Unit 15
Protection of Superconducting Accelerator Magnets – Episode II

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European Organization for Nuclear Research (CERN)

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Lawrence Berkeley National Laboratory (LBNL)

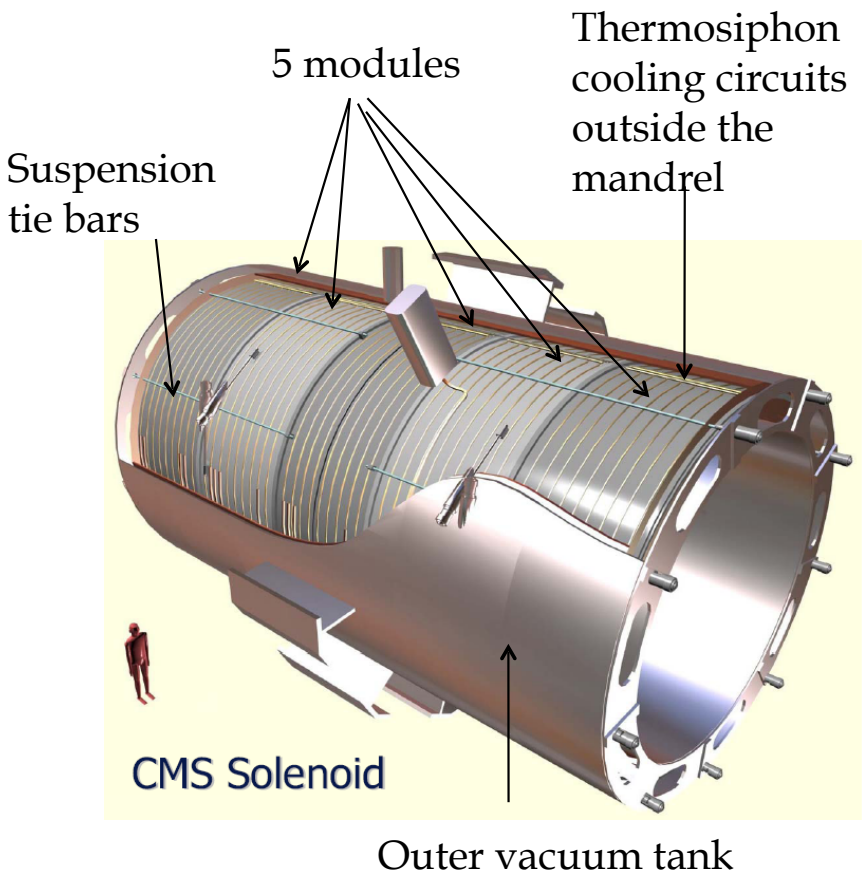
Scope of the Lesson

- Quick refresher
- Some examples
- Some numerical codes
- Summary

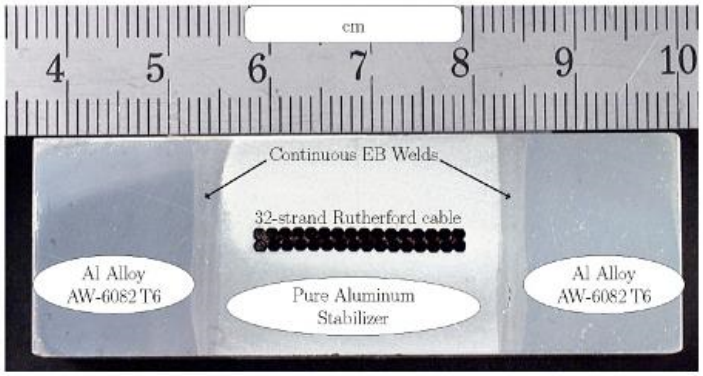
Refresher I

- The goal of quench protection is to convert **safely** magnetic energy into heat.
  - Minimizing hot spot temperature and peak voltages
- Protection strategies rely on various methods
  - Active protection: relies on external resistance and/or protection heaters
  - Passive protection: dissipation in a secondary circuit via magnetic coupling. It can include quench-back.
- Electrical integrity must be guaranteed
  - Importance of the QA methods: hipots and impulse tests
- Quench detection also plays a key role in the protection scheme

Example of CMS: using a coupled secondary



- Compact Muon Solenoid:
  - Proton to proton detector designed to run in LHC
  - 4T, 6 m in diameter, 12.5 m long
  - 2180 turns of superconductor distributed in 5 modules wound inside a 50 mm thick Aluminum cylinder
  - 4 layers of Rutherford like cable
  - Inductance of 14.05 H
  - Stored energy of 2.6 GJ, 12 J/g

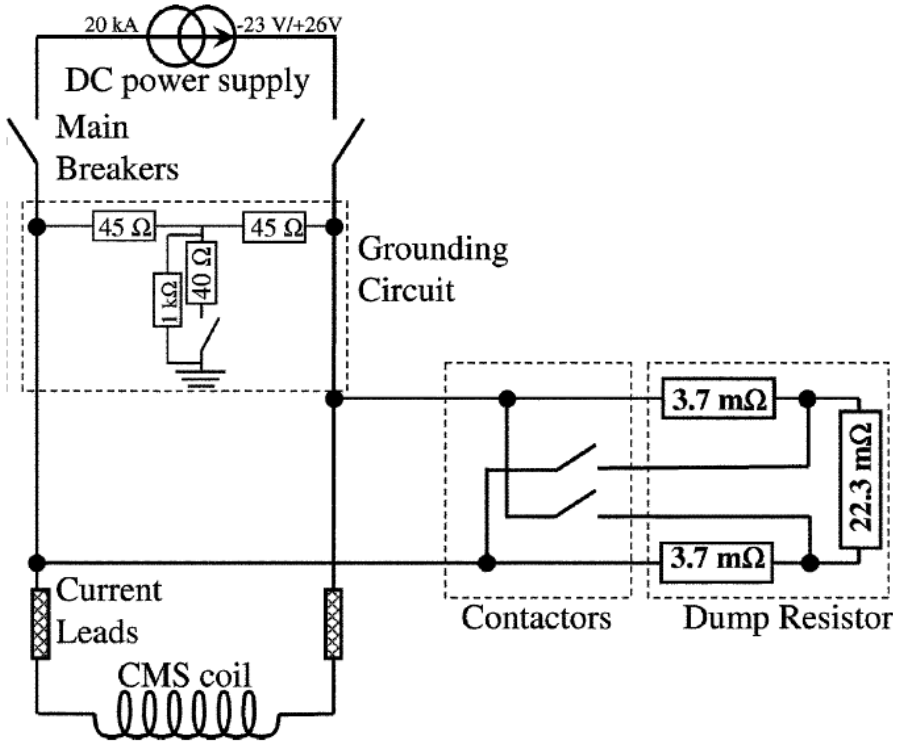


P. Fazilleau *et al.: Analysis and Design of the CMS Magnet Quench Protection, IEEE Trans. Appl. Supercond. Vol. 16, No. 2, June 2006*

CMS protection scheme

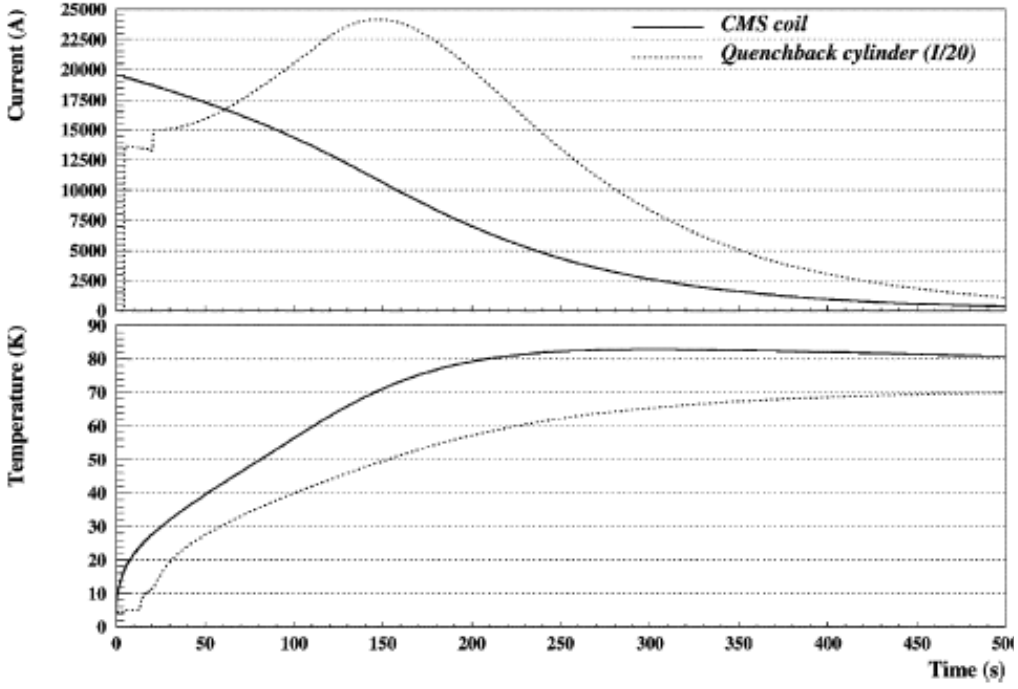
- Design baseline: reliability
  - Components are oversized
  - No active system in the circuit (such as PH)
  - Dump resistor always connected to the coil
    - In parallel during the normal operation
    - In series, after quench detection, once power supply disconnected
  - Quench-back in the aluminum cylinder

P. Fazilleau *et al.: Analysis and Design of the CMS Magnet Quench Protection, IEEE Trans. Appl. Supercond. Vol. 16, No. 2, June 2006*



CMS calculated quench performance

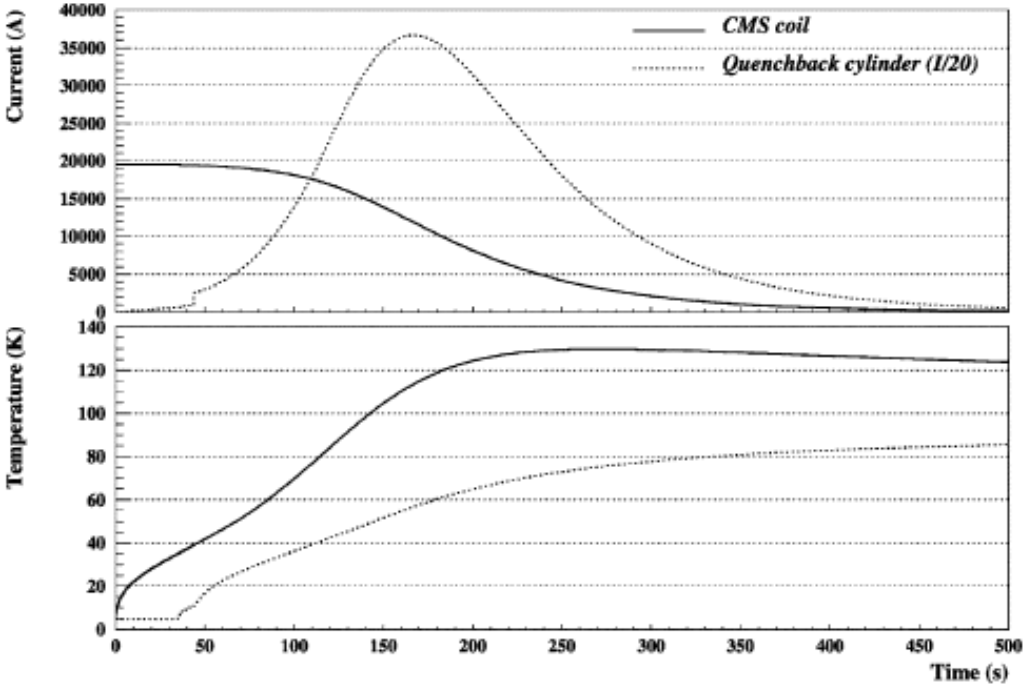
- Slow quench velocity: 1.3 m/s
- Small impact due to dominating quench-back effect
  - ~ 480 kA of eddy currents developed in the cylinder
  - After 21 s, its temperature reaches the critical temperature of the magnet causing the quench to propagate uniformly in the coil due to the thermal contact between coil and cylinder



$I_{initial}$ = 19.5 kA	Time constant ($I_{initial}$/e)	197 s
	Discharge time ($I_{initial}$/100)	557 s
Voltage threshold 1 V	Switch breakers opening time	4.3 s
	Magnet	Quenchback cylinder
Transition		
Beginning	0.00 s	
End	20.6 s (quenchback delay)	
Quenched volume	100 %	
Hot spot temperature	83 K (@ 298 s)	71 K
Final temperatures		
T_{max}	79 K	71 K
T_{mean}	71 K	
ΔT within the winding	13 K	
Dissipated Energies		
E in resistive part	50.6 %	1.6 %
E in dump resistor	47.6 %	
Voltages		
V_{max} (at the terminals of the magnet)	-586.2 V	

CMS: Case of fault scenario

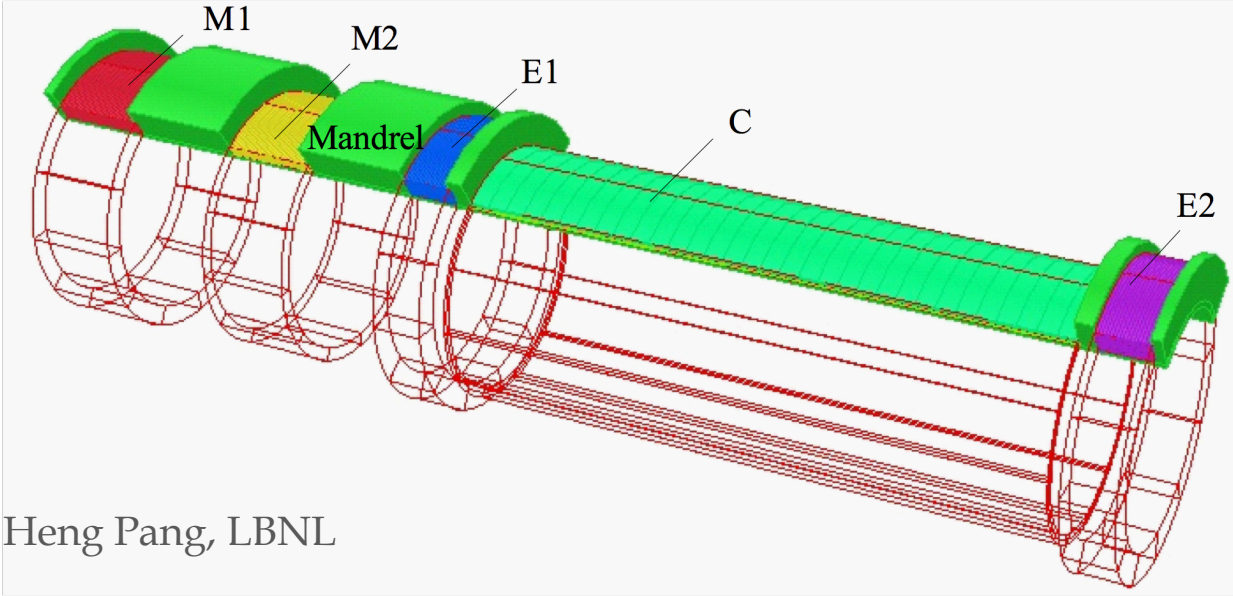
- In fault conditions (absence of detection for example), the passive effect of the quench-back cylinder keeps a reasonable hot spot temperature in the coil



$I_{initial}$ = 19.5 kA	Time constant ($I_{initial}$/e)	210 s
	Discharge time ($I_{initial}$/100)	472 s
Voltage threshold 1 V	Switch breakers opening time	-
	Magnet	Quenchback cylinder
Transition		
Beginning	0.00 s	
End	43.6 s (quenchback delay)	
Quenched volume	100 %	
Hot spot temperature	130 K (@ 270 s)	87 K
Final temperatures		
T_{max}	122 K	87 K
T_{mean}	88 K	
ΔT within the winding	46 K	
Dissipated Energies		
E in resistive part	97.5 %	2.3 %
E in dump resistor	0 %	
Voltages		
V_{max}	44 V	

Example of MICE spectrometer solenoid

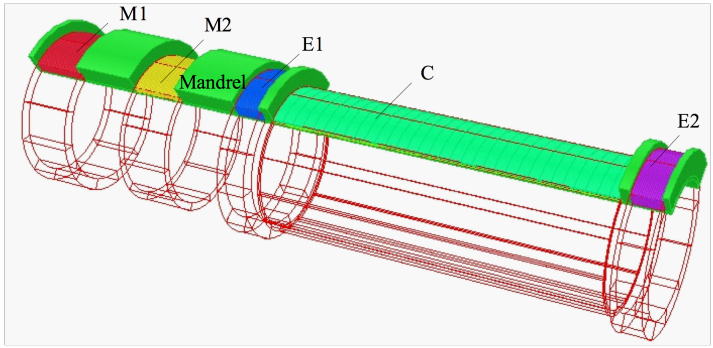
- Part of the Muon Ionization Cooling Experiment MICE to be installed the Rutherford Appleton Lab
- NbTi conductor
- Field ranges from 2.8 to 4 T
- Uniform field region (less than 1%): 1 m long and 0.3 m in diameter
- Stored Energy 3.06 MJ at 258 A



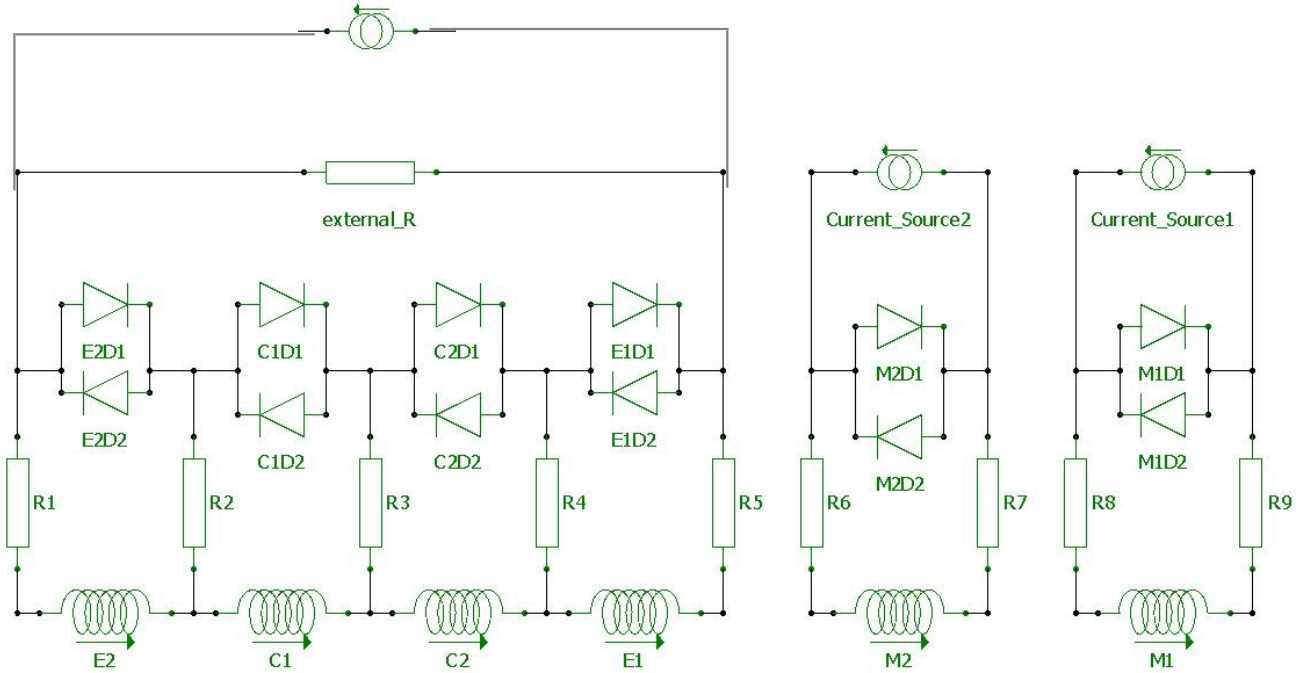
Courtesy of Heng Pang, LBNL

MICE spectrometer Protection scheme

- Use of bypass and external resistors
- Back to back diode
- Rely on quench-back in Aluminum mandrel
  - If one coil quenches, the neighboring coils will be heated by quench-back effect and quench
- Baseline scenario: to have all coils becoming normal as soon as possible

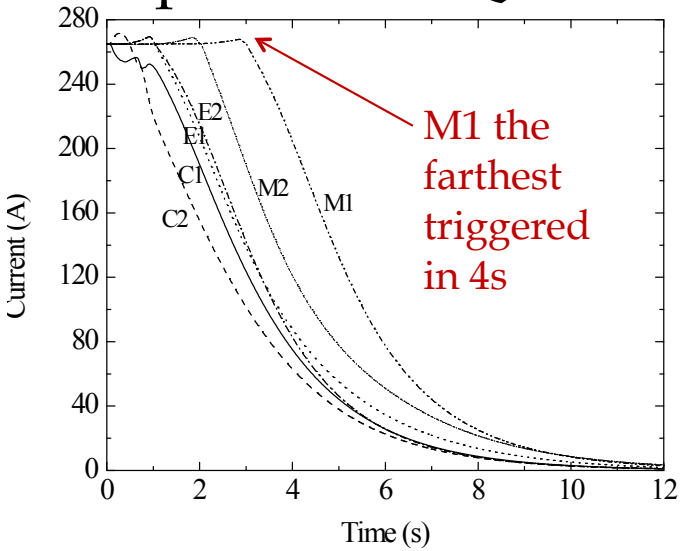


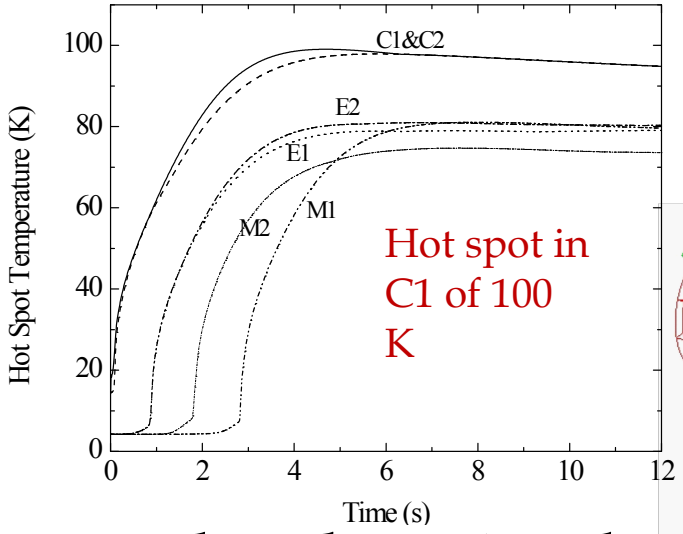
Wang *et al.: Design and Construction of MICE spectrometer solenoids, IEEE Trans. Appl. Supercond. Vol. 19, No. 3, June 2009*



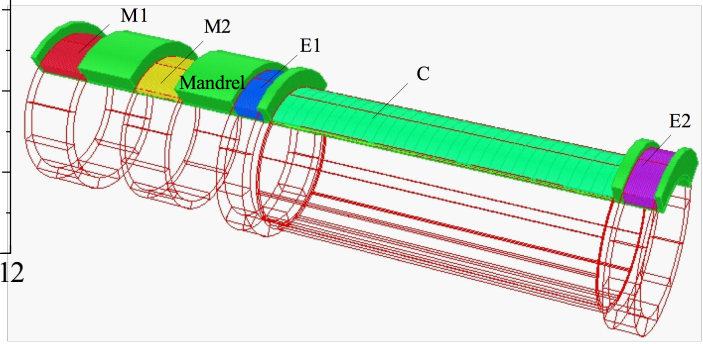
Typical scenarii

- Iop = 265 A. Quench initiated in the C1 coil





Courtesy of Heng Pang, LBNL, unpublished data



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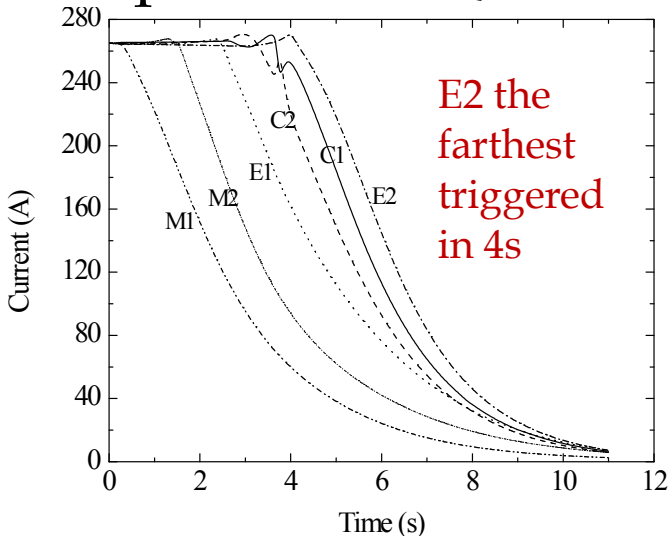
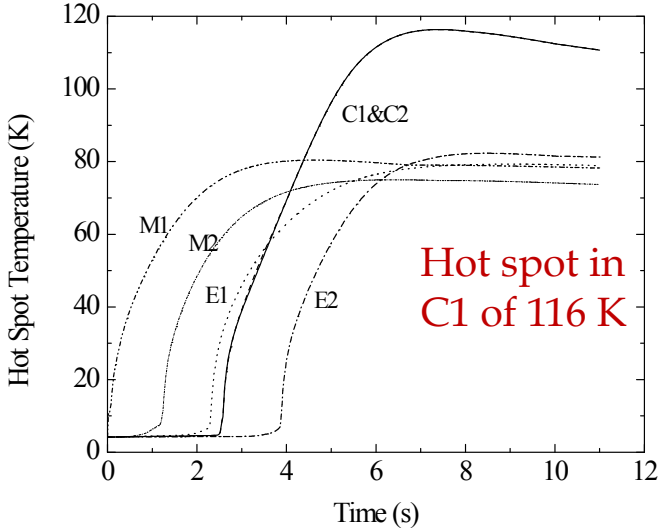
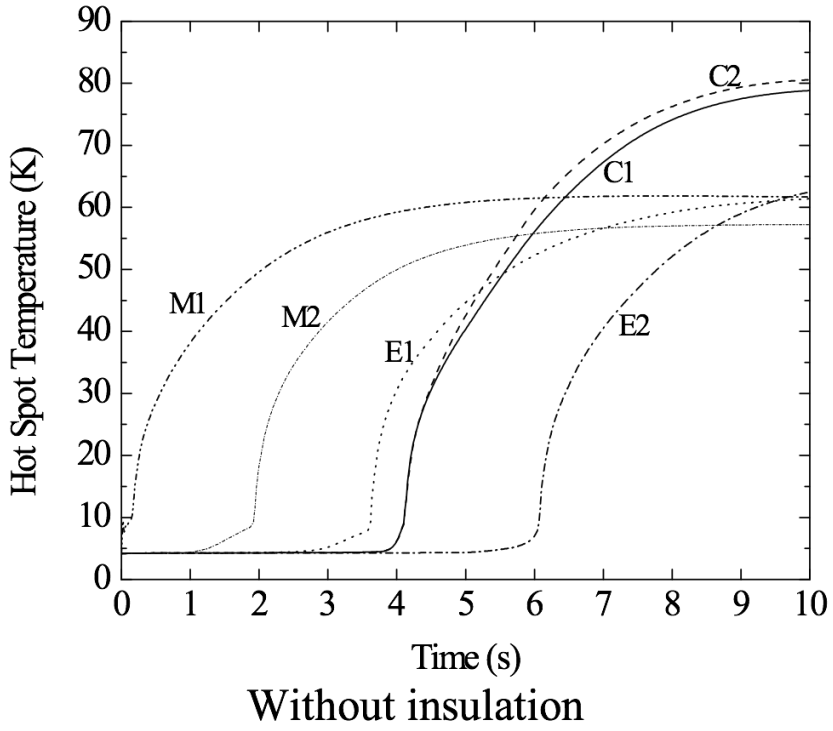




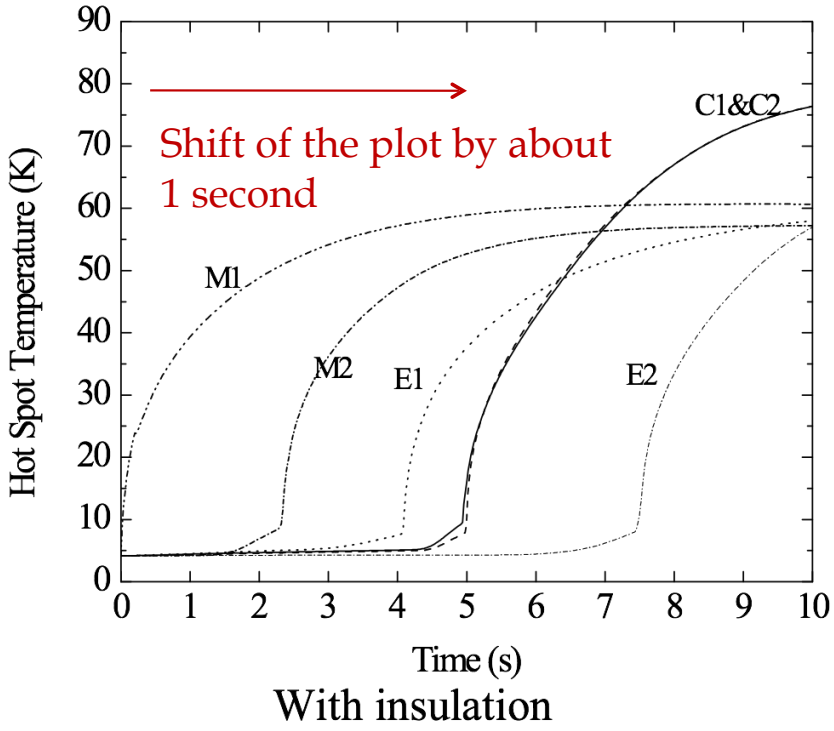
Higher hot spot due to the fact that the quench has to propagate from one end to the other.

Influence of the quench-back

- The insulations between coil and mandrel delays the heat transfer from normal zone to mandrel
- The quench-back will be slowed down accordingly



Without insulation

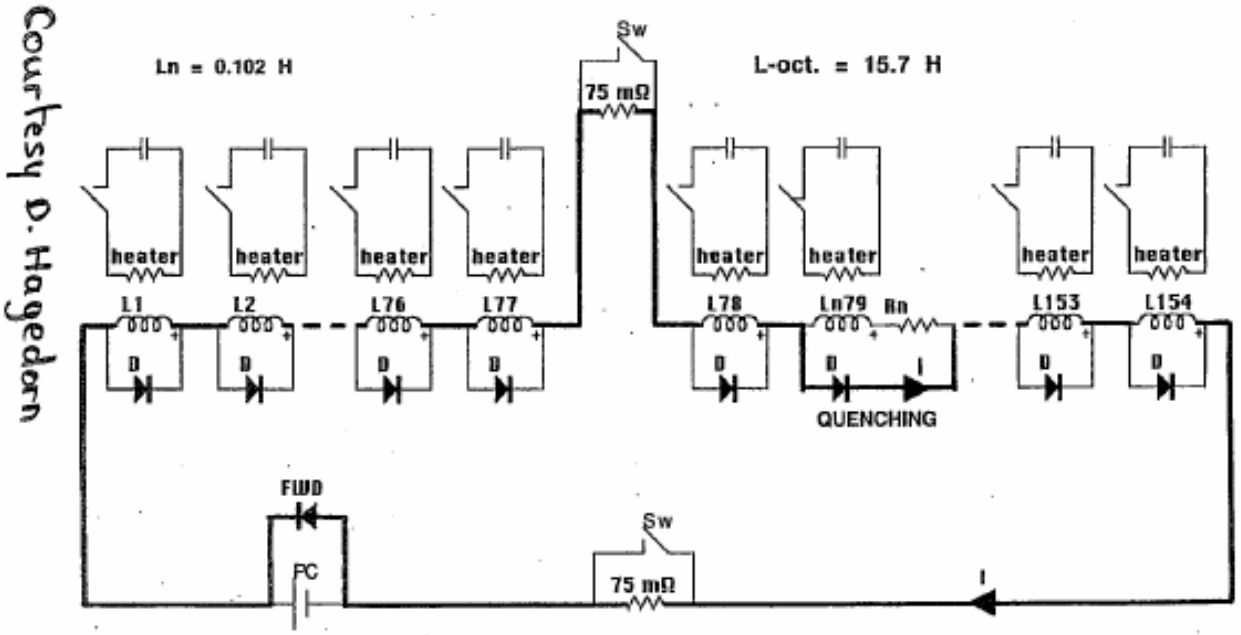


With insulation

Courtesy of Heng Pang, LBNL, unpublished data

LHC design

- In the main ring, the dipoles are connected in series. The principle is
  - to "by-pass" the quenching magnet to avoid dumping all the string energy in one magnet
  - To de-excite the rest of the magnets into a dump resistor
- Combination of various methods: heaters, dump resistor, diodes

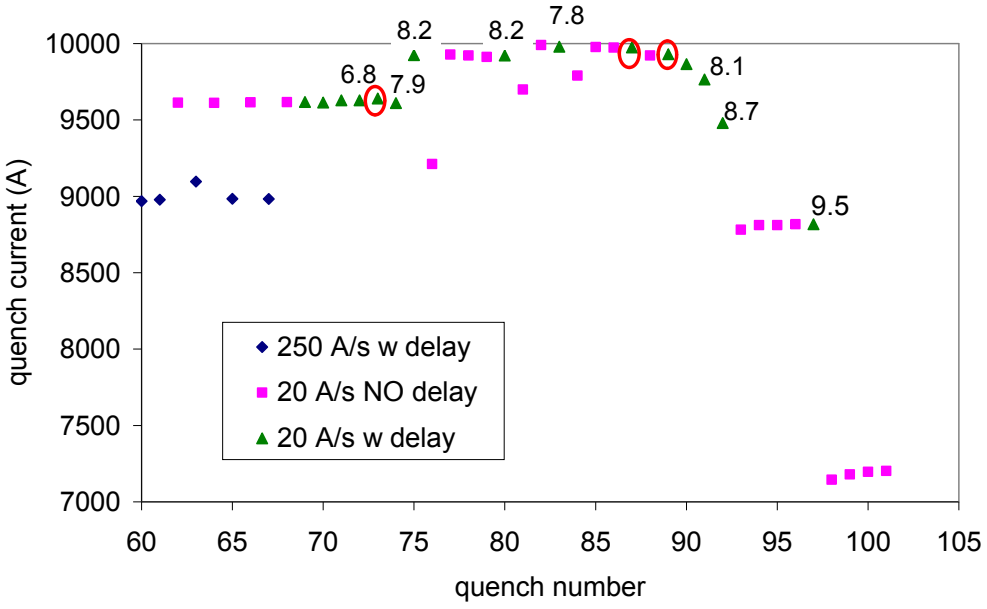


Simplified Powering and Protection Scheme for one LHC-sector (1/8 of LHC) with by-pass diodes

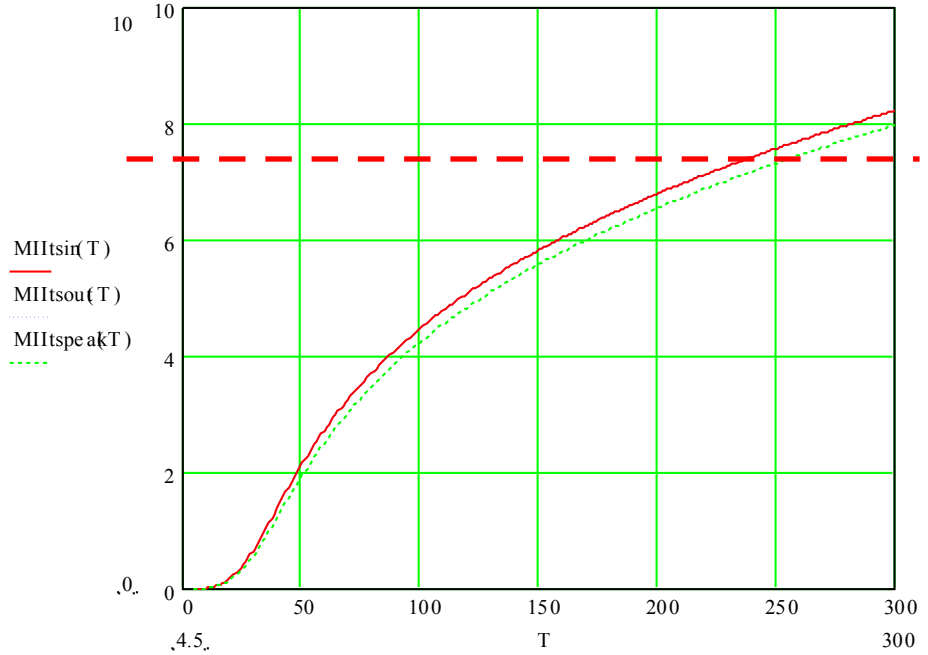
Example for a long Nb_3Sn magnet: protection heater design

- LARP (LHC Accelerator Research Program) Long quadrupole
- Nb_3Sn, 3.6 m long, 460 kJ/m, 240 T/m at 13.75 kA, 12.2 T peak field
- Limits of the conductor known empirically

MIITs study performed on TQ (short version of LQ)



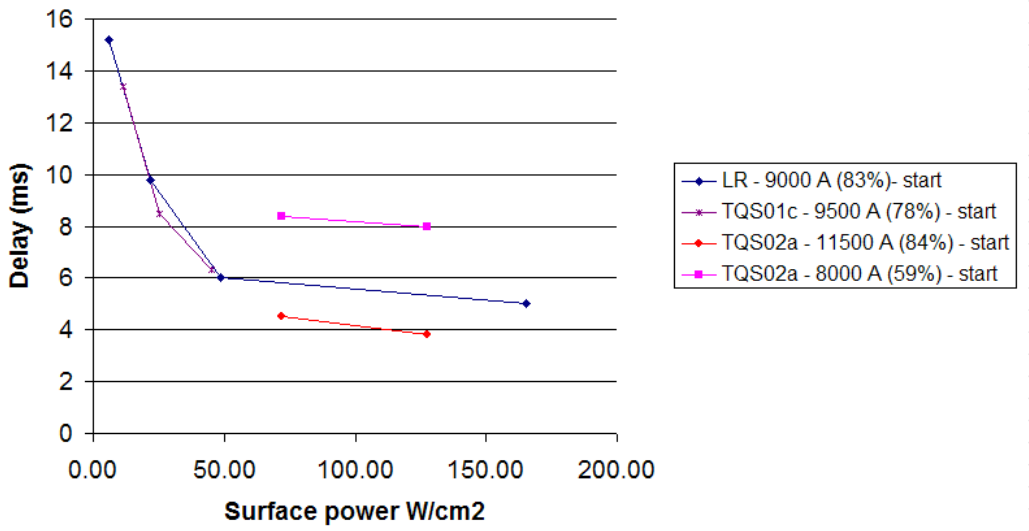
LQ MIITs curve



G. Ambrosio et al, TQS01c test results summary, TD-07-007

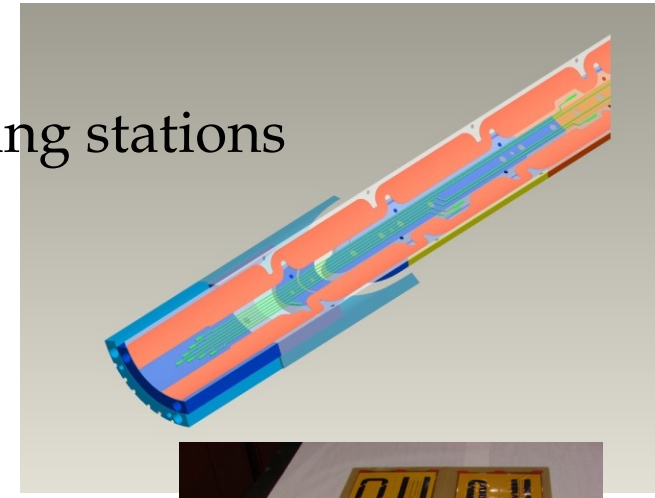
LQ Protection requirements and limitations

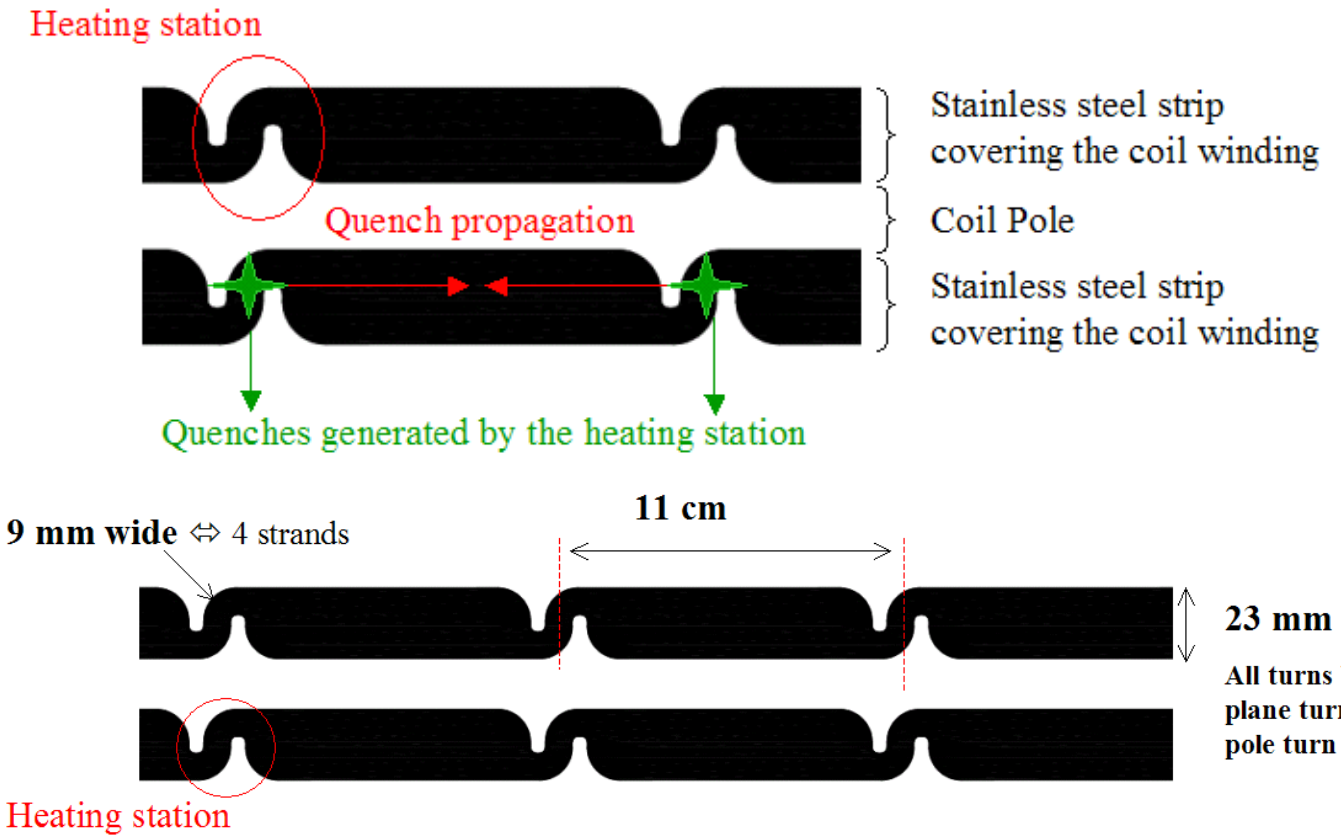
- Analysis showed that the MIITs can stay below 7.5 if
  - Rdump = 60 mohm
  - Full heater coverage with delay shorter or equal to 12 ms
  - Detection time of 5 ms or less
- Limited number of power supplies: 4
- Voltage limited to 450 V, capacitor bank fixed at 19.2 mF
- Power requirements known empirically



LQ protection heaters design

- Due to the length of the magnet: heating stations
- R_{PH} decreased to provide at least 50 W/cm^2 in heating stations
- Heater delay
  - Diffusion time + propagation between heating stations





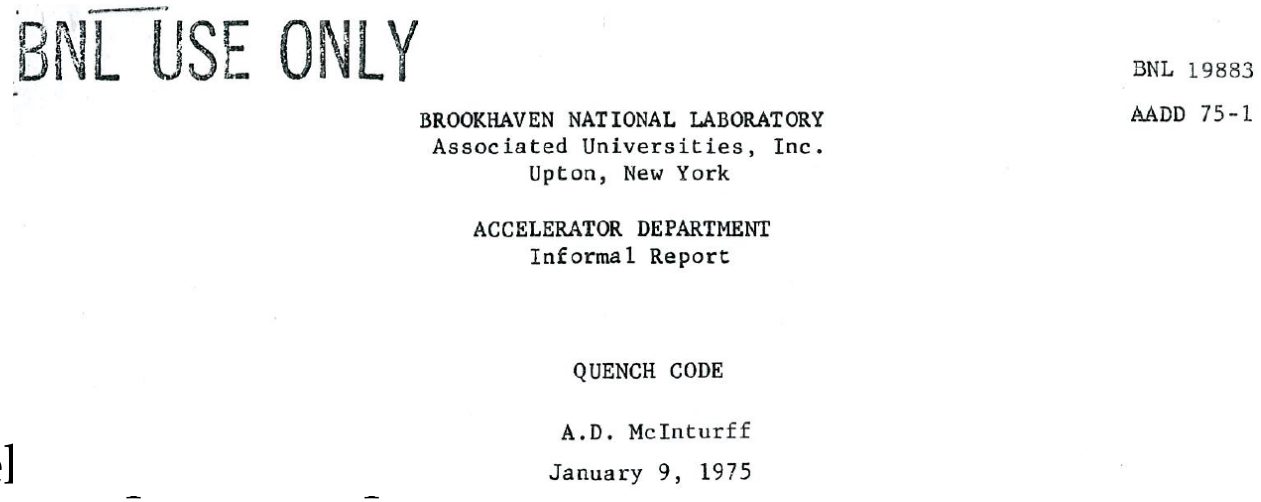
LQ test: 220 T/m 90% Iss
6 MIIts – no degradation

SOME codes available to perform quench protection calculation

- The complexity of the quenching process cannot be represented easily in a single formula
- Need of numerical programs
  - QUENCH from M. Wilson
  - Quenchpro
  - QLASA
  - Roxie Quench module
  - COBHAM Quench module
  - ANSYS
  - Under development: Qcode
  - …

M. WILSON QUENCH program

- Developed by Wilson, 1968 then modified by M.J Newman
- See practical information in



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BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York

ACCELERATOR DEPARTMENT
Informal Report

QUENCH CODE

A.D. McInturff

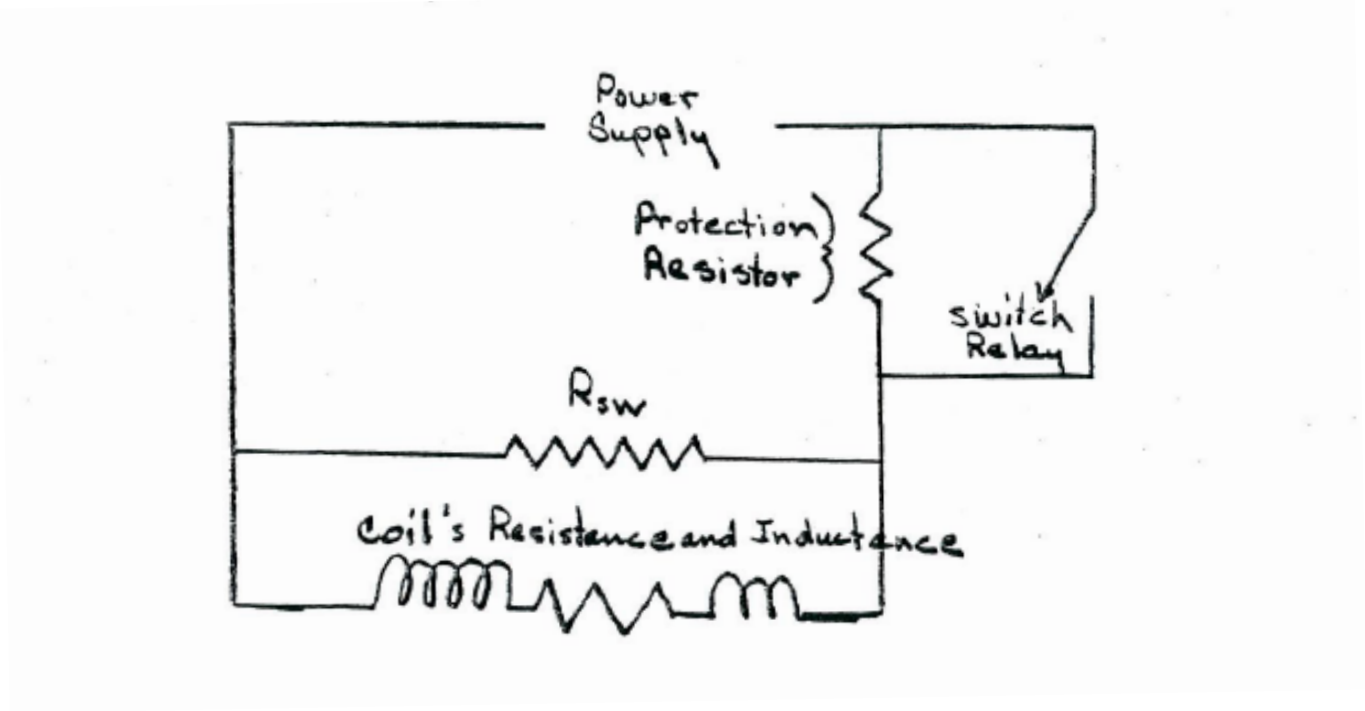
January 9, 1975

- The model
- Material properties are approximated by function of the temperature

- The equation being solved in this code is:

$$R_Q(I,t,T)I + I\frac{R_{SW}R_{PROT}}{R_{SW}+R_{PROT}} + L\frac{dI}{dt} = 0$$

- Assuming the magnet is the following electrical circuit



QuenchPro

- Program in the form of a Mathcad spreadsheet

  P. Bauer et al., Quench protection calculations for Fermilab's Nb3Sn High Field Magnets for VLHC – PART 1, FNAL TD note TD-01-003

- Part 1:
  - Definition of the magnet in a series of 16 sub-coils
  - Preliminary calculations of the material properties
  - Definition of the protection system
    - PH: coverage, delay…
    - Value of the dump
  - Calculation of the resistances, current and temperatures

- Part 2:
  - Definition of each turn coordinates to allow the calculation of the turn to turn inductance => inductance matrix
  - Calculation of the turn to turn voltage and turn to ground voltage

QLASA

- Developed by the superconducting magnet group of the LASA laboratory (University and INFN-Milan)

ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Milano

INFN/TC-04/13
6 Luglio 2004
Rev. 1

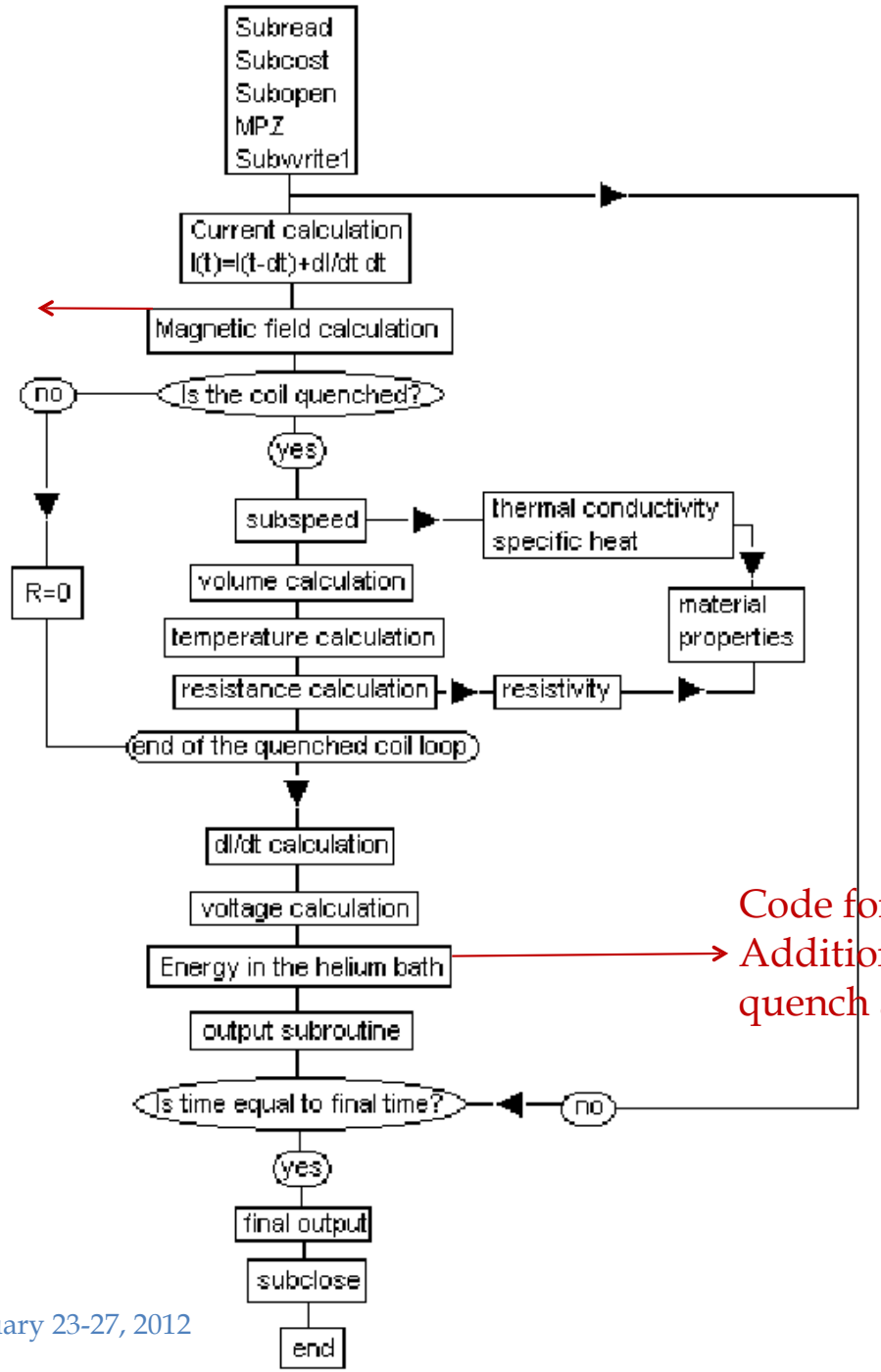
QLASA: A COMPUTER CODE FOR QUENCH SIMULATION IN ADIABATIC MULTICOIL SUPERCONDUCTING WINDINGS

Lucio Rossi [1], Massimo Sorbi [2],

- Mainly intended for adiabatic multiple solenoids
- Analytical approach
- Output: Internal voltage and internal temperatures

QLASA

Initial B field is provided
Linear dependence with current



Inputs

Material properties average over the different components of the winding:

Cp, k, rho

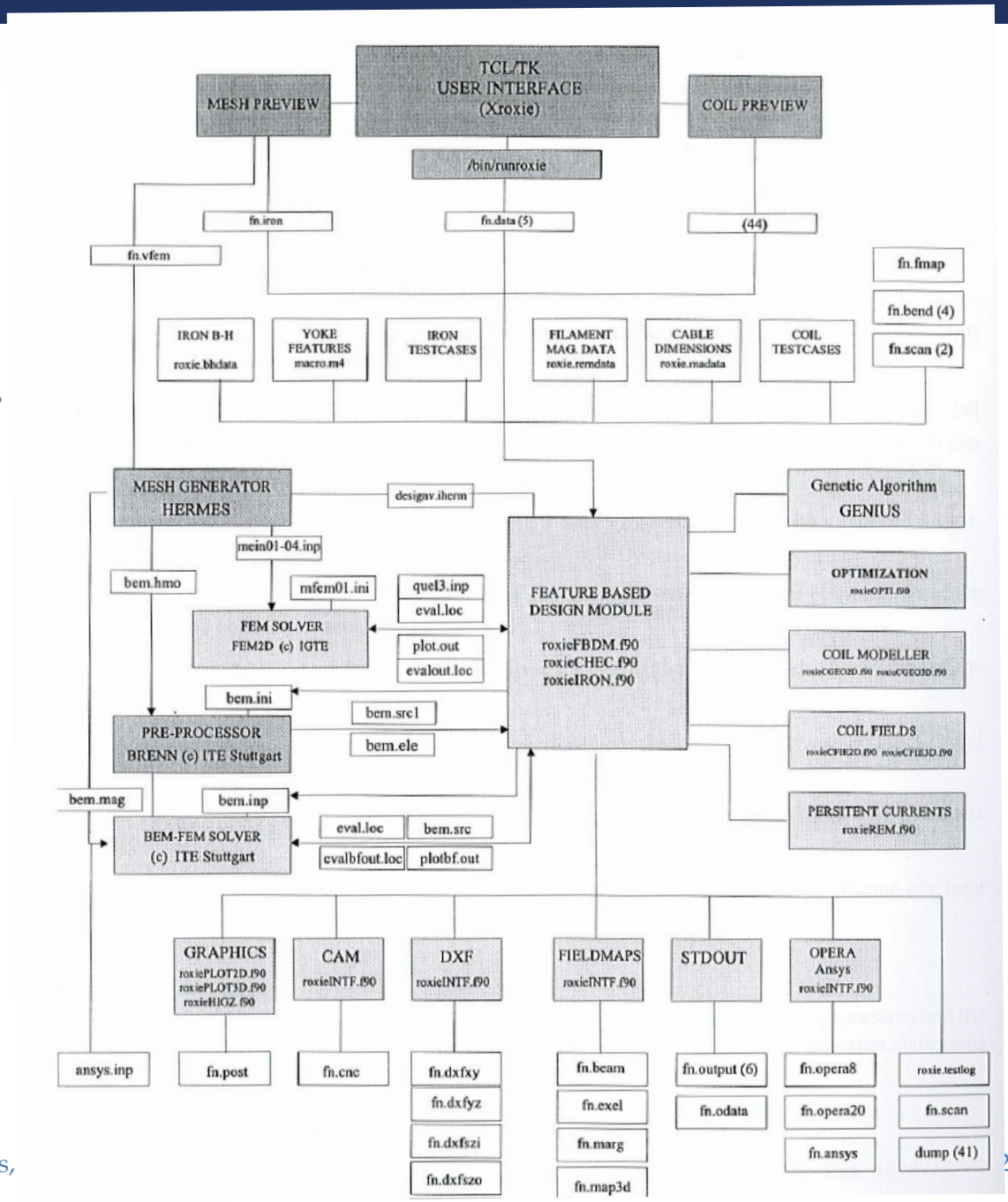
Code for adiabatic magnets
Addition to force all the coil to quench at some point

ROXIE – Quench Module

- New module of the Routine for the Optimization of magnet X-section, Inverse field calculation and coil End design: **ROXIE**
- Software program developed at CERN for the design of the superconducting magnets for the LHC at CERN.
  - Coils represented by a set of current lines, modeling the superconducting strand
  - Optimization of the coil and iron cross-sections
  - End spacer design
  - Yoke design and optimization via coupling method BEM-FEM (Boundary and Finite element)
- Quench module recently developed by N. Schwerg

ROXIE chart

S. Russenchuck, Routine for the Optimization of magnet X-section, Inverse field calculation and coil End design, CERN CAS 99-01



Roxie quench module

- Thermal network described by the heat balance equation

$$\rho(T)c(T,B)\frac{\mathrm{d}T}{\mathrm{d}t} = P + \mathrm{div}\,(\kappa(T,B)\mathrm{grad}\,T)$$

  - In the coil cross-section, each conductor corresponds to a node in the network
  - Longitudinal subdivision has to be supplied by the user
  - Heat sources P: Joule heating in the normal zone, protection heaters (note no diffusion time computation), AC losses in the conductor (which is a form of quench-back)
  - Cooling:
    - LHe trapped in the winding considered. Helium content is supplied by user. Non impregnated coils
    - Cold faces of the winding is also considered and used as a heat sink

Cobham– Opera 3D - Quench module - I

- Is a new program part of the Cobham-Opera-3D environment (commercial)
- Incorporates the non linear solution of the transient problem using the **TEMPO-Transient Thermal Analysis** together with the external circuit analysis
  - Heat equation
- At each stage of the QUENCH analysis
  - material properties are checked
  - If I>Ic a local normal zone is introduced
    - altering the circuit resistance
      - variation of the circuit solution and update of the current in the magnet
      - Scaling of the magnetic field
    - introducing heating
      - heat source in the thermal analysis
      - Propagation to neighboring elements

Cobham– Opera 3D - Quench module - II

- Can be coupled with **ELEKTRA/TR** analysis to model transient electromagnetic fields and external circuits
  - Vector potential formulation (different from Tosca which uses a scalar potential formulation to compute 3D magnetic field)

$$\nabla \times \mathbf{H} = \mathbf{J}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \bullet \mathbf{B} = 0$$

$J=\sigma E$

contribution from the source of current

Reduced vector potential

$$\mathbf{B} = \mu_0 \mathbf{H}_s + \nabla \times \mathbf{A}_\mathbf{R}$$

In free space region containing source of currents

$$\nabla \times \frac{1}{\mu_0} \nabla \times \mathbf{A}_\mathbf{R} = 0$$

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} = -\sigma \frac{\partial \mathbf{A}}{\partial t} - \sigma \nabla V$$

When no current souce
The gradient of V can be set to zero

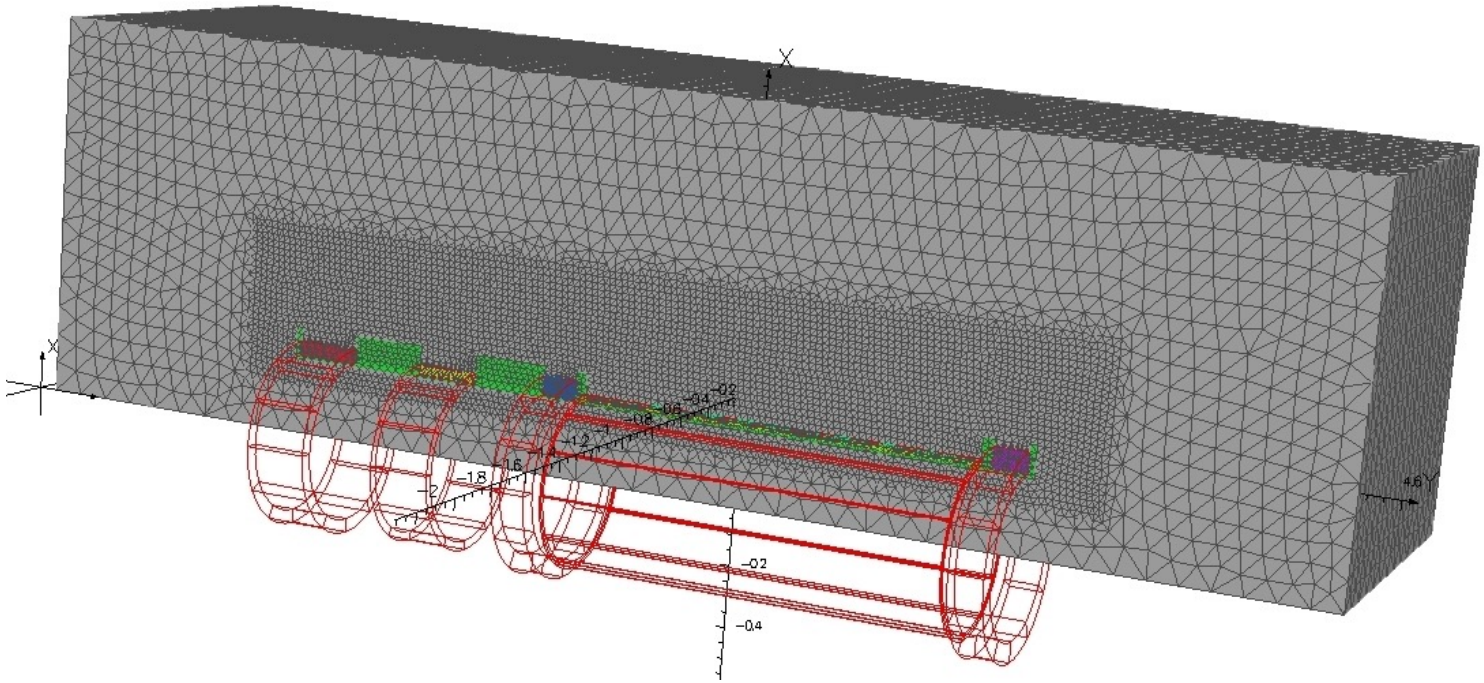
$$\nabla \cdot \sigma \nabla V + \nabla \cdot \sigma \frac{\partial \mathbf{A}}{\partial t} = 0$$

In conductive region where div. J = 0

  - During the analysis, the temperatures, electromagnetic fields, circuit variables… are exchanged between QUENCH and ELEKTRA/TR at every step
  - Adaptive step

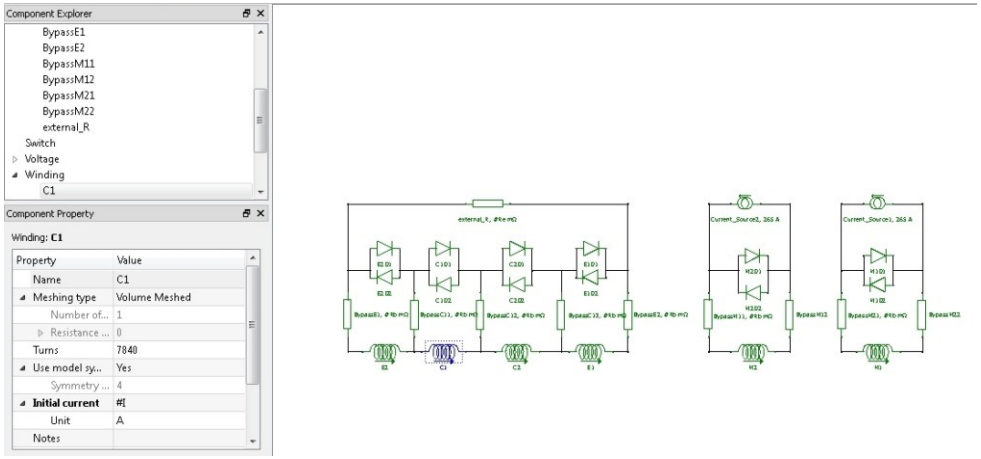
Example of MICE (courtesy of Heng Pang, LBNL)

- The Finite element discretization is supported by the Opera3D geometric **Modeller** which allows the creation of the model
  - Only the coil in case of the simple thermal analysis
  - The coil, some surrounding air (far enough) and any permeable material (iron, aluminum…) when coupled
    - In this case: coils, mandrel and air



Example of MICE – II (courtesy of Heng Pang, LBNL)

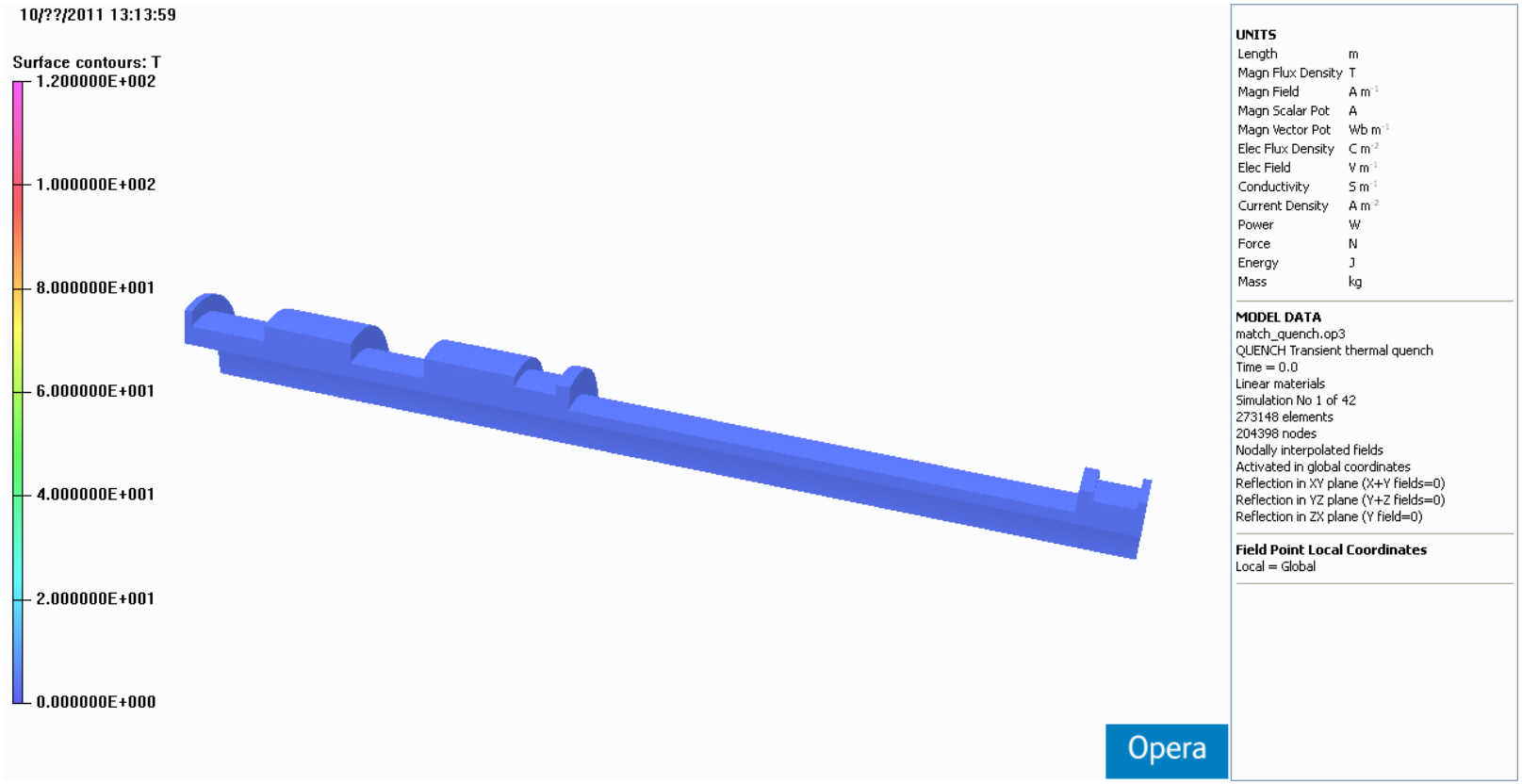
- Definition of the non-linear material properties
  - Thermal conductivity, mass density, specific heat, electrical conductivity, critical current…
  - Need to homogenize the material properties for the conductor
- Definition of the boundary conditions: protection heater
  - Surface selected – heat flux injected
- Definition of the circuit



Example of MICE – III

- Coupled analysis run for MICE
  - Example of the mandrel temperature

Courtesy of Heng Pang, LBNL, unpublished data

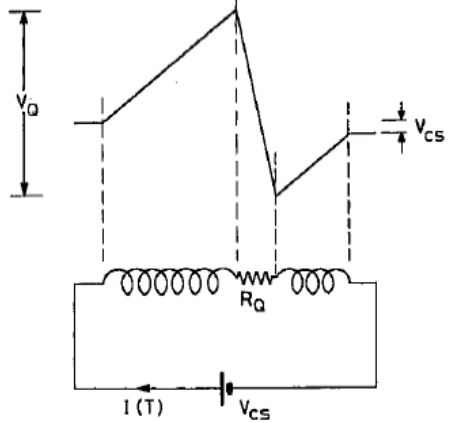


Treatment of the voltages

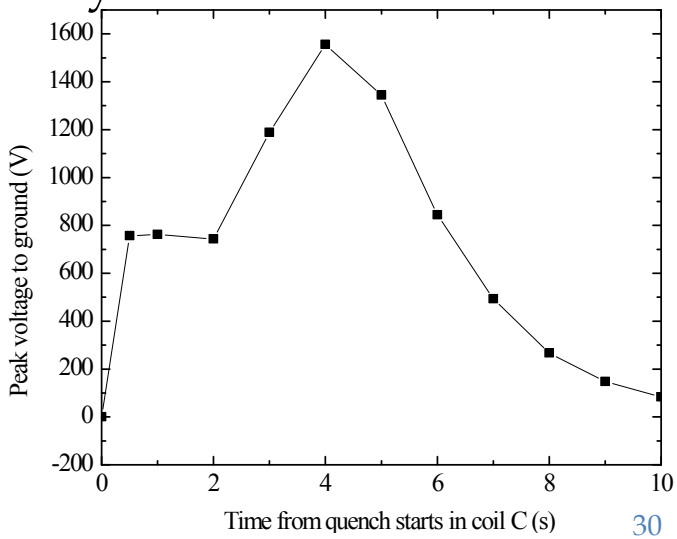
- The QUENCH module does not deal with inductive voltages contributing to
  - Interlayer voltages
  - Peak voltage to ground
- Post-processing of the quench module output

$$V_i = V_{i-1} + \sum_{j=1}^{N} L_{i,j} \frac{dI}{dt} + R_i I_i$$

Martin Wilson



  - Where V_i, R_i are the electrical potential and the resistance of turn i and $L_{i,j}$ the mutual inductance of turn i and j computed analytically.
  - Difference of maximum and minimum potential gives the maximum internal voltage
  - Maximum of the absolute value of the potential gives the maximum voltage to ground



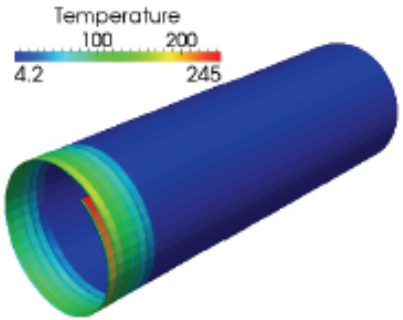
Courtesy of Heng Pang, LBNL, unpublished data

Use of ANSYS

- The commercial Finite-Element- Analysis (FEM) program ANSYS® is widely used to perform structural and thermal analysis of mechanical systems
- It is possible to use it to solve problems that are coupled structurally, thermally and electrically
- Done by S. Caspi et al., and published in "Calculating Quench Propagation With ANSYS", IEEE Trans. Appl. Supercond, Vol. 13, No. 2, June 2003
- Yamada et al. present a thermal – mechanical analysis in "2D/3D Quench Simulation Using ANSYS for Epoxy impregnated Nb3Sn High Field Magnets" in IEEE Trans. On Applied Superconductivity, Vol. 13, No. 2, June 2003

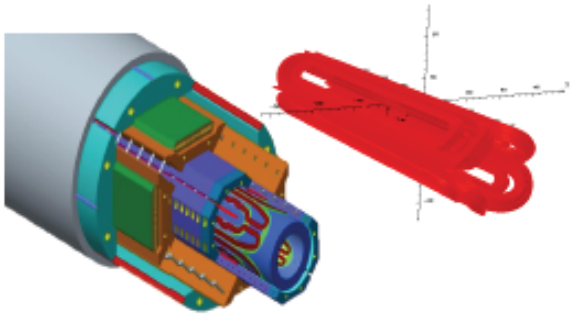
Code development

- D. Arbelaez *et al.: Numerical Investigation of the quench behavior of $Bi_2Sr_2CaCu_2O_x$ wire, IEEE Trans. Appl. Supercond. Vol. 21, No.3, June 2011*
- Initially designed to understand the quench behavior of the Bi2212 conductors (including as well Nb_3Sn properties)
- One-dimensional numerical model



$$\gamma C_p(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\kappa(T)\frac{\partial T}{\partial x}\right) + \rho(T)J_n^2 + Q$$

- Code in the process of being further improved (Tiina-Salmi PhD)
  - Named Qcode
  - To model an accelerator-type coil (instead of a wire)
  - To include protection heater in the model
    - Accounting for shape and heat diffusion from heater to coil



T. Salmi et al, Integrated Quench Protection Model for designing Nb_3Sn High Field Accelerator Magnets, presented at CHATS 2011

Summary

- Some examples of protection schemes
  - Several methods are usually used in one system to provide faster and reliable protection
  - Some details on the protection heater design
- Some examples of codes which treat quench calculation

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