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

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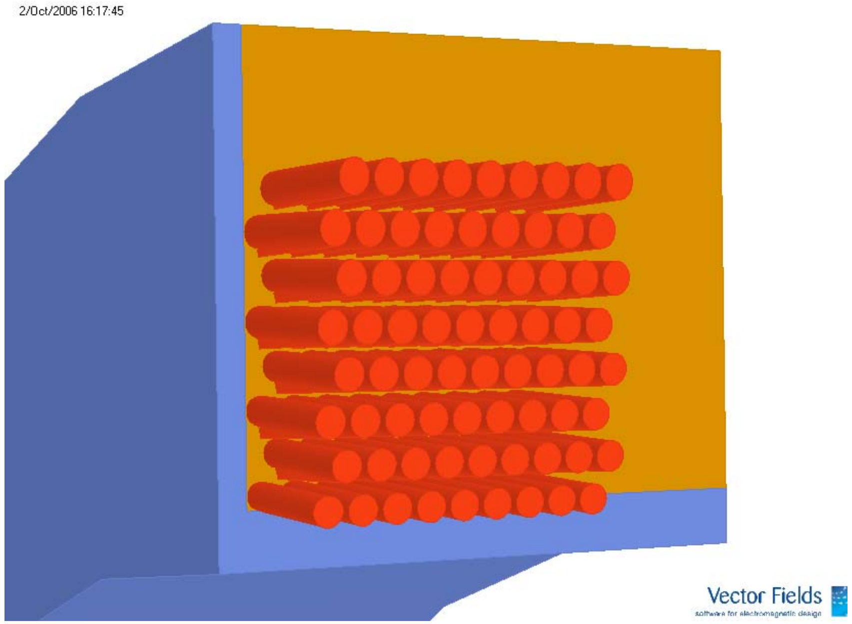
Application

- 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 $$\rho C(T)\frac{dT}{dt} - \nabla.\kappa(T)\nabla T = Q$$
  - 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 *de*coupled
- 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

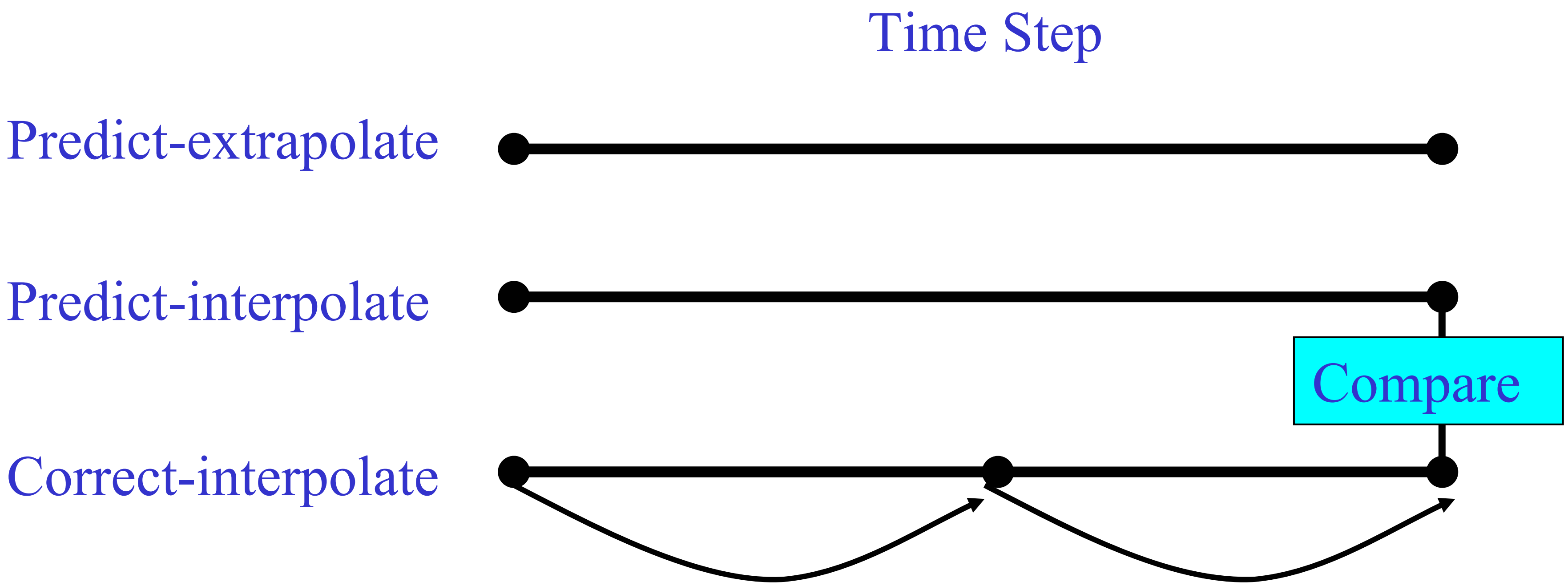
  BUT NOT recommended

  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



Interesting features of the problem (2)

- Representation of the coils in circuit equations

$$\iiint_{\Omega_p} \vec{N}_p . \vec{E}_j \frac{d\vec{A}_j}{dt} d\Omega_p + I_p R = V$$

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

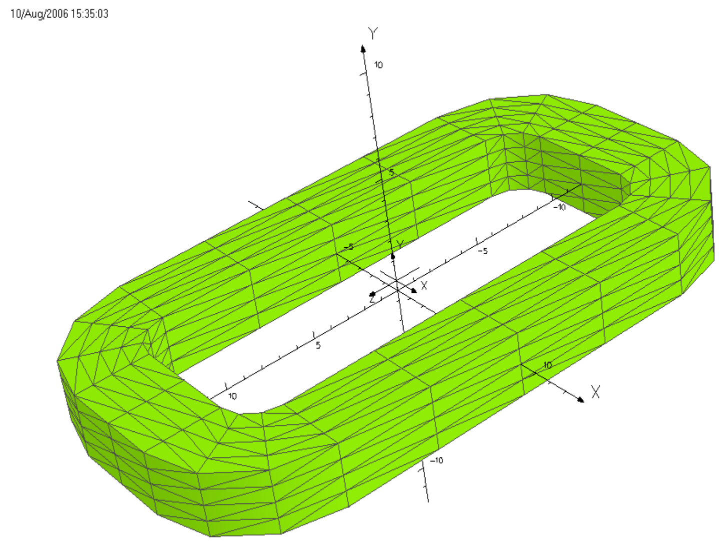
- First release
  - Transient thermal
  - Circuit equations
  - Coil inductance matrix must be provided
- Second release (October 2006)
  - Transient thermal
  - Circuit equations
  - Coupled to transient EM simulation (Elektra)

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

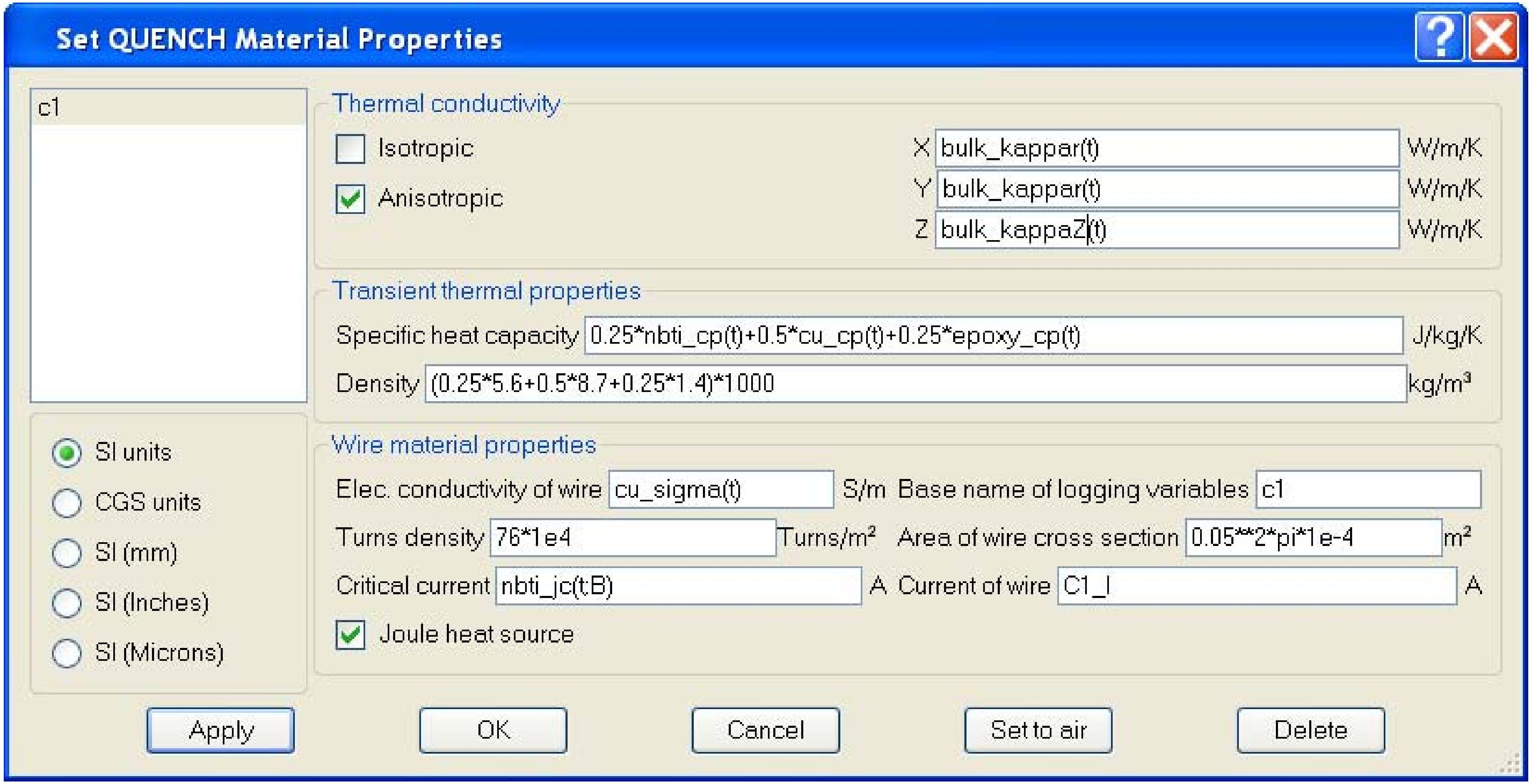
Coil specification

- 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. $10^{a+b*log(t)+c*log(t)^2+d*log(t)^3....}$

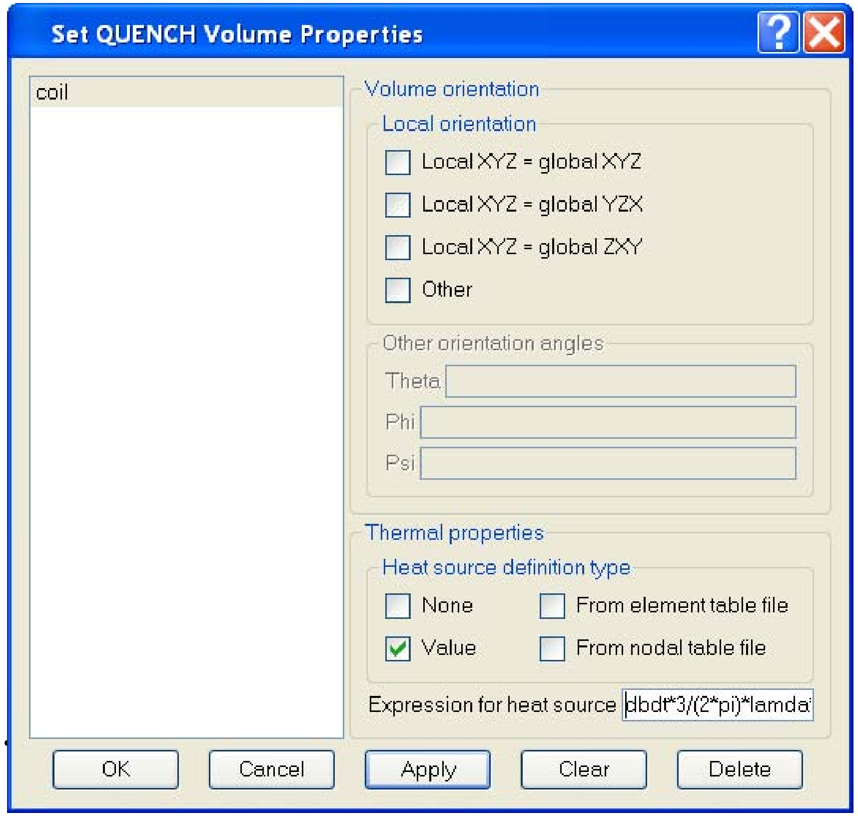
  (Typical NIST format for material properties)

- Tabulated
  - User defined tabulated function eg. JC(T;B)

Heat sources available in QUENCH

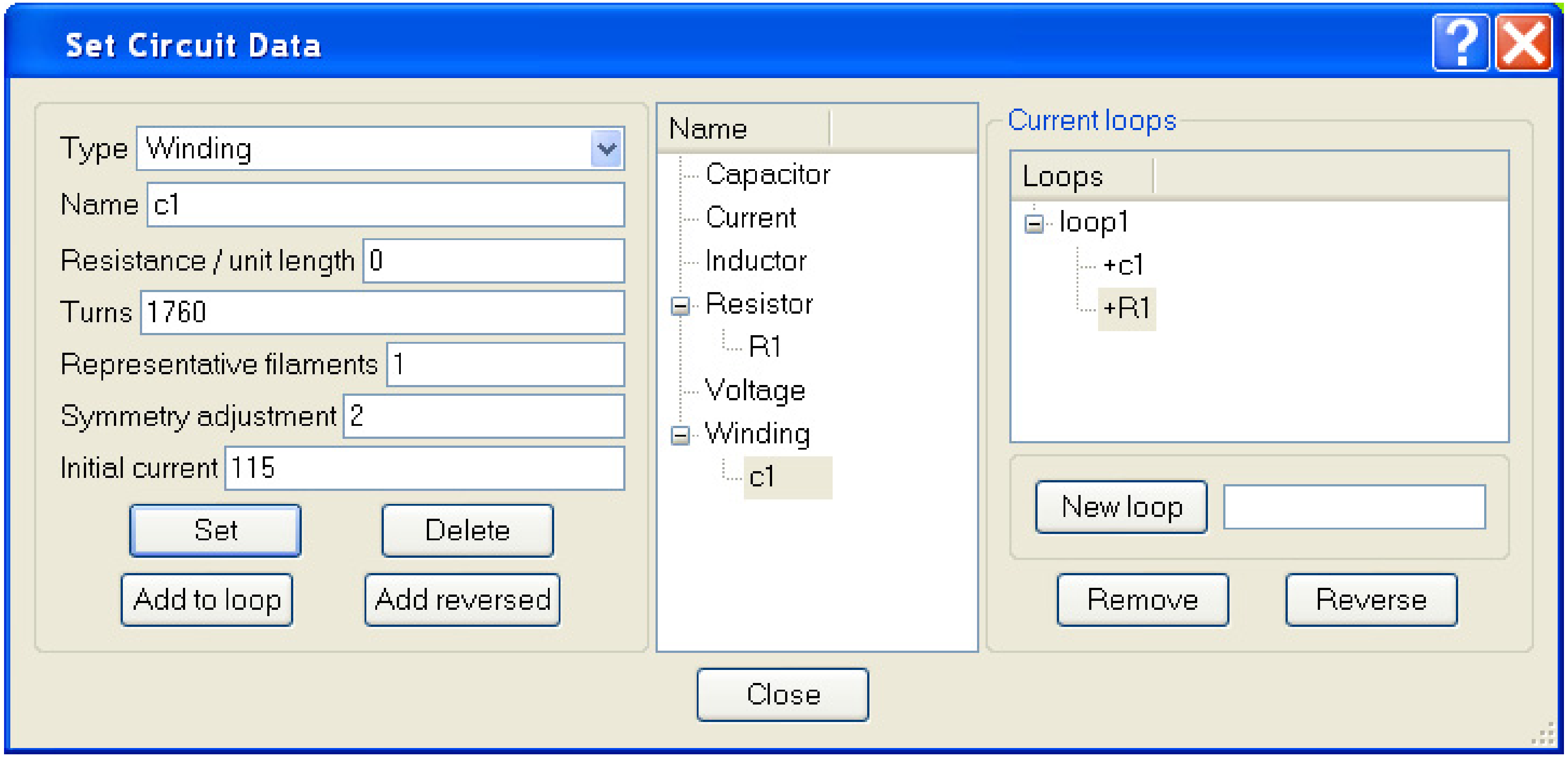
- Joule heating in the normal zone
- Additional heat sources
  - Rate dependent losses

$$\frac{dB}{dt}\frac{2}{3\pi}\lambda_0 J_c(\theta,B)\, d$$



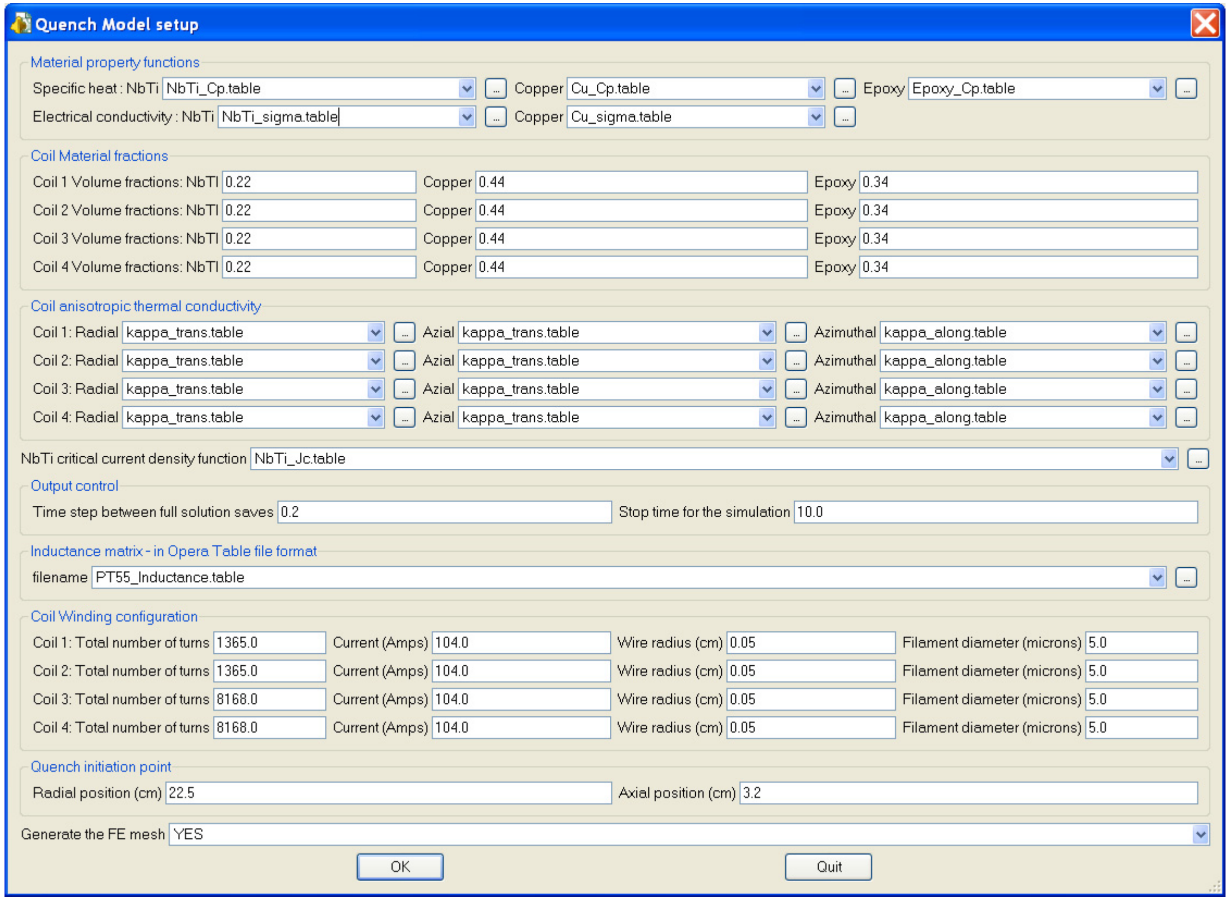
  - Hysteresis losses
  - …………
  - Any function of B, dB/dt, T,Jc..

Protection circuits



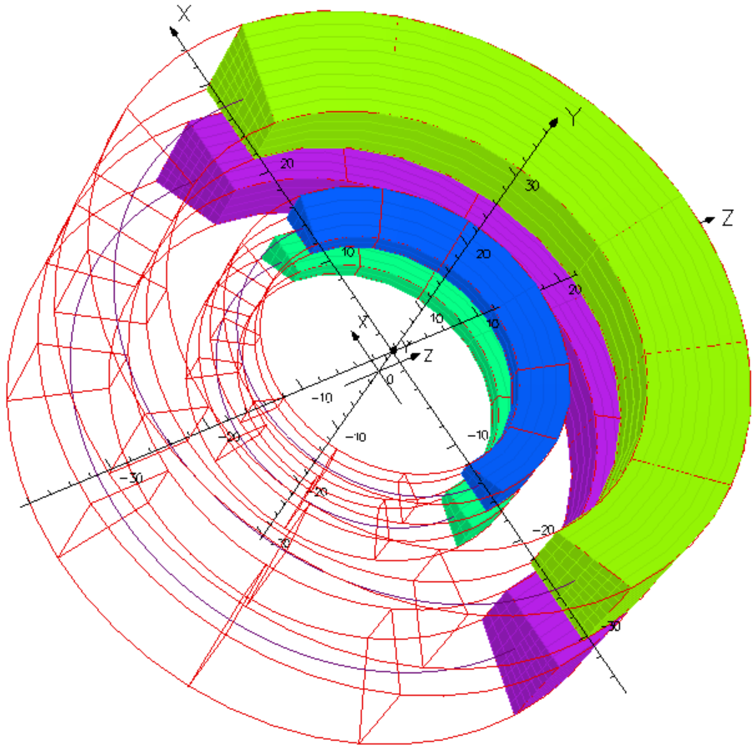
Automating this Process

- A Macro to make this easy for standard quench analyses



Example Model

- PT55 Polarised target magnet



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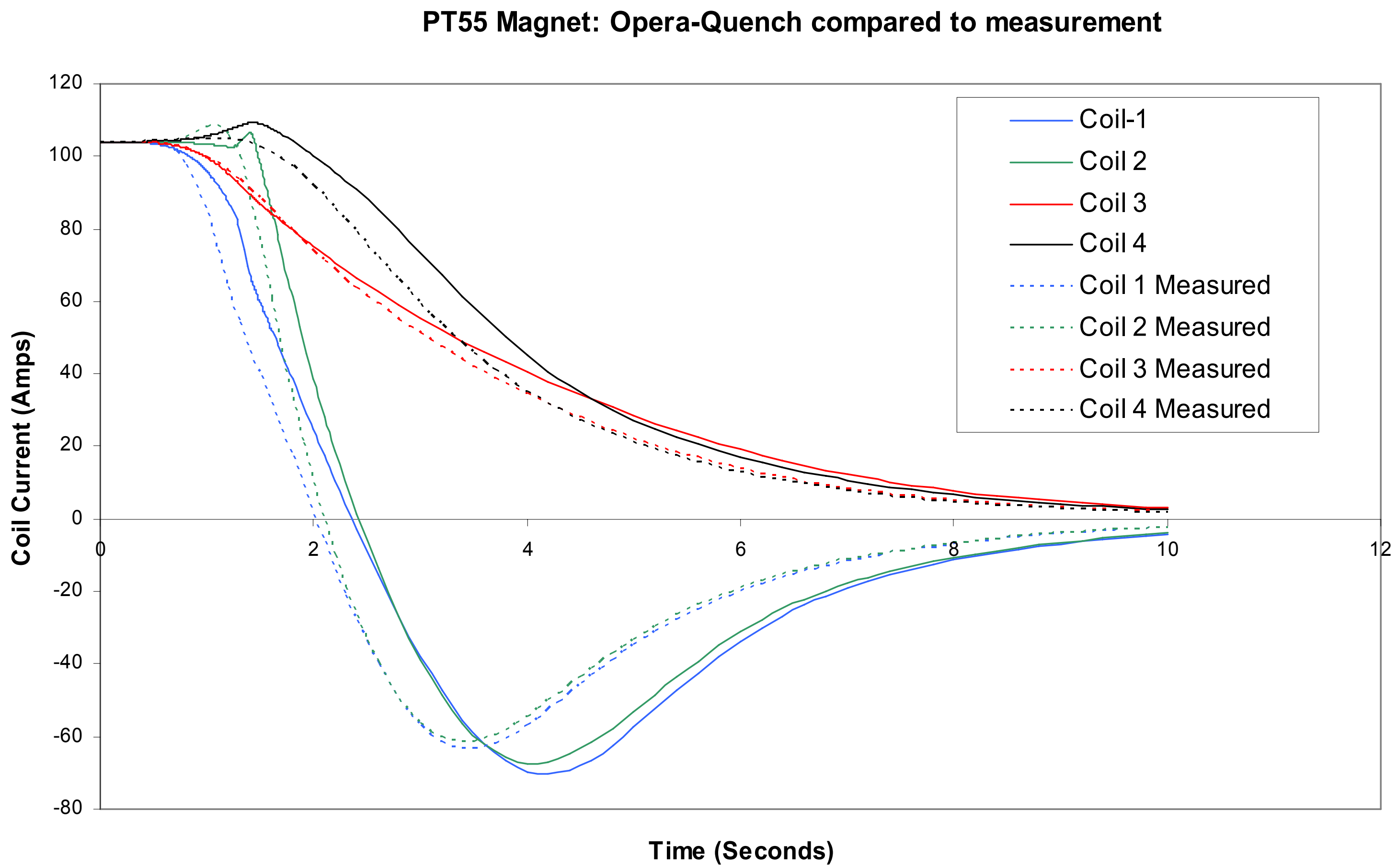
PT55 magnet parameters

- 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



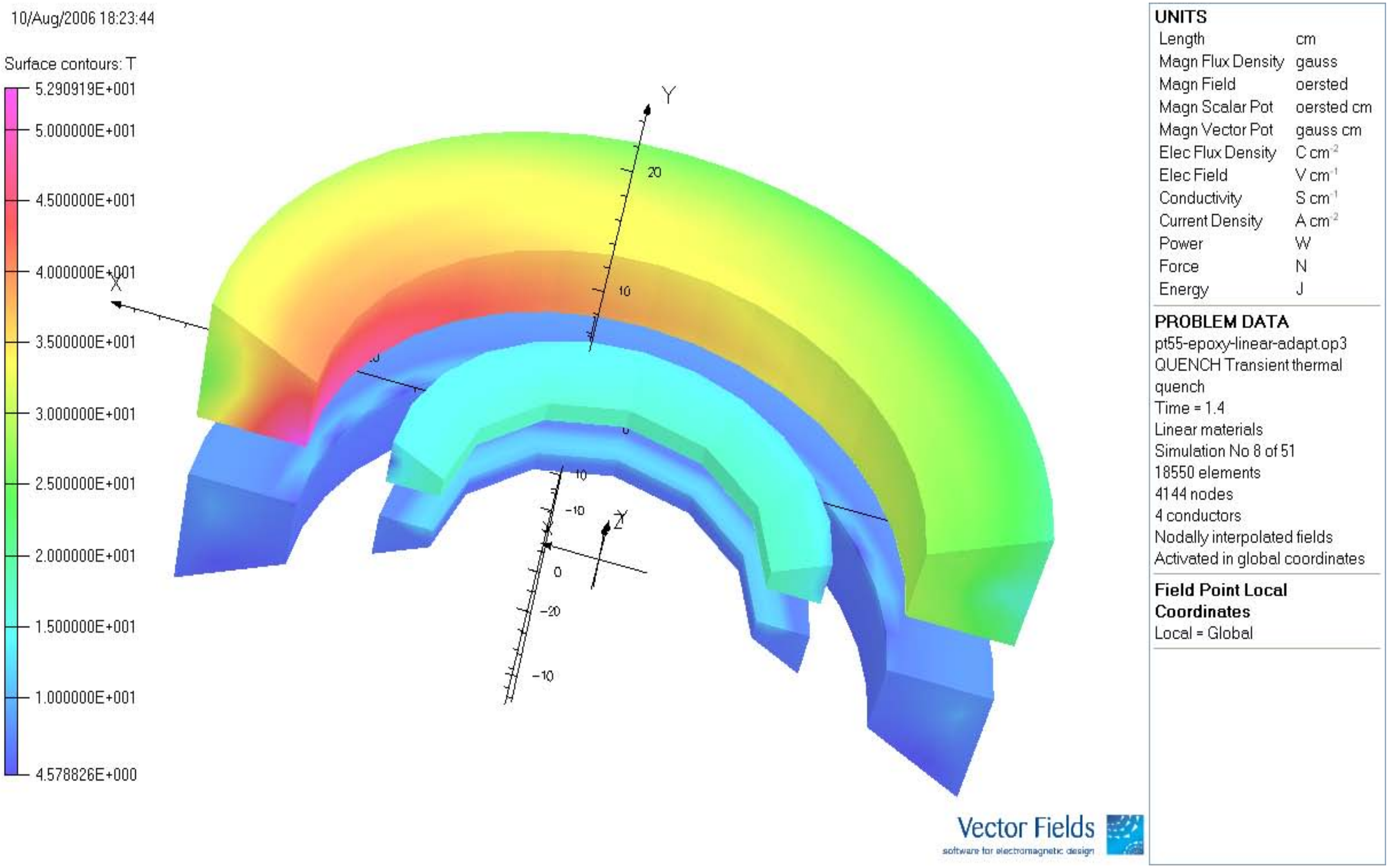
Results

- Output required
  - As a function of time:

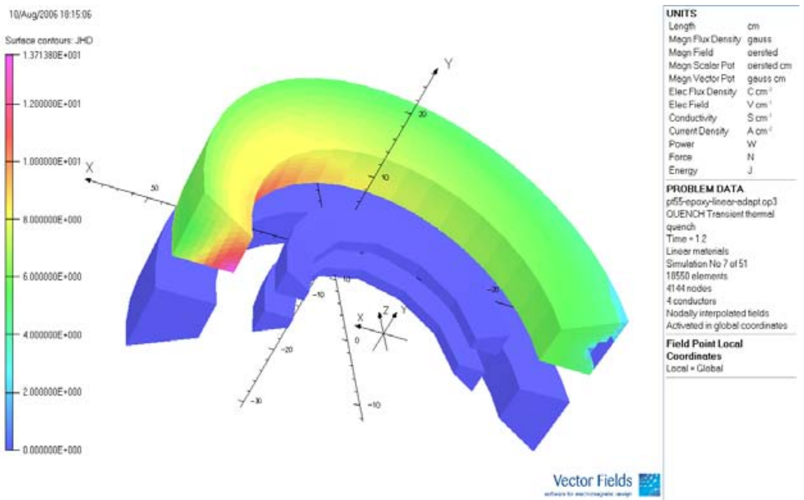
    Current   Resistance   Max_Temperature
    Interlayer_voltage

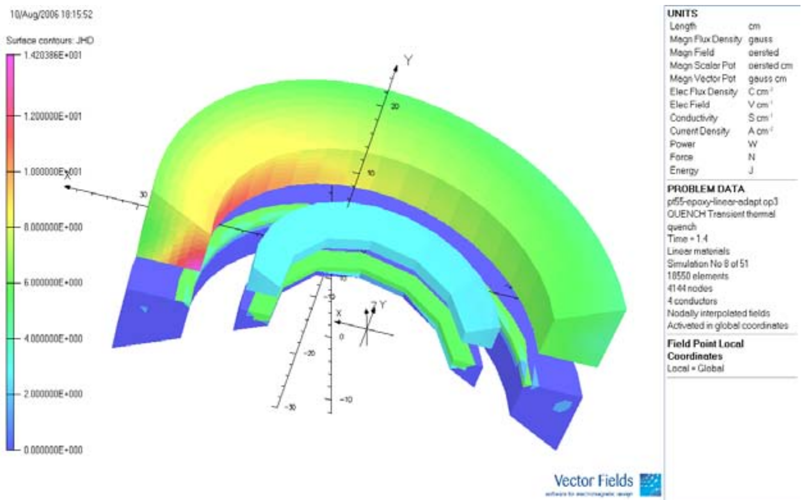
- In addition, for understanding
  - Full solution saved at specified times
  - For subsequent calculation and display
    - Data available includes: Temperature, Joule heat density, B, dB/dt, thermal conductivity ….

Temperature at a particular time

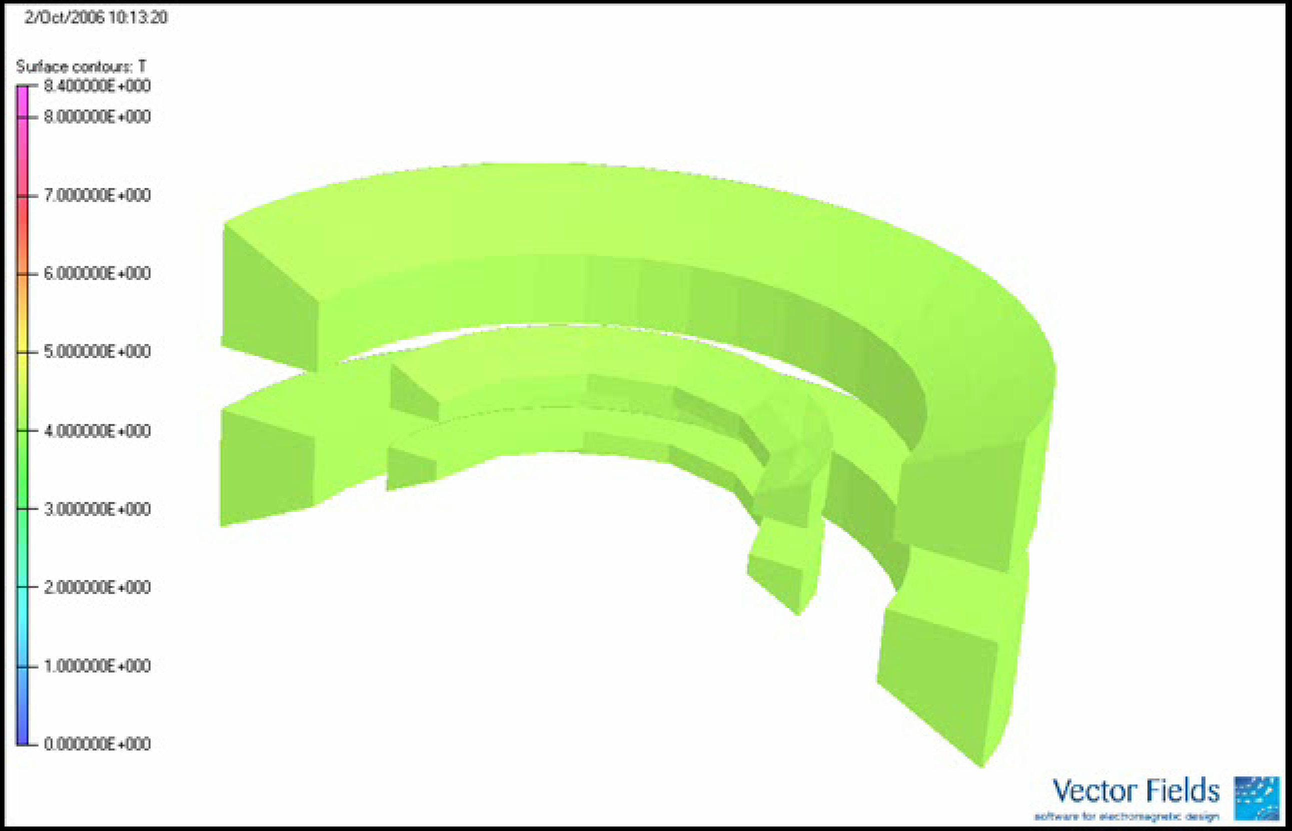


Resistive loss in the normal zones





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



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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