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# Mechanical stress analysis during a quench in CLIQ protected 16 T dipole magnets designed for the future circular collider



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## ABSTRACT

Protecting the magnets in case of a quench is a challenge for the 16 T superconducting dipole magnets presently designed for the 100 TeV: Future Circular Collider (FCC). These magnets are driven to the foreseen technological limits in terms of critical current, mechanical strength and quench protection. The magnets are protected with CLIQ (Coupling-Loss Induced Quench) system, which is a recently developed quench protection method based on discharging a capacitor bank across part of the winding. The oscillation of the magnet currents and the dissipation of the high stored energy into the windings cause electrodynamic forces and thermal stresses, which may need to be considered in the magnet mechanical design. This paper focuses on mechanical stress analysis during a quench of the 16 T cos- $\theta$  and block type dipole magnets. A finite element model allowed studying the stress due to the non-uniform temperature and current distribution in the superconducting coils. Two different CLIQ configurations were considered for the cos- $\theta$  design and one for the block type magnet. The analyses of the mechanical behavior of two magnets during a quench without or with hot spot turn were separately carried out. The simulation results show that the stress related to a quench should be considered when designing a high field magnet.

#### 1. Introduction

The goal of the Future Circular Collider (FCC) project is to design a 100 km long particle accelerator for producing hadron collisions of up to 100 TeV center-of-mass energy [1]. In order to achieve this target, various 16 T Nb<sub>3</sub>Sn magnet designs studies for the Future Circular Collider have been carried out [2–4]. The mechanical behavior of such compact high-field magnets during a quench still requires investigation. Due to the cost-related requirement of compact magnets, high current densities are used. This poses huge challenges to the magnet quench protection and mechanical design. During the quench process, which lasts about 0.5 s, the stored energy is absorbed by the windings, leading to temperature increase of about 70–350 K depending on the location. The rapid thermal expansion of parts of the winding causes thermal

stresses, which may represent additional constraints to the mechanical design.

The cos- $\theta$  and block type dipoles are considered, which are designed within the H2020 funded EuroCirCol project. The cos- $\theta$  dipole is designed at INFN Milan and Genoa sections and details can be found from [5]. The block dipole is designed at CEA Saclay and its details can be found in [6]. The magnet protection is based on the CLIQ (Coupling-Loss Induced Quench) system. The protection schemes for both magnets are designed jointly with CERN and Tampere University of Technology. Details of the protection studies can be found in [7]. In this work we consider cases with two different CLIQ configurations for the cos- $\theta$  and one CLIQ configuration for the block. The CLIQ method is based on discharging a capacitor bank across part of the winding, causing oscillations of the magnet current. The change in coil magnetic field leads

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to interfilament coupling losses [8] within the conductor, which are enough to quench the conductor. The resistance of the quenched magnet drives the magnet current decay and limits the hot spot temperature. Details of the method can be found in [9,10]. In this work we analyze the mechanical implications of the opposing oscillating magnet currents and the coil temperature increase.

The mechanical behavior during a quench of block coil was already analyzed by us in a simplified case [11]. In that case, we did not consider a realistic protection scheme but assumed that the entire winding was uniformly brought to normal state at a given time. The simulated maximum stress after a quench was higher than that during the magnet assembly or operation process. This paper extends and deepens the previous work by considering a realistic protection system (CLIQ) and including also a second type of magnet design.

In this paper, 2D finite element mechanical simulation model of the  $\cos$ - $\theta$  and block magnet cross-sections are established in the commercial simulation software COMSOL [12]. The model geometries are based on the above-mentioned magnet designs. The analyses consider the Lorentz force, thermal stress and stresses resulting from the pre-load and cool down of the magnets. The thermodynamic behavior of the magnet during quench is done using the STEAM co-simulation framework [13] with COMSOL [14], LEDET [15] and PSPICE and results are used as a load to the mechanical model.

The paper is organized as follows: in Section 2 we introduce the two magnet cross-sections and CLIQ protection configurations. In Section 3 we describe the mechanical modeling for calculating the stress during a quench. The calculated results are given in Section 4 and some conclusions are proposed in Section 5.

# 2. Magnet and CLIQ configuration

In order to reduce the amount of the conductor and decrease the coil size, the magnets designed at INFN and CEA are optimized by using two different Nb<sub>3</sub> Sn cable geometries for high field and low field regions [2,4,16,17]. The cross-sections of  $\cos$ - $\theta$  and block magnets are shown in Fig. 1. It can be seen that both magnets consist of four layers. The magnetic flux density distribution in iron yoke and coils at nominal

current is also displayed. Fig. 2 presents the  $\cos\theta$  and block magnet components in detail. The Lorentz forces in the *x* and *y* direction at the nominal current are shown in Table 1. Although the final FCC magnets will have a double-aperture configuration, this work focuses on the single aperture model magnets.

The CLIQ configurations considered in this work are shown in Fig. 3. The performance of a CLIQ depends on the location of its terminals [18]. One configuration is that one CLIQ unit connected between the two double pancakes, which is convenient for the CLIQ leads to connect into the splices between pancakes. This configuration is referred as "first configuration" in this paper and analyzed at the 105% nominal current. The first CLIO configuration is designed for the earlier magnet version in the EuroCirCol project and 105% of the nominal operation current is taken as the design criterion for quench protection system and mechanical structure. For cos-0 magnet, there is another configuration where a CLIQ unit is connected between the layers of the outer double-pancake. In this case the CLIQ lead connection is technically more challenging, but the induced internal voltages during quench are lower. We refer to this configuration as the "second configuration" in the rest of this paper and it is analyzed at nominal current. Now, the nominal current is taken as the design criterion for quench protection system and mechanical structure.

## 3. Mechanical analysis

#### 3.1. Mechanical model and simulation flow chart

The mechanical behavior of the 16 T FCC cos- $\theta$  and block magnets with the CLIQ protection during a quench is discussed and studied in detail now. The 2D finite element model is built in COMSOL to study the mechanical behavior of the magnet in the CLIQ protection system. The mechanical stress analysis is similar to our previous paper considering a uniform quench [11]. The mechanical analysis with the CLIQ protection is carried out considering the four steps: (i) Key insertion process i.e. the pre-loading; (ii) Cool-down process; (iii) Excitation process; (iv) Quench process. The steps (i)-(iii) are already analyzed using ANSYS during the magnet mechanical design [19]. We repeat the



Fig. 1. Magnet cross section with its iron yoke and coils made of two different Nb<sub>3</sub>Sn cables: (a)  $\cos\theta$  (b) block.

F<sub>v</sub> Lorentz force



Fig. 2. One fourth of the magnet structure with materials associated to each component and different coil region.

-3300 KN/m

Table 1   Magnet parameters.						
Cos-0 (v22b 37optd7f8)		Block (v20ar)				
Peak field	16.39 T	Peak field	16.74 T			
Nominal current	11,240 A	Nominal current	11,470 A			
F <sub>x</sub> Lorentz force	6900 KN/m	F <sub>x</sub> Lorentz force	8000 KN /m			

-3800 KN/m

analysis in the next part and is regard it as a validation of our modeling implementation for  $\cos$ - $\theta$ .

F<sub>v</sub> Lorentz force

During the magnet coil current oscillations, the magnetic field distribution is solved from the Maxwell's equations considering the magnetic quasi-state analyses. Once the magnetic flux density distributions are obtained for each calculated time, the Lorentz forces are computed as:  $\mathbf{f}_L = \mathbf{J} \times \mathbf{B}$ ,  $\mathbf{F}_L = \iint \mathbf{f}_L ds$ , where **B** is the magnetic flux density vector, and **J** is the current density vector,  $\mathbf{f}_L$  is the force density and  $\mathbf{F}_L$  is the total force.

A 2D plane stress model of the magnet cross-section is employed. The coils are considered as orthotropic materials, and other components are considered as isotropic material. The material properties for the each component are listed in Table 2. These parameters are extracted from experimental data for High-Luminosity LHC prototype magnets, which have been tested in US LARP [20] and CERN [21]. The same parameters are used in all mechanical design studies within the EuroCirCol 16 T dipole development. The orthotropic material's constitutive equations for the 2-D case can be given as:

Table 2			
Mechanical	properties	of the	materials.

Component	Material	E(GPa)		α
		293 K	1.9 K	$\rm RT \rightarrow 1.9~K$
Coil block	Nb <sub>3</sub> Sn	$E_{x}, E_{\theta} = 25,$ $E_{y}, E_{r} = 30,$ $G_{xy},$ $G_{r\theta} = 21$	$E_{x}, E_{\theta} = 27.5,$ $E_{y}, E_{r} = 33,$ $G_{xy}, G_{r\theta} = 21$	$\alpha_x, \alpha_\theta = 3.1 \times 10^{-3},$ $\alpha_y, \alpha_r = 3.4 \times 10^{-3}$
Magnetic pad, key	Steel 316LN	193	210	$2.8 \times 10^{-3}$
Shell	Aluminium 7050	70	79	$4.2 \times 10^{-3}$
Magnetic yoke, pusher	Iron	213	224	$2.0 \times 10^{-3}$
Pole	Ti6Al4V	115	126.5	$1.7 \times 10^{-3}$
Shim	G10	30	30	$2.5 \times 10^{-3}$
Wedge(cos- θ)	Copper	100	110	$3.37 \times 10^{-3}$
Filler(block)	Al-bronze	110	120	$3.12 \times 10^{-3}$

$$\begin{bmatrix} \varepsilon_i \\ \varepsilon_j \\ \gamma_{ij} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_i} & -\frac{\upsilon_{ji}}{E_j} & 0 \\ -\frac{\upsilon_{ij}}{E_i} & \frac{1}{E_j} & 0 \\ 0 & 0 & \frac{1}{G_{ij}} \end{bmatrix} \begin{bmatrix} \sigma_i \\ \sigma_j \\ \tau_{ij} \end{bmatrix} + \begin{bmatrix} \alpha_i \\ \alpha_j \\ 0 \end{bmatrix} T$$
(1)



Fig. 3. Electrical connection schemes for two different CLIQ configurations. (a) 20 mF 1200 V one CLIQ unit (b) 50 mF 1250 V one CLIQ unit. The color map in the magnet presents temperature at the end of the quench without the hot spot turn.



Fig. 4. The electro-thermal-structural analysis for the 16 T cos- $\!\theta$  and block magnets.

where  $E_{i_b}E_j$  and  $v_{ij}$ ,  $v_{ji}$  are Young's modulus and Poisson's ratio;  $\sigma_i$ ,  $\sigma_j$  and  $\tau_{ij}$  are normal and shear stresses; and  $\varepsilon_i$ ,  $\varepsilon_j$  and  $\gamma_{ij}$  are normal and shear stains;  $\alpha_i$ ,  $\alpha_j$  are coefficient of thermal expansion; *i* represents the *x*, *r* and *j* represents the *y*,  $\theta$ .

The bladder and key technology is used to provide a pre-load [22]. At the key insertion process, the horizontal and vertical assembly interferences between the key and the iron yoke are  $600 \,\mu\text{m}$  and  $10 \,\mu\text{m}$ , respectively. Two different types of contact conditions between the magnet components are applied: the contact condition between Layer 4 and steel pad, keys and iron yoke, iron yoke and Al shell are set sliding; the contact condition between other components is set sticking. As for the boundary conditions in the left side and the bottom side (the symmetry axes), we set  $\mathbf{u} \cdot \mathbf{n} = 0$ , where  $\mathbf{u}$  and  $\mathbf{n}$  are the displacement vector and the unit vector normal to the symmetry axes, respectively. The boundary condition of the outer surface of the shell is displacement free.

The sequential coupling analysis method is employed. At selected time instants the 2-D profiles of temperatures and Lorenz forces are used as a load input into the mechanical model and the stresses are computed. The simulation strategy in Fig. 4 shows the electro-thermal-structural analysis for the 16 T  $\cos-\theta$  and block magnets in the CLIQ protection during a quench.

## 3.2. Verification of the model

We calculate the stress before a quench and compare the results obtained from the present model of  $\cos$ - $\theta$  magnet to those presented in [19], which is computed with commercial software ANSYS. The maximum Von Mises stresses in the coils are reported in Table 3. The largest

# Table 3

Simulated Von Mises stress at different steps. The results from the COMSOL model for the  $\cos\theta$  are compared to the magnet mechanical design reference values, which were obtained from ANSYS simulation [19].

	Von Mises stress (MPa)		Error (%)
	COMSOL	ANSYS	
Key insertion	113	118	4.2
Cool-down	201	212	5.2
Excitation at the nominal current	166	165	0.6

difference between the simulated Von Mises stresses is 5.2% and it occurs after the cool down. Reasons can be the different meshes and different non-linear solvers. Although these differences exist, we assume that this analysis verifies our model implementation and allows us to do predictions for the mechanical behaviors in the CLIQ protection during a quench.

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The Von Mises stress distributions in the coils at different analysis steps are shown in Fig. 5. The maximum Von Mises in the coils is 113 MPa at warm and 201 MPa after cool-down. It decreases to 166 MPa when the magnet is excited by the nominal operation current. The maximum Von Mises is located at the low field cable (layer 3) during key insertion and at the high field cable (layer 2) after cool down process. After the excitation process, the maximum Von Mises occurs in the low field cable (layer 4) again.

## 4. Stress analysis during a quench

The analyses of the mechanical behavior of the two magnets during a quench without or with hot spot turn are considered separately. Case (a), the quench protection system is activated when a natural quench has not occurred, which means that all the turns are still superconducting when CLIQ is activated. Case (b), the simulation considers a hot spot turn (a turn with a natural quench). The difference between the hot spot turn and other turns is that during the 21 ms detection delay, heat is generated in the hot spot turn whereas the other turns remain superconducting and at operation temperature. The 21 ms detection time delay is considered for calculating the hot spot temperature, which is the maximum temperature reached during the quench process. The hot spot temperature is calculated under the adiabatic assumptions, assuming 20 ms detection time delay (including validation) and 1 ms firing delay before CLIQ system is active.

## 4.1. CLIQ activation without initial quench

We consider the quench protection system is activated at 0 ms. Fig. 6 shows the changes of current and maximum temperature in the coils during a quench. There are oscillation currents in the coils at different position before 100 ms and after that, the current in the magnet decreases quickly. The maximum temperature in the coils increases and levels off after 200 ms. The maximum temperature reaches 195 K, 203 K for  $\cos-\theta$  with the first configuration and the second configuration, respectively. For block magnet, it reaches 228 K after a quench.

The temperature distributions in the both magnets after a quench are shown in Fig. 7. The biggest difference between the results obtained for the two CLIQ configurations of the  $\cos$ - $\theta$  magnet resides in the location of the maximum temperature. The maximum temperature is located in the layer 3 for the first CLIQ configuration, while it is located in the layer 4 for the second CLIQ configuration. The different maximum temperature location is due to the different CLIQ lead locations. However, the location of maximum Von Mises stress after the quench is the same for two CLIQ configurations as shown in Fig. 7. The location of the maximum Von Mises stress is similar to the insertion process. With



Fig. 5. Von Mises stress distribution in the coils at different steps: (a) Key insertion, (b) Cool down, (c) Excitation at the nominal current.



Fig. 6. The magnet current decay and maximum temperature development for (a) the first configuration and (b) the second configuration.



Fig. 7. The temperature and Von Mises stress distributions at the quench time 500 ms for (a) the first configuration and (b) the second configuration.

the overall temperature increase, the additional thermal expansion of coil leads to the higher stress. The maximum temperature in the block magnet is 32 K higher than in the cos- $\theta$  magnet with the first CLIQ configuration. However, there is not much difference in the maximum Von Mises stress (block is only 3 MPa higher compared to the first configuration for cos- $\theta$ ). In fact, the location of the maximum temperature in the block is not same as that of the peak stress, and the

temperature shows the negligible effect on the peak stress.

The time evolution of maximum Von Mises stress and maximum stress in r,  $\theta$  directions for cos- $\theta$  magnet and in x, y direction for block magnet are shown in Fig. 8. The maximum Von Mises stress has a local extreme value due to the CLIQ current oscillations at 20 ms for both magnets. This is attributed to the oscillation currents, which occurs at the same time, renders a maximum Lorentz force during the quench



Fig. 8. The maximum Von Mises stress and maximum stress in r,  $\theta$  direction and in x, y direction variation for (a) the first configuration and (b) the second configuration.

process. When the oscillation currents decline, the Lorentz force reduces and consequently the stress declines too. As time goes on, the thermal stress becomes significant and peak stress increases again. The maximum Von Mises stress occurs at the end of the current decay, i.e., when the maximum temperatures in the magnet are reached. The CLIQ current oscillations do not cause increasing the stress. This observation, now with real protection system, strengthens the conclusion made in [11] that it looks like it is enough to consider the stress at the end of the quench for finding the maximum Von Mises stress. However, with lower overall temperature increase, or with higher oscillation of magnet currents, this might not be the case.

The maximum stress in the r direction decreases for the cos- $\theta$  magnet after 20 ms and it has same the trend as the maximum stress in the  $\theta$  direction. The maximum stress in the r,  $\theta$  direction is lower than that at the end of the quench. For the block magnet, the maximum Von Mises stress and stress in the x direction have the same trend. The maximum stress in the y direction decreases after a modest 10 MPa increase soon after the CLIQ activation. After 300 ms, the current and temperature do not vary notably anymore and the maximum stress levels off for both magnets. However, the maximum stress in r direction at the 20 ms for cos- $\theta$  is higher than the maximum Von Mises stress at the end of the quench. The maximum stress in the x direction at the end of the quench. The maximum stress in the x direction at the end of the quench. The maximum stress in the x direction at the end of the quench. The maximum stress in the x direction at the end of the quench is also higher than the maximum Von Mises tress for block magnet at the end of the quench. This additional constraint should to be included in the mechanical design.

## 4.2. CLIQ activation with initial quench

The previous case considered situation where quench protection system is ignited e.g. due to false detection. Now we consider the situation with a spontaneous quench and consider the effects of the hot spot turn on the stress. First, the hot spot turn located in the cable leading to the highest hot spot temperature is considered. Fig. 9 shows the oscillating transport currents after CLIQ discharge and hotspot temperature development during the quench time. The hot spot temperature and Von Mises stress distributions in the magnet cross section after the quench are shown in Fig. 10. For the  $\cos\theta$  magnet, the hot spot temperature reaches 310 K and 284 K after quench with the two CLIQ configurations, respectively. The hot spot temperature is 347 K for the block magnet. The location of the peak stress is the same as without considering the hot spot turn. The local temperature causes the higher stress for  $\cos\theta$  with the first configuration. The peak stresses do not change too much since the location of the hot spot turn is not same as that of peak stress for block with the first configuration and for  $\cos\theta$  with the second configuration. The initial quench occurring in the layer 4 for the first configuration and in the layer 3 for the second configuration were further studied. The maximum Von Mises stress variation during a quench without and with hot spot is shown in Fig. 11. When the hot spot turn and the peak stress are located in the layer 3, the hot spot temperature has influence on the peak stress. The hot spot turn and the peak stress do not occur in the same location and the hot spot temperature has a negligible effect on the peak stress. This indicates that the layer 3 is a risky area and magnet designer should avoid high temperature occurring in this area. For the block magnet, the additional thermal expansion of the hot spot turn has a negligible effect on the peak stress. The location of the maximum stress after a quench appears in the high field coil which is closer to the center of the pole. This can be scenario for a beam loss induced quench also in graded magnets.

Although some Nb<sub>3</sub>Sn magnets can bear 260 MPa with no degradation [23], the mechanical properties of the cable for FCC are still studied and development of advanced Nb3Sn wire is ongoing. It is hard to set a suitable safety limit, but 200 MPa is accepted as a design criterion. Experiments are needed to validate the analysis presented here, and for finding the highest tolerable stress under the transverse load. This paper's primary purpose is to present that in the current designs the peak stress occurs during a quench. In the considered cases the thermal expansion of the winding increased the maximum Von Mises stress notably (51 MPa and 48 MPa from the excitation for  $\cos$ - $\theta$ without considering the hot spot turn for two CLIQ configurations,



Fig. 9. The current in the different coil introduced by CLIQ and the hot spot temperature developed when the initial quench occurs in a location leading to the highest hot spot temperature during the quench time. (a) First configuration. (b) Second configuration.



Fig. 10. The hot spot temperature and Von Mises stress distributions after a quench. (a) the first configuration. (b) the second CLIQ configuration.



**Fig. 11.** The maximum Von Mises stress during a quench without and with hot spot turn. (a) cos-θ for the first CLIQ configuration. (b) block for the first CLIQ configuration. (c) cos-θ for the second CLIQ configuration.

respectively; 31 MPa from the excitation for block without considering the hot spot turn). That may cause limitations to the design of high field accelerator magnets, and require including the quench mechanical analysis in the design of magnet cross-section and mechanical structure.

## 4.3. Coil displacement

The coils displacement is an important factor that should be considered in the design of high field accelerator dipole magnets. Large coil displacement will affects the field quality and change the coil shape. Some changes during quench may not restore for the next cool down. For  $\cos-\theta$  magnet, the positional accuracy of the coil is suggested in the range of 20 µm after excitation [24]. Therefore, it is important to consider coils displacement during a quench.

The coils relative displacement during a quench is presented. Here we consider the relative displacement of the two magnets' coils between before and after a quench for the first CLIQ configuration. Fig. 12 shows the relative displacement of the coil key points. The maximum relative displacement reaches  $325 \,\mu\text{m}$  and  $184 \,\mu\text{m}$  for the cos- $\theta$  and block, respectively. Since the influence of the displacement on the magnetic field is not taken into account in our model, the influence of the displacement on the magnetic field must be further studied.

#### 5. Conclusions

The mechanical behavior during a quench of CLIQ protected  $\cos\theta$  and block main dipole designs for the FCC has been presented. The influence of insertion, cool down, excitation, temperature and current evolution during the quench are considered. Two CLIQ configurations are taken into account for the  $\cos\theta$  design and one for the block design. Quench behavior with and without hot spot turn are studied. The mechanical relative displacements due to mechanical stress are also reported.

The maximum Von Mises stress with the hot spot turn is higher than without the hot spot turn for the  $\cos\theta$  and block magnets. The thermal expansion of the winding increases the maximum Von Mises stress notably (51 MPa and 48 MPa from the excitation for  $\cos-\theta$  without considering the hot spot turn for two CLIQ configurations, respectively; 31 MPa from the excitation for block without considering the hot spot turn). In the analyzed cases the largest Von Mises stress occurs at the end of the quench process. However, this observation should not be taken for granted for any magnet design due to limited number of cases considered, and the simplified modeling using 2D model with homogenized coil internal structure.

The results suggest that in the design of high energy high field magnets, the stress related to a quench should be considered. The



Fig. 12. The relative displacement of the coil key points before and after a quench. The cos- $\theta$  and block are considered in the first CLIQ configuration.

analysis shows that the coils may have stresses above the 200 MPa safety limit. In order to obtain more accurate modeling and better knowledge about the limits, future work should address analysis of coils material parameters and maximum allowed stress for different coils under the transverse load.

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