Design Definition of Stellarator Coil Systems

L. Bromberg, J.H. Schultz
MIT Plasma Science and Fusion Center

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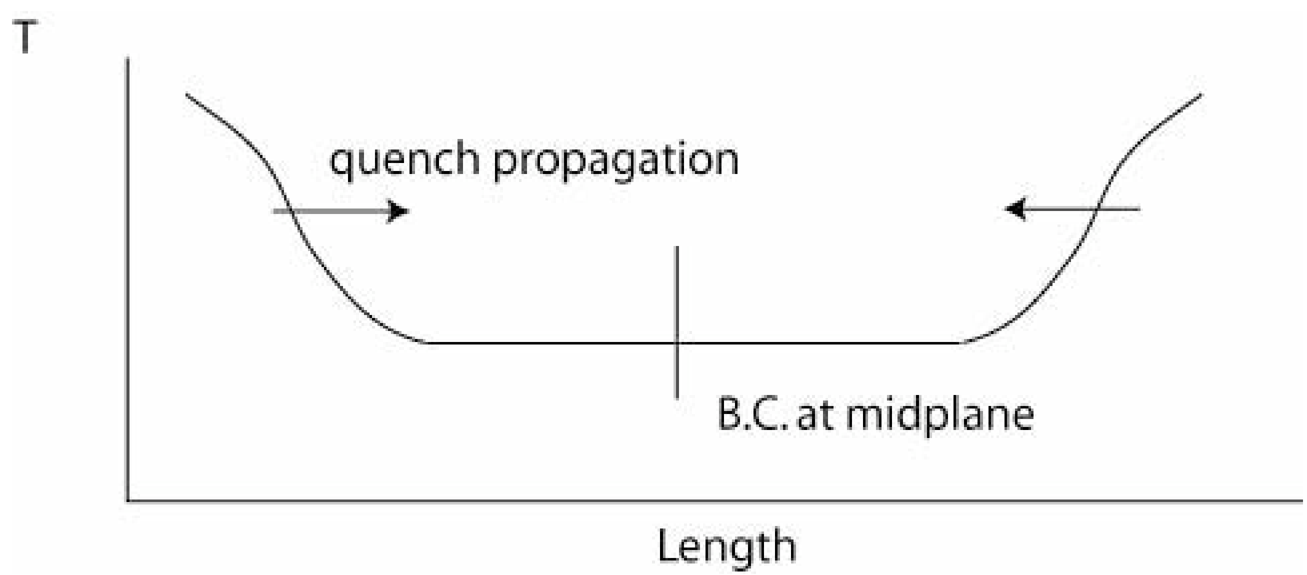
Review of SC options

- High Tc
  - Epitaxial on structure
- Nb_3Sn
  - Wind and react
- Nb3Sn
  - React and wind
  - "Heresy" proposed at the last meeting

Magnet protection

- Large amount of energy needs to be removed from the magnet
  - Difficult to do with low current (implies high voltage)
- Large magnets for HEP are designed for internal dump, as well as MRI magnets
- Requires conductor heating from a resistive heater (over most of the magnet) to drive conductor normal
  - Requirement $T_{conductor}$ ~ 10K (for Nb_3Sn, Nb_3Al), requiring ~ 20 J/kg (0.4 J/cm$^{3)}$
  - Energy required ~ 100 m^3 of conductor ~ 100 MJ
  - For 0.2 s initiation of quench, 100 MW

Superconducting coil protection by use of periodic heaters

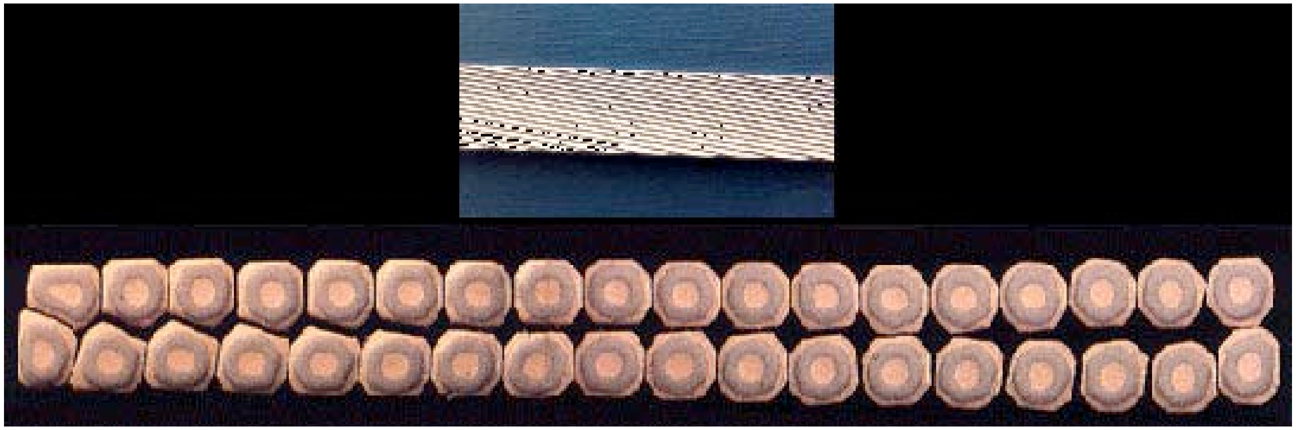


Resistive quench in internal dump

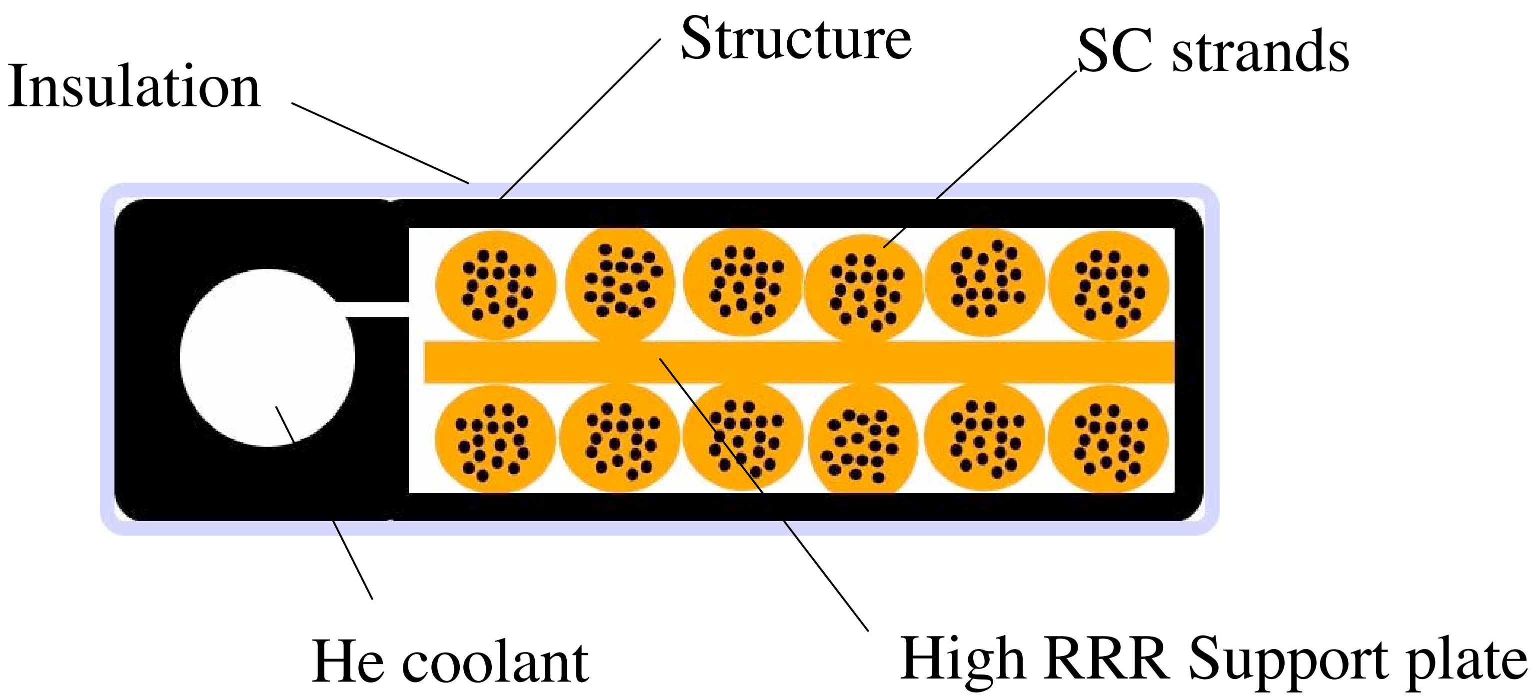
- Low temperature superconductors have relatively high normal zone propagation velocity
  - Several m/s
  - 1 m/s for highly protected SC
  - 10 m/s for lightly protected
- If locally the conductor is heated in a zone smaller than the minimum propagation zone, the normal zone will shrink (recover)
  - Minimum propagation zone in SC is ~ 1 cm.
  - Produce local heating in SC magnet, and depending in quench propagation to fill in through the rest of the coil
  - Does result in increased temperature uniformity, but has the advantage of reducing power required
  - Heater has high resistivity elements about 1 cm long, spaced about 1 m
  - Power decreased by 2 orders of magnitude!

Conductor implications of internal quench

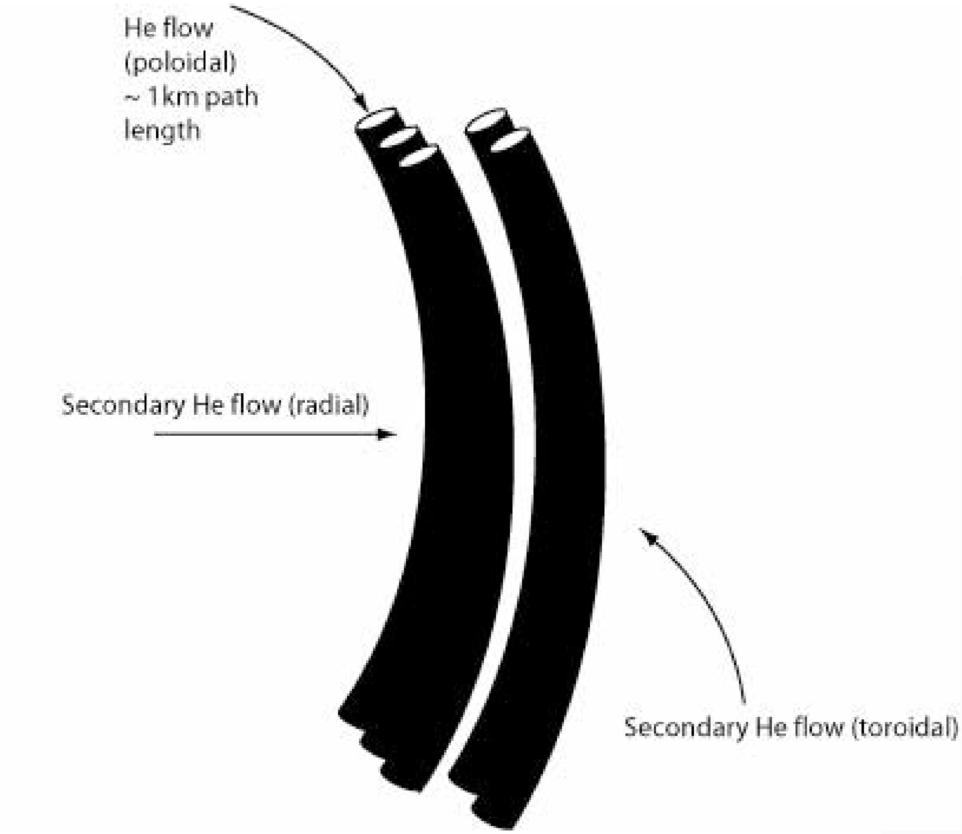
- Low current, small conductor, can use react and wind!
- Can use Rutherford-like cables (conventional high performance cables used in accelerators)
- Largest Rutherford cable made from 60 strands (vs ~ 1000 strands for CICC).
- If quench is symmetrical, no voltages are induced
  - Inductive voltage balances resistive voltage
  - If non-uniform heating, uncancelled voltages will appear
  - Need to determine actual voltages

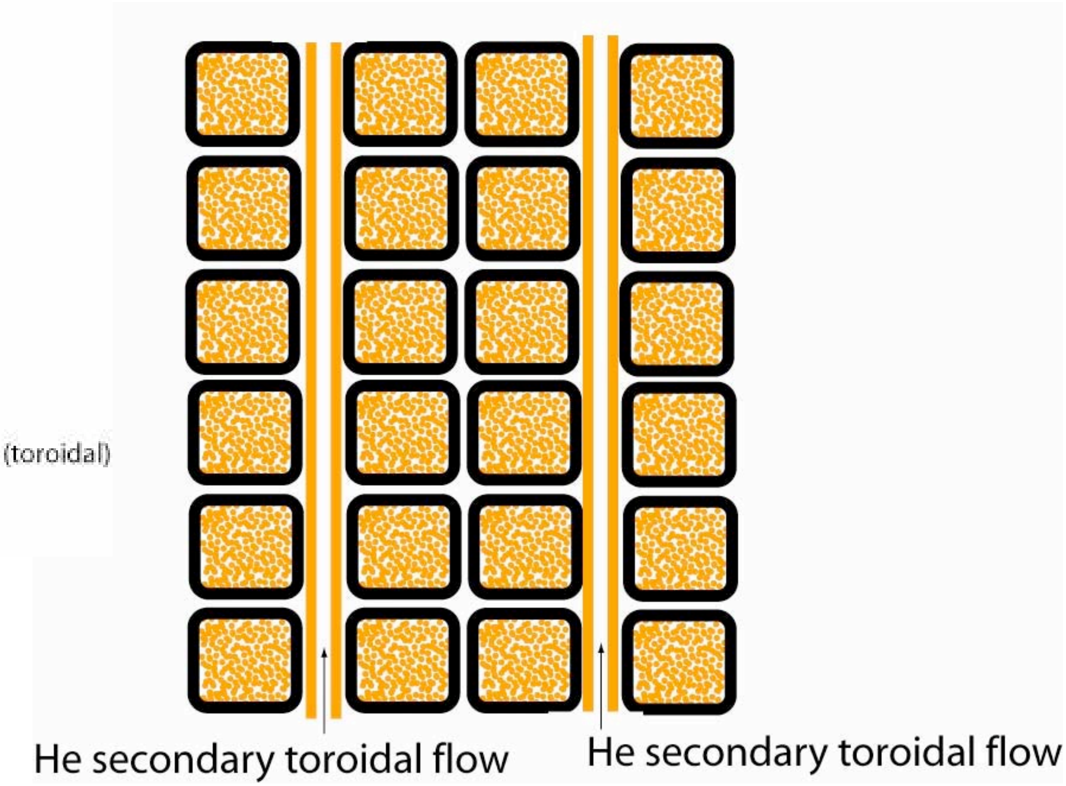


Cooled-Rutherford cable



Multi-loop cooling





Quench propagation code under development

- Comparable temperature between He and conductor
- Detailed electrical properties of materials (heat capacity of metal ignored)
- He properties from tables
  - Heat capacity, density
- Problem:
  - Boundary condition $v = 0$ changes the problem to eigenvalue problem

Analytical model

- For short coils (with pressure relieve)

$$V_q = \sqrt[3]{\frac{2dR}{fL_{\text{coil}}} L_{IQZ} \alpha_0 J^2} \qquad X_q = \left[\left(\frac{L_{IQZ}}{2} \right)^{3/2} + (V_q t)^{3/2} \right]^{2/3}$$

- For long coils (and high pressure):

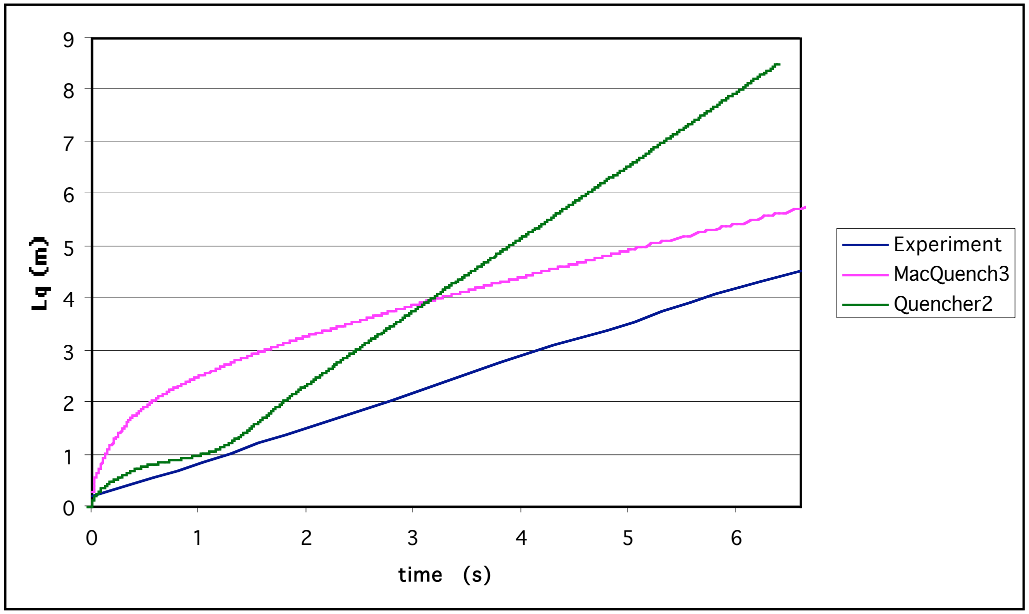
$$V_q = 0.613 \left(\frac{2d_h}{f} \right)^{1/5} \left(\frac{R L_{IQZ} \alpha_0 J^2}{c_0} \right)^{2/5} \frac{1}{t^{1/5}}$$

Preliminary data

- Initial velocities for ARIES CS ~ 5 m/s
  - If distance between normal IPZ ~ 1m , 200 ms for quench
  - Need to determine temperature differential
    - dump to occur in ~ 2 s, so 200 ms is substantial
  - Fast rate of decrease of field provides additional heating of conductor
    - Hysteresis, AC coupling, eddy current loses

Quencher2 vs MacQuench preliminary simulations with wrong B.C.

- Quenchers is better for earlier times
- This it the region of interest (times < 1 s)
- Checked with data of SULTAN (cyrogenic EU test) for ITER



Model of quench

- Because of symmetry, at midplane between heating zones:
  - $dT/dx = 0$
  - $v_{He} = 0$
- These boundary conditions are very different from previous models of quench in CICC
  - $dT/dx = 0$ with v non-zero results in boundary layers at the ends
  - $d^2T/dx^2 = 0$ is used is the most modern quench propagation codes.

Structural issues

- Helium is not going anywhere
  - Thus, large pressure increase when heated
  - Constant volume heating of He results in increases in pressure of ~ 300 to room temperature
  - Initial He pressure ~ 0.6 MPa (6 bar, 4.5 K, above critical point of He).
    - Final pressure, if 150 K temperature, of 80 MPa
    - Sheath around superconductor should be able to support these pressures
    - Typical numbers: 10 mm wide (32 strands), 1 mm sheath, 400 MPa stresses
    - Detailed stress analysis in progress.

Future work

- Finish work on code for modeling quench propagation in Rutherford-like CICC with distributed heaters
  – Get approximate velocities of propagation for ARIES-CS, even if full model is not working
- Paper accepted at Applied Superconductivity Conference
- MIT reviewing patent disclosure on periodic localized heater for large superconducting coils