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**The LHC Incident in Sector 3-4: A Simplified Mechanical Model
to Explain the Mechanical Damages**

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Abstract

On the 19th of September 2008 during powering tests of the LHC main dipole circuit in sector 3-4 an electrical fault occurred. A part of the most important resulting damages were caused by the displacements of cryostated cold masses due to the effect of an over pressurization in the insulation vacuum enclosure. The relative displacement of the interconnected units was resulting in mechanical and electrical damages. Main objects concerned were the mechanical interconnect and the magnet bus bar system. Furthermore electrical arcs induced open breaches in the helium enclosure. In this paper a simplified dynamic numerical model is described to reproduce the observed mechanical defects. In addition the analysis indicates that only a few parameters are dominating the physical quantities in this very complex event.

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The LHC incident in sector 3-4: A simplified mechanical model to explain the mechanical damages

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Abstract—On the 19th of September 2008 during powering tests of the LHC main dipole circuit in sector 3–4 an electrical fault occurred. A part of the most important resulting damages were caused by the displacements of cryostated cold masses due to the effect of an over pressurization in the insulation vacuum enclosure. The relative displacement of the interconnected units was resulting in mechanical and electrical damages. Main objects concerned were the mechanical interconnect and the magnet bus bar system. Furthermore electrical arcs induced open breaches in the helium enclosure. In this paper a simplified dynamic numerical model is described to reproduce the observed mechanical defects. In addition the analysis indicates that only a few parameters are dominating the physical quantities in this very complex event.

Index Terms—Dynamic finite element model, Mechanical displacement of magnets in the LHC sector 3-4.

I. INTRODUCTION

THE simplified FEA model to explain the mechanical damages after the incident in 2008 includes the estimated mechanical loads which occurred during the accident. The computation of the mechanical displacements as well as the observed deformations in the linear elastic and plastic domain should answer the following questions:

- 1) Can the observed cold mass and cryostat displacements be explained by the known mechanical parameters of the entire magnet chain?
- 2) Are the observed residual displacements after the incident representing the maximum values or are larger dynamic displacements responsible for the damage observed on the cold mass and cryostat?

Figure 1 represents a schematic layout of the vacuum subsector assembly in the LHC [3]. The support post for room temperature and the one for 1.9 K are symbolized. In addition one can see the dipole to dipole and dipole to quadrupole interconnections [4], [5].

Fig. 1. Schematic view of subsector in the LHC area; SV: Safety valve; QV: Quench valve; Line E represents the thermal screen.

II. MECHANICS OF INCIDENT

Assuming that the magnets and their cryostats have moved due to the mechanical load which was generated by the overpressure inside the insulation vacuum enclosure, one can focus the study to the regions which are surrounding the vacuum barriers of the Short Straight Sections (SSS) containing the Main Quadrupole (MQ) magnet. Two subsequent cells constitute a vacuum subsector sharing a common insulation vacuum. The insulation vacuum enclosures of neighboring subsectors are separated by so called “vacuum barriers” (7).

TABLE I SUMMARY OF OBSERVED RESIDUAL LONGITUDINAL DISPLACEMENTS IN [MM]. AREA WHICH IS ANALYZED BY THE DESCRIBED FEA HIGHLIGHTED IN BOLD.

Index	Q21	A22	B22	C22	Q22	A23	B23	C23	Q23	A24	B24	C24	Q24	A25	B25	C25	Q25
Cryostat	<2	<2	<2	<2	-7	<2	<2	<2	-187	<2	<2	<2	<2	<2	<2	<2	<2
Coldmass	<2	<2	<2	<2	-20	-65	-104	-141	0	-186	-127	-70	<2	<2	<2	<2	<2

Index	Q25	A26	B26	C26	Q26	A27	B27	C27	Q27	A28	B28	C28	Q28	A29	B29	C29	Q29
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	474	-4	<2	<2	11	<2	<2	<2	<2
Coldmass	<2	<2	<2	<2	<2	57	108	168	-38	232	188	145	95	70	35	3	<2

On the SSS element the pressure has produced the longitudinal forces which have caused the cold mass and cryostat displacements [1]. The validity of this assumption is comforted by the following observation: The cold mass displacements have their highest values close to the SSS equipped with vacuum barrier. Table 1 represents a summary of the observed residual longitudinal displacements. It clearly is confirming the staging of the displacements when moving away from the vacuum barriers in Q23 and Q27 [1]. These barriers are bounding the subsectors and the displacement values decrease gradually towards the neighboring half cells. Figure 2 is showing the schematic view of the vacuum pressure distribution on the cold mass and the insulation vacuum barrier [1]. The pressure reached about 0.8 MPa (8 bar) absolute, resulting in large axial forces on the insulation

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Paolo Fessia, Federico Regis, Friedrich Lackner
European Organization for Nuclear Research, TE department
CERN, Geneva 23, 1211 Geneva, Switzerland; Phone: +41-22-76-73291;
e-mail: Paolo.Fessia@cern.ch; Friedrich.Lackner@cern.ch

of the vacuum separations in between the subsectors. This axial force was equal to 560 kN.

Fig. 2. Pressure load on the magnet cold mass and insulation vacuum barrier

One third of this force was absorbed by the cold mass and two thirds by the vacuum barrier. The force absorbed by the cold mass was therefore transmitted to the outer vessel of the cryostat via the cold support posts [1] as it can be deduced by the formulation below.

Equation (1) and (2) are defining the amount of pressure which was applied on the cold mass (F_{CM}) and the cryostat (F_{Cr}). The vacuum pressure (P_{VAC}) is applied on the circular ring cross-section formed by the cold mass (diameter d_{CM}) and the cryostat (diameter d_{Cr}) resulting in the cryostat force. The cold mass force is given by vacuum pressure applied on the entire cross-section surface plus the force induced by the pressure inside the cold mass (P_{CM}) which is applied on the bellows (diameter d_{Mbell}).

$$F_{CM} = p_{vac} \frac{\pi}{8} (d_{CM}^2 + d_{Cr}^2) + 3p_{CM} \frac{\pi d_{Mbell}^2}{4} \quad (1)$$

$$F_{Cr} = p_{vac} \frac{\pi}{8} (d_{Cr}^2 - d_{CM}^2) \quad (2)$$

The cold support posts (Fig. 3 left) failed after exceeding the material limitations due to the high shear stresses. Due to a rapid succession the total force was applied to the external support jacks (Fig. 3 right). The extensive amount of force was causing the displacements of the cryostats. In the worst case condition this was leading to rupture the ground anchors or the concrete basement of the tunnel [1], [6].

III. DESCRIPTION OF THE MECHANICAL SYSTEM

This study is focused to the region around the SSS in the so called Q23 position on the right side of Point 3 (Q23 see Tab. 1). Furthermore the model is including the LHC arc going from Q22 to Q24 [3]. Table 1 lists the measured values of the longitudinal displacement of the cold masses with respect to the cryostats and of the cryostats with respect to ground, positively counted towards Point 3.

The following main components are represented in the simplified numerical model:

- 1) The magnet cold masses are given by two types, the main dipole cold mass (28000 kg) and the main quadrupole cold mass (6300 kg).
- 2) The cryostats are given by two types, the main dipole cryostat with a mass of 4500 kg and the SSS cryostat also including the Cryogenic Service Module (QQS) with a mass of 1800 kg.
- 3) The cold support posts [6]: These are the elements which

are supporting the cold masses inside the cryostat. One has to separate between dipole and SSS type.

The support concept is based on one fixed support in both types [3]. The dipole cold mass is furthermore guided on the two additional supports on both extremities. The SSS is guided in one additional support point.

Both types are represented by a very stiff joint (see Fig. 3) which blocks the relative movement of the two interconnected objects. The mechanical limit is given by the material strength of these support posts. The breaking strength is shown in Table 2. Therefore, in case the mechanical stress on the post is becoming higher than the maximum allowable mechanical strength the post breaks and the two objects have the possibility to move with respect to each other. This movement is based on a friction coefficient and appears in certain degrees of freedom. In the finite element model this friction coefficient was set to 0.1.

- 4) The external support jack (Fig. 3) to the ground [3]: The anchoring of the cryostat to the ground is based on alignment jacks. As for the cold support posts these elements should also block the movement of the cryostat with respect to the ground until the mechanical stress gets larger than their mechanical strength. In this case the mechanical limit is not exactly given by the mechanical strength of the jack itself but rather by the studs anchoring of the jack into the concrete tunnel basement. Also in this case a material failure of the anchoring enables the relative movement of the cryostat with respect to the ground. The translation is characterized by a friction coefficient which was arbitrary set to 0.3 in the described numerical model.

Fig. 3. Left: Cold support (Glass-fiber epoxy) Right: Alignment jack

- 5) The cold mass interconnects [5]: each cold mass is interconnected with their two neighboring elements. The main objects for the interconnection are given by bellows. The stiffness of these bellows defines the exchanged load between the cold masses in case of relative displacements. These interconnects include the following lines: V1, V2 (Beam-lines); M1, M2, M3 (Bus bar); X (Heat exchange) and N (Auxiliary bus bar).
- 6) The cryostat interconnects: Each cryostat is interconnected to the two neighboring elements. The main stiffness for the interconnection is also given by bellows. This interconnects include the following lines: C (Cryogenic support); E (Thermal screen) and the W bellows (Vacuum enclosure).

IV. THE MODEL

The approach chosen is to build a finite element, lumped-mass model using the code ANSYS.

- 1) Each magnet cold mass is represented by a point-like mass element.
- 2) Each cryostat is represented by a point-like mass element. For the implementation the same element type was chosen as for the magnet.
- 3) Interconnects are modeled using non-linear spring elements with different load-displacement characteristics in the compressive and tensile domains. These characteristics are deduced from the known constructional features of each bellow. Unfortunately these characteristics are only known for the standard operation conditions. The characteristics used in the model were therefore extrapolated to full extension and compression.
- 4) The cold post and the ground anchoring are modeled by two different elements parallel to each other:
 - a. The first element describes and simulates the action of the support post or ground anchoring. This element allows blocking the displacement till the moment in which the load on this element is becoming higher than its strength. This would then cause the breakage of the concerned element. When the load is higher than this limit the element reduces its stiffness to a very small value.
 - b. The second element simulates the friction between the support post and the sliding pad or between the ground anchoring and the concrete basement when movement is allowed.

Table 2 shows the relevant parameters for the dipole and short straight section magnets. These parameters were used for the computation.

TABLE II PARAMETERS FOR THE COMPUTATION

Unit	Dipole	SSS
Mass of cold mass	28000 Kg	6200 Kg
Mass of cryostat	4500 Kg	1800 Kg
Cold foot strength	50 kN	150 kN
Friction of cold feet	0.1	0.1
Jack strength	100 kN	100 kN
Jack friction after breakage	0.2	0.3

Figure 4 shows a simplified sketch of the model. One can see the lumped mass elements for the cold mass and the cryostat. The vertical lines are symbolizing the elements used to simulate the friction effects in the support posts. In addition it corresponds to the elements used to simulate the post breakage after exceeding the material limitations. The spring elements are showing the interconnection based on the non linear spring elements described above.

Fig. 4. Simplified visualization of the FEA model implementation

The model was implemented based on the finite elements listed in Table 3.

TABLE III FINITE ELEMNTS

Interconnection cryostat	Combin39
Interconnection magnet	Combin39
Mass dipole	Mass 21
Mass SSS	Mass 21
Dipole support	Combin40
SSS support	Combin40
Support friction	Contact12

V. RESULT

In order to validate the model, two different comparisons can be made with respect to the observations which were performed in the tunnel after the incident.

- The final displacement of the cold masses:

Figure 5 shows the comparison between the measured values and the results of the simulation. One can see the good correlation between the two series of data. It shows that the dynamic effects using an FEA approach are describing the remaining residual displacements of elements in good agreement in comparison to the measured values.

Fig. 5. Measured cold mass displacement and cryostat displacement in comparison to the results obtained by FEA

- Comparison to observed plastic deformations:

In one case (interconnect QBQI.23) an estimation of the maximum displacement of the cold mass during the dynamic effect was available. The indication was possible due to the plastic deformation of a steel sheet which is protecting the interconnect region. At this location the steel sheet has been compressed between the supporting rings of the W bellows. The plastic deformation of the steel sheet is visible in Fig. 6. It was therefore possible to measure the difference between the final bellows length and the final deformed state of the steel sheet. This difference was measured to be 180 mm confirmed by the model which is explained below.

Figure 7 is showing the computed forces on the cold support posts in function of time. For simulation stability reasons the time zero of the incident is taken at the time step of 4 s in the computation.

Fig. 6. QBQL23R3 interconnection showing the plastic deformation of the protective sheet.

From this graph we can derive in which sequence the forces were applied to the magnets involved. One can see that the first magnet exposed to longitudinal forces was the Q23. The cold support material strength was reached after 5 s causing its failure. The forces are afterwards dropping to zero and are applied on the external support jack which implies force larger than zero due to friction based displacement on the cold mass support. In addition the graph shows that after the breakage of the Q23 cold support at 80kN, the B23 elements cold support was getting exposed to the forces transferred via the interconnect from the Q23. The sequence is continuing within the observed amount of magnets. It stops at about 110s and the remaining residual displacements show good coherence to the one observed in the tunnel.

Fig. 7. Forces on the cold support posts vs. time.

Figure 8 shows the displacements of the cold masses and cryostats over the time. It indicates the residual displacements at the time of 110 s. E.g. the plastic deformation seen on the Q23 magnet steel protection (180 mm) is reproduced to better than 150 mm. The model furthermore was used to compute the speed and acceleration which was seen by the cold masses. The maximum speed was determined to be 0.5 m/s while the maximum acceleration is about 9 m/s^2 .

VI. CONCLUSION

The presented numerical approach was implemented in order to reverse compute the forces and displacements which were causing major faults to the sector 3-4 of the LHC collider. It establishes that the parameters that determine the behavior of the magnet chain are mainly given by the masses of the cold

mass and the cryostat and by the mechanical strength of the cold support posts and of the ground anchors.

Fig. 8. Cold mass and cryostat displacement vs. time

The cold masses in the damage zone of sector 3-4 have experienced much larger displacements than those measured after the incident, in the worst cases a factor of two larger. These large displacements have created important damage on the bus bar system causing secondary electrical arcs and secondary breakage of the helium containment. The computation furthermore was able to demonstrate the sequence of the cold mass support breakage which was leading to further displacements based on friction. In the last section it was shown that the observed plastic deformation on specific components was reproduced.

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