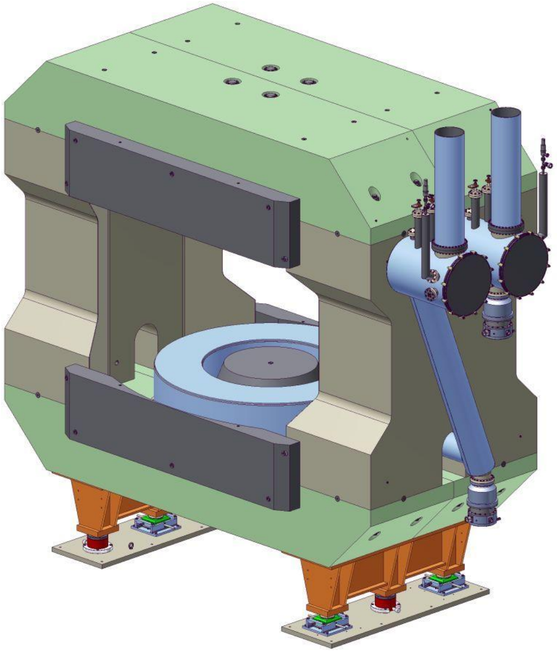
Development of the quench protection system and quench calculations for the superconducting dipole magnet of the CBM experiment

(Разработка системы защиты и моделирование процесса перехода в нормальное состояние сверхпроводящего магнита эксперимента CBM)



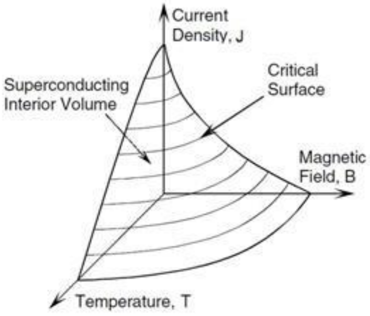
P. Kurilkin, LHEP JINR

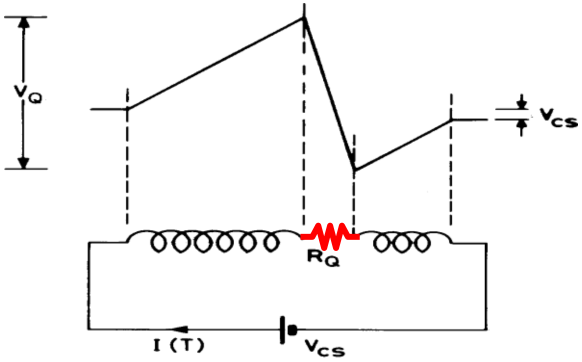
Alushta, 5-12 June 2016

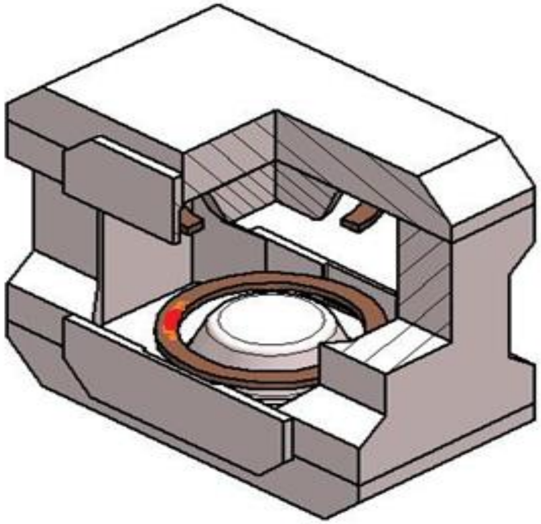
Content of the talk

- Introduction
- Specification of CBM magnet
- Quench protection schemes for CBM magnet:
  a) Energy extraction via dump resistor
  b) Coil heating
- Conclusion

The quench process







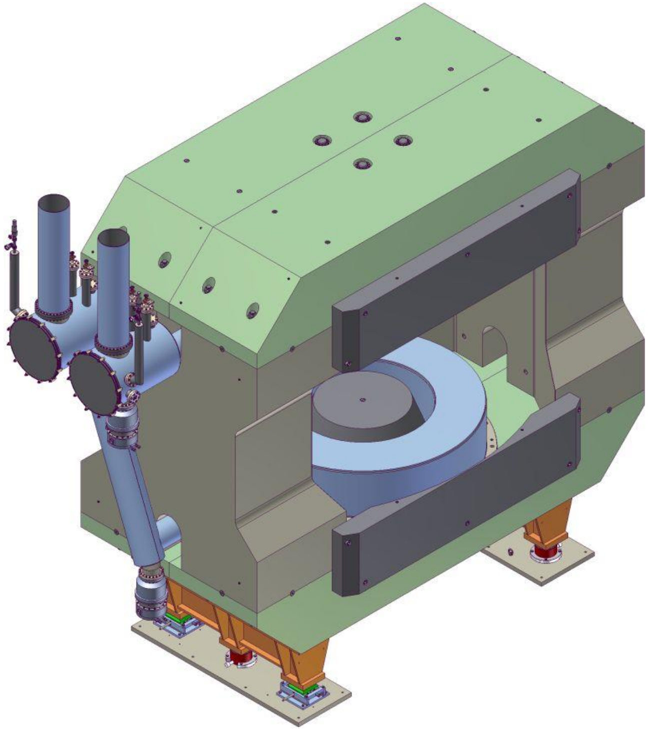
- resistive region starts somewhere in the winding at a **point - this is the problem!**
- it grows by thermal conduction
- stored energy $\frac{1}{2}LI^2$ of the magnet is dissipated as heat
- greatest integrated heat dissipation is at point where the quench starts
- internal voltages much greater than terminal voltage (= V_{cs} current supply)

the quench starts at a point and then grows in three dimensions via the combined effects of Joule heating and thermal conduction

From M. Wilson, 'Pulsed Superconducting Magnets' CERN Academic Training May 2006

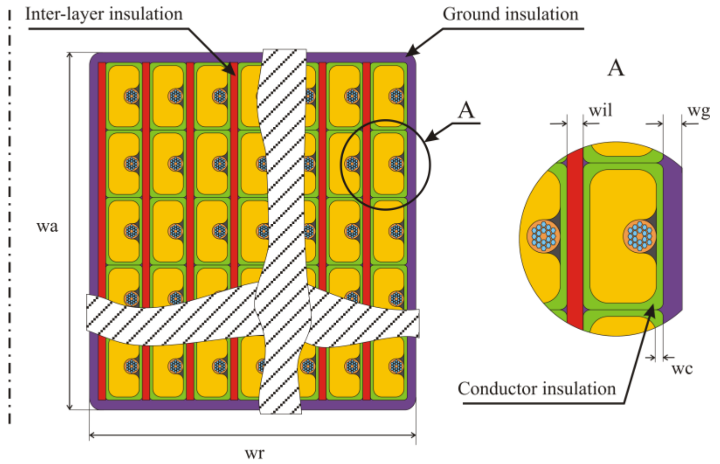
Main parameters of the CBM dipole magnet

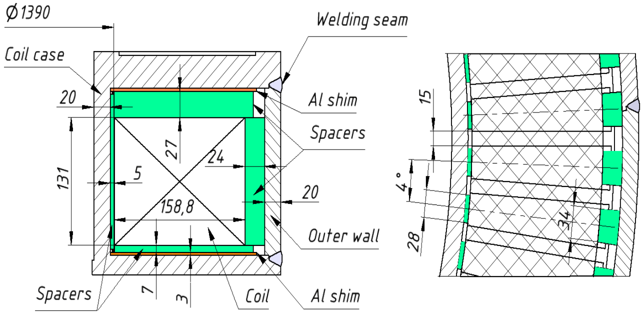
№ п/п	Name of the magnet parameters	Value
1	Vertically opening angle, deg.	±25
2	Horizontally opening angle, deg	±30
3	Free aperture: vertically (horizontally), m	1,4 (1.8)
4	Distance target- magnet core end, m	1,0
5	Field integral, Tm.	1,0
6	Field integral variation over the whole opening angle along straight lines, %	≤ 20
7	Duration of operation per year, month.	3
8	Total working time, year	20
11	Crane lifting during assembly, t	30
12	Maximal floor load, t/m2	100
13	Beam height over the floor, m	5,8

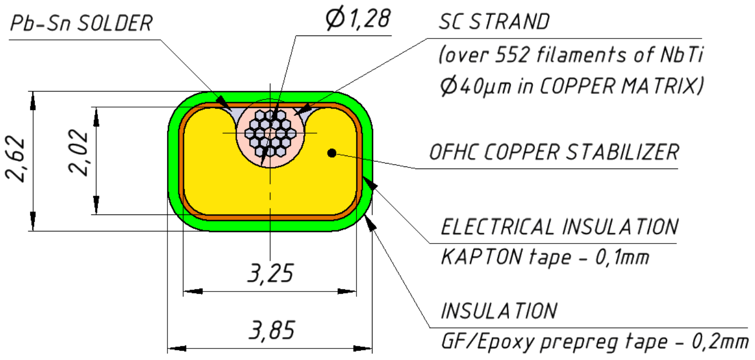


The Technical Design Report for the CBM Superconducting Dipole Magnet. http://www.fair-center.eu/fileadmin/fair/experiments/CBM/TDR/CBMmagnetTDR31102013-nc.pdf

SC coil of magnet







Specifications of the superconducting wire	
Material of SC cable	**NbTi/Cu**
Dimension of conductor	2,02x3.25 mm
Cu(total)/S.C. ratio	**9.1**
Insulation	Kapton + GF tape
Filament diameter	< 40 mm
Number of filaments	~ 552
Twist pitch	45 mm
RRR	>100
Critical current @ 4.2K	1330 A @5 T

Data used in 3D modified SQUID simulation code

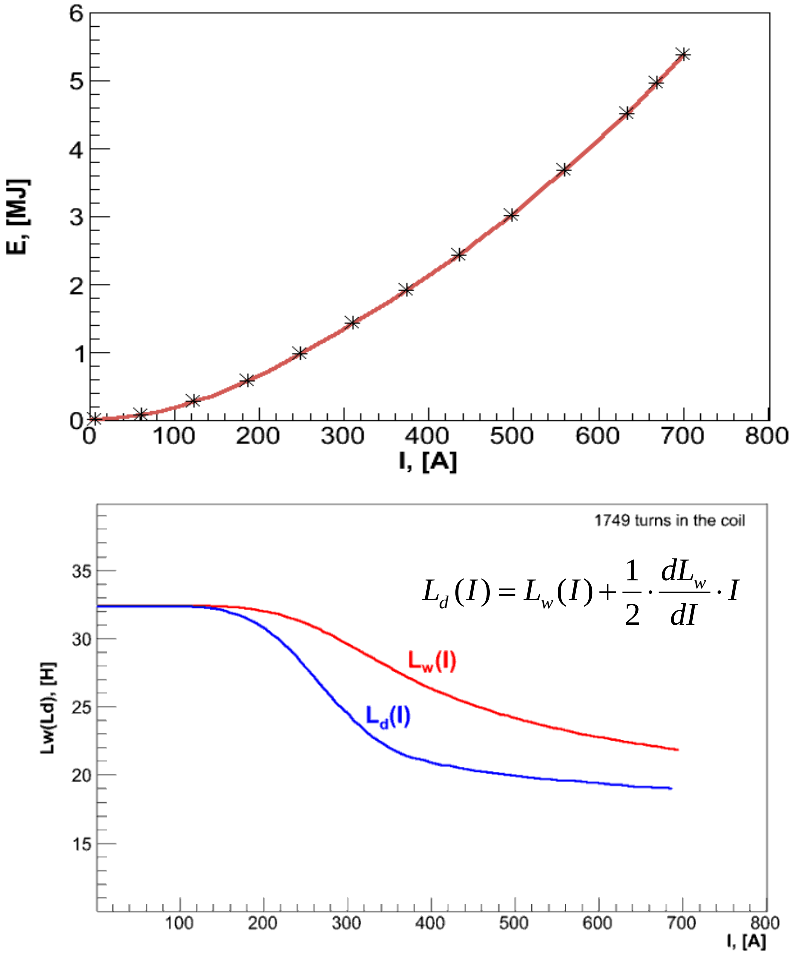


Fig.1: (a) Magnet energy and (b) inductances L_w and L_d (b) vs the current.

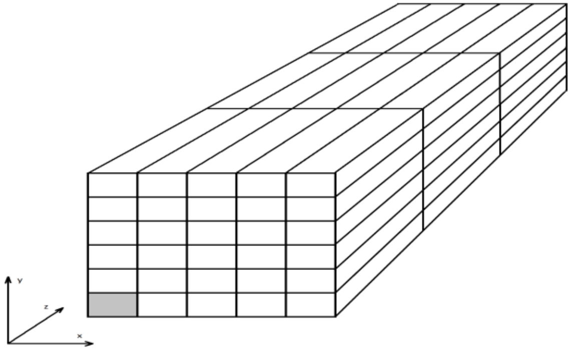
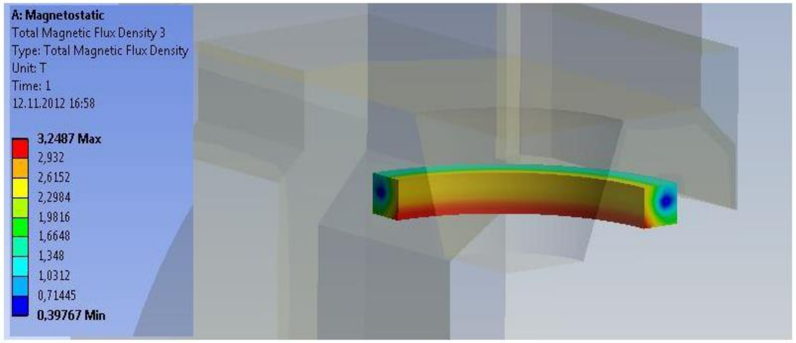


Fig.2: Simplified model in the CBM magnet coil.



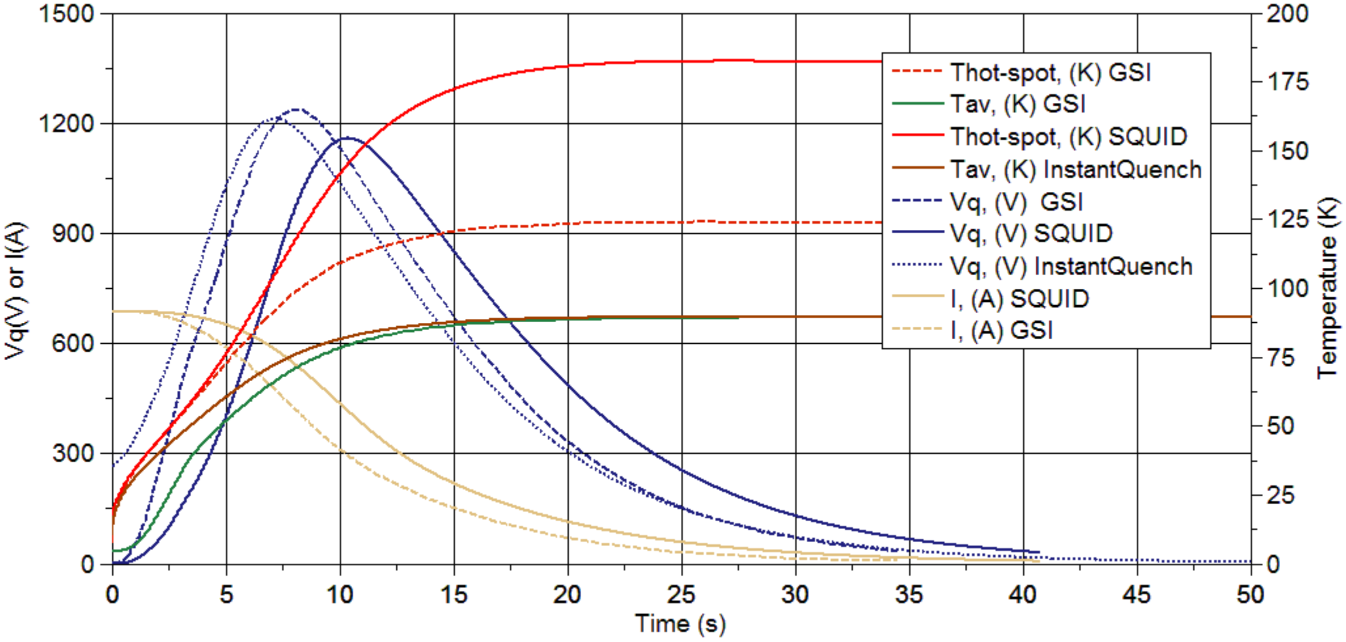
A: Magnetostatic
Total Magnetic Flux Density 3
Type: Total Magnetic Flux Density
Unit: T
Time: 1
12.11.2012 16:58

Fig.3: Magnet field in the coil.

The thermal properties of Kapton:

1. *http:/cryogenics.nist.gov*
2. Dissertation of J. N. Schwerg., “Numerical calculations of Transient Field Effects in Quenching Superconducting Magnets”, Berlin 2010

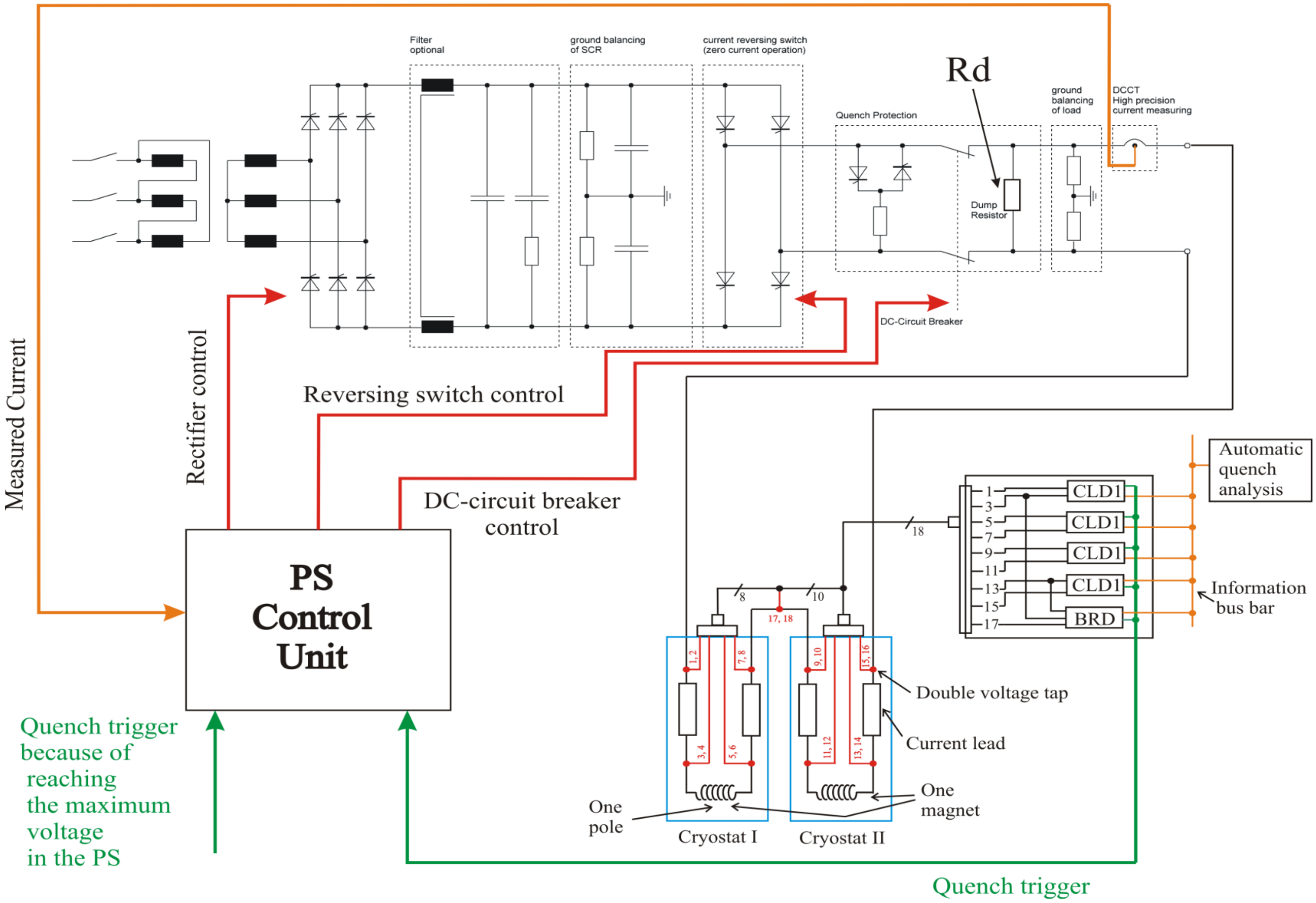
3D quench calculations for CBM magnet



Results of 3D GSI (E.Floch, P.Szwangruber) and SQUID (P.Kurilkin, F.Toral) quench programs.

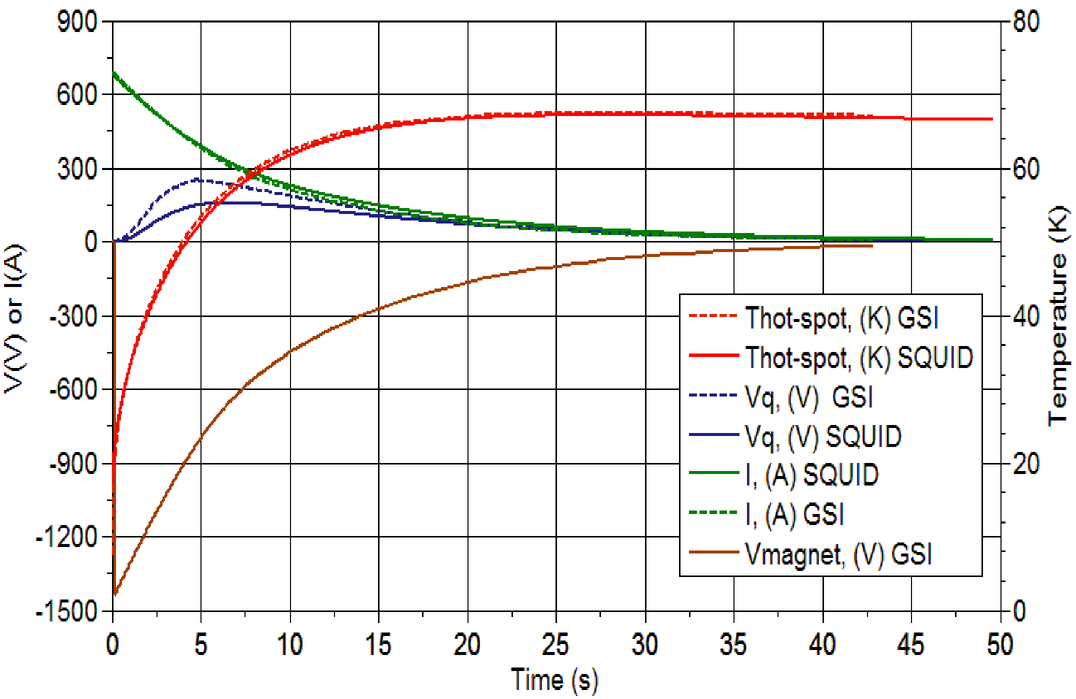
P. Szwangruber et al., ”Three-Dimensional Quench Calculations for the FAIR Super-FRS Main Dipole”, IEEE Transactions on Applied Superconductivity, 23 No.3 (2013) 4701704

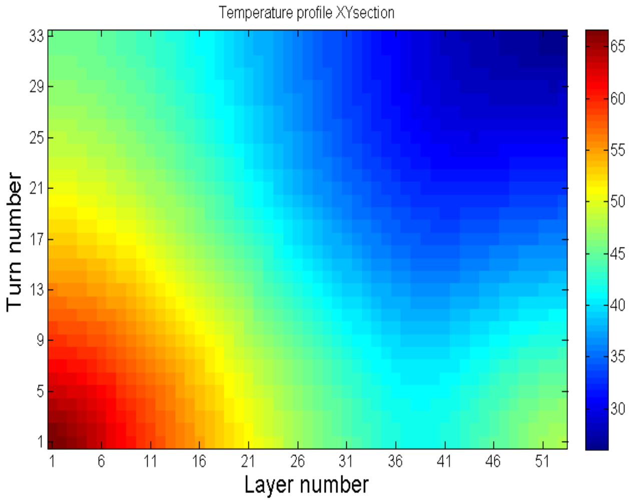
Quench protection and detection scheme of CBM magnet (I)



E. Floch, H. Ramakers (GSI, Darmstadt)

Quench protection and detection scheme of CBM magnet (I): 3D calculation results





3D calculation, Rd=2.1Ohm

3D GSI (*E.Floch, P.Szwangruber)*

3D SQUID (*P.Kurilkin, F.Toral*)

In case of using 1.5-2.1 Ohm resistor 80-86% of 5.15 MJ are dissipated in outside of the coil.

Quench protection scheme of CBM magnet (II)

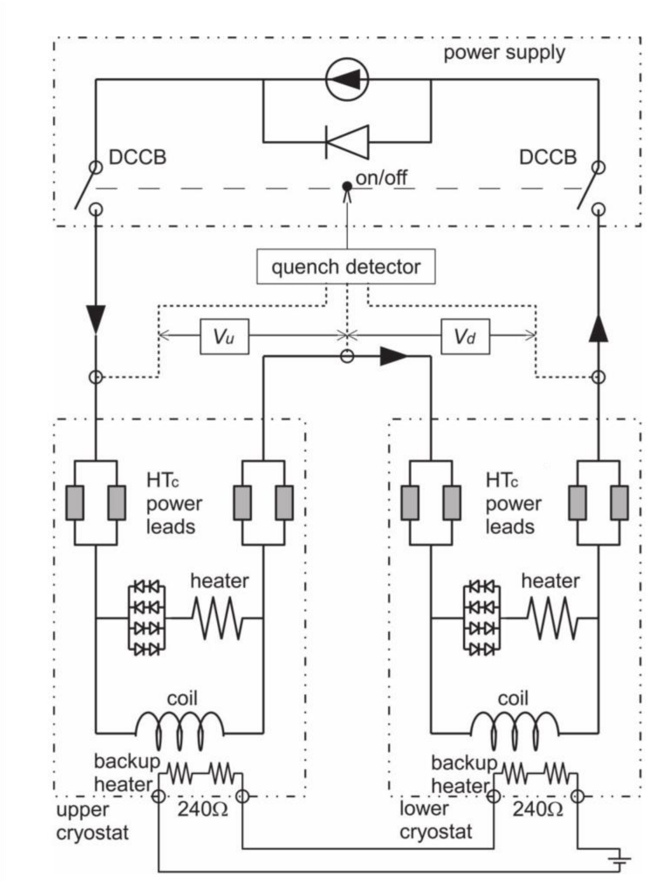


Fig.1: Quench protection scheme for CBM magnet, based on the coil heating

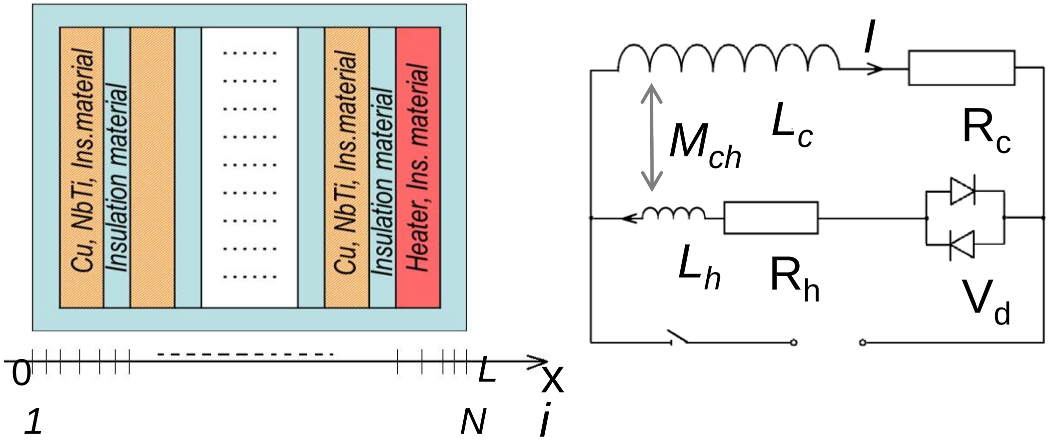


Fig.2: Schematic view of the coil cross section and an electrical scheme used in the 1D calculation.

$$L_{eff}(I)\frac{\partial I}{\partial t}+\left[R_c(B,T)+R_h(B,T)\right]\cdot I+V_d=0$$

$$L=\alpha\cdot N^2,\quad M_{12}=k\cdot\sqrt{L_1\cdot L_2}$$

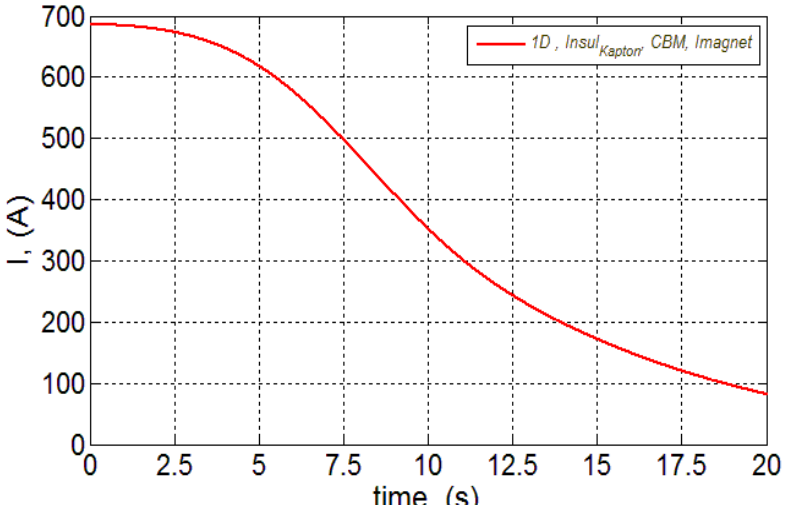
$$L_{eff}=L_c+L_h\pm 2\cdot M_{ch}\approx L_c,\quad V_d<<R_c\cdot I$$

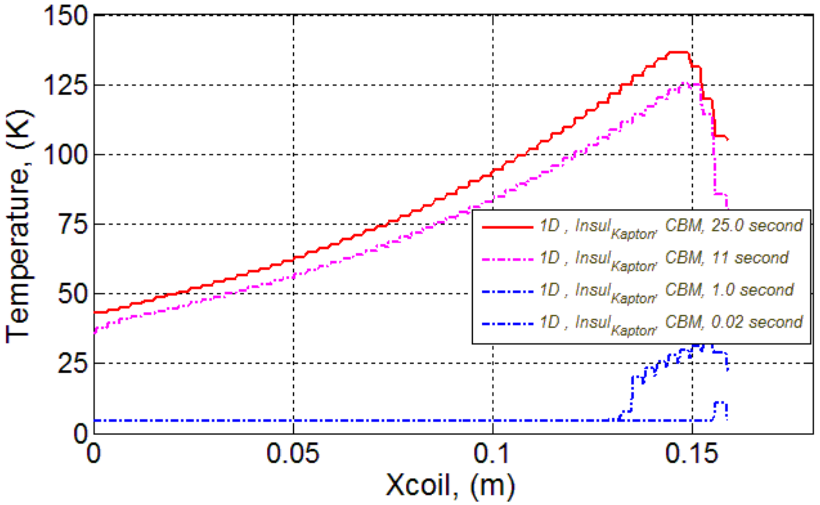
$$\Delta I=\frac{(R_c+R_h)\cdot I}{L_c}\cdot\Delta t$$

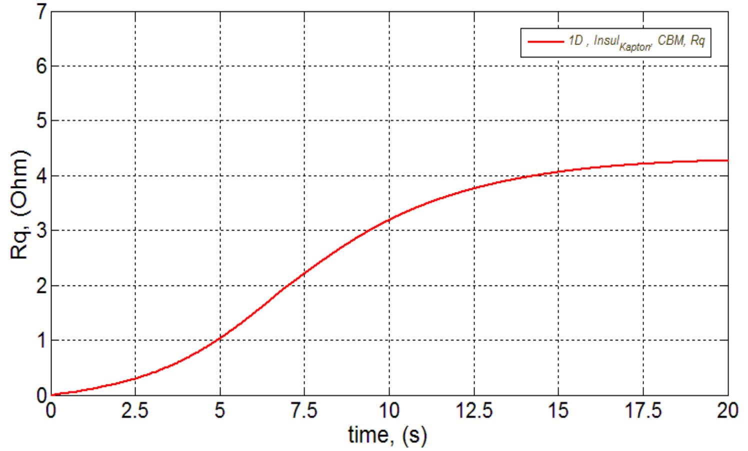
H.Sato et al., IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

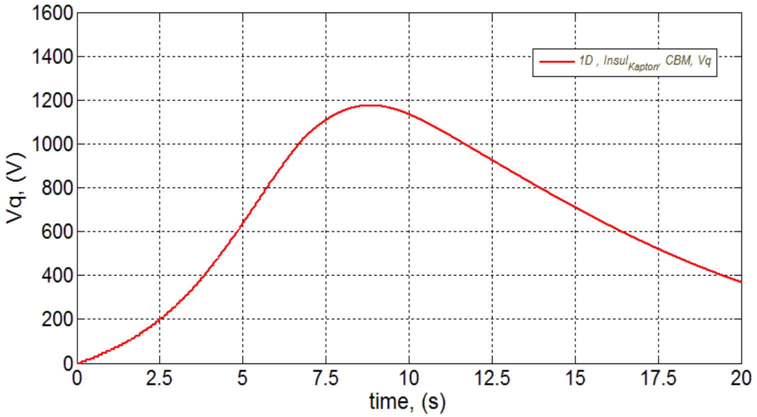
Yukikazu Iwasa "Case Studies in Superconducting Magnet Design and Operational Issues" 2009

Quench protection scheme of CBM magnet (II): 1D calculation results









Heater parameters:

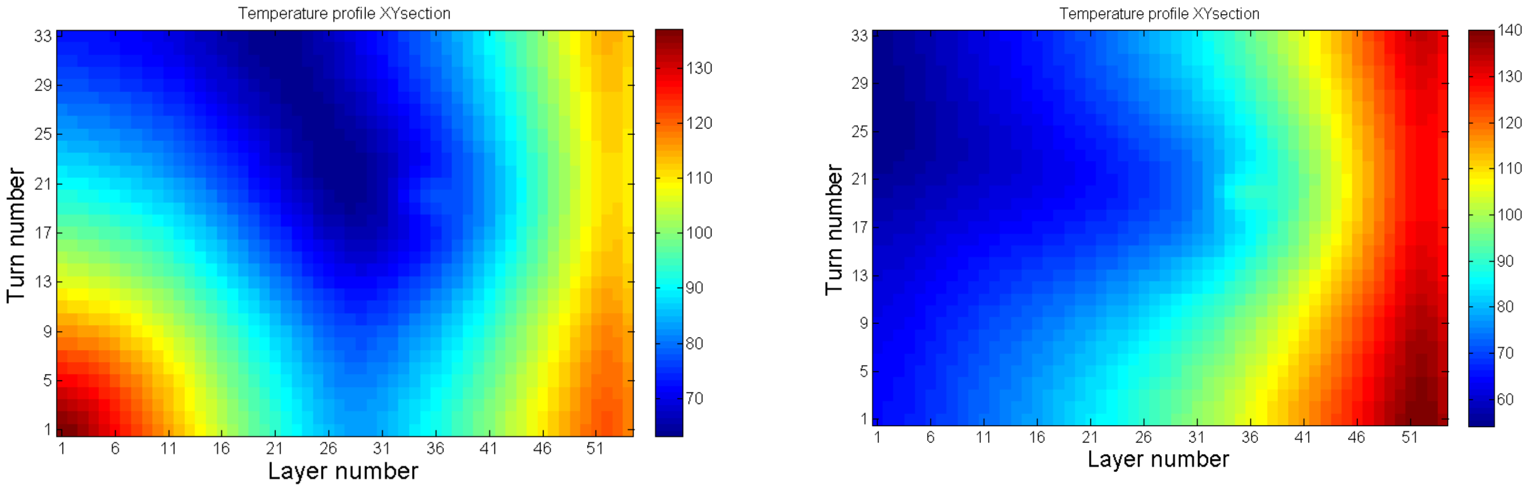
Material: Cu

Size of wire: 2.5x3mm

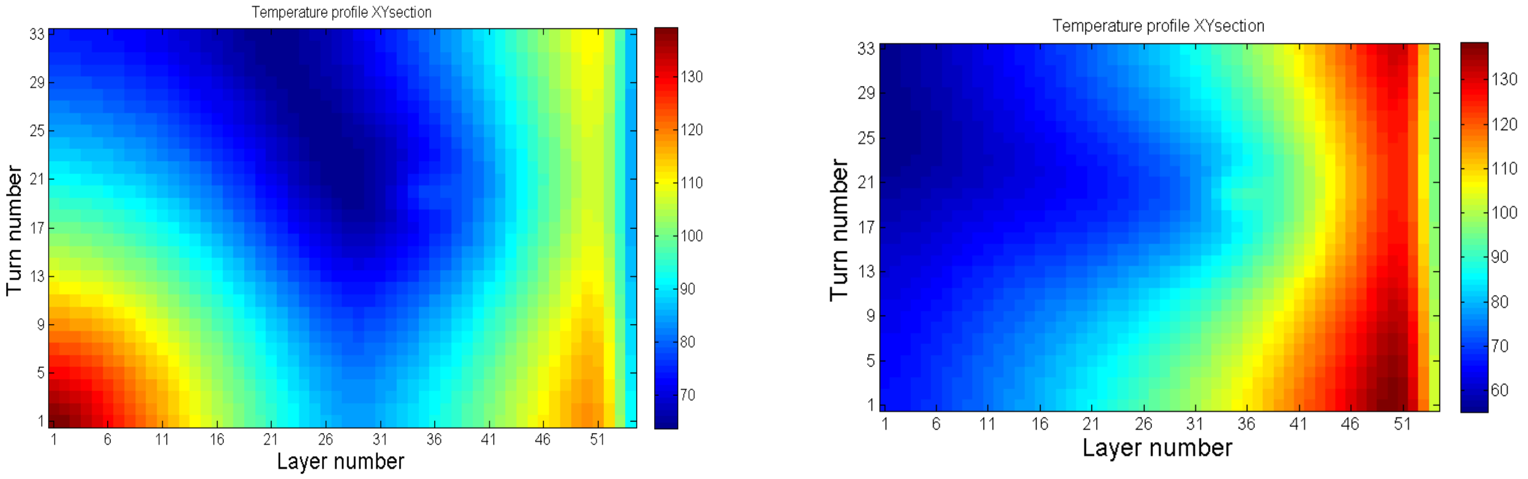
Nturn:35

Quench protection scheme of CBM magnet (II): 3D calculation results:

A)



B)



The temperature distributions in the CBM magnet coil cross section during the quench.
The heater has 33 turn of Cu wire of 2.02x3.25 mm^2 (A) and 3.02x3.25 mm^2 (B)

Outlook

- A potted coil with a nominal current of I_n = 686 A is proposed for the CBM dipole magnet.
- The 3D quench program (*SQUID*) was developed for the CBM magnet quench calculation. The program takes into account the data on magnetic field distribution in the coil and double layer wire insulation.
- The preliminary 3D quench calculations were done for two type of quench protection system.
- The quench protection system for CBM magnet will be based on the energy evacuation via dump resistor.

Thank you for the attention!!!

Instantaneous and homogeneous quench

Initial conditions:

- T_{av} = 10 K, B_{av}=B_{max}/2 at t = 0
- B_{av}(t)= B_{av}(t=0)*I(t)/In

$$L_d(I)\cdot\frac{dI}{dt}+R_q(T_{av})\cdot I=0; \qquad R_q(T_{av})=rl(T_{av})\cdot n_{tpp}\cdot\ell_{1turn}$$

$$\Rightarrow dI=-\frac{R_q(T_{av})\cdot I}{L_d(I)}\cdot dt$$

Eq.1

n_{tpp} is the number of turns per pole and l_{1turn} is the average turn length, L_d is the differential inductance and rl(T_{av}) is the linear resistance.

$$rl_{av}=\left[\frac{1}{rl_{Cu}(RRR,B_{av},T_{av})}+\frac{1}{rl_{NbTi}(T_{av})}\right]^{-1}=\left[\frac{A_{Cu}}{\rho_{Cu}(RRR,B_{av},T_{av})}+\frac{A_{NbTi}}{\rho_{NbTi}(T_{av})}\right]^{-1}$$

rl_{Cu} is the resistivity and A the cross section of one material in one conductor

E.Floch, P.Swangruber, private communication, GSI, June 20th, 2012

Instantaneous quench

Heat equation

$$R_q(T_{av})\cdot I^2\cdot dt = Vol\cdot Cp_{av}(T_{av})\cdot dT_{av} = A_{coil}\cdot \ell_{1turn}\cdot Cp_{av}(T_{av})\cdot dT_{av}$$

$$\Rightarrow dT_{av} = \frac{R_q(T_{av})\cdot I^2}{A_{coil}\cdot \ell_{1turn}\cdot Cp_{av}(T_{av})}\cdot dt$$

Eq.2

A_{coil} is the coil cross section (made of n_{tpp} insulated conductors and the ground insulation) and Cp_{av} is the average specific heat (in J/m^{3}K) of the coil

Average specific heat of one coil

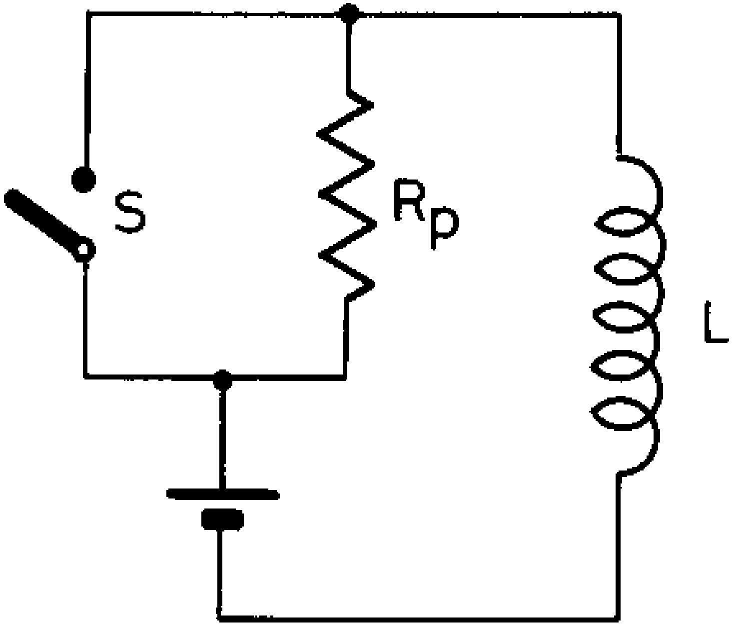
$$Cp_{av}(T) = \left[A_{Cu}\cdot Cp_{Cu}(T) + A_{NbTi}\cdot Cp_{NbTi}(T) + A_{ins}\cdot Cp_{ins}(T)\right]/\left[A_{Cu} + A_{NbTi} + A_{ins}\right]$$

Eq.3

A is the cross section of the corresponding material and “ins” stands for insulation. Cp is the specific heat of the corresponding material.

Results: Tav = 90 K, Vq = 1230 V

Methods of quench protection:
1) external dump resistor



- detect the quench electronically
- open an external circuit breaker
- force the current to decay with a time constant

$$I = I_o e^{-\frac{t}{\tau}} \quad \text{where} \quad \tau = \frac{L}{R_p}$$

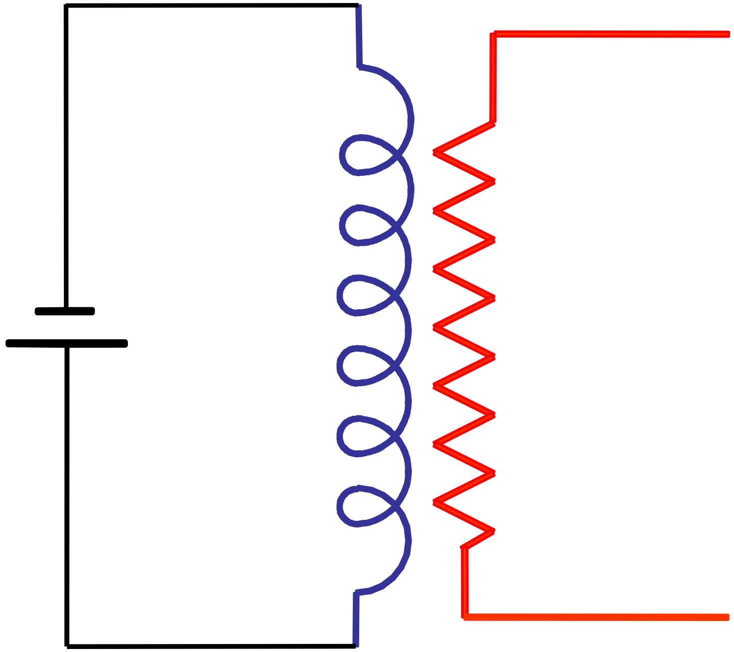
- calculate θ_{max} from

$$J_o^2 \tau = U(\theta_m)$$

Note: circuit breaker must be able to open at full current against a voltage $V = I.R_p$ (expensive)

From M. Wilson, 'Pulsed Superconducting Magnets' CERN Academic Training May 2006

Methods of quench protection:
2) quench back heater



- detect the quench electronically
- power a heater in good thermal contact with the winding
- this quenches other regions of the magnet, effectively forcing the normal zone to grow more rapidly
  ⇒ higher resistance
  ⇒ shorter decay time
  ⇒ lower temperature rise at the hot spot

Note: usually pulse the heater by a capacitor, the high voltages involved raise a conflict between:-

- ***good themal contact***
- ***good electrical insulation***

method most commonly used in accelerator magnets ✓

From M. Wilson, 'Pulsed Superconducting Magnets' CERN Academic Training May 2006