U.S. MAGNET DEVELOPMENT PROGRAM

LBNL Bi-2212 magnet program – where we are and opportunities in 2018?

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Work supported by U.S. DOE OHEP through an Early Career Award and through the U.S. Magnet Development Program, and performed in collaboration with Bruker OST, nGimat LLC, NHMFL/FSU on wire development.

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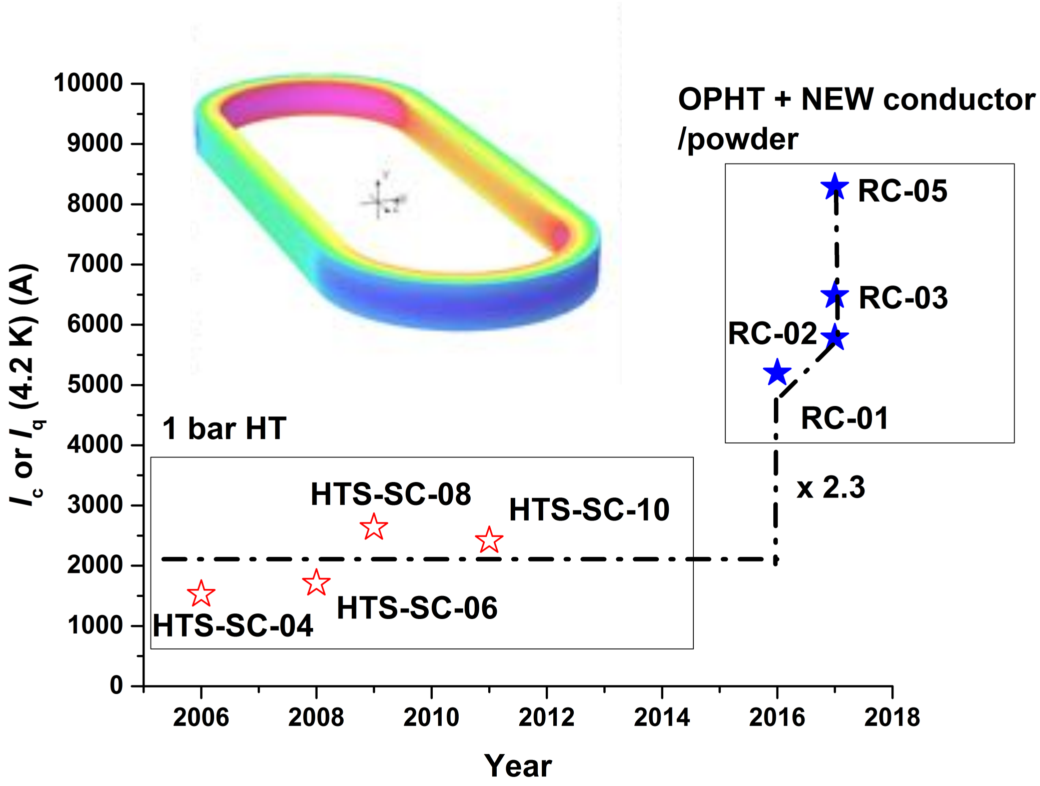
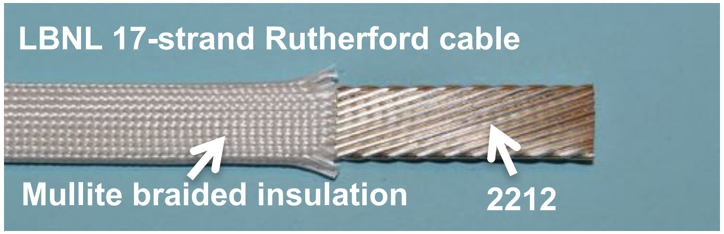
LBNL HTS (2212) subscale magnet program topped with new RC-05 results

Subscale coils allow fast-turnaround test of cable and magnet-relevant technologies.





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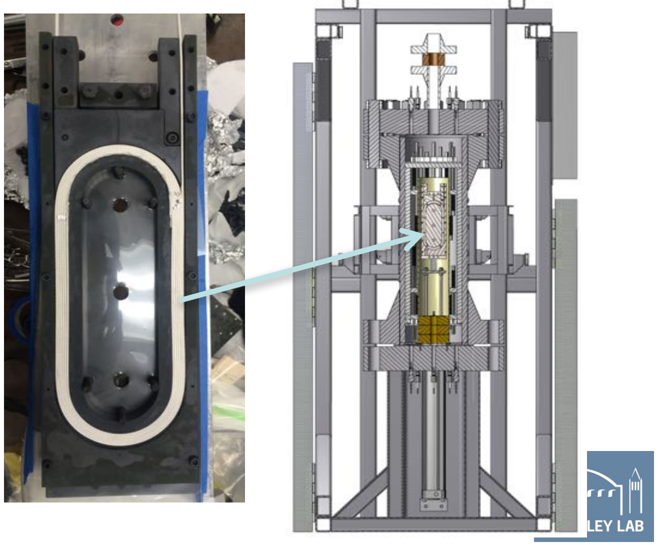
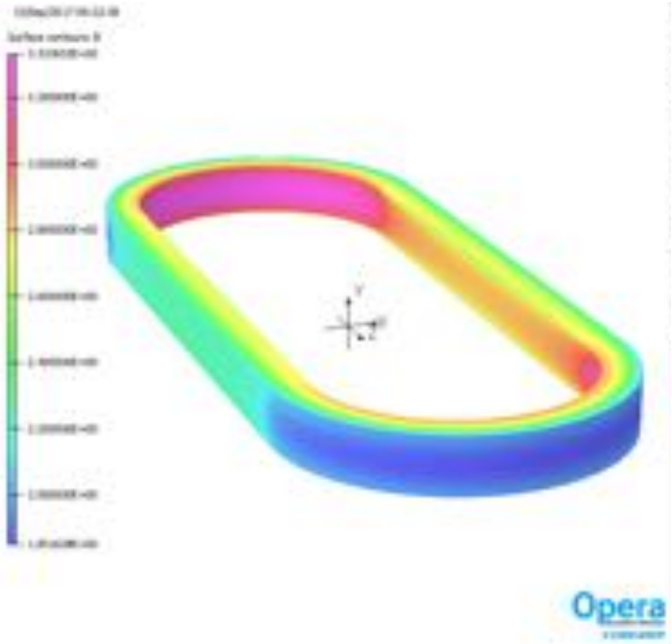
LBNL RC-1,2,3,5 in FSU OP furnace



Parameters of LBNL HTS-SC and RC coils show Bi2212 is now a very relevant high-field conductor

RC5 – peak field – 3.33 T



2-layer x 6-turn racetrack coil based on 17-strand Rutherford cable (1.44 mm x 7.8 mm, strand diameter = 0.8 mm)

140 m conductor, 8 m cable

18 lbs coil thermal mass, 37 cm x 12 cm x 3.1 cm.

50 bar OPHT (@FSU) for RC coils.

RC-01 (5.2 kA, (effective) J_{cable}=463 A/mm^2, (effective) wire J_e=588 A/mm^2.), wax impregnation

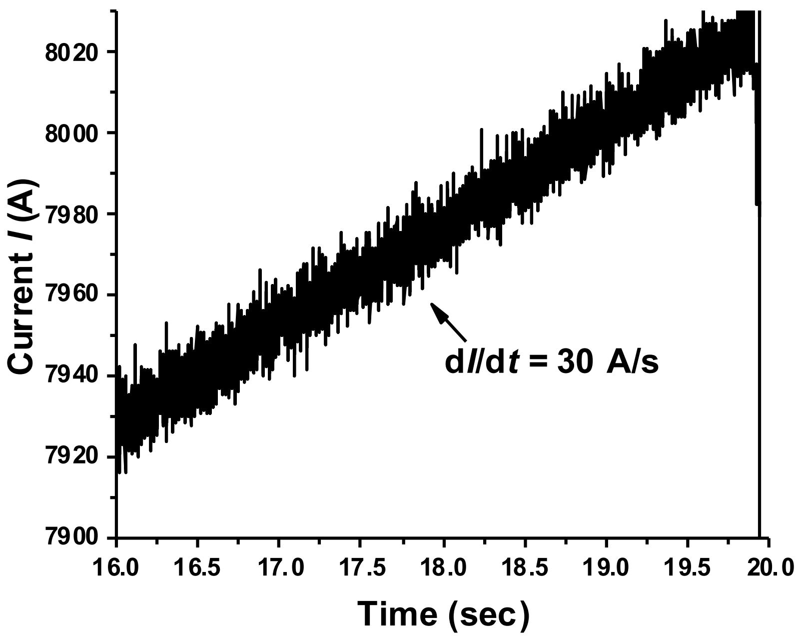
RC-02 (5.8 kA, (effective) J_{cable}=516 A/mm^2, (effective) wire J_e=656 A/mm^2.), wax impregnation

RC-03 (6.5 kA, (effective) J_{cable}=580 A/mm^2, (effective) wire J_e=735 A/mm^2.), NHMFL mix 61 impregnation

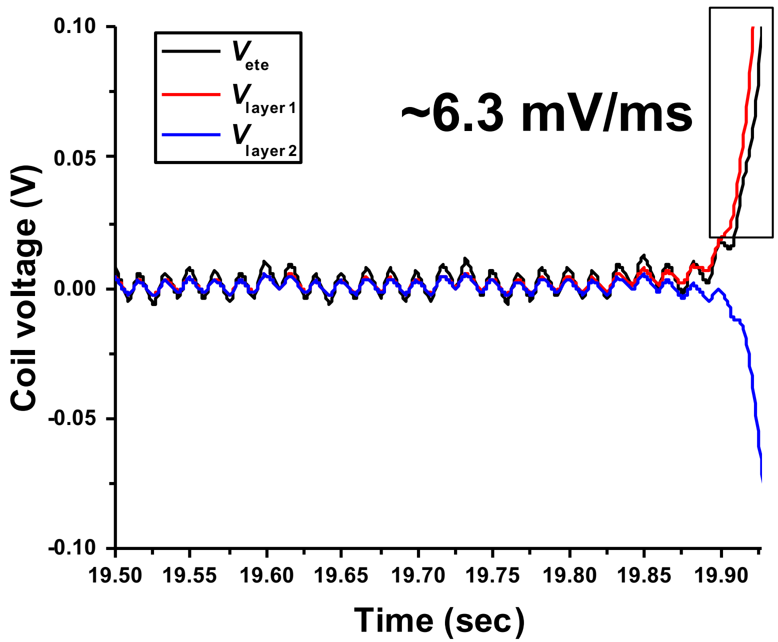
RC-05 (8.3 kA, (effective) J_{cable}=740 A/mm^2, (effective) wire J_e=940 A/mm^2.), CTD101-K impregnation

RC5 reached 8.3 kA and were safely protected. $J_{e,cable}$=740 A/mm^2 and $J_{e,strand}$=940 A/mm^2 (at 3.4 T) are practical current densities for applications

- (Extrapolated to 20 T) $J_{e,cable}$=412 A/mm^2 and $J_{e,strand}$=535 A/mm^2
- Coil was safely protected against quenches.



- A thermal run-off.



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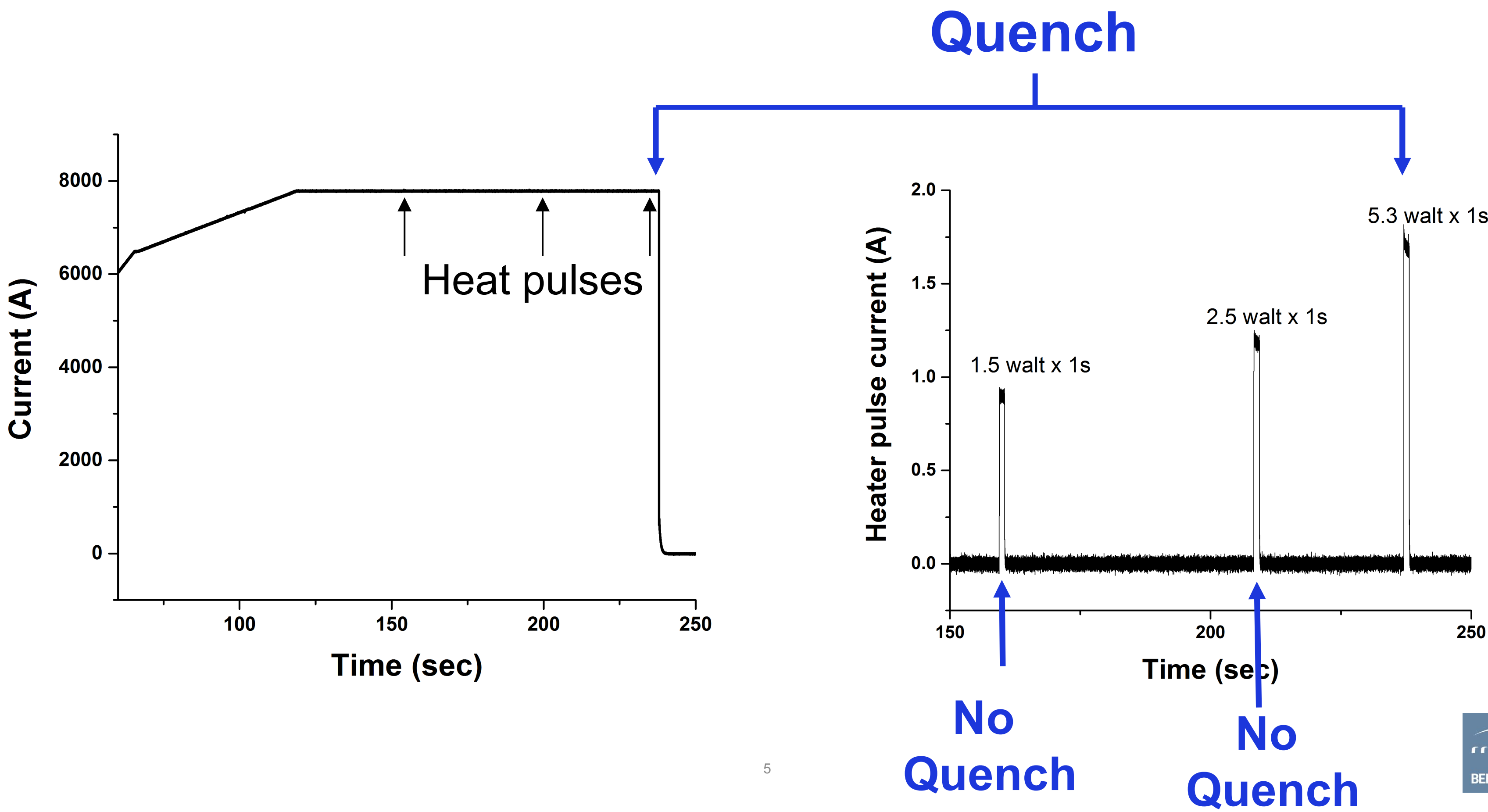
RC5 is quite stable against disturbances, even at 7925 A => robust against training

- No quench against heater pulses at 1.5 W for 1 s, and 2.5 W for 1 s. Finally quenched at 5.3 W for 1 s.
- Heat pulse applied at the turn #1 (straight section, B≈2.5 T).



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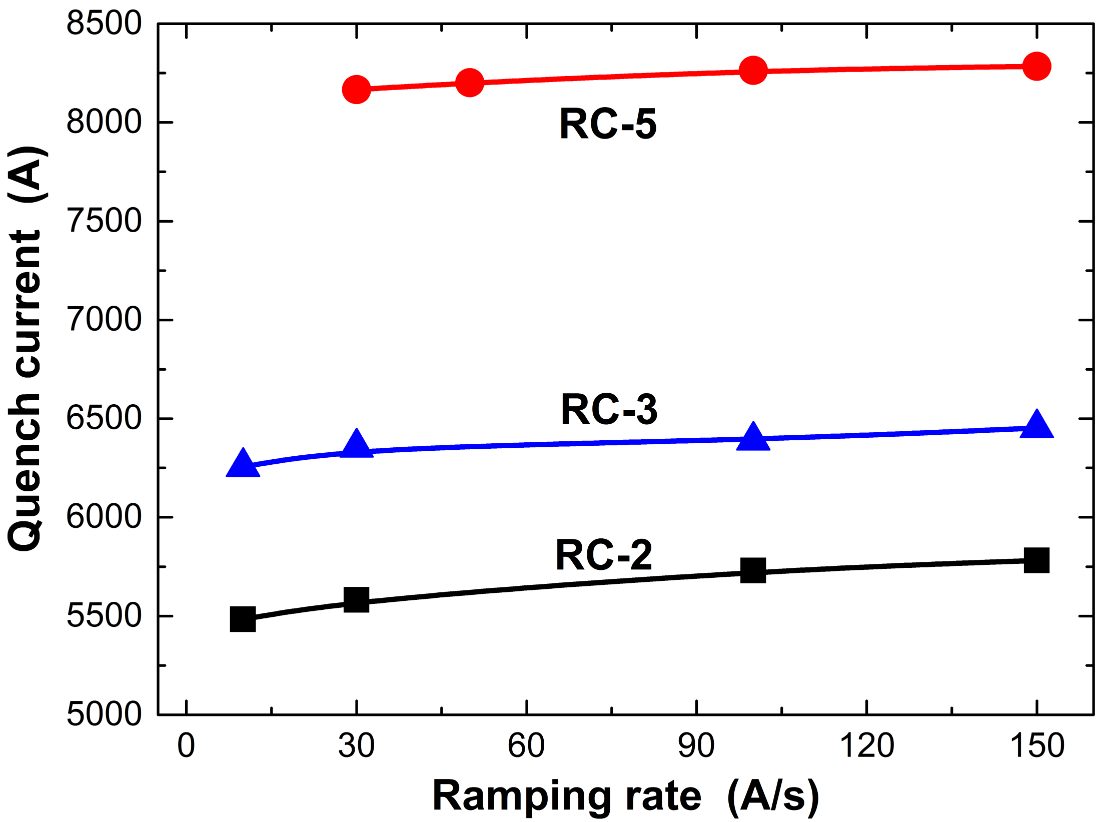
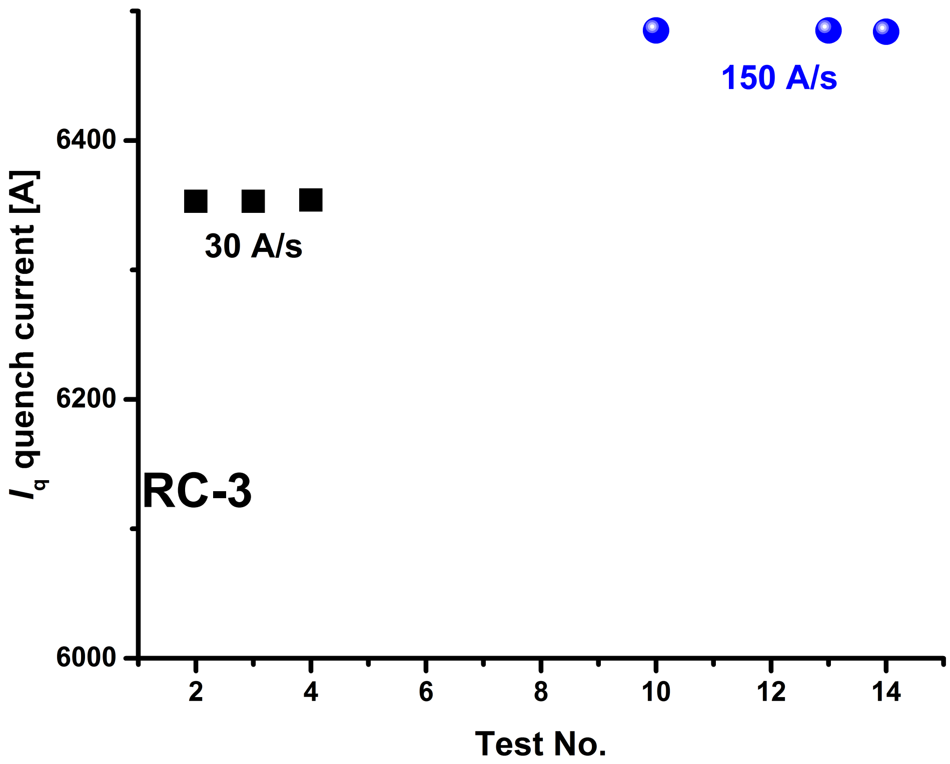
Interesting features of RC coils (1) – Inverse I_q-dI/dt dependence

- **High stability against AC loss.**



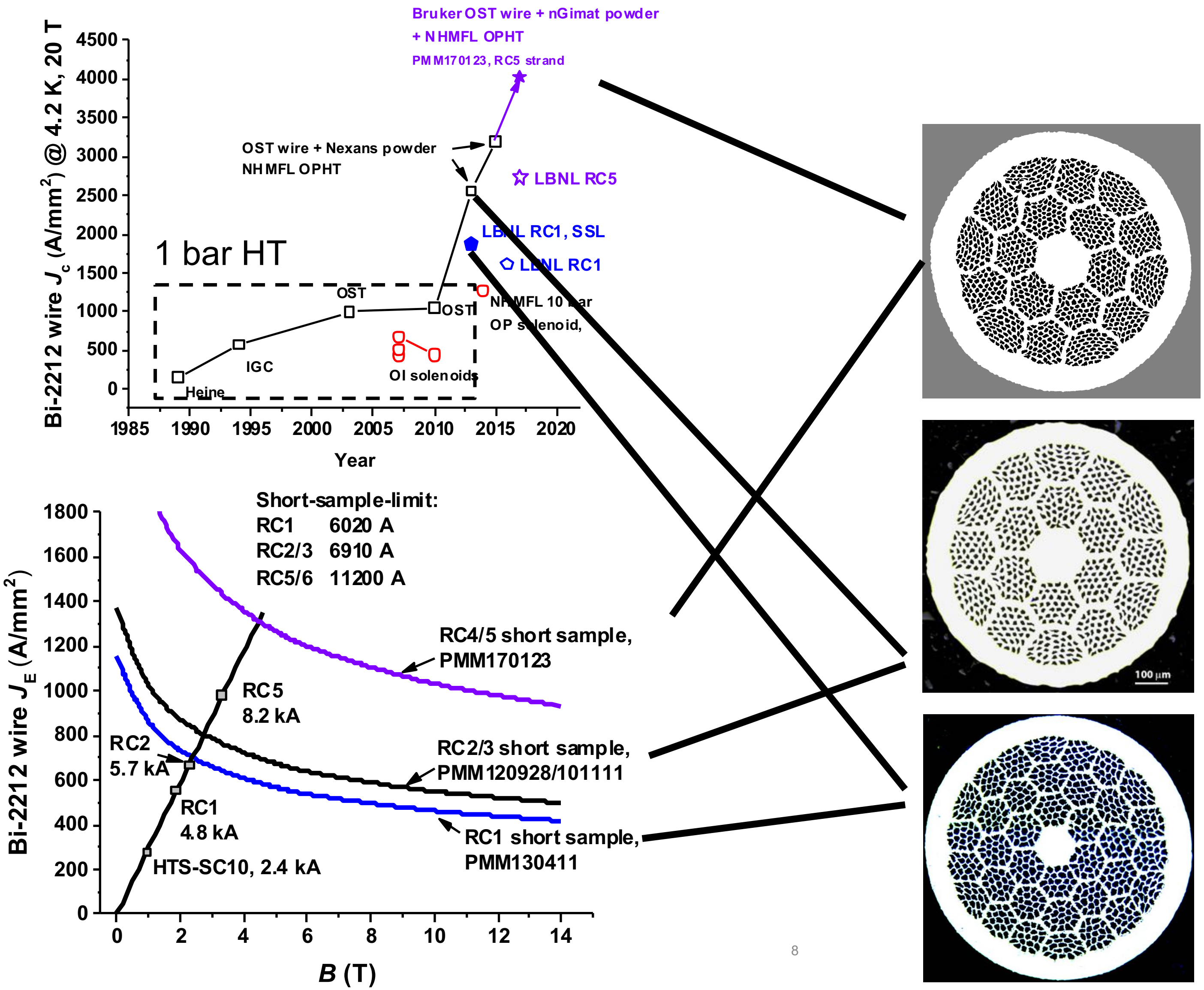
Interesting features of RC coils – a "clock" magnet with I_q reliably produced

A "clock" magnet



RC5 is possible because of advances in powder, wire, cable, and OPHT technologies,

and it also verifies progresses and technological readiness on these fronts.



PMM170123, 55x18, nGimat power LXB-52

Conservative short sample J_E used.
See Larbalestier, MT25 talk

PMM101111, 36x18, Nexans powder 77

PMM130411, 19x36, Nexans powder 77

Contributors – RC5 is a product of successful collaboration between U.S national lab, university, and industries.

- **K. Zhang**, **H. Higley**, A. Lin, L. Garcia Fajardo, J. Taylor, M. Turqueti, T. Shen

- **E. Bosque**, J. Jiang, U.P. Trociewitz, E.E. Hellstrom, D.C. Larbalestier

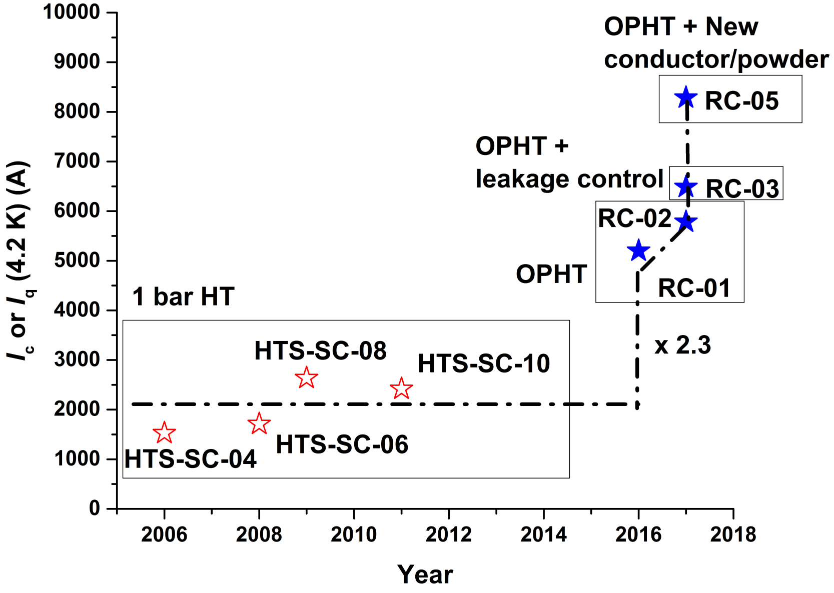
The LBNL RC5 was made from the wire PMM-170123, fabricated by Bruker OST with new Bi-2212 powder developed by nGimat LLC (DOE SBIR support) and donated to LBNL.

- H. Miao, Y. Huang

- **M. White**, R. Nesbit, A. Xu, A. Hunt

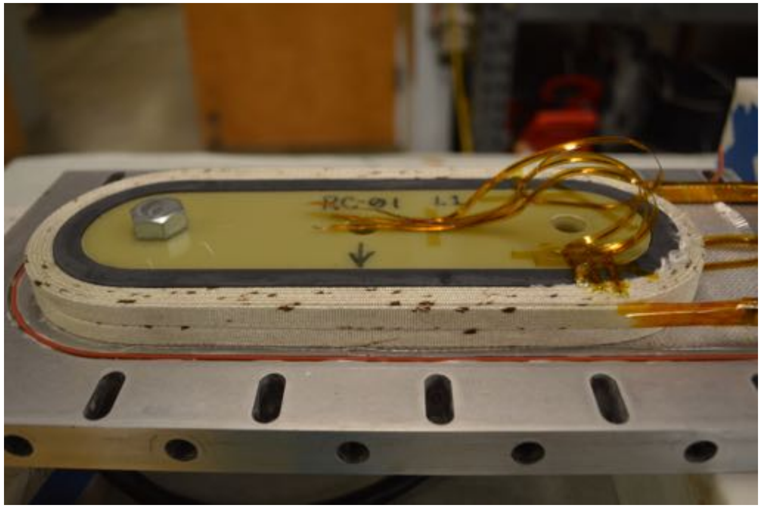
Despite of OP, leakage lingered around; it is controlled by a new NHMFL insulation scheme.

RC2 to RC3: Removing leakage using a new insulation scheme (TiO_2 + mullite).

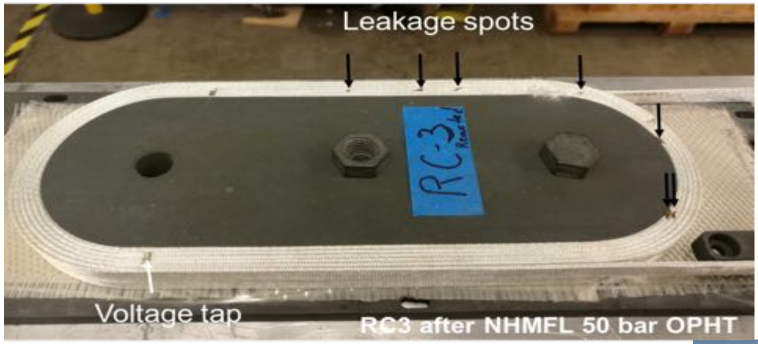


Special thanks to Jun Lu (NHMFL) for providing TiO_2 slurry.

Many leaks in RC1, RC2, RC5.



A few leaks in RC3.



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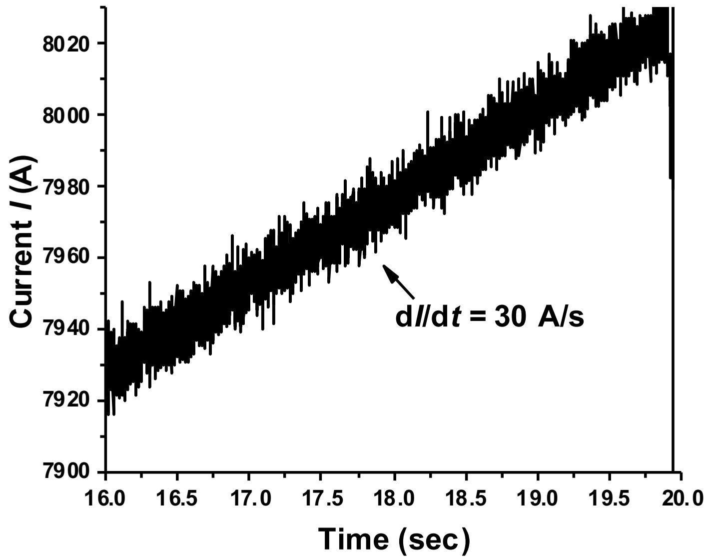
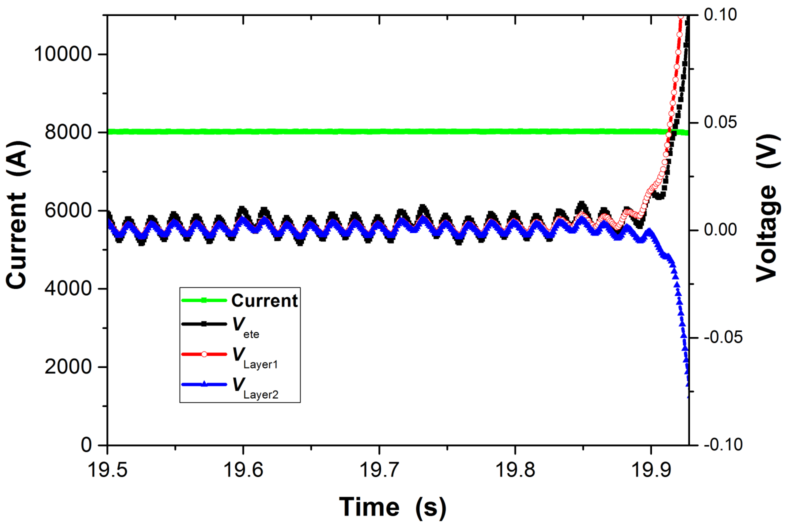
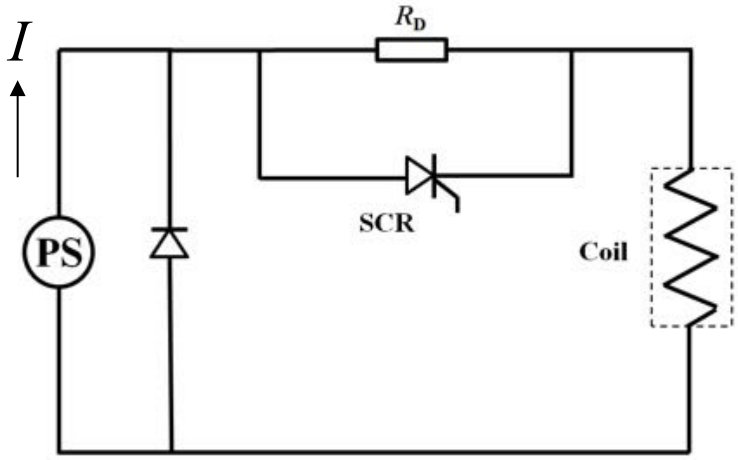
Quench detection and protection at wire J_o of 910 A/mm^2

– Example: A linearly increased current run, coil voltage seems no different from those of LTS magnets







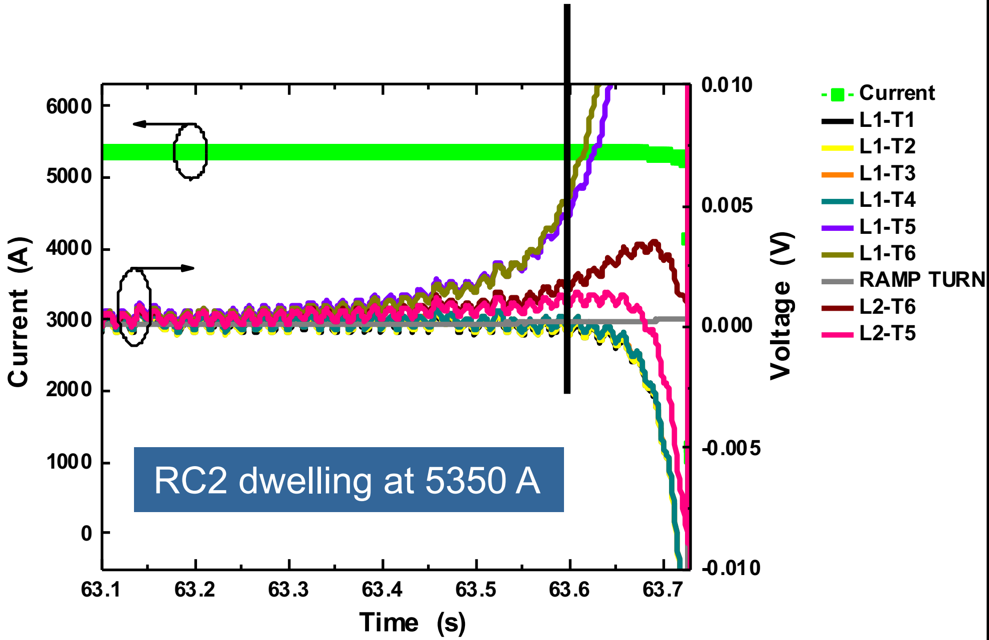
t=19.782 s, *Voltage taking off.*

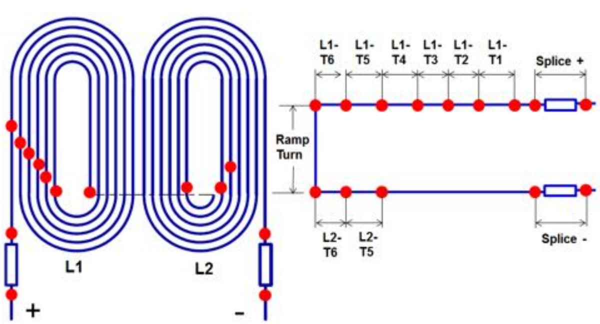
t=19.895 s, V_{ete} = 0.011 V

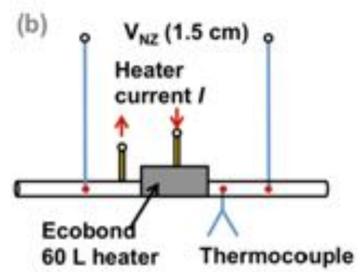
Feasible voltage-based quench detection. Why?

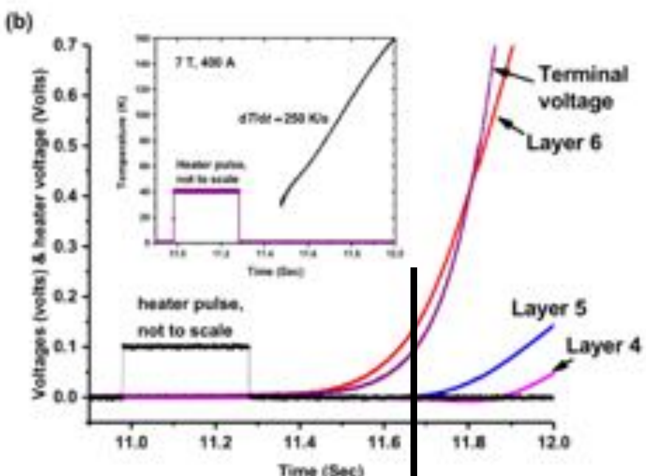
First impression: Quenching doesn't occur with a single, localized hot spot, rather with multiple hot spots with several turns

V_{ete} reached
10 mV – normal zones at four turns









Shen et al. *Supercond. Sci. Technol.* 29 (2016) 08LT01

V_{ete} reached
100 mV – normal zone in one layer

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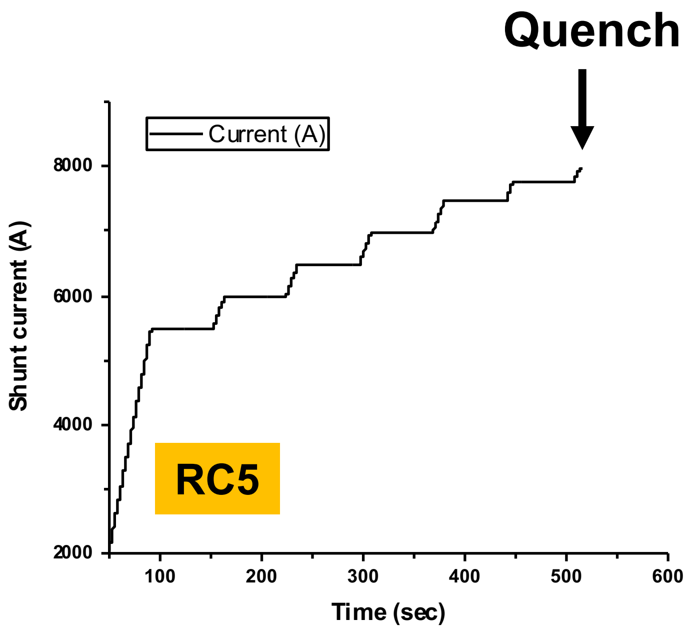
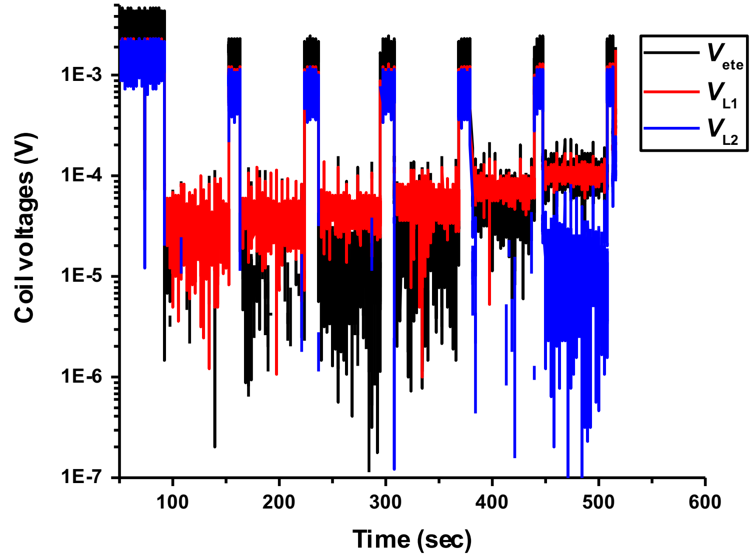
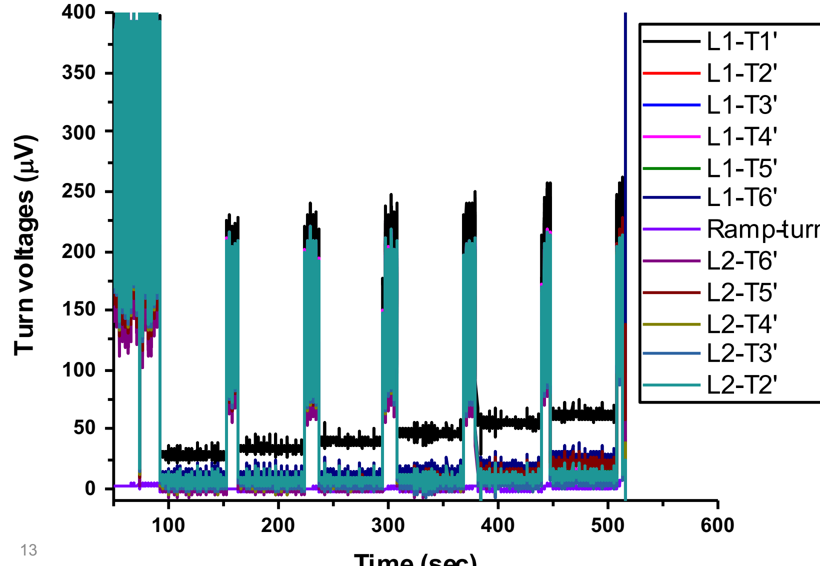
A staircase run that ends with a quench - Voltage rises, though small, are visible during current holds at different levels.







L1-T1 having voltage rises due to heating from splices.

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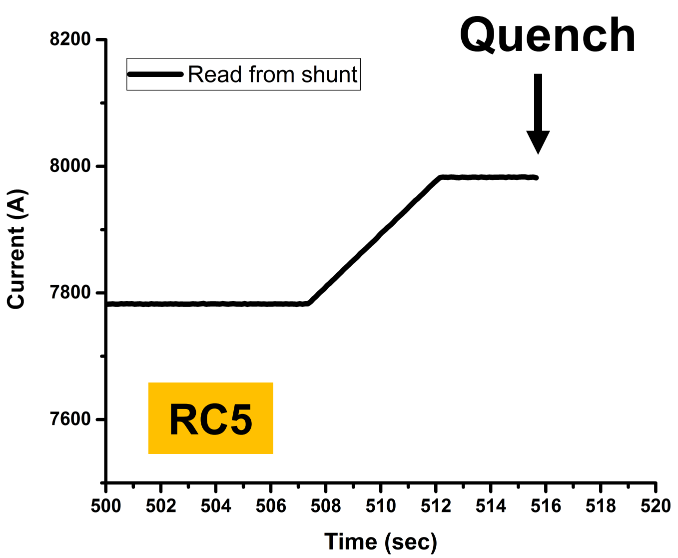
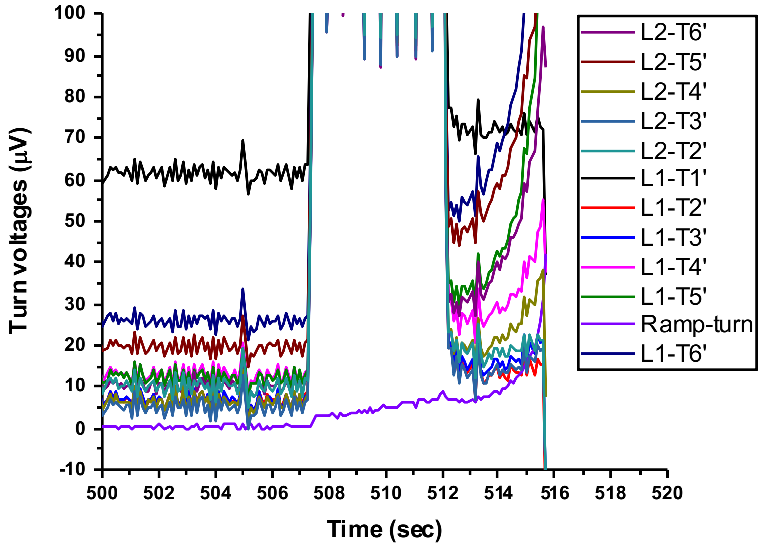
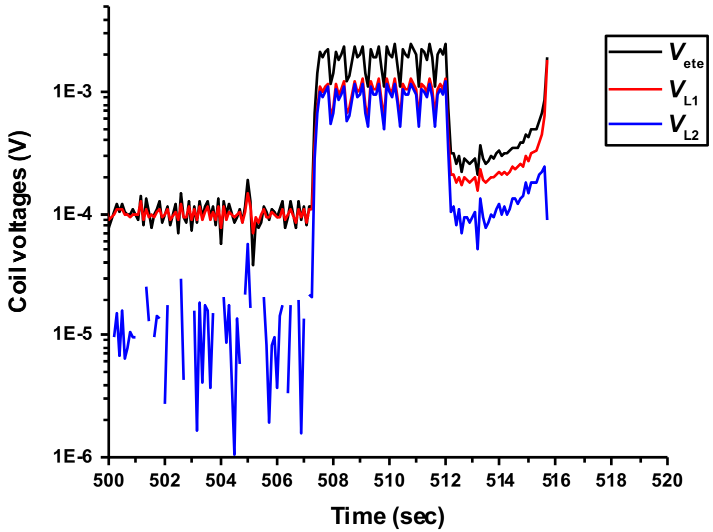
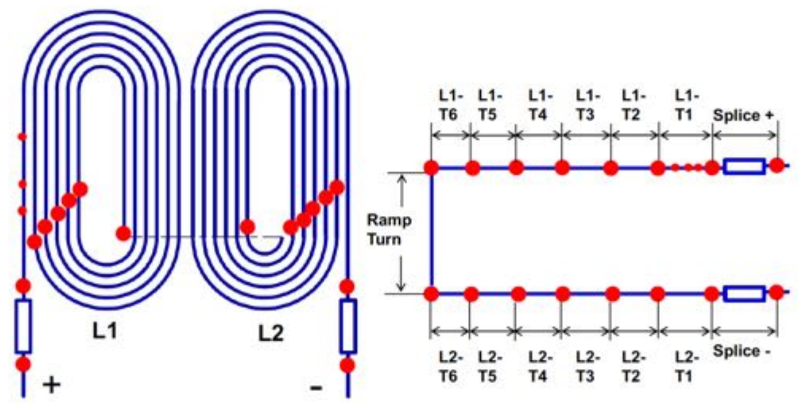
Zoom in the end of the staircase run

Thermal run-off at the inner seven turns.









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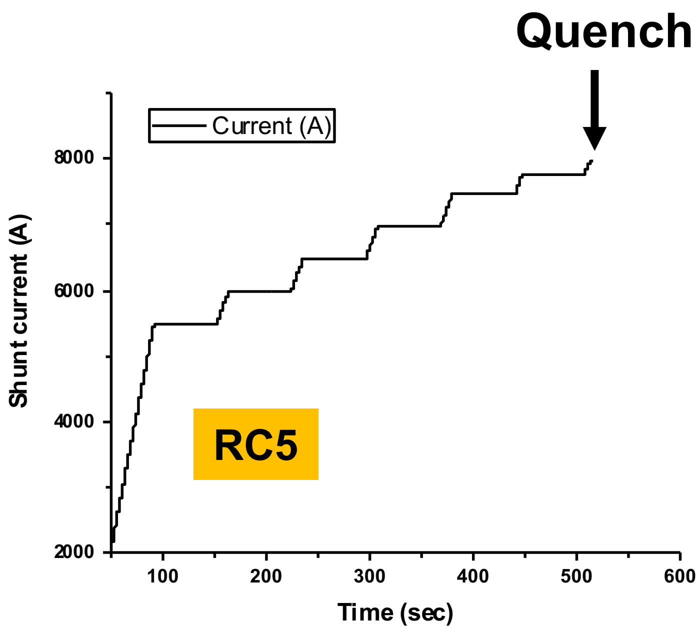
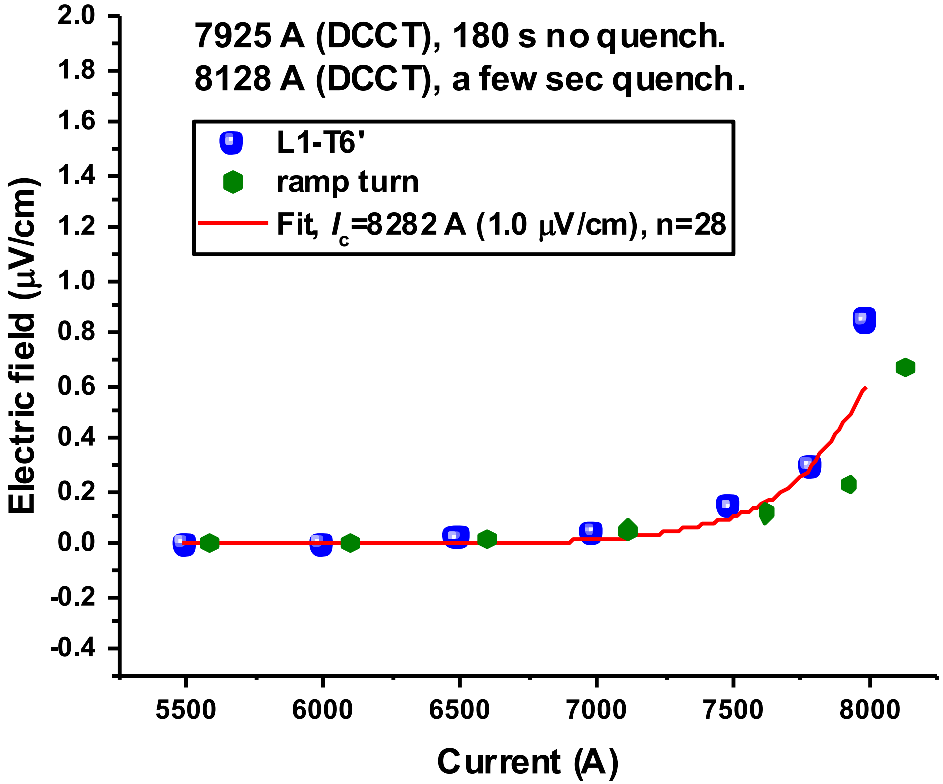
E-I curve and I_c derived from current holding tests





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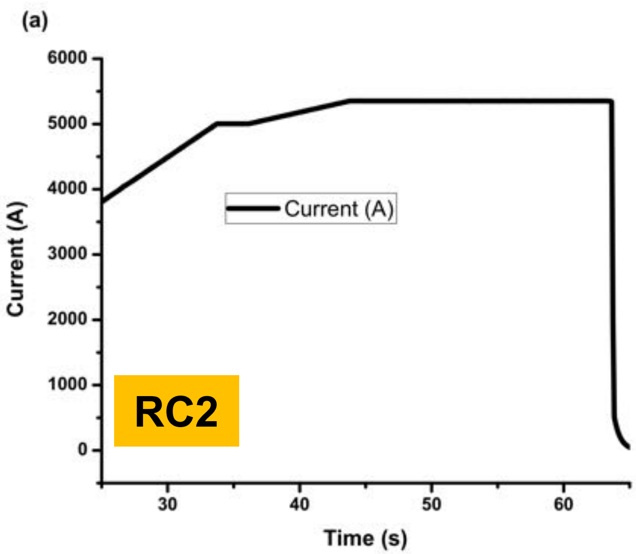
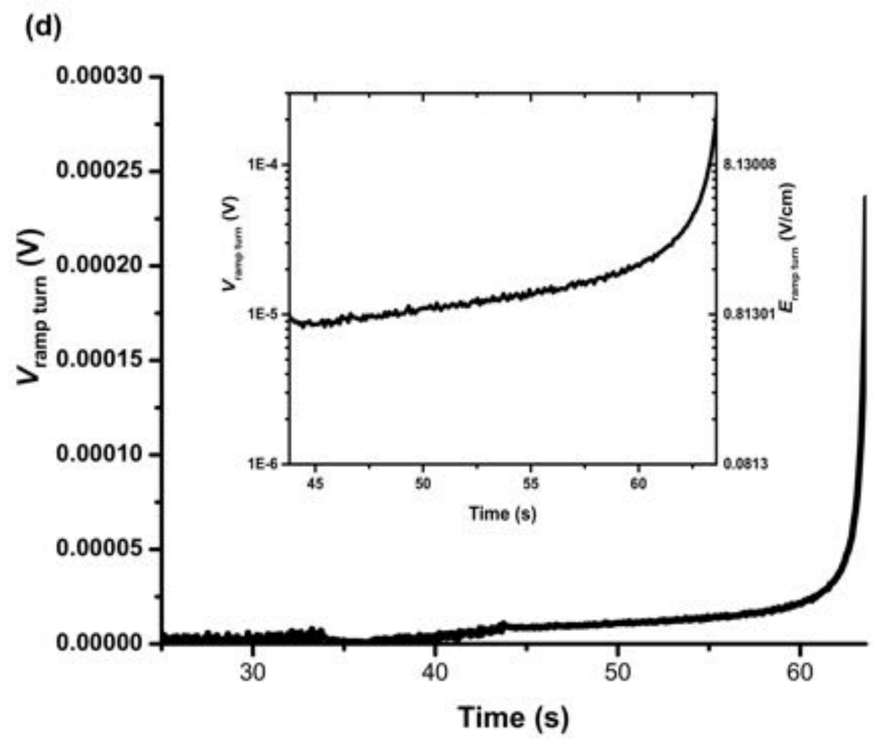
Implications – HTS magnets as a new paradigm for superconducting magnet technology?

- **Is it a superconducting magnet technology without the costly premature quenches due to localized, transient disturbances such as epoxy cracking and conduction motion, and without a quench training?**
- **If yes, an entire different quench detection technique and operation strategy can be employed to provide a new paradigm.**
  - **With modern electronics, targeted voltage taps, and staircase powering scheme, quench detection using voltage taps with improved detection resolution from >100 mV to nearly 10 μV.**
  - **Or maybe**
  - **The magnet does not need to quench.**

Another operation case that illustrates high-stability and possibility of ~10 μV quench detection.





Ball park analysis – 1.125 J into the ramp turn within ~15 s, with the conductor temperature around 14 K.

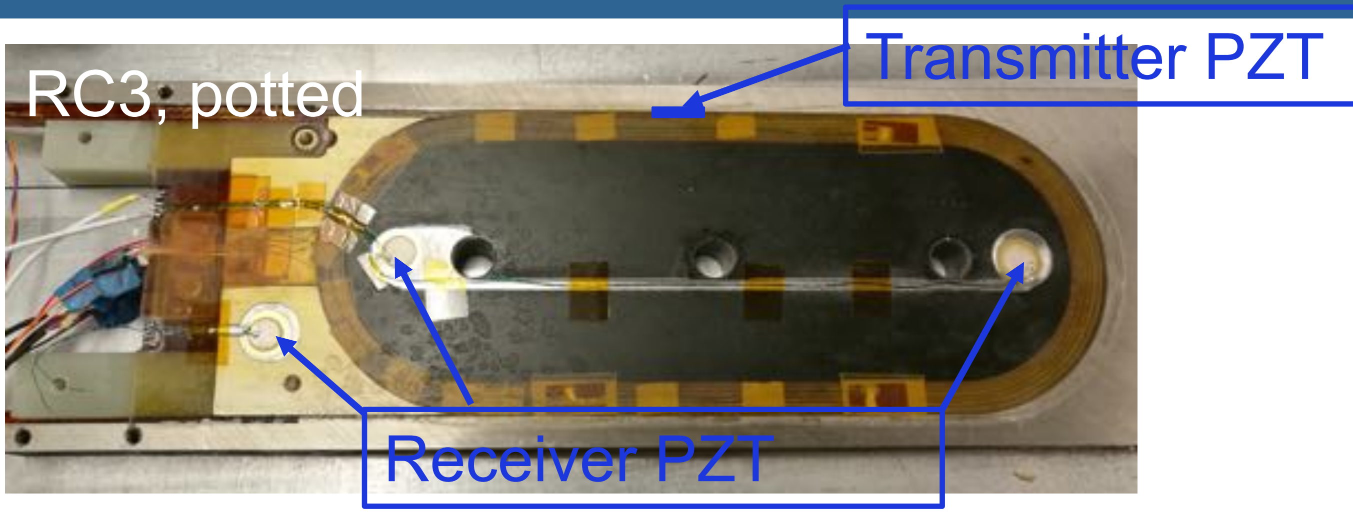
Key messages

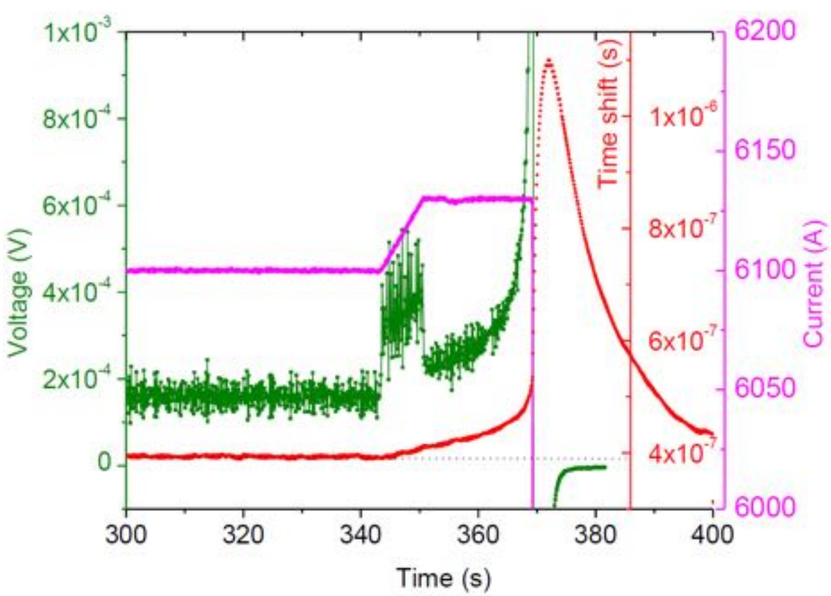
Wire J_e – 940 A/mm^2, cable J_e - 740 A/mm^2, cable I_q - 8300 A, stable at 7800 A, now achieved in LBNL RC5 subscale magnet.

- **2212 conductors are ready for magnets**
- **Significant wire J_c increase in 2017.**

Magnets – with highly stability. Quench detection feasible. New paradigm possible.

Subscale magnet as a technology development testbed - Noninvasive, fast acoustic sensing technique promising for quench detection tested on RC3



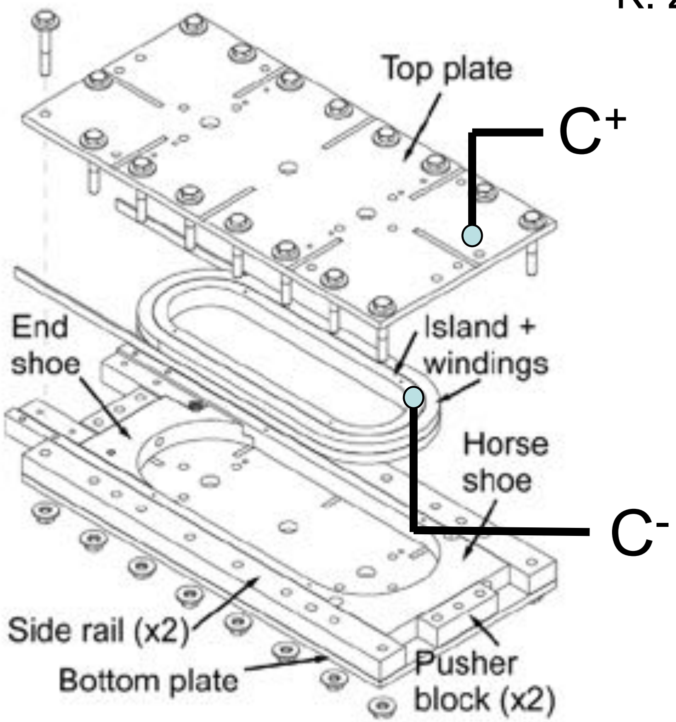


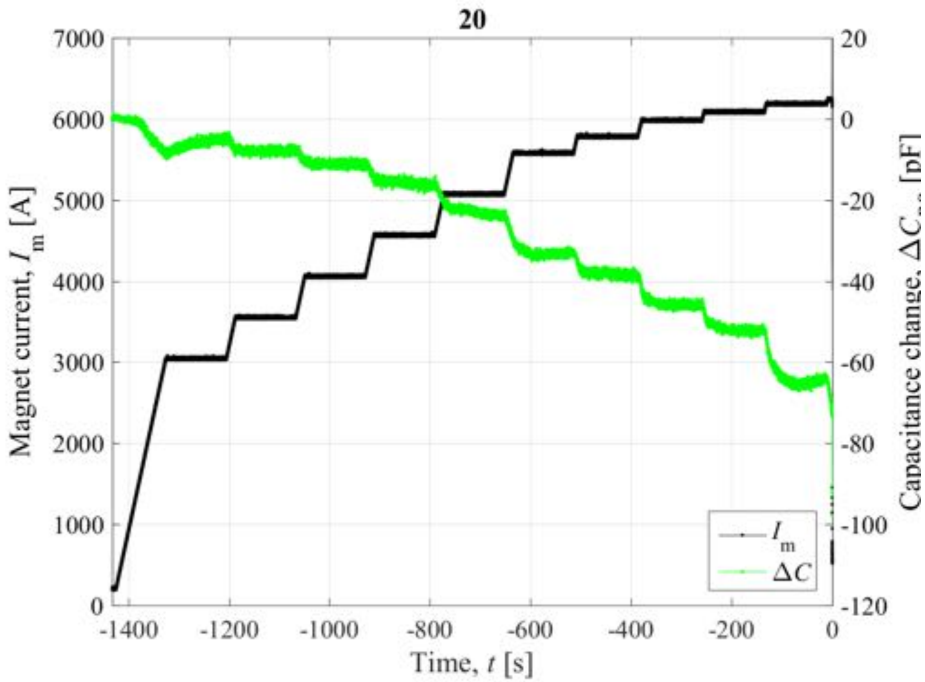
With M. Marchevsky, LBNL

Marchevsky and Gourlay,
Appl. Phys. Lett. **110**, 012601 (2017);

Subscale magnet as a technology development testbed –
Rugged capacitance probing technique promising for monitoring magnet operation and quench detection tested on RC coils

With **E. Ravaioli (LBNL)**, M. Marchevsky (LBN), and K. Zhang (IHEP visiting at LBNL)





- ***Capable of detecting joule heating as small as 10 mW.***

2018 – Task 1 – Continue subscale magnet development to test new technologies and test coils in fields of >10 T

- **Excellent technology test-beds**
  - Conductor and HT technology development support.
  - RC5 + RC6 in common coil configuration generating 5.4 T (Daniel Davis, FSU PhD student visiting LBNL)
  - RC7 + RC8 (with wire twisting), testing CLIQ quench protection.
- **HTS as a new paradigm: Verify if 2212 magnet technology is quench training free at high-fields of >15 T.**
  - 15 T, series-connected Nb_3Sn/2212 in the SD structure as a possibility.
  - Other possibility is 2212 coils in the HD1 structure.

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2018 – Task 2 – Redefine what is possible – 20 T dipole with 2212 CCT technology

Extend high J_c to CCT – 39 cm long BIN5 using the nGimat/Bruker OST wire PMM170725.

- Fabricate and test >3 coils.

Test and design support to finalizing parameters of a 20 T LTS-HTS hybrid dipole.

Opportunities and challenges in 2018

More conductor progress powered by SBIR small business-university-lab – wire industry collaboration likely.

Project resource limited in 2017 and getting more severe in 2018.

- Help from a PhD student in 2017 is gone.
- Technician/designer

- Build up the unique capability – 1 m long, 250 mm bore OP furnace (baseline design).

Outline

- Bi–2212 CCT insert magnets
  - ✓ BIN4 and BIN5 prototypes. Goals and status
  - ✓ BIN6 design options
  - ✓ Increasing the efficiency of CCT magnets
  - ✓ Summary

- 15 T hybrid (Bi-2212 and Nb_3Sn) subscale dipole
  - ✓ Magnetic analysis
  - ✓ Mechanical analysis and modifications to the existent structure
  - ✓ Summary

Bi–2212 CCT insert magnets
BIN4 and BIN5 prototypes. Goals and status

A bit of a reminder…

<u>Specific goals of BIN4</u>:

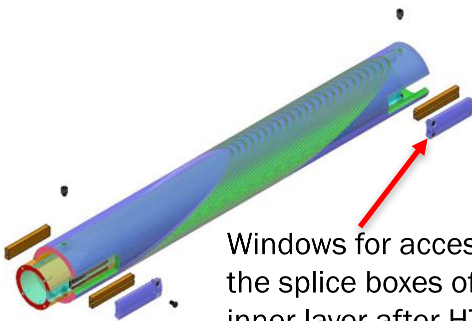
- Test I_c when undergoing 1 bar HT
- Investigate conductor quality after heat treating **both layers together**
- Reach 0.7 T in the bore

<u>Specific goals of BIN5</u>:

- Test I_c when undergoing 50 bar HT

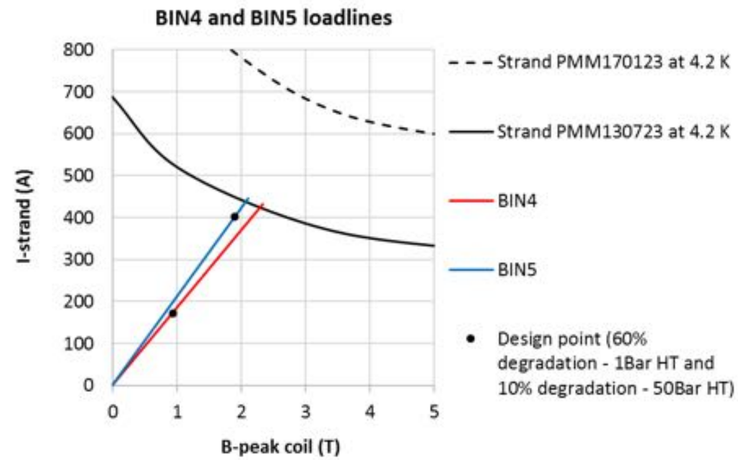
<u>Goals of BIN4 and BIN5</u>:

- Investigate technology issues during manufacturing process and quench propagation and protection techniques.

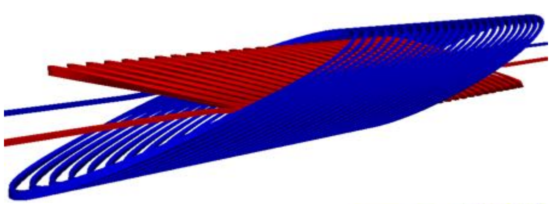


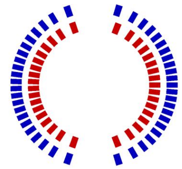
Windows for accessing the splice boxes of the inner layer after HT

PMM130723 is not the state–of–the–art conductor

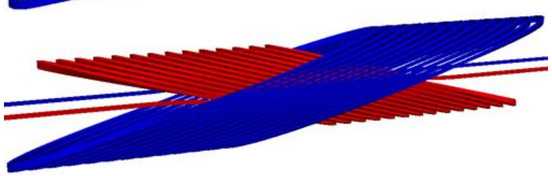


BIN4
Total length: **50 cm**





BIN5
Total length: **39 cm**



9–strand, 0.8 mm Rutherford cable

Coil parameters	Layer 1	Layer 2
Bore diameter (mm)	38.1	51.1
Spar (mm)	1.871	1.971
Outer diameter (mm)	50.3	63.5

Bi–2212 CCT insert magnets
BIN4 and BIN5 prototypes. Goals and status

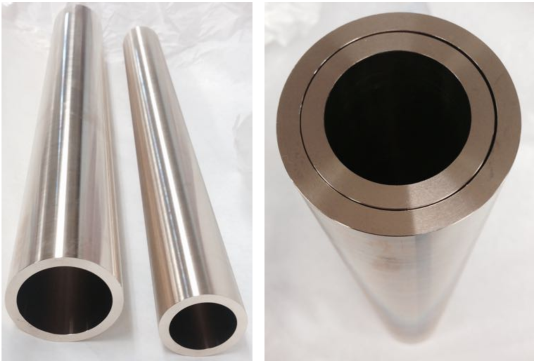
Where were we at the last collaboration meeting?

BIN4:

- The mandrel tubes were purchased, skinned and ready for machining
- The magnet was expected to be tested by the end of 2017

BIN5:

- The shop drawings were under preparation
- The magnet was expected to be under preparation for testing by the end of 2017



Al - Bronze tubes before machining

Where we are?

BIN4:

- The magnet is assembled and ready for HT

BIN5:

- The outer layer is under manufacturing

Why?

BIN4:

- Issues encountered during the manufacturing process
- Deficit of technical support to meet the deadlines

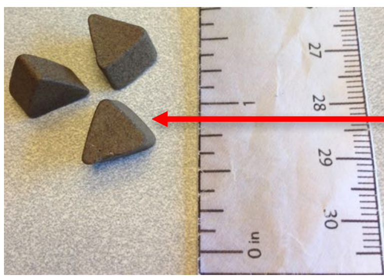
BIN5:

- Change of some features based on the issues encountered during the manufacturing process of BIN4
- Deficit of technical support to meet the deadlines

Bi–2212 CCT insert magnets
BIN4 and BIN5 prototypes. Goals and status

Manufacturing process of BIN4

1. Mandrel polishing
   - ✓ Sharp edges of the mandrels were smoothed in a polishing tumbler filled up with ceramic pieces during 4 h



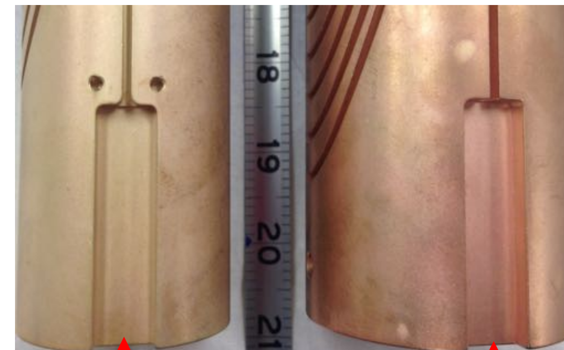
Ceramic points from the tumbler

Al - Bronze mandrels after polishing

Outer layer

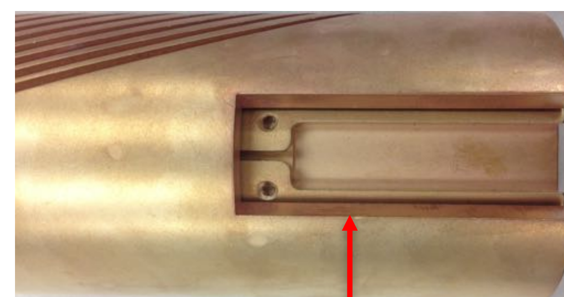
Inner layer

Splice pockets after polishing



Inner layer

Outer layer



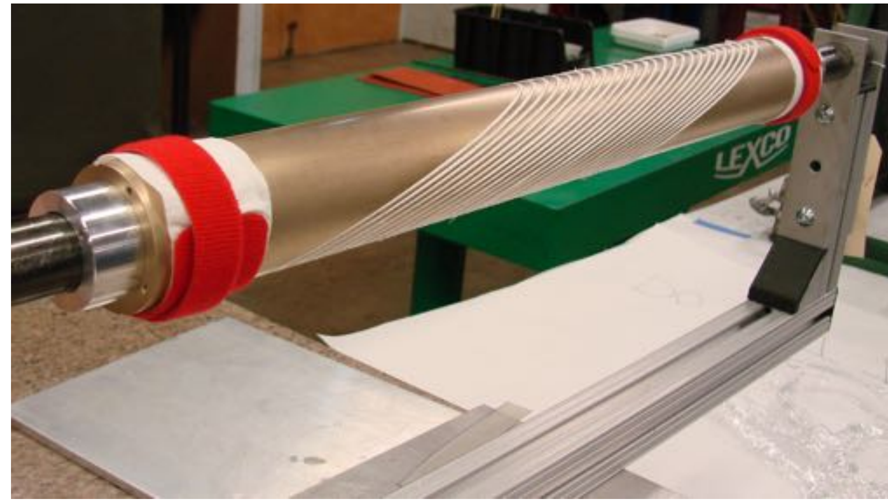
Access to the inner layer after removing windows

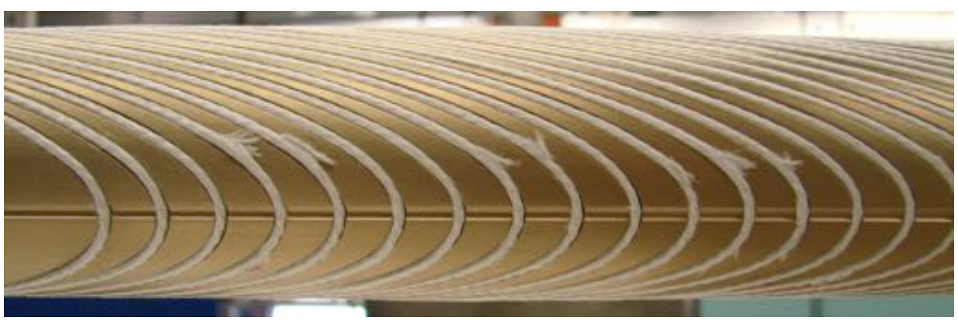
Bi–2212 CCT insert magnets
BIN4 and BIN5 prototypes. Goals and status

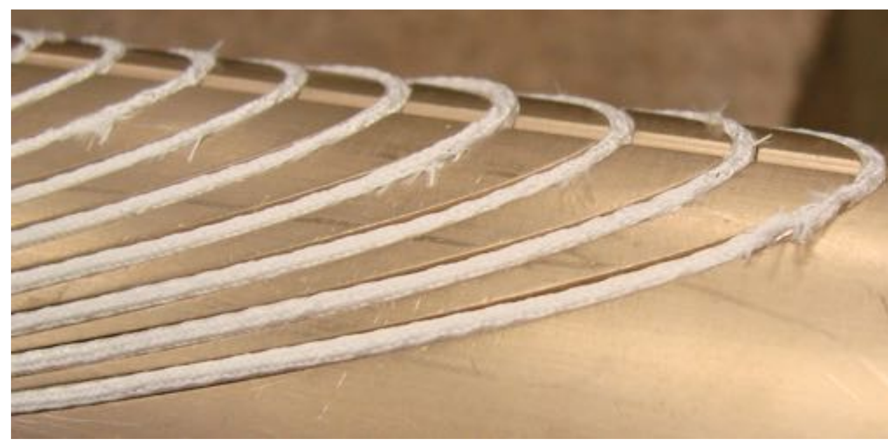
Manufacturing process of BIN4

2. <u>Coil winding</u>

- ✓ Mullite sleeve very brittle. Not adequate for CCT magnets
- ✓ The edges of the channel ripped the insulation, specially at the poles
- ✓ Both coils are shorted almost everywhere (at poles and straight section)





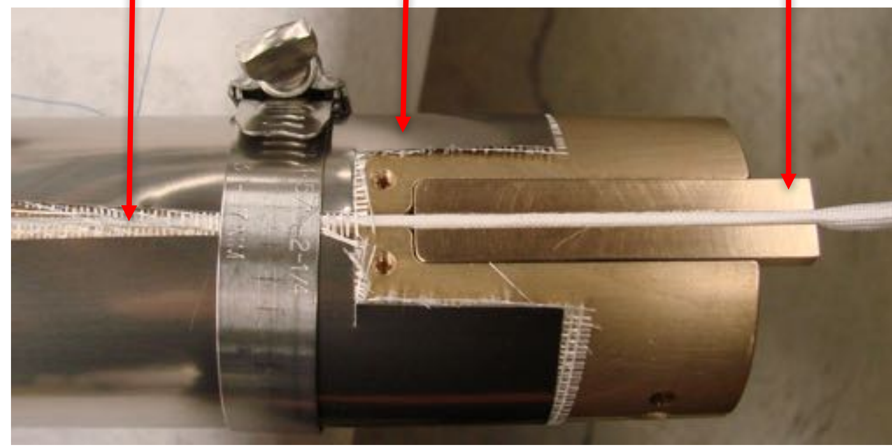


Bi–2212 CCT insert magnets

BIN4 and BIN5 prototypes. Goals and status

Manufacturing process of BIN4

3. <u>Magnet assembly</u>
   - ✓ Insulation between layers consist on mullite sheet and titanium foil
   - ✓ Titanium foil was very stiff and did not keep in place after removing the clamps (need to improve assembly process)



Bi–2212 CCT insert magnets
BIN4 and BIN5 prototypes. Goals and status

Status of BIN4
Furnace needs to be calibrated for HT

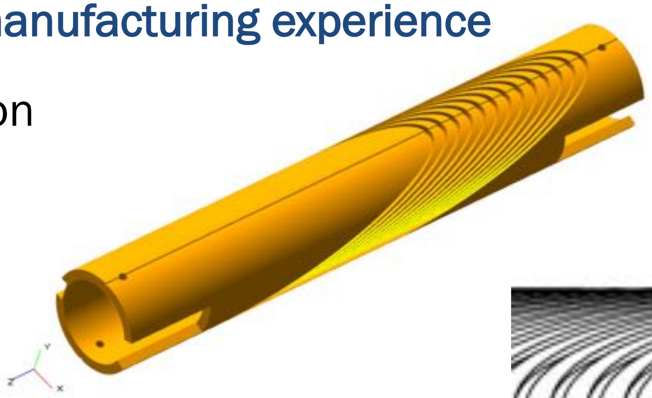
Modifications to BIN5 based on BIN4 manufacturing experience

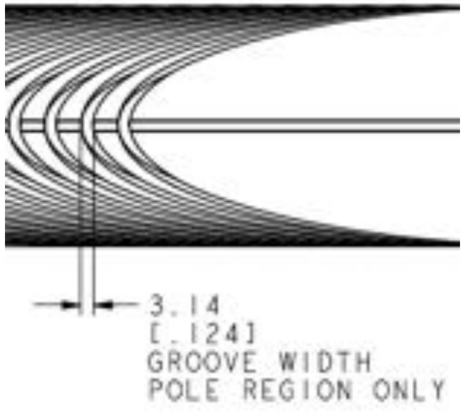
Add gap in the channel at the pole region

- ✓ Easier winding process
- ✓ Less insulation damage

Insulation reinforcement

- ✓ Either two layers of mullite sleeve, or a layer of TiO_2 plus a layer of mullite sleeve





Status of BIN5
Outer layer tube is under manufacturing

Bi–2212 CCT insert magnets
BIN6 design options

U.S. MAGNET DEVELOPMENT PROGRAM

Focusing on MDP short-term goal:

"Bi-2212 inserts that produce 5 T in the bore as standalone and 3 T under a background field of 15 T"

Insert magnet approach

- **Small outer diameter**
- **High J_E in the cross section**

This combination is challenging

- Optimize spar thickness
- Optimize conductor width

- Use the minimum number of layers (reduce the gap for assembly purposes)
- Fit as much conductor as possible (minimize the minimum rib thickness)

Limit: 0.25 mm rib for Aluminum-Bronze mandrels

Bi–2212 CCT insert magnets
BIN6 design options

1st design option for BIN6:

- 2-layer magnet
- 19-strand rectangular Rutherford cable

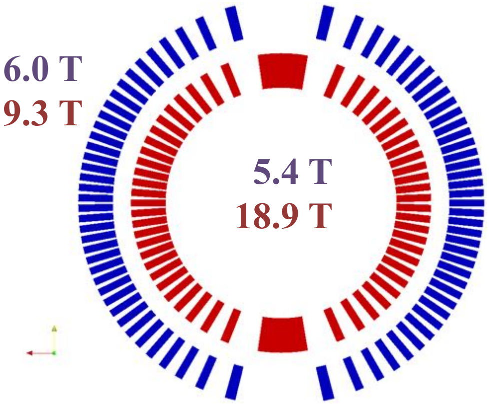
Coil and mandrel parameters	INNER COIL 19-STRAND	Outer Coil 19-strand
BD (mm)	40.00	73.60
ID (mm)	56.00	81.60
OD (mm)	72.80	98.40
a_w (mm)	1.70	1.70
b_w (mm)	8.40	8.40

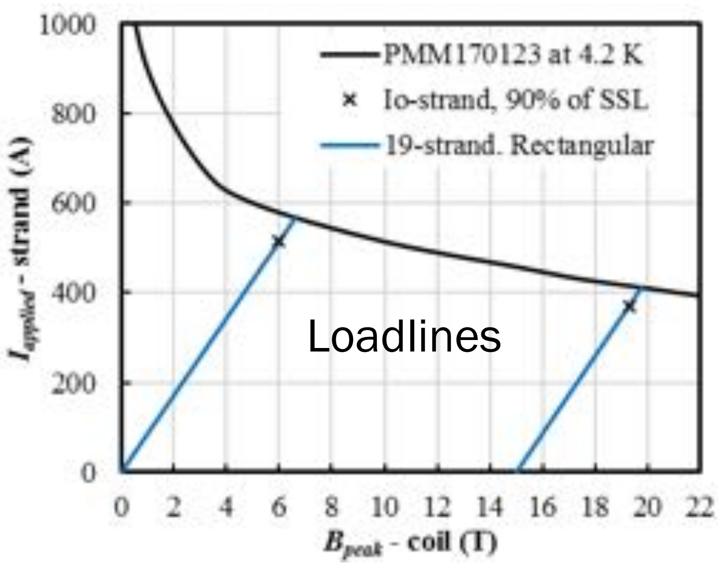
This design meets the short-term goal, but it could be tested under a high field background due to its large *OD*

I_o = 90% of *SSL*

Standalone: 9.8 kA

Background-15 T: 7.0 kA





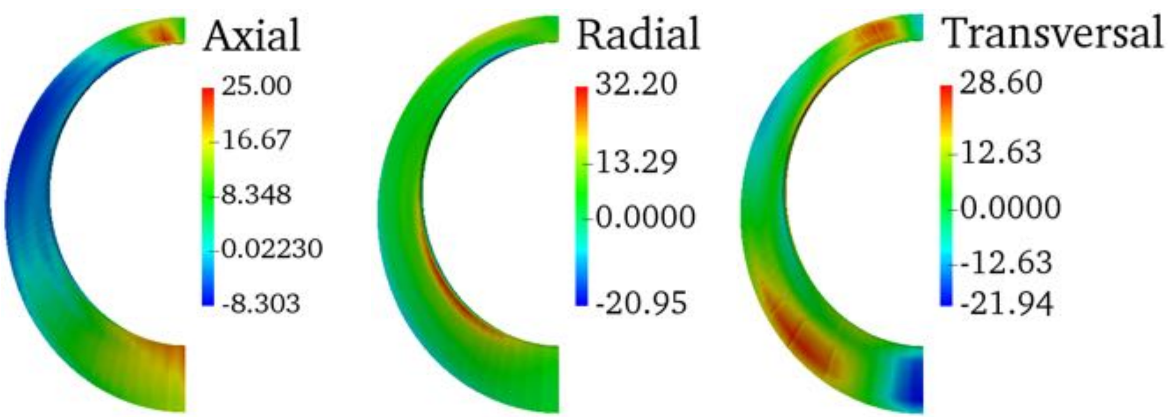
Bi–2212 CCT insert magnets
BIN6 design options

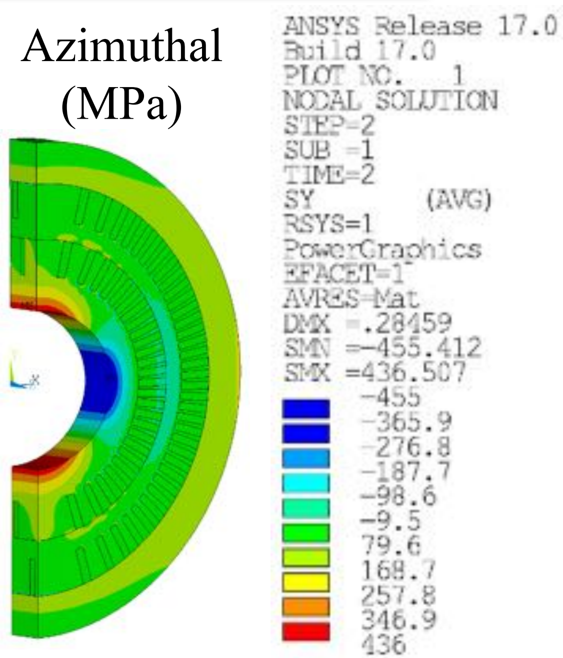
Stress analysis during operation, under uniform background field of 15 T

Stress limits of Bi-2212 conductor (D. R. Dietderich et al. IEEE Trans. Appl. Supercond. II, 1 (2001))

Epoxy impregnated Rutherford cable:
- 60 MPa applied to the wide surface of the cable
- 100 MPa applied to the narrow surface of the cable

Wire:
- Axial stress: ~150 MPa





Stress in MPa. Perspective from the longitudinal axis of the magnet; poles are represented at the top and bottom; the top pole is farther from the reader

Bi–2212 CCT insert magnets

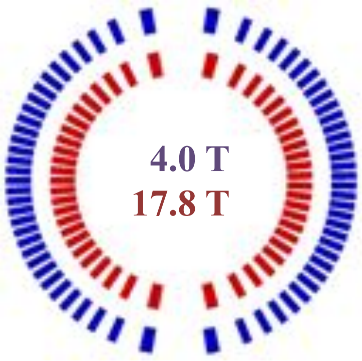
BIN6 design options

2[nd] design option for BIN6:

- 2-layer magnet
- 13-strand rectangular Rutherford cable

Coil and mandrel parameters	Inner Coil 13-strand	Outer Coil 13-strand
BD (mm)	40.00	61.40
ID (mm)	49.00	69.40
OD (mm)	60.60	81.00
a_w (mm)	1.70	1.70
b_w (mm)	5.80	5.80

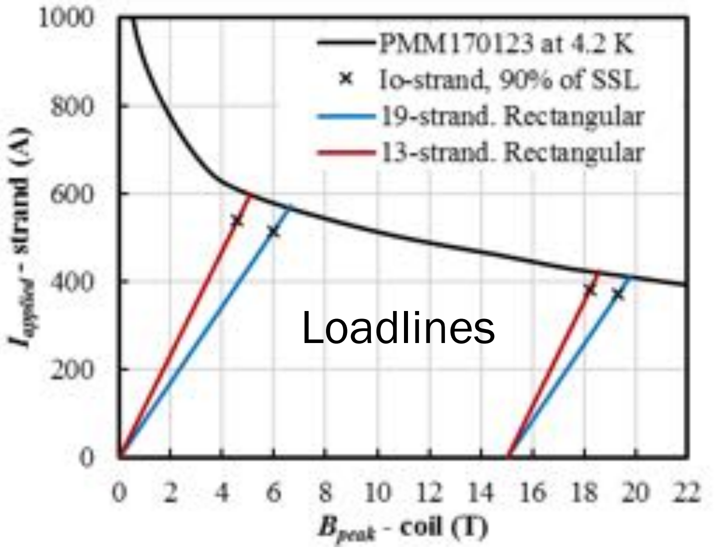
This design does not meet the short-term goal at I_o, but could be tested in an outsert magnet



I_o = 90% of *SSL*

Standalone: 7.0 kA

Background-15 T: 4.9 kA



Bi–2212 CCT insert magnets

BIN6 design options

Stress analysis during operation, under uniform background field of 15 T

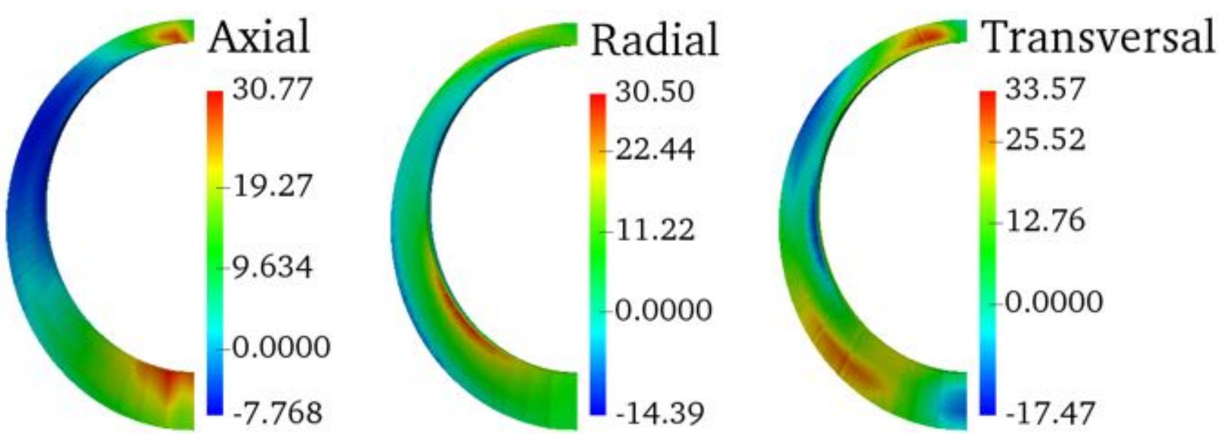
Stress limits of Bi-2212 conductor (D. R. Dietderich et al. IEEE Trans. Appl. Supercond. II, 1 (2001))

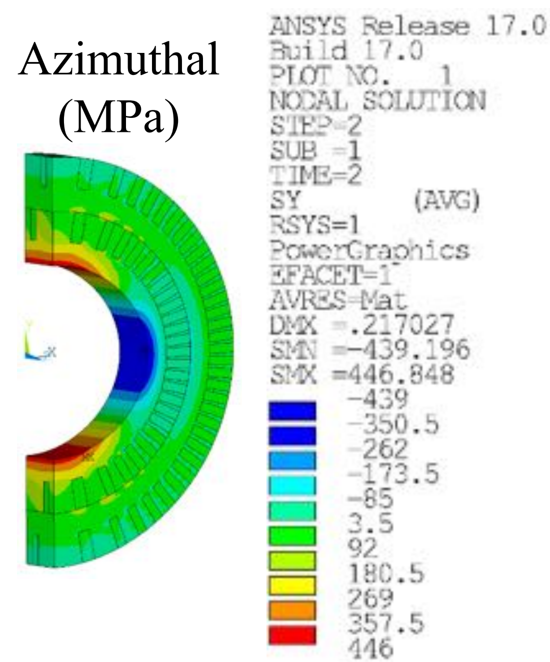
Epoxy impregnated Rutherford cable:

- 60 MPa applied to the wide surface of the cable
- 100 MPa applied to the narrow surface of the cable

Wire:

- Axial stress: ~150 MPa





Stress in MPa. Perspective from the longitudinal axis of the magnet; poles are represented at the top and bottom; the top pole is farther from the reader

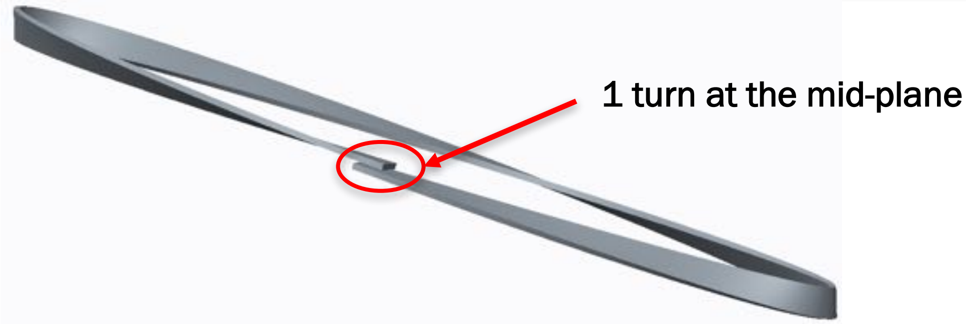
Bi–2212 CCT insert magnets

Increasing the efficiency of CCT magnets

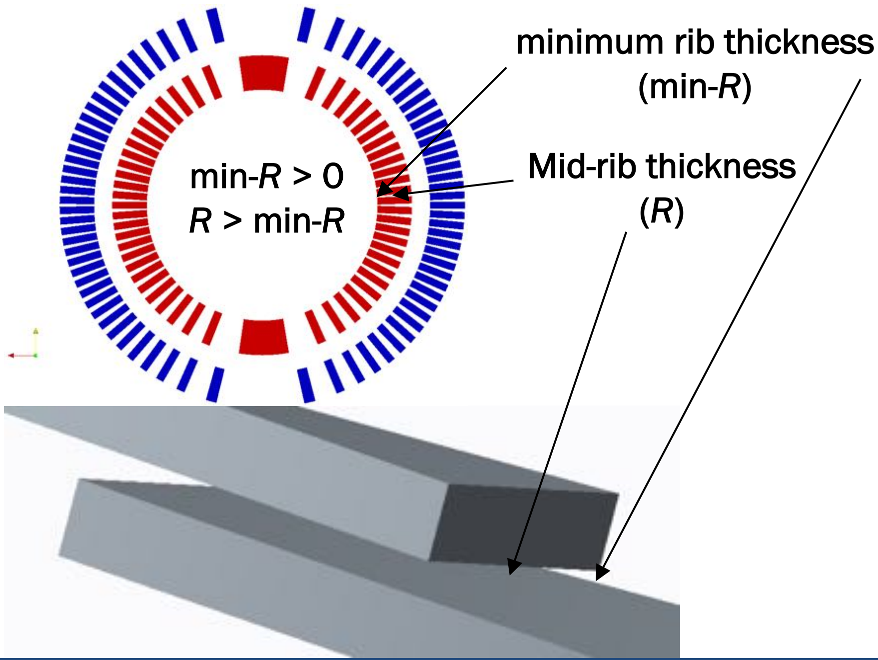
Efficiency:

$$\varepsilon = \frac{\cos(\alpha)}{1+\frac{R}{a_w}}$$

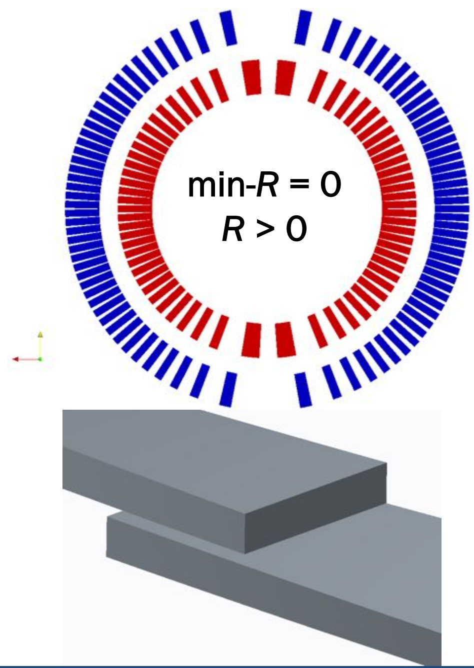
α: Tilt angle
a_w: Thickness of the cable
R: Mid-rib thickness



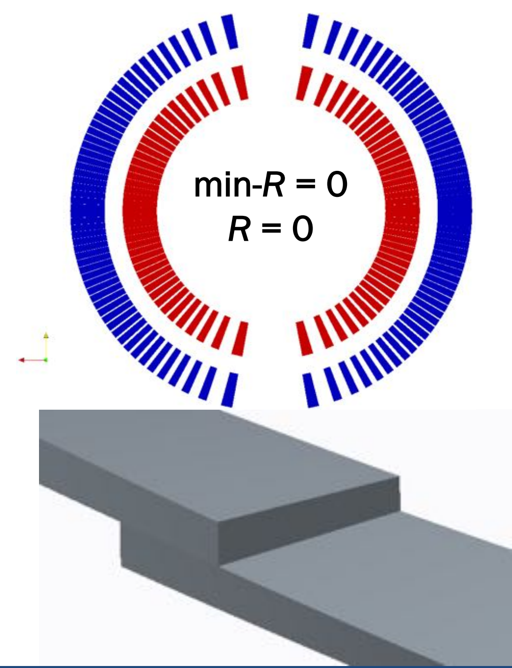
Rectangular cable



Rectangular cable



Keystoned cable



Bi–2212 CCT insert magnets

Increasing the efficiency of CCT magnets

$$\varepsilon = \frac{\cos(\alpha)}{1 + \frac{R}{a_w}}$$

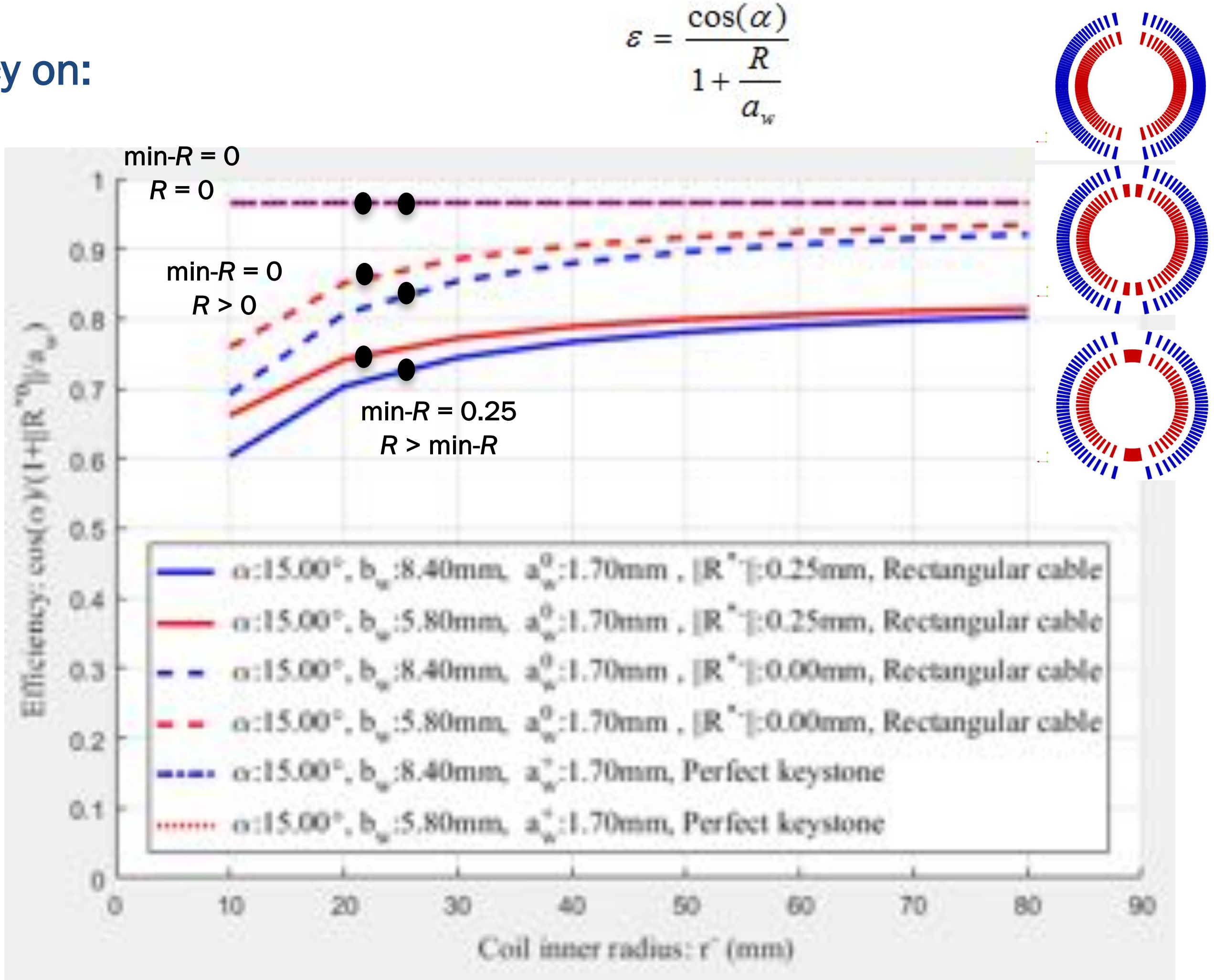
Dependence of the efficiency on:

- The coil's inner radius
- The cable's width
- The rib thickness

Blue plots:
Designs with 19-strand Rutherford cable

Red plots:
Designs with 13-strand Rutherford cable

Black dots:
Efficiency of the inner layer in each design



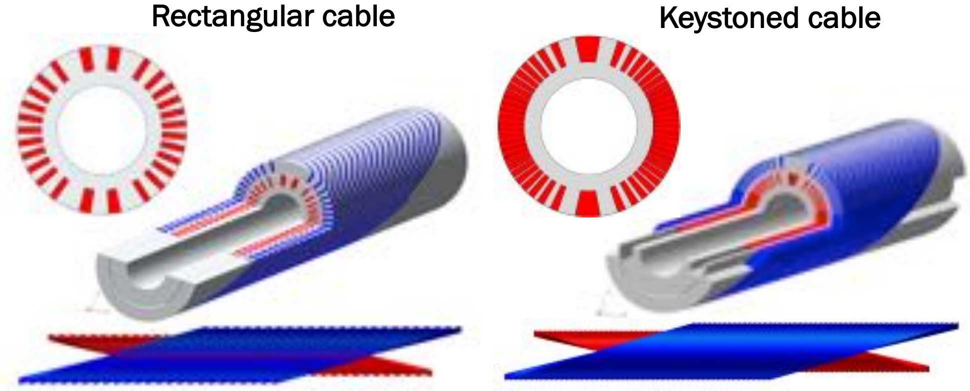
Bi–2212 CCT insert magnets

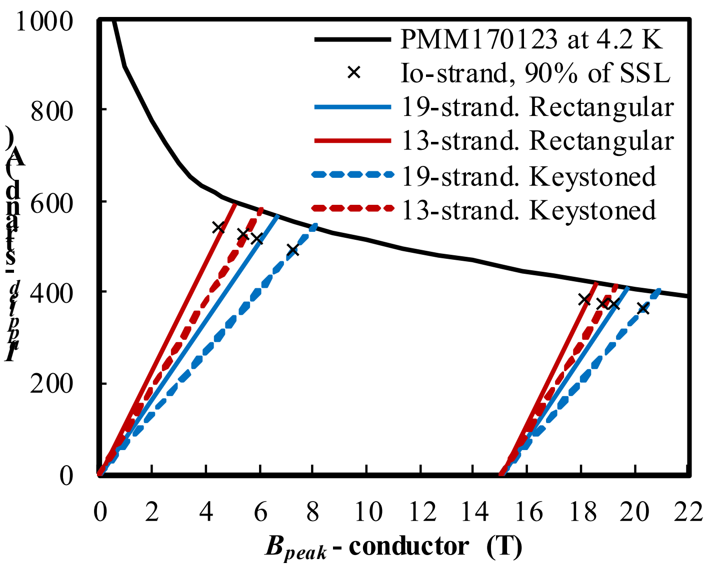
Increasing the efficiency of CCT magnets

Comparison between 19-strand and 13-strand Rutherford cable designs

The design with 13-strand keystoned Rutherford cable meets the short-term goals and could be tested in an outsert magnet

Magnet representation





Designs with keystoned cable

Coil and mandrel parameters	Inner Coil 19-strand	Outer Coil 19-strand	Inner Coil 13-strand	Outer Coil 13-strand
k (deg)	2.52	1.81	3.02	2.21
Parameters (Background field)	19-strand (0 T)	19-strand (15 T)	13-strand (0 T)	13-strand (15 T)
I_o (kA)	9.4	6.9	6.8	4.9
B_c (T)	7.3	20.4	5.4	18.9
B_b (T)	6.7	20.0	4.9	18.5

Summary
Bi–2212 CCT insert magnets

- Two 2-layer CCT prototypes are under construction to test the Bi-2212 technology in CCT magnets (BIN4 and BIN5)
- Two Bi-2212 CCT inserts have been designed to meet the short-term goals of MDP based on:
  - ✓ 19-strand rectangular Rutherford cable (meets the MDP goals but has a very large *OD*)
  - ✓ 13-strand rectangular Rutherford cable (has a smaller *OD* but does not meet the MDP goals)
- For both designs, stress analysis shows that the cable is not at risk
- When using keystoned cables
  - ✓ J_E increases significantly, and so the generated field
  - ✓ The efficiency does not depend neither on the coil's inner radius, nor on the cable's width
  - ✓ High field can be produced with high efficiency, in smaller *OD* CCT magnets
- Detailed mechanical analysis should be performed to ensure the integrity of the conductor

A question still remains:

Could the community provide an outsert magnet with larger bore diameter?
... we need some flexibility in size for the design of the HTS insert magnets

15 T hybrid subscale dipole

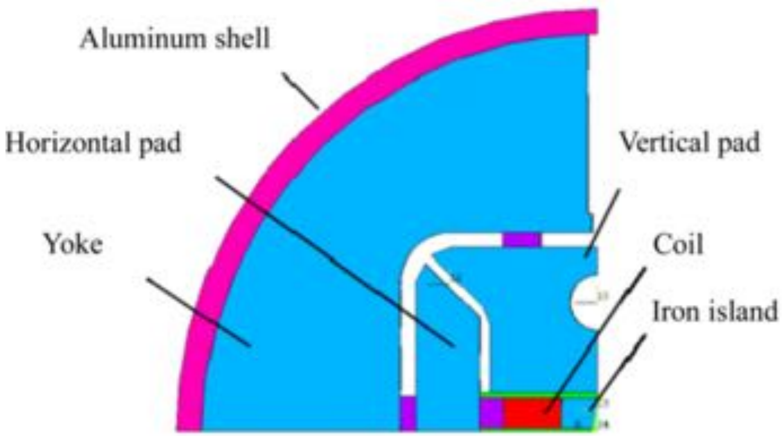
We need to test how Bi-2212 coils would perform at high magnetic field (12-15 T) and high stress (100 MPa)

SD01 structure is currently at LBNL

✓ Designed to reach 12.45 T peak field on Nb_3Sn racetrack coils at SSL

SD01 magnet cross section

(H. Felice et al., IEEE Trans. Appl. Supercond. 17, 2 (2007))



SD01 structure could be modified to fit Nb_3Sn and Bi-2212 coils for a hybrid magnet producing 15 T peak field at SSL

First approach to optimize the size of Bi-2212 and NB_3Sn cables and coils

✓ The number of turns is such that the coils cover all the horizontal space between the island and the iron pad

✓ The island dimension is such that the minimum bending radius of the coil is 20 mm

✓ The diameter of the strands is fixed to 0.8 mm for Bi-2212 and 0.85 mm for Nb_3Sn (most common diameters)

✓ Only the vertical pad and the aluminum shell will be modified

15 T hybrid subscale dipole
Magnetic analysis

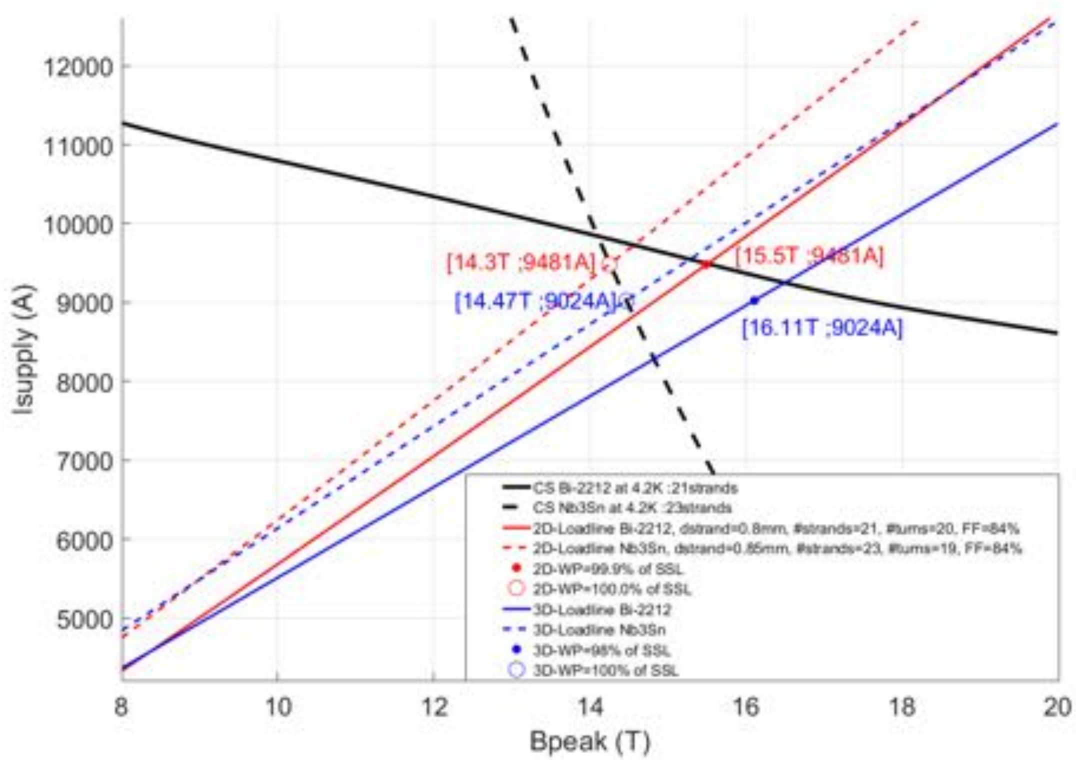
Best scenario in terms of I_{supply} from 2D optimization model

Bi-2212 and Nb_3Sn coils are double pancake racetracks

Parameters (2D optimization)

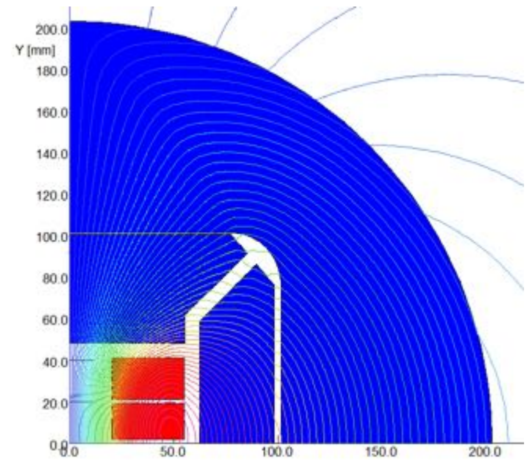
Cable and coil parameters	Bi-2212	Nb_3Sn
No. strands	21	23
No. turns	20	19
Cable filling factor (%)	84	84
B_{coil} at I_c (T)	15.5	14.3
WP (% of SSL)	100	100
I_{strand} at SSL (A)	451	412
$J_{E\ (coil)}$ A/mm^2	633	518

Loadlines (2D and 3D models)

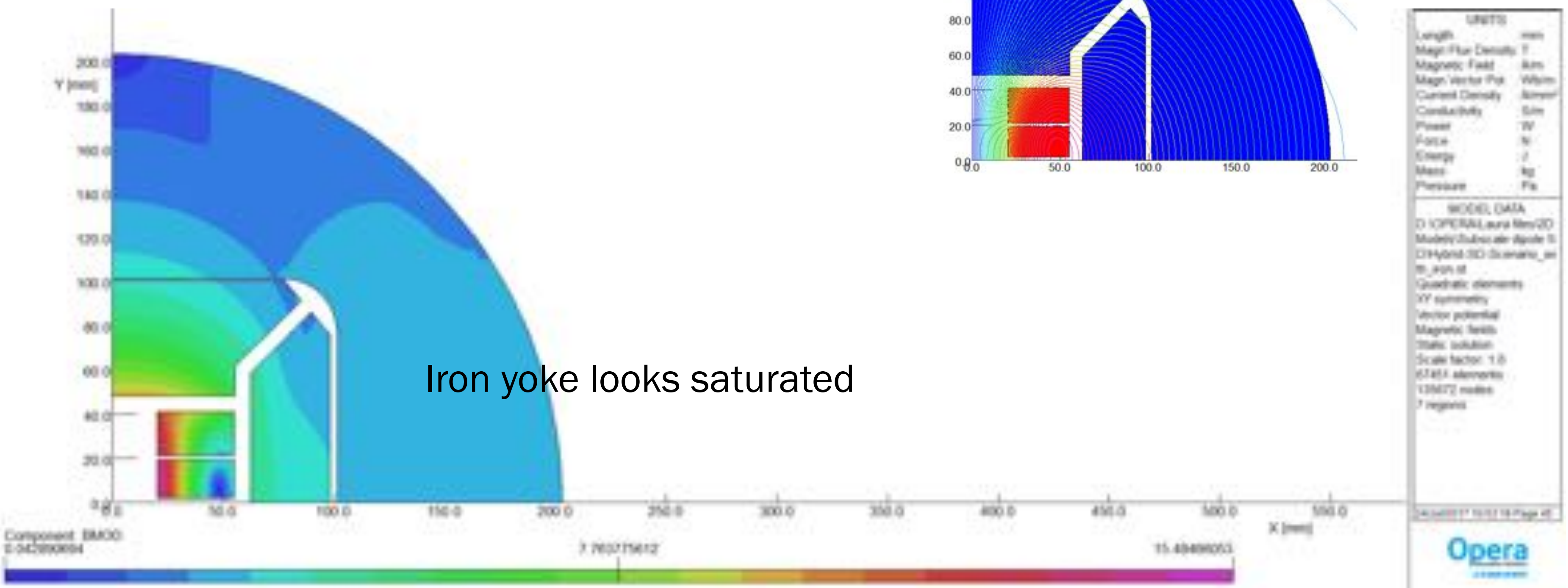


15 T hybrid subscale dipole
Magnetic analysis

Profile of the flux lines



B_{mod} (T) on coils and iron

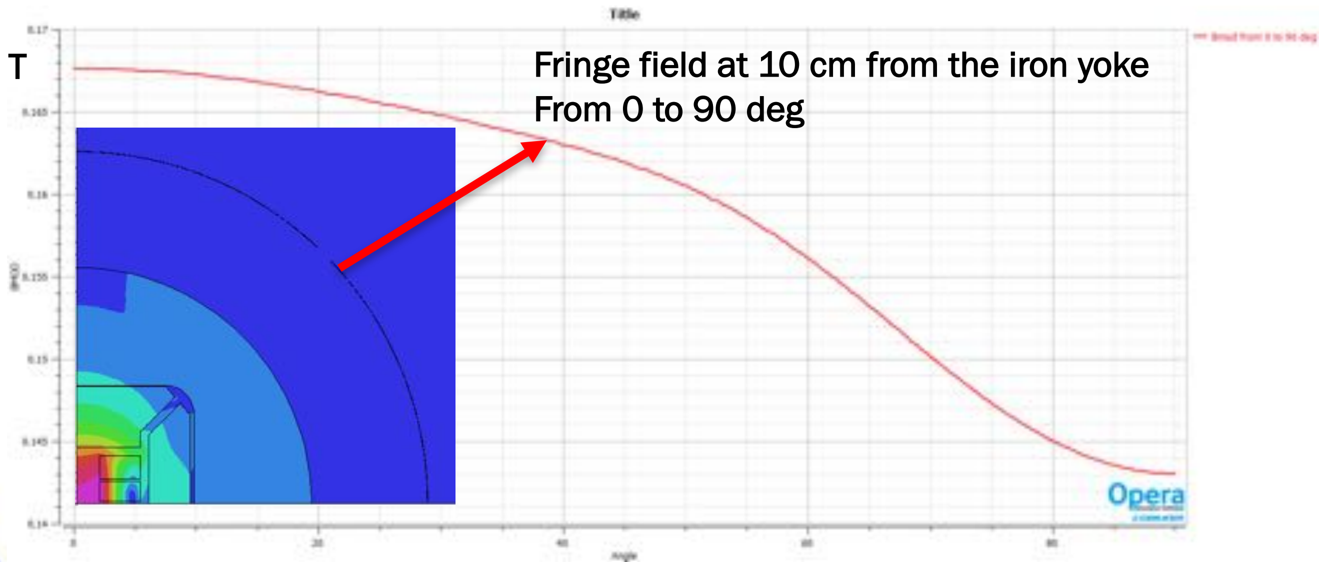


Iron yoke looks saturated

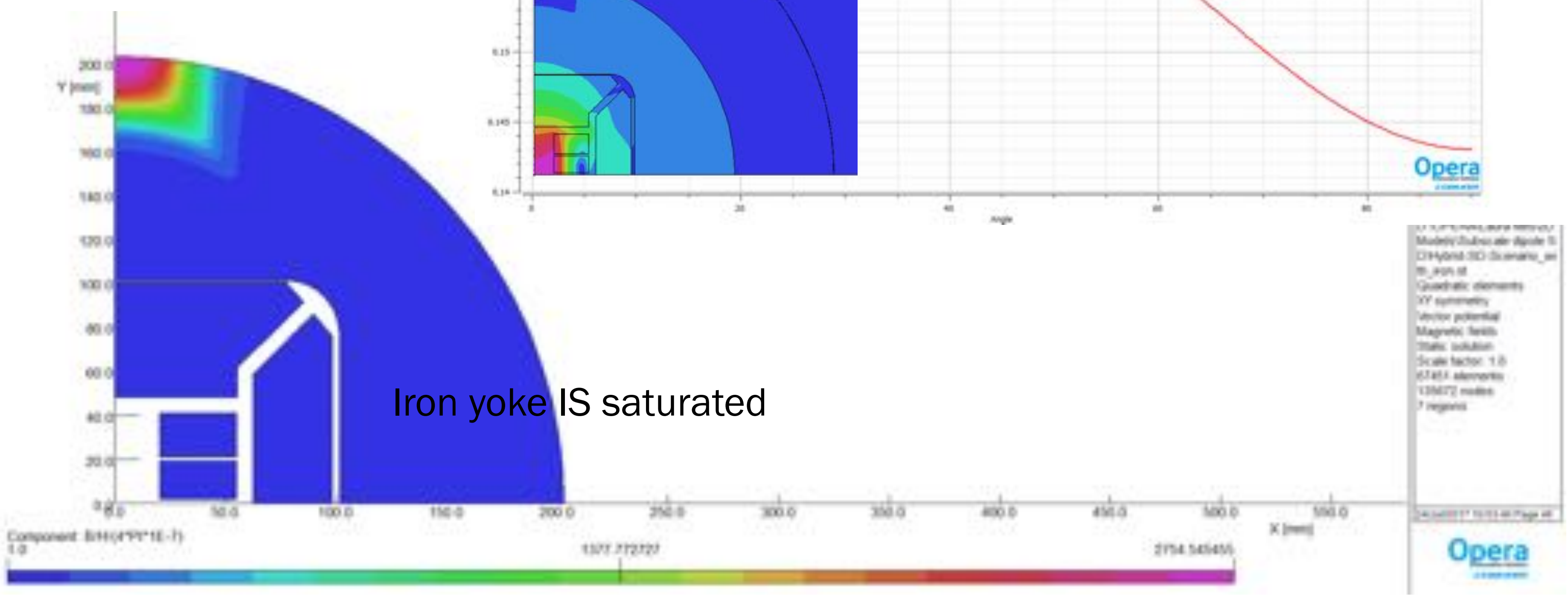
15 T hybrid subscale dipole
Magnetic analysis

Max: 0.168 T

Fringe field at 10 cm from the iron yoke
From 0 to 90 deg

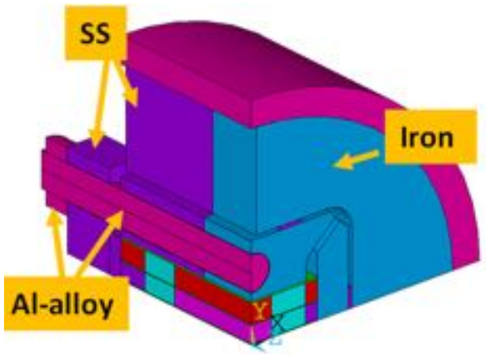


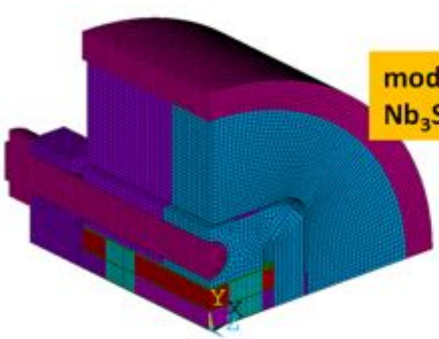
Relative permeability (μ_r)



Iron yoke IS saturated

15 T hybrid subscale dipole
Mechanical analysis and modifications to the existent structure





Interference between hor. key and yoke is set to 0.2 mm

Frictional coefficient is set to 0.2

Tie rod diameter: 36 mm (pre-load of 84,296N x 2 during assembly)

Force component	Assembly	Cool-down	Excitation
F_x by hor. key (N)	169,570	439,630	458,140
F_y by vert. key (N)	116,940	260,630	243,660
F_z by tie rod (N)	84,296	126,020	131,840

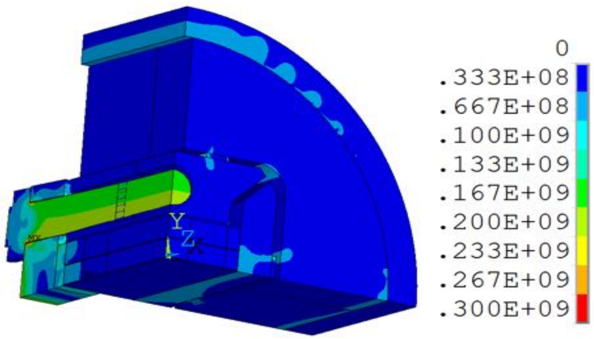
SD structure update:

- ✓ Bladder pressure: 24 MPa
- ✓ Shell thickness increased from 13 mm to 27 mm
- ✓ Tie rod diameter raised to 36 mm
- ✓ AL-7075, (>600 Mpa@4.2K), is selected as the tie rod material

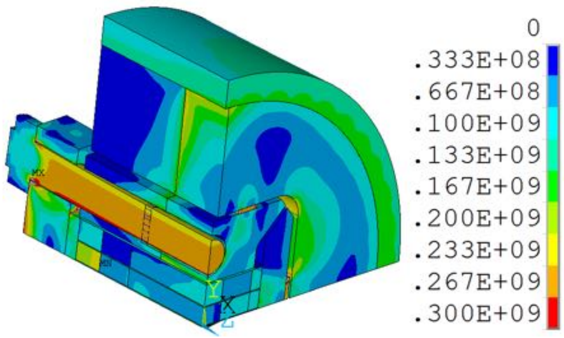
Mechanical analysis by Kai Zhang, PhD student
University of Chinese Academy of Sciences. Institute of High Energy Physics, CAS. LBNL

15 T hybrid subscale dipole
Mechanical analysis and modifications to the existent structure

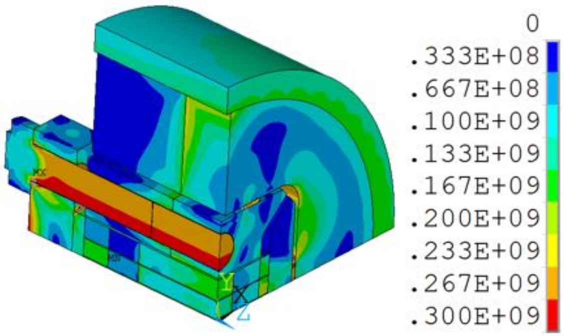
Magnet stress at different load steps



Von-mises stress after assembly



Von-mises stress after cool-down

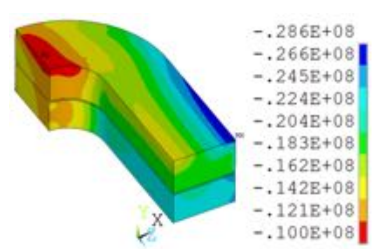
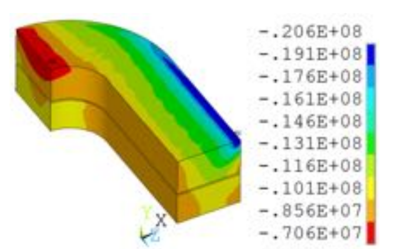
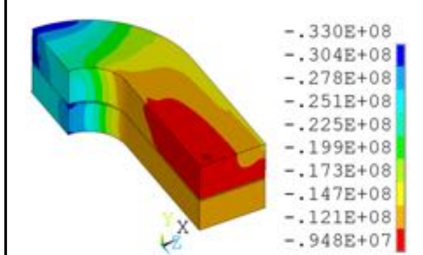
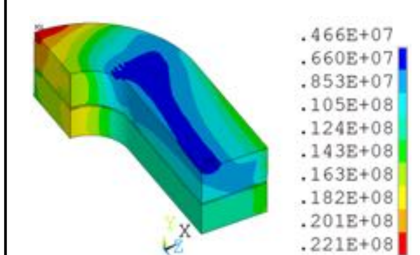
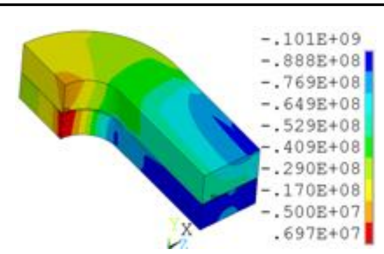
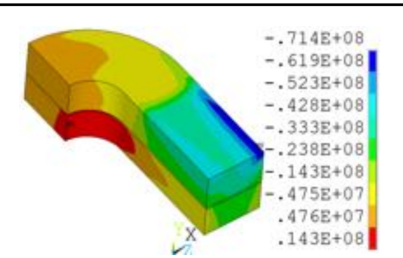
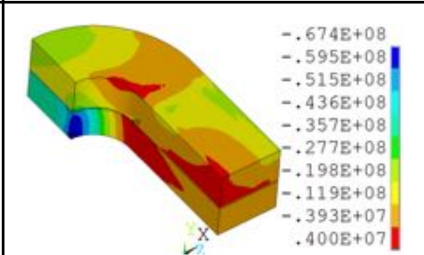
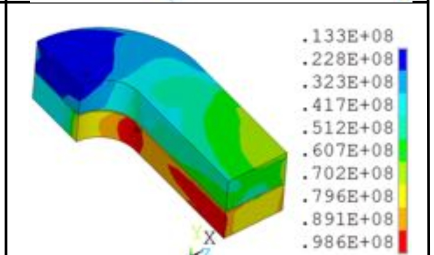
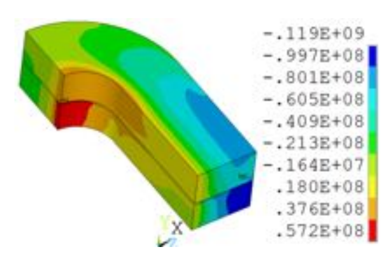
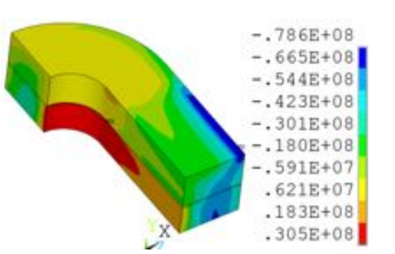
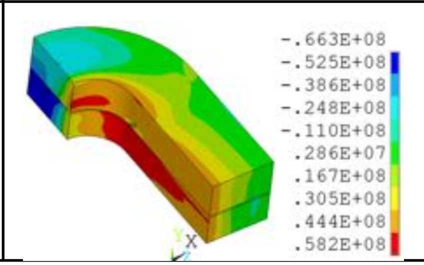
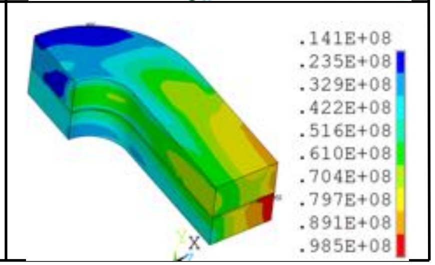


Von-mises stress after excitation

Mechanical analysis by Kai Zhang, PhD student
University of Chinese Academy of Sciences. Institute of High Energy Physics, CAS. LBNL

15 T hybrid subscale dipole
Mechanical analysis and modifications to the existent structure

Coil stress at different load steps

Stress/ Step	σ_x	σ_y	σ_z	*Von-mises*
Assembly				
Cool-down				
Excitation				

Mechanical analysis by Kai Zhang, PhD student
University of Chinese Academy of Sciences. Institute of High Energy Physics, CAS. LBNL

Summary
15 T hybrid subscale dipole

- This SD structure provides the possibility to test Bi-2212 racetrack coils at high magnetic field (~ 15 T) and high stress (~100 MPa)
- The vertical pad, the Al shell thickness and the tie rod diameter of the current structure will need to be modified to fit the coils and to account for larger Lorentz forces.
- The horizontal preload after cool-down is 439,630 N (> $F_{mag}x$ = 862,565 N)
- The required bladder pressure during assembly is 24 MPa
- Each axial AL tie rod needs to be pre-tensioned to provide a preload of 85,000 N x 2 (170,000 N) during assembly