Vector Fields Software

PAC09 – Magnet Workshop

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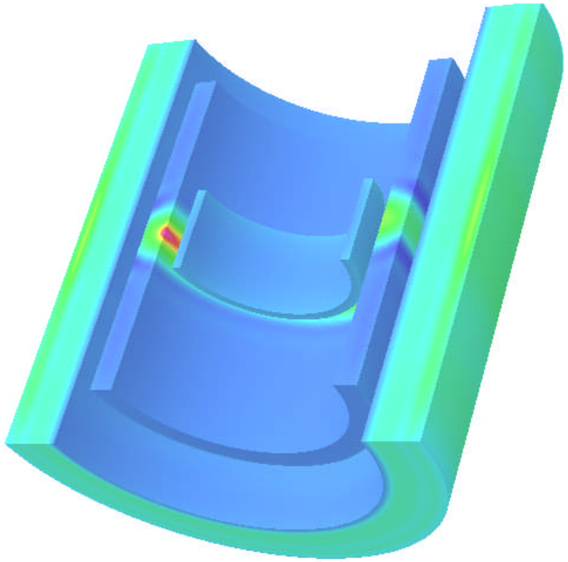
IMPDAHMA

Modelling Quench in HTS coils at 4.2K



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IMPDAHMA
Modelling Quench in HTS coils at 4.2K

- **Review of the project objectives**

- **Developments to achieve the objectives**
  – Quench software improvements (Cobham Technical Services)
  – Measurements of material properties (Southampton University)
  – Manufacture and testing of prototypes (Oxford Instruments)

- **Preliminary success**
  – OIS announce 22T NMR magnet using HTS insert at 4.2K

- **Status of the Quench Software improvements**
  – Mosaic mesh (mixing different element types)
  – Improved methods for non-linear devices eg. Diodes in circuits
  – Circuit schematics
  – Materials database
  – Integrated design environment

- **Results**

Ultra high field magnet systems have a vital role in scientific and medical advances

- Existing superconducting NMR magnets are almost at the limit of field strength that can be achieved with low temperature superconductors
  - Commercial 950MHz magnets (Equivalent to 22.3Tesla)
    Achieved using Nb_3Sn pumped to low temperature (1.2K) to raise the critical field
  - Highest field achievable with Nb_3Sn limit is approximate 24T
- High Temperature Superconductors offer a way forward
  - At 4.2K some HTS materials have critical fields in the range 25 to 30 Tesla
  - But engineering technology needs to be developed for these extreme fields

The project aims to develop the technology required to design ultra high field superconducting magnets to operate at low temperatures, using a combination of low and high temperature superconductors

IMPDAHMA
Project Work programme

1. Develop the software tools required to model Quench in the magnets

    - Improved Quench simulation software
        - Hexahedral mesh to reduce simulation times
        - Better solution methods for non-linear circuits
        - Extended multiphysics analysis eg. monitoring stress during Quench
    - Integrated design environment, that links to
        - Materials database
        - Magnet geometry database
    - Thermo- Electro-Mechanical Models for HTS superconductors

2. Measurements of the material properties from 1->300K
    - HTS conductors
        - Oxford Superconductors Round wire Bi-2212
        - American Superconductors YBCO-123 coated tape
    - Representative HTS composite coil structures

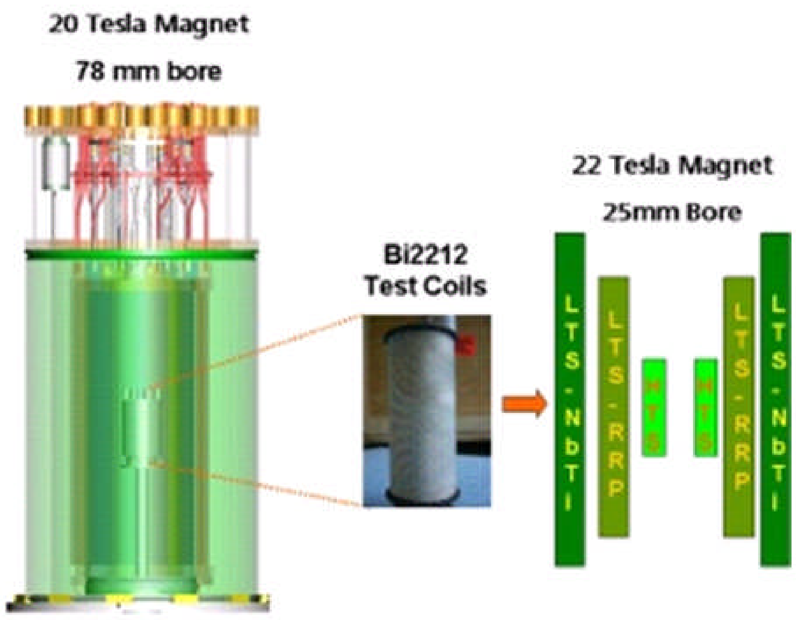
IMPDAHMA
Project Work programme….

3. Development of engineering and manufacturing technology
   - Wind and react procedures for Bi-2212 round wires
   - Wind procedures for YBCO-123 tapes
   - Fabrication of test coils
     - Instrumented for internal voltage and temperature measurement
     - Test coil measurements (Quench initiated by heaters)
     - Supply of coils to Southampton for material measurements
   - Validation of Quench simulations
4. Prototype coils
   - Design and manufacture of prototype coils
     Based on 20T Nb_3Sn/NbTi wide bore NMR testbed magnet
     - 22T with Bi-2212 instrumented small insert coil
     - Ultra high field (30T?) final prototype

IMPDAHMA
Preliminary Success

- **Oxford Instruments has constructed and successfully tested a 22.07T superconducting magnet operating at 4.2K**

  Magnet consisted of:
  - 20T 78mm (wide bore) $Nb_3Sn/NbTi$ magnet
  - Two coil HTS insert (Oxford Superconductors Bi-2212 round wire)



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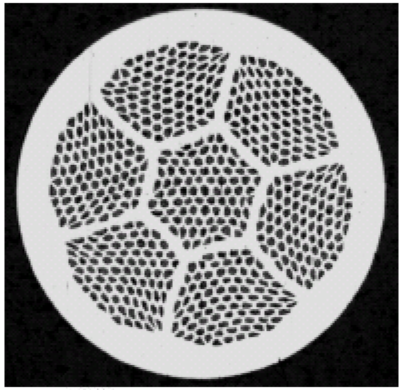
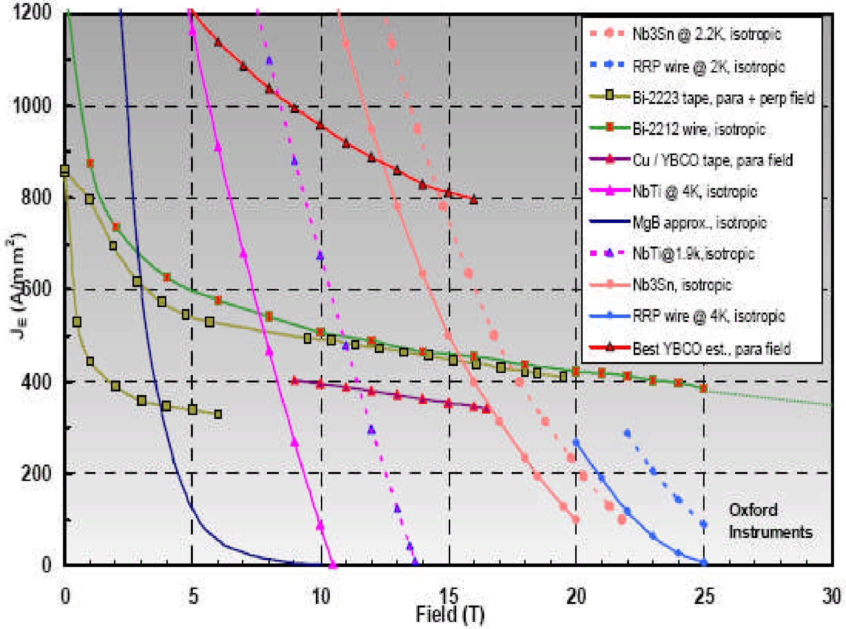
Preliminary Success

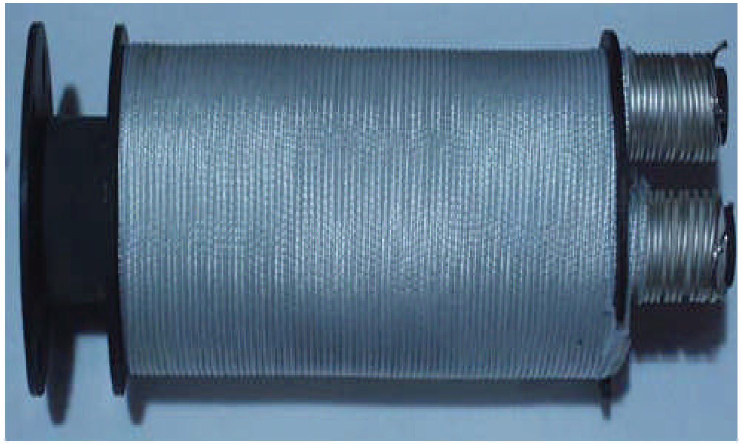


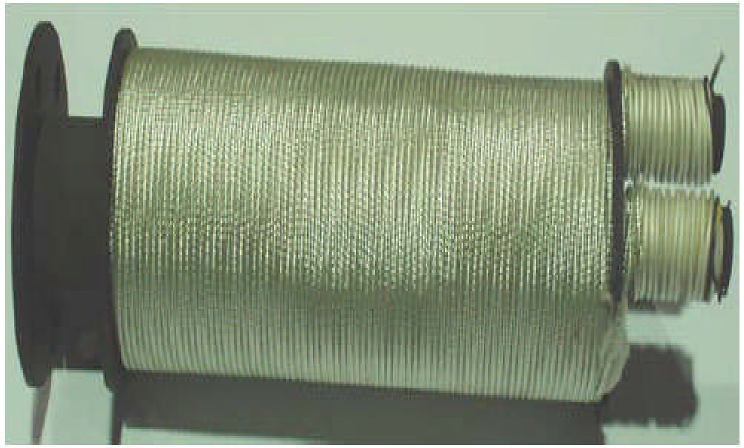
OST Bi-2212 round wire



Critical current for different superconductors

Multilayer test coil before and after reaction



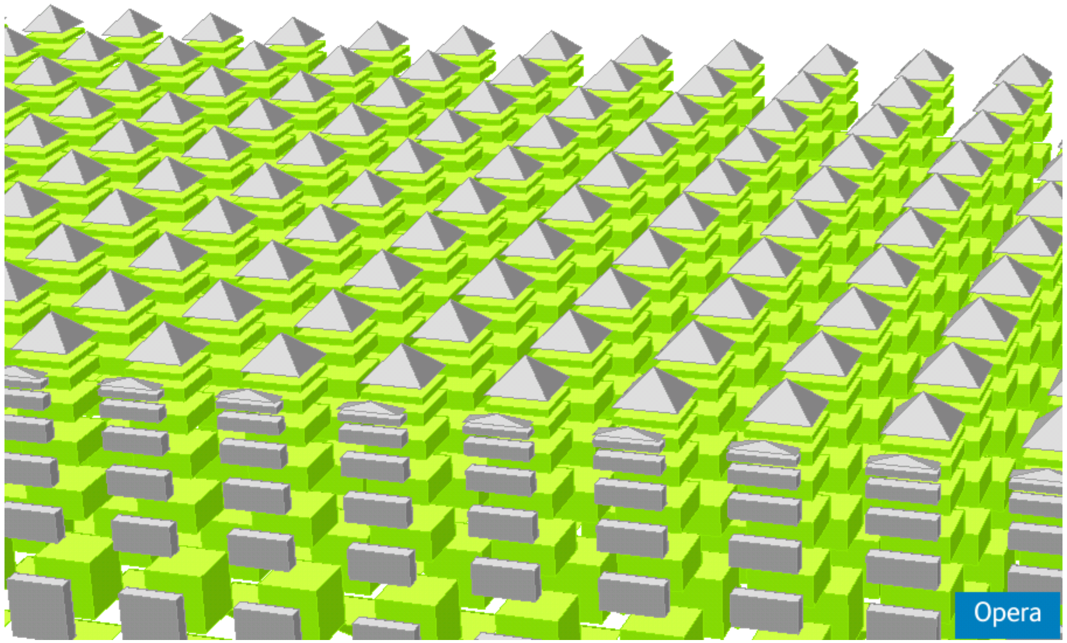


Status of the Quench Software improvements

The development of software tools for HTS applications at low temperature

Development of Software Tools
Improved Quench simulation software

- Facilities for meshing with Hexahedra
  - –Mapped Hexahedral mesh in simple cells
  - –Mixture of element types for contiguous mesh
    - Tetrahedra, Hexahedra, Pyramids & Prisms



Development of Software Tools
Hexahedral mesh

- Gains as a result of using Hexahedra in Quench models
  - Faster for the same accuracy
    - 1/5th number of elements
    - And Quench solution time is proportional to the number of elements because assembly of non-linear matrix terms dominates
  - Extreme aspect ratio elements can be used
    - Avoiding large errors when aspect ratio of tetrahedra exceeds 10:1 (This problem only applies to eddy current and Quench simulations)
    - High aspect ratio elements are required in Quench models
      - Highly anisotropic thermal conductivity (stiff system)
      - Problem can be alleviated by using anisotropic mesh size
        The mesh edge lengths should be related to the anisotropic thermal conductivity – long in the high conductivity direction

Development of Software Tools
Improved Quench simulation software

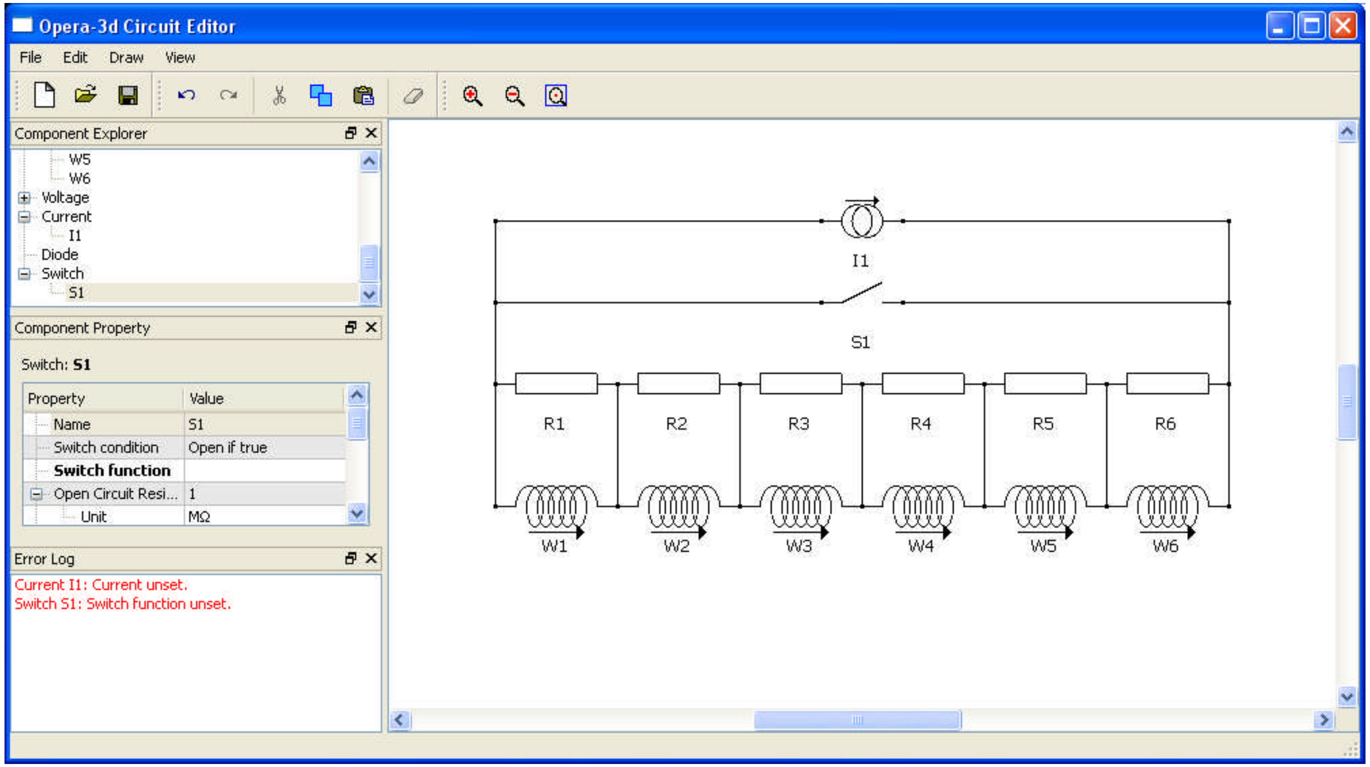
- Better Solution methods for Non-linear Circuits
  - The design of appropriate Quench Protection circuits is important for high field Nb_3Sn/NbTi magnets
    - High field = lots of energy stored in the field = big temperature rises
    - The Nb_3Sn wire is more resistive than NbTi wire (when resistive) and the problem is therefore more extreme than with only NbTi
  - Positive feedback is usually required to avoid magnet damage
    - Heater pads bonded in the coils, that can be heated rapidly using discharge circuits switched on when a fault is detected
    - Linked secondaries to spread the quench (Eddy currents in formers)
  - The protection circuits quickly become complicated and the accurate representation of protection diodes is vital if the switching of heaters is to be predicted reliably

Development of Software Tools
Improved non-linear solution

- Quench analysis requires tightly coupled simulations
  - Electromagnetic – Magnetic fields and eddy currents
  - Electric Circuit - Protection circuit
  - Thermal
- The Non-linear electric circuit components often determine the maximum time step that can be used.
- Whereas the finite element solution of the Electromagnetic and thermal fields dominates the solution time and could use larger time steps.
- A predictor/corrector sub-system iteration has been added into the Non-linear solution scheme of Opera, for the electric circuit equations.
  - Evaluates an approximate impedance matrix for the FE electromagnetic model – based on previous time steps
  - Pre-converges the Electric circuit equations before each Non-linear finite element iteration

Development of Software Tools
Improved non-linear solution…

- Good results for Typical protection circuit diodes
  - Smallest time step increased by a factor in the range 3 to 8
  - Solution times reduced by a factor of 4
- Useful improvement, however an important GAIN for Opera **is**



Circuit schematics input

Linked to Opera-2d and 3d

Development of Software Tools
Improved Quench simulation software

- **Some essential MultiPhysics improvements were clear**
  - Decoupled link to Full Stress analysis required
    - Must be completely automated
    - But not that simple because for this class of NMR magnet it is usual to analyse a detailed model of the windings in 2D (axi-symmetric) including individual turns, insulation, filler, formers and binding.
    - Facilities were therefore required to export body forces and temperature in a format suitable for Abaqus, Ansys & Opera-2d
    - This is not something that could be co-simulated with Quench
  - Approximate calculations that were fast enough to perform at all Quench time steps
    - For the NMR solenoids this includes
      - Unsupported turn hoop stress
      - Iwasa thick coil hoop stress
- **Reacting to results : requirements identified by comparison with measurements, this work is on-going**

Development of Software Tools
Integrated design environment

- Primary objective for Oxford Instruments
  - Creation of a software environment that contains the set of tools and supporting data required for the design of Ultra high field magnets
    - Linked to their magnet database
    - Including the HTS Materials database from Southampton
  - Opera command scripts have been developed to:
    - Access magnet geometry
    - Access winding data (Turns, turns density, wire data)
    - Access Protection circuit descriptions (Spice netlist)
    - Automatically generate the Opera Quench models
- A materials library facility is being implemented in OPERA
  - The Southampton HTS materials library will be available
  - HTS conductors library in collaboration with Sumitomo

Development of Software Tools
HTS Thermo- Electro-Mechanical Models

- Collaboration with Sumitomo to supply a library of Sumitomo HTS conductors properties with Opera
  - First release will only cover high temperature operation (>77K)
  - Properties to be included:
    - Critical current as a function of field and temperature
    - Thermal conductivity
    - Electrical conductivity models (DC and AC)

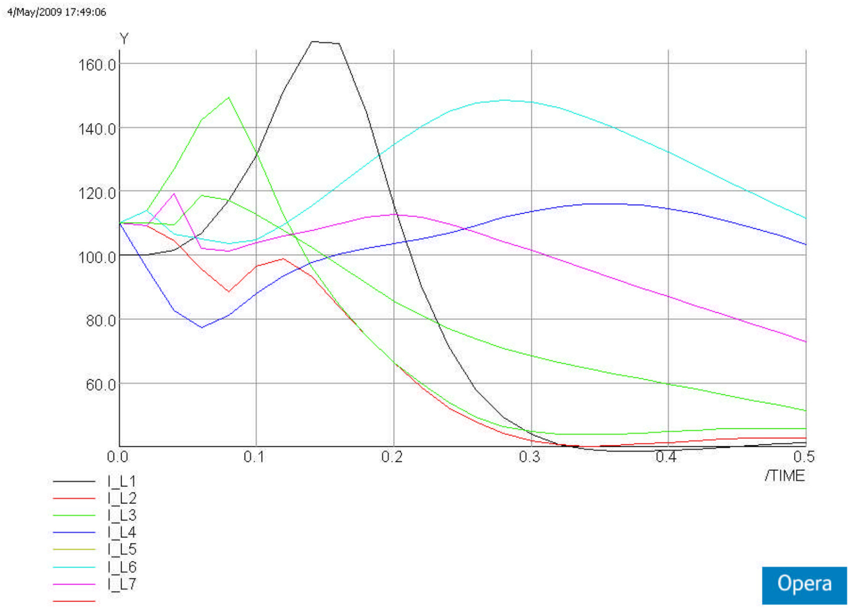
- Special features of HTS materials at low temperature
  The IMPDAHMA project is making prototypes and carrying out measurements to validate the models used to represent HTS conductors for Quench analysis. In particular:
  - Measurement of the Resistive transition and the change in resistance of the conductor as a function of field and temperature
  - Rate dependent losses caused by time varying fields

Results

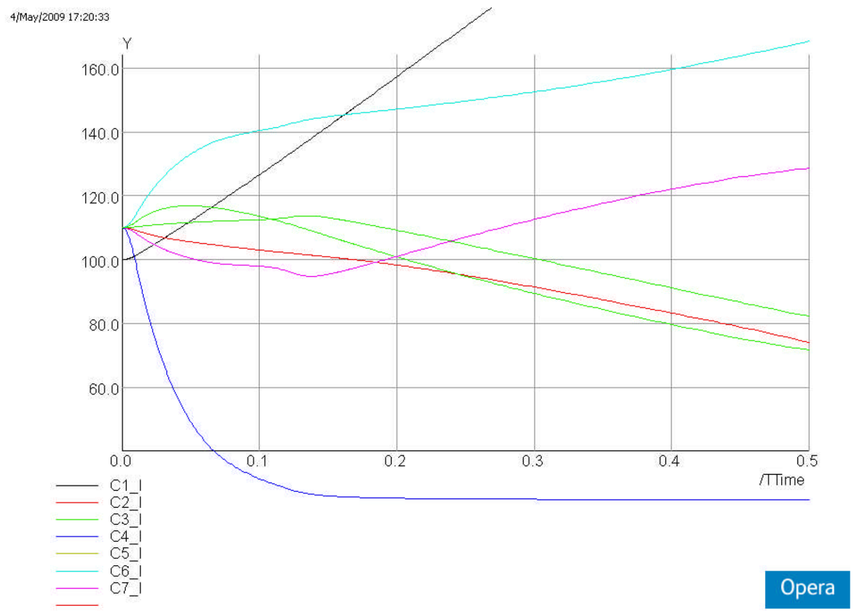
Comparison of simulations with Measurement

IMPDAHMA
Comparison with Measurement

Measured



Calculated



Agreement appears to be limited?

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Discussion of first results

- **Assumptions of simulation**
  - Coil 4 Quenched
  - Power supply switched off immediately
  - Other coils only quench if:
    - They rise above their critical currents that depends on the Field and their temperature, which changes as a result of
      - Conduction
      - Rate dependent losses (eddy currents in the conductors)
  - HTS rate dependent losses based on LTS theory
- **It is clear from the measurements (because the rates of change of current change discontinuously) that:**
  - Coils 5 and 6 quench within 0.05 seconds
  - Coils 1 and 2 quench at 0.15 seconds
  - The simulations do not predict this
- **Initially the current changes agree, but at t=.01?**

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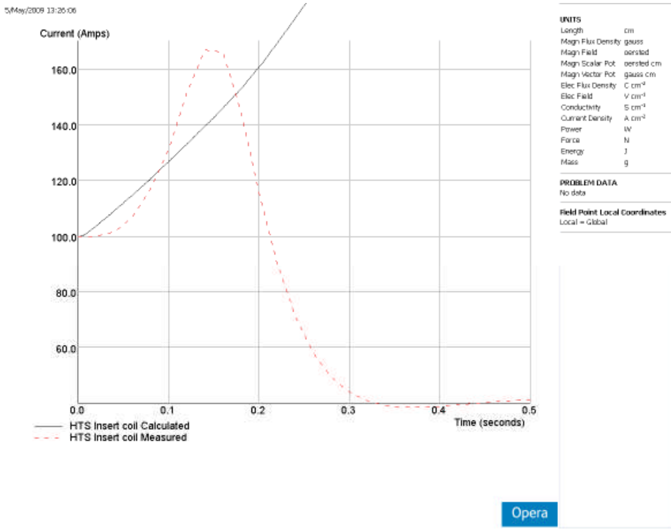
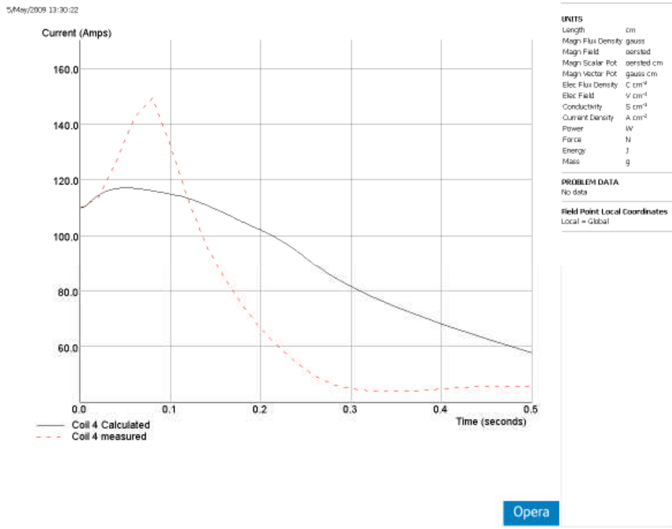
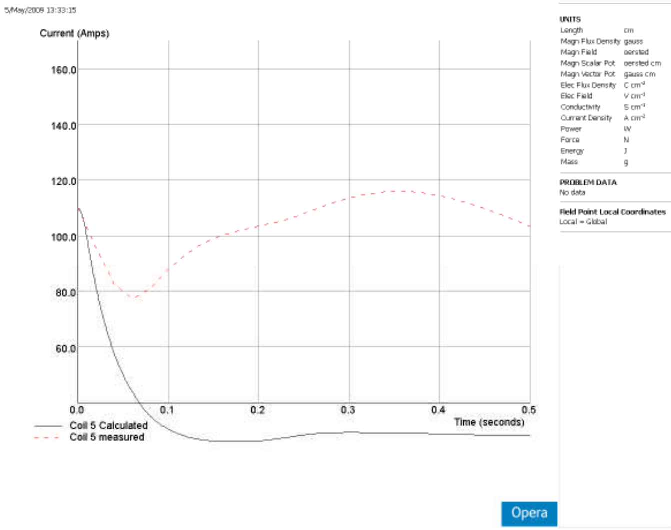
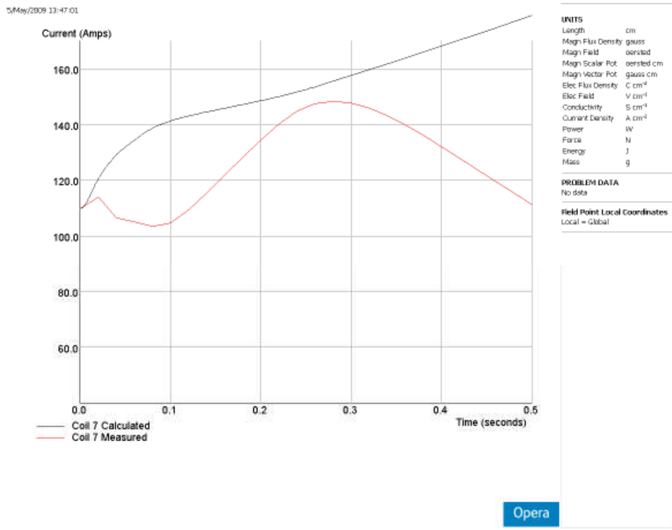
Detailed results









IMPDHAMA
Discussion of first results

- The Opera quench software was designed to avoid having to make assumptions about when a quench would spread to other coils in the system.
  However, the software does not monitor coil stresses and cannot predict micro-movements causing a quench to start in other coils.

- The agreement improves if :
  - Coils 5 and 6 are forced to quench at time=0.05
    (the coils form a single unit with coil 4 and the position where the quench started could explain this)
  - The HTS insert is forced to quench at time 0.15

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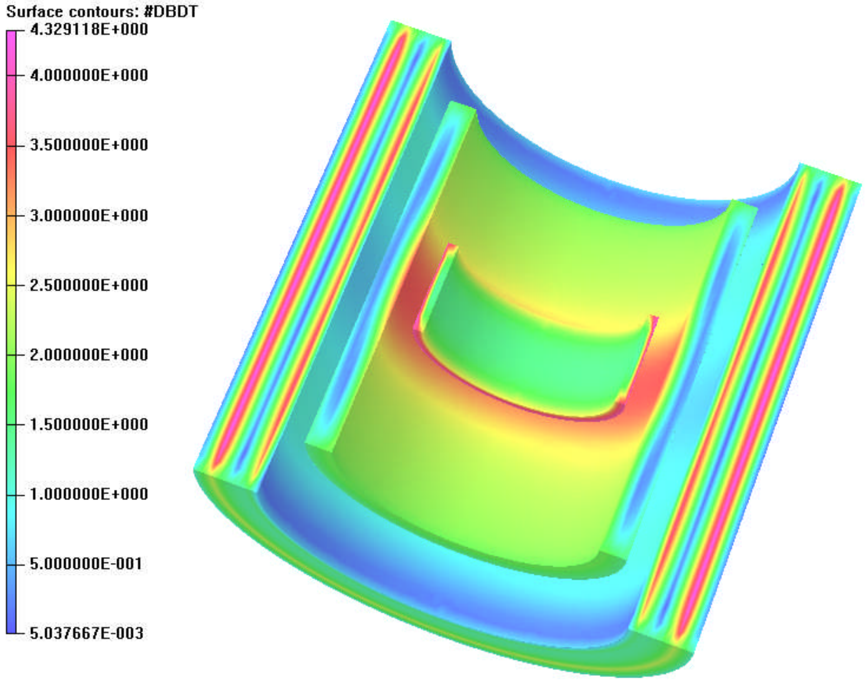
Steps to improve agreement

- Measure rate dependent losses in the HTS and Nb3Sn conductor

The rates of change of field are extreme in this magnet and change quickly as the quench progresses (up to 4Tesla/second)

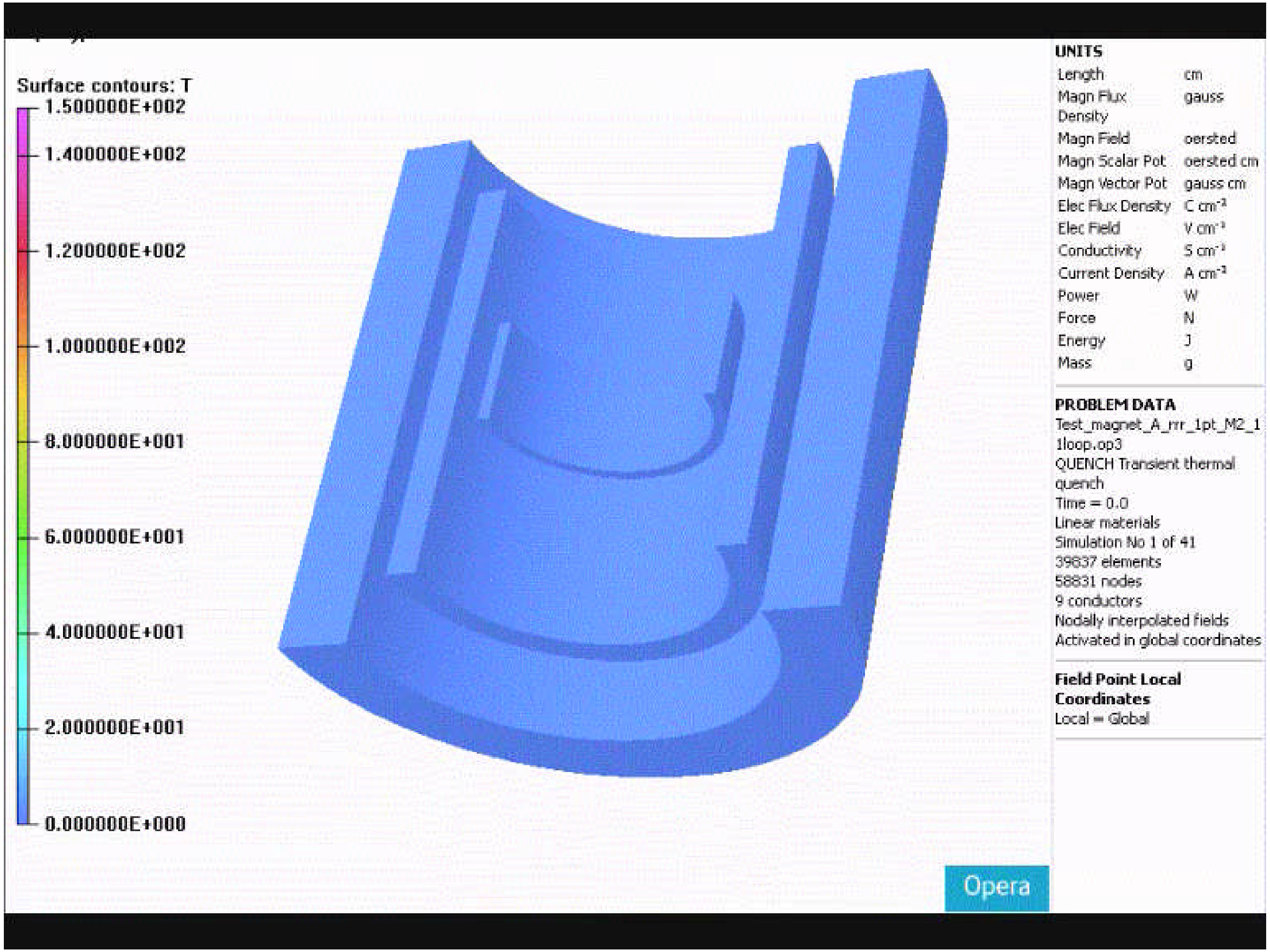


dB/dt (T/s) in the coil structure

Note also that the value changes rapidly with position

Opera

IMPDAHMA
Calculated Temperature versus Time



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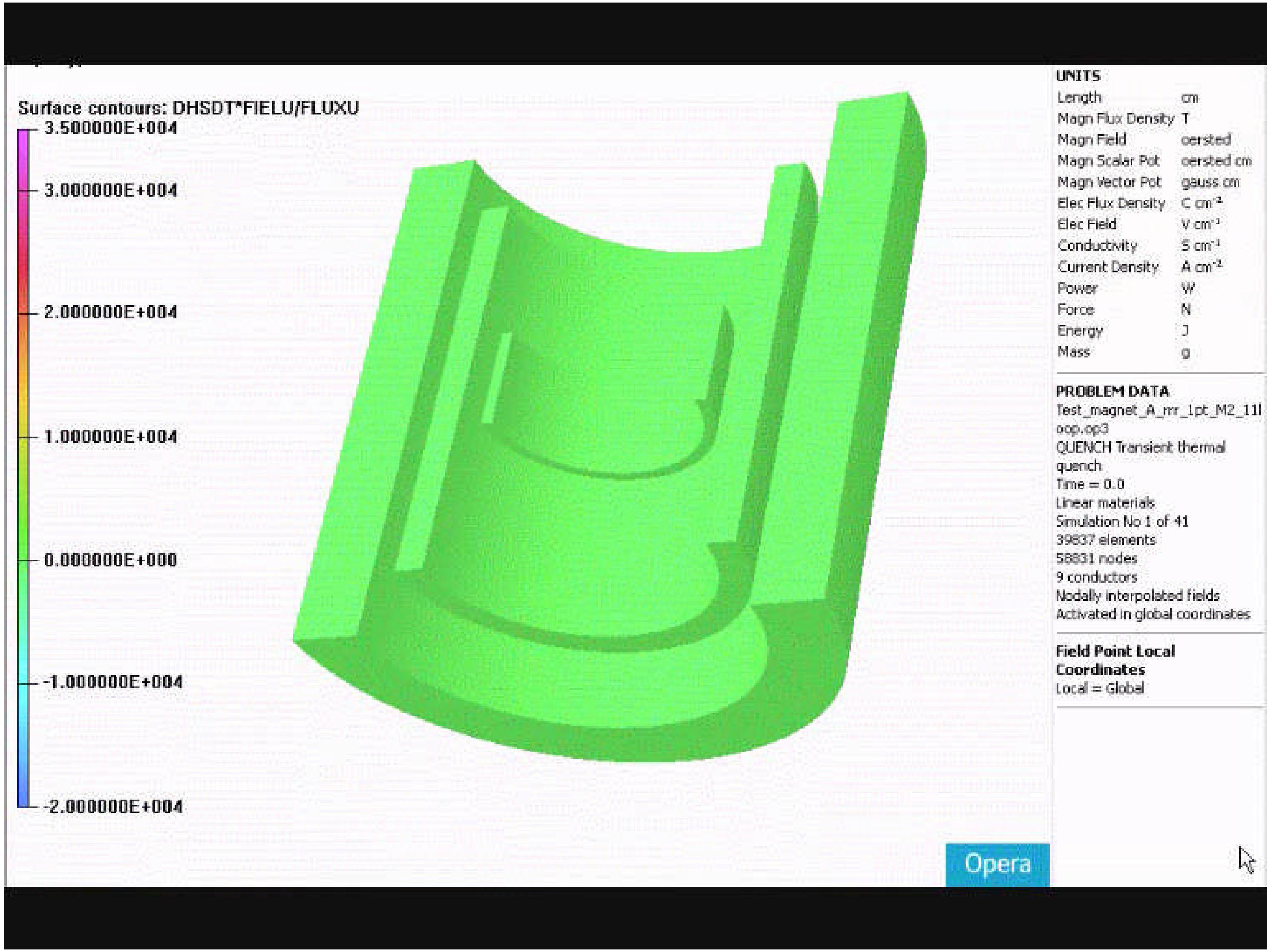
Calculated dB/dT as a function of time



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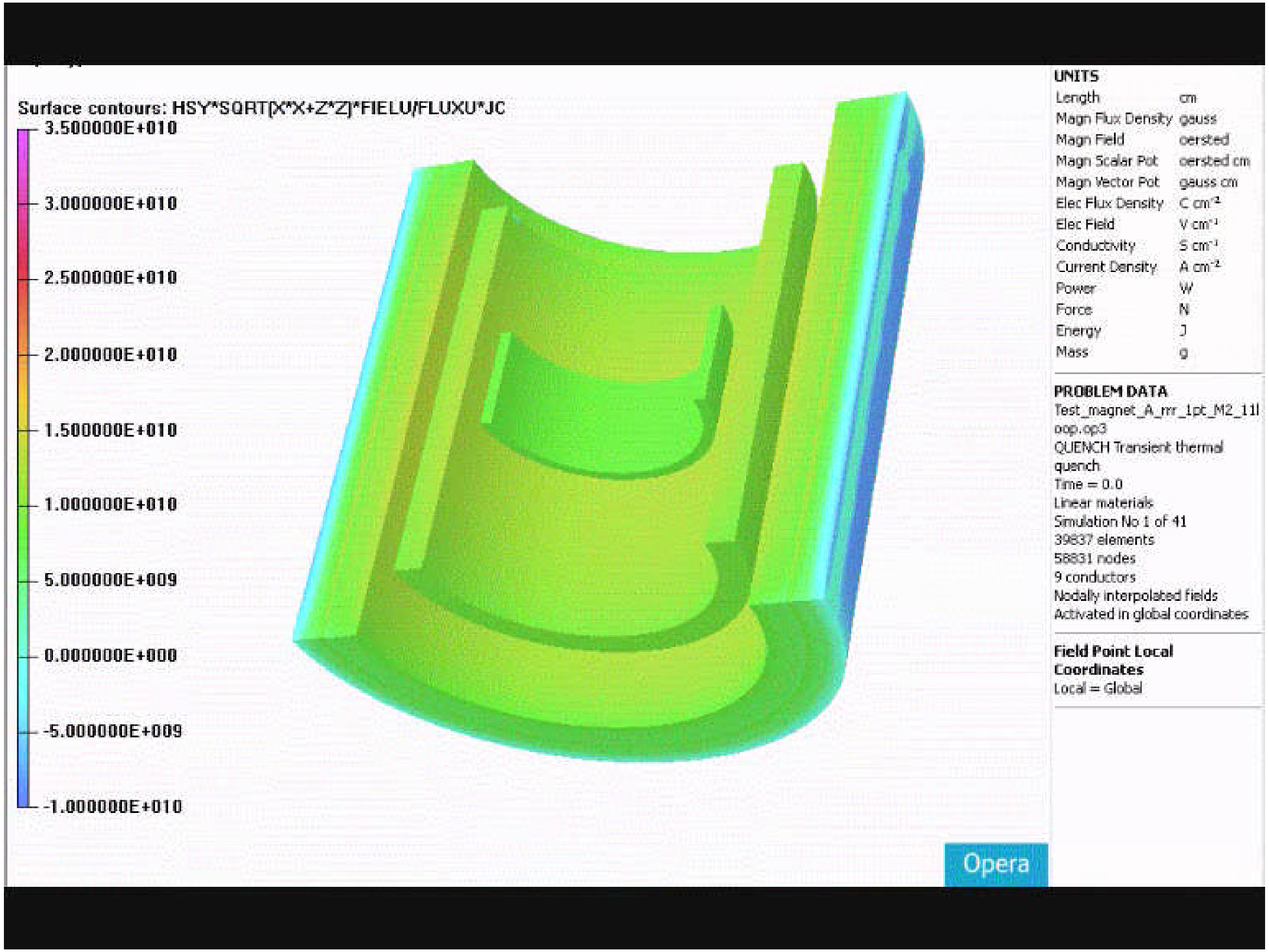
Calculated hoop Stress versus Time



Steps to improve agreement

- **Add facilities to monitor the maximum value of user defined functions in each coil volume**
  - So that a quench can be initiated if the hoop stress rises above a given value (using simple approximations to evaluate approximate stress levels)

Conclusions

- We have 3 months to improve the agreement between simulation and measurement
  (without having to guess when a quench may occur)
- Because the protection circuit for the final prototype (30T?) needs to be finalised