Quench and Stress Coupled Analysis of High T_C Superconducting Coils

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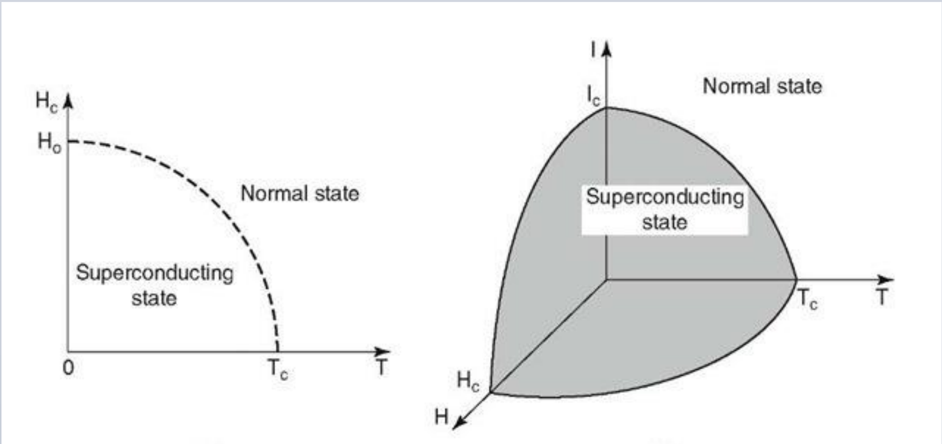
OBJECTIVES

- **Calculate magnetic field configurations due to varying designs of high-T_C superconducting coils**
- **Use magnetic field and current data to calculate Lorentz forces on coils due to self and external fields**
- **Analyze effect of inductively coupled Cu disc inserts on quenching events of high-T_C superconducting coils**

BACKGROUND

- High-T_C superconductors (HTS) are promising candidates for future fusion reactor designs due to their low power loss and high operation temperature
- Superconducting magnets are subject to quench events during which the material suddenly enters the non-superconducting (normal) state
- Quenching can cause rapid temperature increase from Joule heating, boiling-off of cooling fluid, massive voltage spikes, and in worst case, permanent physical damage due to melting and/or mechanical stress



Diagrams in H,T-space and H,T,I-space showing the critical surface above which a material is no longer superconducting

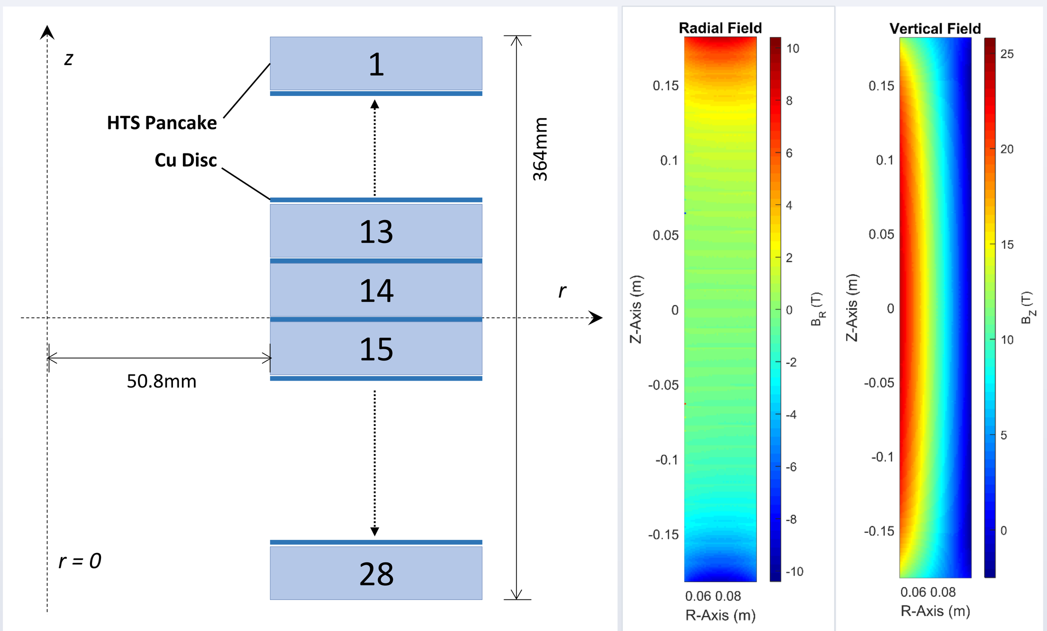
- Intensity of quench events can be mitigated by installing large external dump resistors and inductively-coupled inserts to divert stored magnetic energy
- HTS are also subject to extremely high stress forces caused by the combination of high operating current, temperature, and magnetic field

$$F = \iiint J \times B \; dV$$

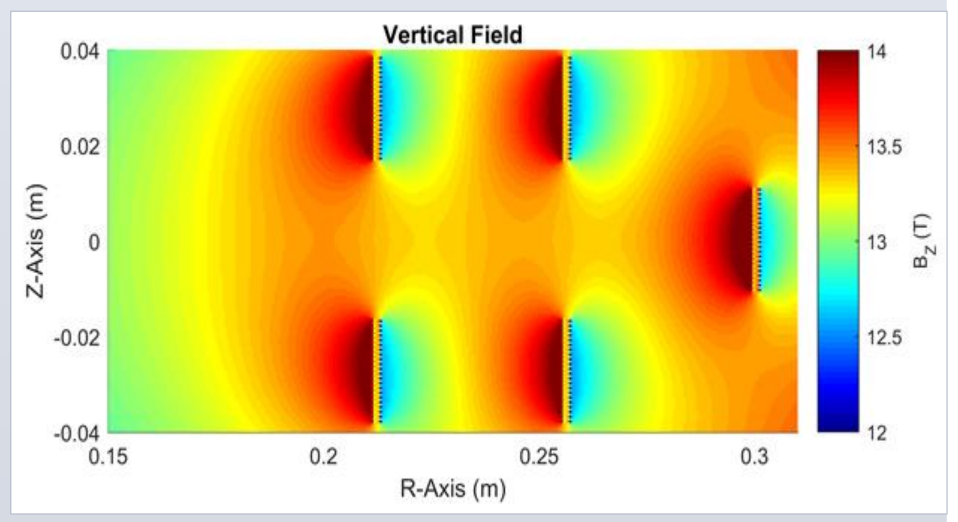
- Exploratory designs of force-balanced coils attempt to minimize stress within coil winding packs

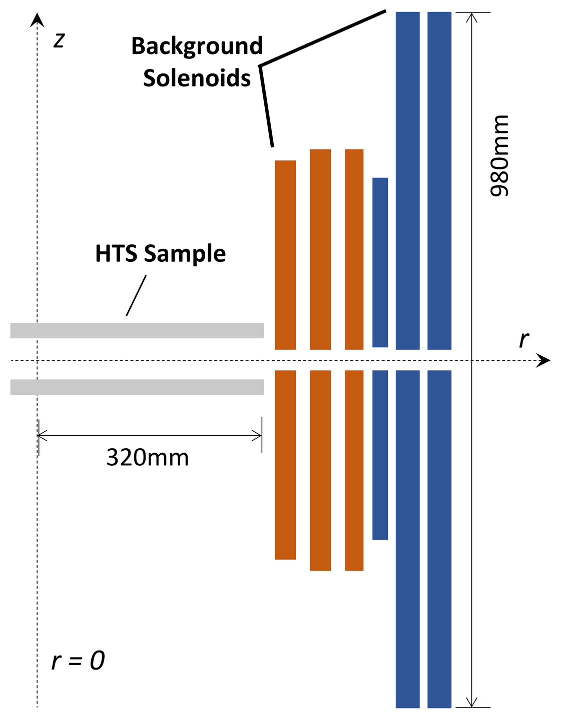
NUMERICAL CALCULATION OF MAGNETIC FIELDS

- Conducting coils modeled as arrays of infinitely-thin current-carrying filaments
- Calculation carried out in FORTRAN, using Biot-Savart law and analytic formulas where appropriate
- Two configurations explored:
  1. *Solenoid composed of 28 HTS pancakes separated by 27 Cu discs*
     - J = 450 A/mm² in HTS pancakes
     - J = 0 in Cu discs
     - All components insulated from each other
     - Pancake cross-section = 48mm x 12mm
     - Disc cross-section = 48mm x 1mm
     - Max. field on solenoid axis is 23.3 T
     - Max. field in winding pack is 23.5 T
  2. *NIFS (National Institute for Fusion Science) Test Design: HTS sample coil placed within the bore of six coaxial low-T_C superconducting solenoids*
     - Background field produced by coaxial solenoids ranges 12 - 14 T vertically and -1 to +1 T radially within bore
     - 30kA coil current produces -2 to +2 T both vertically and radially
     - Average combined field within interior of coil sample is ~13.5 T

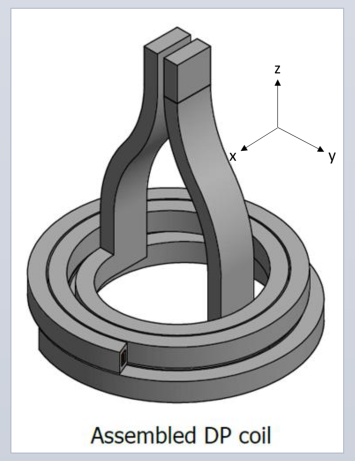


Above, left to right: schematic diagram of solenoid configuration; radial and vertical field distributions within solenoid winding pack





Above: vertical field distribution within solenoid bore; note that the five thin rectangles at r = 0.212, 0.256, and 0.300 outline the sample coil cross-sections
Right: schematic diagram of sample and solenoid configuration



Assembled DP coil

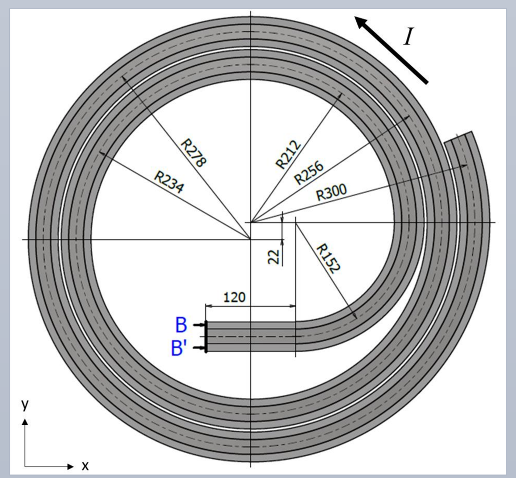
NUMERICAL INTEGRATION OF LORENTZ STRESS FORCES

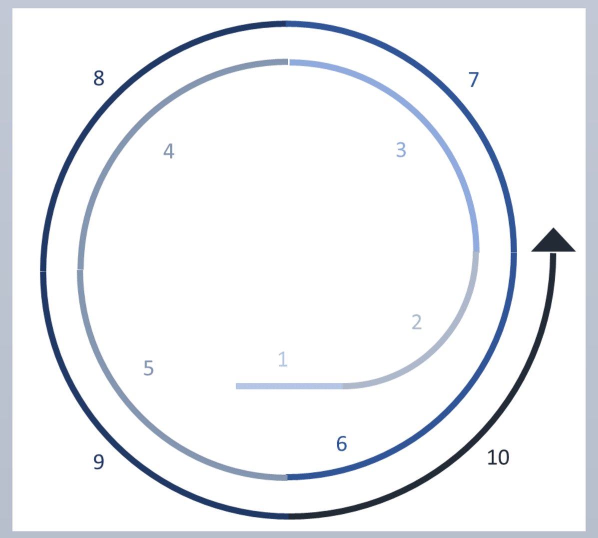
- Magnetic field distributions shown above were used to calculate Lorentz force on upper portion of NIFS HTS sample coil
- Modeled assuming current density in sample is uniform over sample length and cross-section
- Calculation carried out in MATLAB using numerical volume integration

$$\bar{F} = dV \sum_{i,j,k} d\bar{F}_{ijk} = dV \sum_{i,j,k} \frac{I}{A} \hat{n} \times \bar{B}_{ijk}$$

- Net vertical force of 37 kN upward
- Average radial force per length is ~390 N/mm outward
- Lower portion of coil experiences approximately the same radial force but opposite vertical force
- Net force on entire sample tends to stretch its radius and compress its height
- Conclusion: expected stress is too high; a redesign and subsequent recalculation of forces will be necessary to ensure structural integrity during operation

Segment #	F_r (kN)	F_z (kN)	F_y (kN)
1	-	-0.08	-46.10
2	93.3	-2.01	
3	135.6	-3.65	
4	146.2	-4.30	
5	146.1	-4.20	
6	167.5	-4.40	
7	166.3	-4.83	
8	170.2	-4.93	
9	170.2	-4.86	
10	180.0	-4.25	





Above, left to right: diagram of coil upper portion with casing; diagram showing division of coil into one straight segment and nine 90-degree segments; table of Lorentz forces on each segment of coil in radial, vertical, and y-planar directions

ANALYSIS OF INDUCTIVE COUPLING

- Inductively coupled Cu discs can improve energy extraction from a quenching system by converting stored magnetic energy into induced currents in the discs
- Mutual inductances are calculated using the Neumann formula:

$$M_{ij} = \frac{\mu_0}{4\pi} \oint_{C_i} \oint_{C_j} \frac{d\bar{s}_i \cdot d\bar{s}_j}{|\bar{r}_i - \bar{r}_j|}$$

- Self inductances are calculated using the same formula with the qualification $|\bar{r}_i - \bar{r}_j| > a/2$ where a is conductor thickness, plus a correction term
- HTS pancakes modeled with 640 turns each
- Cu discs modeled with 1 turn each

a.

Pancake No.	1	2	14	15	27	28
M_{ij} (mH)	70.3	55.3	3.37	2.86	0.60	0.54

b.

Disc No.	1	2	14	15	26	27
M_{ij} (μH)	102.5	72.9	4.84	4.11	0.99	0.89

c.

Disc No.	1	2	14	15	26	27
M_{ij} (nH)	190.6	133.6	8.21	6.95	1.71	1.48

Selections from the inductance matrix between: a) pancake 1 and pancakes 1-28; b) pancake 1 and discs 1-27; c) disc 1 and discs 1-27.

FUTURE WORK

- Run simulations of fast energy extractions with coupled magnetic, thermal, and circuit equations to study temperature and current behavior of pancakes and discs
- Compare inductive inserts with varying material properties and geometric configurations to determine key parameters for fast energy extraction
- Explore different coil geometries for NIFS sample to minimize stresses during operation

REFERENCES

- H. Witte et al., "Reduction of the Hot Spot Temperature in HTS Coils", *Applied Superconductivity IEEE Transactions on*, 2014.
- H. Witte, "FEA Simulation of HTS Pancakes", Brookhaven Nat. Lab., 2013.
- Critical surface image from: https://www.kullabs.com/classes/subjects/units/lessons/notes/note-detail/3526.
- NIFS diagrams are property of NIFS.

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