CONSEQUENCES OF A HYPOTHETICAL INCIDENT FOR DIFFERENT SECTORS

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Abstract

During the 2009 long shutdown, the LHC machine has been partially consolidated by adding safety relief devices in order to better protect the cryostats against large helium release and consequently to mitigate the risks of collateral damages. After recalling the present relief valve implementation and other mitigations related to the collateral damages, this paper describes the damage process of a hypothetical incident, presents its consequences for the different sectors and for beam energies up to 5 TeV with emphasis on the induced downtime.

INTRODUCTION

The 19th September 2008 incident of LHC [1] has created heavy wide-spread damages and collateral damages of the machine like:

- He vessel and beam pipe perforation,
- mechanical damage of MLI,
- contamination by soot of MLI and beam pipes,
- contamination by MLI of vacuum enclosure and beam pipes,
- buckling of bellows,
- rupture of supports and ground anchors,
- damage to tunnel floor,
- mechanical damage to interconnects,
- secondary electrical arcs.

Following this incident, the machine has been repaired and partially consolidated in 2009 in order to restart the operation of the machine at reduced beam energy of 3.5 TeV, i.e. at reduced currents in the main magnets. The new protection scheme of the vacuum enclosure implemented to prevent or limit the pressure build-up in case of large helium release is defined [2]. The long straight sections are fully consolidated, except two Q6 quadrupoles (in R2 and L8). The continuous cryostat of sectors S1-2, S3-4, S5-6 and S6-7 are fully consolidated, as well as the most critical subsectors of the continuous cryostat of the sector S4-5. The remaining parts of the machine are partially consolidated.

A hypothetical electrical arc could appear in a cryo-magnet interconnect like during the September 2008 incident or in a cryo-magnet coil like during the Noell 4 incident in SM18. The corresponding consequences on the machine damages are different and are developed here after for beam energies varying from 3.5 to 5 TeV.

MAXIMUM CREDIBLE INCIDENT UP TO 5 TeV IN CASE OF AN ELECTRICAL ARC IN A MAGNET INTERCONNECT

In case of an electrical arc in a cryo-manget interconnect, up to 3 interconnect lines containing main electrical bus bars can be damaged. However, the corresponding discharged helium flow from the cold-mass circuit to the vacuum enclosure is limited by the free cross-section of the cold-mass laminations which corresponds to 2 x 60 cm^2 [3]. This total cross-section can be created already at a main magnet current of 6 kA corresponding to a beam energy of 3.5 TeV. For the continuous cryostat of LHC, the discharge mass-flow through this breach corresponds to 30 kg/s.

Leaving the cold-mass, the discharged helium is then heated by the power dissipated by the electrical arc. The temperature of the helium heated by the electrical arc power and which has to be discharged through the safety devices protecting the vacuum enclosure depends on:

- the stored magnetic energy,
- the current discharge time constant,
- the heat transferred by convection from the environment.

Figure 1 shows the stored magnetic energy and the discharged helium temperature as a function of the beam energy for the continuous cryostat.

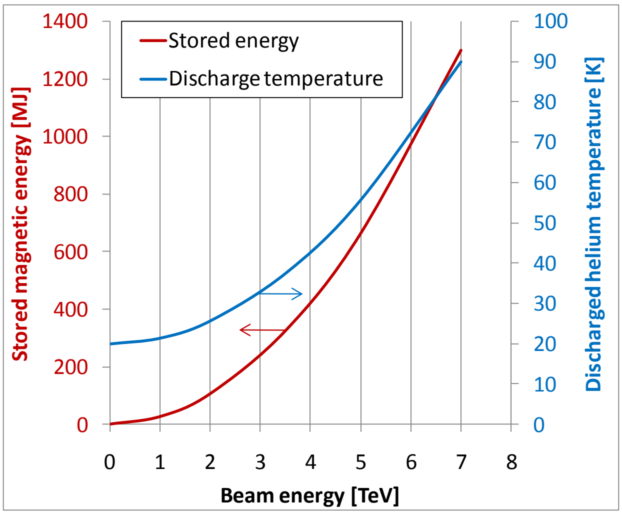

Figure 1: Stored magnetic energy and the discharged helium temperature versus beam energy.

The 19th September 2008 incident occurred at a main current of 8.7 kA which corresponds to a equivalent beam energy of 5 TeV. Figure 2 shows the footprint of the incident electrical arc as well as possible smaller ones. With “smaller” electrical arc (i.e. lower magnetic stored energy and/or lower discharge time constant), perforation of the beam pipe cannot be excluded with the present consolidation status (electrical insulation of the beam pipe interconnects foreseen in the next long shutdown).

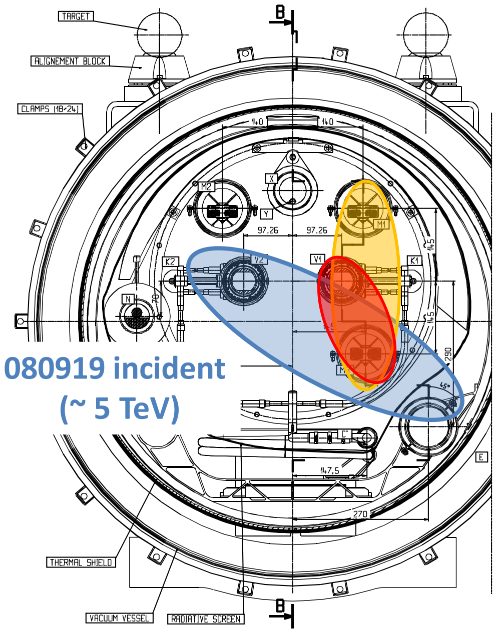

Figure 2: Footprint of electrical arcs.

With the present consolidation status the maximum pressure appearing during a hypothetical incident is shown in Figure 3 for beam energy of 3.5 and 5 TeV.

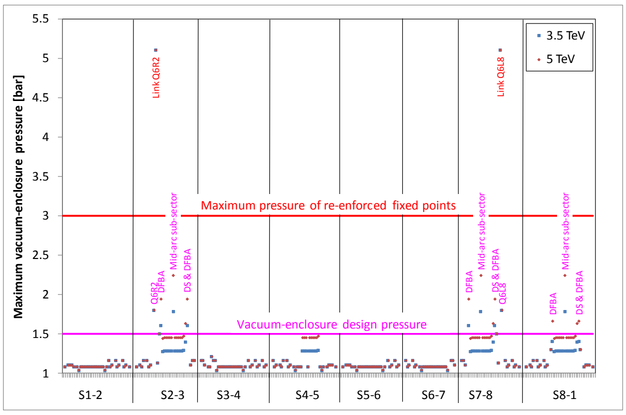

Figure 3: Maximum vacuum enclosure pressure.

Two links of Q6 cryo-magnets (see Table 1) are pressurized above the threshold corresponding to the maximum pressure which can be handled by the reinforced fixed-points (3 bar). These links which have an external diameter of 200 mm can withstand this overpressure.

Other sub-sector vacuum enclosures exceed slightly their design pressure threshold of 1.5 bar (see Table 1). However, the overpressures remain compatible with the design margins of vacuum enclosures. Above 1.9 bar, plastic deformations could occur in the vacuum barriers of the short straight sections; consequently, at 5 TeV, the vacuum barriers of the mid-arc sub-sectors in S2-3, S7-8 and S8-1 could be affected (see Table 1).

Table 1: Maximum pressure in off-design cases

Vacuum sub-sector	**Pmax [bar]**	
	3.5 TeV	5 TeV
Link Q6R2 & Q6	5.1	5.1
Q6R2 & Q6L8	1.8	1.8
Mid-arc S2-3, S7-8 & S8-1	1.8	2.3
DFBA HCM R2, L3, R7 & L8	1.6	2.0
DFBA HCM R8 & L1	1.4	1.7
DS L3, L8 & L1	1.4	1.6

: In conclusion, mechanical collateral damages are no longer expected up to beam energy of 5 TeV. Figure 4 shows the updated fault tree of an electrical arc in a cryo-magnet interconnect up to 5 TeV. Nevertheless remaining damages are:

- He vessel and beam pipe perforation,
- mechanical damage of MLI,
- contamination by soot of MLI and beam pipes,
- contamination by MLI of vacuum enclosure and beam pipes,
- mechanical damage of instrumentation cabling.

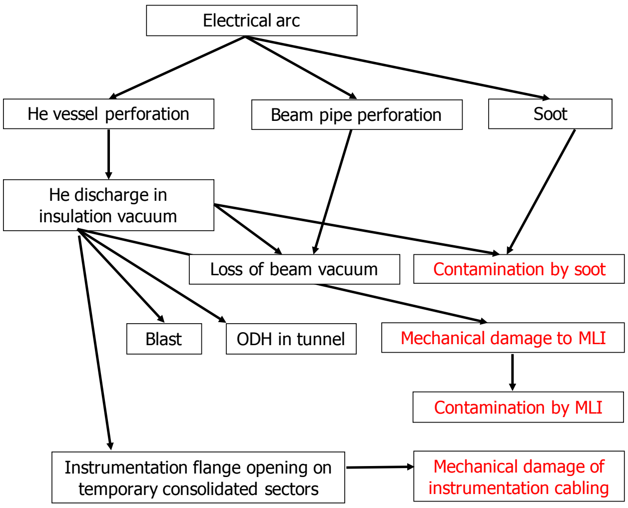

Figure 4: Updated fault tree of an electrical arc in a cryo-magnet interconnect up to 5 TeV.

Contamination by soot of MLI and contamination by MLI of vacuum enclosure will be propagated all over the sub-sector vacuum enclosure, i.e. over a length up to 214 m. These contaminations will affect the thermal performance of the sub-sector cryo-magnets. However, the existing overcapacity margin existing on the cryogenic system could allow postponing the repair to the next scheduled long shutdown.

Helium vessel and beam pipe perforation by the electrical arc will require the immediate removal of the two adjacent cryo-magnets.

The mechanical damage of instrumentation cabling mainly for beam position monitors must be in situ repaired on the four short straight sections of the concerned sub-sector before operation restart.

Concerning the mechanical damage of the MLI, the affected length can be scaled from the 19th September 2008 incident taking into account the frictional pressure drop and the discharge valve distribution. In case of a new incident up to 5 TeV, the affected length is scaled to about 130 m, i.e. about 10 cryo-magnets (2/3 of a standard sub-sector). MLI plays an important role in protection of the cold-mass enclosure in case of catastrophic break of the insulation vacuum by air or by helium. Without MLI, the heat flux entering the cold-mass increase up to a factor 10 (from 5 kW/m^2 to 50 kW/m^2) and the pressure relief system protecting the cold-mass enclosure is definitely undersized. Consequently the mechanical damage of MLI in the cryo-magnets by the high helium flow-rate is critical and need to be repaired before operation restart.

Concerning the contamination by soot of the beam pipe, the affected length can be scaled from the 19th September 2008 incident taking into account the quantity of soot introduced during the beam pipe pressurization. During the September 2008 incident, the V1 beam pipe was pressurized to 3.5 bar (without rupture disk opening) and the corresponding contaminated length was 600 m. In case of a new incident, the beam pipe pressurization is limited to 1.1-1.5 bar, i.e. a factor 2.3 to 3 lower. The new expected affected length will be from 200 to 250 m. The contaminated beam pipes cannot be cleaned in situ and the corresponding cryo-magnet must be transported at ground level for cleaning or must be exchanged before operation restart.

Concerning the contamination by MLI of the beam pipes, the full continuous cryostat (~2900 m) will be affected and must be in situ cleaned before operation restart.

All together up to 14 cryo-dipoles and 4 short straight sections will have to be removed and re-installed. The corresponding repair downtime is estimated to about 8 months. This repair downtime could be extended up to about one year if critical components like current feed boxes are affected.

MAXIMUM CREDIBLE INCIDENT UP TO 5 TeV IN CASE OF AN ELECTRICAL ARC IN A CRYO-MAGNET COIL

In case of an electrical arc in a cryo-magnet coil, the beam pipe is directly perforated. This electrical arc will also create a resistive transition of the magnet producing a pressure increase inside the cold-mass enclosure and the beam pipe. Figure 5 shows the corresponding fault tree and the resulting damages:

- mechanical damage of nested and PIM bellows of the beam pipe,
- contamination by soot of the beam pipe.

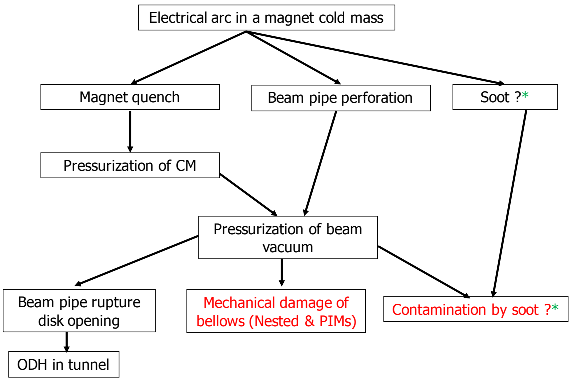

Figure 5: Fault tree of an electrical arc in a cryo-magnet coil.

The mechanical damage of the beam pipe bellows occurs when the pressure reaches the buckling pressure of 3.5 and 5 bar respectively for the PIM and nested bellows. Figure 6 shows the maximum pressure developed in the cold-mass following a dipole resistive transition for two current discharge time constants (tc=100 and 50 s). To remain below the buckling pressure of the PIM bellows, the beam energy has to be limited to 3.5 TeV with a current discharge time constant of 50 s. At 5 TeV, the driving pressure inside the cold mass could reach 17 bar corresponding to the quench-valve setting pressure. The beam pipes are presently protected against pressure build-up by only two rupture disks located at the continuous cryostat extremities. Figure 7 shows the pressure profile of the beam pipes for driving pressures of 10 and 17 bar. In both case, more than 600 m of beam pipe could be affected by the buckling of bellows.

Above a beam energy of 3.5 TeV, a large fraction of the continuous cryostat can be affected by the buckling of bellows. The PIM bellows can be exchanged in situ; the exchange of the nested bellows requires the removal of cryo-magnets.

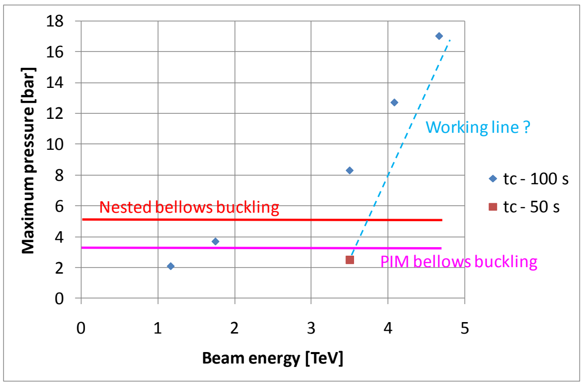

Figure 6: Maximum cold-mass pressure following a dipole resistive transition.

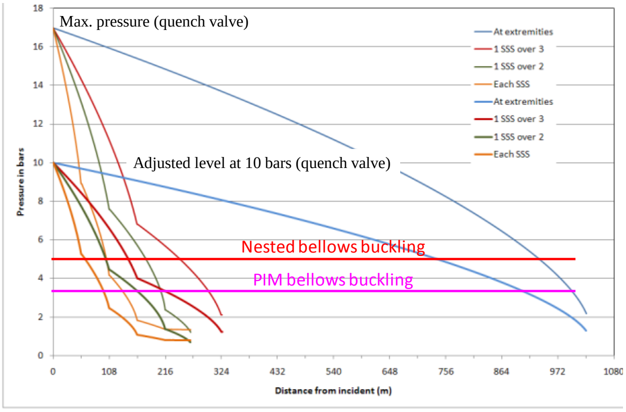

Figure 7: Pressure profile of beam pipes.

CONCLUSION

In case of an electrical arc in a cryo-magnet interconnect, the present consolidation, up to 5 TeV, will suppress mechanical collateral damages in adjacent sub-sectors. Nevertheless, mechanical damage of the MLI in the concerned sub-sector as well as contamination of the beam pipe(s) could require heavy repair work. With the present consolidation status, a new incident will still have big impact on the machine downtime (8 to 12 months).

In case of an electrical arc in a cryo-magnet coil, a limited impact at 3.5 TeV is assumed with only one magnet to be exchanged requiring at least 4 months of downtime. The impact could be more critical above 3.5 TeV with the additional damage of bellows over several sub-sectors.

In conclusion, a hypothetical incident caused by an electrical arc during the 2011/12 operation could seriously impact the LHC physics program. Consequently, corresponding risks must be carefully assessed.

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