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Modeling quenches
A Review of the tools

Helene Felice

With great help from many:

Giorgio Ambrosio, Berhnard Auchmann, Philippe Fazilleau, Massimo Sorbi, Heng Pan, Lidia Rossi, Tiina Salmi…

WAMSDO – Jan 15th to 16th 2013 - CERN

Introduction

A review of several codes. For each code:

- **Code "ID"**
  - Overview
  - Programming
  - Validation
  - Distribution / Availability
  - Some users
  - Some references

- **Brief description**

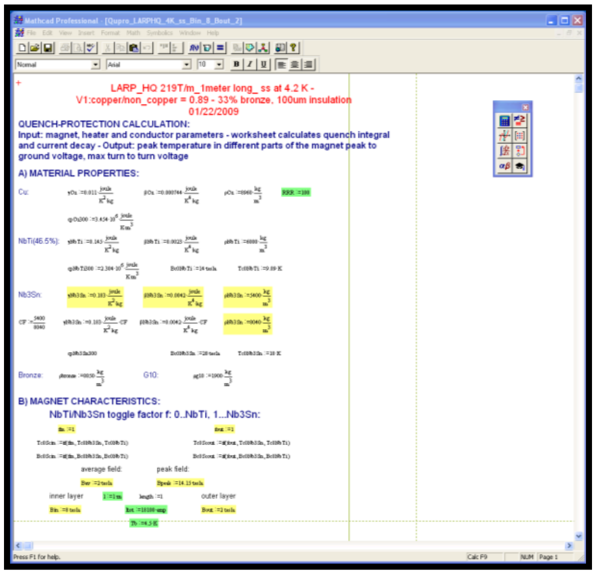
Non exhaustive list of codes

We can distinguish 2 kinds od codes:

- **Highly specialized "quench protection" codes**
  - QuenchPro
  - QLASA
  - ROXIE
  - Cobham Vector Field Quench Analysis program

- **More general codes applied to quench protection:**
  - FEM codes: ANSYS, CAST3M

QuenchPro ID



QuenchPro developed at FNAL by P. Bauer

Overview

Adiabatic model

Calculation of the hot spot temperature and current decay

Programming

Mathcad 7 spreadsheet developed by Pierre Bauer

Validation

LQ and comparison with QLASA

Availability

Available upon request to the owner (Pierre Bauer or Giorgio Ambrosio)

Some users

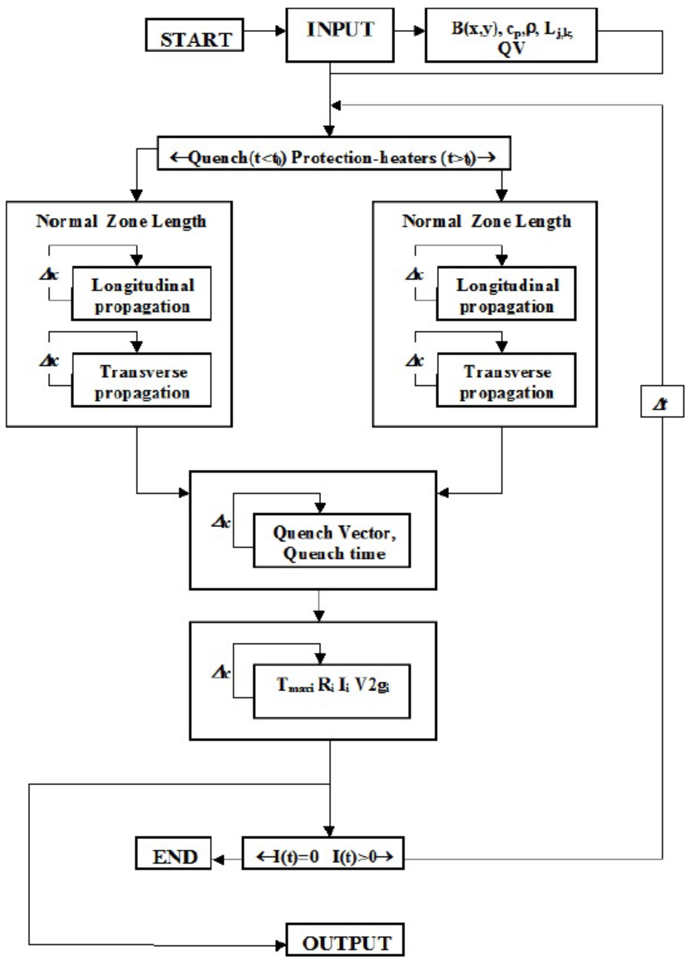
Giorgio Ambrosio (FNAL), Helene Felice (LBL)

Some References

P. Bauer et al., FNAL TD-00-027, FNAL TD note TD-01-003 and 4

Lidia Rossi, FNAL TD-12-11

QuenchPro - Principle



Flowchart from Lidia Rossi thesis – TD-12-11

Part 1:

- **Input**
  - Definition of the magnet in a series of 16 sub-coils
  - Magnet Operational Parameters: field, bath temperature
  - Preliminary calculations of the material properties
  - Definition of the protection system
    - Value of the dump
    - PH: coverage, delay…
    - Detection time
- **Normal zone propagation Routine** – for each time step
  - Calculation of the resistance
  - Current decay: exponential
  - Temperature: computed based on the MIITs accumulation at t_i

QuenchPro – Principle(II)

Part 2:

- **Voltage computation**

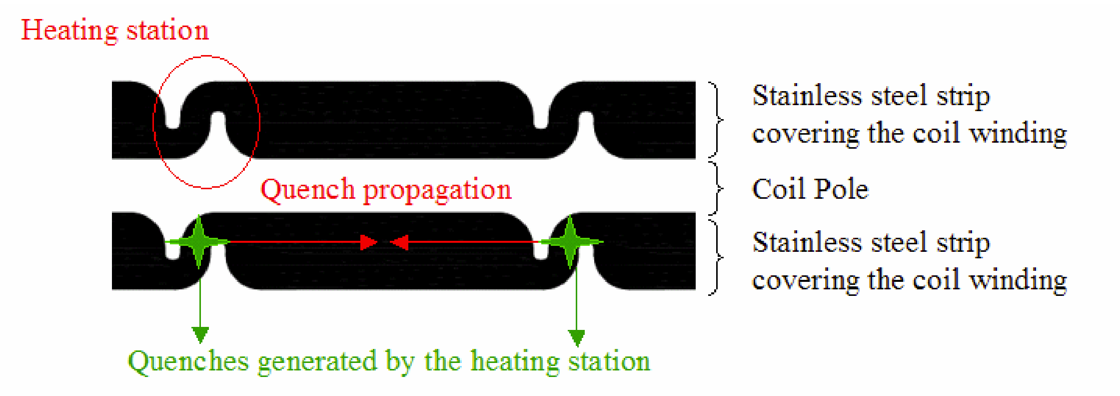
- Definition of each turn coordinates to allow the calculation of the turn to turn inductance => inductance matrix
- Calculation of the turn to turn voltage and turn to ground voltage

Some Limitations

- Absence of user manual
- Various versions modified by various people
- No quench-back effect

QuenchPro improvement by Lidia Rossi (available upon request to G. Ambrosio)

Implementation of heating stations (Tiina Salmi's talk)



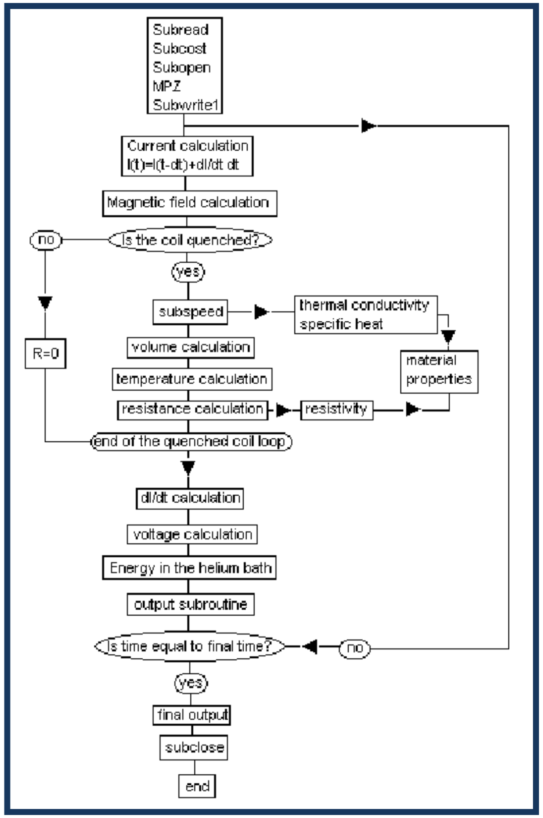
Example of LARP Long Quad (LQ)

- Normal zone growth account for quench propagation from heating stations

Implementation of the differential inductance

- Initially constant in the original QuenchPro
- "If" loop to introduce L(I)

QLASA - ID



Overview

Quench code developed at **LASA**

Adiabatic assumption for hot spot temperature

Initially intended for superconducting solenoids and inductively coupled elements

No quench-back effects

Programming

Fortran 77

Availability

Available upon request to the owner (QLASA)

Some users

Massimo Sorbi (INFN – LASA)

Some References

L. Rossi, M. Sorbi, INFN/TC-04/13

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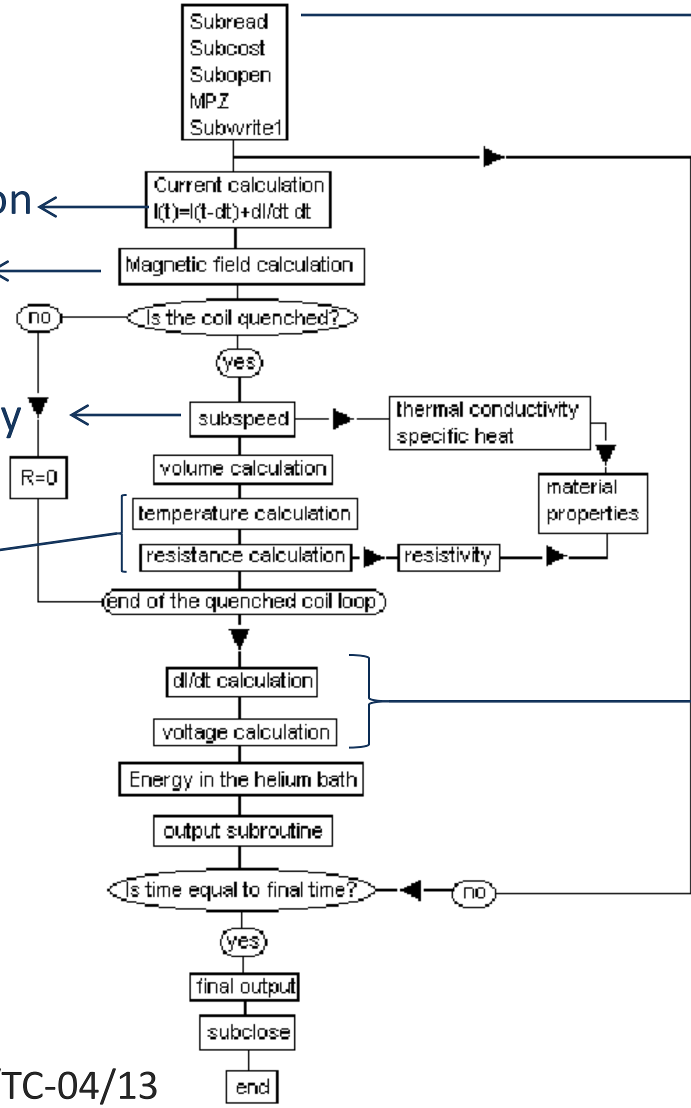
QLASA - Principle

Current computation

B computation

Propagation velocity computation

Resistance and Temperature



Flowchart from INFN/TC-04/13

Reads the input data

- Geometry
- Time steps
- Vtaps location
- Self an Mutual inductance
- Cable components
- …

Current decay

Voltage:

- Driven Mode: Accounting for change of mode of the power supply (from current mode to voltage mode)
- Persistent mode available

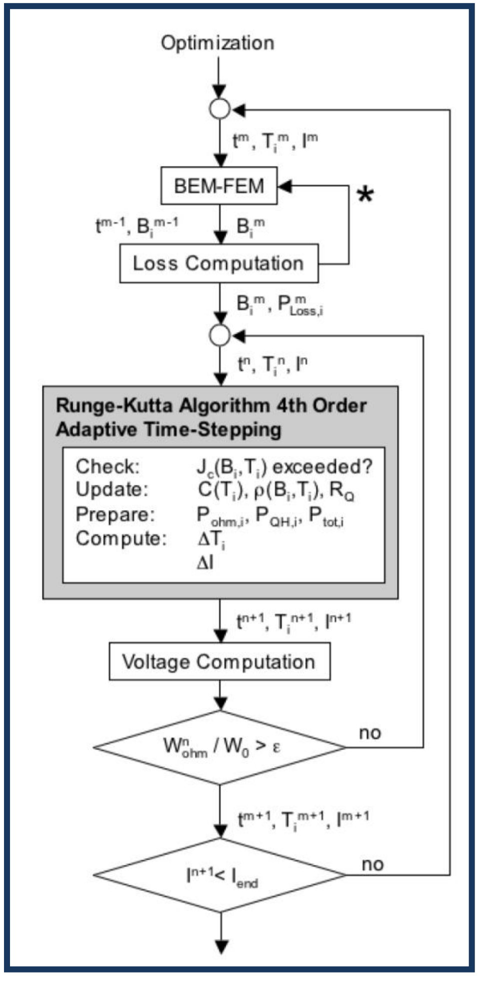
QLASA Material properties: MATPRO

Lucio Rossi and Massimo Sorbi, “ MATPRO : A Computer Library Of Material Property At Cryogenic Temperature”, CARE-Note-05-018-HHH

Fortran 77 computer library providing some electrical and thermal properties of the most common materials used for the construction of superconducting magnets. The physical properties dealt by the code are:

1. Density.
2. Specific heat.
3. Electrical resistivity
4. Thermal conductivity.

ROXIE Quench Module ID



Overview

Solve the heat equation by FEM

Programming

Developed by Nikolai Schwerg and Bernhard Auchmann

Validation

TQ , 11 T dipole

Availability From CERN with the ROXIE license

Some users

Bernhard Auchmann, Susanna Izquierdo Bermudez (CERN)

Tiina Salmi (LBNL)

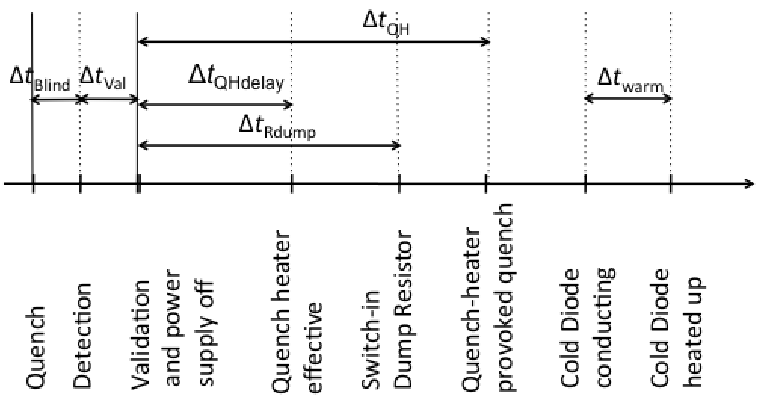
Some References

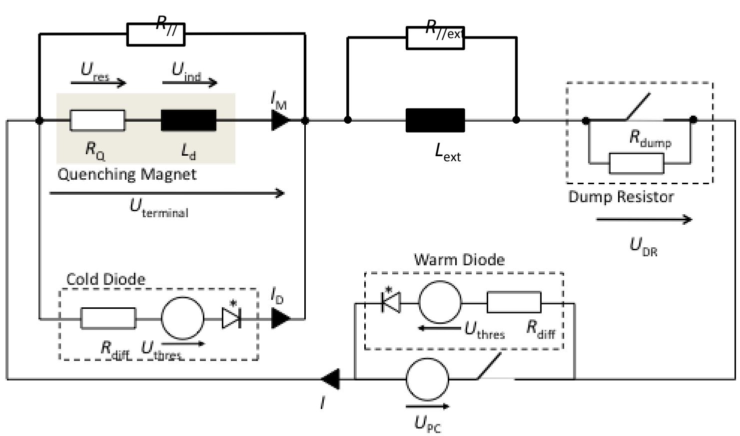
N. Schwerg et al.,, IEEE Trans. On Magn., Vol. 44, N. 6, June 2008

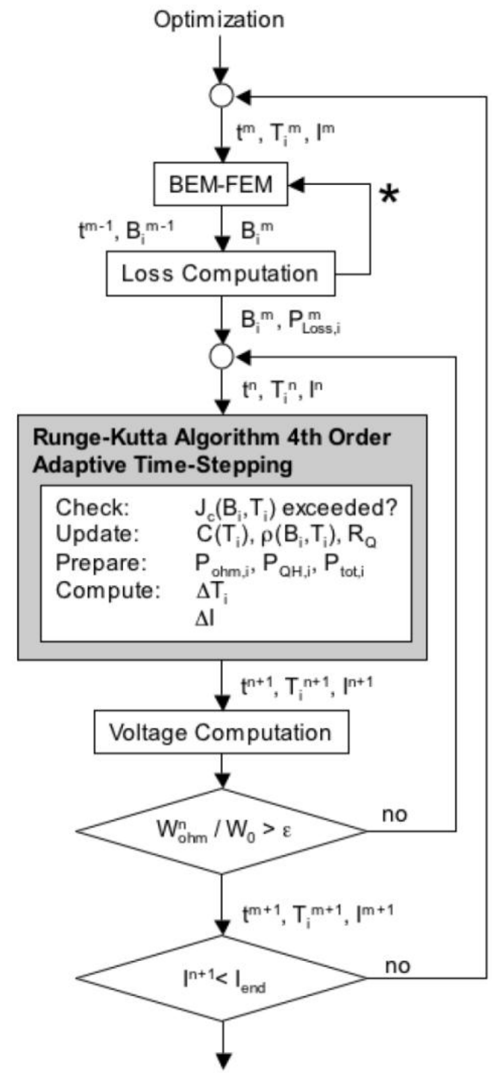
N. Schwerg et al., IEEE Trans. On Appl. Supercond, Vol. 19, No. 3, June 2009

ROXIE - Description

N. Schwerg et al., “Quench simulation in an integrated design environment for superconducting magnets”.
IEEE Trans. on Magn., vol 44, June 2008.







ROXIE Description (II)

The heat equation is discretized by an equivalent thermal network model.

$$C\frac{\mathrm{d}T}{\mathrm{d}t} = P_{\mathrm{Joule}} + P_{\mathrm{beam}} + P_{QH} - \mathrm{div}\,\lambda\,\mathrm{grad}\,T$$

In the coil cross-section, each conductor corresponds to a node in the network

The thermal model considers:

- non-linear heat capacity
- anisotropic, non-linear thermal conductivity
- cooling to a cold surface,
- the influence of helium
- heat sources due to ohmic heating,
- quench heaters: no diffusion time computation
- induced losses (which is a form of quench-back)

- Choose between 2D and 3D modeling: Longitudinal subdivision has to be supplied by the user (check minimum quench zone, initial voltage rise, etc.).

ROXIE Material properties

G. Manfreda, Review of ROXIE's material properties database for quench simulation, EDMS 1178007, Nov 2011

MATPRO:

- collection of cryogenic material properties from Università degli Studi di Milano and Istituto Nazionale di Fisica Nucleare (INFN)
- developed with the work, among the others, of Lucio Rossi and Massimo Sorbi.
- database used by QLASA quench simulation code;

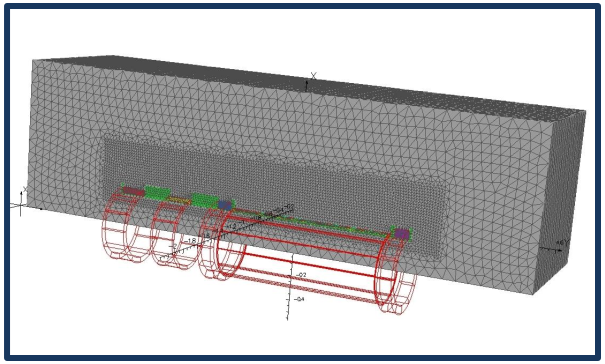
NIST: the official website of the National Institute of Standard and Technology contains a database of cryogenic material properties;

CUDI : the software for Rutherford cable modeling from Arjan Verweij computes some material properties useful for quench simulation, that are reported in the user manual;

CryoComp:

- collection of properties for materials commonly present in superconducting magnets.
- version 5.1. CryoComp material properties are for example used in Qcode from Lawrence Berkeley National Laboratory.

Cobham Vector Field – Quench Analysis Program



Overview

The Quench Analysis Program is one of the Analysis programs of the Opera-3D Analysis Environment.

- Incorporates the non linear solution of the transient problem using the **TEMPO-Transient Thermal Analysis**
- Can be coupled with **ELEKTRA/TR analysis** to model transient electromagnetic fields and external circuits

Validation

Wilson code, MICE spectrometer

Availability

$$ Cobham

Some users

Heng Pan (LBNL)

Vector Field Quench Analysis Program
Material Properties

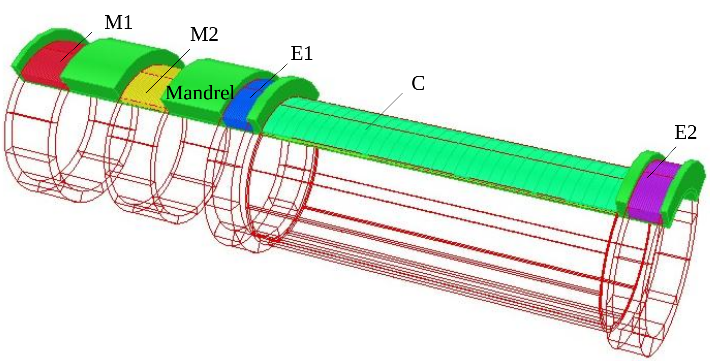
- Material need to be homogenized.
- Material properties used at LBNL: Cryocomp.

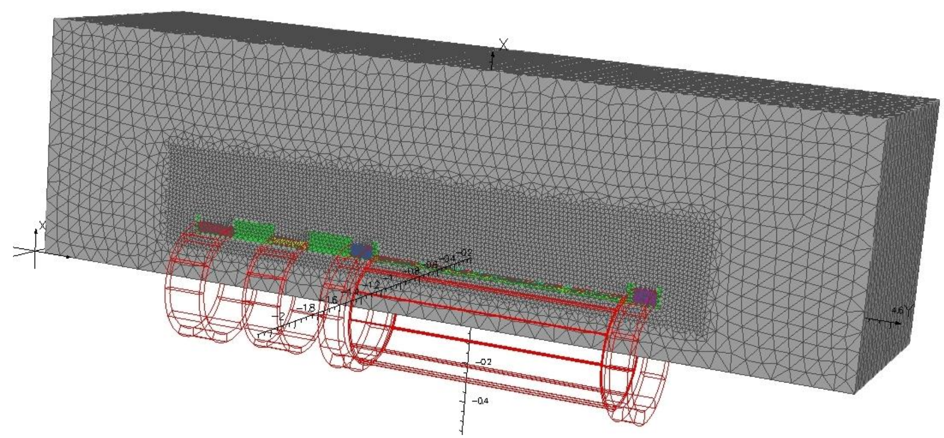
Example of MICE (courtesy of Heng Pang, LBNL)

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

The Finite element discretization is supported by the **Opera3D geometric Modeller** which allows the creation of the model

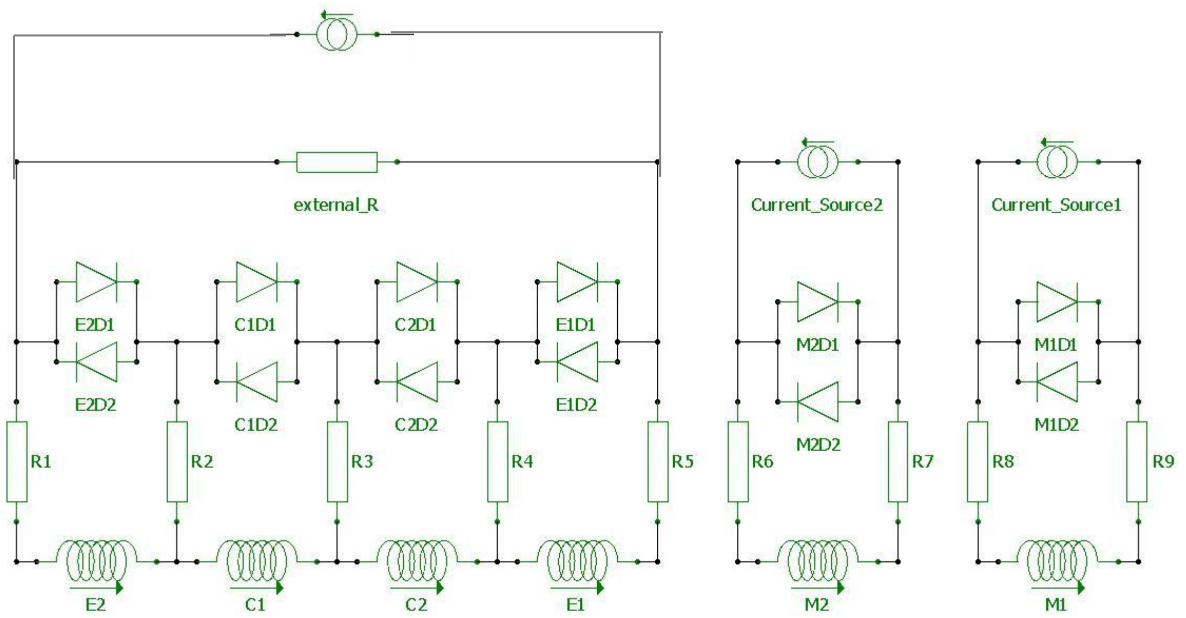
- Only the coil in case of the simple thermal analysis
- The coil, some surrounding air (far enough) and any permeable material (iron, aluminum…) when coupled
    - In this case: coils, mandrel and air





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*

FEM - ANSYS

Programming

FEM

Availability

$$ ANSYS

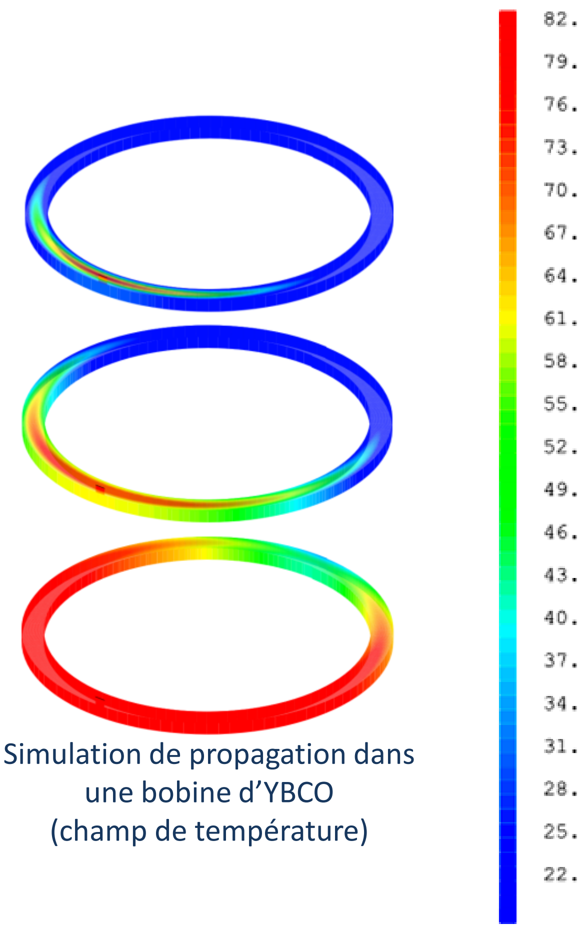
Some users

S. Caspi (LBNL), P. Ferracin (CERN), R. Yamada (FNAL)

Some References

- S. Caspi et al., and published in “Calculating Quench Propagation With ANSYS”, IEEE Trans. Appl. Supercond, Vol. 13, No. 2, June 2003
- P. Ferracin et al., “Thermal, Electrical and Mechanical Response to a Quench in Nb3Sn Superconducting Coils”, ”, IEEE Trans. Appl. Supercond, June 2004
- 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

FEM CAST3M- ID



Simulation de propagation dans une bobine d'YBCO (champ de température)

Overview

Finite element analysis developed and used at CEA

Used to compute eddy currents in surrounding coil components => quenchback

Used also for quench propagation computation in YBCO coils

Programming

FEM

Validation: CMS, RD3b

Availability: Free

Some users: Philippe Fazilleau (CEA)

Some References

P.Verpeaux, T. Charras, and A. Millard,"CASTEM 2000 une approche moderne du calcul des structures," in *Calcul des structures et intelligence artificielle*, Pluralis, 1988, pp. 261–271.

P. Fazilleau et al. "The R3B-GLAD Quench Protection System", IEEE Trans. On Applied Superconductivity, Vol.. 20, No. 3, June 2010

In summary

- A NON EXHAUSTIVE list of codes
- Need to pick the right code fitting the user goals
- Most of the codes are free and accessible but might lack documentation

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Appendix

Results for MICE spectrometer (Cobham VF)
Typical scenarii

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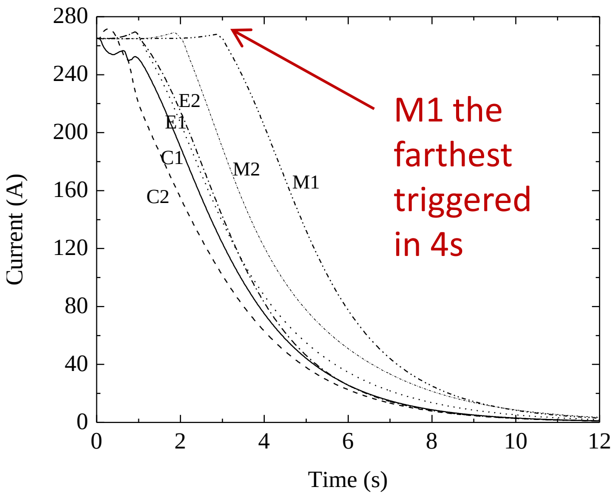
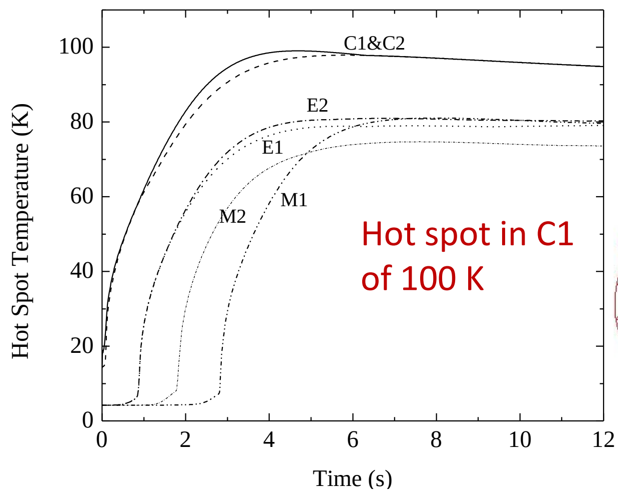
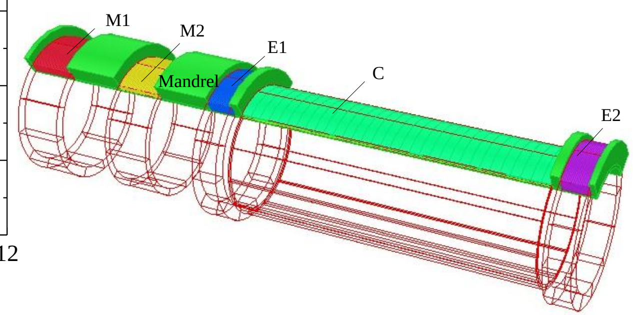
- Iop = 265 A. Quench initiated in the C1 coil

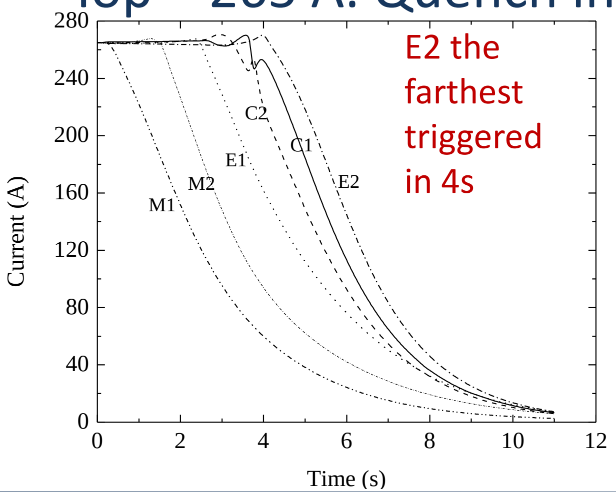


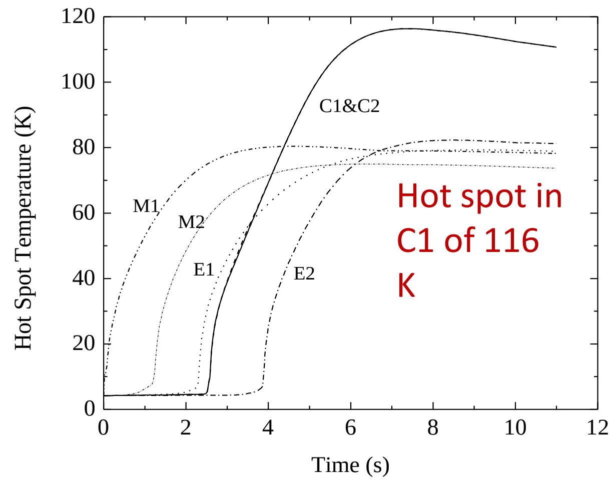


Courtesy of Heng Pang, LBNL, unpublished data



- 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.

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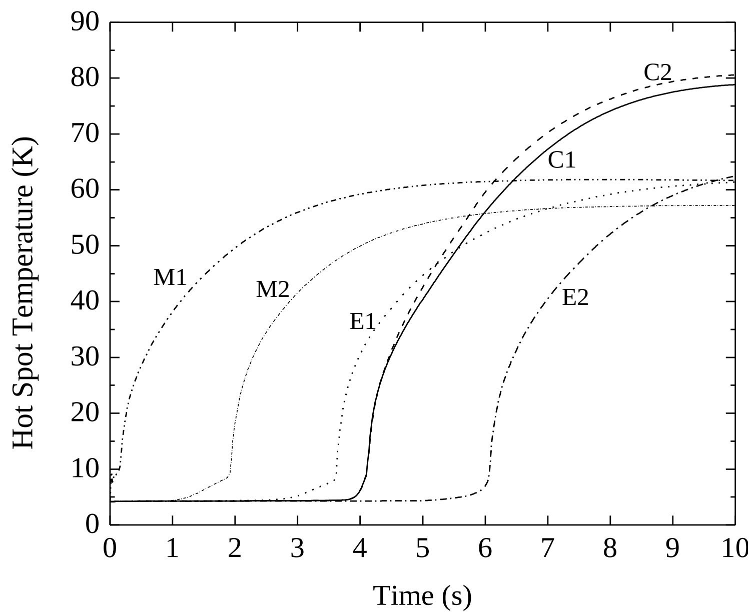
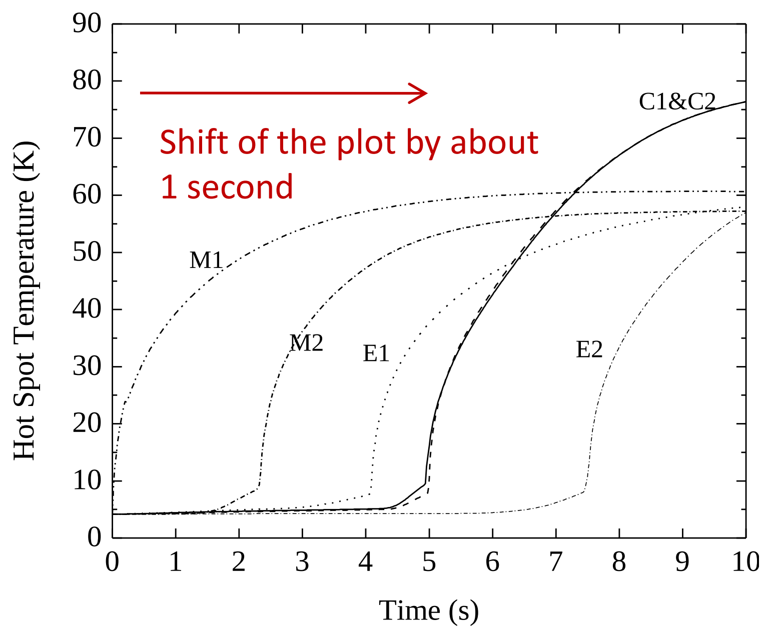
Results for MICE spectrometer (Cobham VF) Influence of the quench back

- 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