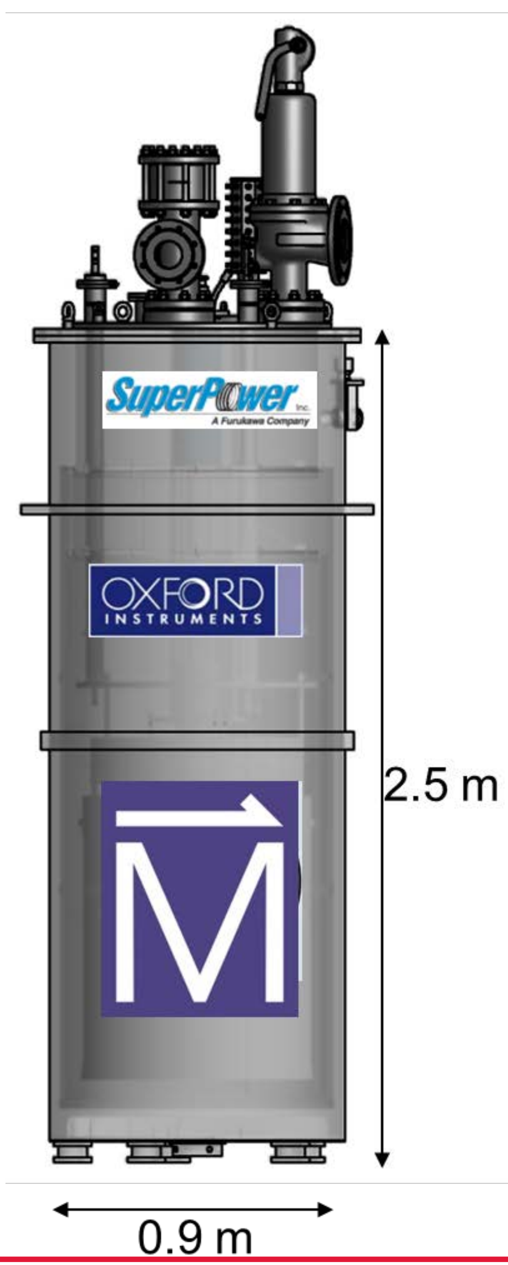
Introduction – 32 T Concept

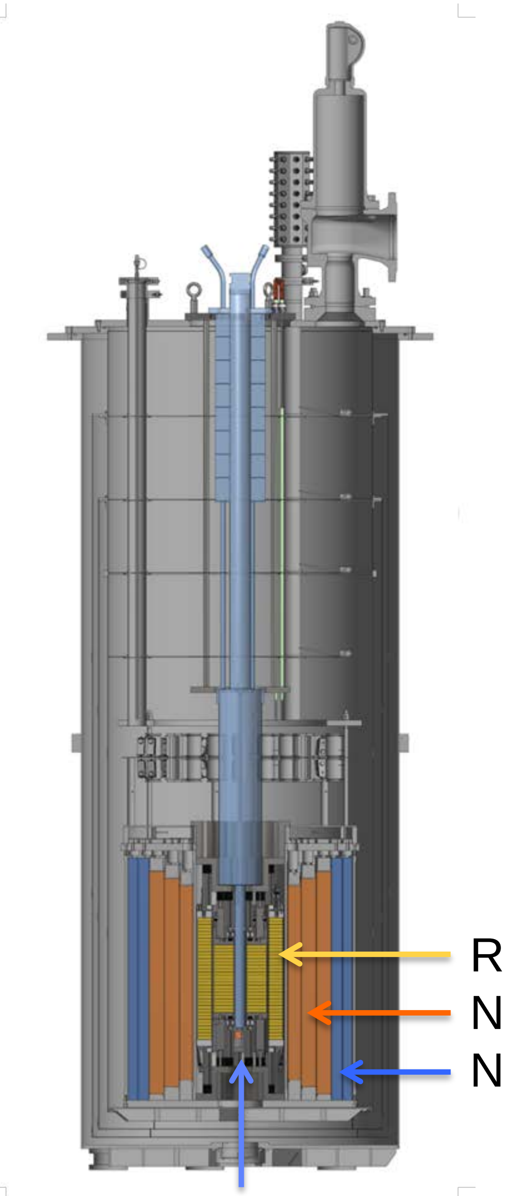
(2009)

- User magnet for 20 years of materials research
  - Target above 30 T, bore of at least 32 mm desirable
  - Ramp to field in one hour
  - Modest uniformity
- 200 A/mm^2 in the windings
  - Generic target for reasonably compact 30T class magnets
  - This was aggressive and unprecedented at the time for a user magnet
- Conventional Copper current density levels
- Not aggressive in strain
  - Relative to critical strain
- Operation at no more than 70% of I_c
- 15 T LTS outer magnet, separately and concurrently developed *by industry*
  - Higher J_{ave} in LTS windings below ~15 T
  - At 250 mm bore, a challenging magnet in its own right
- Simple 4.2 K helium bath
- Conductor specification must meet routine capability of vendor

The 32 T magnet: a user magnet

(2011)





REBCO: 2 double pancake coils

Nb_3Sn

NbTi

Dil. fridge or VTI

Key parameters:

Center field	32 T
Clear bore	34 mm
Ramp time	1 hour
Uniformity 1 cm DSV	5×10^{-4}
Operating temperature	4.2 K
Stored energy	8.3 MJ
Expected cycles/20 years	50,000
System weight	2.6 ton

15 T / 250 mm bore LTS magnet

17 T / 34 mm bore REBCO coils

Separately powered, simultaneously ramped

LTS Outsert for 32 T

(2012)

Specifications

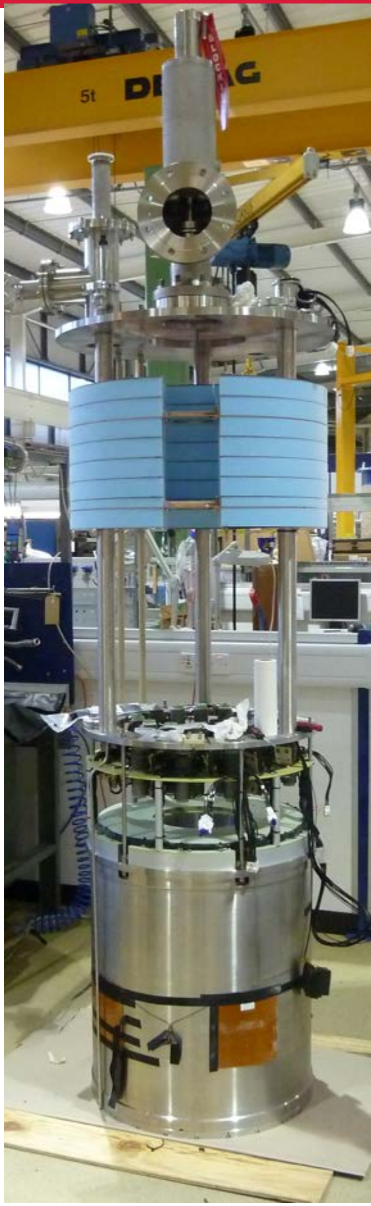
- 15 T, 250 mm bore, 4.2 K
- One hour to full field
- Radial field component < 1.5 T over HTS coil volume
- Must be tolerant of HTS insert coil quench
  - Note: HTS quench behavior unknown at the time of order
- LTS quench must not destroy HTS coil

Required Collaborative effort

- Especially on quench management

Outcome

- 5-coil NbTi + Nb_3Sn magnet
- Passive + active quench protection
- 268 A operating current for 15.0 T
- Rated at 15.3 T stand-alone
- 294 H self inductance
- 7.0 MJ stored energy



Completed Outsert at Oxford Instruments (2014)

32 T Parameters

(2013)

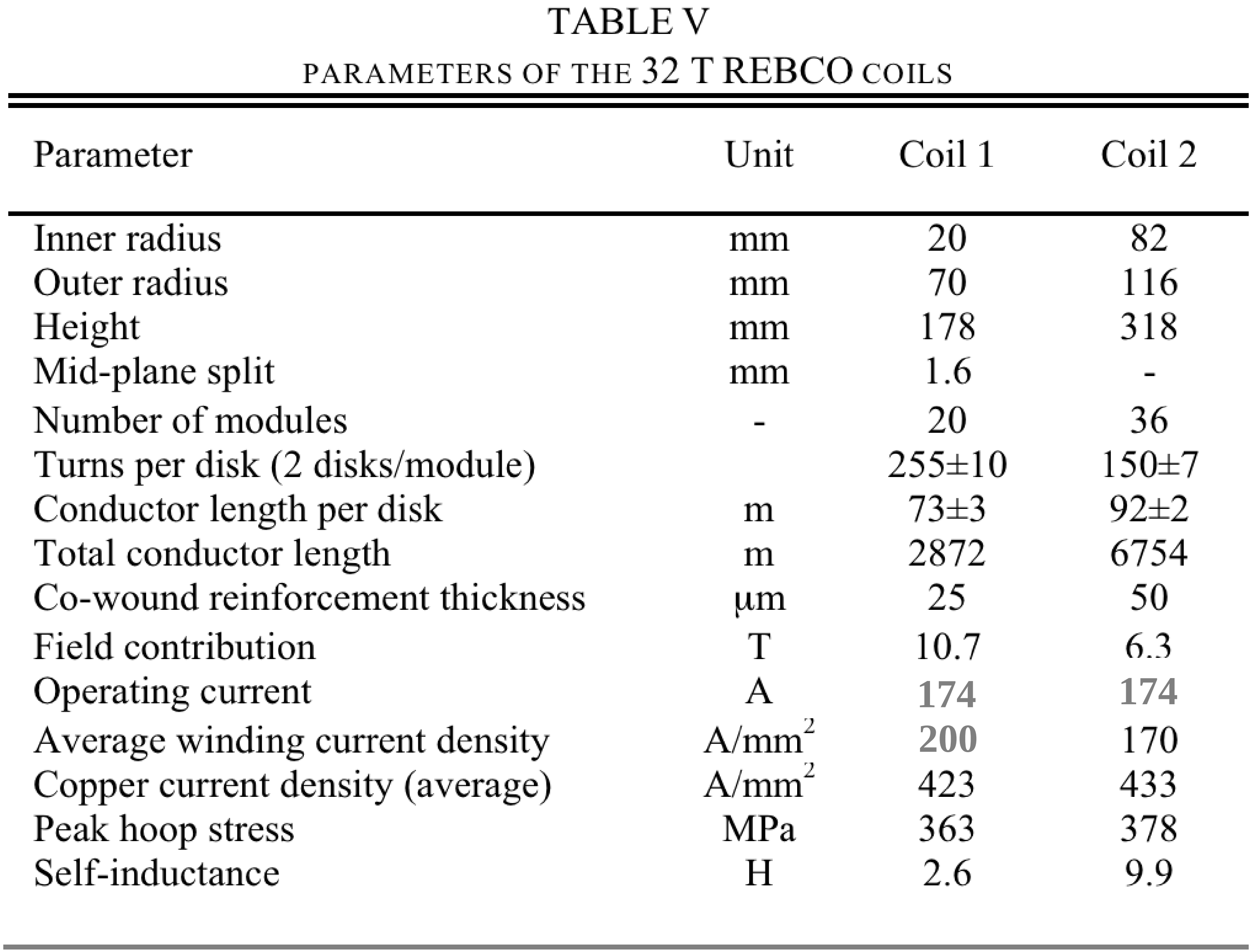


TABLE V
PARAMETERS OF THE 32 T REBCO COILS

Parameter	Unit	Coil 1	Coil 2
Inner radius	mm	20	82
Outer radius	mm	70	116
Height	mm	178	318
Mid-plane split	mm	1.6	-
Number of modules	-	20	36
Turns per disk (2 disks/module)		255±10	150±7
Conductor length per disk	m	73±3	92±2
Total conductor length	m	2872	6754
Co-wound reinforcement thickness	µm	25	50
Field contribution	T	10.7	6.3
Operating current	A	**174**	**174**
Average winding current density	A/mm^2	**200**	170
Copper current density (average)	A/mm^2	423	433
Peak hoop stress	MPa	363	378
Self-inductance	H	2.6	9.9

32 T and selected other projects for perspective

Project	Group	Type	delta B [T] HTS / LTS	HTS	Jave [A/mm2]	ID/OD/height [mm]	Opera -tional	Comment
32 T	NHMFL	User magnet	17 / 15	REBCO	200	40/140/178	2017?	Insulated
				REBCO	170	164/232/320		
25 T Cryofree	Tohoku	User magnet	10.6 / 14	(REBCO) Bi-2223	103	96 / 278 / 389	2016	Insulated
28 T NMR	Bruker	User magnet	??	??	??	??	??	??
28 T Demo	RIKEN	Demon-stration	11.5 / 17.1	REBCO	371	40 / 68 /210	-	27.6 T record
				Bi-2223	164	81 / 125 / 384		
Muon collider solenoid	Brook-haven	Demon-stration	15+ / 0	REBCO	539	25/91/64	-	No insulation
26 T NI	Sunam/ NHMFL	Demon-stration	26 / 0	REBCO	404-221	35/172/ 327	-	No insulation
30.5 T NMR	MIT	User magnet	18.8 / 11.7	REBCO	547	91 /118 / 324	2018/ 2020 ?	No insulation
				REBCO		151 / 168 / 392		
				REBCO		196 / 210 / 466		

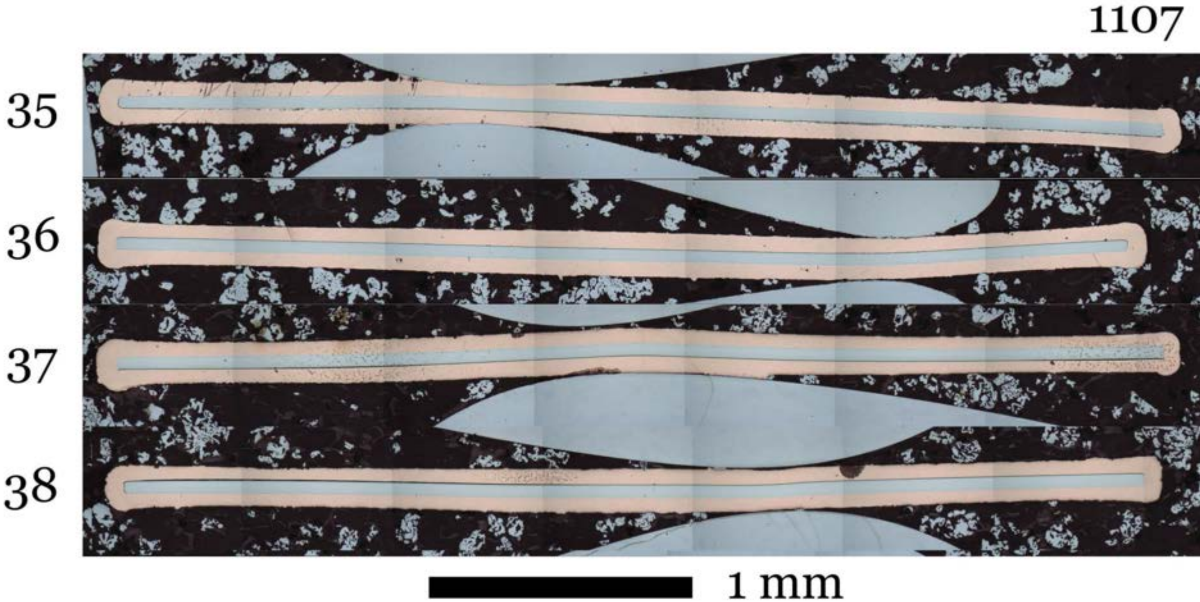
Test coil and prototype coil phase: new technology (2013)

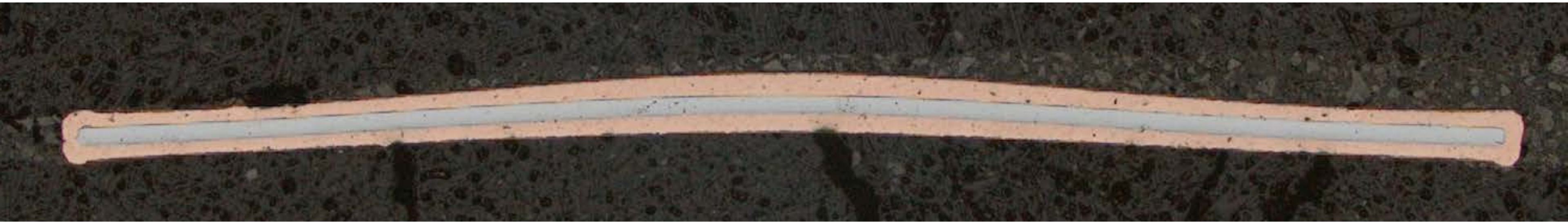
Key topics to resolve:

- Construction
  - Winding, joints, terminals, cross-overs, reinforcement

- Dog-boning: ~12% void in windings
- Thickness (and Cu-area) variability with non-standard 50 μm plating target
- Pre-2013: width variability

Abraimov led conductor evaluation effort





Test coil and prototype coil phase: new technology (2013)

Key topics to resolve:

- Construction
  - Winding, joints, terminals, cross-overs, reinforcement

- Stagnant "Helium bubble"
  - At - $B_z \cdot dB_z/dz > 2100\ T^2/m$: downward magnetic force on helium gas (bubbles) exceeds buoyancy (few % of HTS volume: near top & inner diameter of coils)
  - Expect locally $10^4\ T^2/m$: Poor cooling in part of HTS coil for lack of liquid helium
  - Radial thermal conductivity is poor in windings as well

  - Coil design focus on
    - Radial conductive elements just above windings
    - Axial thermal conductivity of windings: flat pancakes!

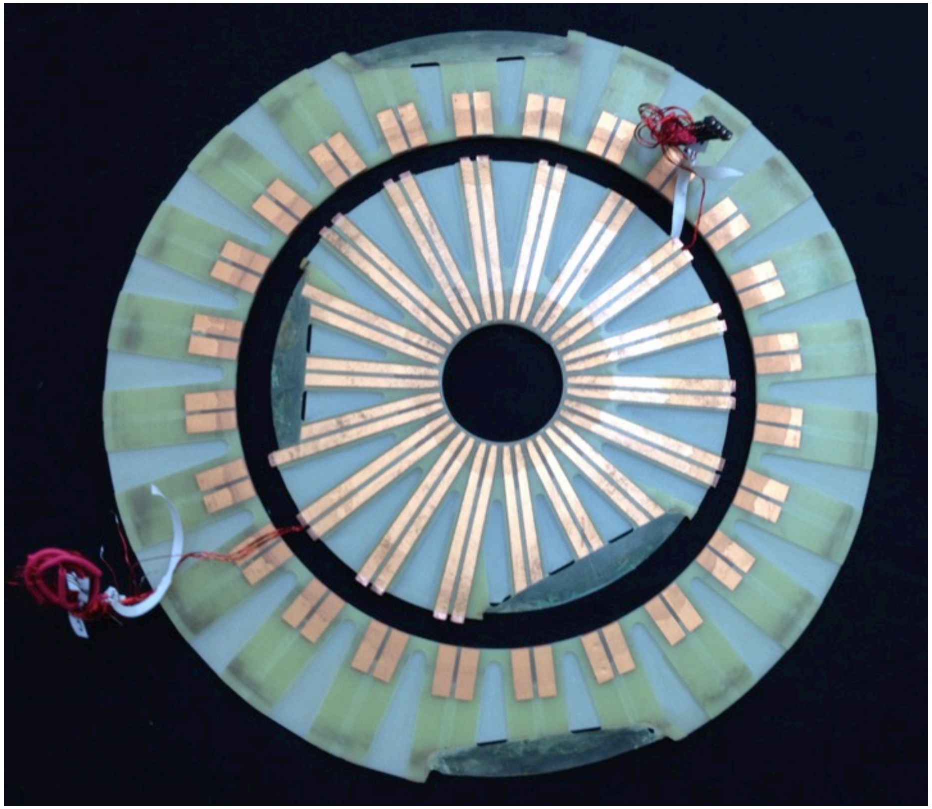
Pre-2013:
Width variations causing uneven surface: ± 100 μm

Since 2013: ± 10 μm: flat!

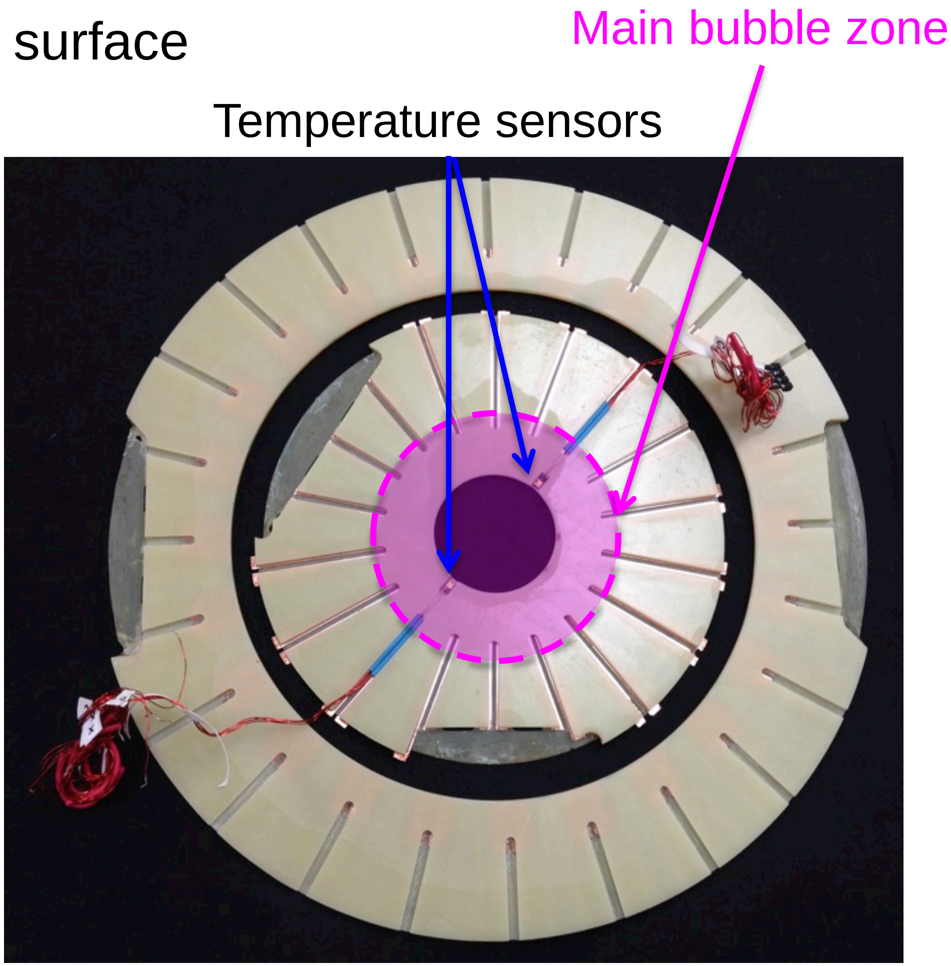
Test coil and prototype coil phase: new technology (2013)

32 T Cooling disks with

- Embedded radial Cu strips and
- Helium channels on top and bottom surface



Bottom, facing windings, thin G-10 cover



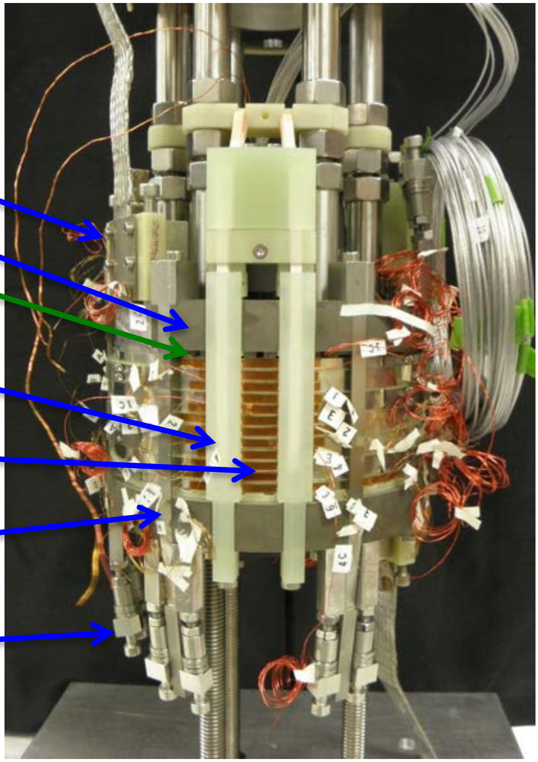
Top, facing top flange

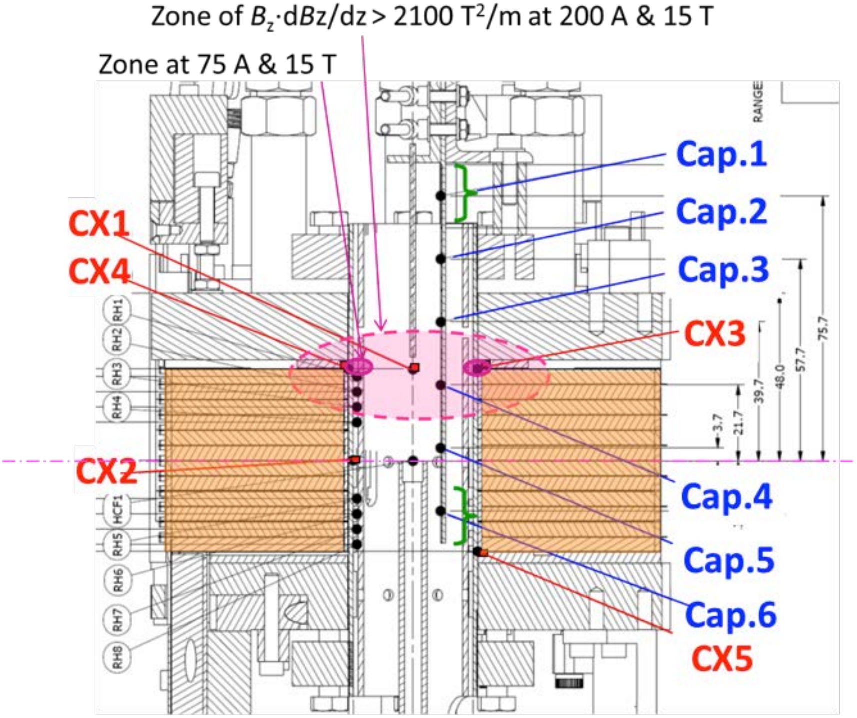
Prototype coil 20/70 in 15 T background

(2013)

Coil cross section with bubble region in pink

- Top terminal
- Top flange
- Cooling disk
- Cover for quench heater wiring
- 6 modules / 12 pancakes
- Axial compression strap
- Tension mechanism for strap





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

- Capacitive sensors confirm the bubble forms as expected
- Temperature sensors confirm the temperature remains ~4.2 K

Test coil and prototype coil phase: new technology (2013)

Key topics to resolve:

- Construction
  - Winding, joints, terminals, cross-overs, reinforcement
- Stagnant “Helium bubble”
  - At - $B_z \cdot dB_z/dz > 2100$ T^2/m: downward magnetic force on helium gas (bubbles) exceeds buoyancy
- Quench detection
  - Conventional approach with balanced voltage taps & 100 mV threshold adequate
- Quench protection
  - Active quench heaters
  - Numerical simulation tools with “HTS physics”

Quench, what to worry about?

32 T has a separately powered LTS and HTS circuit

- First worry is an LTS quench causing a stress peak in HTS

If a REBCO coil is designed with any reasonable I_c margin:

- The temperature margin is large, much larger than LTS equivalent
  - No spontaneous HTS quenches

- Worry first about preventing damage causing a quench
  - Stress-concentrations in windings, terminals, joints, conductor delamination
- Then worry about preventing the quench causing (more) damage

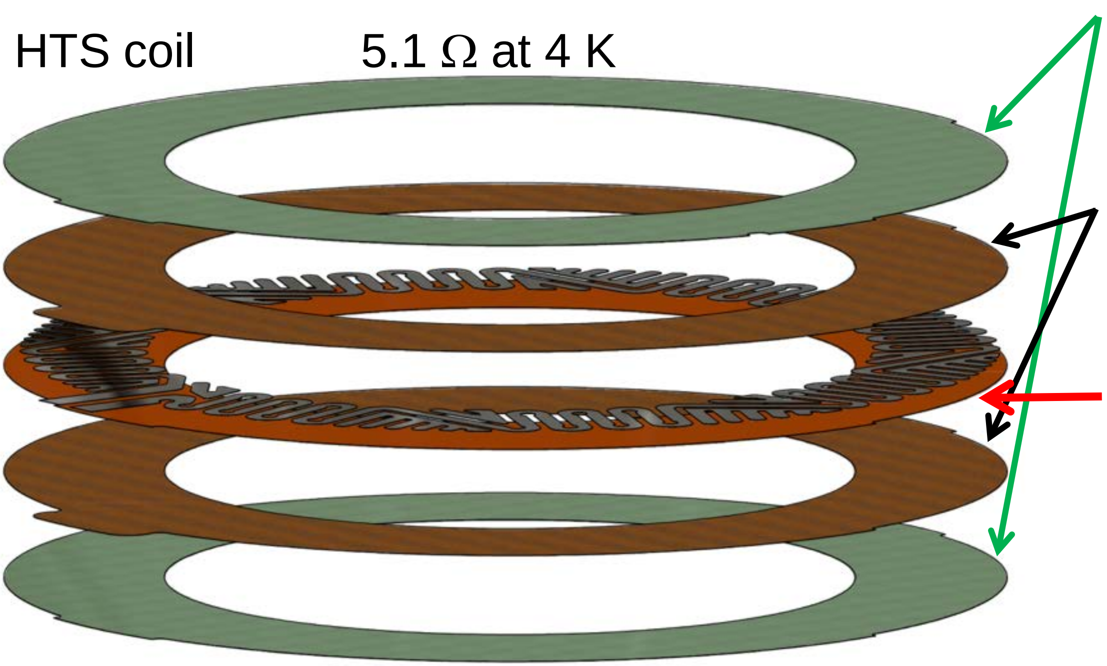
HTS: root problem is damage causing a quench, not the other way around*

*: if there is any I_c margin in the magnet design

Quench Protection Heater Assembly

(2013)

Outer HTS coil 5.1 Ω at 4 K



Epoxy Fiberglass G-10

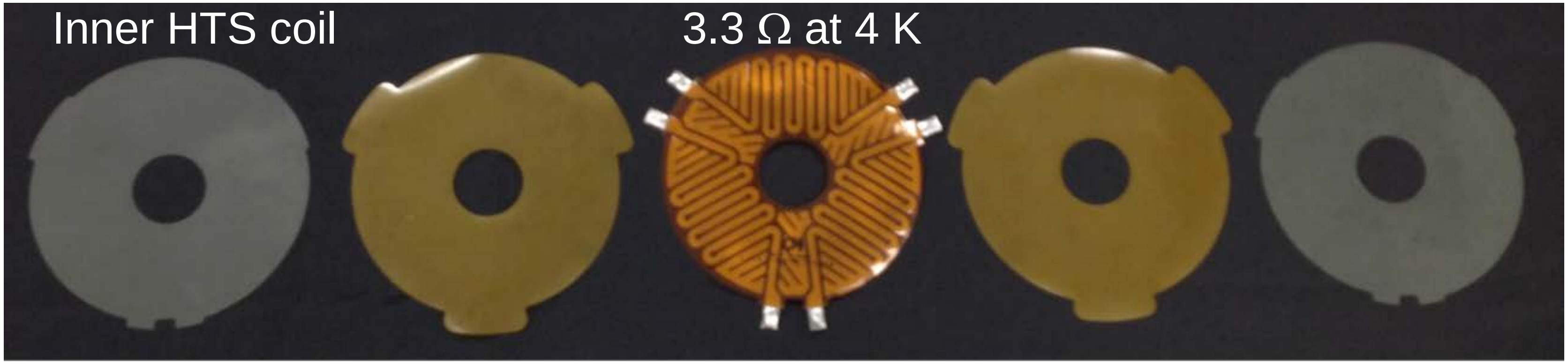
Mechanical strength

Kapton

Insulation

Heater assembly

- Steel element
  Power, temperature
- Kapton
  Insulation



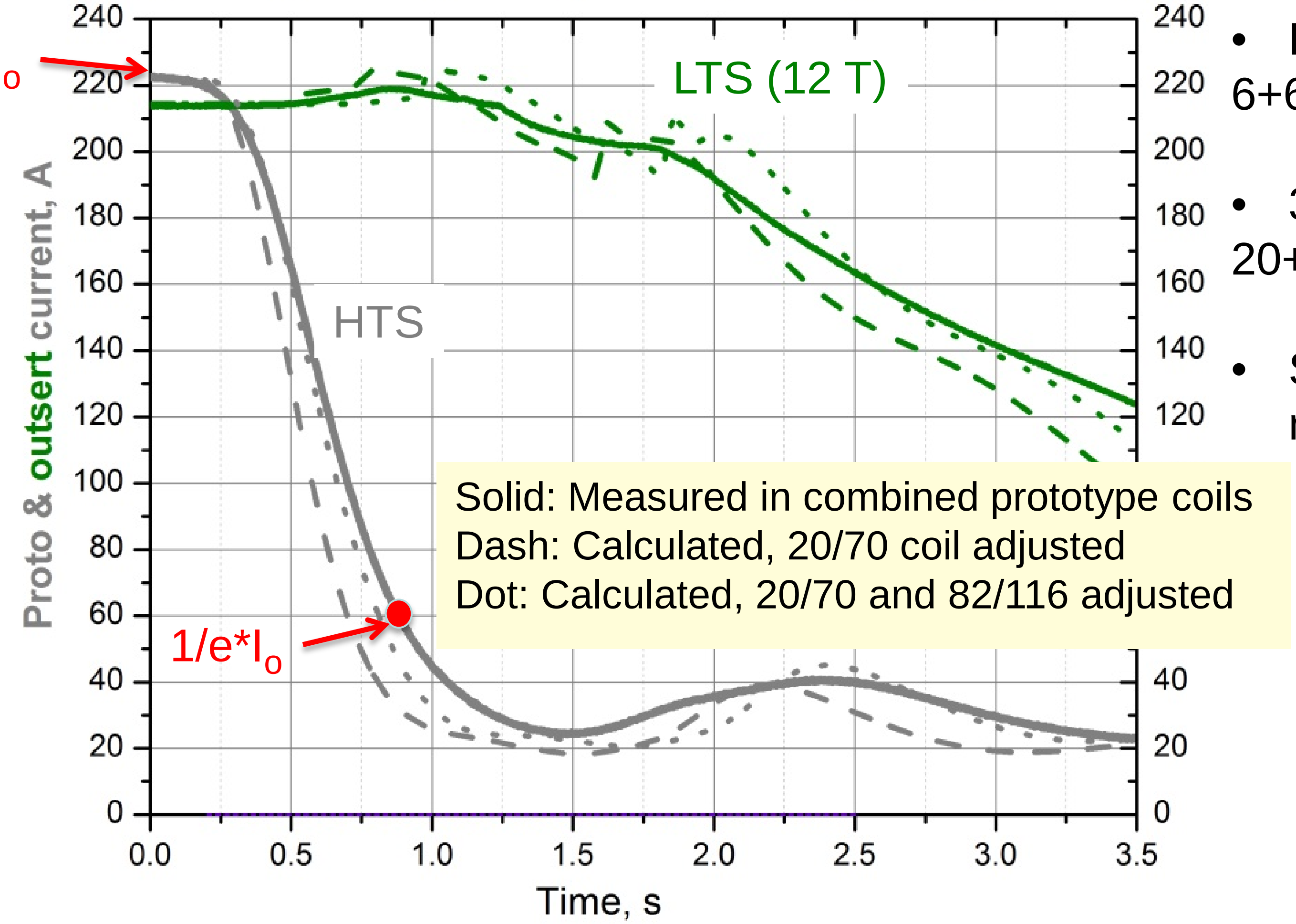
Prototype phase experimental goals (2013)

- Quench heater performance
  - Quench initiation, coil protection with dump resistor
- HTS Quench protection
  - Discharge HTS stored energy using only quench heaters
- Quench simulation
  - Generate sufficient data to benchmark quench simulation code
- HTS + LTS quench protection
  - Determine behavior of LTS coils during HTS quench
  - Quench LTS (manually) and protect HTS with quench heaters
- Load cycling
  - Meet and exceed design stress values repeatedly
  - Mostly tests terminals, joints, reinforcement etc.
- AC-loss
  - Measure helium boil-off while ramping

We did all that, and generated 27 T all-superconducting demonstration magnet record

Quench data and simulation

(2015)



Solid: Measured in combined prototype coils
Dash: Calculated, 20/70 coil adjusted
Dot: Calculated, 20/70 and 82/116 adjusted

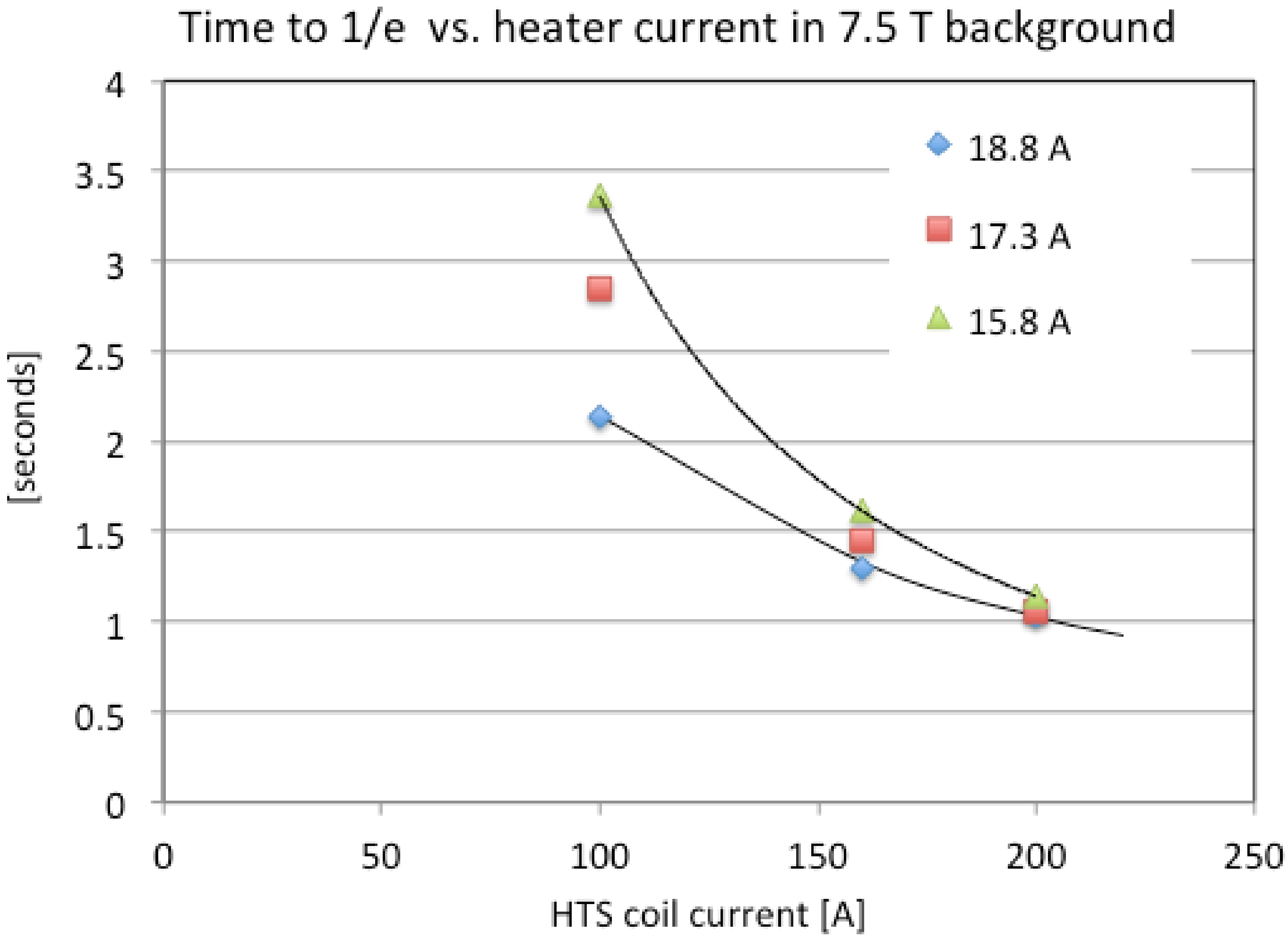
- Prototypes:
  6+6 double pancakes
- 32 T:
  20+36 double pancakes
- Same 15 T LTS magnet

- Quench heaters effective
- Simulation is sensitive to I_c variations within variability of short sample data
  - Especially for oldest conductor (~2012) in the 20/70 prototype coil
  - Would like to have more $I_c(B,\text{angle})$ data in 10-50 K range on recent full-width samples

Quench heater performance

(2015)

Case of HTS quench only



- HTS decay time sensitive to quench heater current at lower coil current
    - Still well below decay time of LTS Outsert

HTS + LTS quench protection

(2015)

- No degradation observed in *deliberate* quenches in 32 T prototype coils
  - Or quenches caused by false positive in detection

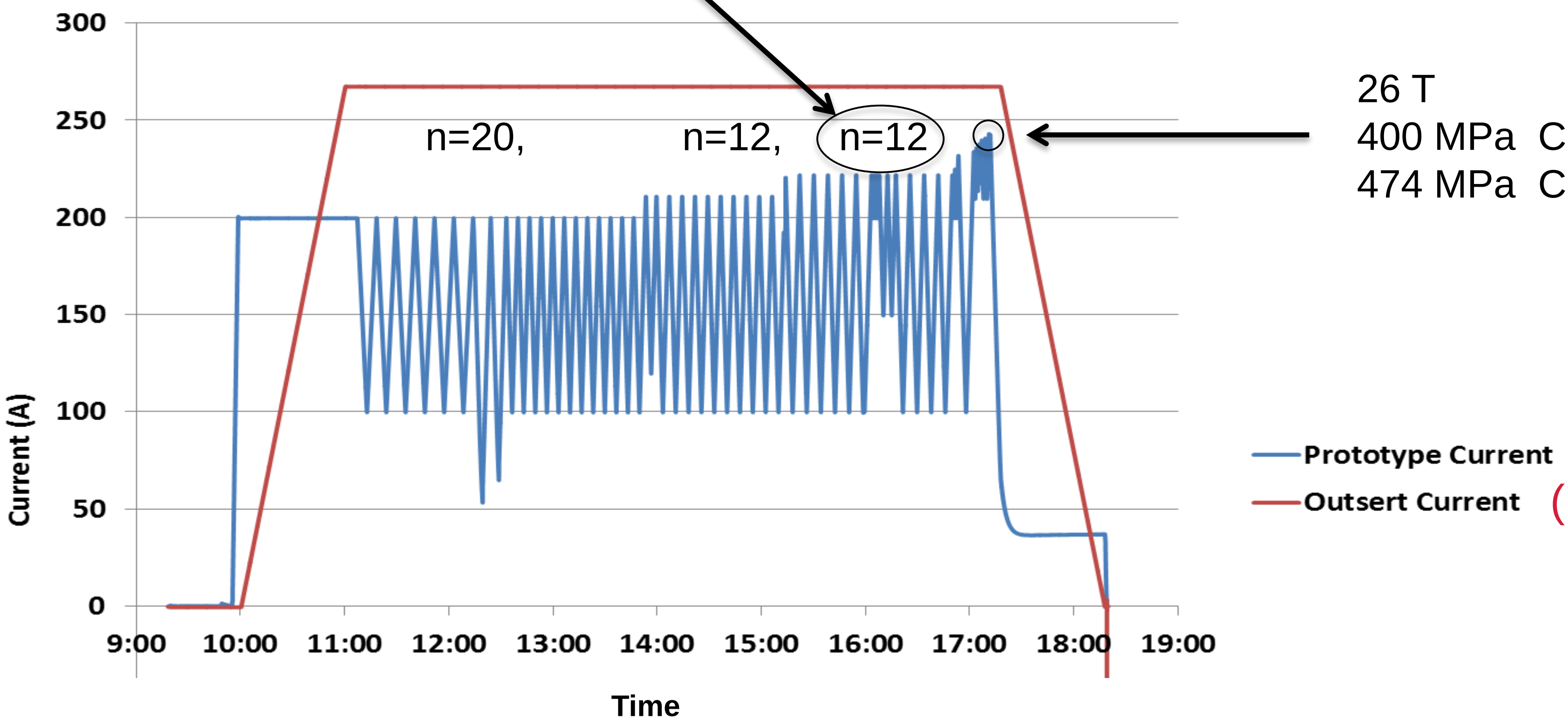
Scenario	HTS	LTS	Central field
Full field, LTS quench	200 A	268 A, 15 T	24.6 T
False positive	222 A	214 A, 12 T	22.7 T
HTS quenched	200 A	134 A, 7.5 T	17.1 T
LTS quenched	200 A	134 A, 7.5 T	17.1 T
False positive	173 A	134 A, 7.5 T	15.8 T
HTS self-field	200 A	0 A, 0 T	9.6 T

HTS –LTS high-field quenches can be protected

Prototype load cycling

(2015)

12 times
362 MPa Coil 1 (**100%** of 32 T design) ✓
436 MPa Coil 2 (**115%** of 32 T design ✓



(14 T)

26 T
400 MPa Coil 1
474 MPa Coil 2

32 T reference peak hoop stress in HTS: Coil 1: 363 MPa

Coil 2: 378 MPa

Prototype phase: learned and open questions (2015)

- Testing confirmed viability of developed technology

- Prototype quench behavior dominated by inner coils: 20/70
  - With lowest I_c and oldest conductor (pre-32 T spec)
  - Temperature margin lower than in 32 T
  - So 32 T needs more powerful heaters than prototypes
  - Could not study some aspects of 82/116 outer prototype coil as desired
    - Which has conductor representative of the 32 T conductor

- 32 T Quench calculations quite sensitive to input parameters
  - Within error bars of available data
  - Need deliberate test quench in 32 T (with low background field) to verify quench protection parameters are set adequately for full-field quench
    - Can't rely on simulations alone

REBCO conductor specification

(2013)

Specifications negotiated (took 2 years) for 12 km conductor that

- Meet 32 T project needs
- Are routinely achieved in production runs: “*catch the outliers*”

Insufficient I_c correlation (at the time) between 77 K, SF and 4.2 K in-field

- ➢ Specify I_c at 4.2 K and most demanding field and angle in coil
- ➢ Verify parameters in all conductors in *collaborative* NHMFL/SP QA program

Parameter	**UNIT**	**Value**
I_c at 4.2 K, 17 T, 18° angle	A	≥256
n-value at 4.2 K, 17 T, 18° angle	-	>25
Thickness (average over all pieces)	mm	≤0.170
Width	mm	4.10±0.05
Cu stabilizer cross-sectional area	mm^2	0.42±0.01
RRR stabilizer	-	>50
Hastelloy C267 (half hard) cross-sectional area	mm^2	0.20±0.01
Joint resistivity (77 K)	$n\Omega\text{-}cm^2$	≤160
Piece length Coil 1 / Coil 2	m	60 / 110

I_{op} = 180 A, later 173 A

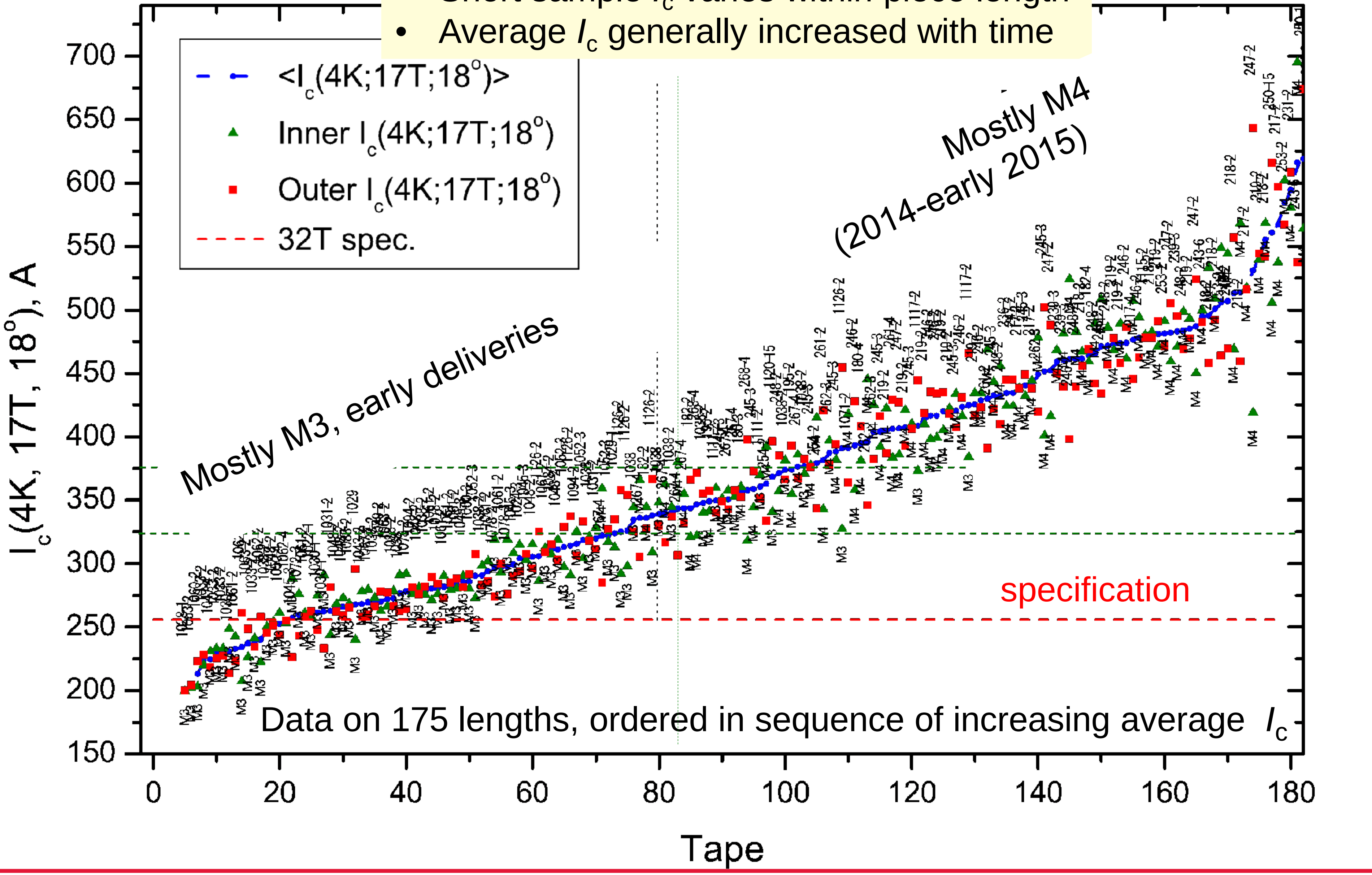
→ Well within spec with mid-slit

(≤ 50 nΩ per joint)

REBCO conductor received

(2015)

- Short sample I_c varies within piece length
- Average I_c generally increased with time



Mostly M3, early deliveries

Mostly M4 (2014-early 2015)

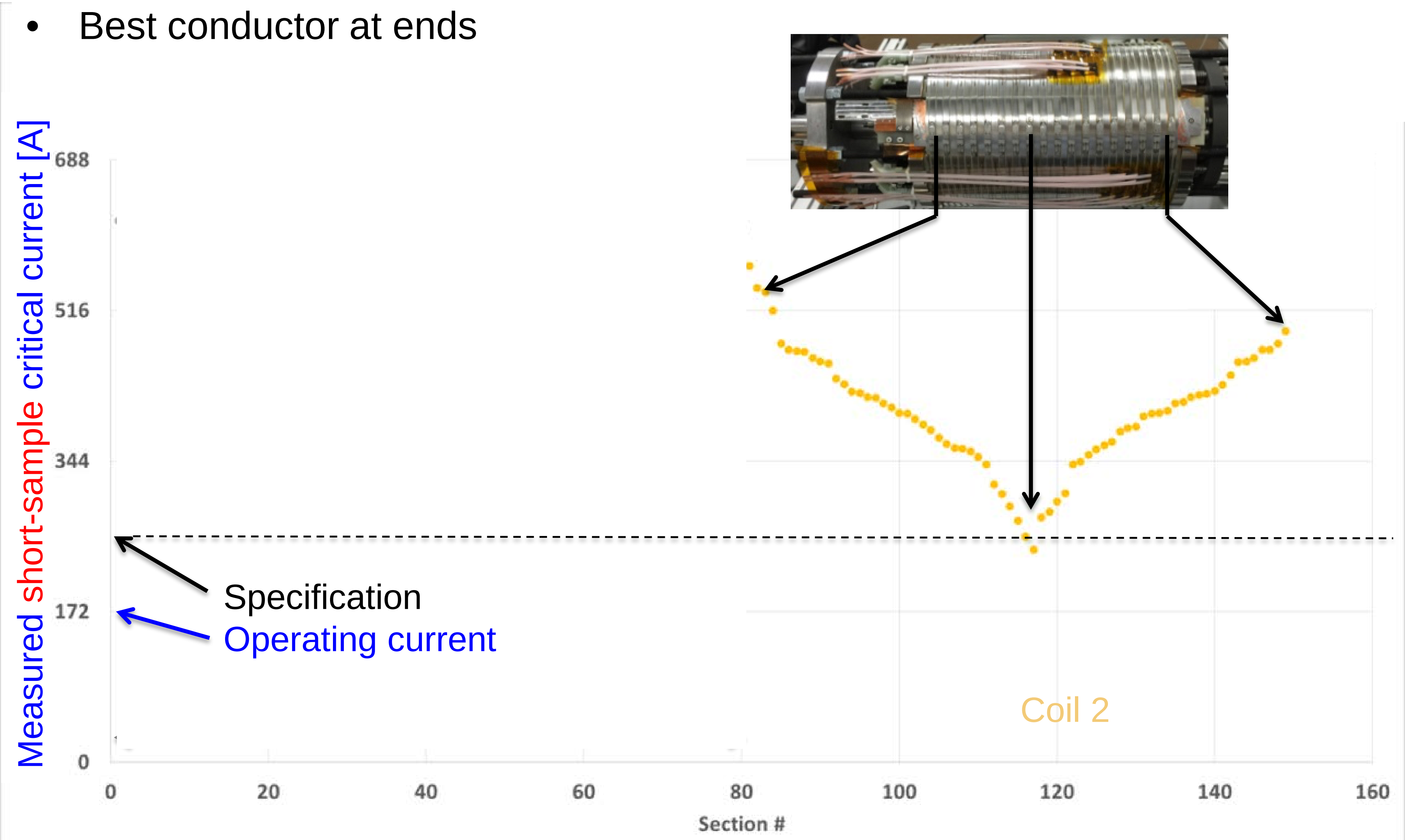
specification

Data on 175 lengths, ordered in sequence of increasing average I_c

32 T assembly

Placement of conductor:

- Best conductor at ends

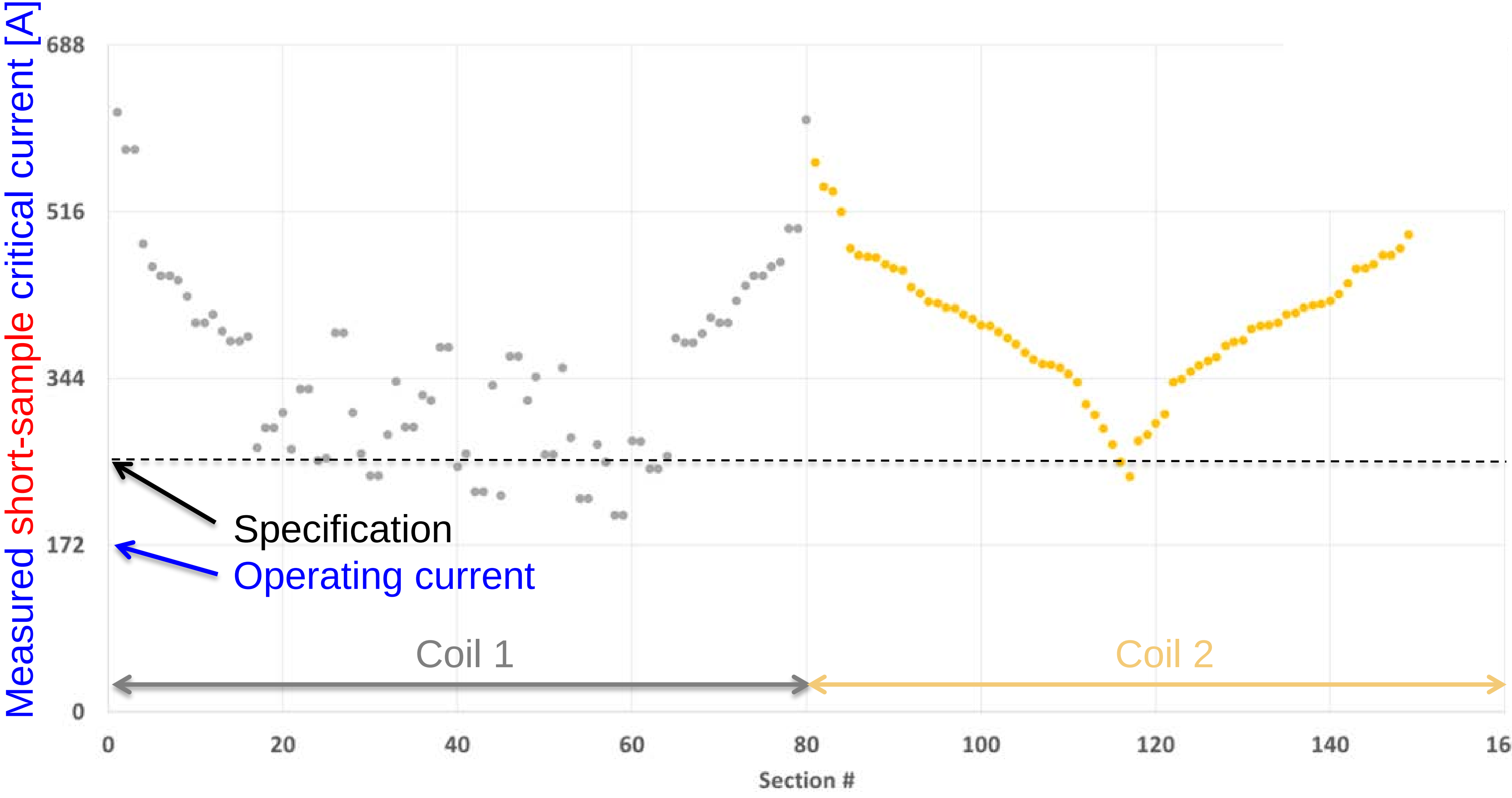


32 T assembly

(2015)

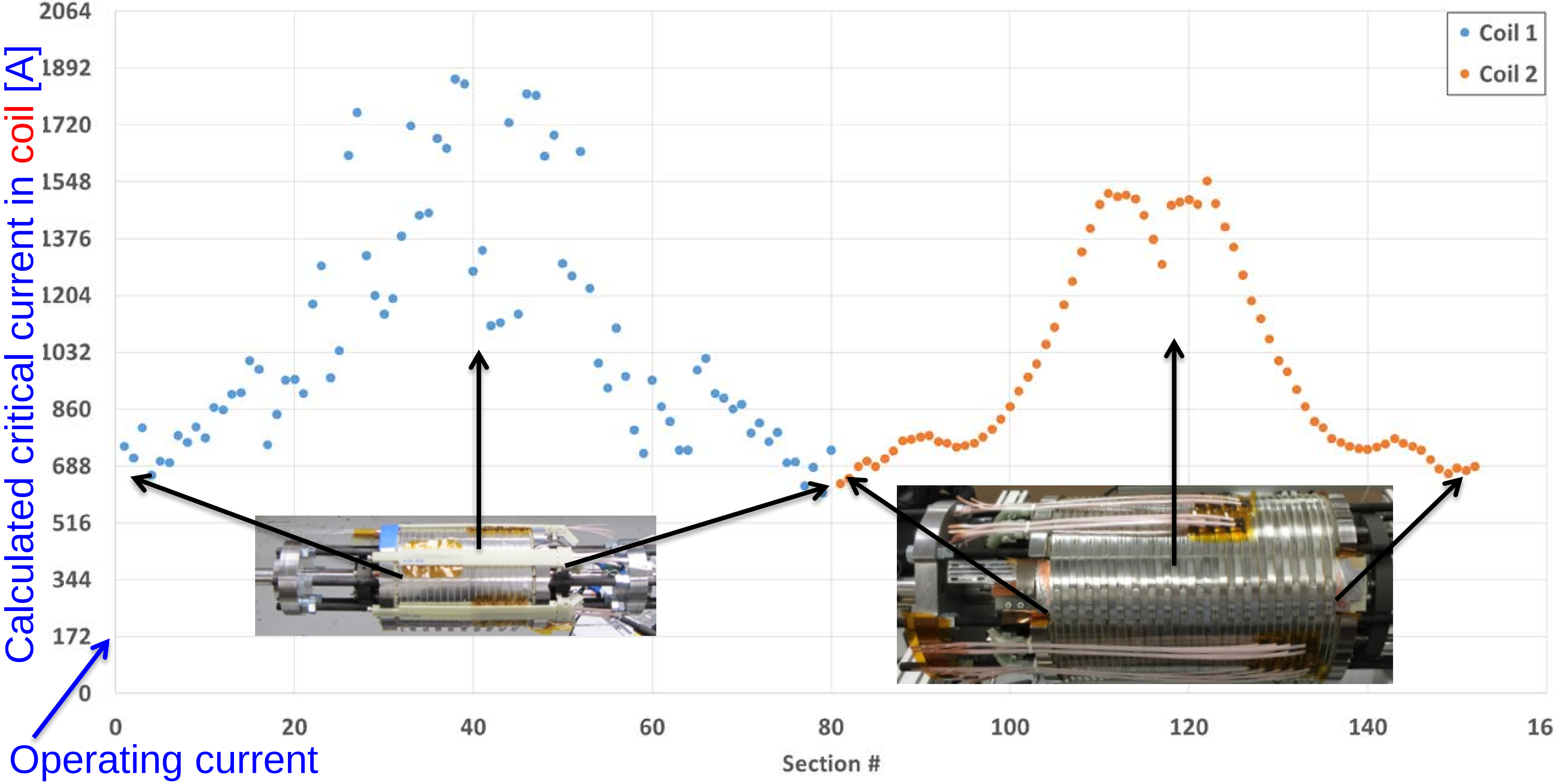
Placement of conductor in the two REBCO coils:

- Best conductor at ends
- For Coil 1 also based on turn density for *B* uniformity



32 T Assembly (2015-2016)

- Calculated critical current at full field
  - I_c at actual magnetic field and angle
  - Operating current is 1/10 to 1/3 of critical current

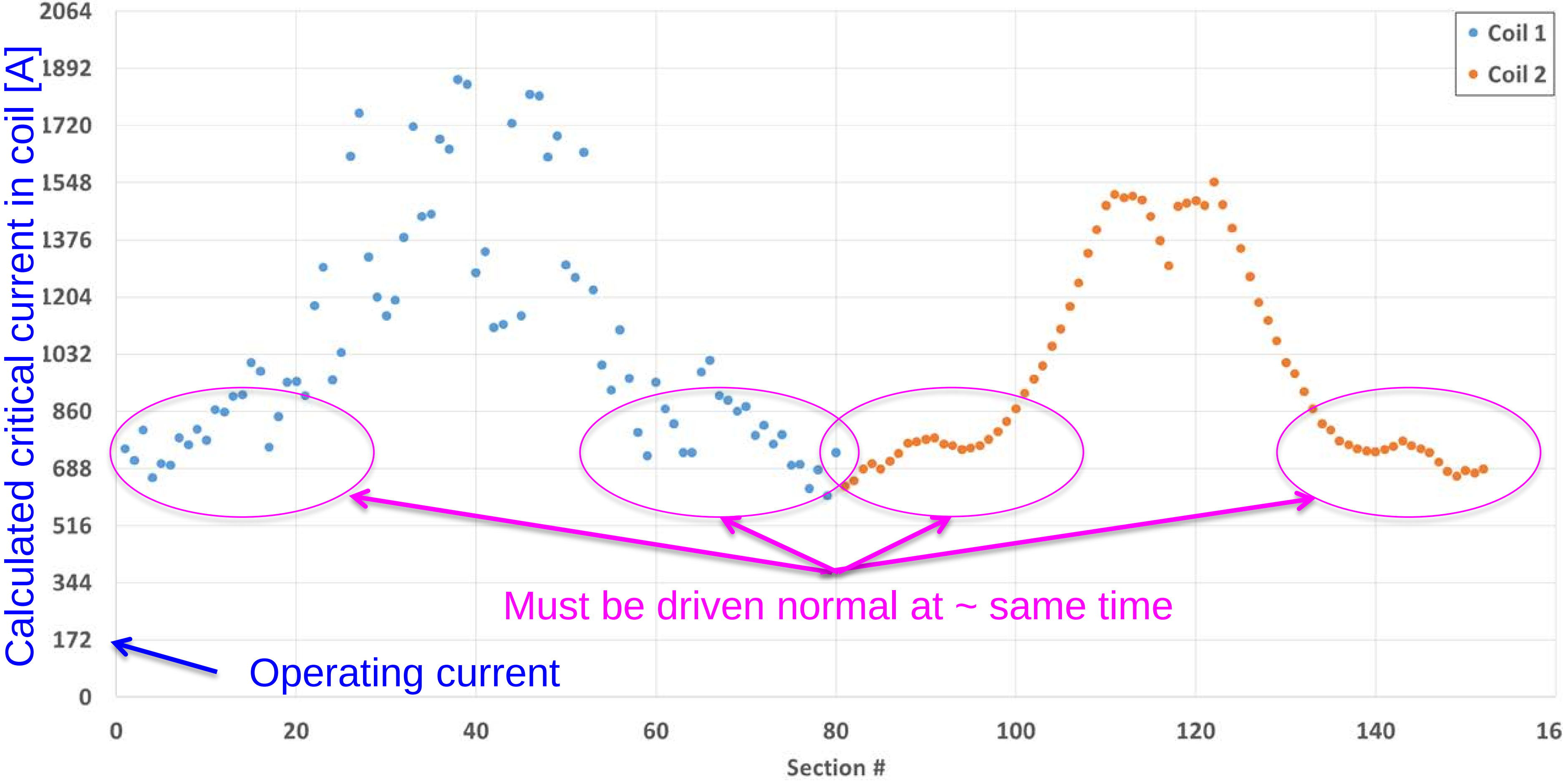


Operating current

32 T Assembly

(2015)

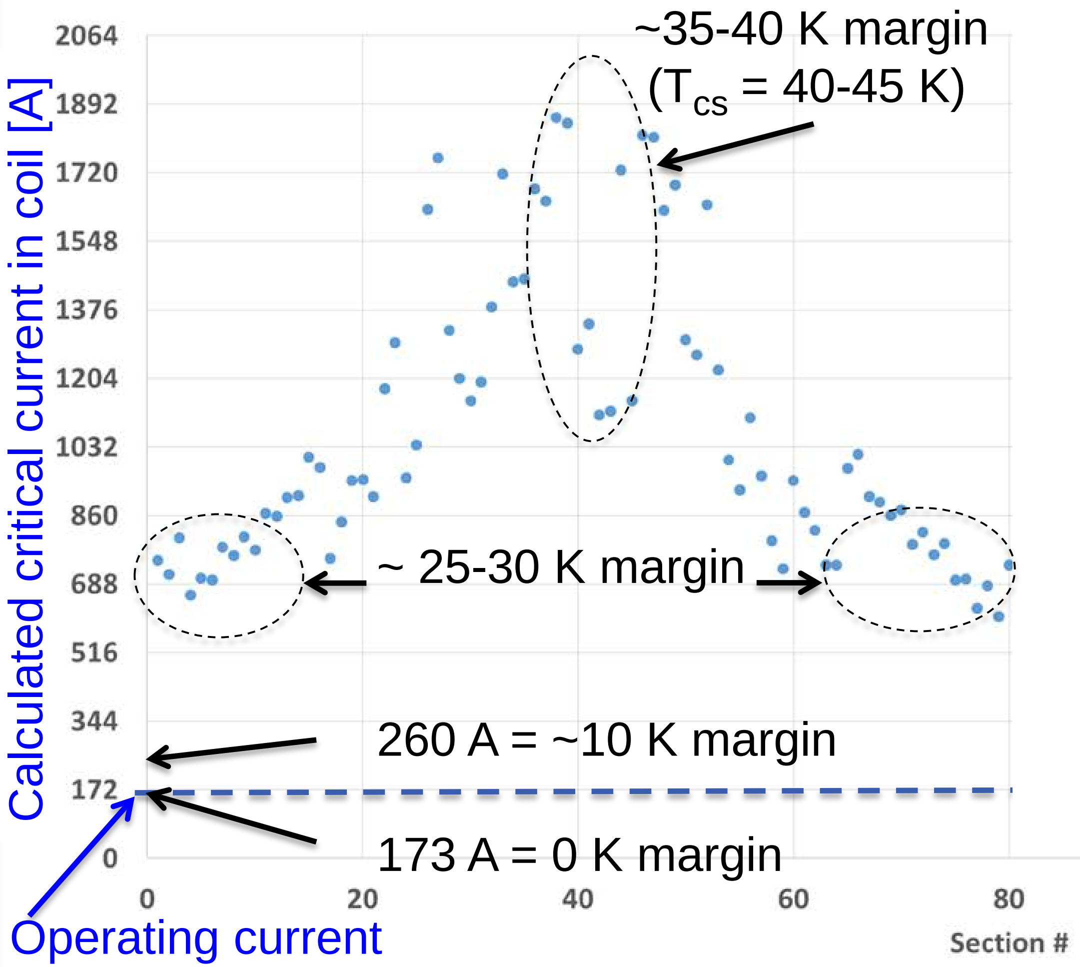
- In quench, about half coil the HTS volume must be driven normal to absorb stored energy (Hot spot temperature < 200 K)
- Calculated critical current at full field
  - Probably an acceptable I_c-margin distribution



Initial T margin

(2016)

- Temperature margin goes up during quench as field and current decay
  - Once current decay starts, it becomes harder to drive rest of HTS to normal state
  - Desirable to have large fraction of coil volume with ~ same temperature margin



~35-40 K margin (T_{cs} = 40-45 K)

~ 25-30 K margin

260 A = ~10 K margin

173 A = 0 K margin

Operating current

- Operating at 70% of I_c would give > 10 K initial temperature margin
- 32 operates at 33-10% of I_c

Initial T margin

(2016)

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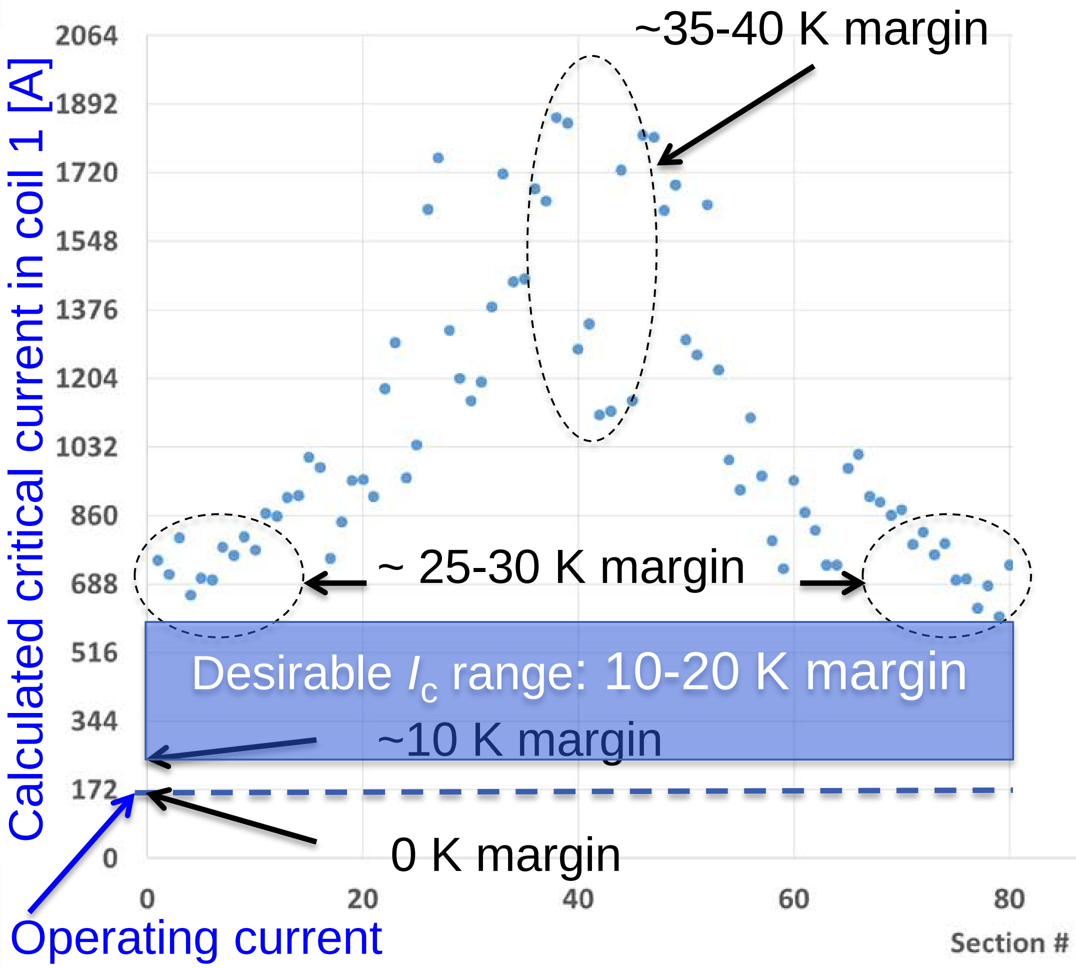

~35-40 K margin

~ 25-30 K margin

Desirable I_c range: 10-20 K margin

~10 K margin

0 K margin

Operating current

- Operating at 70% of I_c would give > 10 K initial temperature margin
- 32 operates at 33-10% of I_c

Initial T margin

(2016)

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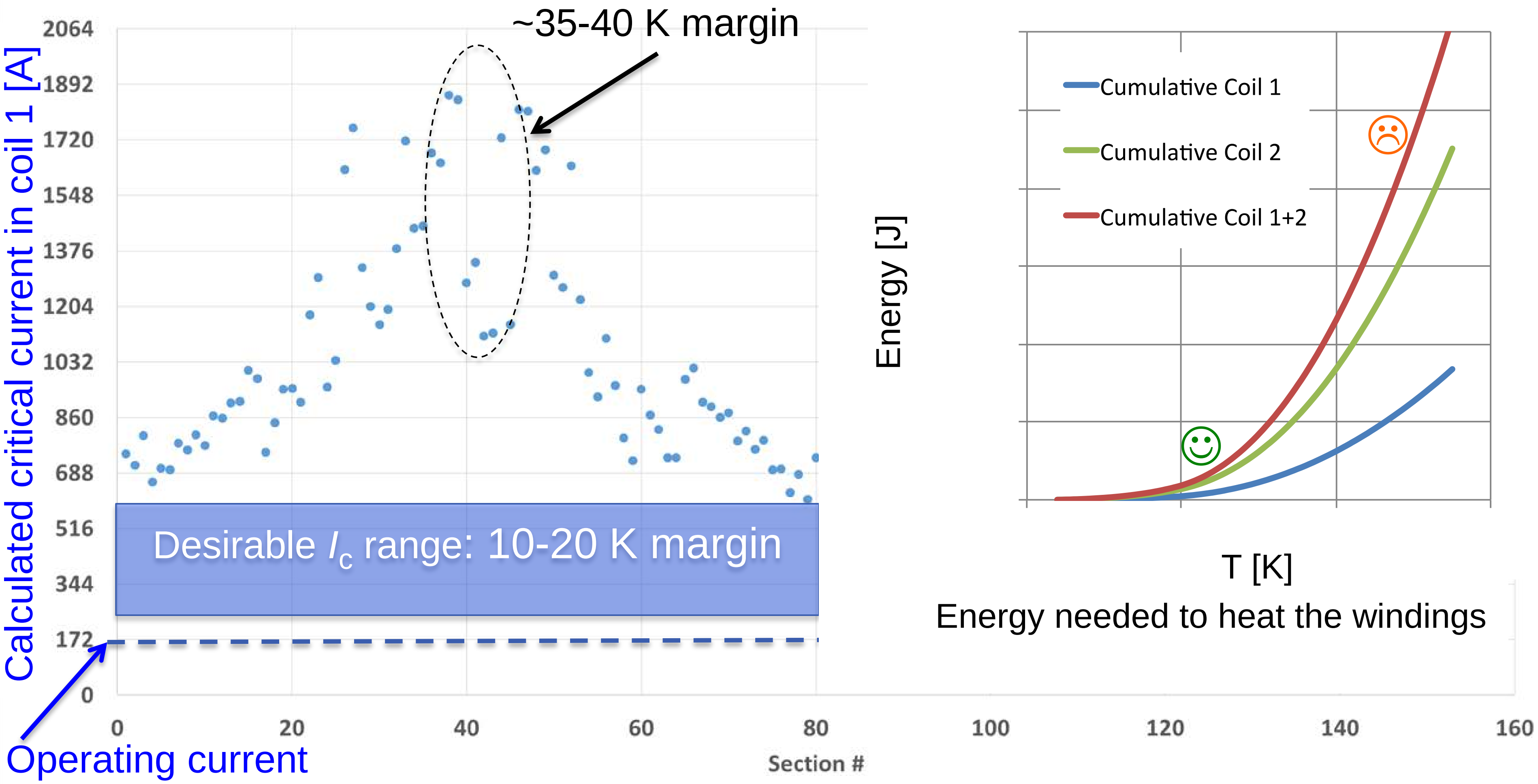


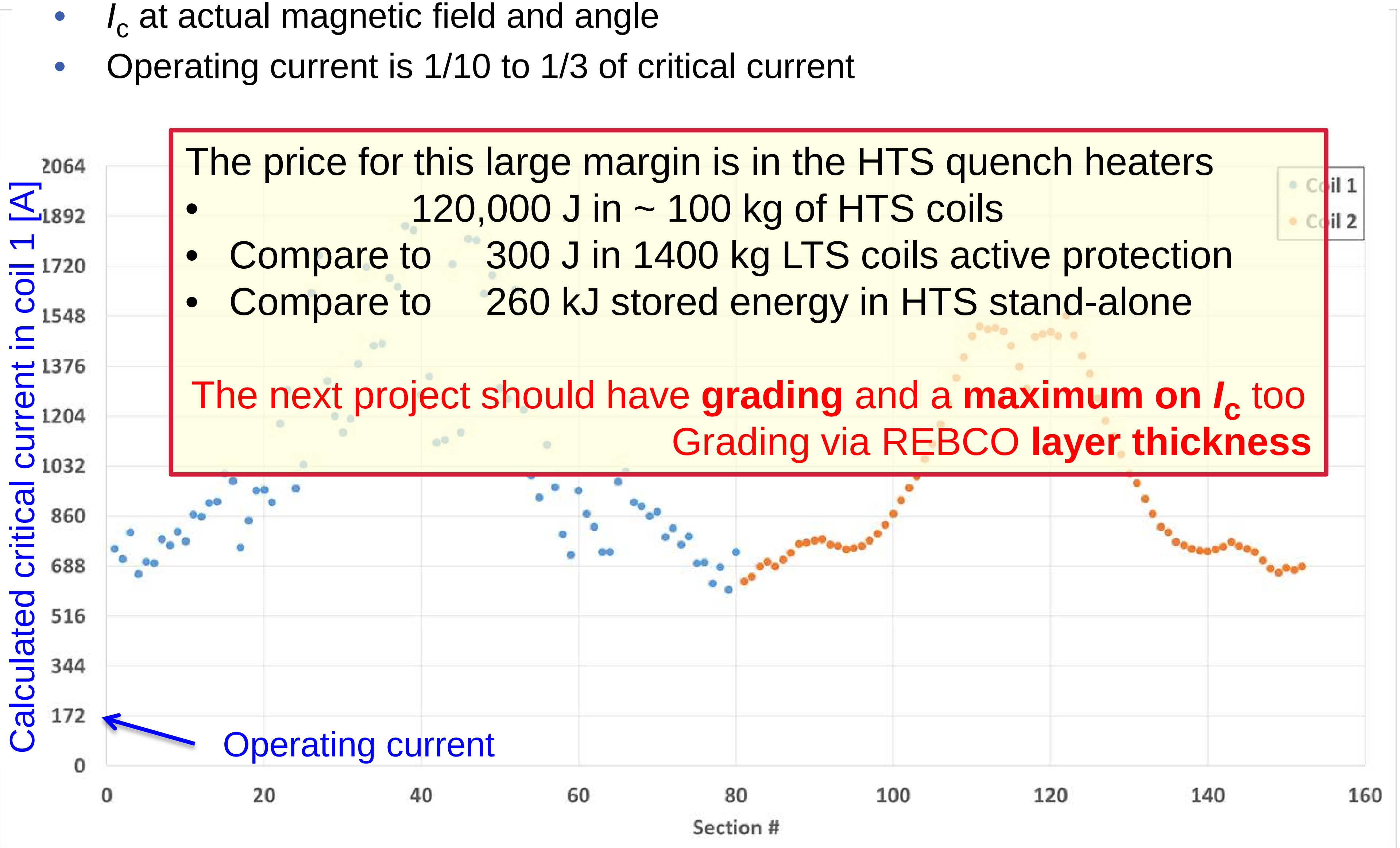
Desirable I_c range: 10-20 K margin

Operating current

Energy needed to heat the windings

REBCO conductor (2016)

- Calculated critical current at full field
  - I_c at actual magnetic field and angle
  - Operating current is 1/10 to 1/3 of critical current



Calculated critical current in coil 1 [A]

Operating current

The price for this large margin is in the HTS quench heaters

- 120,000 J in ~ 100 kg of HTS coils
- Compare to 300 J in 1400 kg LTS coils active protection
- Compare to 260 kJ stored energy in HTS stand-alone

The next project should have **grading** and a **maximum on I_c** too

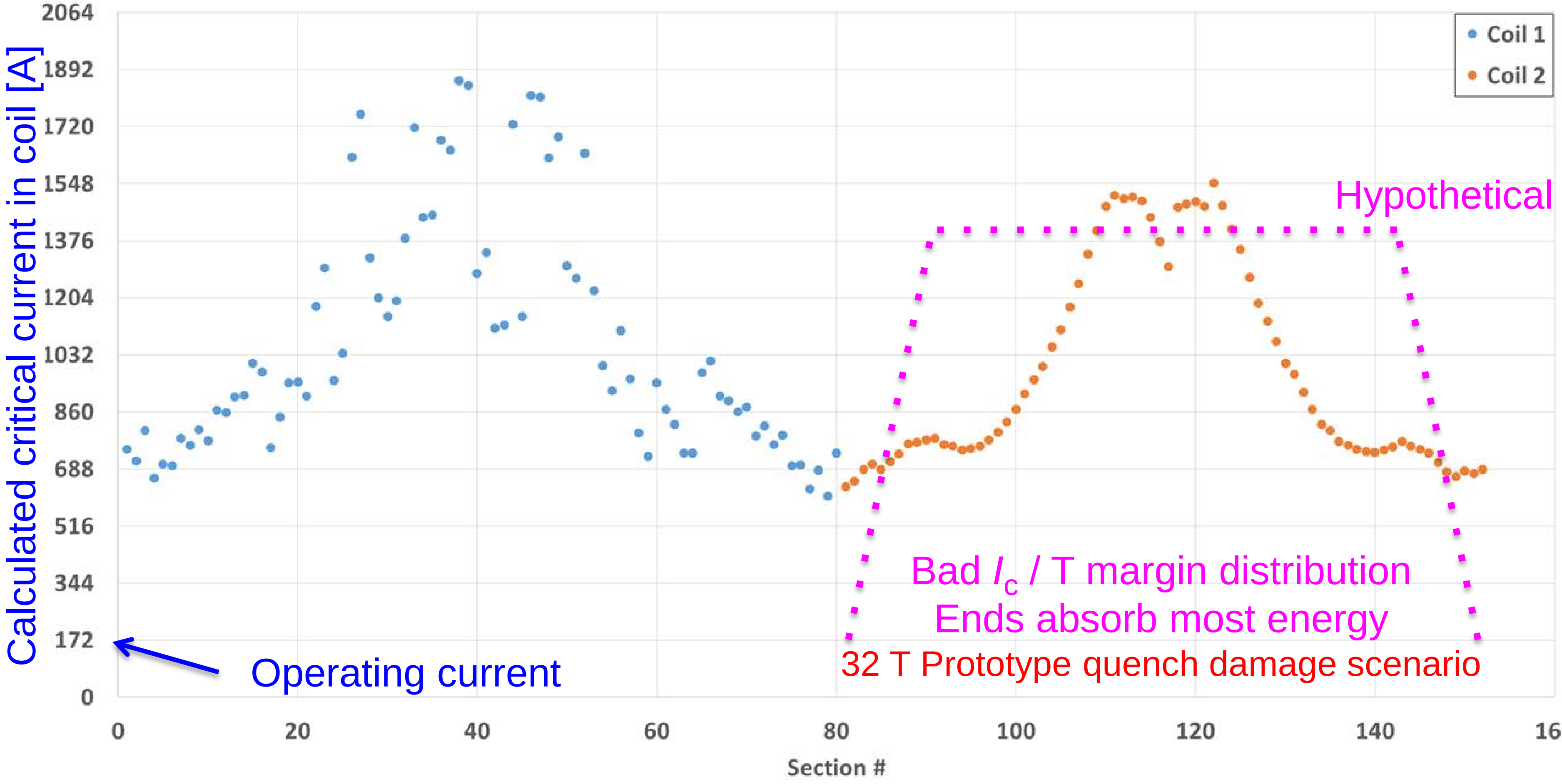
Grading via REBCO **layer thickness**

REBCO conductor

(2015)

- Temperature margin goes up during quench as field and current decay
  - Once current decay starts, it becomes harder to drive HTS to normal state
  - If a small volume fraction has much lower I_c / temperature margin as the rest,

it will absorb almost all stored energy and overheat



Hypothetical

Bad I_c / T margin distribution

Ends absorb most energy

32 T Prototype quench damage scenario

Operating current

32 T Full field quench simulation

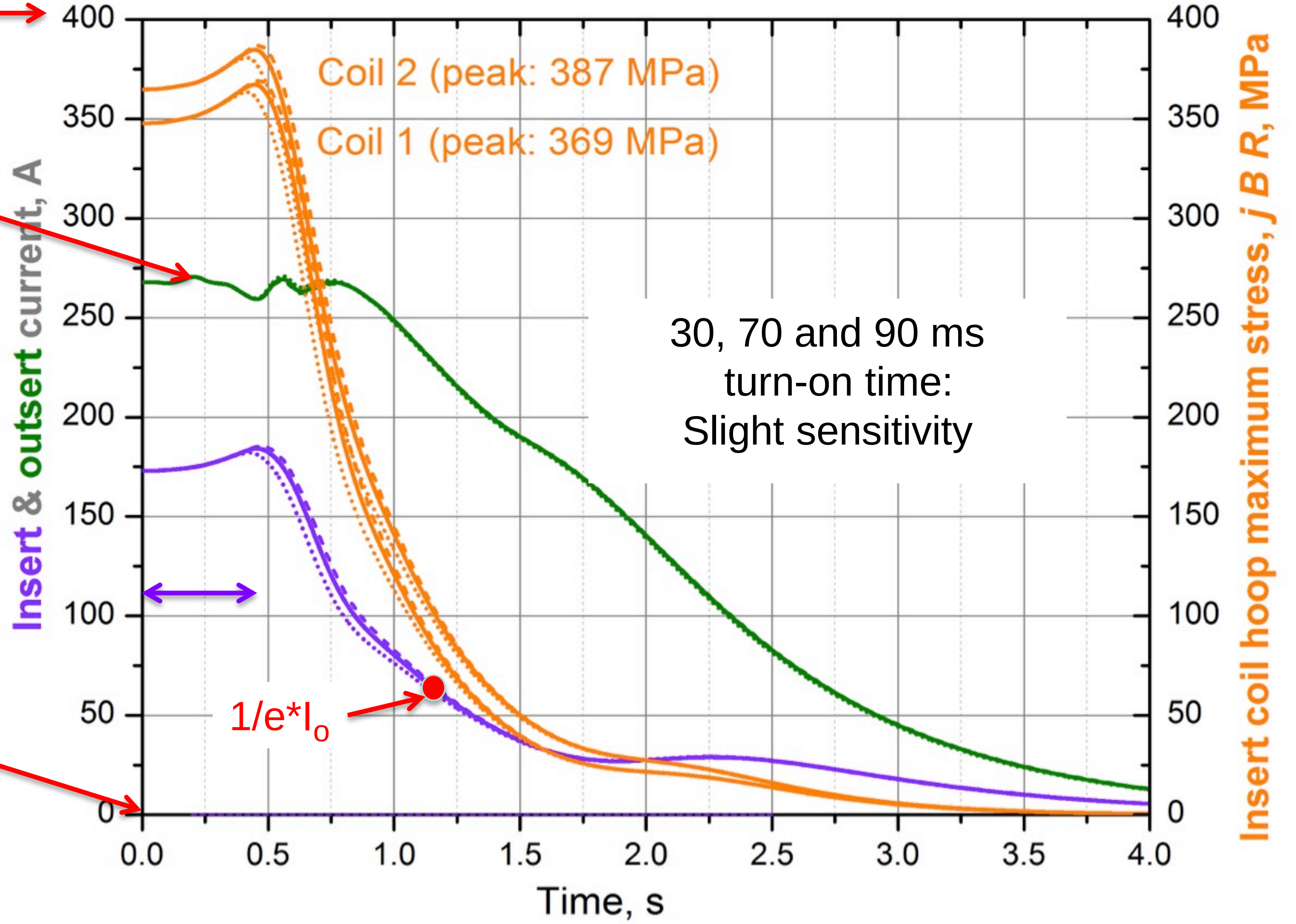
(2016)

- Key: time to reach current sharing temperature in REBCO insert
  - Determined by heater power and temperature margin

Design σ limit →

Current decay in inner Nb_3Sn coil

t = 0, LTS quench



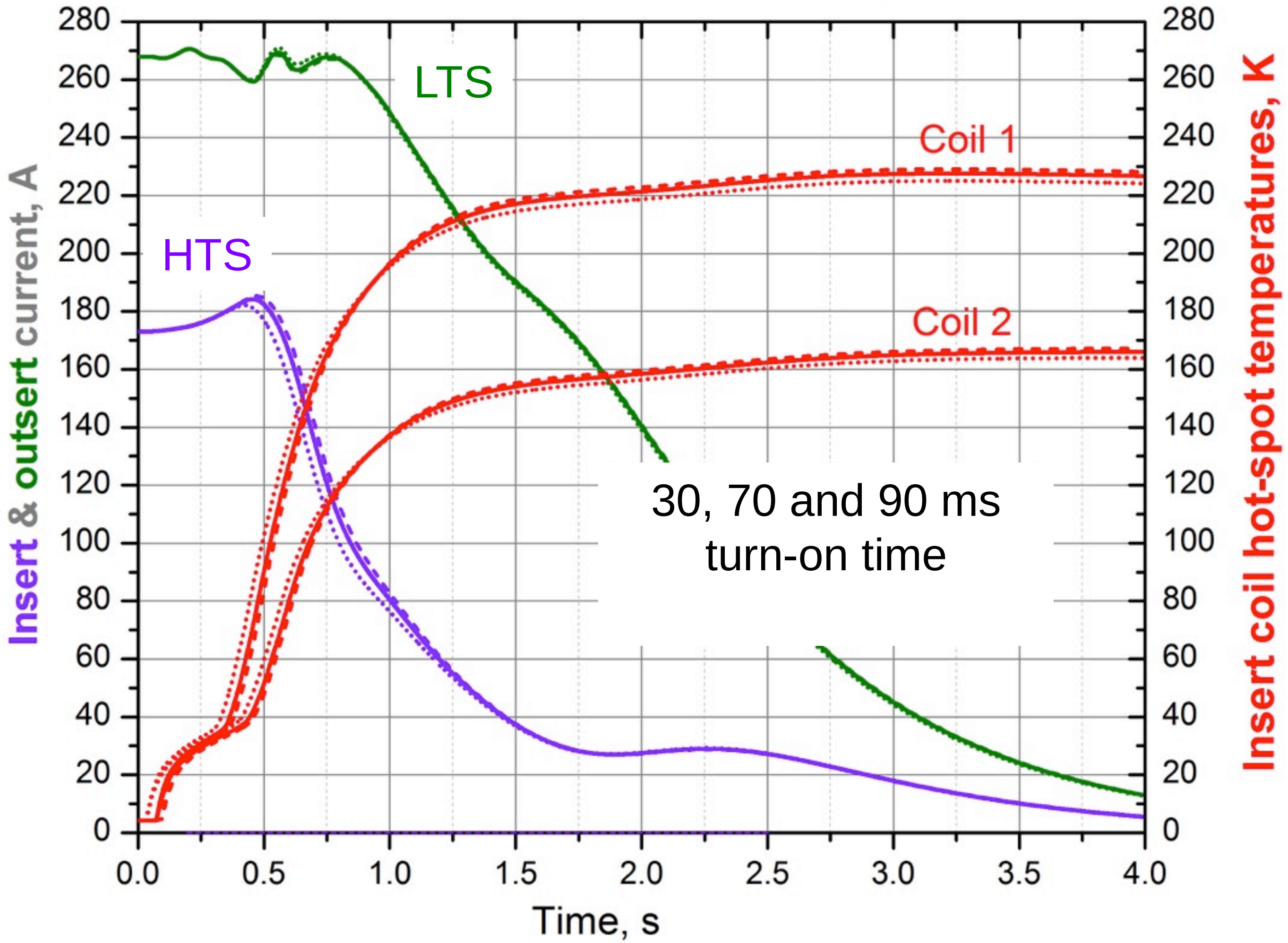
30, 70 and 90 ms turn-on time: Slight sensitivity

$1/e*I_o$

32 T Full field quench simulation

(2016)

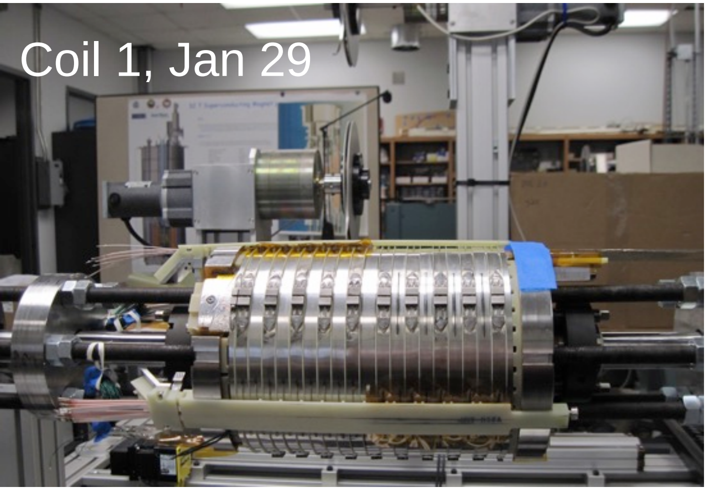
- Can’t quite make 200 K target hot-spot temperature
  - Sensitivity to turn-on time and heater power (> 23 A) is low

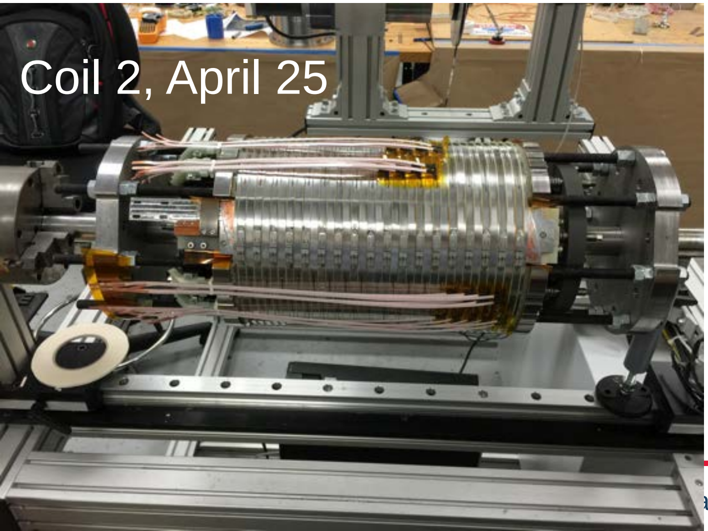


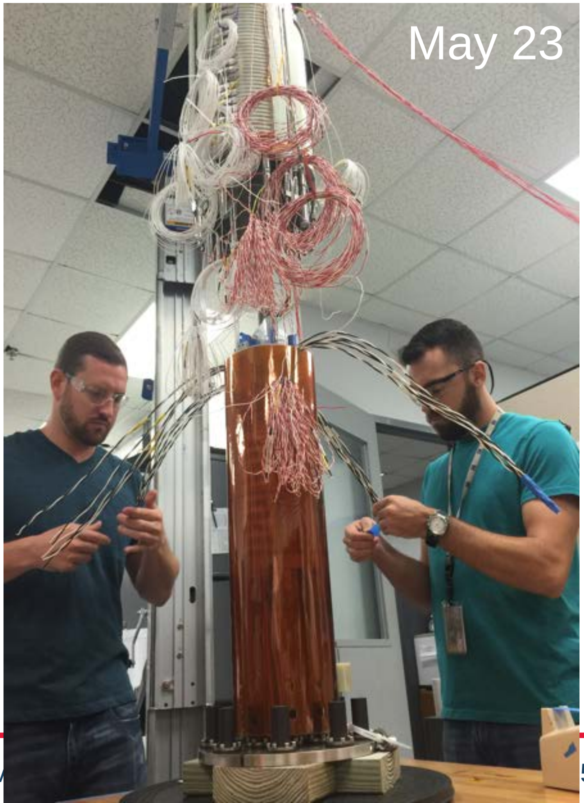
Construction

(2013)

Assembly from double pancake modules to complete coils and all electrical tests takes 2-3 months per coil


Coil 1, Jan 29


Coil 2, April 25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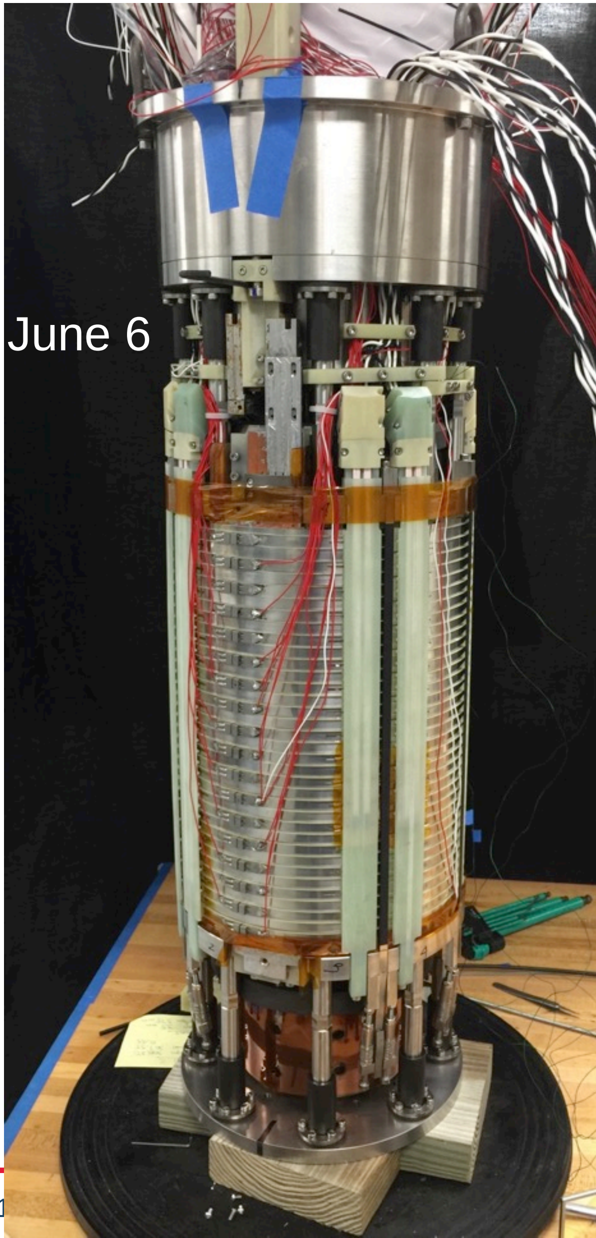

June 6

32 T assembly

(2016)

(June 29)

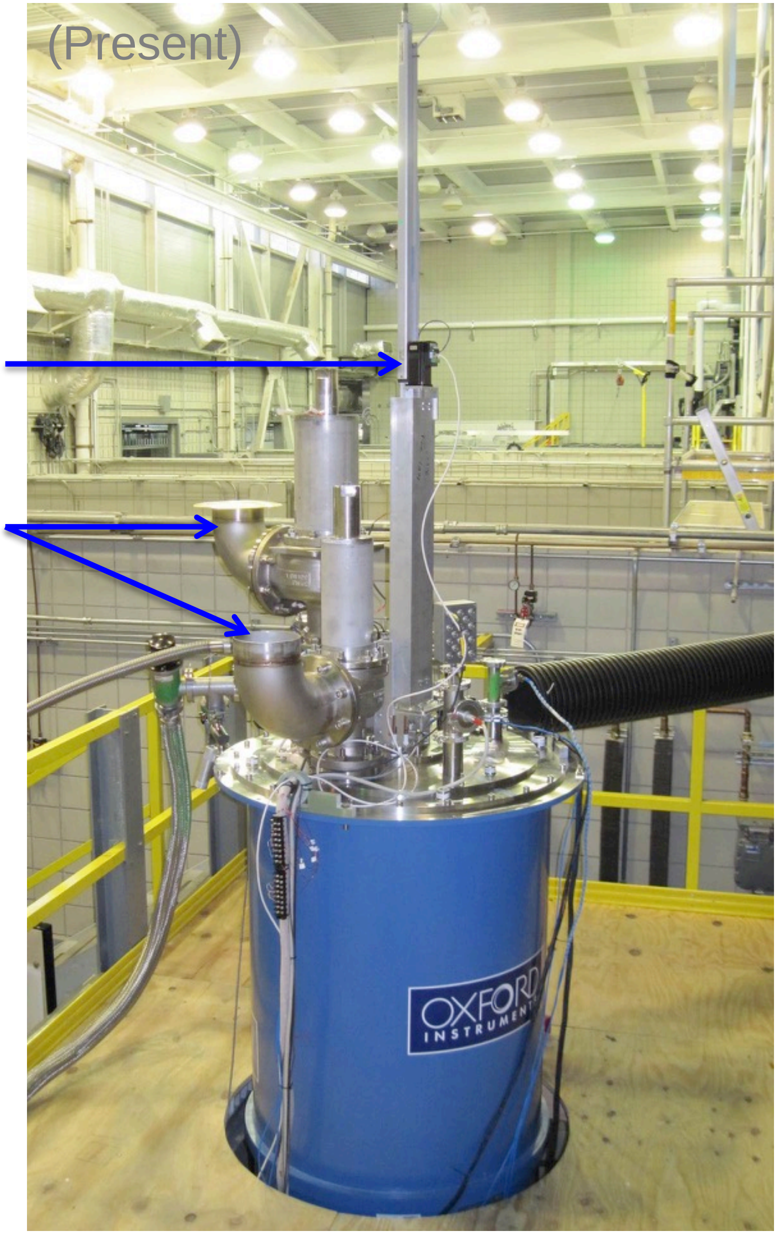
(August 11)

HTS assembly going into LTS magnet

32 T magnet going into cryostat

32 T in Cell 4

(2016)



Axial Hall probe mapper
(temporary)

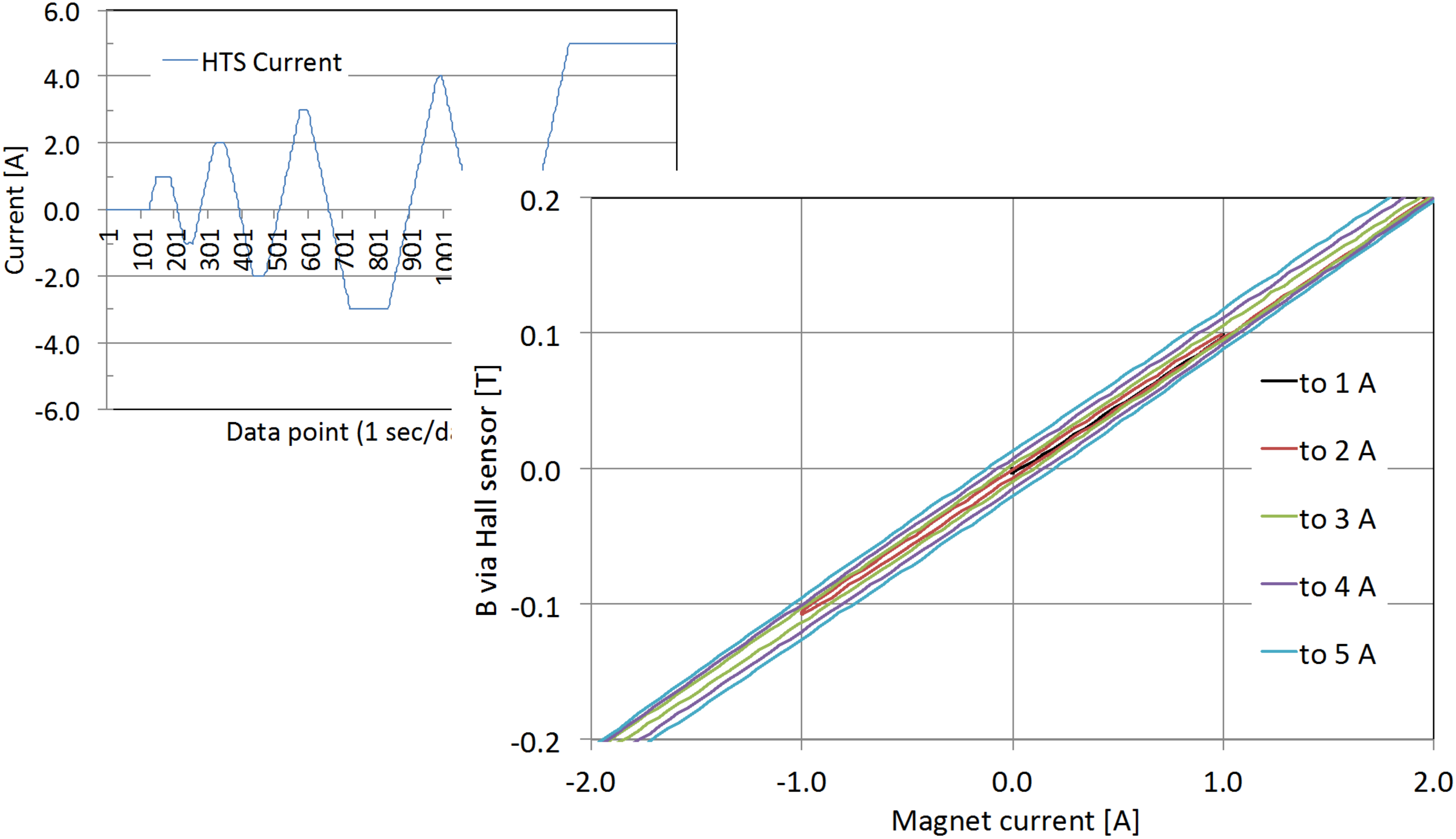
Quench valves

32 T HTS coils at 77 K

(2016)

Operating only the REBCO coils

- Observable hysteresis in center field

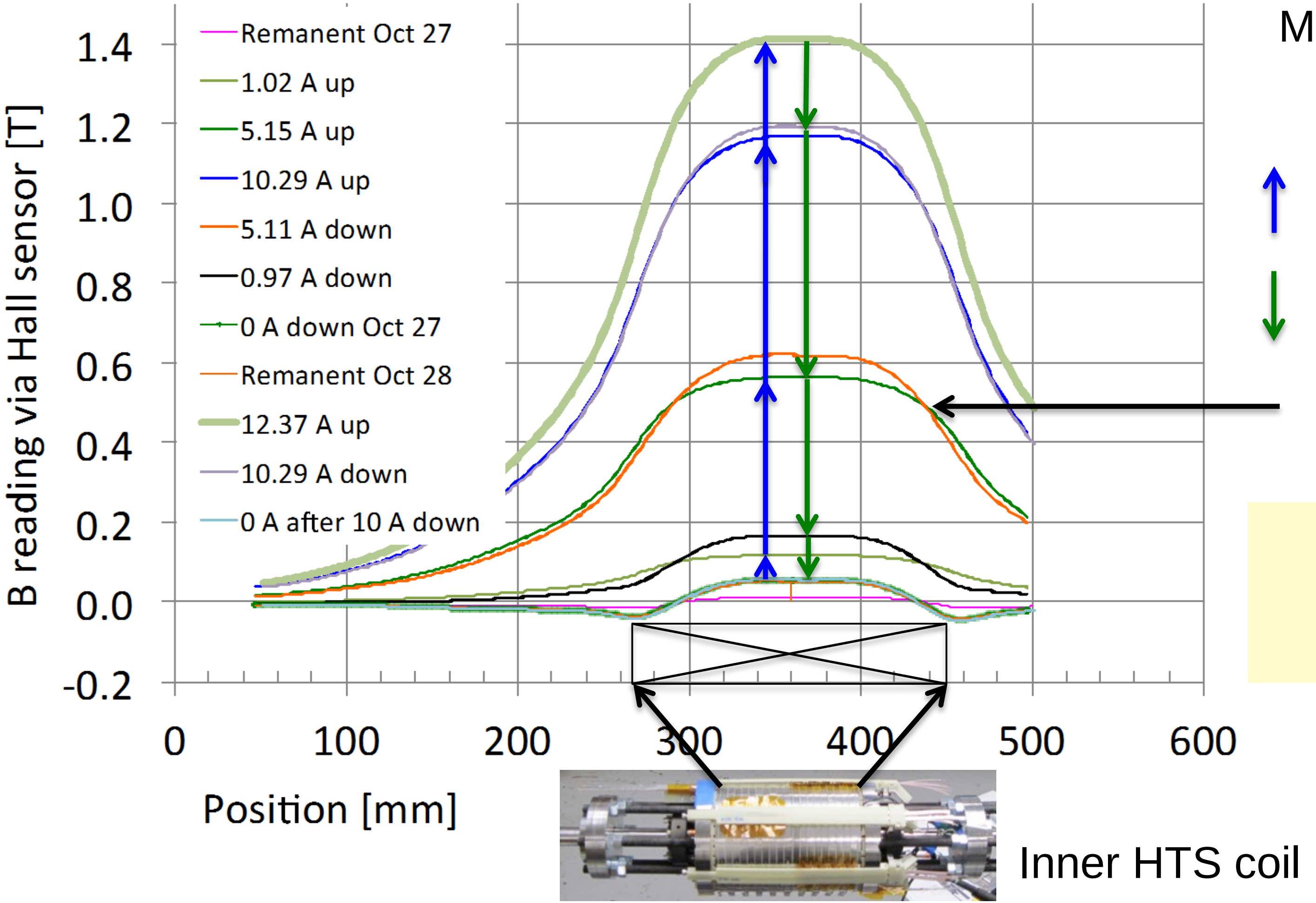


32 T HTS coils at 77 K

(2016)

- B_z versus *z* map in 0-1-5-10-12-10-5-1-0 A stepwise current sweep
  - Observable hysteresis in center field
  - Change in axial field, profile depending on history
  - Remanent field up in center, down at ends

Magnetic field on axis



Inner HTS coil

We'll see how this translates to behavior at 4.2 K

Next

(2017)

- At 4.2 K: Test quench-protection heaters in HTS coil near full current
  - In low background field
- Compare with simulation
  - Adjust protection settings as necessary
- Stepwise increase of current to 32 T
  - In synchronized HTS+LTS operation

Dec. 9, 2016

Future location of 32 T magnet
February 16, 2017
Completion planned for April

32 T test phase: learned

(2013)

- Measureable hysteresis in B_{central} at 77 K
  - Axial field profile changes too from ramping up to ramping down
  - Can be tool to improve uniformity once fully understood
- HTS-LTS magnet > 30 T is new technology
  - Quench detection and protection are complicated systems
  - Testing all equipment in normal and fault modes is time consuming
    - Brings out otherwise hidden issues

Summary

(2016)

- 32 T magnet combines sizeable LTS and HTS coils
  - Insulated HTS coated conductor, up to 200 A/mm^2 in modular windings
  - Required collaborative effort with LTS magnet and HTS conductor vendor
- Status of 32 T
  - LTS magnet (15 T/250 mm bore) is fully qualified
  - HTS coils are wound and assembled, mounted in LTS bore
  - Magnet mechanically and electrically checked out at room temperature
  - 77 K transport current testing and axial field map done
  - Quench detection and protection systems stand-alone testing ongoing
- Next
  - Complete test protocol including operation to 32 T
- Key observations
  - Conductor developed quickly to far above I_c specification by late 2014
    - Conductor development is fast compared to time scale of projects like this
  - Stress and HTS & LTS quenches are manageable using chosen technology
    - Large temperature margin requires powerful quench heaters
    - Desirable to engineer temperature margin across coil: minimum and maximum

Thank You!

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