Quench estimations of the CBM magnet

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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 ~ 52%

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.

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

Minimal energy for the normal zone propagation:

, 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 1.3 kV;
- the thickness of interlayer insulation is about 0.9 mm, assuming breaking voltage for insulation of 10 kV/mm2 – among the lowest values, we have safety factor at least 9/1.3 = 7 for the breaking voltage

Hot spot temperature estimation

The current goes only through the copper matrix which resistance is of three orders lower than resistance of the superconductor. In adiabatic condition the current going through it generates Joule heating:

$$\rho(T)\frac{\Delta l}{S_{Cu}} \cdot I^2(t)dt = \Delta l \cdot S \cdot \gamma \cdot C_p(T)dT \,,$$

$$U(T) = \int_{4.2}^{T_{max}} \frac{\gamma C_p(T)dT}{\rho(T)} = \frac{S_{Cu}}{S} \cdot J_0^2(t) \cdot \Delta t \,,$$

The Δt time may be considered as sum of $\tau 0$ and $\tau/2$, where $\tau/2$ is half of the characteristic time of the current decay. The $\tau 0$ is time of the normal zone spreading without visible current decay that is at the beginning of the quench. The $\tau/2$ time relates to decaying current with an exponent coefficient of $\tau \sim L/R$.

$\Delta t = \tau 0 + \tau/2$

Current decay from the TDR and U(T)

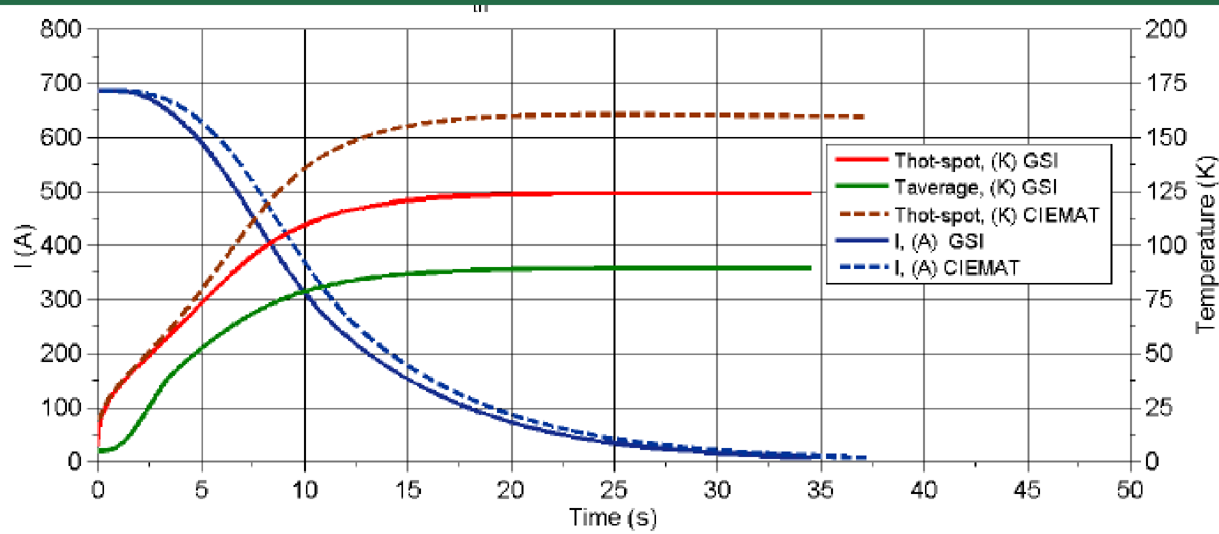
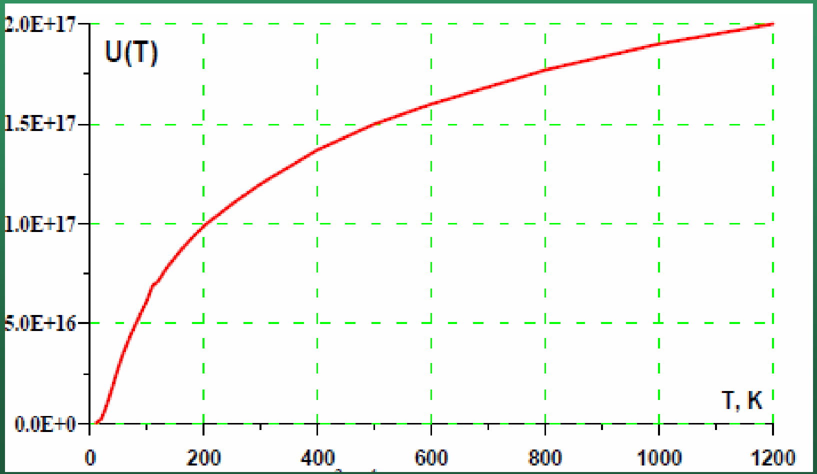


Figure 32. 3D quench calculation of the CBM dipole - the magnet current, hot-spot temperature and the average coil temperature.

The current decay is represented of exponent decay and the linear part without decay.

The maximal temperature is calculated by U(T) graph.



Normal zone propagation

- The velocity of the normal zone propagation along the wire

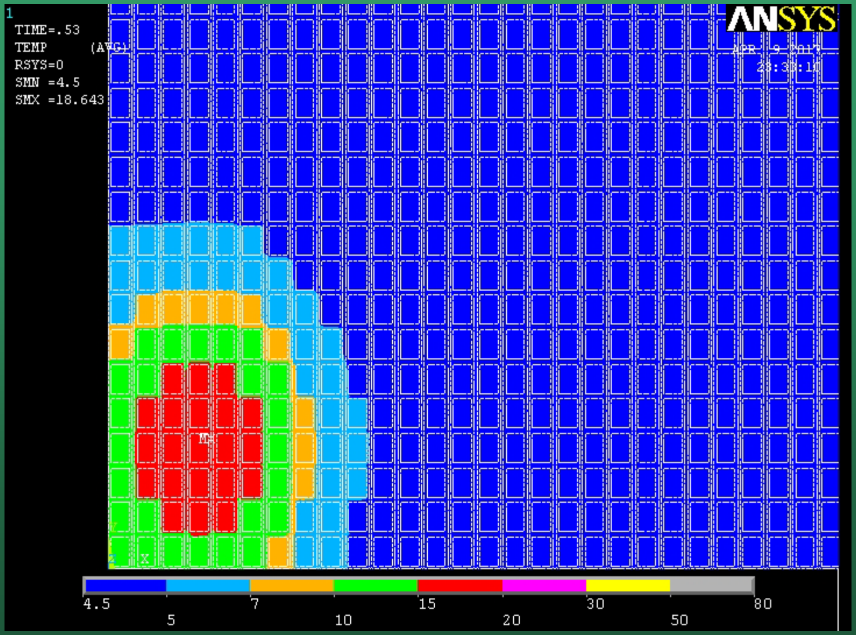
$$v_a = \frac{J_e}{\rho C}\sqrt{\frac{L_0 \cdot T_s}{T_c - T_s}}$$

v ~ 7.3 m/s

- The transverse velocity of the normal zone propagation was calculated in ANSYS

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.



Effect of secondary circuits

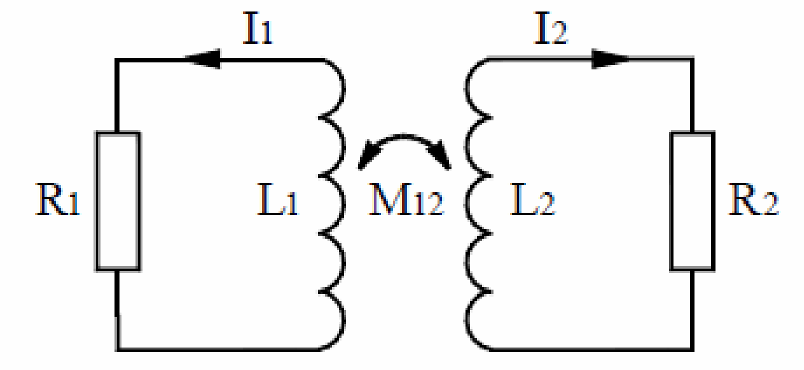
- The taper parts of the iron yoke are secondary circuits – passive protection effect

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

The result of the solving is [7]:

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

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



The characteristic time of the taper parts is ~ 1 s.

- As a result, the amplitude of decaying current may be reduced by ~ 10% that gives reduction of the left part of the equation below by 20%.

$$U(T) = \int_{4.2}^{T_{max}} \frac{\gamma C_p(T)dT}{\rho(T)} = \frac{S_{Cu}}{S}\cdot J_0^2(t)\cdot \Delta t,$$

Results

- These estimations considered energy dissipation in one winding only. In the current design the normal zone will reach the other winding.
- The estimations were made without heating of the insulation, so the average temperature after a quench is 110 K as compared with TDR.
- The maximal temperature is 210 K, without presence of the taper iron. With taper iron it will be 190 K.
- After counting the insulation the hot spot temperature will be 150-160K.
- The insulation thickness is high. The proposed thickness goes from the TDR where SC cable was made by soldering that may give some spikes of the solder.
- After a quench the winding will be cooled down to 65 K after dissipation of the stored energy in one coil. Time ~ 15 min.
- The CBM magnet is quench protected as the hot spot temperature is well below 200 K.