STRATEGY FOR CONSOLIDATION TO AVOID INCIDENT AND COLLATERAL DAMAGE

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INTRODUCTION

The session addressed the consolidation programme being planned in the LHC as a consequence of the incident in sector 3-4. Other consolidations already planned and which are neither aimed to avoid an incident similar to that of sector 3-4 nor to mitigate its consequences are the subject of session 5. The quench protection system (QPS) is being upgraded to efficiently protect the bus-bar segments in the main circuits and thus detect a fault similar to the one seen in sector 3-4. The improvement of the vacuum and beam insulation relief system in case of overpressure, and the reinforcement of the supports in SSS with vacuum barrier have been launched to avoid the collateral damage caused by lost cryogenic integrity of magnet system.

INSULATION VACUUM AND BEAM VACUUM OVERPRESSURE RELEASE

Insulation vacuum

In view of the observed displacements of the magnets in sector 3-4 the pressure build-up in the insulation vacuum has been reviewed.

Currently three spring loaded DN90 devices are located in the SSS, 100 m apart. The vacuum vessel and vacuum barrier were designed to withstand the internal pressure under 1.5 bars, corresponding to a maximum helium release with a mass flow of 2 kg/s. However, during the incident in sector 3-4 the internal pressure, estimated from the external bellows deformation, reached 7 bars and an equivalent peak mass flow of 20 kg/s. It is thus clear that the existing pressure relief devices are not sufficient.

Besides, the most accepted maximum credible incident (MCI) scenario contemplates damaging the three main bus bar lines which will rapidly empty the cold mass circuit. This will release the helium at a rate of 40 kg/s. This value of the mass flow is taken to recalculate the pressure build-up in the insulation vacuum and compare the different solutions proposed.

The first proposal is to use all existing ports in the SSS assemblies as pressure relief ports. In an average cryogenic sub-sector one can find four SSS and in each of them two DN100 ports for insulation vacuum equipment, two additional DN100 ports for BPM cable feed-through and one DN63 port for cryogenic instrumentation. Replacing the clamps on 17 out of 20 of these ports by spring load clamps could be done both in cold and warm sectors and would increase the cross section by a factor 10. The pressure build-up in case of a maximum credible incident will reach about 3bars in the vacuum barrier which could be tolerated but is above the limit of the specifications. The fixation to the floor also becomes critical at this pressure. Further testing and possibly reinforcement of the jacks should be envisaged.

The second proposal is to replace the clamped flanges by spring loaded clamps in one DN100 per SSS and to add extra relief devices DN200 in each dipole. The cross section in this case will increase by a factor 33 and the pressure build-up will be reduced below the design values for the vacuum barrier and the floor fixation. However, drilling the holes in the dipole cryostat can only be made in warm sectors. Special cases in the dispersion suppressor and in the mid-arc sub-sector will need a second DN200 valve installed in some dipoles.

Tests of the spring loaded clamps and of the DN200 installation have been made successfully. The provisional schedule for the installation of DN200 relief valves in sectors 1-2, 3-4, 5-6 and 6-7 foresees the end of the task by week 14.

The estimation of the pressure build-up inside the stand alone magnets in the LSS and the inner triplet magnets has not been done yet. The situation for the DFBs has not been studied either.

Beam vacuum

The consequences of the incident in sector 3-4 for the vacuum insulation were an excessive pressurization of the beam tubes leading to the rupture of a burst disk, buckling of the beam vacuum bellows and transport of pollution along the beam tube.

Inside the beam vacuum enclosure, rupture disks are present at the extremities of the arc. The addition of intermediate rupture disks in the arc is being investigated but no implementation is planned yet. They can be added at any time as the ports are already available.

IMPROVED ANCHORING SYSTEM OF SSS WITH VACUUM BARRIER TO AVOID DISPLACEMENT

According to the specification already mentioned in last section, the floor supports are designed to withstand a pressure of 1.5 bar in the vacuum barrier which translates to 120 kN in the supporting system. Tests performed in 2003 showed that the failure limit for exceptional conditions occurred at about 150 kN. It is however known that during the incident in sector 3-4 the pressure exceeded 1.5 bar and that some supports did not resist the longitudinal load.

From the improvement on the pressure relief system suggested in the previous section, the support system for SSS with vacuum barrier in the sectors that will not be equipped with DN200 relief valves needs to be reviewed. The floor supports have to resist to internal pressures of 240 kN (3 bars) compatible with the maximum pressure estimated from a MCI. Besides, the new system has to be installed on the present jacks and has to allow the access to them for future alignment.

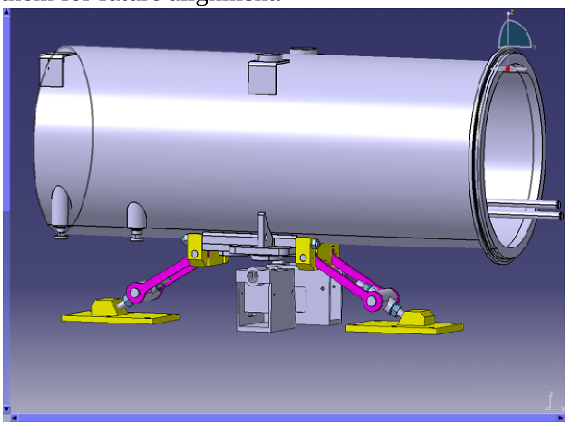

Figure 1: Schematic of the reinforcement structure for the jacks of SSS with vacuum barrier

After some iteration, the retained solution is shown in Figure 1. Stress deformation and contact under load have been verified. A prototype has been already successfully tested. The installation could be done in warm and cold sectors in three phases:

1. Drilling the floor. Needs to be done when no liquid helium in the sector is present for safety reasons. Two weeks per sector.
2. Installing the reinforcement; two weeks per sector.
3. Alignment check. One week per sector.

A total of 25 days per sector is foreseen, compatible with the current planning. It is felt that installing the supports even for those sectors in which the pressure relief valves are going to be implemented is still necessary as the resistance of the supports to 1.5 bars is still marginal.

The DFBA will then become the next weak point in the chain. An equivalent reinforcement is being studied.

BUS BAR JOINTS STABILITY AND PROTECTION

Starting from the fact that on September 19th in sector 3-4an interconnection broke open, two possible scenarios have been worked out to explain the observations. In both cases, a bad longitudinal contact between the wedge and U-profile and the bus-bar stabiliser is needed. A resistive heating in the joint or bus-bar is the other factor needed to reproduce the voltage evolution across the bus-bar. In both cases, the heating produced in the resistive part warms the well insulated splice area. The adjacent, well cooled bus-bars act as quench stoppers. Voltage increase and heat deposition remain localised around the splice area until a resistive transition occurs and propagates. The phenomenon is completed by an extremely fast increase of temperature and voltage called a thermal runaway in which the solder and copper melt breaking the circuit.

According to simulations in both analyzed scenarios, the thermal runaway will be avoided by setting the QPS threshold voltage below 1 mV. A QPS threshold of 0.3 mV is needed to protect the main dipole bus and the joints in all thought-out conditions. This value can possibly be slightly modified when more experimental data (RRR, cooling, propagation speed) become available.

Fast thermal runaways resulting from sudden transient disturbances without intermediate stable heating are not protectable by any QPS system whatever the threshold. To avoid such fast thermal runaways one needs to assure either good thermal contact between joint and U-profile/wedge, or good electrical and thermal contact between the bus-bar stabiliser and the joint. Clamping should be envisaged to ensure the first condition.

The model and conclusions are very similar for the RQ circuits but this issue has not been studied for other magnets.

QPS UPGRADE AND RE-COMMISSIONING

The upgrade of the quench protection system of the LHC has been triggered by two independent events for which two additional protection systems have been developed. The first event was a secondary, thermally activated quench, symmetric between the two apertures of a dipole that went unnoticed for more than half a second. The detection signal that triggers the quench system is based on a difference between the voltage readout signals of the two apertures of a magnet. In the case of the observed in the tunnel symmetric quench, both voltages increased over 4 V while the difference signal stayed well under the voltage threshold (100mV). The MIITS integral that determines the potential damage to the magnet was of 50 MA^2s which indicating potential damage of the magnet. To avoid this pitfall, the new symQ system will compare the absolute voltage across any magnet with neighbouring magnets. The threshold for this new system will be 200 mV. Four adjacent magnets will protect each other and whenever the quench heaters of three of the magnets in a subset have been triggered, the fourth magnet will also be triggered.

The basic design of the SymQ system based on flash FPGA is finished and the prototype is underway. The system will be redundant and independent from the original quench protection system. Tests of the radiation tolerance of the individual components are scheduled.

The second event was the incident in sector 3-4 in which a bus-bar quench was detected but at a threshold known now to be much too high. Local detection of excessive voltage for all bus-bar segments in a circuit is being implemented with a threshold of 300 μV as suggested in the previous section and with an integration time of 10 s. Available voltage taps in the circuits, used up to now only for diagnostics, will be wired to the 1200 DQQBS cards. This system re-uses the existing design for the protection of HTS leads in LHC that has been successfully commissioned. The radiation resistance of these cards also needs to be assessed. The expected resistance resolution of this system is 1 nOhm.

Both systems require pulling 240 km of cables in the LHC tunnel. Additional crates and power supplies will be housed in the existing racks located under the mid dipoles. The impact on the existing QPS system has been minimized.

These systems will only be implemented in the arc dipole and quadrupole circuits. The protection of the bus-bars was proposed for as the first phase and the symmetric quenches at the next shutdown due to a longer delay in the development and production. The energy should then be limited to 4 TeV for the first run. During the discussion, it appeared clear that both upgrades are required for the next LHC start-up. The commissioning of the new QPS system will be carefully done to avoid false triggers. Regular scans of the circuits will be planned to monitor the splices evolution.

RISK ANALYSIS FOR THE DIFFERENT CONSOLIDATION PROPOSALS

Among the solutions proposed in this and other sessions to avoid a similar incident to that of sector 3-4 and its collateral damage we can find:

1. Upgrade the QPS system for detection of bad splices in bus-bars.
2. Update the powering procedures to include calorimetric measurements and electrical measurements in bus-bar segments and magnet.
3. Implement DN200 ports in dipoles in half of the machine.
4. Use the existing SSS ports as pressure relief valves by using spring loaded clamps in the remaining sectors of in all LHC machine.
5. Reinforce the anchoring for SSS with vacuum barrier

A new set of solutions was proposed by J. Strait:

1. Add pressure relief valves or rupture disks in the beam vacuum system.
2. Improve the pressure relief system also in DFBs, stand alone magnets and inner triplet
3. Anchoring of the DFBA supports
4. Provide an intelligent reaction to quenches detected in bus-bars and other sensible equipment either by opening the quench release valves at a lower pressure or by firing more quench heaters to speed up the current decay.

Improving the pressure relief systems for the insulation and beam vacuum is highly recommended at least in warm sectors. However, if applying the same modifications to the other sectors jeopardizes the physics run this year, it is not recommended. A sophisticated reaction to quenches like firing the quench heaters in a large number of magnets seems delicate, should be studied carefully and is therefore not recommended for the near future.

There is the possibility of finding new potentially dangerous splices in the machine after cool down. If the splice is inside a magnet, the eventual damage will be limited to one or two magnet and the consequences of an incident will be indeed minimized by the measures already accepted. The implications of such an accident are then comparable to replacing the same magnet before the run, so it is not recommended to change the magnet immediately but wait for the following shutdown. If a bad splice is however detected in a bus-bar segment, the consequences of an accident are much worse and the repair easier so it is recommended to warm up and repair the splice.

A beam energy of 5 TeV for this year run is considered achievable and at the same time, useful for its potential for physics discovery.