QUENCH LIMIT CALCULATION FOR STEADY STATE HEAT DEPOSITS IN LHC INNER TRIPLET QUADRUPOLE MAGNETS

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Abstract

In hadron colliders such as the LHC, the energy deposited in the superconductors by the particles lost from the beams or coming from the collision debris may provoke quenches detrimental to the accelerator operation.

A Network Model is used to simulate the thermodynamic behavior of the superconducting magnets. In previous papers the validations of network model with measurements performed in the CERN and Fermilab magnet test facilities were presented. This model was subsequently used for thermal analysis of the current LHC inner triplet quadrupole magnets for beam energy of 3.5 TeV and 7.0 TeV. The detailed study of helium cooling channels efficiency for energy deposits simulated with FLUKA was performed. The expected LHC inner triplet magnets quench limit is presented.

INTRODUCTION

The Large Hadron Collider (LHC) is currently operating at CERN and producing pp collisions at centre-of-mass energy $\sqrt{s}$ =7 TeV and the luminosity maximum achieved during 2011 year operation is L=$3.5\cdot 10^{33}$cm^{-2}s^{-1}. The nominal value of collision energy is $\sqrt{s}$ =14 TeV and the nominal luminosity is L=10^{34} cm^{-2}s^{-1}. This corresponds to interaction rate of $8\cdot 10^{8}$ s^{-1}, which represents a power of ~900 W per beam and the majority of it is directed towards IT [1].

One of the operation issues of the LHC is related to the quenches induced in the superconducting magnets by the particles lost from the beams or coming from the collision debris [2], especially in Inner Triplet (IT) final focusing quadrupole magnets [3]. In order to cope with this problem a control system has been developed to predict imminent beam induced quenches and dump the beam before quenching any of the main magnets. This system is based on beam loss monitors (BLM) [4] and is using beam dumps, collimators and beam absorbers. The BLM system is measuring the energy released by secondary particles, created by lost protons or collision debris hitting the beam screen, the cold bore and the superconducting coils. The activation threshold for the BLM system needs to be set comparing the energy deposition due to the hadronic and electromagnetic shower to the expected quench level of the SC magnets. The beam loss duration ranges from a few nano-seconds (transient) to several seconds (steady state), depending on the specific failure/operation mode. Steady state losses are mainly caused by the debris of the proton-proton interactions at accelerator insertion regions. The heat flow in magnet coils at steady state regime is mainly limited by the size of the helium cooling channels and the heat conduction of the cable insulation. The power dissipation in the superconducting magnet components leads to a complex process of the heat flow, but in many cases a simplified model for heat transfer is sufficient. In this paper a summary results of extensive studies of the LHC IT magnets are presented.

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NETWORK MODEL

A Network Model was developed to study the thermodynamic behavior of the magnet coils and to calculate the quench levels of the superconducting magnets for given beam loss profiles as well as to optimize heat flow paths in new designs of superconducting accelerator magnets [5-8]. The model uses the thermal-electrical analogy, where electrical circuits are used to model the thermal quantities. The advantage of network model is that there are no free tuning parameters. Only the heat conductivity and the geometry are used to calculate the steady-state heat transfer within magnet coils.

The fundamental unit of the network model is the superconducting cable [6, 8]. Other network model elements (coil insulation, helium channels) are included in the model with segmentation corresponding to the cable unit dimensions. The values of the thermal conductivity for calculating the thermal resistance of each thermal element come from a commercially available database [9] and from literature [10-11].

The inner triplets, installed in four LHC Insertion Regions (ATLAS, ALICE, CMS, LHCb), consist of 70 mm coil aperture superconducting quadrupoles – 6.4 m long Q1 and Q3 (MQXA developed by KEK) and 5.5 m long Q2A and Q2B (MQXB developed by FNAL). They are powered in series and operate at 204 T/m for nominal beam energy. The magnet coils consists of four cable layers for Q1 and Q3 coils and two cable layers for Q2 coils. A detailed study of Q2A coils are presented in this paper. The Q2A coil inner cable has 37 strands, each 0.808 mm in diameter, the outer cable has 46 strands, each 0.648 mm in diameter. The cables are insulated with 9.5 mm wide polyimide tape. The inner cable insulation consists of 25 µm thick polyimide (Kapton) tape with 50% overlap surrounded by 50 µm thick tape with 2 mm gaps. The outer cable insulation consists of 25 µm thick polyimide tape with 50% overlap surrounded 25 µm thick polyimide tape with 50% overlap. The helium annular channel between the beam pipe and the coil of 1.45 mm wide and the cold bore of 1.85 mm thick were implemented into model as well [12].

ENERGY DEPOSITION STUDY

The ATLAS Insertion Region[a] has been modeled in FLUKA [13-14] taking into account all main elements along the beam line (TAS, IT quadrupoles and correctors), the experimental vacuum chamber, the tunnel and the experimental cavern. Since recently, the machine model can be built automatically from LHC optics files once the description of the geometry, materials and magnetic field is available for each component [15]. The study was focused on the energy deposition in the Nb-Ti coils of the triplet quadrupoles and in the stainless steel cold bore alongside the triplet due to debris coming from the collisions at the interaction point, being the latter ones simulated using the FLUKA built-in interface to DPMJET III [16]. The benchmarking of the FLUKA predictions against BLM measurements during the 2010 LHC operation showed remarkable agreements [17]. Nonetheless, the here reported Monte Carlo estimations should be taken with some margin due to systematic uncertainties related to the machine model and to their dependence on a thin phase space portion of the collision debris.

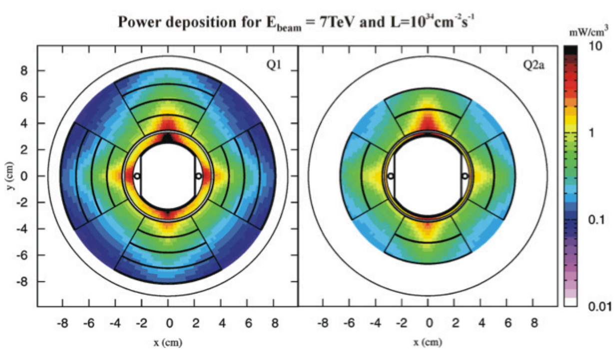

Figure 1: 2D map of the energy deposition in the Q1 (MQXA) and Q2A (MQXB) transverse section at the longitudinal position of the maximum, due to collision debris from proton-proton interactions. The geometrical model implemented in FLUKA is superimposed.

Two scenarios have been simulated: (a) 7 TeV per proton with 142.5 μrad vertical half-crossing angle. (b) 3.5 TeV per proton with 120 μrad vertical half-crossing angle. Beam divergence and vertex position distributions have been implemented.

The energy deposition in the coils is scored using a 3D cylindrical mesh with ~10 cm longitudinal bins, 2-degree azimuthal bins and 2.5 mm radial bins. Steady-state heat loads are displayed in Figure 2 by the longitudinal profile of the peak power density ε_{max} averaged over the radial dimension of the innermost coil layer. The maximum value, located at the end of Q1 and beginning of Q2A, is about 3.5 mW/cm^3 for the 7 TeV per beam scenario at nominal luminosity. On the other hand, for the maximum luminosity reached in 2011, the scenario (b) gives a maximum value of 0.35 mW/cm^3. A factor 2 increases these numbers roughly if one looks at the innermost radial bin. Figure 1 shows an asymmetry between the North and South poles in Q1 and Q2A. In the Q3 the asymmetry is reversed by the magnetic field effect.

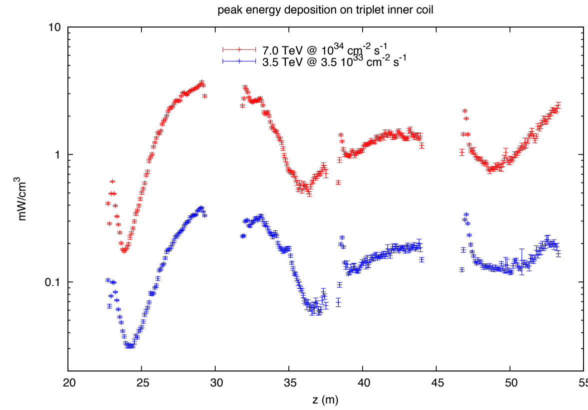

Figure 2: Longitudinal profile of ε_{max} along the innermost coil layer of the magnets of the inner triplet, induced by proton-proton collision debris. Error bars indicate statistical uncertainties.

THERMAL NETWORK SIMULATION

In order to study the thermal behavior of Q2A magnet (MQXB) a 2D numerical calculations with network model were performed. The MQXB thermal model included all the features of the Nb-Ti coil and implemented cable and coil insulation scheme, annular helium channel between coil and beam pipe as well as beam pipe and its insulation. Two heat deposition profiles calculated for ATLAS Insertion Region and discussed in previous section have been implemented in the model in order to study the temperature increase in the coil. An interpolation algorithm was run on the FLUKA output in order to fit the FLUKA heat load map to the MQXB coil conductor map. Also heat load in the beam pipe was implemented into the model. Quench limit was calculated with network model by implementing in the model the modified heat load profile. The modified profile was obtained by multiplying the nominal heat load values by a scaling factor.

The available temperature margin in the inner coil cables layer is almost factor two lower than in the outer ones. In opposite the heat load is higher in the inner coil and the energy peak is localized at the coil mid-plane. This indicates that beam induced quench will develop mostly in the inner cable layer. The results of MQXB network model simulations for the inner cable layer are shown in Figs. 3-4. Zero in these figures indicate the magnet mid-plane, positive and negative x-values indicate cables in the coils part adjacent to the mid-plane and y-values indicate available temperature margin, temperature increase in the cables above bath temperature T_0=1.9 K for the nominal heat load (shown in Fig. 2 for E_{beam} = 7 TeV) and the temperature increase in the cables at quench limit (peak values presented in Table 1).

[a] The results of the energy deposition for the CMS Inner Triplet are similar except for the (minor) effect of the different crossing plane. Past studied have showed that vertical crossing plane (as in ATLAS) leads to a slightly higher energy deposition on the IT coils.

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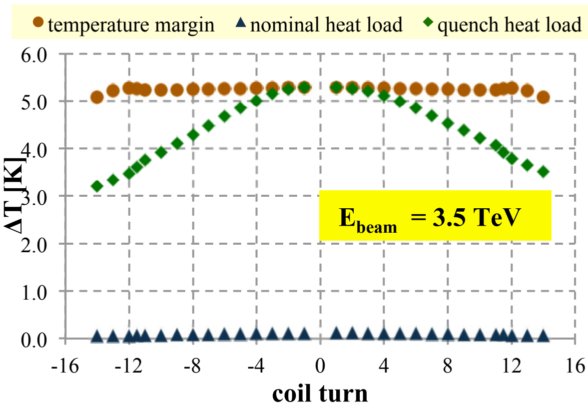

Figure 3: MQXB coil inner cable layer. The results of simulation for E_{beam} = 3.5 TeV and L=$3.5\cdot10^{33}$cm^{-2}s^{-1}. Zero in this figure indicate magnet mid-plane, positive and negative x-values indicate turns in the coils part adjacent to the mid-plane and y-values indicate available MQXB temperature margin at LHC beam energy of 3.5 TeV, temperature increase in the cables above bath temperature T_0=1.9K for the nominal heat and temperature increase in the cables at quench limit.

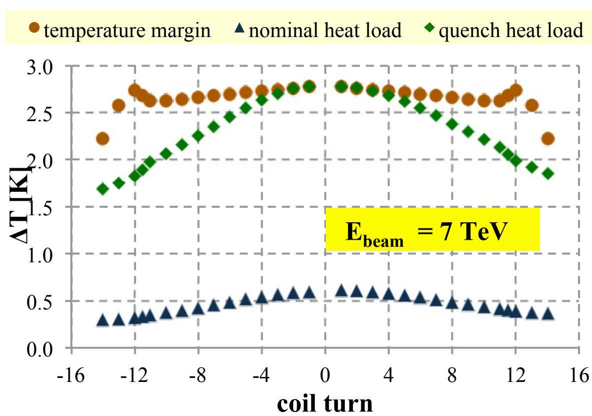

Figure 4: MQXB coil inner cable layer. The results of simulation for E_{beam} = 7 TeV and L=10^{34} cm^{-2}s^{-1}.

Table 1: MQXB Quench Limit and Heat Load Calculated with FLUKA for Beam Energy 3.5 TeV and 7 TeV.

Beam Energy (TeV)	Calculated Heat Load (mW/cm^3)	Quench Limit (mW/cm^3)
3.5	0.35	24*
7.0	3.5	9.1

CONCLUSION

The LHC inner triplet quadrupole magnet MQXB (Q2A) was analyzed with network model. Two heat load distribution calculated with FLUKA at luminosity L=$3.5\cdot10^{33}$ cm^{-2}s^{-1} and L=$1.0\cdot10^{34}$ cm^{-2}s^{-1} were implemented in model in order to quantitative study the MQXB coil thermal properties.

The results show temperature increase in the coil due to beam induced heat load. However the temperature rise is below the quench limit as shown in the table. At nominal LHC condition (E_{beam} = 7 TeV and L=10^{34}cm^{-2}s^{-1}) a safety quench limit factor is 2.6.

The thermal studies of LHC inner triplet magnets will continue using refined heat load maps.

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