Coupled Transient Thermal and Electromagnetic
Finite Element Simulation of Quench in
Superconducting Coils

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Application

- A development for use in the design of:
  - Wire and cable wound magnets
    - Filled coil structures (resin, wax, etc.)
    - And possibly helium filled open structures
Introduction

• Superconducting magnets normally operate close to critical current
  • To minimise material costs
  • To minimise manufacturing costs
  • Because it is essential for the application
    and therefore

• Superconducting magnets Quench
  Even with best design and excellent manufacturing technology
The Quench process

• Probably initiated by a micro movement in the coil
  • A small energy release raises the superconductor above its critical temperature (because at 4.2K specific heats are very small) and it becomes resistive (normal)

• If the superconductor is not cryogenically stable (Copper to Superconductor ratio less than 6:1)
  • Heat from the resistive region conducts through the coil and spreads the quench
  • As the coil currents start to change dB/dt losses in the conductor cause more heating
Quench Tolerant

• Magnets must be designed to survive a quench
  • Basic design parameters
    • Conductor (Cu:Sc ratio, size and current)
    • Subdivide coil (add protection circuits to each)
  • Quench detection
    • Turn off the power supply (if there is one)
  • Protection circuit
    • Linked to heater pads
  • Conducting formers – Quench back
Formulation and Implementation

• Transient Thermal

\[ \rho C(T) \frac{dT}{dt} - \nabla \cdot \kappa(T) \nabla T = Q \]

• First and second order nodal elements

• Transient EM

\[ \nabla \times \frac{1}{\mu} \nabla \times \vec{A} + \sigma \left( \frac{d\vec{A}}{dt} + \nabla V \right) = \vec{J} \]

• First order edge elements

• Thermal and EM (+circuits) are closely decoupled

• Galerkin time integration method
Interesting features of the problem (1)

**Extreme non-linearity**

- **Specific Heat & Thermal & Electrical Conductivity**

- Newton Raphson Non-linear solutions are implemented
  
  **BUT NOT recommended**

  Large time steps and therefore temperature changes make the non-linear equations slow to solve

- Most effective method = all non-linearity handled within the adaptive time integration procedure
Extreme non-linearity …

- Adaptive Time integration

Diagram:

- Predict-extrapolate
- Predict-interpolate
- Correct-interpolate

Time Step: Compare
Interesting features of the problem (2)

- Representation of the coils in circuit equations

\[ \iiint_{\Omega_p} \vec{N}_p \cdot \vec{E}_j \frac{d\vec{A}_j}{dt} d\Omega_p + I_p R = V \]

where \[ \vec{N}_p I_p = \vec{J} \]

And \( N_p \) is a discrete turns density vector derived from the current density distribution

- The coils must be meshed in both the thermal and EM models
Interesting features of the problem (3)

- Thermal simulation is ‘stiff’
  - Anisotropic Thermal conductivity
    - 5000 along the wire (Cu dominates)
    - 1 normal to the wire (Resin & insulation)
  - A Factor of 5 worse than expected (at 4.2K)
    - Heat conducted by phonons
    - Phonons reflected by material discontinuities

- Use an Anisotropic mesh
  - To reduce stiffness of the system
  - Would be better with Hexahedra!
QUENCH module for OPERA-3d

- Uses finite element methods to simulate the transient thermal & Electromagnetic behaviour of superconducting magnets.
- Developed in collaboration with
  - Oxford Instruments & Siemens Magnet Technology
- Model includes:
  - Superconducting coils
  - Associated structures (formers)
  - Protection circuit
QUENCH Module

- First release
  - Transient thermal
  - Circuit equations
  - Coil inductance matrix must be provided

- Second release (October 2006)
  - Transient thermal
  - Circuit equations
  - Coupled to transient EM simulation (Elektra)
Model required for Quench simulation

- Coil geometry
- Winding orientation
- Turns density and wire data
- Protection circuit
- Material properties
  - Anisotropic non-linear thermal conductivity
  - Non-linear specific heat
  - Non-linear electrical conductivity
Coil specification

• Automatic creation of the winding data from OPERA’s standard conductor set
  • Solenoids
  • Racetracks
  • Bedsteads
  • Constant perimeter end
  • Arcs and bars
  • curvy bricks

• Then add materials, heat source, winding, circuit data…..
Coil materials
Non-linear material properties

• Functional
  • eg. $10^a + b \log(t) + c \log(t)^2 + d \log(t)^3$ ....
  (Typical NIST format for material properties)

• Tabulated
  • User defined tabulated function eg. JC(T;B)
Heat sources available in QUENCH

- Joule heating in the normal zone
- Additional heat sources
  - Rate dependent losses
  - Hysteresis losses
  - ............
  - Any function of $B$, $dB/dt$, $T$, $J_c$.

\[
\frac{dB}{dt} \frac{2}{3\pi} \lambda_0 J_c(\theta, B) \ d
\]
Protection circuits
Automating this Process

- A Macro to make this easy for standard quench analyses
Example Model

- PT55 Polarised target magnet
PT55 magnet parameters

- 60 degree access and exit angles
- Main coil pair – 8168 turns/coil
- Correction coil pair – 1365 turns/coil
- C361 superconducting wire (2:1 Cu:NbTi)
- Peak Field 5.6T
- Total inductance 98Henries
- Central field 2.5T
Measured and Calculated

PT55 Magnet: Opera-Quench compared to measurement

- Coil 1
- Coil 2
- Coil 3
- Coil 4
- Coil 1 Measured
- Coil 2 Measured
- Coil 3 Measured
- Coil 4 Measured
Results

• Output required
  • As a function of time:
    Current  Resistance  Max_Temperature
    Interlayer_voltage

• In addition, for understanding
  • Full solution saved at specified times
  • For subsequent calculation and display
    • Data available includes: Temperature, Joule heat
density, B, dB/dt, thermal conductivity ….
Temperature at a particular time
Resistive loss in the normal zones

Note that all the coils quench in this example, and that the coupled coils quench because dB/dt losses raise them above critical temperature.
CONCLUSIONS

- Coupled Transient thermal and Electromagnetic simulations have been developed to simulate Quenching of superconducting magnets

- Current as a function of time - Results compare very well with measurement

- Interlayer voltage as a function of time – Results compare reasonably well, but more measurements required