Quench calculations for the superconducting dipole magnet of CBM experiment at FAIR

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Abstract. The scientific mission of the Compressed Baryonic Matter (CBM) experiment is the study of the nuclear matter properties at the high baryon densities in heavy ion collisions at the Facility of Antiproton and Ion Research (FAIR) in Darmstadt. The 5.15 MJ superconducting dipole magnet will be used in the silicon tracking system of the CBM detector. It will provide a magnetic field integral of 1 Tm which is required to obtain a momentum resolution of 1% for the track reconstruction. This paper presents quench modeling and evaluation of candidate protection schemes for the CBM dipole magnet. Two quench programs based on finite-difference method were used in simulation. One of them is currently used at GSI, and the other based on CIEMAT (Madrid, Spain) was modified to perform quench calculation for the CBM magnet.

1. Introduction
The Compressed Baryonic Matter (CBM) will be one of the four major scientific experiments of the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt\cite{1}. The goal of the CBM research program is to explore the QCD phase diagram in the region of high baryon densities using high-energy nucleus-nucleus collisions. This includes the study of the equation-of-state of nuclear matter at high densities, and the search for the deconfinement and chiral phase transitions. The geometrical acceptance of the CBM detector systems is full $2\pi$ for azimuth ($\phi$) and from $2.5^\circ$ to $25^\circ$ for polar ($\Theta$) angles. Muon and electron pairs created during particle decays will be measured during separate runs. In electron configuration the following detectors will be used: Micro-vertex Detector (MVD), Silicon Tracking System (STS), then Ring Imaging Cherenkov Detector, Transition Radiation Detectors, Resistive Plate Chambers for time-of-flight measurements, Electromagnetic Calorimeter (ECAL) and Projectile Spectator Detector. In muon configuration the RICH detector will be replaced by the Muon Detection System and ECAL will be removed.

The superconducting magnet \cite{2} is a central component of the CBM detector setup. The target, MVD and STS with a polar angle acceptance of $\pm 25^\circ$ and a horizontal acceptance of $\pm 30^\circ$ will be placed in the magnet gap. For design of any superconducting magnet, an analysis of its stability is necessary. An important phenomenon in superconducting magnets is quenching.
Quench is a process of a resistive transition in a superconducting magnet. There are many factors that cause a superconducting coil of a magnet to a quench, such as mechanical disturbance, heat disturbance, nuclear radiation, flux jump, etc.\[3, 4, 5\]. During the quench, the energy stored in the magnet, and power provided by the power supply can cause a high temperature rise in the region where quench started, as well as high voltages in the coil and between the coil and ground. These factors may char the insulation or even melt the conductor and destroy the magnet. Thus the quench must be detected fast and some actions should lead to a shutdown of the power supply and the discharge of the magnet by dissipation of its energy via a dump resistor, or onto the own thermal mass of the magnet.

During last decades, several approaches to model the quench propagation in the superconducting magnets have been proposed \[6\]. In this paper, the results of the numerical quench modeling and evaluation of candidate protection schemes for the CBM dipole magnet are presented.

2. CBM dipole magnet

The H-type superconducting magnet of the CBM experiment is designed to provide a vertical magnetic field with bending power of 1 Tm over a length of 1 m from the target. A perspective view of the magnet with the support is presented in Fig. 1. The magnet yoke consists of two conical poles and two horizontal and two vertical parts to close a flux return. Two cylindrical superconducting coils will be installed in their respective cryostats and will be cooled separately by helium bath based cooling system like the SAMURAI magnet at RIKEN\[7\]. The maximum energy storage is evaluated as 5.15 MJ when the operating current of the CBM magnet is rated at 686 A. The design of coil for the CBM magnet is based on the design of the Super-FRS dipole\[8\]. Each coil has 1749 turns and 53 layers. The superconducting wire is a Nb/Ti wire. The conductor insulation consists of 0.1 mm polyimide type and 0.2 mm glass fiber (G10) material. Each layer is additionally insulated from the others by three layers of 0.1 mm fiber glass fabric with epoxy resin. The detailed description of the CBM magnet can be found in \[2\].

3. Quench calculations for the CBM magnet

In the magnet design it is necessary to calculate the temperature, voltage and current in case of a quench. There are several levels of quench simulation. The simplest level of modeling is
performed within the framework of adiabatic model. This model is based on implementation of the well-known balance equation between Joule heating due to the current and temperature increase through specific heats. The heat propagation through the coil on this level is ignored. One of such approximation is “instantaneous quench”[2, 9]. The “instantaneous quench” means that the whole coil is heated up instantaneously above the critical temperature. The calculation is performed for short-circuit magnet and gives good estimation of the maximum quench voltage. The value of average temperature will be lower than real “hot spot” (the location of initial quench in the coil) temperature.

The second level of approximation includes the heat propagation within the coil. This implies having a multidimensional mesh of the coil and the code on this level incorporates the magnetic distribution in the coil and also the model of critical surface. The heat exchange between the coil and helium bath is not taken into account on this level. The 3D quench calculations for the CBM magnet coil have been carried out by two numerical programs based on the finite-difference method. One of them is used currently at GSI and its detailed description can be found in [10]. The other (SQUID) based on CIEMAT numerical code[11] was adapted to perform the quench simulation for the CBM magnet. The coil is represented as a straight slab with a length equal to the average turn length. A regular mesh is applied to the slab so that the cross-section of the one mesh element equal to the cross-section of the insulated conductor. Longitudinally, the coil is divided into a number of slices which define a mesh element size. The material properties are homogeneous within each mesh element.

The electrical equation for the short-circuit magnet is predicted by the following differential equation:

\[ L_d(I) \frac{dI}{dt} + R_q(T_{av}) \cdot I = 0 \] (1)

where \( L_d \), \( I \), \( R_q \) and \( T_{av} \) are the differential inductance, magnet current, quench resistance and average temperature, respectively.

The heat balance equation per unit volume of the coil can be presented as:

\[ \rho(T) \cdot J^2 = C(T) \frac{dT}{dt} - \nabla \cdot (K(T)\nabla T) \] (2)

where \( C(T) \) is specific heat per unit volume (\( Jm^{-3}K^{-1} \)), \( K(T) \) is thermal conductivity (\( Wm^{-1}K^{-1} \)), \( \rho(T) \) is resistivity (\( \Omega \cdot m \)). It means that the energy deposited due to Joule effect in the unit volume is stored in the material increasing its temperature and it is evacuated to the nearby material by conduction. This equation is solved by means of the finite-difference method. The quench programs couple the thermal (Eq.2) and electrical (Eq.1) equations at each time step. The material properties (NbTi, Cu, insulation) are recalculated for each iteration. They depend on the temperature and magnetic field. The quench origin is simulated by the set of temperature of one (or several, depending on the minimal propagation zone) element slightly above its critical value. The quenched element is located in the inner layer of the coil where the field is higher. In the simulation one can get the “hot spot” temperature, coil voltage, current and also quench propagation velocities.

The results of quench modeling for the CBM coil at 686 A are presented in Fig.2. The results of the “hot spot” temperatures calculated by GSI and SQUID 3D quench program are shown by red solid and red dashed lines, respectively. The average coil temperature is presented by the green and brown lines for GSI and “Instantaneous quench” calculations, respectively. The maximum temperature during the quench is about 180 K. All models give that the maximum quench voltage is about of 1200 V. The magnetic field distribution in the coil of the CBM magnet taken from designers has been used in the SQUID computations, while the GSI quench simulations have been performed for the uniform distribution of the magnetic field. It should be noted that the SQUID modeling has been performed for the double insulated conductor.
The protection system is necessary to reduce the maximum “hot spot” temperature during the quench below 100 K. Two possible quench protection systems for the CBM magnet were considered.

The first one is based on the extraction of the energy stored in the magnet via a dump resistor. The details can be found in [2]. The dump resistor is connected in parallel to the magnet and it is always on. In case of the quench the magnet will be disconnected from the power supply and the magnet current will be dumped via the dump resistor. The dump resistor with resistance of $1.9 - 2.1 \Omega$ will be used. The quench simulation showed that in this case around 80 – 86% of the energy stored in the magnet (5 MJ) will be dissipated outside of the cryostat. Fig.3 presents the quench calculation results using the 2.1 Ohm dump resistor for the energy extraction. Simulation shows that the maximal “hot spot” temperature in the coil in this case is about 70 K. The maximum voltage across the magnet (1441 V) occurs when the dump resistor turns on. Fig.4 shows the temperature profile distribution in the coil cross section when the “hot spot” temperature has a maximum value.

The second quench protection system is similar that is used for the SAMURAI dipole magnet at RIKEN (JAPAN)[7]. This system is based on the heating of the outer layer of the coil. In this case, the transition of the winding of the coil to the normal state occurs faster than in the previous case. In this scheme, the superconducting coil is connected in parallel with the low-temperature (“cold”) diodes and a copper heater wire that are connected in series. The quench detector monitors the difference of the voltage between the upper and the lower coils. In case of a quench, the coils are cut off from the power supply, and the current flows in the closed circuit consisting of the superconducting coil, the diodes and the heater wire. The outermost layers of both coils are forced to quench simultaneously due to the heat generated by the heater wire. Then the normal zone in the coils propagates from the outer to the inner layer. The simulations of the quench process at different start condition and resistance of the coil heater have been performed[12]. The maximum quench voltage is about 1200 V. Fig.5 and Fig.6 present the temperature distribution in the cross section of the CBM magnet coil in case when the quench appears in the inner and outer layer of the coil, respectively. For the heating of the outermost layer of the coil, the copper heater with 33 turns of wire with the cross section of $2.02 \times 3.25 mm^2$ was used. The maximum “hot spot” temperature is about 140 K. The obtained results show also the big temperature gradient in the CBM magnet coil cross section in case of the heating of the coil. The use of the copper heater with the cross section of $2.02 \times 3.25 mm^2$ in the quench simulations gives the similar results.
Figure 5. 3D quench simulation for the CBM magnet: temperature distribution in the coil cross section. Quench appears in the inner layer of the coil winding. Heater parameters are described in the text.

Figure 6. 3D quench simulation for the CBM magnet: temperature distribution in the coil cross section. Quench appears in the outer layer of the coil winding. Heater parameters are described in the text.

4. Conclusion
The research program of the Compressed Baryonic Matter experiment aims at the exploration of the QCD phase diagram in the regime of high densities and moderate temperatures. The superconducting dipole magnet for the CBM experiment is designed to have a large pole gap and wide horizontal opening. It will be a unique component of the CBM detector setup. The SQUID and GSI [10] quench programs have been used to the quench simulation of the CBM dipole magnet. Both programs properly take the dependence of strong variation of the matter properties from the temperature properties into account. They also use the adaptive time stepping which significantly reduce calculation time. Using both programs, we computed that the energy extraction resistor needs to extract 85% of the energy stored in the magnet.

The quench protection system based on the energy evacuation from the dump resistor of 1.9 – 2.1Ω is chosen for the CBM magnet due to the lower “hot spot” temperature and the lower temperature gradient in the coil winding.

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