Quench calculations of the CBM magnet

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November, 2019

Outline

- Stability questions
- Quench parameters
- Quench calculations in BINP
- Comparisons TDR and BINP calculations
- Conclusions

Quench parameters

- Stored energy – 5 MJ
- Inductance – 21 H
- Current – 686 A
- Cold mass of one coil – 1800 kg
- Cold mass of one winding – 790 kg
- E/M ratio for two windings – 3.2 kJ/kg
- SC wire parameters – high Cu/SC ratio and Iop/Icr on the load line ~ 57%

Main parameters of the magnet

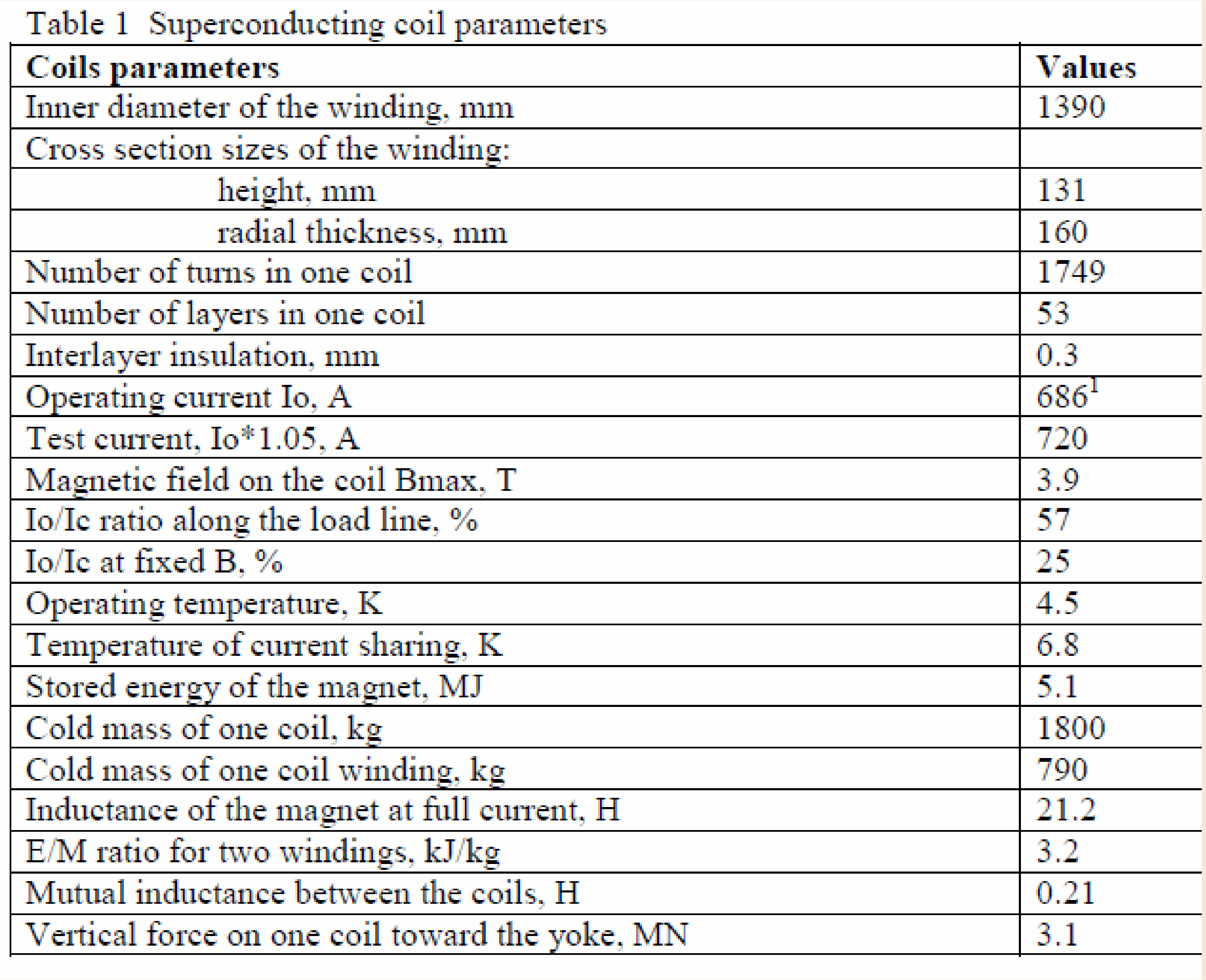


Table 1 Superconducting coil parameters

Coils parameters	**Values**
Inner diameter of the winding, mm	1390
Cross section sizes of the winding:	
height, mm	131
radial thickness, mm	160
Number of turns in one coil	1749
Number of layers in one coil	53
Interlayer insulation, mm	0.3
Operating current Io, A	686[1]
Test current, Io*1.05, A	720
Magnetic field on the coil Bmax, T	3.9
Io/Ic ratio along the load line, %	57
Io/Ic at fixed B, %	25
Operating temperature, K	4.5
Temperature of current sharing, K	6.8
Stored energy of the magnet, MJ	5.1
Cold mass of one coil, kg	1800
Cold mass of one coil winding, kg	790
Inductance of the magnet at full current, H	21.2
E/M ratio for two windings, kJ/kg	3.2
Mutual inductance between the coils, H	0.21
Vertical force on one coil toward the yoke, MN	3.1

Stability of the superconducting winding

Stability parameters are

The minimal length of the normal zone propagation in a SC wire is

$$L = \sqrt{\frac{2\lambda(T_c - T_o)}{\rho J_c^2}},$$

, where λ - thermal conductivity coefficient of the copper matrix, ρ - electrical resistivity of the copper, Jc – current density, Tc and To – critical and operation temperature of the wire.

= **0.073 m**.

Minimal energy for the normal zone propagation:

$$E = C\gamma A T_{av}\sqrt{\frac{2\lambda(T_c - T_o)}{\rho J_c^2}},$$

, where Cγ - heat capacity [J/(kg*K)], A – cross-section area of the wire, Tav – average temperature of the temperature rise.

= **7.9 mJ**.

Uniform dissipation energy in one winding

The uniform dissipation of the stored energy in one coil is described in the TDR [1] that is according the current design of the CBM magnet. Heat exchange between the winding and the stainless steel case was not counted. In this case we have:

- E/M ratio is about 6.5 kJ/kg;
- coil temperature after such uniform quench will be about 90 K;
- resistance of one winding after such quench is about 4 Ohm;
- characteristic time of the current decay is about 10 s (L/R);
- the estimated voltage inside the winding, relating the case when a quench started inside the coils (non-uniform quench), is about 0.7 kV;
- the thickness of interlayer insulation is about 0.9 mm, including 0.2 mm of Kapton tape. The breaking voltage of Kapton tape is ~ 20 kV. Neglecting breaking voltage of the rest insulation, we have safety factor at least 20/0.7 = 29 for the breaking voltage.

Quench calculations in BINP

Main quench calculations were described in the TDR performed by the team from Joint Institute of Dubna and the team from CIEMAT.

These estimations were performed at the following conditions:

a) the Matlab code was used for this purpose. The current-inductance dependence is presented on the Fig. which was taken from the TDR works;

b) the equations for the two coupled circuits were calculated in this code which are, see Fig. below:

c) the starting conditions for solving these equations were the 10 K for the one coil while the other stayed cool and the 40 K for hot wire for the hot-spot calculations. The validity of these conditions is described below.

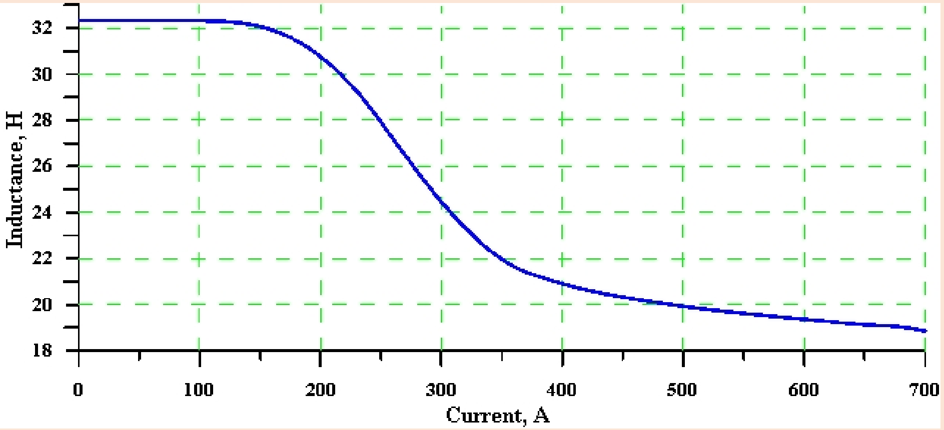
d) while the L1 inductance is dependent of the current the L2 and M inductances should also has some dependence on the current due to presence of the iron yoke. Though in the calculations the fixed values of the latter inductance were used such as L2 = 1.09*10^{-5} H and M = 1.2*10^{-2} H.

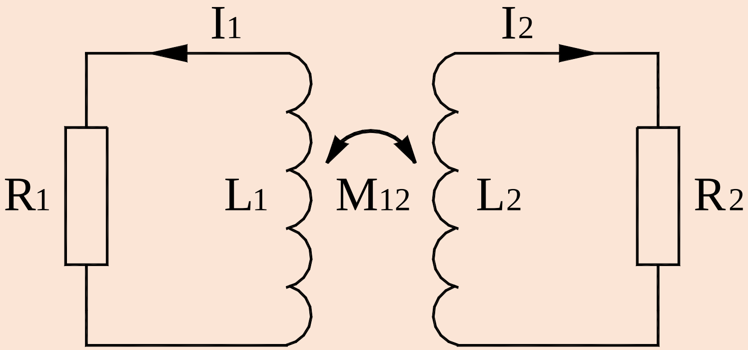
e) the R2(T) resistance of the copper cases was dependent on the temperature. This resistance changes its value from ~ 10^{-7} Ω to 5*10^{-6} Ω during a quench.

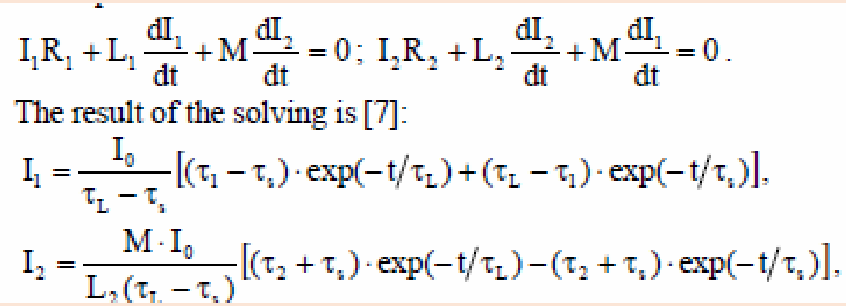
f) The estimated inductance of one pole with ANSYS is about 7*10-7 H. The estimated resistance at ρ = 8.6*10-8 Ω*m at 273 K for iron is about R = 6.4*10-7 Ω. Anyway the poles were not included in the calculations to escape more complexity. They will make benign effect on the quench behavior characteristics: on voltage, hot-spot temperature and as external energy extractors.

g) quench-back effect was not accounted.

h) RRR of the wire was 100, while the real wire should have > 100.







$$I_1R_1 + L_1\frac{dI_1}{dt} + M\frac{dI_2}{dt} = 0;\; I_2R_2 + L_2\frac{dI_2}{dt} + M\frac{dI_1}{dt} = 0.$$

The result of the solving is [7]:

$$I_1 = \frac{I_0}{\tau_L - \tau_s}\left[(\tau_1 - \tau_s)\cdot\exp(-t/\tau_L) + (\tau_L - \tau_1)\cdot\exp(-t/\tau_s)\right],$$

$$I_2 = \frac{M\cdot I_0}{L_2(\tau_L - \tau_s)}\left[(\tau_2 + \tau_s)\cdot\exp(-t/\tau_L) - (\tau_2 + \tau_s)\cdot\exp(-t/\tau_s)\right],$$

Normal zone propagation

The velocity of the normal zone propagation along the wire

$v_a = \frac{J_e}{\rho C} \sqrt{\frac{L_0 \cdot T_s}{T_c - T_s}}$ **will take about 0.67 s for the normal zone to go around one turn of the coil**

v ~ 7.3 m/s

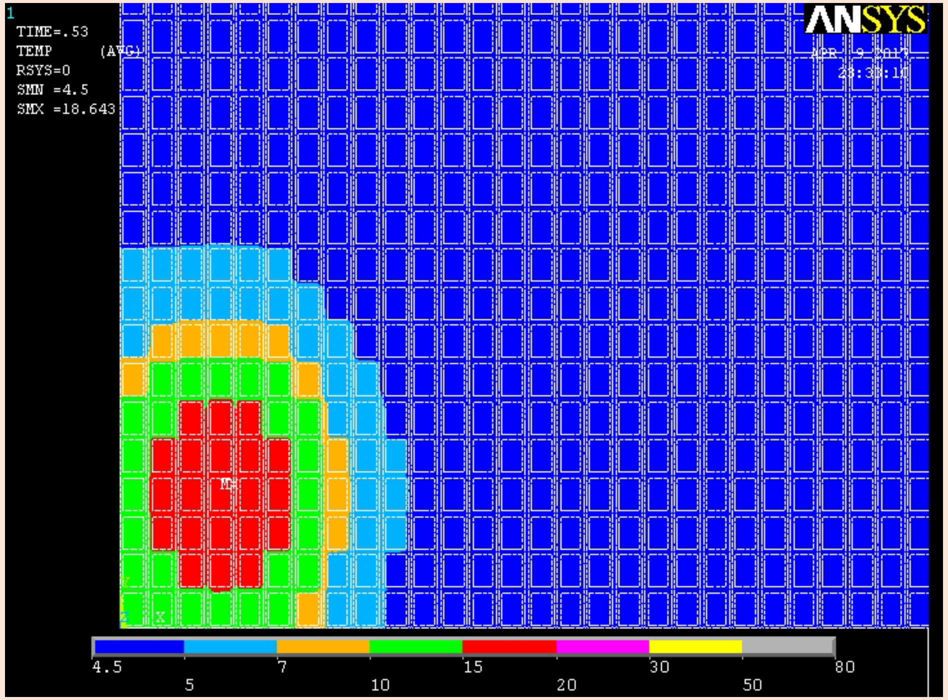
The transverse velocity of the normal zone propagation

was calculated in ANSYS 2D

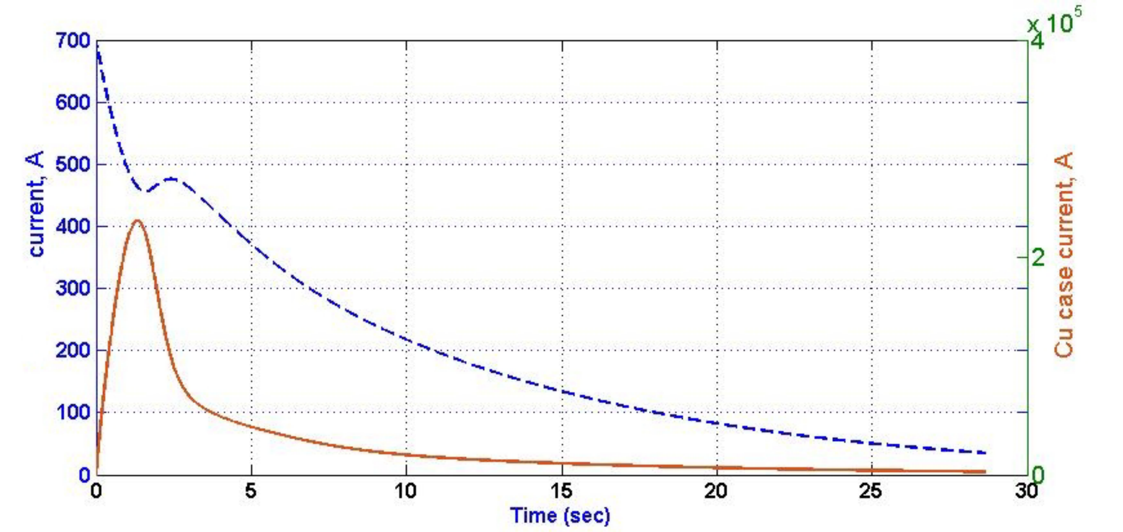
v ~ 0.05 m/s - too slow due to thick layer of insulation

As a positive moment from this - another coil will be quenched by

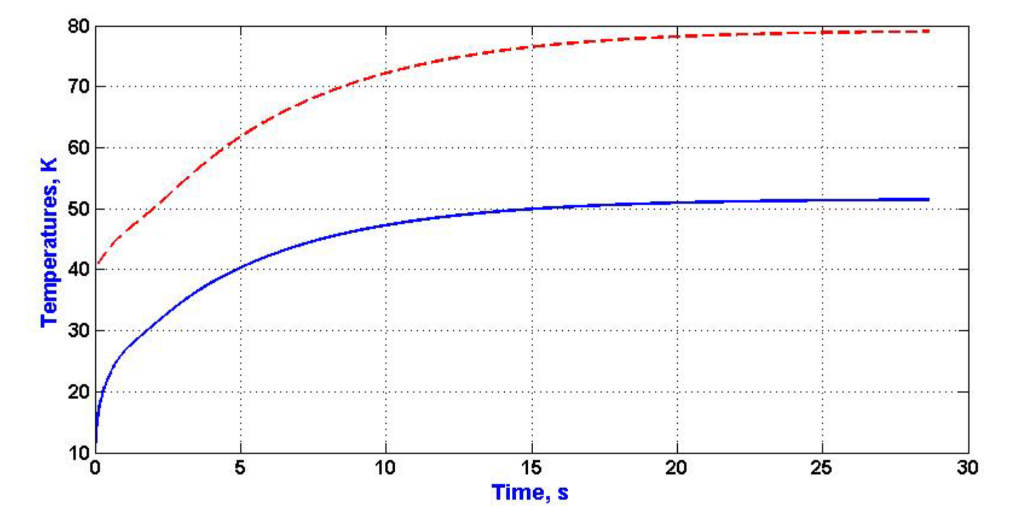
decreased heat transfer to helium.



Quench with dump resistor, R_d = 2.1 Ohm



The currents behavior during the quench with the dump resistor. The blue is for the magnet, the red is for the copper case, maximal value is ~ 0.22 MA only (2 MA – total current)! The resistive voltage is 250 V.



The blue line is for the magnet, the red line is for the hot-spot temperature. It assumed that the dump resistor was switched on after 3 s.

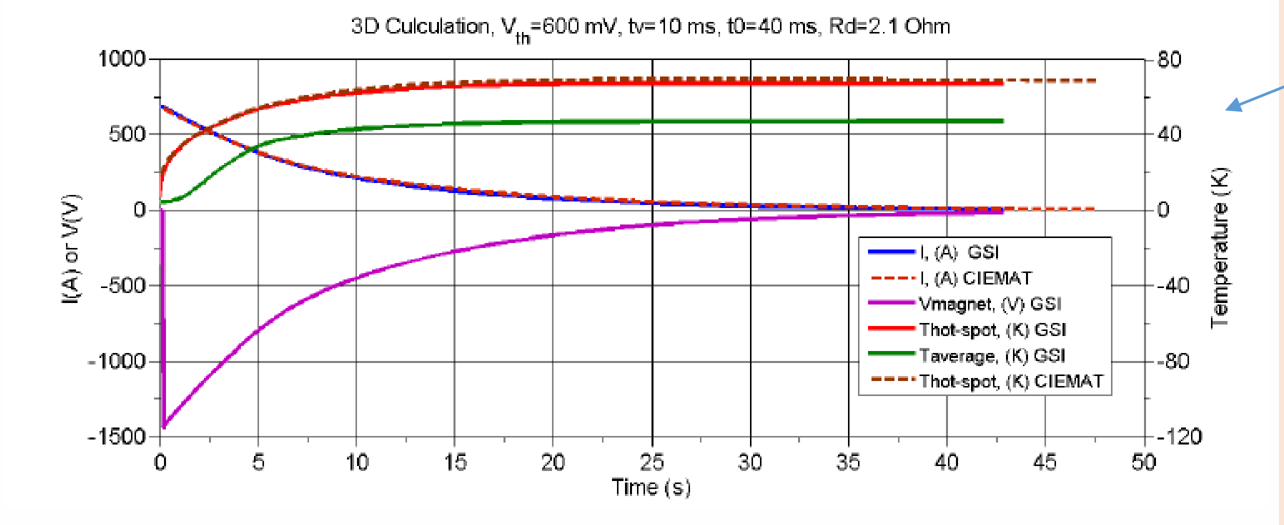


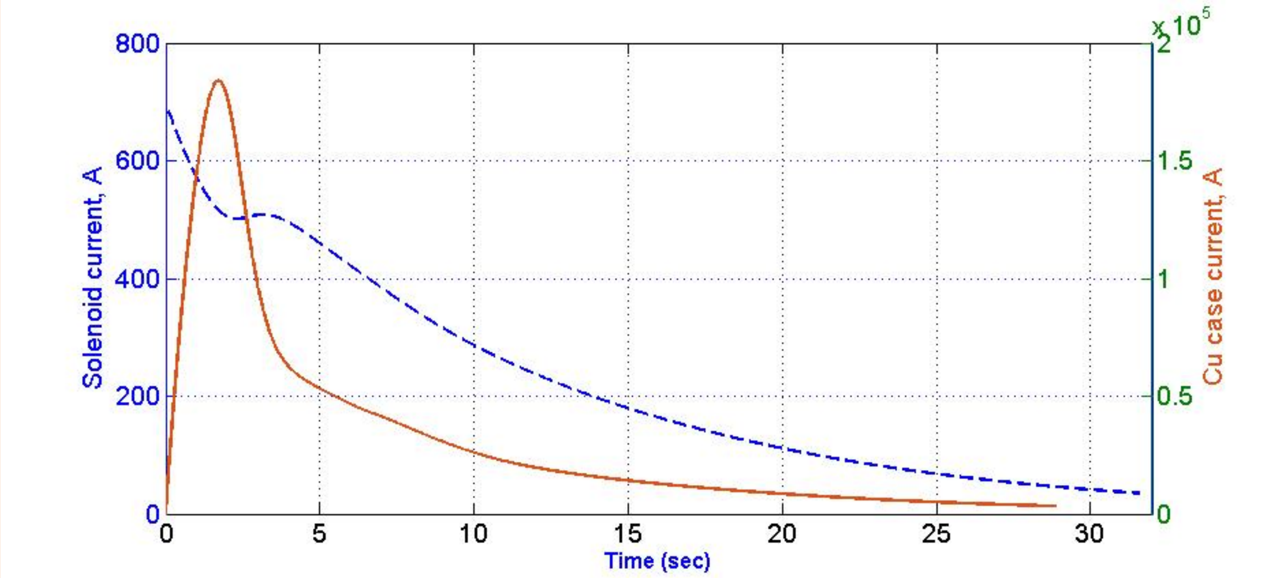
Figure 34. 3D quench calculation of the CBM dipole - magnet current, magnet voltage and the maximum (hot spot) coil temperature

The TDR calculations

Conclusion:

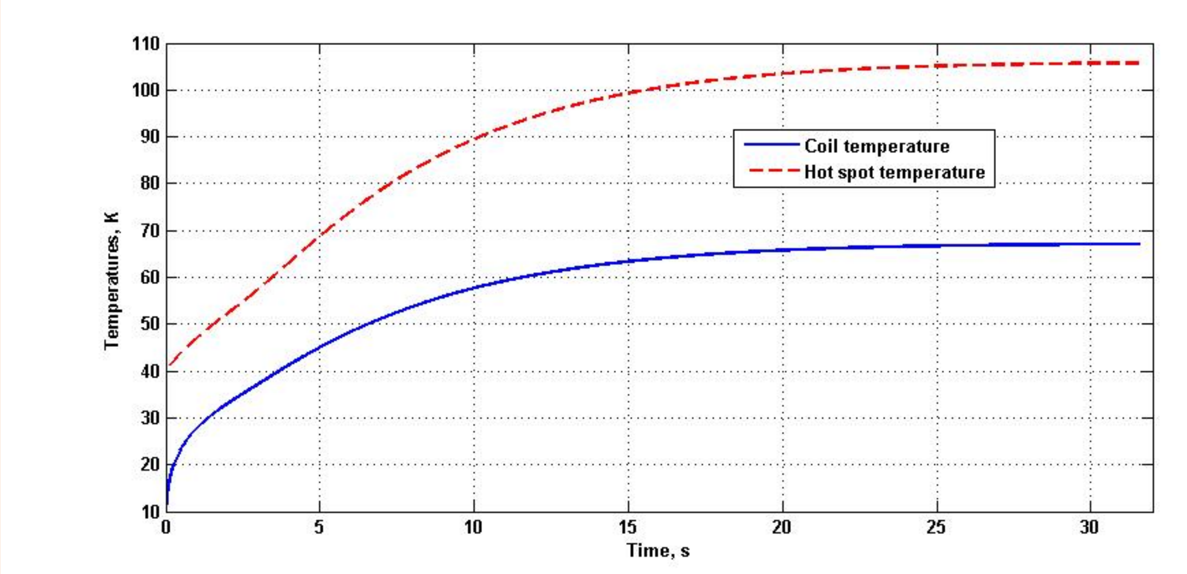
The results of the two calculations are close.

Quench with dump resistor, R_d = 1.0 Ohm - taken as design parameter!



The currents behavior during the quench with the dump resistor. The blue is for the magnet, the red is for the copper case, maximal value is ~ 0.18 MA only! Total current is 2 MA.

The resistive voltage is 472 V.



The blue line is for the magnet, the red line is for the hot-spot temperature. It assumed that the dump resistor was switched on after 3 s.

The magnet and the hot spot temperatures are about 68 K and 106 K respectively.

The energy extracted by the dump resistor is 2.53 MJ that is ~ 50% of the stored energy.

1. Quench of the short circuited magnet, $R_d = 0$

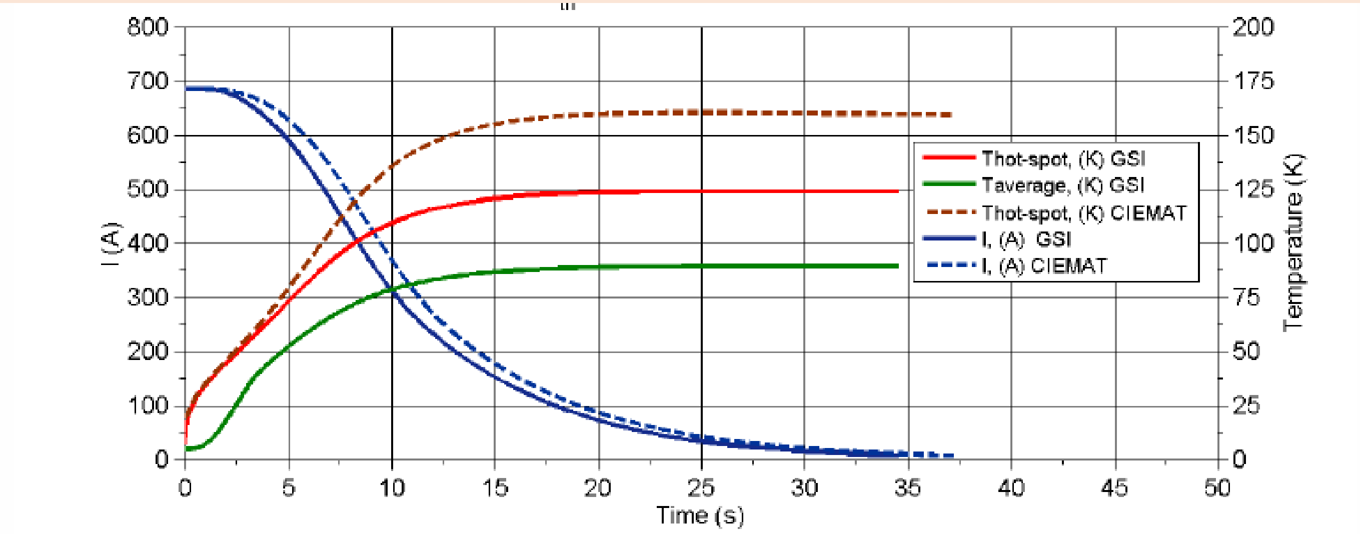
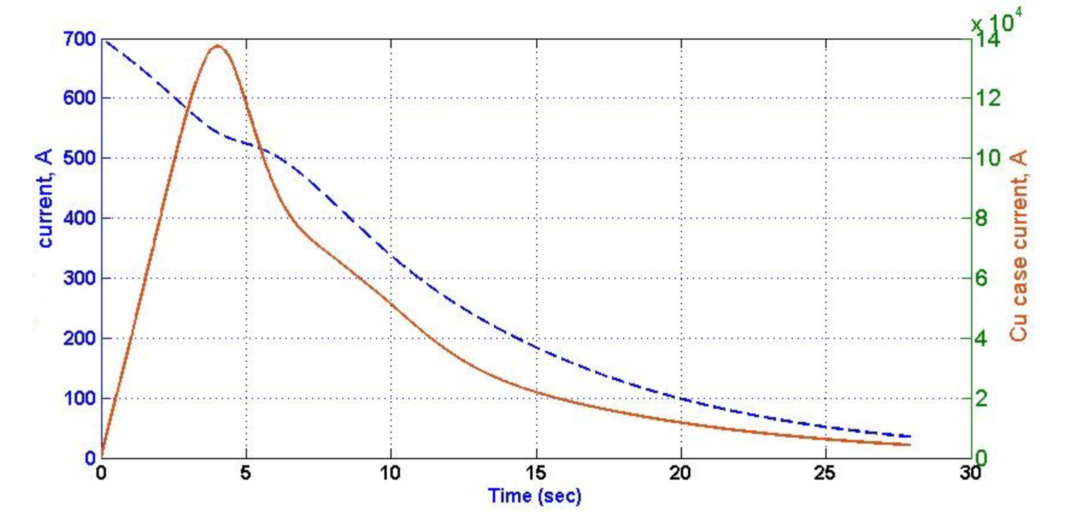


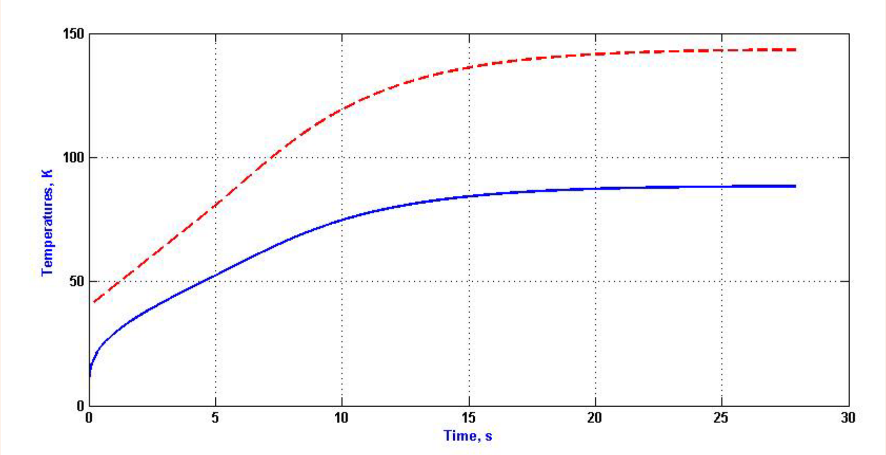
Figure 32. 3D quench calculation of the CBM dipole - the magnet current, hot-spot temperature and the average coil temperature.

TDR calculations.

The current and the hot spot temperatures are presented here.

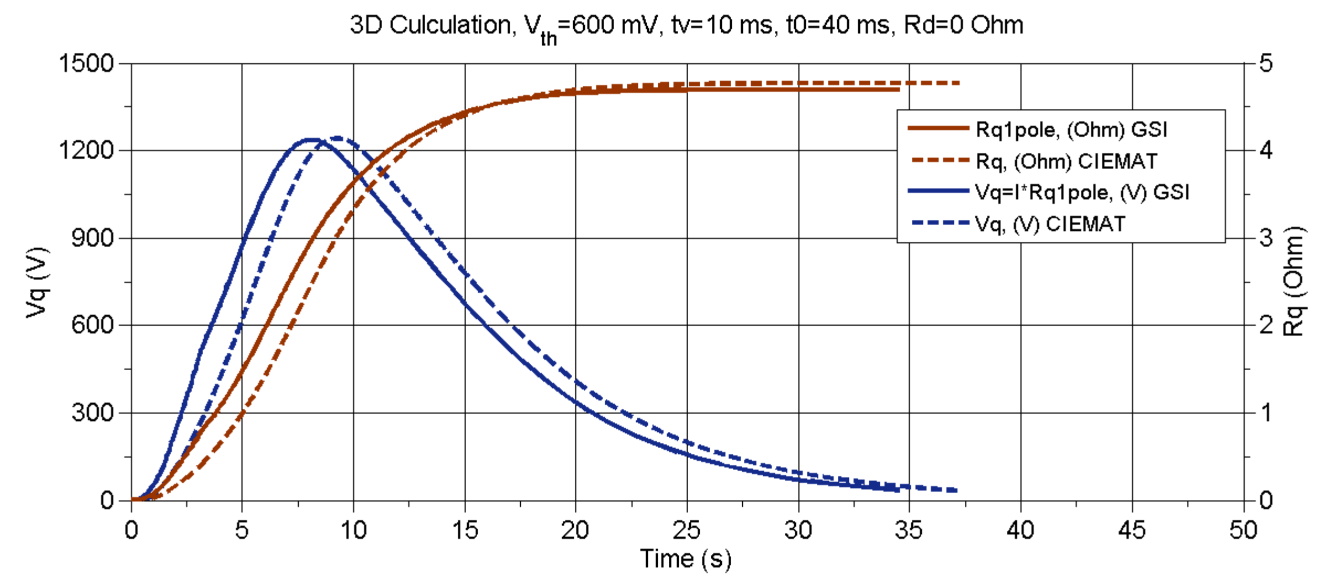


The blue line is the magnet current, the red line is the copper case current. Its maximal value is **0.14 MA only**.



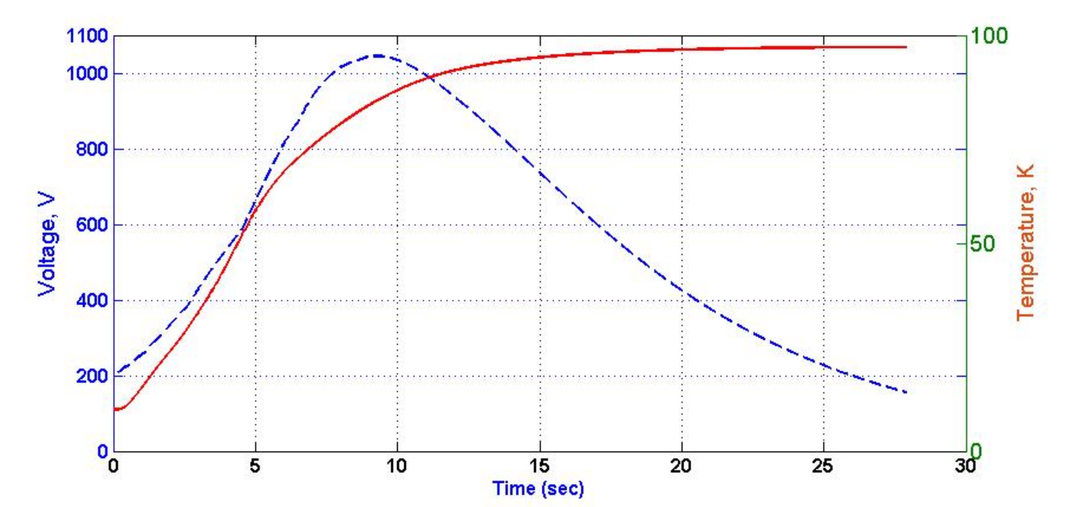
The hot spot temperature

2. Quench of the short circuited magnet, $R_d = 0$



TDR calculations.

The voltage and coil resistance are presented here.

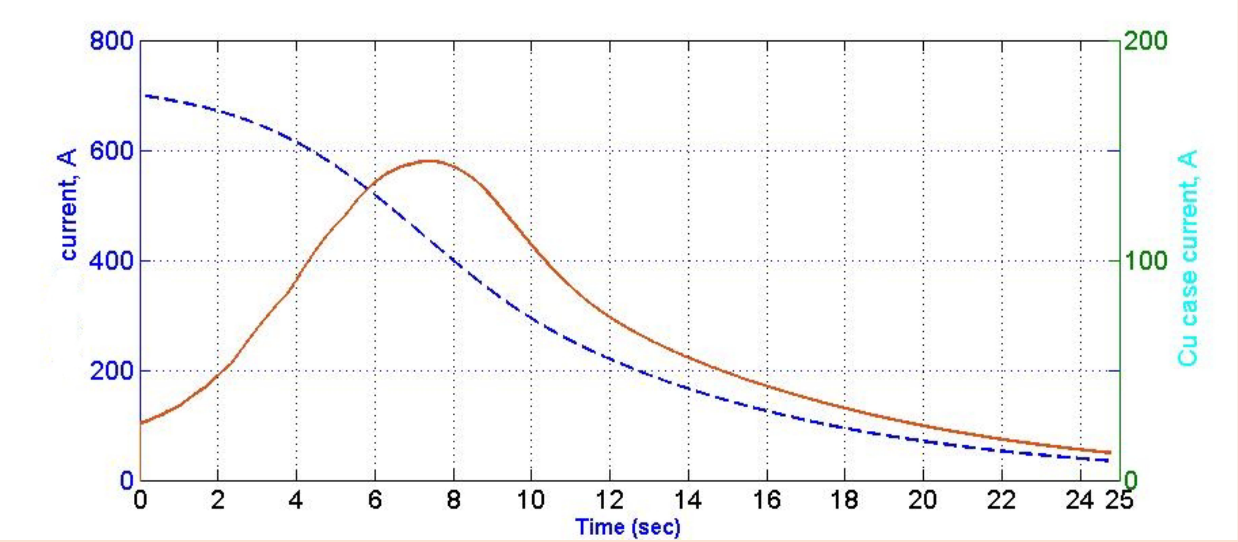


TDR calculations.

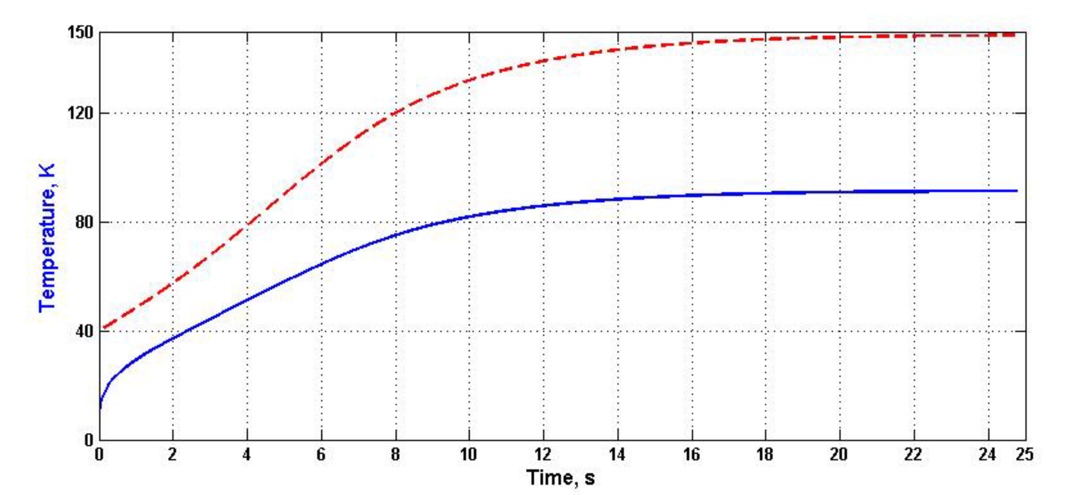
The voltage and quenched coil temperature are presented here.

The maximal resistive voltage here is ~ 1050 V.

Quench of the short circuited magnet, Rd = 0, R_2 >> 10-7 Ω



The currents behavior during the quench of the short-circuited magnet and with R_2 >> 10-7 Ω than R for the copper case.



The temperatures behavior during the quench of the short-circuited magnet and with high R2 value.

The blue line is for the magnet, the red line is for the hot-spot temperature.

The maximal resistive voltage here is 1242 V.

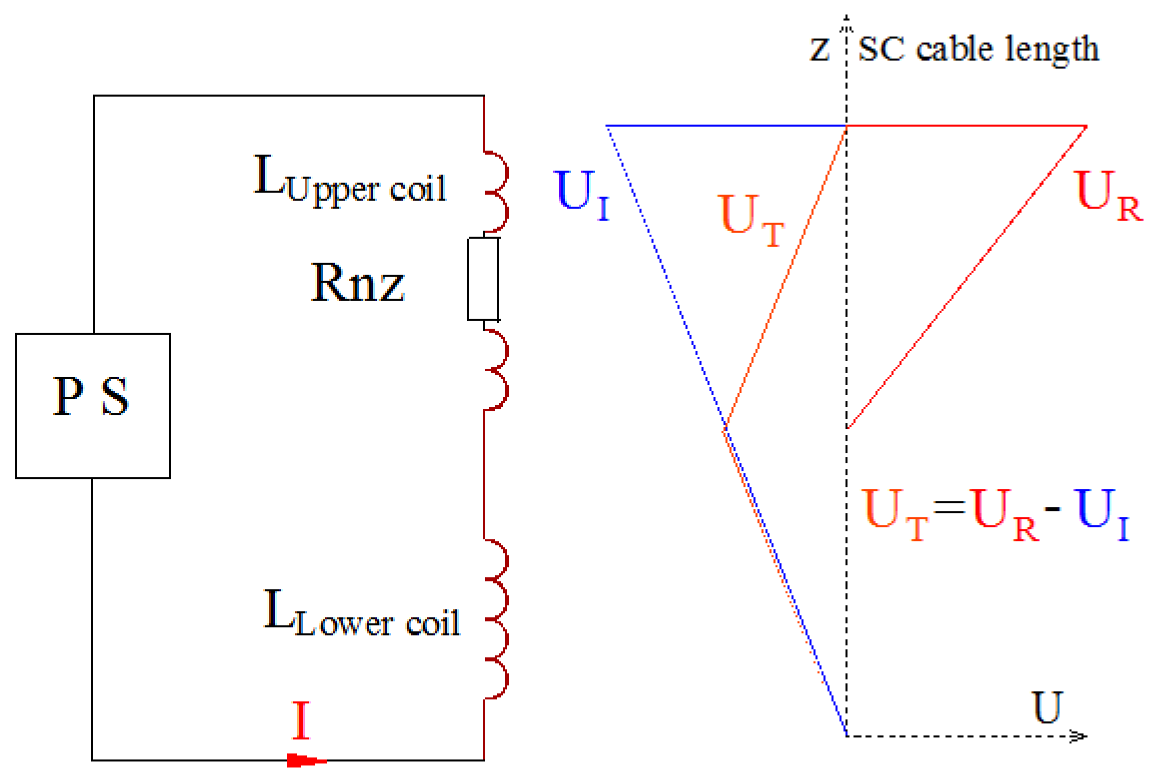
Total voltage in the winding

The total voltage (between the SC winding and ground) can be evaluated as shown in this figure.

The inductive voltage is distributed uniformly between two coils, so the total voltage is twice less than resistive voltage.

$U_{total} = U_{resistive}/2$

At R_{dump} = 1 Ohm, U_{total} = 472/2 = 236 V.



Bus bars protection

The bus bar longest length is 5 m (between one current lead and the lower coil).

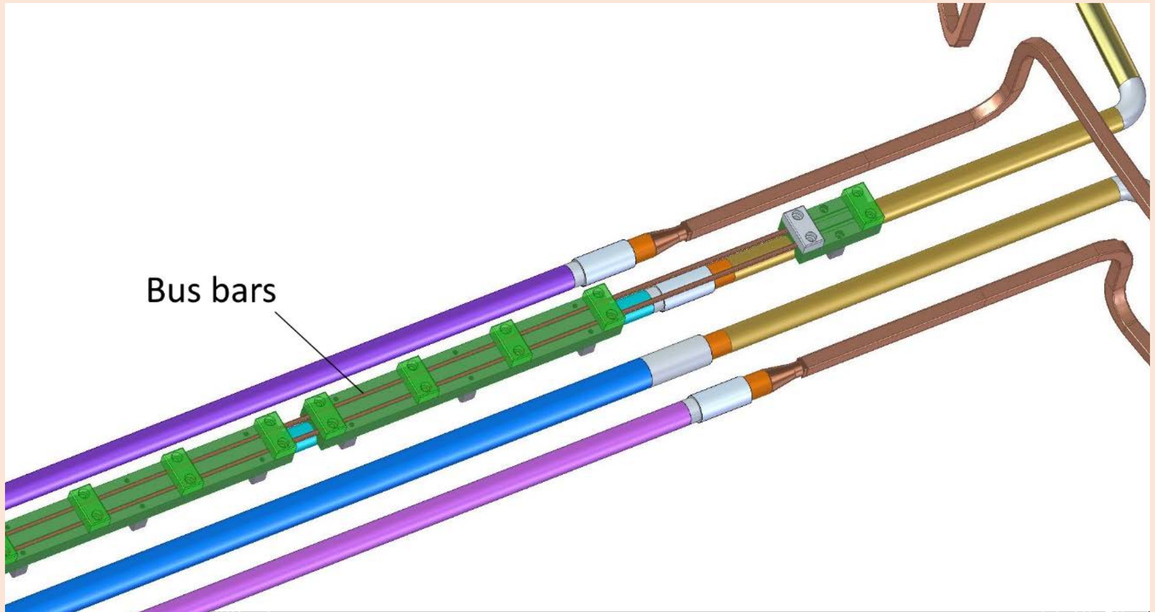
The bus bar may be normal by the following reasons:

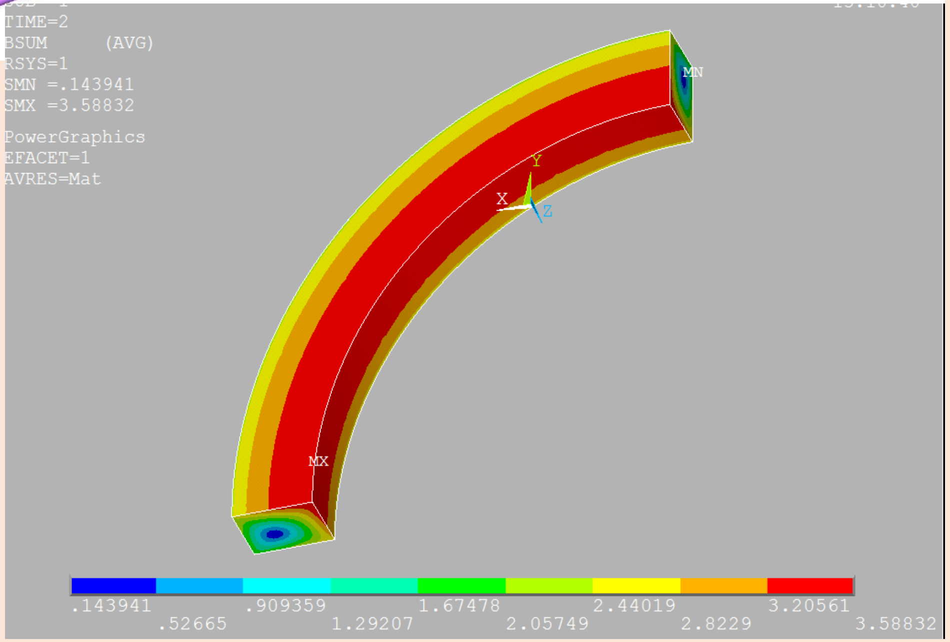
- gas condensate drops (most probable reason).
- external friction movements (due to helium pressure changes is unclear)
- Internal friction movement (Lorentz force is 5 N/m between the bus bars and up to 2 kN/m from 3T field by the coil)
- assembling faults

In case of no active protection, the hot spot will be on this bus bar, so the total time of the current decay should be increased by 5/7 = 0.7 s. The characteristic time of the current decay is ~ 10 s and + 3 s for heating. So, there is no problem here.

Conclusions:

1. **Rigid fixation of the bus bars by the coil is important.**
2. **Careful assembling.**
3. **No problems there during a quench.**





Current leads protection

The current leads need protection – parallel shunt resistor of brass.

The resistance of the shunt is $R_{sh} = \rho*L/S$, $R = 3.2*10^{-8}*0.3/2.25*10^{-5} = 4.3*10^{-4}$ Ohm. This resistance should be much lower than the resistance of the HTS current lead in a normal state.

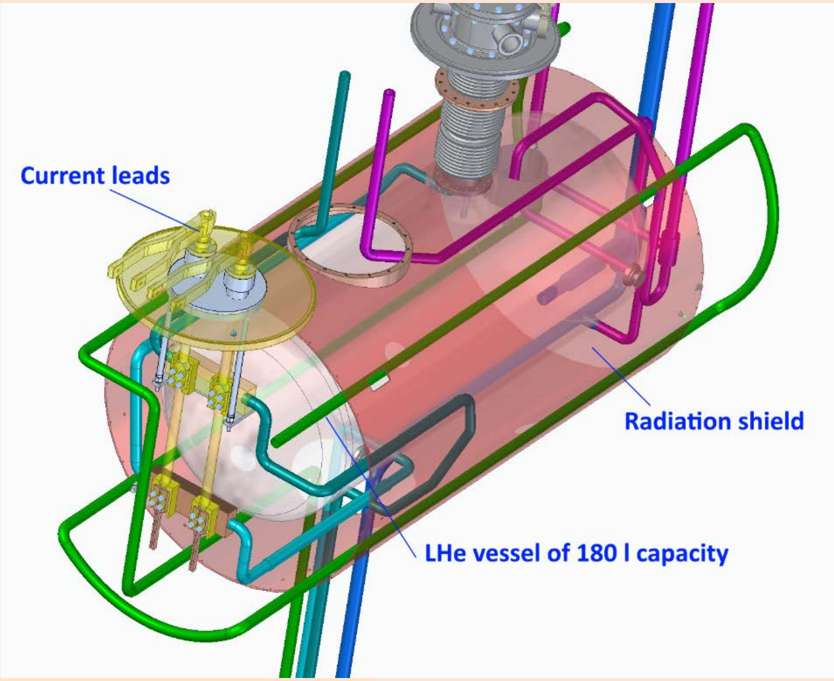
In a worst quench case, the normal zone will appear on the current lead, then is goes to the magnet to make it normal. The velocity of the normal zone propagation is ~ 7 m/s, the characteristic time of the current decay is ~ 14 s, so the total time of the current decay in the shunt is t = 3 m/ 7 (m/s) + 14/2 = 7.4 s. The energy dissipated in the shunt is:

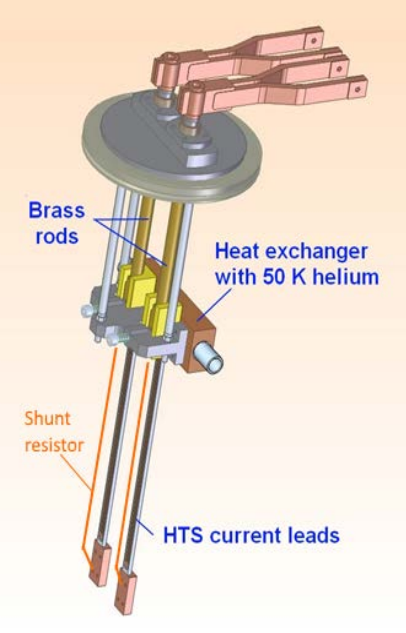
$E = I^2*R_{sh}*t = 700^2*4.3*10^{-4}*7.4 = 1.56$ kJ.

The volume of the shunt is $V = 0.3*2.25*10^{-5}= 6.75*10^{-6}$ m^3.

The volumetric enthalpy of the shunt is $2.3*10^5$ kJ/m^3 that corresponds to ~ 120 K temperature. **So, the chosen parameters of the brass shunt are satisfying.**

The shunt resistor gives additional 0.156 W power to helium, to be compared with 0.212 W from the current leads itself. So, the total heat load will be 0.37 W to 4.5 K temperature surfaces.





More probably is the normal zone on the bus bar will heat the current lead to critical temperature ~ 77 K.

Shunt sizes LxWxT:
300 mm
15 mm (11 mm)
1.5 mm (2 mm)

Results

- These estimations considered energy dissipation in one winding only. In the current design the normal zone will reach the other winding.
- In ordinary conditions the most part of the stored energy will be extracted on the dump resistor of 1 Ohm. The average temperature in the quenched coil will be ~ 68 K. The hot-spot temperature will be well below 106 K.
- The maximal voltage will be between two coils.
- The calculations of the short-circuited magnet shows the hot-spot temperature about 150 K and the internal voltage around 600 V.
- The copper cases of the coils have some influence on the quench but not high. The resistance of the copper cases changes by ~ 14 times during a quench. The cylindrical iron poles will also affect the quench behavior but less than the copper cases.
- In total the CBM magnet coils looks protected from quench effects. Attention should be paid to bus bars insulations especially in the cold mass zone.
- The bus bars and HTS current leads protection was considered.