Unit 15
Protection of Superconducting Accelerator Magnets – Episode II

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(with many thanks to **Helene Felice)**
Saclay

Scope of the Lesson

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

Refresher I

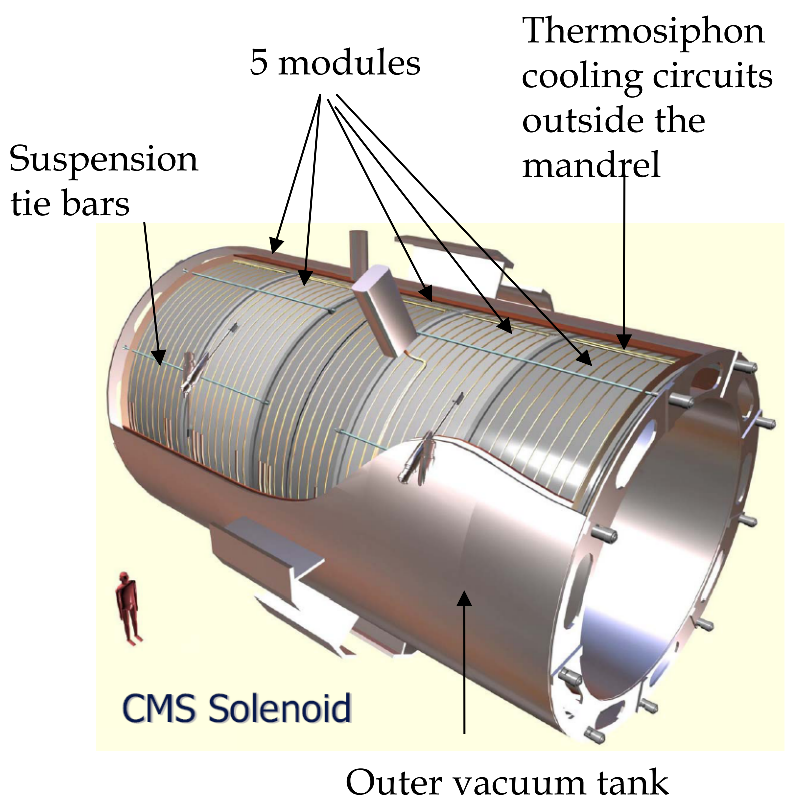
- The goal of quench protection is to convert **safely** magnetic energy into heat.
  - Minimizing hot spot temperature and peak voltages

- 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

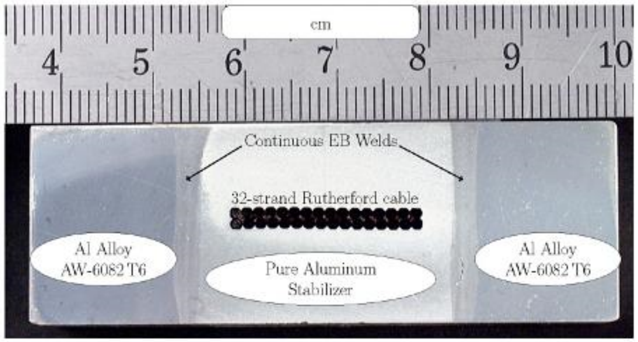
- Quench detection also plays a key role in the protection scheme

Example of CMS: using a coupled secondary



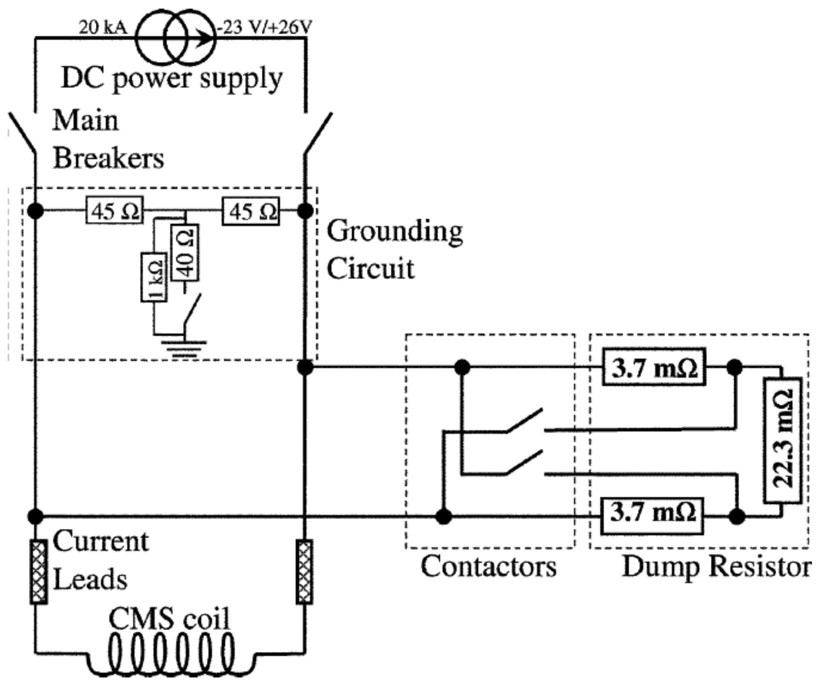
- Compact Muon Solenoid:
  - Proton to proton detector designed to run in LHC
  - 4T, 6 m in diameter, 12.5 m long
  - 2180 turns of superconductor distributed in 5 modules wound inside a 50 mm thick Aluminum cylinder
  - 4 layers of Rutherford like cable
  - Inductance of 14.05 H
  - Stored energy of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

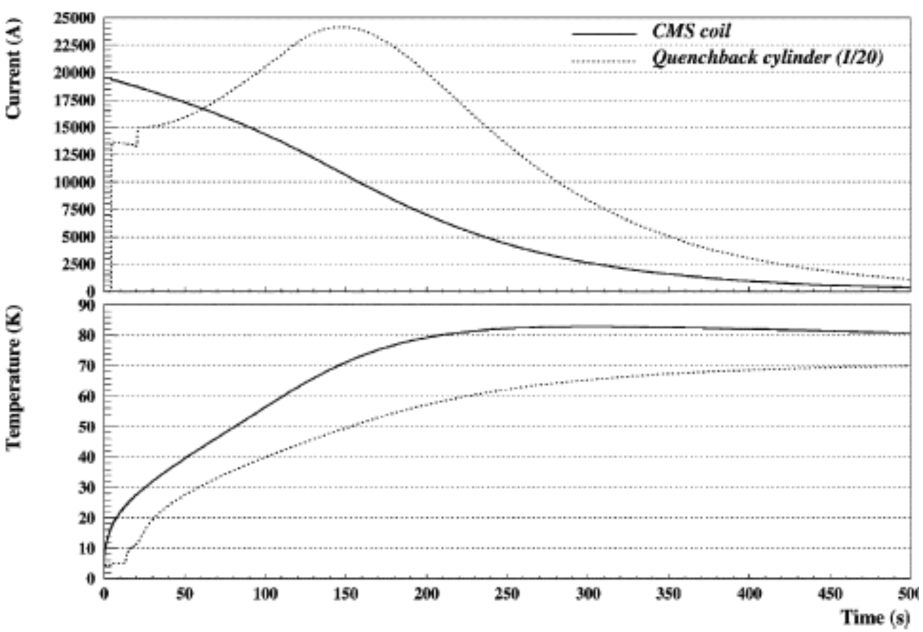
- Design baseline: reliability
  - Components are oversized
  - No active system in the circuit (such as PH)
  - Dump resistor always connected to the coil
    - In parallel during the normal operation
    - In series, after quench detection, once power supply disconnected
  - Quench-back in the aluminum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

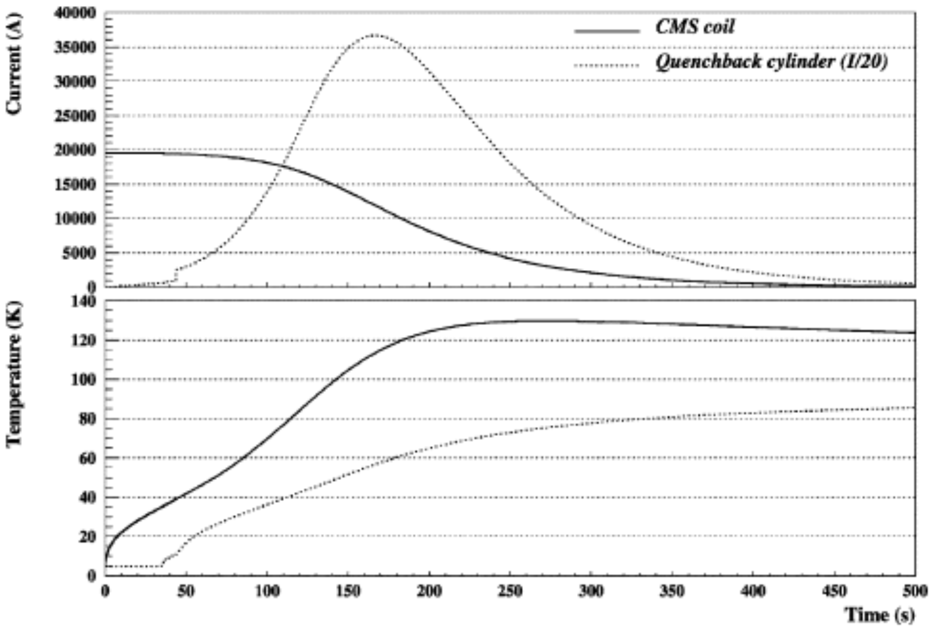
- Slow quench velocity: 1.3 m/s
- Small impact due to dominating quench-back effect
  - ~ 480 kA of eddy currents developed in the cylinder
  - After 21 s, its temperature reaches the critical temperature of the magnet causing the quench to propagate uniformly in the coil due to the thermal contact between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

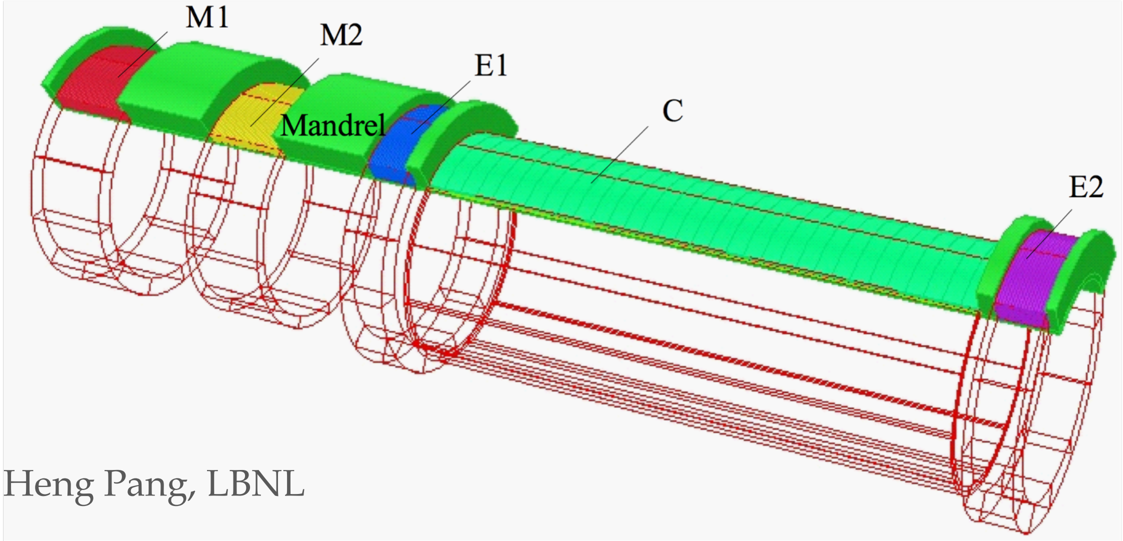
- In fault conditions (absence of detection for example), the passive effect of the quench-back cylinder keeps a reasonable hot spot temperature in the coil



$I_{initial}$ = 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

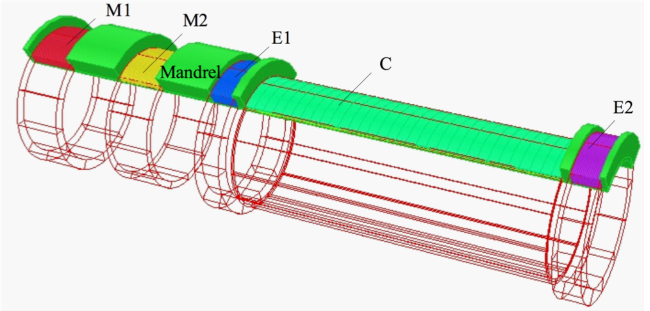
- Part of the Muon Ionization Cooling Experiment MICE to be installed the Rutherford Appleton Lab
- NbTi conductor
- Field ranges from 2.8 to 4 T
- Uniform field region (less than 1%): 1 m long and 0.3 m in diameter
- Stored Energy 3.06 MJ at 258 A

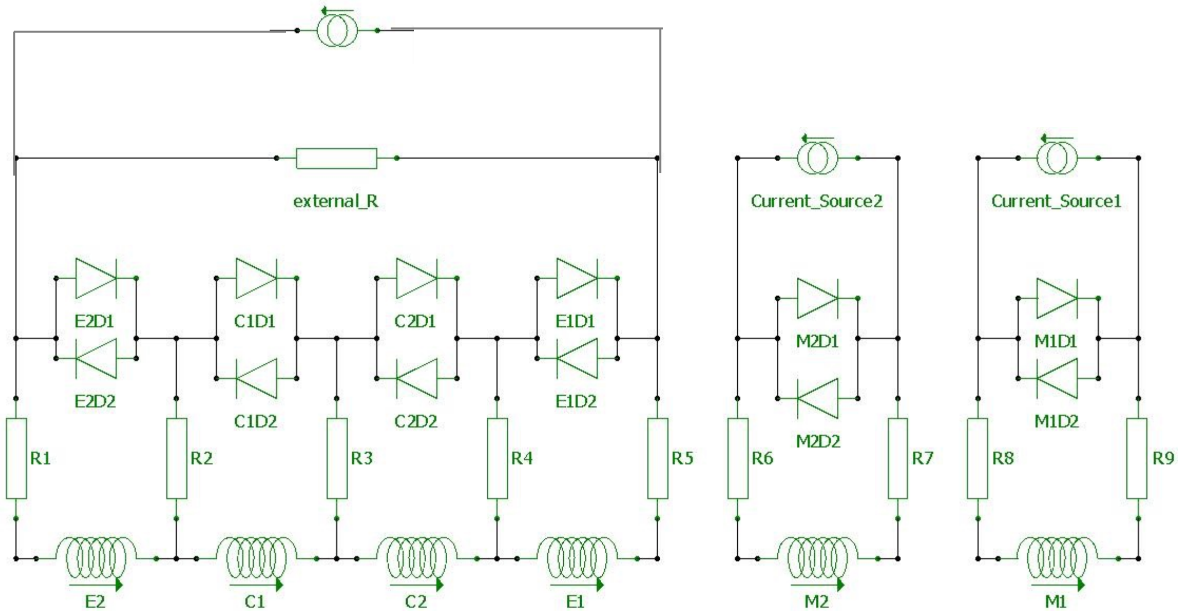


Courtesy of Heng Pang, LBNL

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

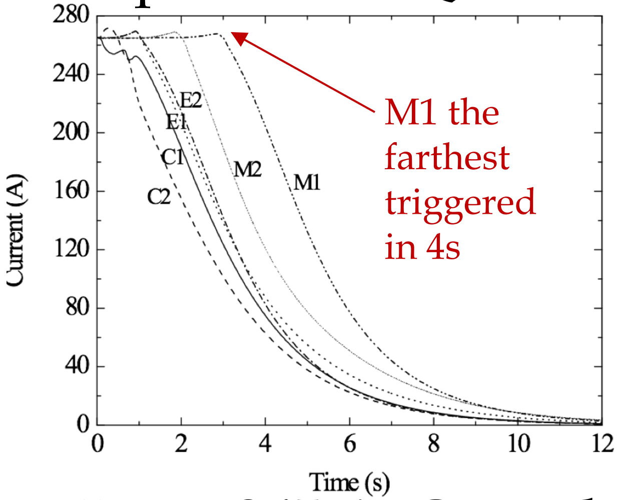


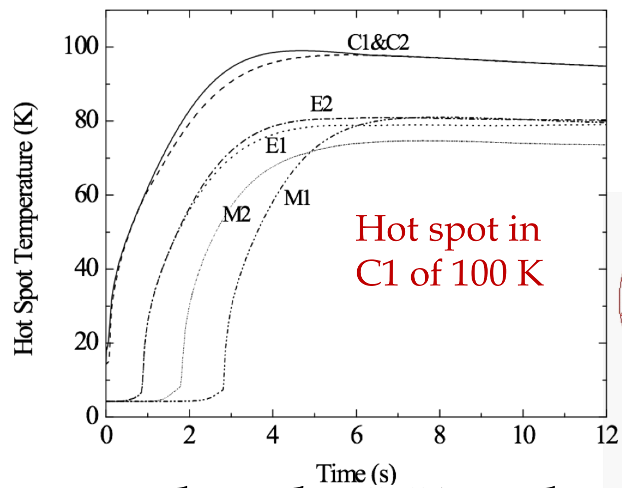


Wang *et al.*: *Design and Construction of MICE spectrometer solenoids, IEEE Trans. Appl. Supercond. Vol. 19, No. 3, June 2009*

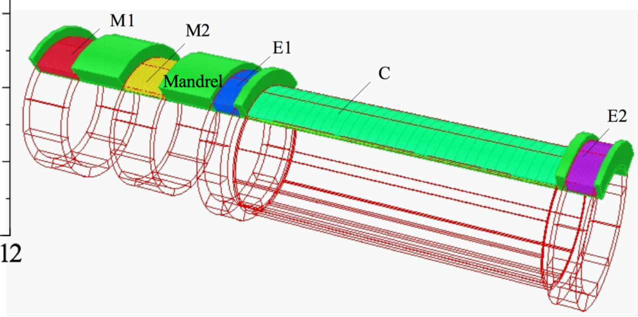
Typical scenarii

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

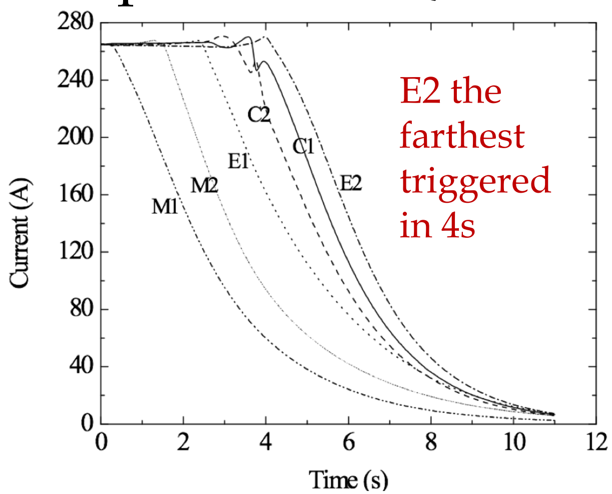


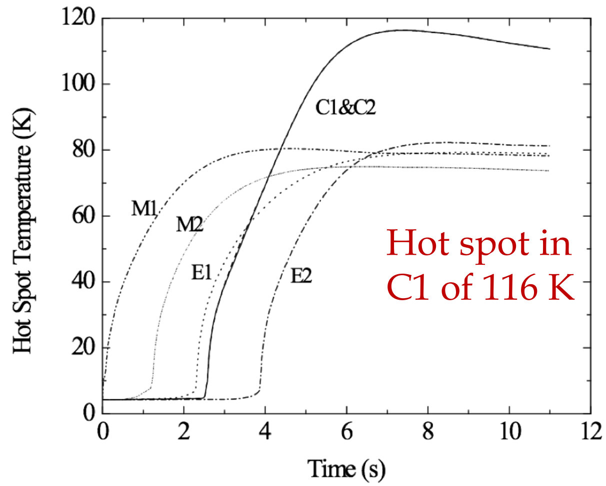


Courtesy of Heng Pang, LBNL, unpublished data



- Iop = 265 A. Quench initiated in the M1 coil

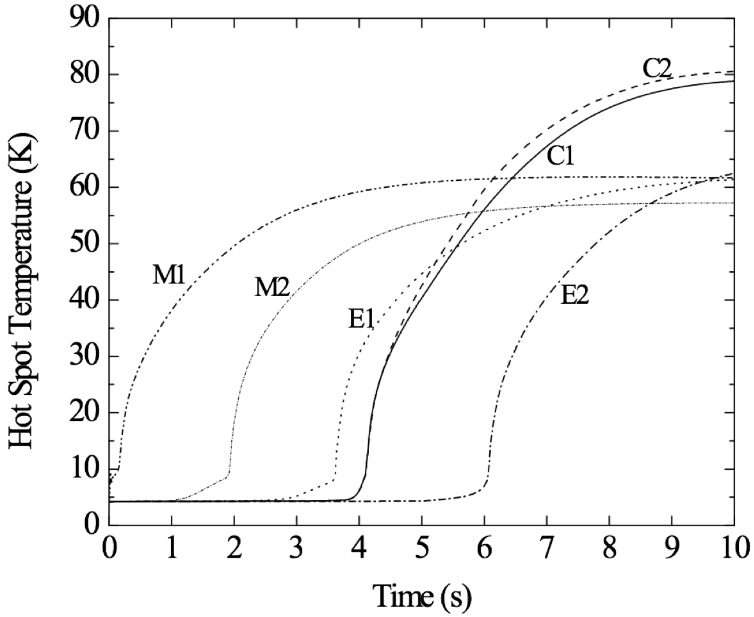




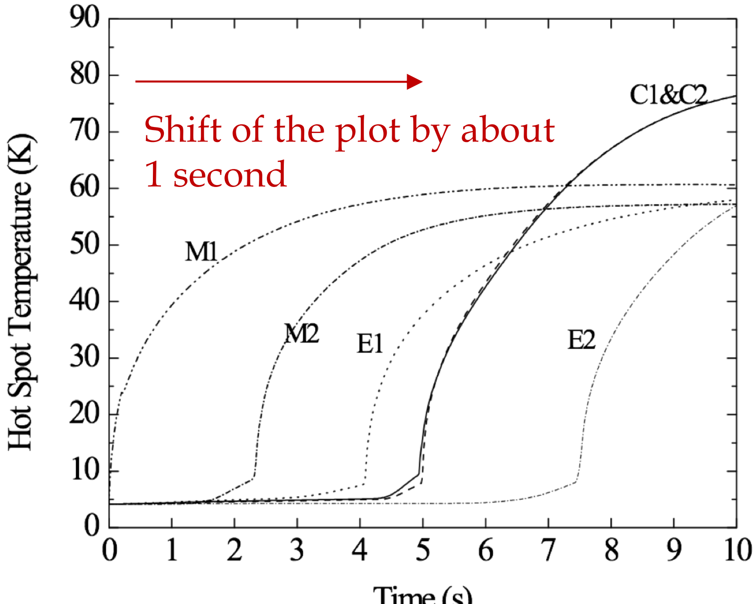
Higher hot spot due to the fact that the quench has to propagate from one end to the other.

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

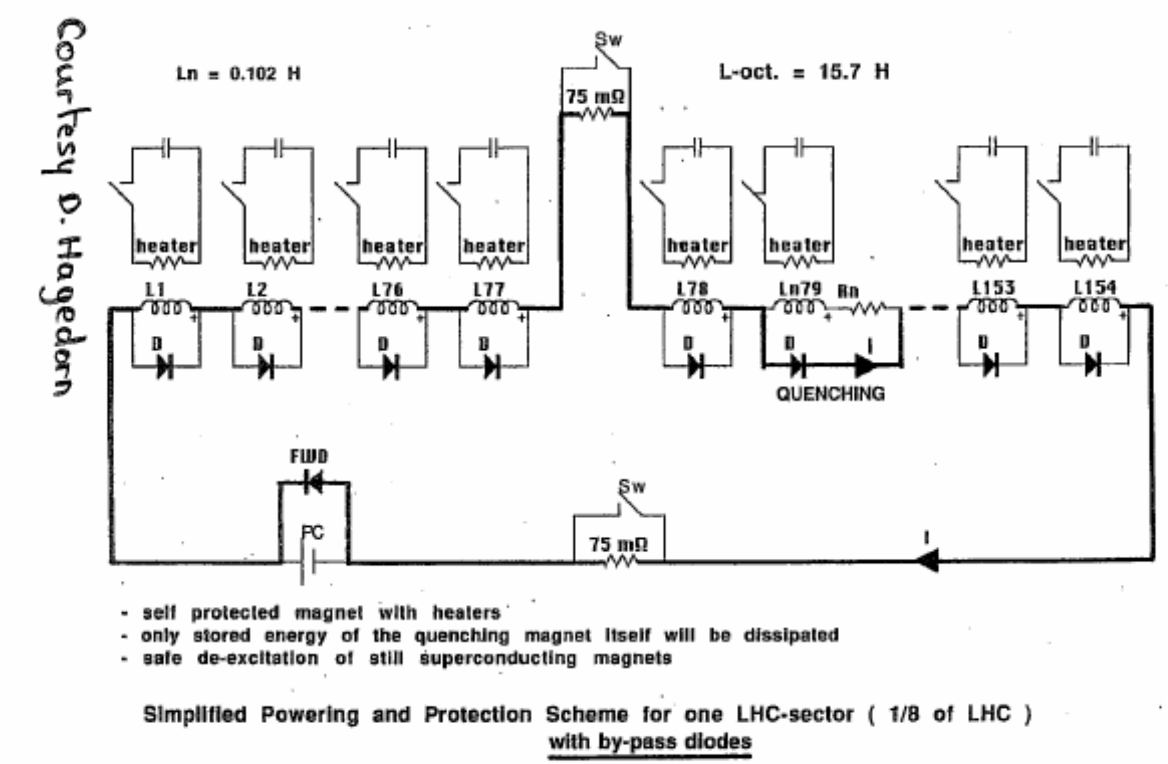


With insulation

Courtesy of Heng Pang, LBNL, unpublished data

LHC design

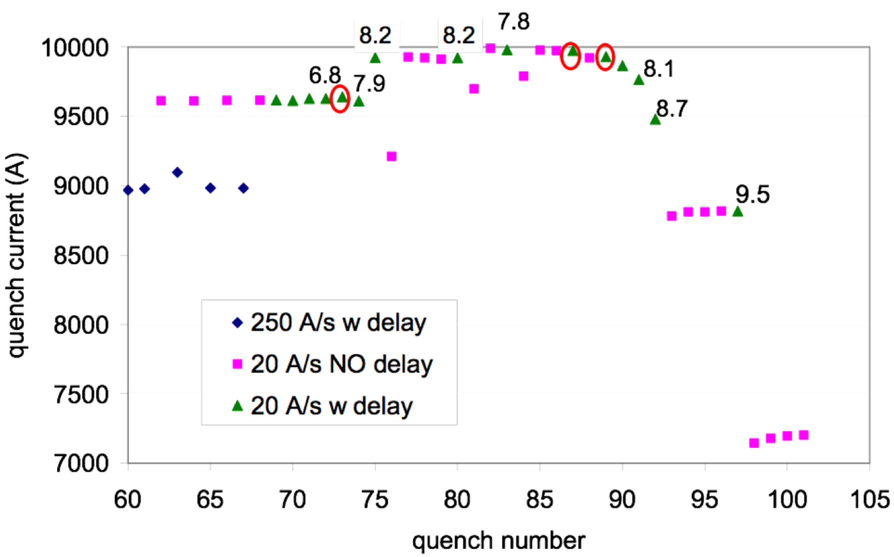
- In the main ring, the dipoles are connected in series. The principle is
  - to "by-pass" the quenching magnet to avoid dumping all the string energy in one magnet
  - To de-excite the rest of the magnets into a dump resistor
- Combination of various methods: heaters, dump resistor, diodes



Example for a long Nb_3Sn magnet: protection heater design

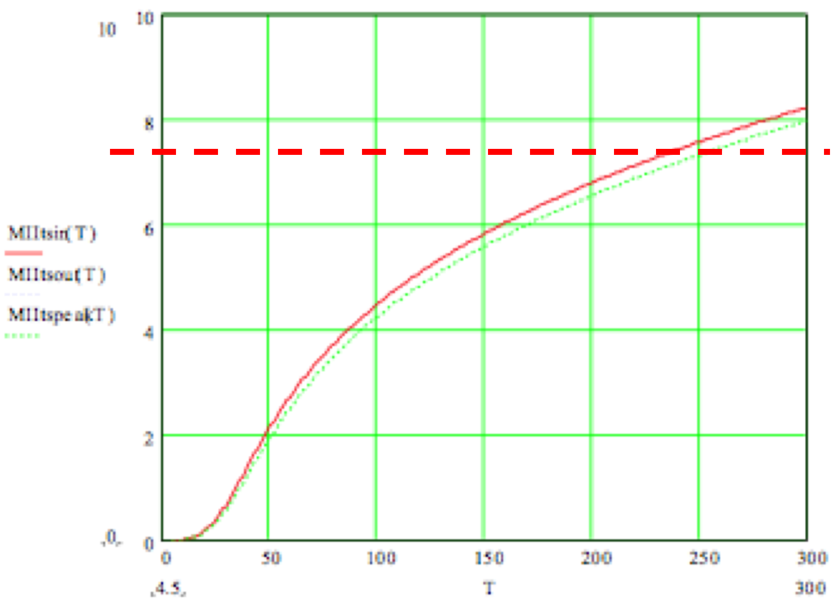
- LARP (LHC Accelerator Research Program) Long quadrupole
- Nb_3Sn, 3.6 m long, 460 kJ/m, 240 T/m at 13.75 kA, 12.2 T peak field
- Limits of the conductor known empirically

MIITs study performed on TQ (short version of LQ)



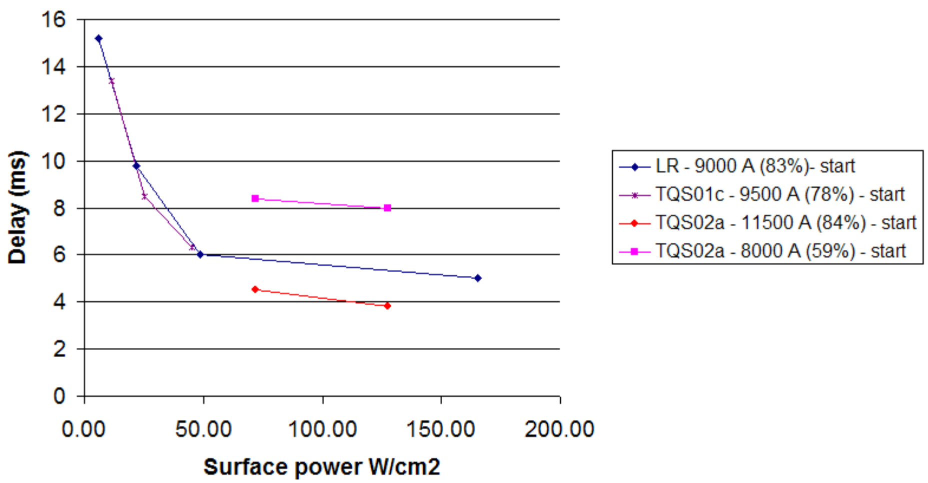
G. Ambrosio et al, TQS01c test results summary, TD-07-007

LQ MIITs curve



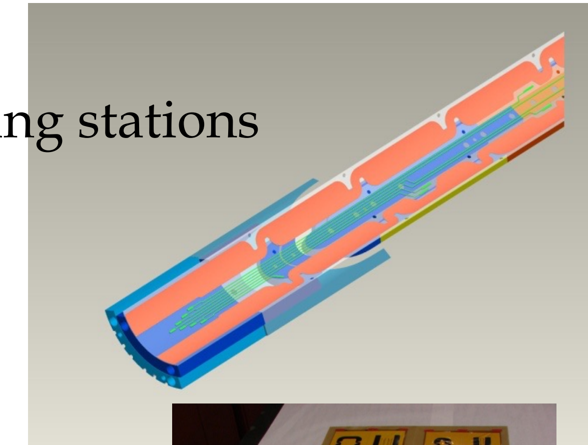
LQ Protection requirements and limitations

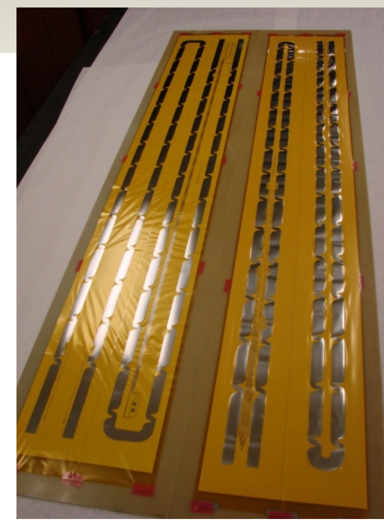
- Analysis showed that the MIITs can stay below 7.5 if
  - Rdump = 60 mohm
  - Full heater coverage with delay shorter or equal to 12 ms
  - Detection time of 5 ms or less
- Limited number of power supplies: 4
- Voltage limited to 450 V, capacitor bank fixed at 19.2 mF
- Power requirements known empirically

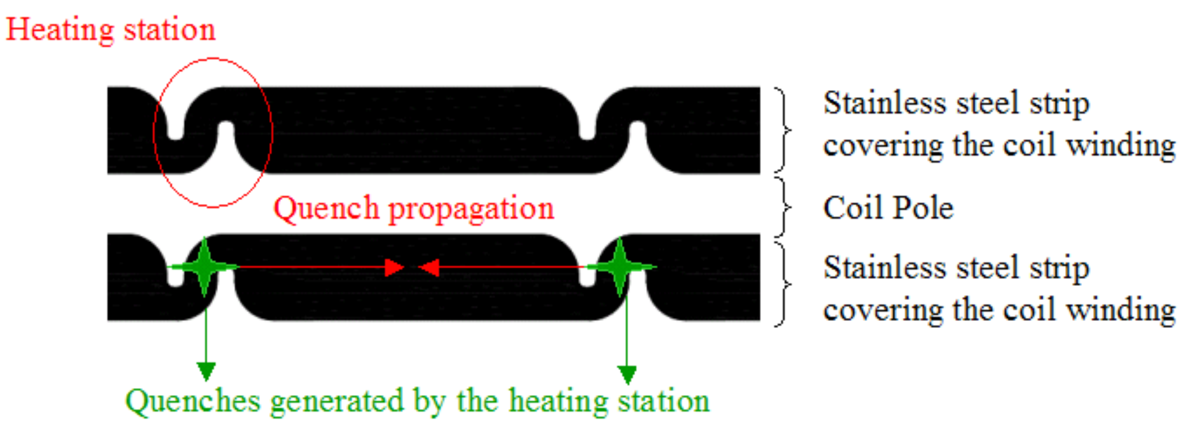


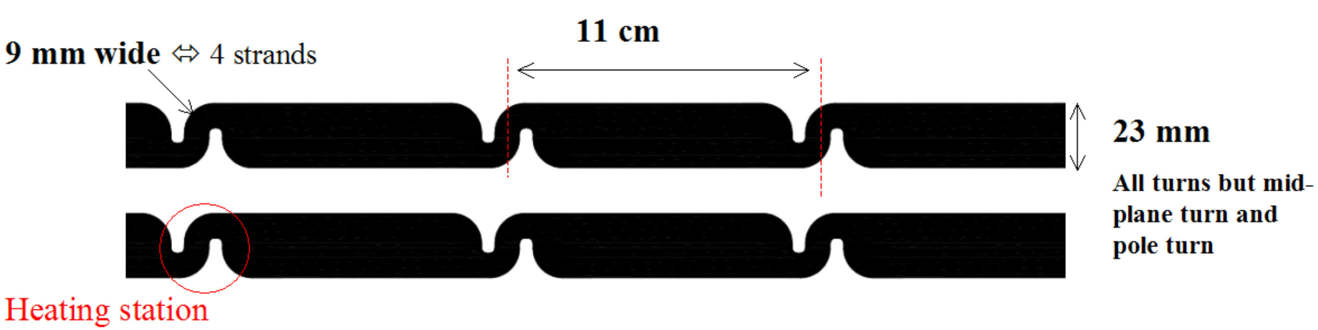
LQ protection heaters design

- 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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AADD 75-1

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

ACCELERATOR DEPARTMENT
Informal Report

QUENCH CODE

A.D. McInturff

January 9, 1975

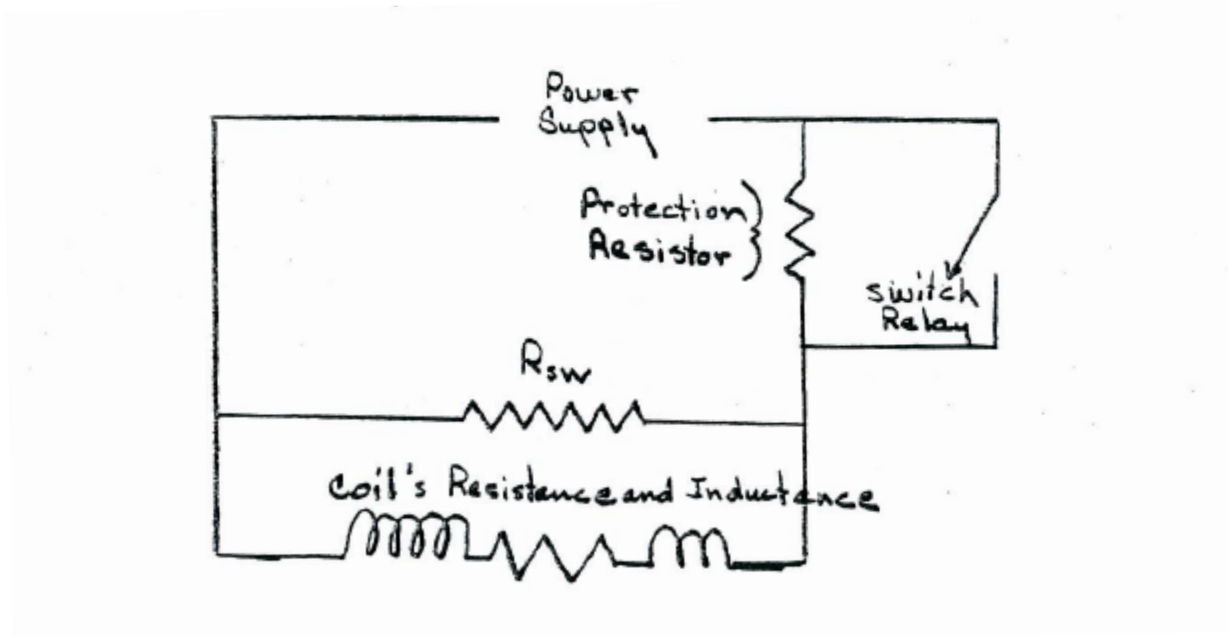
- The model
- Material properties are approximated by function of the temperature

Wilson model

- 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

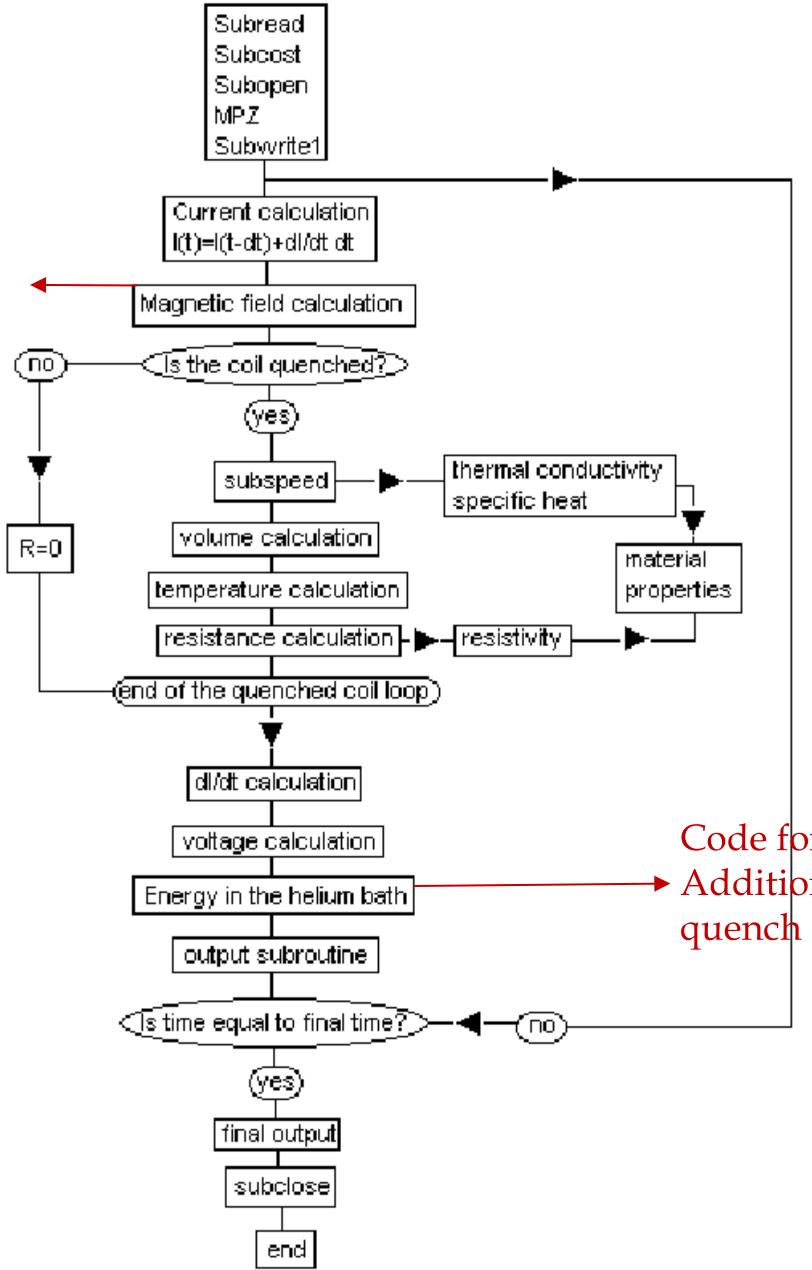
INFN/TC-04/13
6 Luglio 2004
Rev. 1

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

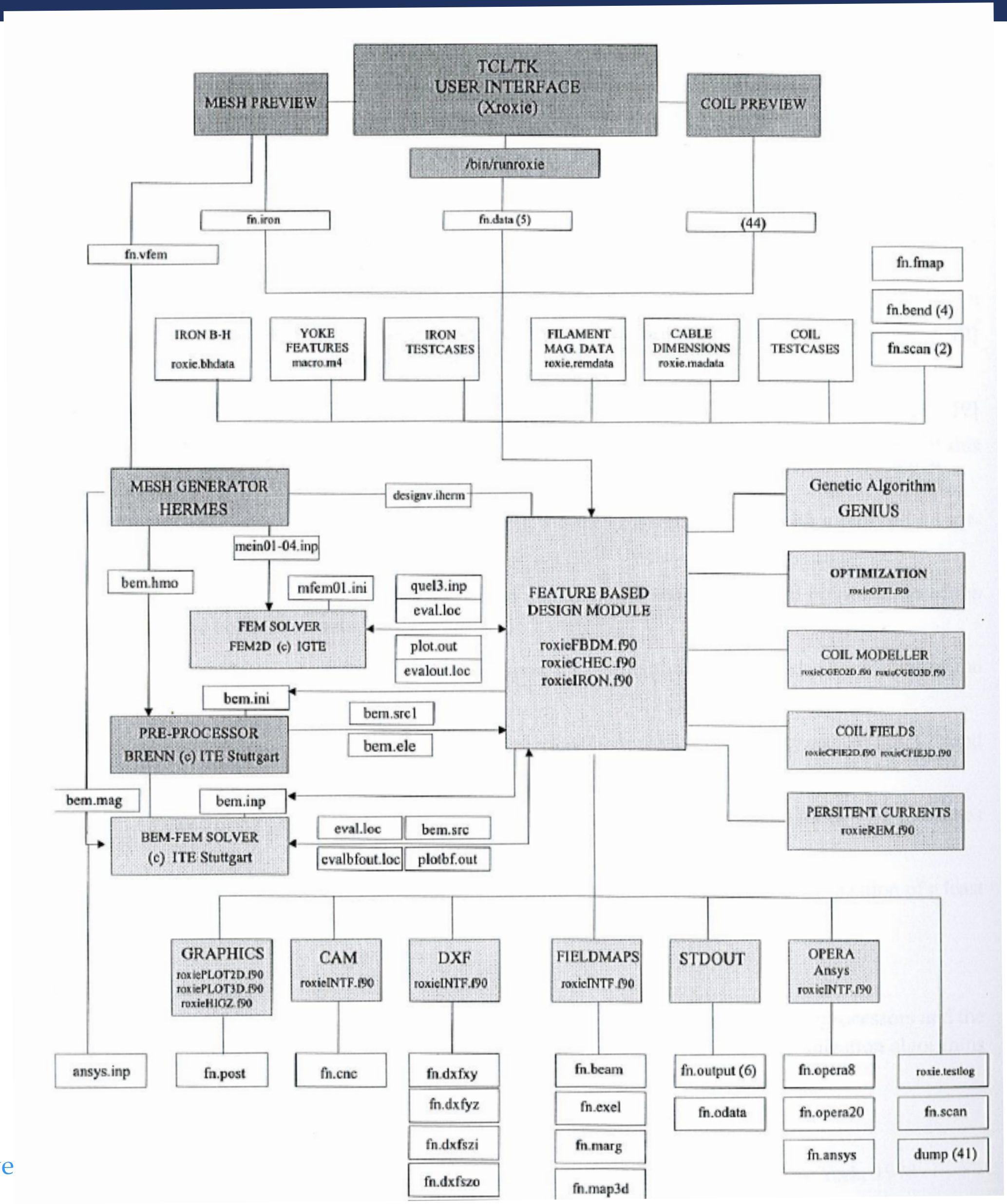
Code for adiabatic magnets
Addition to force all the coil to quench at some point

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=σE

contribution from the source of current

Reduced vector potential

$$\mathbf{B} = \mu_0 \mathbf{H}_s + \nabla \times \mathbf{A_R}$$

In free space region containing source of currents

$$\nabla \times \frac{1}{\mu_0} \nabla \times \mathbf{A_R} = 0$$

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

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

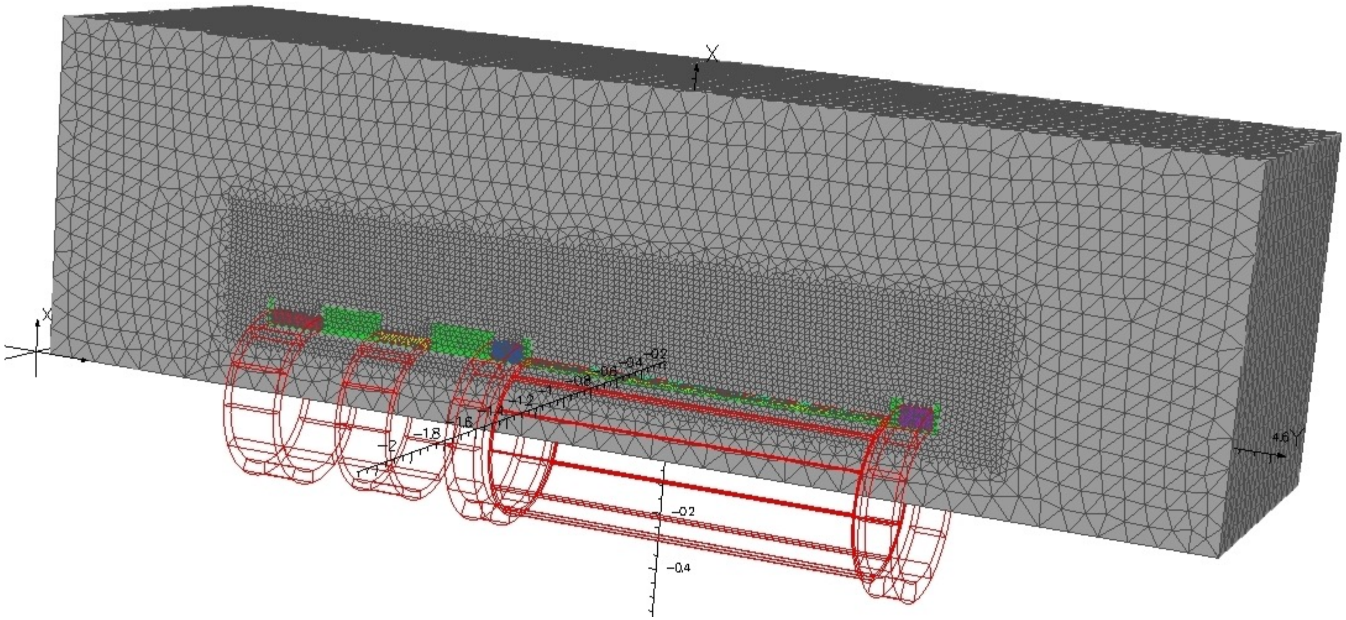
$$\nabla \cdot \sigma \nabla V + \nabla \cdot \sigma \frac{\partial \mathbf{A}}{\partial t} = 0$$

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)

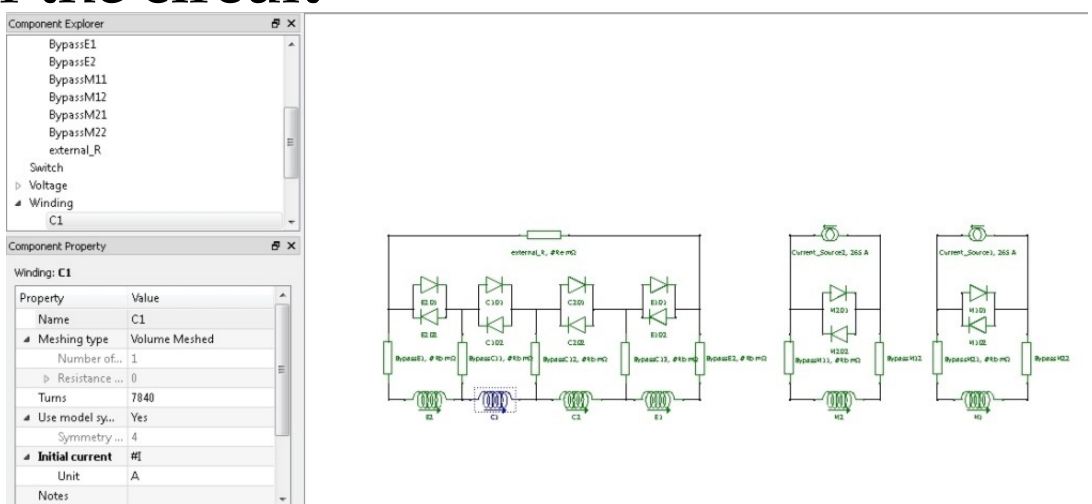
- The Finite element discretization is supported by the Opera3D geometric **Modeller** which allows the creation of the model
  - Only the coil in case of the simple thermal analysis
  - The coil, some surrounding air (far enough) and any permeable material (iron, aluminum…) when coupled
    - In this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

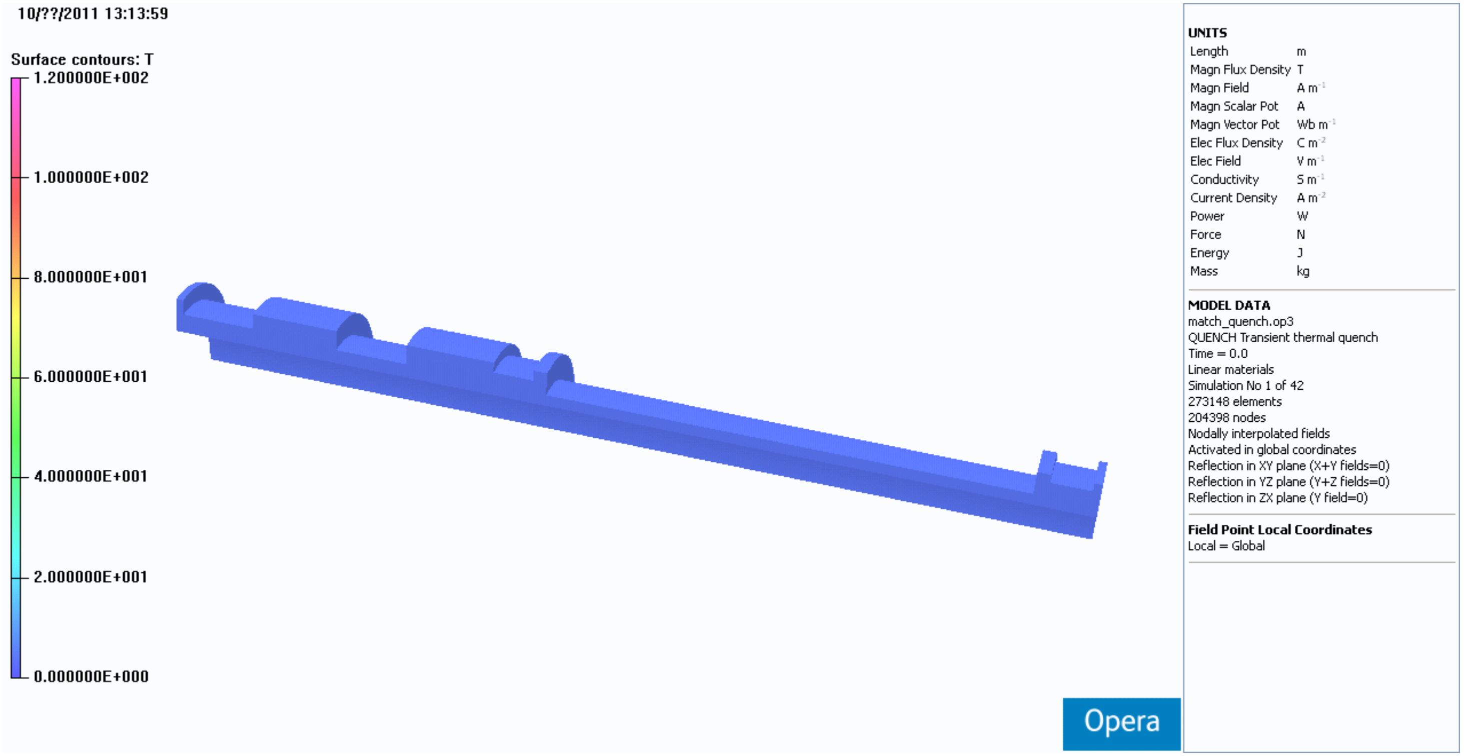
- Definition of the boundary conditions: protection heater
  - Surface selected – heat flux injected
- Definition of the circuit



Example of MICE – III

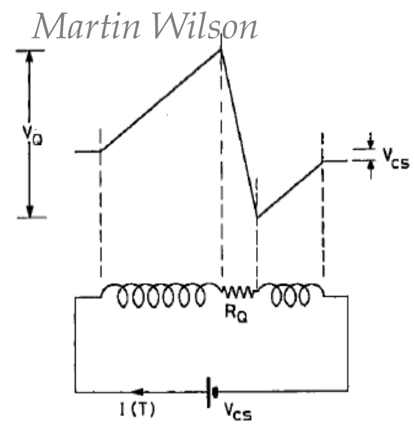
- Coupled analysis run for MICE
  - Example of the mandrel temperature

Courtesy of Heng Pang, LBNL, unpublished data



Treatment of the voltages

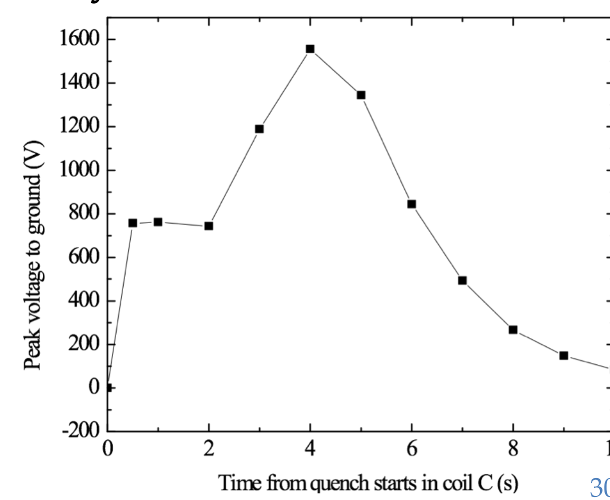
- The QUENCH module does not deal with inductive voltages contributing to
  - Interlayer voltages
  - Peak voltage to ground



- Post-processing of the quench module output

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

  - 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



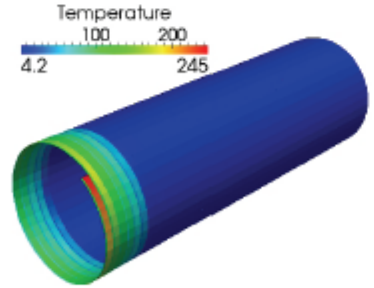
Courtesy of Heng Pang, LBNL, unpublished data

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

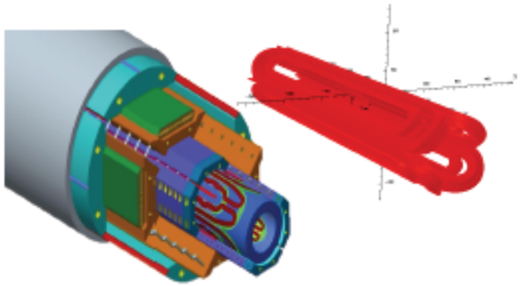
Code development

- 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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