Risk Analysis for the Different Consolidation Proposals

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Scope of the Talk

- This talk concerns risks and mitigations for sector 34 type events in 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) will be addressed in my talk "Maximum Credible Incidents" tomorrow.

Actions planned to avoid future Sector 34 type events

- Improved bus fault detection system.
  - Detection threshold reduced from 1 V to ≤0.3 mV.
  - Local, rather than global fault detection.
  - Implemented with “symmetric quench” detection system.

- Improved QA techniques and procedures for safely detecting anomalous resistance in magnets and bus bars.
  - “Snap-shot” measurements of individual magnet voltages (≤10 nΩ sensitivity)
  - Voltage measurement with new bus detection system (≤10 nΩ sensitivity)
  - Calorimetric measurements as backup and cross-check (≤50 nΩ sensitivity)

Actions planned to mitigate effects of a Sector 34 type event

- Vastly improved pressure relief on main magnet cryostats
  - Add DN200 ports to each dipole cryostat, and convert 2 DN100 ports on each SSS to be pressure relief devices.
  - x40 capacity of current system - will maintain P < 1.5 bar even for an event twice as bad as 19 Sep (40 kg/s vs. 20 kg/s)
  - Staged implementation:
    - Full implementation now in four sectors: 12, 34, 56, 67
    - Full implementation in other sectors deferred to next year.
    - In deferred sectors (23, 45, 78, 81), convert 4 DN100 ports on each SSS to be pressure relief devices => x8 capacity of current system => maintain pressure < ~2.5 bar for 40 kg/s
- Improved anchoring of SSS with vacuum barriers to the floor
  - Limits "domino effect" if new relief system is not adequate.
  - However cold post + vacuum barrier are not strong enough to have been able to withstand the sector 34 pressure, had the jacks to the floor not broken.

Additional Mitigation Under Consideration

- Additional pressure relief on the beam vacuum system
  - Can add burst discs at pumping ports at each SSS
  - If the beam tube is pressurized via the cryostat, as in the sector 34 incident, beam vacuum relief is in parallel with the much more efficient new cryostat relief system.
  - If the beam tube is pressurized directly from a magnet cold mass, e.g. an electrical arc inside a magnet, enhanced beam vacuum relief could reduce peak pressure away from the origin of the event and thereby protect the nested bellows and PIMs.

Additional Mitigations That Could/Should Be Considered*

- Close all vacuum sector valves during <u>all</u> hardware commissioning phases, either initial commissioning to full field, or "re-commissioning" after a long stop => protect adjacent sectors.

  This is so obvious and so simple, that I assume it will be done, and I will not discuss it further.

- Ensure that the anchoring of DFBAs to the ground is as strong as the improved anchoring of the SSS.
- Enhance the pressure relief on other cryostats.
  - DFBs
  - Inner triplets
  - Stand-alone and "doublet" magnets in the matching section
- Prompt opening of quench valves in response to quenches/faults in magnets adjacent to sensitive equipment, e.g. triplets, injection regions, RF region.

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*See "Maximum Credible Incidents," Wednesday 17:00

Further Mitigations That Could/Should Be Considered

- More sophisticated response to bus faults
  - Open all quench valves promptly
    => minimize pressure behind any potential He vessel rupture
  - Fire most (or all) quench heaters; dump switches delayed ~1 sec
    => extract energy from magnetic field more quickly.

    e.g. with 10 of 13 cryo sub-sectors (40-42 half-cells) quenched:
    - Pressure in D-line remains below 20 bar
    - Reverse voltage on "unquenched" diodes < 65 V
    - 75% of stored energy is extracted in ~1 sec.
    - Subsector(s) with bus fault not quenched => minimize local pressure.

    Or with all 54 of 54 half cells quenched, dump delayed ~1 sec:
    - Almost 100% of stored energy is extracted in ~1 sec.
    - No large voltages from dump resistors => diodes are protected.
    - *But,* pressure in D-line exceeds 20 bar => loss of helium.

Options / Decisions

- Warm up remaining four sectors to install DN200 relief ports?
- Add burst discs to beam vacuum at all SSS?
- Add DN200 ports (or equivalent) to other cryostats (DFB, triplets*, stand-alone magnets*)?
  - Those that are or can be easily warmed now?
  - All vulnerable components, even if this requires warming additional sectors?
- Implement more sophisticated quench response?
  - Before running with beam?
  - Before powering above some specified level?
  - As required equipment and algorithms can be developed and validated, without regard to running schedule?

*To be addressed in "Maximum Credible Incidents," Wednesday 17:00

Options / Decisions

- What if additional resistive splices – bus or magnet – are found in the almost 50% of the machine that has not been systematically surveyed?
- What beam energy to run during 2009?
  - May depend on hardware consolidation decisions
  - May depend on existence of resistive splices in the machine

Range of Scenarios: What is actually in the Machine?

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 number of excitations, and
- trips the QPS or otherwise is detected before creating an arc.

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

Possible Courses of Action

1) Baseline consolidation, operate to 5 TeV.

2) Baseline consolidation + improved pressure relief and anchoring of DFBs + improved beam vacuum pressure relief, operate to 5 TeV.

3) Baseline consolidation + enhanced safety of DFBs + more sophisticated response to bus faults, operate to 5 TeV.

   Options for any of the above courses of action,
   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

<u>- or -</u>

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

1) Baseline consolidation, operate to 5 TeV.

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

- + Best of all possible worlds – 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 – physics at 5+5 TeV
- - 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 gained with machine and detector operations up to the point the fault becomes unacceptable
- - Run could be terminated early to make repairs, or the beam energy could be limited below 5 TeV

1) Baseline consolidation, operate to 5 TeV.

D : Rapidly developing magnet electrical fault creating an arc.

+ Experience gained with machine and detector operations up to the point that the fault occurs.
- ~4 months down time to replace magnet and clean beam tube => end of 2009 run.
- Damage limited to affected magnet (diode protection) and possibly its neighbor (soot).
- Potential over-pressurization and contamination of beam tube.

Alternative Scenario:

Correct magnet electrical faults found before running:

+ Damage to 1 or 2 magnets, and potentially to the beam tube, are avoided.
- ~4 months down time to replace magnet.
- Potentially no 2009 run, and no experience with machine and detector operations until 2010.

1) Baseline consolidation, operate to 5 TeV.

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

+ Experience gained with machine and detector operations up to the point the fault occurs.
- Energy released in arc is similar to the 19 September event.
- Affected magnets (≥2) strongly damaged; likely damage to many cryostats in affected cryo sub-sector => need to replace many magnets (10~20?).
- Extensive contamination of beam tube, although more limited than the 19 September event (no secondary arcs); little damage to bellows and PIMs away from the epicenter (improved pressure relief).
- 6-8 months down time to replace magnet and clean beam tube => delay 2010 startup if this event happens late in 2009 run.
- Potential damage to DFB if arc is in DS without DN200 ports. => Up to year down time if DFB must be substantially rebuilt.

1) Baseline consolidation, operate to 5 TeV.

Alternative Scenario:

Correct bus bar electrical faults found before running:

+ Damage to 1 or 2 cryo sub-sectors and to the beam tube are avoided.
- ~4 months down time to repair bad bus bar.
- Potentially no 2009 run, and no experience with machine and detector operations until 2010.

2) Baseline + enhanced pressure relief on DFBs and V-line, and enhanced anchoring of DFBs

- All scenarios:
  - Adding relief valves to the DFBAs requires local warmup of DS sub-sector => risk of delayed startup if PIM fingers buckle.

A : no faults.

B : stable electrical faults.

C : unstable electrical faults, but no arc.

- o Other consequences are the same as in the baseline case.

D : Rapidly developing magnet electrical fault creating an arc.

- o Other consequences are the same as in the baseline case.
- \+ Reduced risk to nested bellows and PIMs if arc punctures beam tube.

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

- o Other consequences are the same as in the baseline case.
- \+ Reduced or no damage to DFB, even for fault in DS.
- \+ Reduced or no pressure-induced mechanical damage for fault *in* the DFB (but extensive electrical damage).

3) Baseline consolidation + enhanced safety of DFBs and V-line + more sophisticated response to bus faults

All scenarios:

- Risk of substantially delayed startup due to need to develop and prove new systems => could put 2009 running at risk.
- Risks if new protection system is not fully proven before use:
  - Reduced operational efficiency (longer cryo recovery time)
  - Damage to diodes, if too many magnets quench
  - Loss of helium, if too many magnets quench

A : no faults

B : stable electrical faults

C : unstable electrical faults, but no arc

D : electrical arc in a magnet

- Other consequences are the same as case 2.

3) Baseline consolidation + enhanced safety of DFBs + more sophisticated response to bus faults

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

- o Other consequences are the same as in case 2, *except*
- + Energy available to arc is reduced by ~75%.
  => reduced magnet damage and fewer magnets to replace
  => reduced production of "soot" to contaminate beam tube
- + Reduced pressure and flow into cryostat.
  => reduced damage to cryostats in affected sub-sector
  => reduced spread of contamination in beam tube
- + Repair down-time may be shortened.

4) Defer operations until all consolidations and improvements are implemented

A : no faults
B : stable electrical faults
C : unstable electrical faults, but no arc
- No running in 2009 => must wait for 2010 for experience with the accelerator and physics with the experiments.
- There are no advantages if this is what is in the machine.

D : electrical arc in a magnet
X : electrical are in a bus bar
+ Collateral damage minimized if an event of this type occurred.
  But,
o The additional improvements would not reduce the likelihood of such an event.
  And
- No running in 2009 => must wait for 2010 for experience with the accelerator and physics with the experiments.

Summary and Conclusions

Warm up remaining four sectors to install DN200 relief ports?

- Considering the dramatically reduced risk of an electrical arc, due to the improved bus fault detection system; and
- 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,
  - 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;

I believe that the benefits of running in 2009 far outweigh the risks of not fully implementing the improved cryostat pressure relief this year.

Summary and Conclusions

Add burst discs to beam vacuum at all SSS?

- Adding burst discs to the beam vacuum system at each SSS could protect nested bellows and PIMs in case electrical fault inside a magnet directly punctures the beam tube.
  => Should strongly consider implementation in arcs that are warmed.

Add DN200 ports (or equivalent) DFBs?

- The DFBs are particularly vulnerable to a sector 34 type event occurring in the DS or in the DFB itself
- A damaged DFB will result in extensive down-time
  => Should strongly consider enhancing pressure relief in the DFBs
    - In the arcs that are warmed
    - Study the possibility of doing so "now" in the other arcs.

Summary and Conclusions

Implement more sophisticated quench response?

- A more sophisticated response to a bus fault
  - Open quench valves promptly
  - Fire quench heaters in 10 of 13 sub-sectors, delaying the dump switch by ~1 sec

  could significantly reduce collateral damage from a major bus fault.
- Such an improved system will take substantial time to develop and validate to ensure that it functions as intended with 100% reliability.

  => Should study this proposal and implement it (or something like it) if and when it can be proven.

  => Should ***not*** be a prerequisite for running in 2009.

Summary and Conclusions

What if additional resistive splices are found in magnets in LHC?

- Replacing a magnet with a resistive (10's nΩ) splice could take up to 4 months, which would put the 2009 at risk if the problem is detected only in the summer.
  - => Should systematically and promptly examine SM18 data for magnets in sectors 12, 23, 34, and 45 to learn if there are resistive magnet splices there.
- Down time to replace a magnet following an internal arc would not be dramatically longer than that to replace it before it fails.
- Probability of an electrical arc from a bad internal splice is low.
  - => No significant advantage to replacing magnet "now" relative to potential loss of the 2009 run.

Summary and Conclusions

What if additional resistive bus bar splices are found in LHC?

- Nature of sector 34 bus resistance is not known => probability of a resistive bus splice rapidly opening is not understood.
- Electrical arc in a dipole bus can create substantial damage, even with improved cryostat pressure relief, resulting in substantial down time, possibly delaying 2010 run.
- Electrical arc would once again destroy the evidence of what might be a systematic fault in the bus bars.

=> Should open and repair any resistive bus bar splices that are found.

Summary and Conclusions

What energy to run during 2009?

- One of the key steps is acceleration through the "snap-back" region => operation above 450 GeV is essential.
- 1 + 1 TeV would be an important milestone:
  - Higher energy (by 20 MeV per beam) than the Tevatron.
  - Opportunity to compare basic elastic and total cross-sections between p-p and $\bar{p}$-p at $\sqrt{s} = 2$ TeV.
  - Opportunity to gain "routine" running experience with "modest" beam energy and "modest" magnetic forces and stored energy, before advancing to "riskier" territory.
- 5 + 5 TeV (or close to that) is an achievable goal.
  - All sectors except 34 and the inner triplet at 5L have been powered to 5.5 TeV for at least a few hours.
  - All magnets have been individually tested to > 7 TeV.
  - New systems greatly reduce the risk of a major incident.
  - Experiments are ready (and eager) for this energy.

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