RISK ANALYSIS FOR THE DIFFERENT CONSOLIDATION PROPOSALS

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Abstract

In parallel with the repairs in sector 34, improvements are planned or in progress to a number of systems, to allow safe detection of faults similar to the one which caused the incident of 19 September, and to limit the damage should a similar incident nonetheless occur. These include improved bus and quench detection systems, improved pressure relief for the insulating and beam vacuum systems, and improved anchoring of the SSS to the tunnel floor. Not all of the planned mitigations, however, may be fully implemented before the restart of the LHC in 2009. This paper reviews the potential benefits of partial or complete implementation of each of the planned improvements, individually or together with others, and conversely the potential risks (consequences) of delayed implementation, as well as the risks that remain even after the planned consolidation is complete. It also identifies several improvements beyond the baseline set, that could reduce the risks of future operations. Considering all proposals and the different risks, comments are made on what would be the best strategy for consolidation, and on the strategy for operations under different consolidation scenarios.

INTRODUCTION

This paper concerns risks and mitigations for events of the type that occurred on 19 September 2008 in sector 34[1]. The analysis presented here is limited to the main magnets in the arc common cryostats. Other types of risks and mitigations, including those in the long straight section superconducting magnets (matching section and inner triplet) are addressed in a companion paper[2].

The risk analysis was carried out and the recommendations were developed based on two assumed boundary conditions that were called into question[3,4] during this workshop: that warming up the additional four sectors not initially planned for warmup would result in a delay of several months in restarting the LHC; and that operation of the accelerator complex during the winter would be out of the question. Although relaxation of these boundary conditions would almost certainly result in alteration of some of the conclusions, the contents of this paper reflect the analysis as presented at the workshop, based on the original assumptions.

PLANNED ACTIONS

Two main actions are being undertaken to minimize the probability of sector 34 type events: upgrades to the quench detection system (QPS)[5] and improved instrumentation and procedures for identifying anomalous resistances in the superconducting magnets and bus bars[6].

The improved bus fault detection system will reduce the detection threshold from 1 V to ≤300 μV, and allow local, rather than global fault detection. In addition, a new system will be implemented to detect quenches which develop symmetrically between the two apertures of a main dipole or between the two half-coils of a quadrupole aperture.

Methods for detecting anomalous resistances in the magnets and bus bars, resulting most likely from poorly made joints, have been developed in the aftermath of the 19 September incident. These include "snap-shot" measurements using the existing QPS, which allow detection of bad splices inside magnets with approximately 10 nΩ sensitivity; voltage measurement with the new bus detection system, with sensitivity below 1 nΩ; and calorimetric methods using the cryogenic system, which can detect any anomalous resistances in the superconducting magnet system larger than 40-50 nΩ.

These improvements will greatly reduce the risk of another event of the 19 September type, but they cannot completely eliminate the risk[7]. Thus a number of additional actions are planned to mitigate the consequences of a similar event, should one nonetheless occur.

The most important of these is to vastly improved pressure relief on main magnet cryostats[8]. This consists of adding a DN200 port to each dipole cryostat, and converting two existing DN100 ports on each SSS to be pressure relief devices. This will increase the relief capacity relative to the current system by about a factor of 40, which will maintain the cryostat pressure to be < 1.5 bar, even for an event twice as bad as 19 September (peak flow of 40 kg/s vs. 20 kg/s). The baseline plan is a staged implementation: the full system is installed in sectors 12, 34, 56, and 67 during the current shutdown, but full implementation in other sectors is deferred to next year. In the deferred sectors (23, 45, 78, and 81), which will not be warmed to room temperature this year, four existing DN100 ports on each SSS will be converted to be pressure relief devices. This will give eight times the capacity of the current system and maintain the pressure below about 2.5-3 bar for a 40 kg/s leak from the 1.9K helium system.

A second improvement, particularly important for the sectors with only a partially upgraded pressure relief, is to improve the anchoring to the ground of the SSS with vacuum barriers[9]. This should limit the "domino effect" if new relief system is not adequate. However, it should be noted that the cold post + vacuum barrier would have broken under the pressure of the 19 September event, had the jacks to the floor not broken first.

A third proposed improvement is to augment the pressure relief on the beam vacuum system by adding burst discs at the pumping ports at each SSS. If the beam tube were pressurized via the cryostat, as in the sector 34 incident, the additional beam vacuum relief would be in parallel with the much more efficient new cryostat relief system, and therefore would not reduce the peak pressure substantially. However, if the beam tube were pressurized directly from a magnet cold mass, e.g. due to an electrical arc inside a magnet, the enhanced beam vacuum relief could reduce the peak pressure away from the origin of the event and thereby protect the nested bellows and plug-in modules (PIMs).

POSSIBLE ADDITIONAL ACTIONS

The event on 19 September would have been worse, had it occurred near the end of the sector, and had MLI fragments and soot from the electrical arc contaminated adjacent sensitive equipment, for example the SC RF cavities. This risk can be reduced in the future by closing all vacuum sector valves during all hardware commissioning phases, either initial commissioning to full field, or “re-commissioning” after a long shutdown. This procedure is so obvious and so simple, that I assume it will be followed, and I will not discuss it further.

The damage could also have been worse had the incident occurred near the end of the sector and damaged a DFBA, for which there are no spares[10]. The risk of collateral damage in such a case could be reduced by enhancing the pressure relief in the DFBAs, and by ensuring that they are adequately anchored to the floor. Since the insulating vacuum of the DFBAs is common with the adjacent dispersion suppressor (DS), the DFBAs could be further protected by installing the full cryostat pressure relief into *all* DS, including those sectors that are not planned to be warmed to room temperature this year.

The collateral damage from a sector 34 type event could be reduced by a more sophisticated response of the cryogenics and quench protection systems to bus faults. Opening all quench valves promptly would minimize the pressure behind any potential helium vessel rupture. Firing most or all of the quench heaters would extract energy from magnetic field quickly, and thereby limit the energy available to an electrical arc, were one to form. However, not quenching the magnets in the subsector where the bus fault occurred would minimize the pressure in the region of the hole in the liquid helium vessel. Major risks of such a procedure are: 1) The reverse voltage across the diodes of the last few magnets to quench would exceed the rated voltage and damage them; and 2) The peak pressure in the D-line would exceed 20 bar, breaking rupture discs at the surface, with resultant loss of helium. The first risk could be avoided by delaying the opening of the energy extraction switches by ~1 sec. The second risk could be avoided by correcting fabrication and installation flaws that make the helium recovery tanks on the surface unusable[11].

Until the helium recovery system flaws are corrected, the second risk could be avoided by quenching only about ¾ of the cryogenic subsectors, which would keep the pressure below about 17 bar[12]. This procedure would also result in acceptable reverse voltages across the diodes in unquenched magnets, even if the extraction switches were opened promptly. However, in this case, about ¼ of the stored energy of the magnet circuit would remain available to an electrical arc.

OPTIONS AND DECISIONS

Given the range of risks and potential mitigating measures that could be undertaken, there are a number of options to consider and decisions to be made. These include the following:

- Should the remaining four sectors be warmed up to install DN200 relief ports?
- Should burst discs be added to the beam vacuum pumping ports at all SSS?
- Should DN200 ports (or equivalent) be added to the DFBAs and all DS sub-sectors? Should this be done at all locations, or only those that are or can be easily warmed now?
- Should a more sophisticated bus-quench response algorithm be developed and implemented?
- What if additional resistive splices – bus or magnet – are found in the approximately 50% of the machine that has not been systematically surveyed?
- What beam energy to run during 2009?

RANGE OF SCENARIOS: WHAT IS ACTUALLY IN THE MACHINE?

To decide which actions to take before restarting the LHC and which to defer, it is useful consider five scenarios about what the hardware conditions of the machine actually are, and how they might develop with successive powering cycles. These scenarios cover a full range, from conditions that are completely benign, to ones which would have the potential for another 19 September type incident:

A: There are no further faults in the bus bars or magnets

B: There is an electrical fault in a magnet or the bus bars, which
- is detected prior to beam startup,
- is sufficiently benign to allow operations, and
- is electrically and mechanically stable for $E \leq E_{max}$ (~5 TeV)

C: There is an electrical fault in a magnet or the bus bars, which
- is initially either invisible or benign,
- is not electrically stable with successive powering cycles, and
- trips the QPS or otherwise is detected before creating an electrical arc.

D: There is an electrical fault in a magnet, which
- is initially either invisible or benign, and then
- develops rapidly and creates an electrical arc

X: There is an electrical fault in the bus bars, which
- is initially either invisible or benign, and then
- develops rapidly and creates an electrical arc

POSSIBLE COURSES OF ACTION

There is a range of consolidation actions that could be taken, leading up to the full restarting of the LHC. In this analysis, four possible courses of action are considered:

1) Baseline consolidation:
    - Improved bus fault and symmetric quench detection,
    - Systematic search for bad joints,
    - Phased cryostat pressure relief improvement,
    - Improved SSS anchoring.
2) Baseline consolidation plus:
    - Improved pressure relief and anchoring of DFBAs,
    - Improved pressure relief on all DS sub-sectors, which share a common insulating vacuum space with the adjacent DFBAs,
    - Improved beam vacuum pressure relief.
3) Baseline consolidation, enhanced safety of DFBAs and of the beam vacuum system, plus:
    - More sophisticated response to bus faults.

Options for any of the above courses of action are:
  a) Defer to next year the correction of any bus or magnet electrical faults found before running, or
  b) Correct bus or magnet electrical faults found before running.

4) Defer operations until all consolidations and improvements are implemented.

CONSEQUENCES OF DIFFERENT COURSES OF ACTION

The consequences of each of the possible courses of action are analyzed in the following paragraphs for each of the hardware scenarios. As noted in the introduction, this analysis assumes two boundary conditions that were called into question[3,4] during this workshop: that warming up the additional four sectors not initially planned for warmup would result in a delay of several months in restarting the LHC; and that it would not be possible to operate the accelerator complex during the winter. Under these assumptions, the baseline plan called for a short run in the fall of 2009, followed by a long run starting in the spring of 2010. Further consolidation actions would be completed during the long winter shutdown between the two runs. Since, in this scenario, the 2009 run would start at the end of September, any significant delay could result in the cancellation of the fall 2009 run, delaying the restarting of the LHC until the spring of 2010. Although relaxation of these boundary conditions would almost certainly result in alteration of some of the conclusions, the contents of this paper reflect the analysis as presented at the workshop, based on the original assumptions.

In the following paragraphs, positive consequences are indicated by “+”, negative outcomes by “–”, and neutral comments by “◆”. For courses of action 2, 3 and 4, the consequences listed are those relative to the preceding case.

1) Baseline Consolidation

A: There are no further faults in the bus bars or magnets.
  + The best of all possible worlds, resulting in physics at 5+5 TeV.

B: Faulty magnet or bus bar splices found, which are stable with running to 5 TeV.
  + Almost the best of all possible worlds, resulting in physics at 5+5 TeV.
  – Need to replace bad magnet(s) or repair bus bars next year.

C: Faulty magnet or bus bar splices, which deteriorate and exceed QPS threshold after some time.
  + Experience is gained with the machine, and some physics data are collected, up to the point the fault becomes unacceptable.
  – The run could be terminated early to make repairs, or the beam energy could be limited.

D : Rapidly developing magnet electrical fault creating an electrical arc.
  + Experience is gained with the machine, and some physics data are collected, up to the point the incident occurs.
  – The affected magnet, and possibly its neighbor, are damaged, but others are not (diode protection).
  – If the electrical arc punctures, the beam tube, it could be damaged due to over-pressurization and contamination.
  – About 4 months down time would be required to replace the magnet and clean the beam tube, ending the 2009 run.

  If all electrical faults inside magnets were corrected before starting the machine, then the consequences would, instead, be the following:
  + Damage to 1 or 2 magnets, and potentially to the beam tube, would be avoided.
  – Up to 4 months down time would be required to replace the affected magnet(s).
  – There would potentially be no 2009 run, and therefore no experience with machine and detector operations until 2010.

X : Rapidly developing bus bar electrical fault creating an electrical arc.
  + Experience is gained with the machine, and some physics data are collected, up to the point the incident occurs.
  – The energy released in the electrical arc would be similar to that in the 19 September event.
  – The affected magnets (≥ 2) would be heavily damaged; likely damage to many cryostats in the affected cryo sub-sector due to heavy venting of helium, requiring replacement of many (10~20?) magnets.
  – Extensive contamination of the beam tube, although more limited than the 19 September event (no secondary electrical arcs); little damage to bellows and PIMs away from the epicenter (improved pressure relief).
  – 6-8 months down time to replace magnets and clean the beam tube => delay 2010 startup if this event happened late in 2009 run.
  – Potential damage to a DFBA if the electrical arc is in a DS without DN200 ports => up to one year

down time if the DFBA must be substantially rebuilt.

If all bus bar electrical faults were corrected before starting the machine, then the consequences would, instead, be the following:

+ Damage to 1 or 2 cryo sub-sectors and to the beam tube would be avoided.
– 2-3 months down time to repair bad bus bar.
– There would potentially be no 2009 run, and therefore no experience with the machine and no physics data collected until 2010.

2) Baseline Plus Additional Safety Measures for DFBAs and Beam Vacuum

Adding relief valves to the DFBAs and adjacent DS sub-sectors in those sectors not currently planned to be warmed up would require at least a local warmup of eight DS sub-sectors, with potentially negative consequences that are independent of the different hardware scenarios:

– Risk of delayed startup if PIM fingers buckle, requiring a complete sector warmup.

The other consequences, according to the different hardware scenarios, are the following:

A: There are no further faults in the bus bars or magnets.

B: Faulty magnet or bus bar splices found, which are stable with running to 5 TeV.

C: Faulty magnet or bus bar splices, which deteriorate and exceed QPS threshold after some time.

- ◆ In all three scenarios, the consequences are the same as in the baseline course of action.

D : Rapidly developing magnet electrical fault creating an electrical arc.

+ Reduced risk to nested bellows and PIMs if the electrical arc punctured the beam tube.
◆ Other consequences are the same as in the baseline course of action.

X : Rapidly developing bus bar electrical fault creating an electrical arc.

+ Reduced or no damage to the adjacent DFBA, if the fault occurred in a DS.
– Extensive electrical damage if the fault occurred in a DFBA, but
+ Reduced or no pressure-induced mechanical damage for a fault in a DFBA.
◆ Other consequences are the same as in the baseline case.

3) Baseline Plus Additional Safety Measures for DFBAs and Beam Vacuum, Plus More Sophisticated Response to Bus Faults

The planning, development, implementation, and proving of the more sophisticated algorithms for responding to a bus fault must be done with considerable care, to ensure that the system yields the planned improvement in equipment safety and has no unforeseen, undesirable "side effects." This means that there are potentially negative consequences that are independent of the different scenarios about the machine hardware:

- Risk of a substantial delay to the startup due to the extended system development period => could put the 2009 at risk.
- Risks if the new protection system is not fully proven before use: reduced operational efficiency, due to longer recovery time after a triggering of the bus fault system; damage to diodes, if too many magnets quench; loss of helium, if too many magnets quench.

A: There are no further faults in the bus bars or magnets.

B: Faulty magnet or bus bar splices found, which are stable with running to 5 TeV.

C: Faulty magnet or bus bar splices, which deteriorate and exceed QPS threshold after some time.

D : Rapidly developing magnet electrical fault creating an electrical arc.

- ◆ In all four scenarios, the consequences are the same as for course of action #2.

X : Rapidly developing bus bar electrical fault creating an electrical arc.

+ Energy available to an electrical arc is reduced by at least 75%, resulting in reduced magnet damage and fewer magnets to replace, and reduced production of "soot" to contaminate the beam tube.
+ Reduced pressure and flow into the cryostat, resulting in reduced damage to the cryostats in the affected sub-sector and reduced spread of contamination into the beam tube.
+ Repair down-time may be shortened.
◆ Other consequences are the same as for course of action #2.

4) Defer Operations Until All Consolidations and Improvements Have Been Implemented

A: There are no further faults in the bus bars or magnets.

B: Faulty magnet or bus bar splices found, which are stable with running to 5 TeV.

C: Faulty magnet or bus bar splices, which deteriorate and exceed QPS threshold after some time.

In all three of these scenarios, the consequences are the same.

– No running in 2009 => must wait until 2010 for experience with the accelerator and for physics with the experiments.
– There are no advantages if any of these scenarios corresponds to the actual situation in the machine.

D : Rapidly developing magnet electrical fault creating an electrical arc.

X : Rapidly developing bus bar electrical fault creating an electrical arc.

+ Collateral damage would be minimized if an event of one of these types were to occur.
◆ However, the additional improvements implemented during the extended shutdown would not reduce the likelihood of such an event.
– No running in 2009 => must wait until 2010 for experience with the accelerator and for physics with the experiments.

CONCLUSIONS

Analysis of the various hardware scenarios and of the consequences of taking the different potential courses of action discussed above, allow us to address the questions posed earlier in this paper.

Should the remaining four sectors be warmed up to install DN200 relief ports? Considering the dramatically reduced risk of an electrical arc, due to the improved bus fault detection system; considering the substantial reduction in potential for collateral damage in case of an electrical arc, due to full implementation of improved SSS anchoring to the floor, and the phased implementation of improved cryostat relief; and considering that full implementation would delay until 2010 the opportunity to learn what other challenges are yet to be encountered with the accelerator and the experiments; <u>the benefits of running in 2009 far outweigh the risks of not fully implementing the improved cryostat pressure relief this year</u>.

Should burst discs be added to the beam vacuum pumping ports at all SSS? Considering that an electrical fault inside a magnet could pressurize the beam tube up to the 17 bar opening pressure of the quench valves, potentially damaging many nested bellows and PIMs; and considering that adding burst discs on the beam vacuum system at each SSS could substantially limit the damage in such an incident, <u>addition of beam vacuum system burst discs should be strongly considered for the sectors that are warmed up, and also for the other sectors, if it can be done without warming them up</u>.

Should DN200 ports (or equivalent) be added to the DFBAs and all DS sub-sectors? Should this be done at all locations, or only those that are or can be easily warmed now? Considering that the DFBAs are particularly vulnerable to a sector 34 type event occurring in a DS or in a DFBA itself; and considering that a damaged DFBA would result in extensive down-time; <u>improved pressure relief should be implemented in the DFBAs in the sectors that are warmed, and the possibility of implementing the enhanced pressure relief in the other DFBAs and DS sub-sectors “now” should be studied.</u>

Should more sophisticated quench response algorithms be developed and implemented? Considering that a more sophisticated response to a bus fault (opening the quench valves promptly, firing the quench heaters in 10 of the 13 sub-sectors, and delaying the opening of the extraction system switches) could significantly reduce collateral damage from a major bus fault; <u>more sophisticated algorithms in response to bus faults should be studied seriously and be implemented if and when they can be proven</u>. However, considering that such an improved system will take substantial time to develop and validate, to ensure that it functions as intended with 100% reliability, <u>implementation should not be a prerequisite for running in 2009</u>.

What if additional resistive splices are found inside magnets in the approximately 50% of the machine that has not been systematically surveyed? Considering that replacing a magnet with a resistive (10’s nΩ) splice could take up to 4 months, which would put the 2009 run at risk if the problem is detected only in the summer, <u>data from SM18 magnet tests and all other relevant sources should be systematically and promptly examined for magnets that are in sectors 12, 23, 34, and 45</u>, to learn if there are resistive splices in magnets installed in these sectors. However, considering that down time to replace a magnet following an internal electrical arc would not be dramatically longer than that to replace it before it fails; considering the potential loss of the opportunity to run the LHC in 2009; and considering that the probability of an electrical arc developing from a bad internal splice is low; <u>there is no significant advantage to replacing a magnet with a resistive splice, if that would delay the start of the 2009 run</u>.

What if additional resistive bus splices are found in the approximately 50% of the machine that has not been systematically surveyed? Considering that the nature of sector 34 bus resistance is not known with certainty, and therefore the probability of a resistive bus splice rapidly opening is not understood; considering that an electrical arc in a dipole bus can create substantial damage and result in major down time, even with the improved cryostat pressure relief; considering that the inventory of spare magnets will not be replenished for some time; considering that an electrical arc would once again destroy the evidence of what might be a systematic fault in the bus bars; and considering that the recurrence of another event like that on 19 September could engender a crisis of confidence, <u>any bus bar splices with anomalous resistance ($\gtrsim$1 nΩ, vs. 0.35 nΩ for a good splice and the specification of <0.6 nΩ) should be opened, carefully examined, and repaired</u>.

What beam energy to run during 2009? Considering that one of the key steps is acceleration through the “snap-back” region, <u>operation above 450 GeV is essential</u>. Considering that it could be useful to gain some operating experience with modest beam energy and modest magnetic forces and stored energy, before advancing to “riskier” territory; and considering the utility of comparing basic elastic and total cross-sections between p-p and $\bar{p}$-p at $\sqrt{s}$ = 2 TeV, <u>a short run at 1+1 TeV could be interesting</u>. Considering that all sectors, except 34 and the inner triplet at 5L, have been powered to 5.5 TeV for at least a few hours; considering that all magnets have been individually tested to >7 TeV; considering that the new systems will greatly reduce the risk of a major incident; and considering that the experiments are ready (and eager) to explore the energy frontier, <u>5+5 TeV is a desirable and achievable goal</u>.

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