

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

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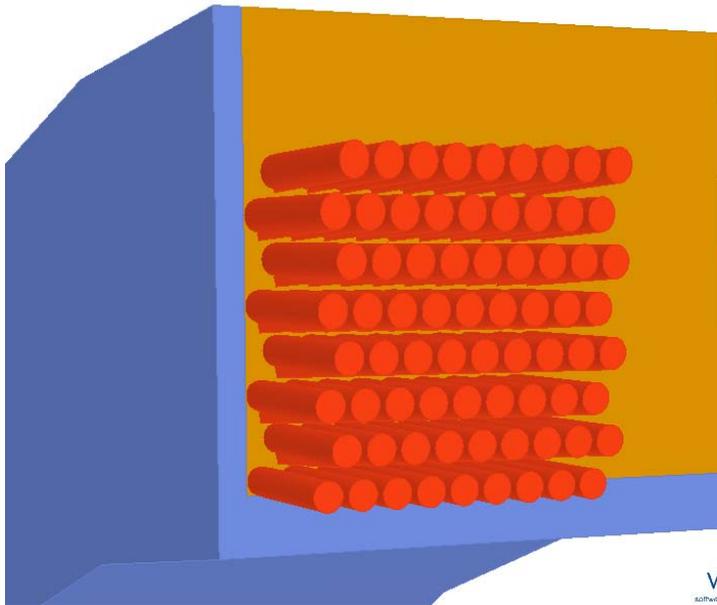
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Application

- 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

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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

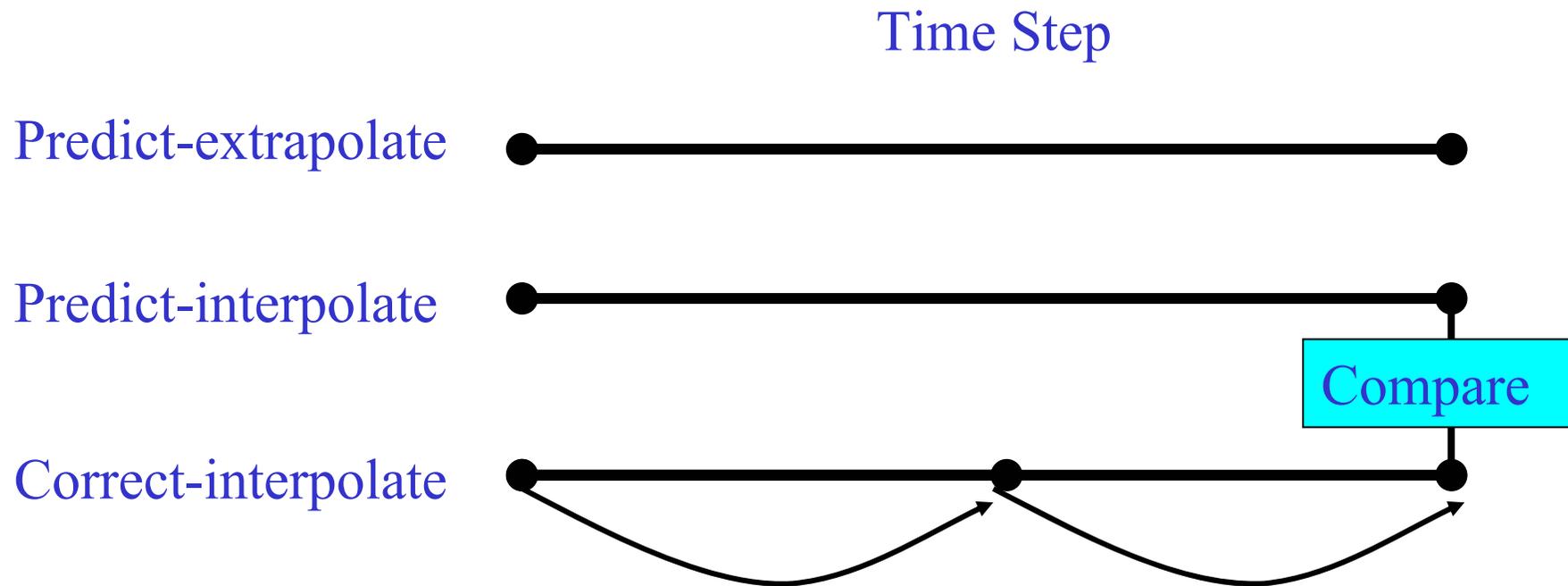
Interesting features of the problem (1)

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



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)

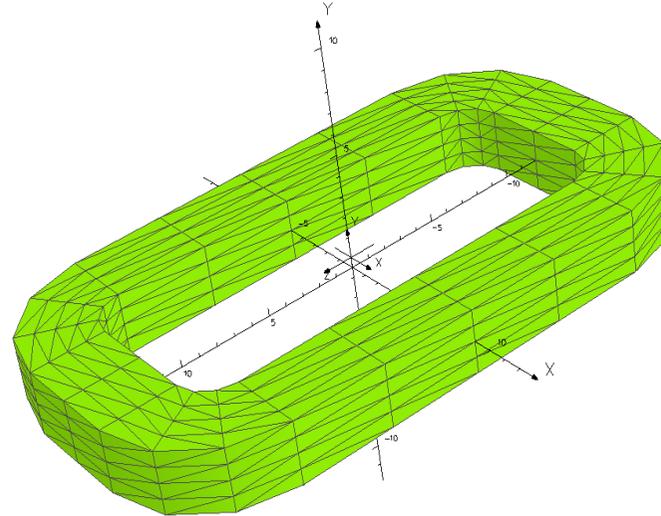
Model required for Quench simulation

- 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

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- Then add materials, heat source, winding, circuit data.....

Coil materials

Set QUENCH Material Properties

c1

Thermal conductivity

Isotropic

Anisotropic

X W/m/K

Y W/m/K

Z W/m/K

Transient thermal properties

Specific heat capacity J/kg/K

Density kg/m³

Wire material properties

SI units

CGS units

SI (mm)

SI (Inches)

SI (Microns)

Elec. conductivity of wire S/m Base name of logging variables

Turns density Turns/m² Area of wire cross section m²

Critical current A Current of wire A

Joule heat source

Apply OK Cancel Set to air Delete

Non-linear material properties

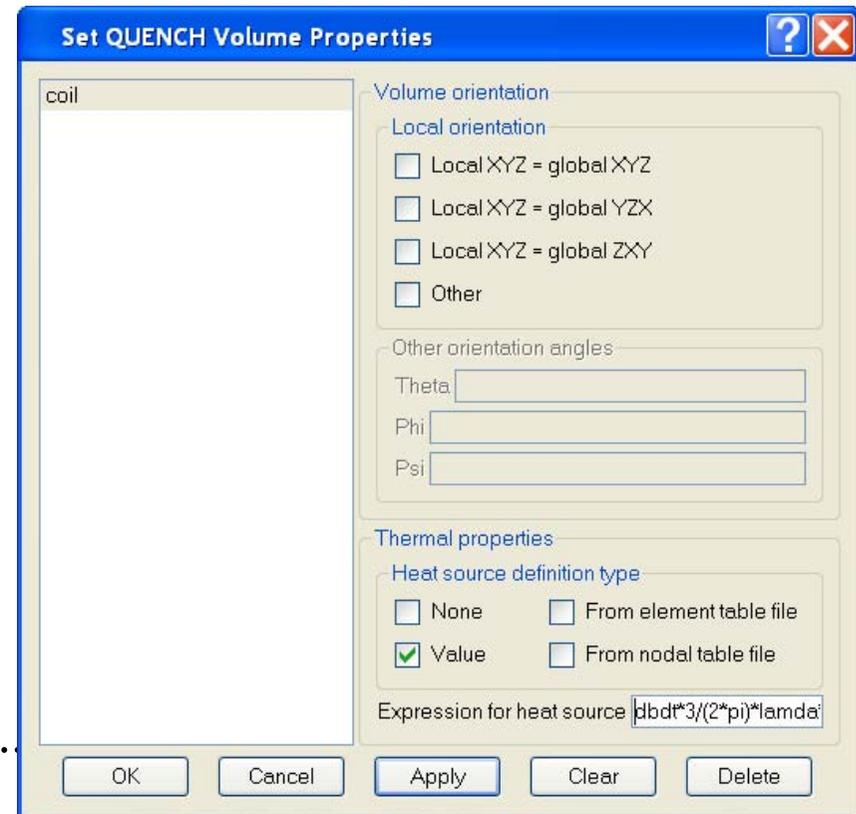
- Functional
 - eg. $10^{a+b*\log(t)+c*\log(t)^2+d*\log(t)^3\dots}$
(Typical NIST format for material properties)
- Tabulated
 - User defined tabulated function eg. JC(T;B)

Heat sources available in QUENCH

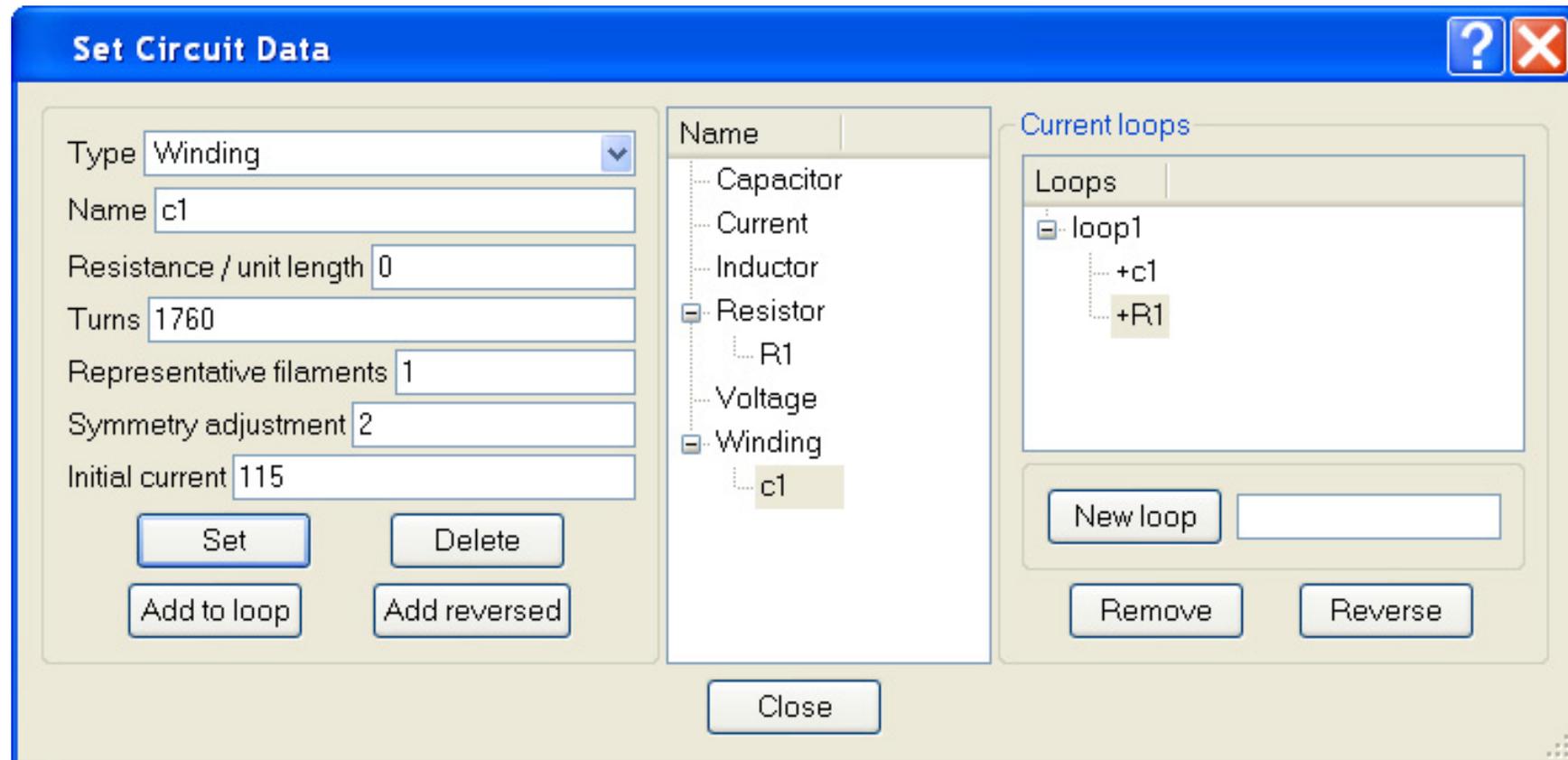
- Joule heating in the normal zone
- Additional heat sources
 - Rate dependent losses

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

- 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

Quench Model setup

Material property functions

Specific heat : NbTi | NbTi_Cp.table | ... | Copper | Cu_Cp.table | ... | Epoxy | Epoxy_Cp.table | ...

Electrical conductivity : NbTi | NbTi_sigma.table | ... | Copper | Cu_sigma.table | ...

Coil Material fractions

Coil 1 Volume fractions: NbTi 0.22 | Copper 0.44 | Epoxy 0.34

Coil 2 Volume fractions: NbTi 0.22 | Copper 0.44 | Epoxy 0.34

Coil 3 Volume fractions: NbTi 0.22 | Copper 0.44 | Epoxy 0.34

Coil 4 Volume fractions: NbTi 0.22 | Copper 0.44 | Epoxy 0.34

Coil anisotropic thermal conductivity

Coil 1: Radial | kappa_trans.table | ... | Azial | kappa_trans.table | ... | Azimuthal | kappa_along.table | ...

Coil 2: Radial | kappa_trans.table | ... | Azial | kappa_trans.table | ... | Azimuthal | kappa_along.table | ...

Coil 3: Radial | kappa_trans.table | ... | Azial | kappa_trans.table | ... | Azimuthal | kappa_along.table | ...

Coil 4: Radial | kappa_trans.table | ... | Azial | kappa_trans.table | ... | Azimuthal | kappa_along.table | ...

NbTi critical current density function | NbTi_Jc.table | ...

Output control

Time step between full solution saves | 0.2 | Stop time for the simulation | 10.0

Inductance matrix - in Opera Table file format

filename | PT55_Inductance.table | ...

Coil Winding configuration

Coil 1: Total number of turns | 1365.0 | Current (Amps) | 104.0 | Wire radius (cm) | 0.05 | Filament diameter (microns) | 5.0

Coil 2: Total number of turns | 1365.0 | Current (Amps) | 104.0 | Wire radius (cm) | 0.05 | Filament diameter (microns) | 5.0

Coil 3: Total number of turns | 8168.0 | Current (Amps) | 104.0 | Wire radius (cm) | 0.05 | Filament diameter (microns) | 5.0

Coil 4: Total number of turns | 8168.0 | Current (Amps) | 104.0 | Wire radius (cm) | 0.05 | Filament diameter (microns) | 5.0

Quench initiation point

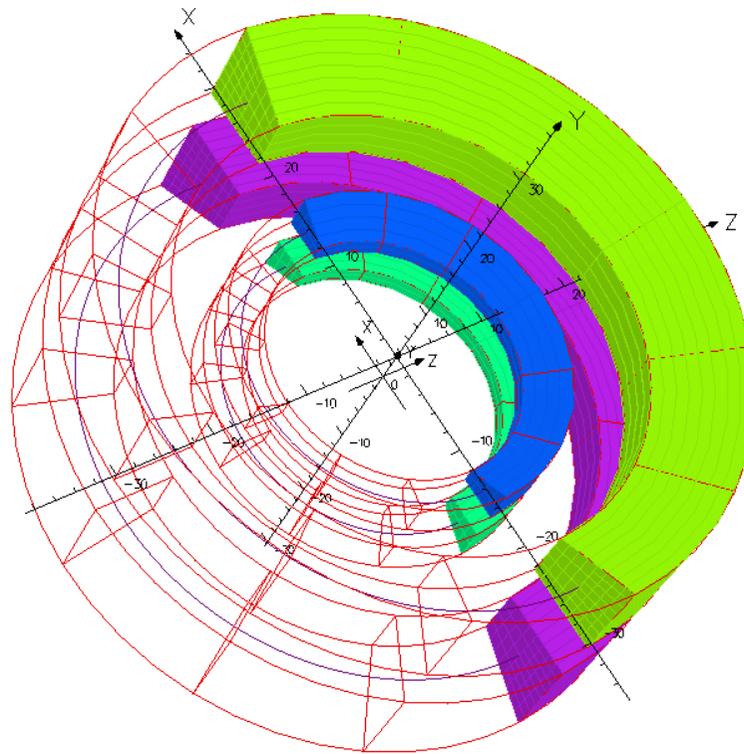
Radial position (cm) | 22.5 | Axial position (cm) | 3.2

Generate the FE mesh | YES | ...

OK | Quit

Example Model

- PT55 Polarised target magnet



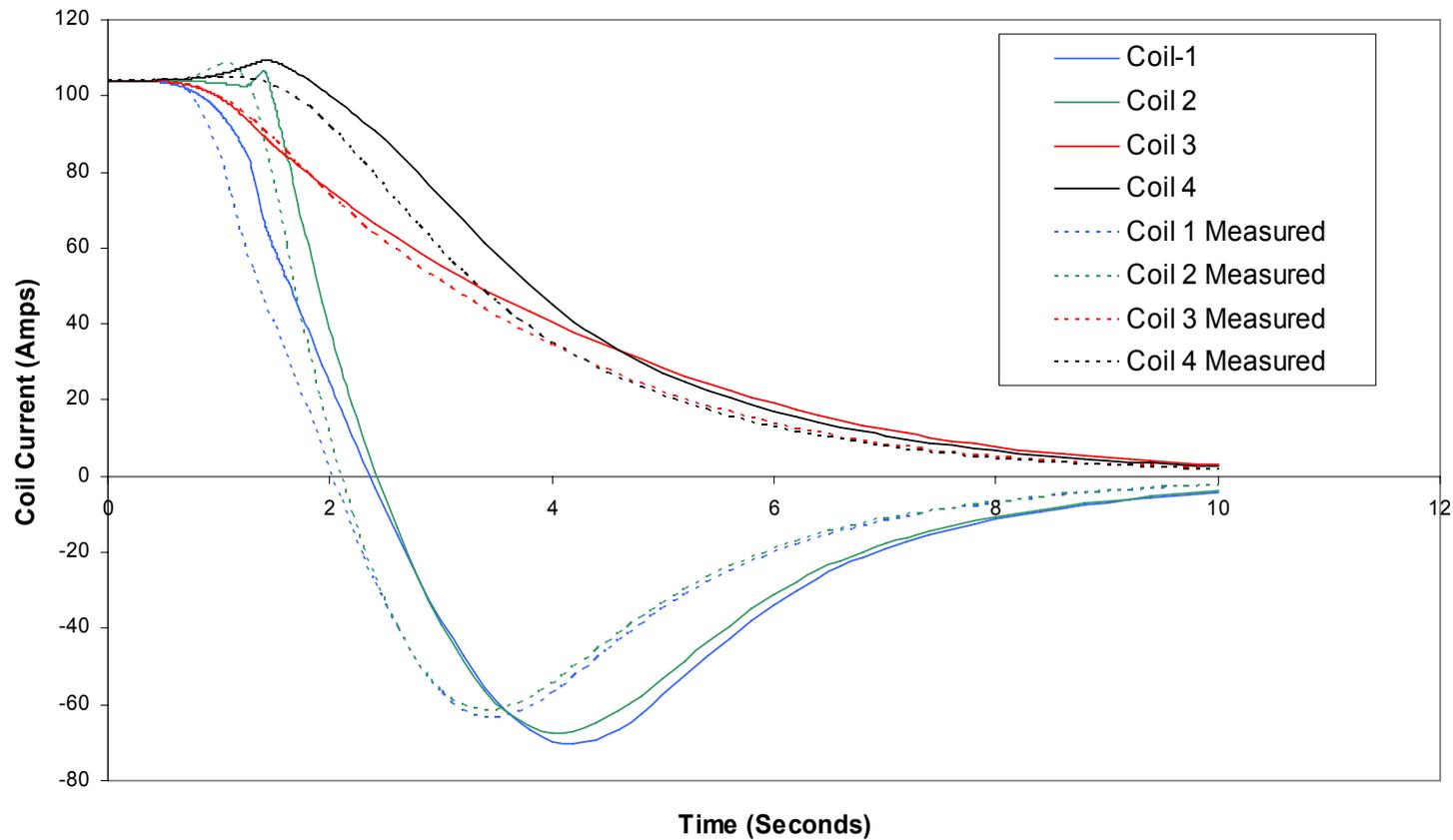
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PT55 magnet parameters

- 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

PT55 Magnet: Opera-Quench compared to measurement



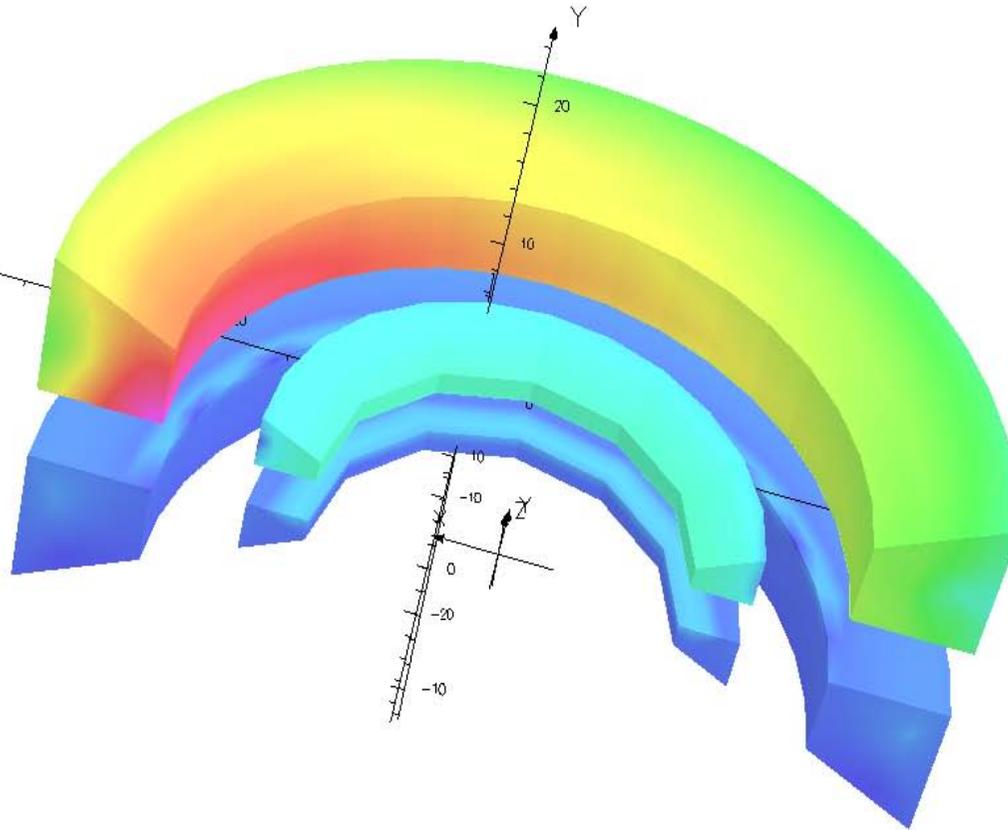
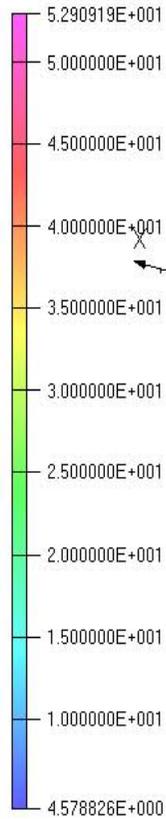
Results

- 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

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Surface contours: T



UNITS	
Length	cm
Magn Flux Density	gauss
Magn Field	oersted
Magn Scalar Pot	oersted cm
Magn Vector Pot	gauss cm
Elec Flux Density	C cm ⁻²
Elec Field	V cm ⁻¹
Conductivity	S cm ⁻¹
Current Density	A cm ⁻²
Power	W
Force	N
Energy	J

PROBLEM DATA
pt55-epoxy-linear-adapt.op3
QUENCH Transient thermal
quench
Time = 1.4
Linear materials
Simulation No 8 of 51
18550 elements
4144 nodes
4 conductors
Nodally interpolated fields
Activated in global coordinates

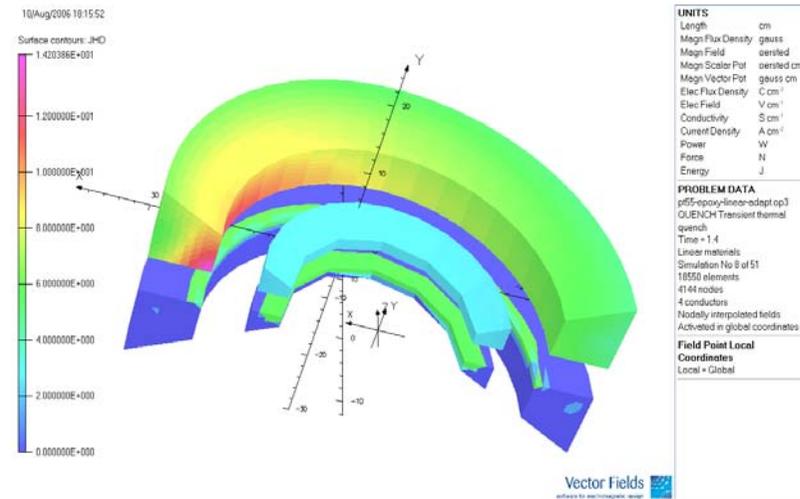
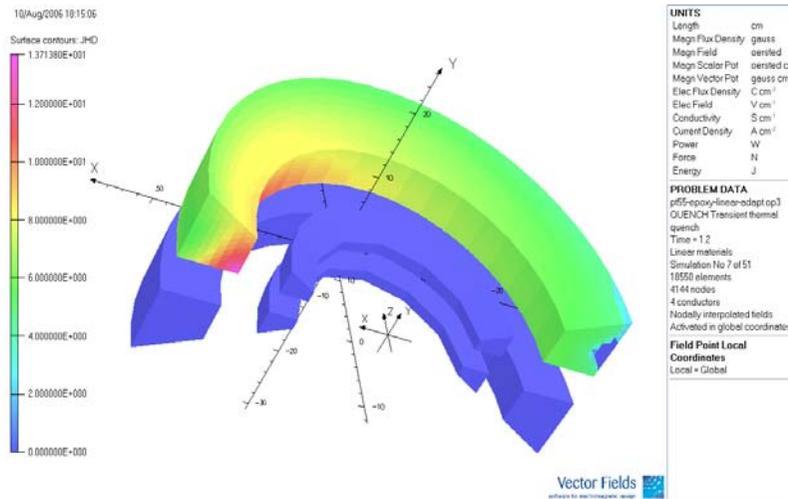
**Field Point Local
Coordinates**
Local = Global

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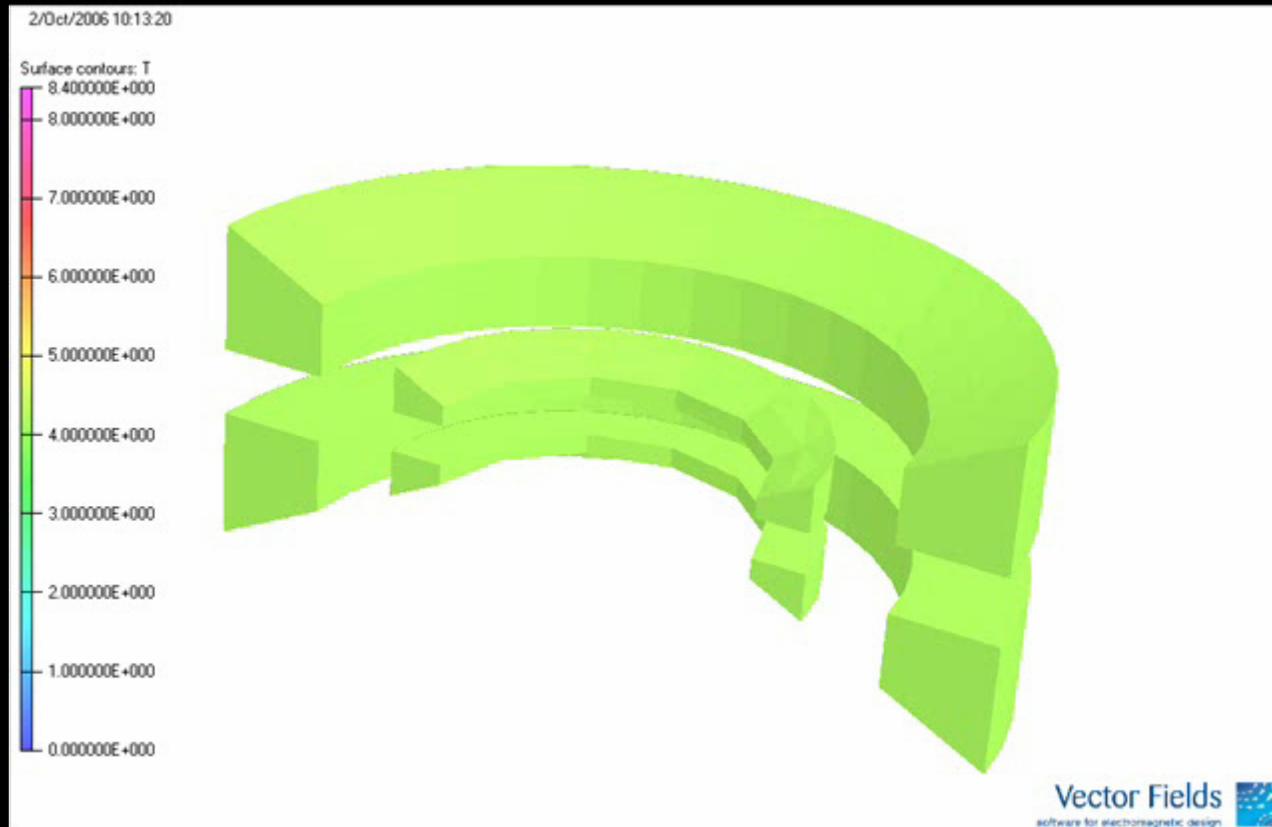
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Resistive loss in the normal zones



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