Abstract

- This presentation provides an overview of the stability of superconducting coils, specifically regarding incident radiation, operating conditions, and coil manufacturing. Incident radiation hampers the lifetime of the coils and the testing of the effects of radiation is also considered. A discussion and data on the stability parameter n of the superconductor transition region are also included. Finally, the effects of removing the insulation of a superconducting coil is given, including some solutions to subsequent engineering complications.

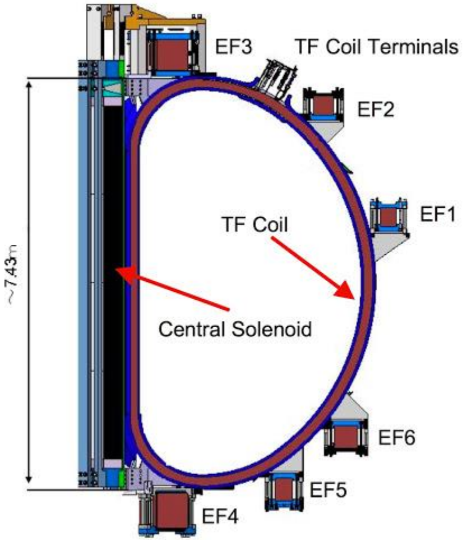
Superconducting Coil Performance and Quench Protection

Shawn Simko; Advisor Dr. Yuhu Zhai

August 12th 2020

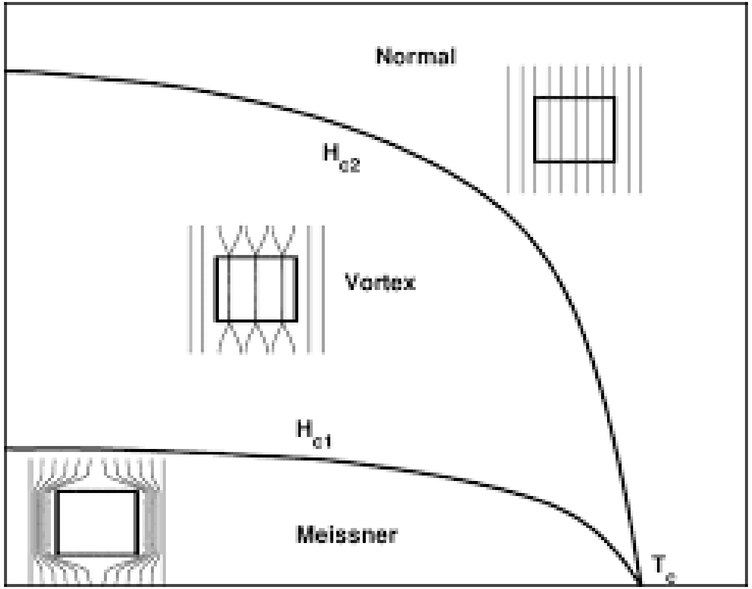
Outline

- Superconducting Coil Performance In Fusion Reactors Is Limited By:
  - Incident Neutron Irradiation
  - Mechanical and Thermal Stability
  - Coil Design



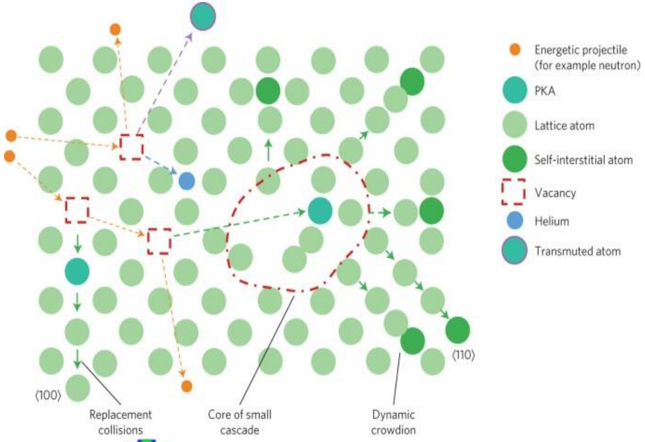
Superconductors[7]

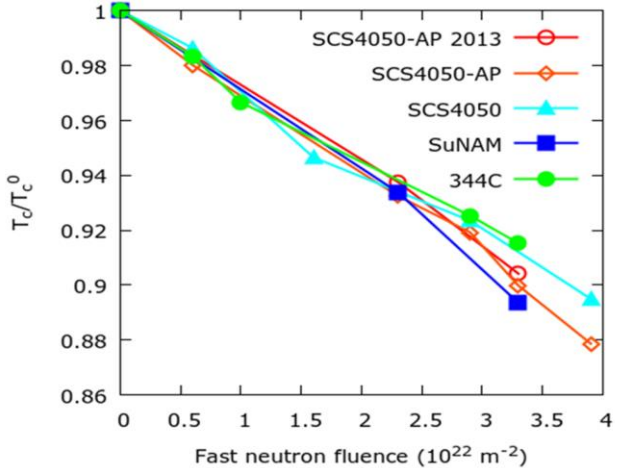
- Superconductors exhibit no DC resistance within the superconducting region defined by a upper critical temperature, applied magnetic field, and current density limit
- Superconductors come in two flavors
  - Type I Superconductors perfectly expel the magnetic field from the bulk
  - Type II exhibit regions of perfect bulk expulsion and regions of magnetic field penetration above a secondary intrinsic transition temperature, magnetic field boundary
- Relevant Superconductors are usually Type II



Neutron Irradiation[1]

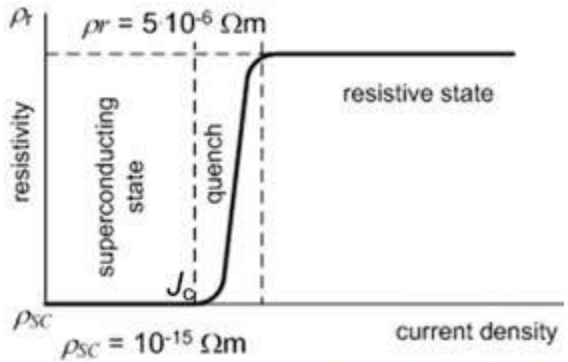
- Neutron Collisions Generate Crystal Defects
  - These Form Diffuse Sites for Magnetic Field Penetration
  - Reduce Volume of Superconducting Regions and allow for greater interaction between vortices leading to declining performance
- Irradiation response is found through exposure in nuclear fission reactors to fast neutrons (>1MeV) to match fusion neutron energy specta
  - Typically near the reactor core
  - Cadmium Shielding is useful to reduce thermal and epithermal neutron counts
  - Oregon State, Sandia Natl. Labs, and MIT reactors have high neutron flux (>10^{17} n*cm^2/s) and large fast to thermal neutron ratio (>1) capabilities





Stability[2]

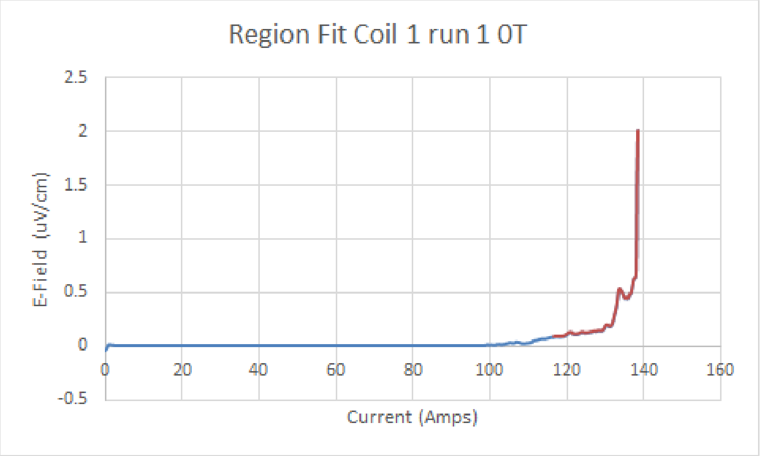
- Since R = 0, by Ohm’s law, V ≈ 0 across a Superconductor
- When a superconductor transitions to a normal state (quenches), R > 0, so V > 0 and thus a electric field E > 0 results
- E scales as $\frac{E}{E_c} = \left[\frac{I}{I_c}\right]^n$ where E_c is a selected criterion (usually 1-.01 µV/cm), I_c is the corresponding current, and n is some constant
    - Tested using a voltmeter and ammeter in a cryogenic env.
    - The n-value denotes stability of the superconductor as it approaches the upper limit of its performance
    - High n-values indicate a sharp take-off, allowing operation near the boundary without experiencing resistance and subsequent ohmic heating
    - Low n-values indicate a shallow take-off, such that quenching does not occur suddenly, allowing for a reactive control system to head-off quenching



$Nb\text{-}Sn_3$ N-value Data

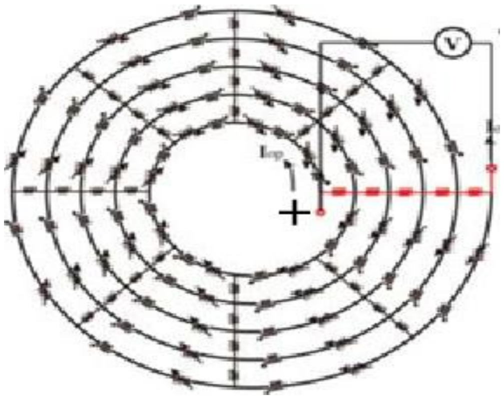
- Typical N-values for $Nb\text{-}Sn_3$ coils extend from ~15 to 40
  - Shown are N-values found for a $Nb\text{-}Sn_3$ coil with non-insulated wire
  - N-values tend to decrease with increasing applied external magnetic field
- Magnetic Training[7]
  - Due to the lack of insulation, wires are able to slip across each other within the coil winding
  - Due to the low temp., the heat capacity is low, so frictional heating is greatly magnified
  - Thus, for the first runs, n-values are lower than in later runs, and the take off region is elongated, as they have not settled within the winding

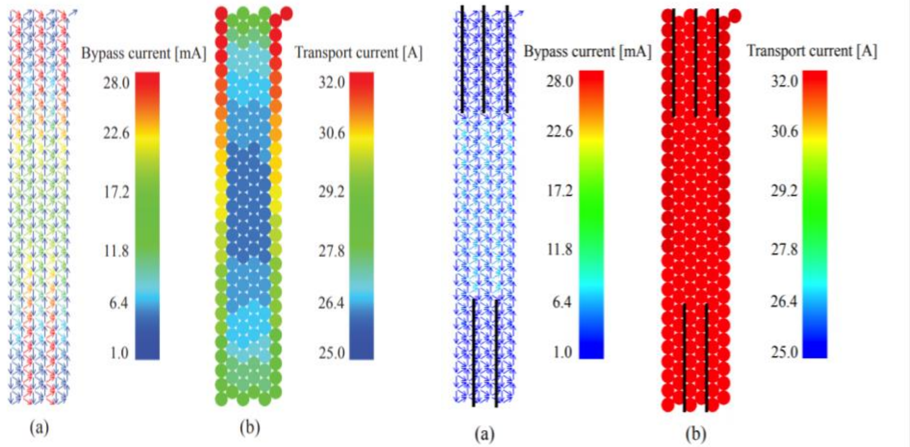
B Ext. (T)	N-value
0	24.53
1	19.40
3	16.00



Coil Design

- No insulation coils have potential to provide protection against quenching[3],[5]
  - Current can bypass quench sites radially
  - However, this creates a LR circuit with a much larger time constant, increasing charge time
    - Metallic Strip Co-winding[6]
  - Current also bypasses unevenly based on location within the winding
    - Targeted Insulation Design[4]





Acknowledgements And Sources

Thank you to Dr. Yuhu Zhai for advising this project.

This work was made possible by funding from the Department of Energy for the Summer Undergraduate Laboratory Internship (SULI) program. This work is supported by the US DOE Contract No. DE-AC02-09CH11466.

- [1] Fischer, D X, et al. "The Effect of Fast Neutron Irradiation on the Superconducting Properties of REBCO Coated Conductors with and without Artificial Pinning Centers." *Superconductor Science and Technology*, vol. 31, no. 4, 2018, p. 044006., doi:10.1088/1361-6668/aaadf2.
- [2] Ghosh, Arup K. "V–I Transition and n-Value of Multifilamentary LTS and HTS Wires and Cables." *Physica C: Superconductivity*, vol. 401, no. 1-4, 2004, pp. 15–21., doi:10.1016/j.physc.2003.09.006.
- [3] Hahn, Seungyong, et al. "HTS Pancake Coils Without Turn-to-Turn Insulation." *IEEE Transactions on Applied Superconductivity*, vol. 21, no. 3, 2011, pp. 1592–1595., doi:10.1109/tasc.2010.2093492.
- [4] Noguchi, So, et al. "Numerical Electromagnetic Simulation of Effective Partial-Insulation NbTi Superconducting Coil." *Physics Procedia*, vol. 65, 2015, pp. 233–236., doi:10.1016/j.phpro.2015.05.131.
- [5] Wang, Xudong, et al. "Turn-to-Turn Contact Characteristics for an Equivalent Circuit Model of No-Insulation ReBCO Pancake Coil." *Superconductor Science and Technology*, vol. 26, no. 3, 2013, p. 035012., doi:10.1088/0953-2048/26/3/035012.
- [6] Wang, Y, and H Song. "Influence of Turn-to-Turn Resistivity and Coil Geometrical Size on Charging Characteristics of No-Electrical-Insulation REBCO Pancake Coils." *Superconductor Science and Technology*, vol. 29, no. 7, 2016, p. 075006., doi:10.1088/0953-2048/29/7/075006.
- [7] Wilson, Martin. "Superconducting Magnets for Accelerators." *Superconducting Magnets for Accelerators Lecture 1 Superconducting Materials*, Cern, 2006, cas.web.cern.ch/sites/cas.web.cern.ch/files/lectures/zakopane-2006/wilson-lect.pdf.