A computer code for comprehensive analysis of quench in pool-cooled and adiabatic superconducting multi-coil magnets

Andy Gavrilin

National High Magnetic Field Laboratory (NHMFL)

Florida State University (FSU)

Tallahassee, Florida, USA

CHATS - AS 2013

Cambridge, MA

10th October, 2013

Contents

Introduction. A fully automated version of the quench code.

1. What types of superconducting magnets?

-Multi-coil pool-cooled or adiabatic magnets of solenoid and/or pancake type. Not CICC.

-"Standard"/typical closely-packed windings (NMR, MRI, etc.). The effect of helium on the thermal diffusion is limited or negligible.

-Co-axial coils (no need yet to automate a more general version of the code).

-No race-tracks yet (can be included on request).

2. Wire wound, cable wound can be considered, too.

3. Majority of electric circuits.

5. Both active (incl. heaters) and passive quench protection. The quench-back options are not automated yet (no requests so far).

4. Both HTS and LTS. The version for LTS is completed and being used. The full (LTS and/or HTS) version development is coming close to completion.

The idea: To make a sophisticated quench code a "do-it-yourself" tool for magnet designers (who are not really magnet analysts and, positively, not programmers at all). A smart "black box".

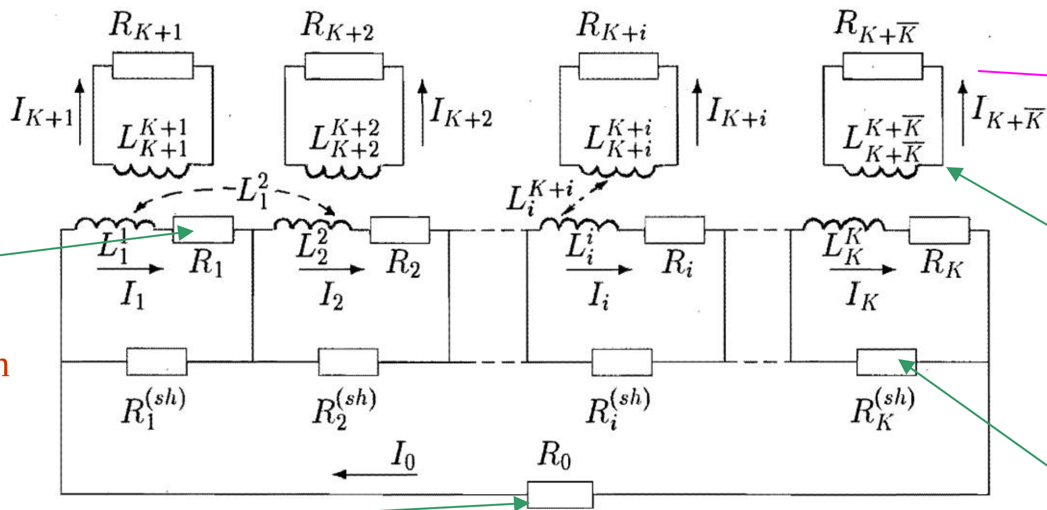
The purpose: A superconducting magnet design and/or design optimizing from the standpoint of quench protection.

Requirements and wishes from users

1. Not to deal with programming. No special software (Fortran) is to be installed. A very simple manual or no manual at all.
2. To have easily understandable input in the form of tables (few input files). The user is assumed to deal with the input files only.
3. The tables are supposed to be naturally and conveniently organized and quickly modified when required.
4. Availability of an appendable data base of conductors (a separate file).
5. To have a developed data base of material properties integrated with the code as a “black box”.
6. Automatic calculation of the magnetic field maps and the inductance matrix by the code (based upon a magnet configuration). - No effort by the code user is required.
7. Output presented as a set of digital files (with explaining comments and directions) for post-processing, utilizing Excel, Origin, etc.
8. Some protection against inadequate input is desirable.

Features Included: Electric Circuit

a coupled thermal and circuit problem



A normal zone resistance in a section due to quench propagation or a heater operation

Secondary winding, mandrel, shell, etc.

(more difficult to automate)

PS or diode

Shunt resistance and/or array of diodes

$$\gamma C \frac{\partial T_i}{\partial t} = \nabla(\kappa \nabla T_i) + Q_V + Qs$$

$$\sum_{k=1}^{K+\overline{K}} L_i^k \frac{dI_k}{dt} + \left(R_i(t) + R_i^{(sh)}\right) I_i = R_i^{(sh)} I_0 \,, \quad I_0 = \frac{\sum_{k=1}^{K} R_k^{(sh)} I_k}{R_0 + R_k^{(sh)}} \,;$$

$$R_i^{(sh)} \neq 0,\ i = 1,\ldots, K; \quad R_i^{(sh)} \equiv 0,\ i = K+1,\ K+\overline{K}$$

Features Included: Thermal Problem – No Simplifications!.

1. The discrete structure of the windings is not homogenized (not an anisotropic continuum based model):

- **each coil (of a multi-coil magnet) is a set of nested thermally coupled helicoids (or pancakes);**
- **turn-to-turn (axial) and layer-to-layer (radial) thermal diffusion through the insulation.**

2. Inter-coil thermal coupling is allowed.

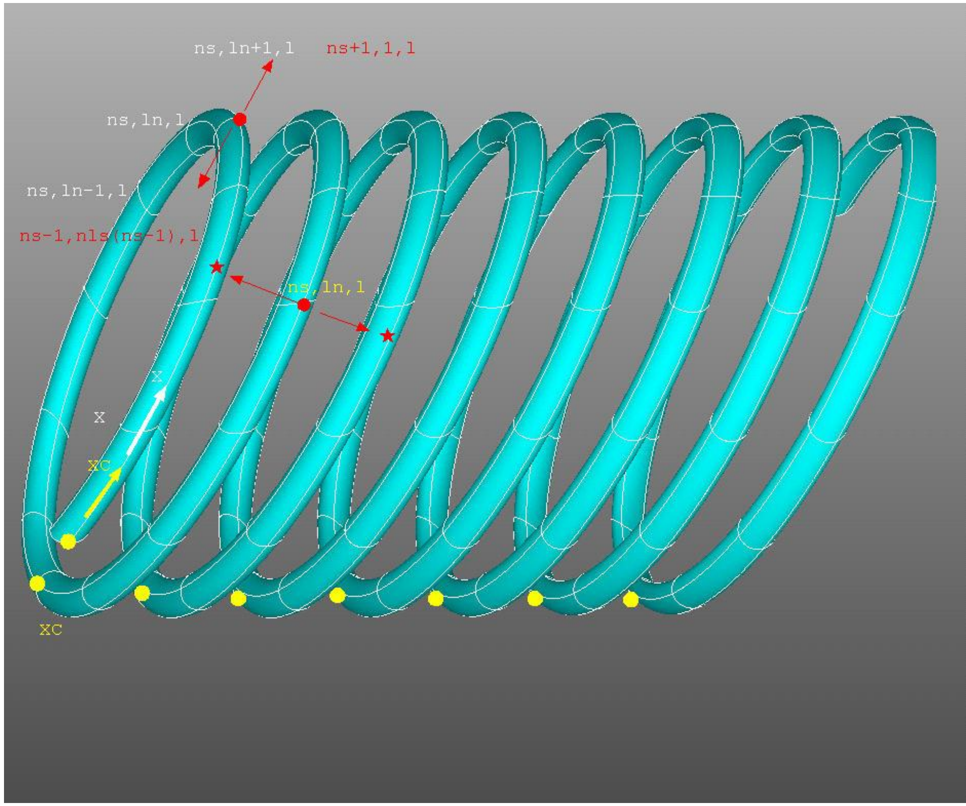
3. The 3D case can be easily transformed to the 2D case through manipulations with the mesh.

4. Heat transfer to LHe on the coil external surface can be included (typically, no need).

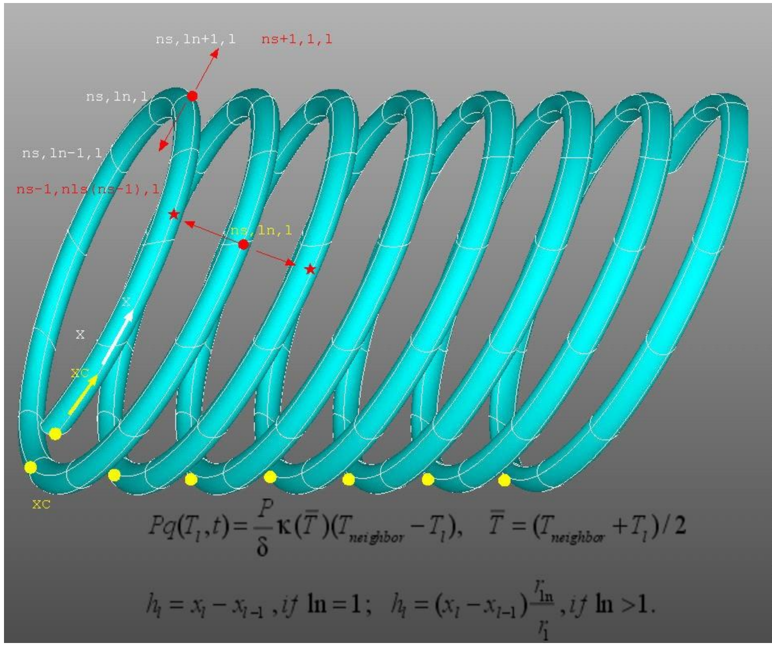
5. Time-variable magnetic field and strain distributions (Nb3Sn) are included "as is". Very detailed maps of magnetic field components within each coil are prepared.

6. AC losses and index heating in the wire. The up-to-date approach.

7. Etc.



The features included. Thermal problem.



$$(A_{Cu}C_{Cu}+A_{SC}C_{SC}+A_{ins}C_{ins})\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(A_W\kappa_W\frac{\partial T}{\partial x}\right)+$$
$$+\left[A_WQ_J+A_WQ_{AC}+A_WQ_{index}\right]+$$
$$+\sum_{i=1}^{4}\frac{P_i}{\delta_i}\kappa_i^{(ins)}(\bar{T}_i)\left(T^{(i)}-T\right)$$

$$T=T(x,t);\ A_W=A_{Cu}+A_{SC}$$

$$A_{Cu}C_{Cu}+A_{SC}C_{SC}+A_{ins}C_{ins}=A_{Cu}\ C_{Cu}(T)+A_{SC}C_{SC}(T,B,\varepsilon,j)+A_{ins}C_{ins}(T)$$
$$B=B(x,t);\quad j=j(t)=I(t)/A_{SC}\quad (\textit{there is no strain dependence for NbTi})$$

$$A_W\kappa_W=A_W\kappa_W(T,B)\,.$$

$$A_WQ_J+A_WQ_{AC}+A_WQ_{index}=$$
$$=A_WQ_J(T(x,t),I(t),B(x,t),\varepsilon(x,t))+$$
$$+A_WQ_{AC}(T(x,t),B(x,t),\varepsilon(x,t),\dot{B}(x,t),I(t))+A_WQ_{index}(I(t))$$

$$\sum_{i=1}^{4}\frac{P_i}{\delta_i}\kappa_i^{(ins)}(\bar{T}_i)(T^{(i)}-T)=$$
$$=\frac{P_1}{\delta_1}\kappa_1^{(ins)}(T^{(1)}-T)+\frac{P_2}{\delta_2}\kappa_2^{(ins)}(T^{(2)}-T)+\frac{P_3}{\delta_3}\kappa_3^{(ins)}(T^{(3)}-T)+\frac{P_4}{\delta_4}\kappa_4^{(ins)}(T^{(4)}-T)$$
$$\bar{T}_i=\frac{T^{(i)}+T}{2};\quad e.g.,\bar{T}_1=\frac{T^{(1)}+T}{2};$$
$$P_1=P_2=P_{axial};\ P_3=P_4=P_{radial};\quad \kappa_1^{(ins)}=\kappa_2^{(ins)}=\kappa_{axial}^{(ins)};\quad \kappa_3^{(ins)}=\kappa_4^{(ins)}=\kappa_{radial}^{(ins)}.$$

Solved using a finite-difference method

Requirements and wishes from users

1. Not to deal with programming. No special software (Fortran) is to be installed. A very simple manual or no manual at all.
2. To have easily understandable input in the form of tables (few input files). The user is assumed to deal with the input files only.
3. The tables are supposed to be naturally and conveniently organized and quickly modified when required.
4. Availability of a separate appendable data base of conductors (a separate file).
5. To have a developed data base of material properties integrated with the code as a "black box".
6. Automatic calculation of the magnetic field maps and the inductance matrix by the code. - No effort by the code user is required.
7. Output presented as a set of digital files (with explaining comments and directions) for post-processing, utilizing Excel, Origin, etc.
8. Some protection against inadequate input is desirable.

The input files

Describing a magnet system configuration and the magnet quench protection system:

Geometry.dat

Inter_coil_thermal_contacts.dat

Quench_protection_circuit.dat

Triggers.dat

A quench initiation details and output control:

Solver_and_output_control.dat

Quench_initiation.dat

The data base of conductors available:

Wire_parameters.dat

Wire_critical_current.dat

The key, subscription control

Key.dat

Input. Conductor data base

wire_parameters - Notepad

File Edit Format View Help

Total number of wire brands/types/kinds available presently (the total number of lines in the table given below, with no regard for the columns' titles) :

14

							-------- matrix data ---------:			--- AC loss data ----:			
wire/conductor name/brand	wire/conductor brand code	bare wire width (effective diam if round), cm	bare wire height, cm	wire shape code: 0 - rectang. 1 - round	superconductor/ matrix(Cu,bronze, Ta) ratio in bare wire	NbTi or Nb3Sn - ? 0 - NbTi 1 - Nb3Sn	wire matrix RRR effective value	alpha	beta	supercond filament effective diameter, mcm	n-tau effective value, ms	wire insulation thickness, cm	wire insulation brand type: 1 - formvar/PVA 2 - polyimid/kapton 3 - epoxidized glass-cloth (G10)
name 1	2	0.130	0.0720	0	0.74000	0	100.	3.6095e-07	5.2845e-11	6.5	0.01	0.0025	2
name 2	9	0.043	0.0310	1	0.74000	0	100.	3.6095e-07	5.2845e-11	6.7	0.01	0.0017	1
name 3	8	0.044	0.0390	1	0.74000	0	100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0021	1
name 4	7	0.048	0.0520	1	0.74000	0	100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0022	1
name 5	6	0.062	0.0605	1	0.74000	0	100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0022	1
name 6	5	0.075	0.0710	1	0.74000	0	100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0025	1
name 7	4	0.070	0.0745	1	0.74000	0	100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0025	1
name 8	3	0.080	0.0839	1	0.74000	0	100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0025	1
name 9	10	0.050	0.0380	1	0.74000	0	100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0019	2
name 10	1	0.074	0.0720	1	0.30000	1	40.	3.6095e-07	5.2845e-11	3.5	0.01	0.0065	3
name 11	11	0.045	0.0408	1	0.70000	0	100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0018	2
nam2 12	12	0.036	0.0333	1	0.75000	0	100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0018	2
name 13	13	0.037	0.0333	1	0.69000	0	100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0018	2
name 14	14	0.042	0.0404	1	0.42000	0	100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0018	2

Wire's matrix resistivity:
R=R0*(1+alpha*T^4)+beta*B=(R@r.t.)/RRR/(1+alpha*4.2^4)*(1+alpha*t^4)+beta*B, T<78K, [Ohm m].

`r.t.` = 293K, R@r.t. = 1.70e-08 Ohm m

The coefficients and the resistivity itself are in SI units.

EN 2:13 PM 10/7/2013

Input. Conductor data base

wire_parameters - Notepad

File Edit Format View Help

Total number of wire brands/types/kinds available presently (the total number of lines in the table given below, with no regard for the columns' titles) :

14

wire/conductor name/brand	wire/conductor brand code	bare wire width (effective diam if round), cm	bare wire height, cm	wire shape code: 0 - rectang. 1 - round	superconductor/ matrix(Cu,bronze, Ta) ratio in bare wire	NbTi or Nb3Sn - ? 0 - NbTi 1 - Nb3Sn
name 1	2	0.130	0.0720	0	0.74000	0
name 2	9	0.043	0.0310	1	0.74000	0
name 3	8	0.044	0.0390	1	0.74000	0
name 4	7	0.048	0.0520	1	0.74000	0
name 5	6	0.062	0.0605	1	0.74000	0
name 6	5	0.075	0.0710	1	0.74000	0
name 7	4	0.070	0.0745	1	0.74000	0
name 8	3	0.080	0.0839	1	0.74000	0
name 9	10	0.050	0.0380	1	0.74000	0
name 10	1	0.074	0.0720	1	0.30000	1
name 11	11	0.045	0.0408	1	0.70000	0
nam2 12	12	0.036	0.0333	1	0.75000	0
name 13	13	0.037	0.0333	1	0.69000	0
name 14	14	0.042	0.0404	1	0.42000	0

Input. Conductor data base

-------- matrix data ---------:			--- AC loss data ----:			
wire matrix RRR effective value	alpha	beta	supercond filament effective diameter, mcm	n-tau effective value, ms	wire insulation thickness, cm	wire insulation brand type: 1 - formvar/PVA 2 - polyimid/kapton 3 - epoxidized glass-cloth (G10)
100.	3.6095e-07	5.2845e-11	6.5	0.01	0.0025	2
100.	3.6095e-07	5.2845e-11	6.7	0.01	0.0017	1
100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0021	1
100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0022	1
100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0022	1
100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0025	1
100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0025	1
100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0025	1
100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0019	2
40.	3.6095e-07	5.2845e-11	3.5	0.01	0.0065	3
100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0018	2
100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0018	2
100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0018	2
100.	3.6095e-07	5.2845e-11	7.0	0.01	0.0018	2

```
 Wire's matrix resistivity:
 R=R0*(1+alpha*T^4)+beta*B=(R@r.t.)/RRR/(1+alpha*4.2^4)*(1+alpha*t^4)+beta*B, T<78K, [Ohm m].

`r.t.` = 293K, R@r.t. = 1.70e-08 Ohm m

 The coefficients and the resistivity itself are in SI units.
```

Input. Conductor data base. Critical current (LTS)

wire_critical_current - Notepad

File Edit Format View Help

```
Critical current density, in A/sq.m, Jc(B,T,e) = C(B)*f(B,T,e), where C(B)=a0+a1*B,                        if  0 < B < B1
(in the superconductors, non-copper Jc)                                  C(B)=b0+b1*B+b2*B^2+b3*B^3+b4*B^4+b5*B^5, if B1 < B < B2
                                                                         C(B)=c0+c1*B,                             if  B > B2
```

wire/conductor name/brand	wire code	B1, T	B2, T	a0	a1	b0	b1	b2
name 1	2	5.	9.	0.73860355E+11	0.	0.43870E+11	-0.05132E+11	0.04135E+11
name 2	9	6.	9.	0.88427519E+11	0.	4.98238E+11	-1.83974E+11	0.27546E+11
name 3	8	3	6.	0.61418111E+11	0.	2.50458E+11	-1.92160E+11	0.68320E+11
name 4	7	5.	9.	0.51343900E+11	0.673182E+10	0.50473E+11	-0.05904E+11	0.04757E+11
name 5	6	5.	8.	0.85067987E+11	0.	0.50529E+11	-0.05911E+11	0.04763E+11
name 6	5	5.9	9.1	0.76095308E+11	0.	2.67039E+11	-0.88398E+11	0.13710E+11
name 7	4	5.	8.5	0.69357831E+11	0.	0.41197E+11	-0.04819E+11	0.03883E+11
name 8	3	6.	9.	0.58395432E+11	0.	-4.29251E+11	2.08925E+11	-0.29861E+11
name 9	10	5.	9.	0.81874859E+11	0.	0.48632E+11	-0.05689E+11	0.04584E+11
name 10	1	10.	13.	2.78227981E+11	0.	9.83624E+11	-2.21951E+11	0.22901E+11
name 11	11	5.	9	0.81874859E+11	0.	0.48632E+11	-0.05689E+11	0.04584E+11
name 12	12	5.	9.	0.81874859E+11	0.	0.48632E+11	-0.05689E+11	0.04584E+11
name 13	13	5.	9.	0.81874859E+11	0.	0.48632E+11	-0.05689E+11	0.04584E+11
name 14	14	5.	9.	0.81874859E+11	0.	0.48632E+11	-0.05689E+11	0.04584E+11

The list of wire brands available can be extended (the number is not limited, practically), but do not change the file format (e.g., do not delete the empty lines or add them, etc.).

The wire codes should be the same as in file `wire_parameters.dat`. Field B is in Testa [T].

For Nb3Sn wires the Twente scaling law is employed in the code. The field dependence of `C`, C=C(B), is not really strong (`C` is assumed to be a constant according to the Twente scaling law), but the dependence is introduced so as to fit better, if not perfectly, the measurements of Ic against B by the wire makers.

Input. Conductor data base. Critical current

wire_critical_current - Notepad

File Edit Format View Help

```
Critical current density, in A/sq.m, Jc(B,T,e) = C(B)*f(B,T,e), where C(B)=a0+a1*B,                         if  0 < B < B1
(in the superconductors, non-copper Jc)                               C(B)=b0+b1*B+b2*B^2+b3*B^3+b4*B^4+b5*B^5, if B1 < B < B2
                                                                      C(B)=c0+c1*B,                             if  B > B2
```

wire/conductor name/brand	wire code	B1, T	B2, T	a0	a1	b0	b1	b2	
name 1	2	5.	9.	0.73860355E+11	0.	0.43870E+11	-0.05132E+11	0.04135E+11	[illegible]
name 2	9	6.	9.	0.88427519E+11	0.	4.98238E+11	-1.83974E+11	0.27546E+11	[illegible]
name 3	8	3	6.	0.61418111E+11	0.	2.50458E+11	-1.92160E+11	0.68320E+11	[illegible]
name 4	7	5.	9.	0.51343900E+11	0.673182E+10	0.50473E+11	-0.05904E+11	0.04757E+11	[illegible]
name 5	6	5.	8.	0.85067987E+11	0.	0.50529E+11	-0.05911E+11	0.04763E+11	[illegible]
name 6	5	5.9	9.1	0.76095308E+11	0.	2.67039E+11	-0.88398E+11	0.13710E+11	[illegible]
name 7	4	5.	8.5	0.69357831E+11	0.	0.41197E+11	-0.04819E+11	0.03883E+11	[illegible]
name 8	3	6.	9.	0.58395432E+11	0.	-4.29251E+11	2.08925E+11	-0.29861E+11	[illegible]
name 9	10	5.	9.	0.81874859E+11	0.	0.48632E+11	-0.05689E+11	0.04584E+11	[illegible]
name 10	1	10.	13.	2.78227981E+11	0.	9.83624E+11	-2.21951E+11	0.22901E+11	[illegible]
name 11	11	5.	9	0.81874859E+11	0.	0.48632E+11	-0.05689E+11	0.04584E+11	[illegible]
name 12	12	5.	9.	0.81874859E+11	0.	0.48632E+11	-0.05689E+11	0.04584E+11	[illegible]
name 13	13	5.	9.	0.81874859E+11	0.	0.48632E+11	-0.05689E+11	0.04584E+11	[illegible]
name 14	14	5.	9.	0.81874859E+11	0.	0.48632E+11	-0.05689E+11	0.04584E+11	[illegible]

The list of wire brands available can be extended (the number is not limited, practically), but do not change the file format (e.g., do not delete the empty lines or add them, etc.).

The wire codes should be the same as in file `wire_parameters.dat`. Field B is in Testa [T].

For Nb3Sn wires the Twente scaling law is employed in the code. The field dependence of `C`, C=C(B), is not really strong (`C` is assumed to be a constant according to the Twente scaling law), but the dependence is introduced so as to fit better, if not perfectly, the measurements of Ic against B by the wire makers.

In the case when an HTS conductor is used, the Ic-dependence is supposed to include that on the magnetic field angle.

Input. A magnet configuration

geometry - Notepad

File Edit Format View Help

total number of coils	total number of electrical sections
17	7

Number of coils in each section of the electrical circuit (only coils with subsequent ordinal numbers can be pieced together in a section):

2 5 2 1 1 1 5

coil #	inner & outer radii: a1, cm	a2, cm	end-planes position: b1,cm	b2,cm	Iop, A	number of turns/coil	number of layers/coil	wire/conductor brand code	winding filler type code: 1- epoxy,2- wax	inter-layer glass-cloth insulation thickness,cm	superposition of pre-strain and thermal & mech. strains due to cooling down, %	effective/ average strain due to Lorentz forces at rated current, %
1	4.05	4.55	-17.0	17.0	100.000	4000	8	1	1	0.	0.018	0.13
2	4.55	5.70	-17.0	17.0	100.000	5000	10	1	1	0.	0.014	0.12
3	5.80	7.00	-16.0	-8.0	100.000	1000	12	2	2	0.01	0.	0.
4	6.00	6.70	-3.5	-2.5	100.000	60	6	2	2	0.	0.	0.
5	6.50	7.00	-1.5	1.5	100.000	90	4	2	2	0.	0.	0.
6	6.50	7.00	3.0	4.0	100.000	60	6	2	2	0.	0.	0.
7	6.00	7.00	8.00	16.00	100.000	1000	13	2	2	0.	0.	0.
8	7.60	8.00	-25.0	25.0	100.000	3000	7	3	2	0.	0.	0.
9	8.01	8.50	-25.0	25.0	100.000	2500	5	4	2	0.	0.	0.
10	8.50	9.50	-25.0	25.0	100.000	11000	20	5	2	0.	0.	0.
11	10.00	11.00	-25.0	25.0	100.000	8000	11	6	2	0.	0.	0.
12	11.02	12.00	-25.0	25.0	100.000	8200	9	7	2	0.	0.	0.
13	12.11	13.00	-12.0	-9.0	100.000	1000	20	8	1	0.	0.	0.
14	12.11	13.00	9.0	12.0	100.000	1000	20	8	1	0.	0.	0.
15	12.11	13.00	-6.0	-4.0	100.000	700	20	8	1	0.	0.	0.
16	12.11	13.00	4.0	6.0	100.000	700	20	8	1	0.	0.	0.
76	13.20	13.00	-26.0	26.0	100.000	12000	20	8	1	0.011	0.	0.

Input. A magnet configuration

geometry - Notepad

File Edit Format View Help

```
total              total number
number             of electrical
of coils           sections

 17                 7

Number of coils in each section of the electrical circuit (only coils with subsequent
ordinal numbers can be pieced together in a section):

 2     5     2     1     1     1     5
```

coil #	a1, cm (inner & outer radii)	a2, cm	b1,cm (end-planes position)	b2,cm	Iop, A	number of turns/coil	number of layers/coil
1	4.05	4.55	-17.0	17.0	100.000	4000	8
2	4.55	5.70	-17.0	17.0	100.000	5000	10
3	5.80	7.00	-16.0	-8.0	100.000	1000	12
4	6.00	6.70	-3.5	-2.5	100.000	60	6
5	6.50	7.00	-1.5	1.5	100.000	90	4
6	6.50	7.00	3.0	4.0	100.000	60	6
7	6.00	7.00	8.00	16.00	100.000	1000	13
8	7.60	8.00	-25.0	25.0	100.000	3000	7
9	8.01	8.50	-25.0	25.0	100.000	2500	5
10	8.50	9.50	-25.0	25.0	100.000	11000	20
11	10.00	11.00	-25.0	25.0	100.000	8000	11
12	11.02	12.00	-25.0	25.0	100.000	8200	9
13	12.11	13.00	-12.0	-9.0	100.000	1000	20
14	12.11	13.00	9.0	12.0	100.000	1000	20
15	12.11	13.00	-6.0	-4.0	100.000	700	20
16	12.11	13.00	4.0	6.0	100.000	700	20
17	13.20	13.00	-26.0	26.0	100.000	12000	20

Input. A magnet configuration

wire/conductor brand code	winding filler type code: 1- epoxy,2- wax	inter-layer glass-cloth insulation thickness,cm	superposition of pre-strain and thermal & mech. strains due to cooling down, %	effective/ average strain due to Lorentz forces at rated current, %
1	1	0.	0.018	0.13
1	1	0.	0.014	0.12
2	2	0.01	0.	0.
2	2	0.	0.	0.
2	2	0.	0.	0.
2	2	0.	0.	0.
2	2	0.	0.	0.
3	2	0.	0.	0.
4	2	0.	0.	0.
5	2	0.	0.	0.
6	2	0.	0.	0.
7	2	0.	0.	0.
8	1	0.	0.	0.
8	1	0.	0.	0.
8	1	0.	0.	0.
8	1	0.	0.	0.
8	1	0.011	0.	0.

Input. A magnet configuration. Inter-coil thermal links, if any.

Inter-coil_thermal_contacts_1 - Notepad

File Edit Format View Help

Inter-coil radial thermal contact management

Here one needs to specify if there is a thermal contact between adjacent coils in the radial direction to be taken into consideration, or not.

Coil #	Contact code with adjacent coil: YES - 1, NO - 0	Inter-coil (additional) insulation thickness, cm	Inter-coil insulation material code: 1 - formvar/PVA, 2 - kapton/polyimid 3 - epoxidized glass-cloth
1	1	0.	2
2	0	0.	2
3	0	0.	3
4	0	0.	3
5	0	0.	3
6	0	0.	3
7	0	0.	3
8	1	0.	3
9	1	0.	3
10	0	0.	3
11	1	0.	3
12	0	0.	3
13	0	0.	3
14	0	0.	3
15	0	0.	3
16	0	0.	3

The coils are assumed to be numbered in order of increasing outer diameter (the innermost coil is coil 1, whereas the outmost coil is assumed to have the largest ordinal number). The numbering in the example (Excel spread sheet) provided is perfect (and unchanged).

Input. Quench protection circuit

quench_protection_circuit - Notepad

File Edit Format View Help

```
Quench protection circuit characteristics:

No PS in service, but its resistance, or a parallel resistance,
or their combination, [Ohm], R0 =

 1.0E-03

                                                     Diode array (if any)
section #     Shunt path          Diode array used   threshold voltage (to open the path)
              resitance, Ohm      NO - 0, YES - 1    (absolute value), Volt

    1           0.50                  0                    0.5
    2           0.50                  0                    0.5
    3           0.1                   0                    0.4
    4           0.1                   0                    0.4
    5           0.1                   0                    0.4
    6           0.1                   0                    0.4
    7           0.1                   0                    0.4
```

There is one more file triggers.dat to specify heaters, if any, their dimensions, locations, delay times, etc.

Input. Quench initiation

quench_initiation_1 - Notepad

File Edit Format View Help

```
Quench is initiated at the following location (a single turn,
360 deg. long, is normalized with the use of a "temperature
disturbance" - "local spontaneous perturbation" at time = 0):

Coil #      Layer #        Turn #          Temperature
                       in the layer        disturbance
                                            value, K

  3           2              78              10.2
```

Input. Output control

solver_and_output_control_1 - Notepad

File Edit Format View Help

```
                          Input for the solver:

Time-step of the numerical scheme, s           Time period of interest        Relative error (tolerance)
(finite-difference implicit-explicit           after the quench starts, s     in solving the circuit equations
method)
     2.0e-05                                         2.0                           1.0e-06


                          Output control:

8 points in time (s) at which the temperature distributions within the coils are supposed to be written to
files `out_temp_#.dat`, in ascending order:

  0.01       0.1       0.2       0.25       0.5      1.0       1.5      1.95
```

Input and further…

After the code reads the input files,

- it will start analysis of the magnet configuration and the windings' structure so as to establish properly the transverse thermal links in the turn-to-turn, layer-to-layer and coil-to-coil directions to simulate the heat diffusion within and between the coils.

- Also, the computational mesh will be created and the magnetic field maps and

- the inductance matrix will be calculated and written to output files,

- and several other output files will be opened to write the solution to them.

Let us start… After the exe-file icon is double-clicked :

C:\Data\OI quench 2\Quench_OI_1.exe

```
The inductance matrices are being calculated...



The inductance computation has been completed.

Three files have been created :

inductance_matrix_coils.dat
inductance_matrix_electric_sections.dat
invserse_inductance_matrix_electric_sections.dat
________________________________________________________________________


 Should the magnetic field within the coils be
 calculated/re-calculated (mapped/re-mapped)?

IF NO (no need, since the field distribution
within all the coils was mapped previously:
files `Br.dat` & `Bz dat`for the given magnet
topology are complete and ready to use),
THEN ENTER `0` .

IF YES (the field map is to be created, it is the very first run),
THEN ENTER `1` :

1
```

Running…

C:\Data\OI quench 2\Quench_OI_1.exe

```
The magnetic field R- and Z-components distributions mapping is in progress ...

It may take some time, up to an hour or so, depending on
the map size and your computer processor capabilities...

The magnetic field mapping has been completed.

 Files `Br.dat` & `Bz dat` have been created so as to be used
in the future for as long as the magnet topology is unchanged.

THE QUENCH SIMULATION IS IN PROGRESS ........
```

Output

After the computation is completed, the code provides info about the output files

Main characteristics of quench:

Out_coil_Tmax.dat	Hot-spot temperature evolution in the coils
Out_coil_current.dat	Coil currents evolution
Out_currsh.dat	Evolution of currents through the shunt resistances/diodes
Out_coil_Bmax.dat	Evolution of maximum field in the coils
Out_coil_Resist.dat	Evolution of each coil Ohmic resistance, if any
Out_coil_Volt_induct.dat	Evolution of inductive voltage across each coil
Out_coil_Volt_resist.dat	Evolution of resistive voltage across each coil
Out_coil_Volt_term.dat	Evolution of terminal voltage across each coil

Temperature distribution in the coils at 8 specified instants of time:

out_temp_**1**.dat, out_temp_**2**.dat, out_temp_**3**.dat, out_temp_**4**.dat, out_temp_**5**.dat, out_temp_**6**.dat, out_temp_**7**.dat, out_temp_**8**.dat

The output files

out_coil_Tmax - Notepad

File Edit Format View Help

Maximum (hot-spot) temperatures in coils, [K], and the absolute maximum location (coil #)

Time, s	#	Tmax_abs	1	2	3	4	
0.0000000E+00	1	4.200000	4.200000	4.200000	4.200000	4.200000	4
3.1999999E-04	1	10.97062	10.97062	4.200000	4.200000	4.200000	4
6.3999998E-04	1	11.70212	11.70212	4.200000	4.200001	4.200000	4
9.5999998E-04	1	12.34556	12.34556	4.200000	4.200004	4.200002	4
1.2800000E-03	1	12.92147	12.92147	4.200001	4.200006	4.200003	4
1.6000000E-03	1	13.44503	13.44503	4.200001	4.200009	4.200004	4
1.9200000E-03	1	13.92656	13.92656	4.200001	4.200012	4.200005	4
2.2399998E-03	1	14.37341	14.37341	4.200002	4.200015	4.200006	4
2.5599999E-03	1	14.79073	14.79073	4.200002	4.200017	4.200008	4
2.8800000E-03	1	15.18356	15.18356	4.200003	4.200020	4.200009	4
3.1999999E-03	1	15.55512	15.55512	4.200003	4.200023	4.200011	4
3.5199998E-03	1	15.90802	15.90802	4.200003	4.200026	4.200013	4
3.8399999E-03	1	16.24438	16.24438	4.200004	4.200028	4.200014	4
4.1600000E-03	1	16.56597	16.56597	4.200004	4.200031	4.200015	4
4.4799997E-03	1	16.87427	16.87427	4.200004	4.200034	4.200016	4
4.7999998E-03	1	17.17054	17.17054	4.200005	4.200036	4.200018	4
5.1199999E-03	1	17.45584	17.45584	4.200005	4.200039	4.200019	4
5.4400000E-03	1	17.73113	17.73113	4.200006	4.200042	4.200021	4
5.7600001E-03	1	17.99721	17.99721	4.200006	4.200044	4.200022	4
6.0799997E-03	1	18.25479	18.25479	4.200006	4.200047	4.200024	4
6.3999998E-03	1	18.50449	18.50449	4.200006	4.200050	4.200025	4
6.7199999E-03	1	18.74689	18.74689	4.200006	4.200052	4.200026	4
7.0399996E-03	1	18.98247	18.98247	4.200007	4.200055	4.200027	4
7.3599997E-03	1	19.21180	19.21180	4.200007	4.200058	4.200028	4
7.6799998E-03	1	19.43561	19.43561	4.200007	4.200062	4.200030	4
7.9999994E-03	1	19.65471	19.65471	4.200008	4.200068	4.200033	4
8.3200000E-03	1	19.86990	19.86990	4.200009	4.200075	4.200036	4
8.6399997E-03	1	20.08144	20.08144	4.200010	4.200084	4.200039	4
8.9599993E-03	1	20.28687	20.28687	4.200011	4.200093	4.200042	4
9.2799999E-03	1	20.48605	20.48605	4.200012	4.200102	4.200045	4
9.5999995E-03	1	20.67945	20.67945	4.200013	4.200111	4.200048	4
9.9200001E-03	1	20.86749	20.86749	4.200014	4.200120	4.200052	4
1.0240000E-02	1	21.05055	21.05055	4.200016	4.200129	4.200055	4
1.0559999E-02	1	21.22899	21.22899	4.200016	4.200138	4.200058	4
1.0880000E-02	1	21.40312	21.40312	4.200017	4.200147	4.200061	4
1.1200000E-02	1	21.57321	21.57321	4.200018	4.200155	4.200065	4

The output files

Out_coil_Volt_resist - Notepad

File Edit Format View Help

Resistive voltages, I x R, in coils, Volts

Time, s	1	2	3	4	5	6
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.00
3.1999999E-04	0.2749637	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
6.3999998E-04	0.2751265	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
9.5999998E-04	0.2752969	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
1.2800000E-03	0.2754730	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
1.6000000E-03	0.2756542	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
1.9200000E-03	0.2758399	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
2.2399998E-03	0.2760297	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
2.5599999E-03	0.2762231	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
2.8800000E-03	0.2764200	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
3.1999999E-03	0.2766205	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
3.5199998E-03	0.2768243	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
3.8399999E-03	0.2770312	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
4.1600000E-03	0.2772411	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
4.4799997E-03	0.2774537	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
4.7999998E-03	0.2776690	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
5.1199999E-03	0.2778869	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
5.4400000E-03	0.2781072	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
5.7600001E-03	0.2783298	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
6.0799997E-03	0.2785546	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
6.3999998E-03	0.2787815	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
6.7199999E-03	0.2790104	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
7.0399996E-03	0.3717583	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
7.3599997E-03	0.5550382	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
7.6799998E-03	0.5552970	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
7.9999994E-03	0.7406160	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
8.3200000E-03	0.7409517	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
8.6399997E-03	0.7413507	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
8.9599993E-03	0.7418195	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
9.2799999E-03	0.7423478	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
9.5999995E-03	0.7429160	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000
9.9200001E-03	0.7435024	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.000

The output files

out_temp_8 - Notepad

File Edit Format View Help

Time = 1.95001995073835 sec

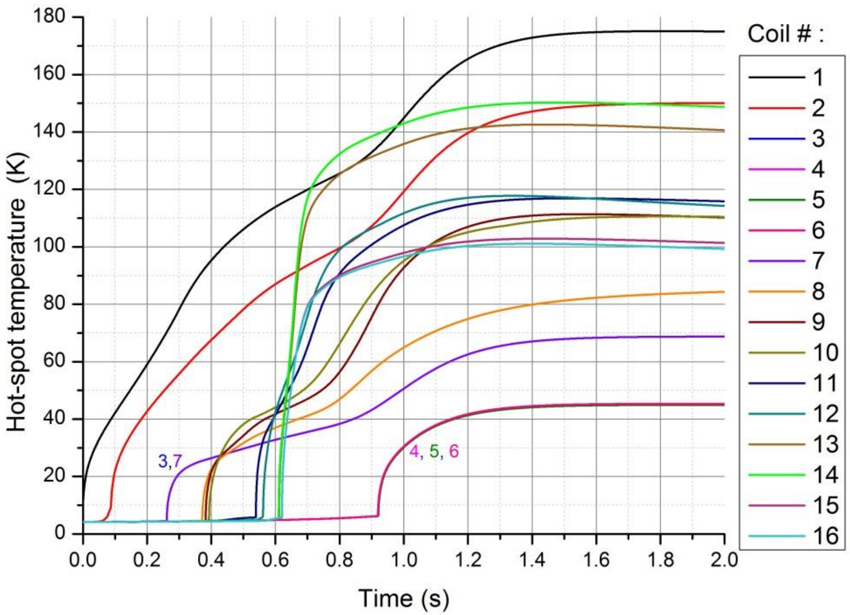
Instantaneous temperature distributions in the coils :

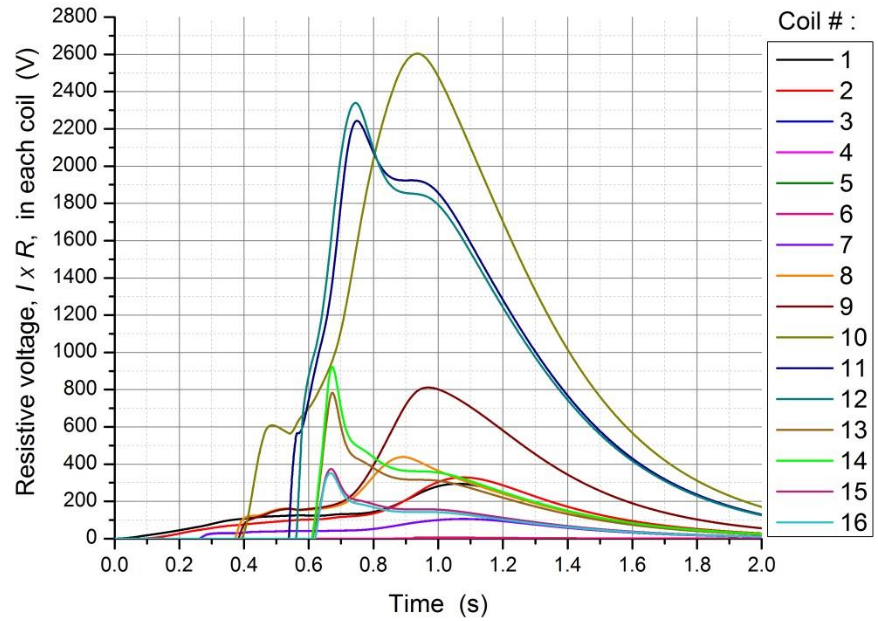
Each column presents the temperature distribution within a given layer.
The number of columns equals the number of layers in a given coil.
The first (at the left) column corresponds to the first (innermost) layer of the coil.
The last (at the right) column corresponds to the outmost layer of the coil.

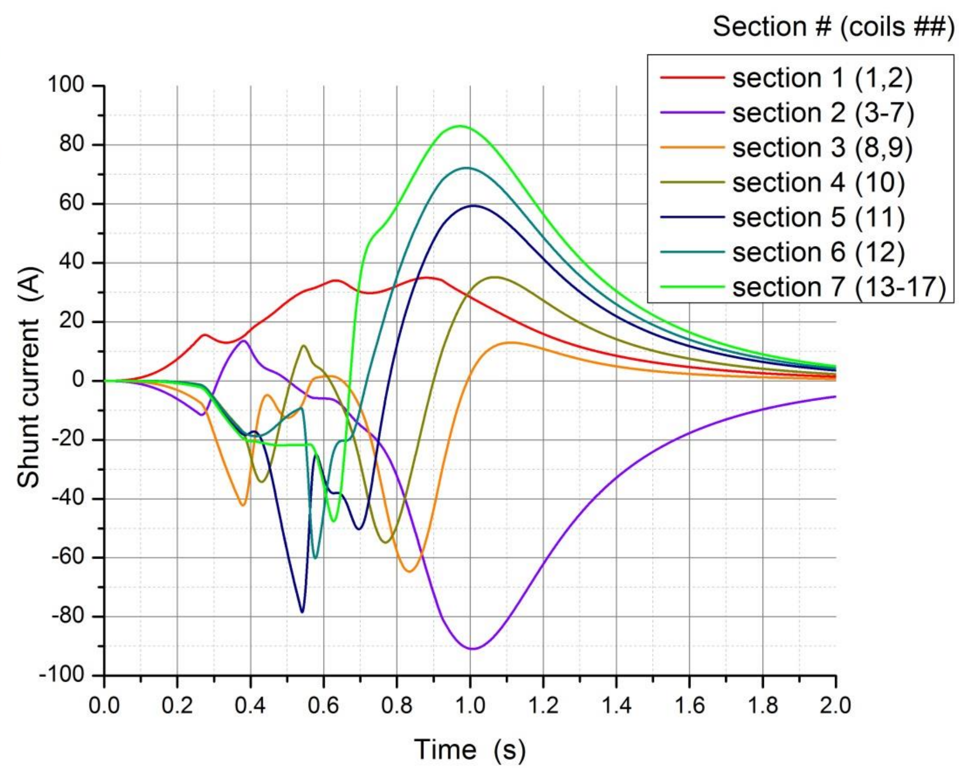
Coil # 1 8 layers 378 turns/layer :

6.842089	6.841757	6.841190	6.840486	6.839739	6.839047	6.838503	6.838191
6.842089	6.841757	6.841190	6.840486	6.839739	6.839047	6.838503	6.838191
6.842656	6.842318	6.841740	6.841022	6.840262	6.839560	6.839005	6.838688
6.843717	6.843369	6.842775	6.842039	6.841259	6.840538	6.839970	6.839643
6.845206	6.844848	6.844237	6.843479	6.842677	6.841934	6.841348	6.841010
6.847064	6.846696	6.846068	6.845288	6.844461	6.843696	6.843092	6.842744
6.849236	6.848858	6.848213	6.847411	6.846562	6.845775	6.845153	6.844794
6.851669	6.851282	6.850621	6.849800	6.848928	6.848120	6.847482	6.847114
6.854315	6.853920	6.853245	6.852405	6.851513	6.850686	6.850032	6.849656
6.857127	6.856729	6.856040	6.855183	6.854273	6.853429	6.852762	6.852377
6.860065	6.859663	6.858966	6.858093	6.857168	6.856308	6.855628	6.855238
6.863098	6.862690	6.861987	6.861101	6.860161	6.859288	6.858597	6.858200
6.866194	6.865781	6.865072	6.864175	6.863222	6.862337	6.861636	6.861233
6.869327	6.868910	6.868194	6.867286	6.866322	6.865426	6.864717	6.864309
6.872474	6.872052	6.871330	6.870413	6.869439	6.868533	6.867817	6.867405
6.875616	6.875192	6.874462	6.873537	6.872554	6.871640	6.870917	6.870501
6.878739	6.878312	6.877575	6.876643	6.875652	6.874731	6.874002	6.873583
6.881831	6.881401	6.880657	6.879719	6.878721	6.877794	6.877060	6.876638
6.884883	6.884451	6.883698	6.882755	6.881752	6.880819	6.880081	6.879656
6.887888	6.887451	6.886693	6.885744	6.884737	6.883799	6.883057	6.882628
6.890839	6.890396	6.889634	6.888681	6.887670	6.886728	6.885982	6.885552
6.893729	6.893284	6.892519	6.891563	6.890547	6.889601	6.888852	6.888420
6.896560	6.896113	6.895346	6.894386	6.893366	6.892417	6.891665	6.891232
6.899330	6.898882	6.898112	6.897150	6.896127	6.895174	6.894420	6.893985
6.902039	6.901589	6.900818	6.899853	6.898827	6.897871	6.897115	6.896678
6.904687	6.904236	6.903463	6.902495	6.901466	6.900509	6.899750	6.899312
6.907274	6.906823	6.906048	6.905078	6.904046	6.903086	6.902325	6.901885
6.909802	6.909350	6.908574	6.907601	6.906568	6.905605	6.904841	6.904394
6.912272	6.911819	6.911041	6.910068	6.909032	6.908067	6.907296	6.906848
6.914686	6.914232	6.913453	6.912477	6.911439	6.910472	6.909694	6.909245
6.917044	6.916590	6.915809	6.914831	6.913792	6.912818	6.912038	6.911589

The output visualization







Further development and computational time

1. New features can be added on request, such as
   - Quench back
   - Non-coaxial coils
   - Non-solenoidal windings
   - Multi-PS circuits

2. Materials data base is to be extended (more types of insulation)

3. Even more general electric circuit.

4. …….

Philosophy: A family of the code versions with different features may turn out to be preferable to a single extremely general version including all thinkable features.

Computational time: ~4 hours for a big magnet consisting of 10-20 coils/sections if an up-to-date workstation is employed. Seems to be long… But! On a multi-core processor PC ~10-20 runs in parallel are possible.

Summary

A fully automated version of the quench code has been created and verified.

It is used presently for a quench analysis at the NHMFL and not only.

Feedback is very welcome... right now

THANK YOU.