MAXIMUM CREDIBLE INCIDENTS

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Abstract

Following the incident in sector 34, considerable effort has been made to improve the systems for detecting similar faults and to improve the safety systems to limit the damage if a similar incident should occur. Nevertheless, even after the consolidation and repairs are completed, other faults may still occur in the superconducting magnet systems, which could result in damage to the LHC. Such faults include both direct failures of a particular component or system, or an incorrect response to a "normal" upset condition, for example a quench. I will review a range of faults which could be reasonably expected to occur in the superconducting magnet systems, and which could result in substantial damage and down time to the LHC. I will evaluate the probability and the consequences of such faults, and suggest what mitigations, if any, are possible to protect against each.

INTRODUCTION

This paper surveys a range of credible incidents involving the superconducting magnet system, that could have serious negative impact on the operations of LHC. Possible mitigations, which could either reduce the probability of these incidents occurring, or reduce their impact if they do, are also discussed.

The title bears a little discussion, to set the scope of this paper. The word "maximum" is defined here to apply to any incident which would result in substantial loss of capability of the LHC: extended down time, ending a physics run whenever it occurred, or extended running with reduced performance. Since a computation of the probability of various incidents is not possible, an incident is taken to be "credible" based on a judgment as to whether or not it is plausible that such an incident could occur during the lifetime of LHC. Finally, it should be noted that the title refers to plural "Incidents." A range of incidents will be discussed that are "maximal" in some metric or another, or near enough to being "maximal" that they need to be considered.

This paper is "limited" to incidents involving hardware failures in the superconducting magnet system. These can include faults initiated by the superconducting magnet system which "maximally" damage itself, e.g. the 19 September 2008 event[1]; or faults initiated by the superconducting magnet system which "maximally" damage other systems, either in the machine or the experiments.

"Maximal" incidents involve the uncontrolled release of large stored energy, which is available in magnetic fields (e.g. 1.2 GJ in the dipole circuit in each sector), the cryogenic system (high forces from high pressures, thermal damage due to rapid temperature changes), and the beam (360 MJ per beam at nominal energy and beam current). The first two are the subject of this paper, while the third is covered in several companion papers[1,2,3]. The "maximum credible incidents" discussed here all involve the release both of electrical and pressure energy.

To understand which magnet circuits are capable of inducing a "maximum" incident, we need to look at the circuits with the largest stored energy. The relevant circuits are the "quench protection units," that is the effective circuit once the quench protection system has triggered. The ten highest energy circuits[4] are listed in Table 1.

Table 1: Magnet Circuit Stored Energy

Circuit	Type	E (MJ)
MB-bus	Bus	1067
MQ-bus*	Bus	43
MB	Dipole	6.9
MQXB (Q2)†	Quad	2.7
MQXA (Q1, Q3)	Quad	2.3
MQY*†	Quad	1.9
MQM*†	Quad	0.9
MBRC/B/S (D2,D4,D3)	Dipole	0.9
MQ*	Quad	0.8
MBX (D1)	Dipole	0.4

* Individually powered apertures - energy summed due to coupling between circuits.

† two magnets powered in series

THE MAXIMUM CREDIBLE INCIDENT

An incident resulting from an electrical fault in the main dipole bus, which generates an electrical arc and in turn ruptures the helium vessel, as happened on 19 September, is probably THE Maximum Credible Incident involving a hardware failure, since it involves: the electrical system with the largest stored energy – the whole dipole circuit; and the largest single volume of helium in the tunnel – one cryogenic system sub-sector, which is up to 300 m long. An event of this type could be worse than that on 19 September, if the electrical arc, originating in the dipole bus, were to breach one or both of the (powered) quadrupole bus lines (Fig 1[1]). In this case, the additional 43 MJ from the quadrupole system would be available to form electrical arcs. More important, however, is that with two or more of interconnect pipes broken, the flow of helium into the cryostat would be up to twice as large as in the sector 34 incident. This defines the new "Maximum Credible Incident"[1]. Minimizing the probability of such an event, and minimizing the collateral damage should one

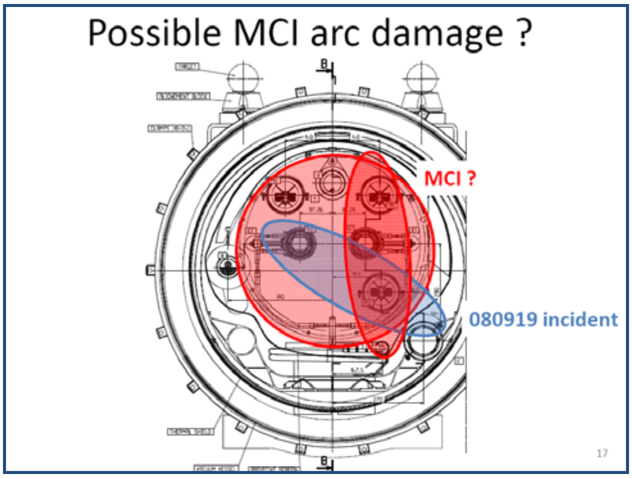

Figure 1: The Maximum Credible Incident, resulting in twice the helium flow rate into the cryostat relative to the 19 September 2008 incident.

nonetheless occur, is the subject of many papers at the 2009 LHC Performance Workshop, e.g., [1,7-11].

To minimize the probability of this sort of event, two main actions are being undertaken. First, a new bus quench detection system[7] is being installed, which will reduce the threshold for detecting a bus fault from 1 V to 0.3 mV. This system will be able to detect any resistive sections of the bus before a thermal runaway can result in the opening of the bus[8]. In particular, had it been in place on 19 September, it would have safely shut down the power system and the incident would not have occurred. Second, a new set of procedures and measurement techniques have been developed, utilizing the existing quench protection system, the new bus fault detection system, and the cryogenic system, to systematically survey the machine for anomalous resistances. The sensitivity is at the 10 nΩ level for splices inside the main magnets, and <1 nΩ for the main bus bars[9]. This will allow faulty joints to be identified during the hardware (re)commissioning phase, such that they can be corrected before running the machine.

While these measures will drastically reduce the probability of a 19 September type event, they cannot absolutely eliminate the possibility. A bus failure could occur without being detected in time, even by the new bus detection system, if a bus cable segment were to suddenly quench (e.g. due to beam loss) at a point where there is both a discontinuity in the copper stabilizer (see Fig. 2[10]) and poor thermal contact between the superconducting cable and the stabilizer[8]. Gaps of the sort shown in Fig. 2 are not uncommon in the machine, due to component tolerances. A joint made without additional solder may have good electrical contact between the two superconducting cables, due to the pre-tinning of the wires, but the electrical and thermal contact between the cable and copper and across the copper-to-copper joints may be poor. It cannot be ruled out that this configuration occurs at least once among the many thousand high-current bus splices in the LHC.

Figure 2: An intentionally poorly made bus joint, illustrating the possibility of a gap in the copper stabilizer.

Thus, despite the improvements in bus fault detection, it is essential to take further actions to minimize the extent of the damage if another MCI were to occur. Two main improvements are being undertaken, to vastly increase the pressure relief capacity on the main magnet cryostats[11] and to strengthen the anchoring to the ground of the SSS with vacuum barriers[12]. Several additional possible improvements, including enhanced pressure relief on the beam vacuum system and a more sophisticated system response to bus faults, are discussed in [13].

ELECTRICAL FAULT IN A DISPERSION SUPRESSOR OR DFB

The sector 34 incident, or one like it, could have resulted in even more significant damage had it occurred in a dispersion suppressor (DS) sub-sector, since the DFBA shares a common insulating vacuum space with it. Were an MCI to occur in the future in one of the eight DS subsector which will have only the intermediate pressure relief installed, the peak pressure in the DFBA cryostat could still reach 2.5-3 bar. The DFBA (see Fig. 3) has a square cross-section cryostat, making it vulnerable to damage due to high internal pressure. Another likely failure mode would be the collapse of the chimneys for the HTS leads. In addition, the existing anchors to the floor may not be adequate in all cases to restrain the 2.5-3 bar pressure forces. Since each DFBA is unique in its design, there are no spares[14]. Therefore, damage to a DFBA would result in long down time for repair or replacement.

Figure 3: A DFBA.

An electrical fault, resulting in an electrical arc, that occurred *inside* a DFBA would certainly result in serious damage to the DFBA. Potentially all of the magnet circuits could be involved in such an incident. There is a “bottleneck” between the DFBA and the adjacent magnet cryostat, which makes pressure relief from the DFBA to the main cryostats relatively ineffective. If adequate pressure relief were provided on the DFBA cryostat, the extent of the pressure-induced damage could be reduced, maximizing the number of components that could be re-used for rebuilding the DFBA. To minimize the down time resulting from such an event, it is important to have an adequate pool of spares for all critical DFBA parts.

Similar considerations apply to all of the other DFBs in the machine, in particular the DFBMs and DFBLs, which power the standalone and semi-standalone magnets, and the DFBXs, which powers the inner triplets. As for the DFBAs, there are no spare, since the number of variants is almost as large as the number of installed units (15 variants of DFBM and DFBL for 28 installed units, and 6 variants of DFBX for 8 installed units).

There are several measures that can be taken to protect the DFBs and limit the damage, should an MCI occur in the DS (or other magnet strings attached to a DFB) or in a DFB itself. These include:

- Adding DN200 ports to all DS, even in the sectors not currently planned to be warmed up.
- Ensuring adequate pressure relief on all standalone, semi-standalone, and triplet magnets.
- Improving the pressure relief on the DFBs themselves.
- Ensuring that the anchoring to floor is adequate.
- Changing the response of the quench protection system (QPS) to a bus fault inside a DFBA or DS:
  - Open the DS quench valves early (to limit the pressure, and therefore the flow into the cryostat).
  - For a DFBA fault, do not open dump switch adjacent to it, (to limit the voltage across the electrical fault).
  - Fire many quench heaters away from DFBA/DS (to limit the energy available to the electrical arc).

INDIVIDUAL DIPOLE FAILURE

An electrical arc could occur inside a dipole (or quadrupole) due to the opening of an inter-aperture or inter-pole splice, or due to a turn-to-turn short within the coil. In this case the fault would be “behind” the diode and therefore only the stored energy in one magnet would be involved, which is <1% of the stored energy available to a bus fault. The QPS would fire the quench heaters in the affected magnet, dissipating the stored energy within ~1 sec, i.e. ~1% of the time constant for a bus event. Nonetheless, the available energy (even for a quadrupole) is more than sufficient to breach the helium vessel or the beam tube. Any leak to the cryostat would be smaller than that for the MCI discussed above, and therefore the enhanced pressure relief system would limit the cryostat pressure to a safe level. The affected magnet would be heavily damaged, but there would be little damage to adjacent magnet. However, soot and MLI could contaminate the beam tube, as on 19 September.

The consequences would be more serious, if the electrical arc punctured the beam pipe directly from the helium vessel rather than via the cryostat. Since the only existing pressure relief on the beam tube are burst discs at the ends of the common cryostat, which may be more than 1 km away, the beam tube could be pressurized up to the 17 bar opening pressure of the quench valves. The high pressure would cause widespread damage to the plug-in modules and nested bellows. Even if the beam tube could be cleaned *in situ*, and even if the magnets away from the epicenter were fundamentally undamaged, every magnet with a damaged nested bellows would have to be removed from the tunnel for repair.

Two measures could be taken to protect the beam tube against such an event:

- Substantially improve the beam vacuum pressure relief, by installing burst discs on the pumping lines at each short straight section.
- If an electrical arc could be distinguished from a quench, the quench valves in the cryogenic sub-sector containing the affected magnet could be opened early to limit the pressure.

FAILURE OF THE DIODE BYPASS

If the bypass diode circuit were to fail during a dipole or quadrupole quench (or other fault), then the current from the rest of the circuit would continue to flow through the quenching magnet during the 100 s decay time of a fast power abort. The quenching magnet would be grossly overheated, and there would be risk of an insulation failure or other electrical failure, resulting in an electrical arc. With the full stored energy of the dipole (or quadrupole) circuit involved, the consequences would be similar to a bus rupture.

Such an event could occur if a diode were installed backwards. However, careful checks are done of diode polarity, making this unlikely. The simple failure of a diode is also unlikely to cause such an event, since diodes generally fail “shorted” rather than “open.”

A circumstance that could credibly result in the failure of the diode bypass mechanism is the following. In addition to the inter-aperture and two inter-pole splices in the end of a dipole, there is a splice between one of the magnet leads and the bus bar that passes through the magnet. This splice overlaps with one of the T-joints to the bypass diode, as shown in Fig. 4. This splice, in contrast to the others in the end of a magnet, is not clamped inside an insulating box. Thus, it is at greater risk than the others of opening if it is not well made. Since at least two unsoldered splices have been found in magnet ends, it is possible that one of these more vulnerable splices is also unsoldered somewhere in the machine. Were one of these splices to spontaneously open, it is conceivable that the ensuing electrical arc could break the bus connection to the diode, with results equivalent to an interconnect bus rupture. The only defense against such a risk, beyond the measures already taken against a 19 September scale incident, is to systematically measure the resistance of this splice in

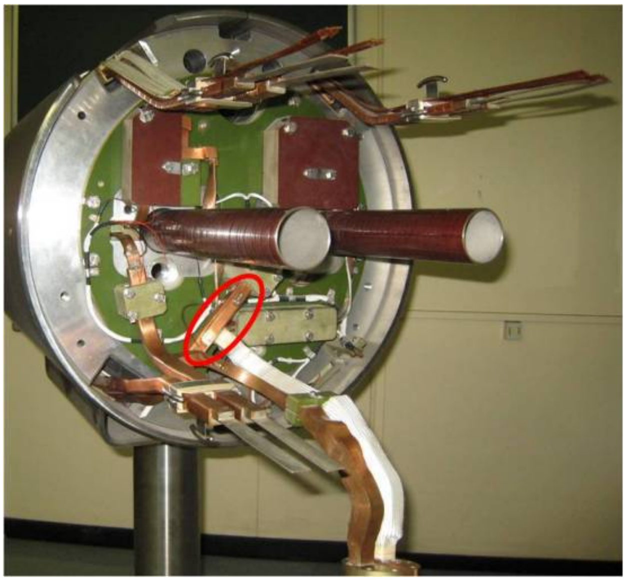

Figure 4: The connection end of a dipole, with the vulnerable splice indicated.

each dipole in the machine, to ensure that they are all well made. Any dipole that is found to have a faulty joint at this point should be replaced prior to running. The configuration of the joints to the diodes in the main quadrupoles needs to be examined to determine if a risk of this sort exists in them, as well.

INNER TRIPLET

The stored energy in the triplet (7.3 MJ) is comparable to that in one main dipole (6.9 MJ). The powering scheme is complex, involving three power converters, as shown in Fig. 5. There are diodes across each power converter, which divide the triplet into three circuits once a quench occurs, and each magnet has to absorb only its own stored energy (2.3 MJ for each of the Q1 and the Q3, and 2.7 MJ for the Q2 pair).

Both the quench protection system and the bus bar design for the inner triplet are quite different from the those for main magnets. The QPS measures voltages that cover the bus bars together with the magnets, and the response to a bus quench is identical to that to a coil quench. If one magnet or its associated bus bar quenches, all three power converters are turned off, and the quench heaters in all of the magnets are energized. Thus, even for a bus quench, the energy stored in the magnetic field is dissipated in ~1 sec.

The inner triplet bus (Figs. 6 and 7) consists of a 13 kA superconducting cable, soldered to an all copper cable of the same geometry. These buses have been designed and tested[15] so that quenches in them will propagate and therefore be detected by the QPS, and so that they have the capability to safely carry the full current during the quench detection and current decay periods. The splice configuration at the Q1-Q2 and Q2-Q3 interconnects (Fig. 7) is complex, following the complexity of the powering scheme.

The risk of an inner triplet bus failure is low, but the consequences would be substantial. The splices are inside thin-walled (0.25 mm) bellows, which are vulnerable to puncture/rupture in case of an electrical arc. Although the circuit is segmented, so as to limit the stored energy involved in a quench to the individual magnet, a splice fault would involve two of the three circuits. Thus, most of the stored energy in the triplet system (Q1+Q2 or Q2+Q3) would be involved. Scaling from the size of the hole that was made in the beam tube, following a turn-to-turn short in an early SSC dipole test[16], where the stored magnetic energy was ~0.26 MJ and the quench protection was similar to that in the triplet, it is clear that an electrical arc at an inner triplet interconnect could fully rupture the interconnect bellows. This would result in a flow area similar to that in the dipole-dipole interconnect involved in the 19 September event. Due to the limited helium volume of the inner triplet (180 kg, including the D1), it is unlikely that a peak flow as large as 20 kg would result. However, the existing cryostat relief system consists only of three 67 mm ports, one each on the DFBX and on the Q3-Q2 and Q2-Q1 interconnects. Its capacity, on the order of 1 kg/s, would certainly be inadequate for such an event.

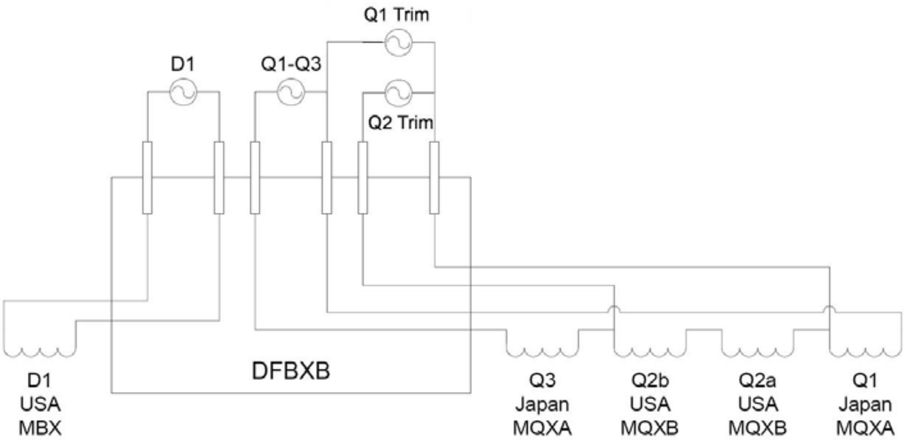

Figure 5: Inner triplet powering scheme.

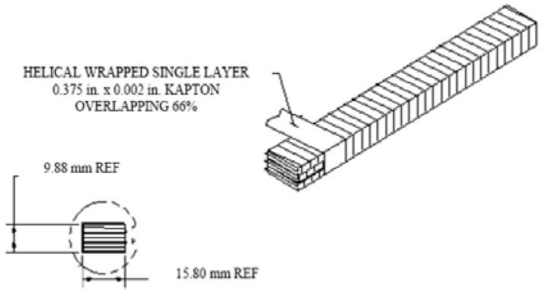

Figure 6: Inner triplet (Q2) bus assembly. Three bus bars are utilized, one to make the series connection between the Q2a and Q2b, one to carry the Q1 current, and one to return the combined Q1-Q2 current.

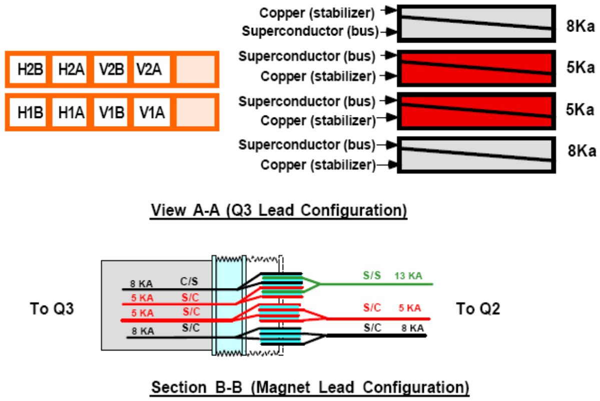

Figure 7: Inner triple bus and splice configuration at the Q2-Q3 interconnect.

If such an event were to occur, the pressure in the cryostats could rise to several bar, and the resultant collateral damage would be of the same type as would occur (and has occurred) in an MCI in the main magnets:

- The jacks that support the quadrupoles would fail for a cryostat pressure $\gtrsim 1.5$ bar.
- The D1 could also be pushed off its stands.
- The DFBX (Fig. 8) is vulnerable to damage similar to the DFBAs.

The consequences would be serious, since there is only one spare of each type of magnet for the inner triplets (including the D1), and essentially no chance to make additional ones. There are no spare DFBXs.

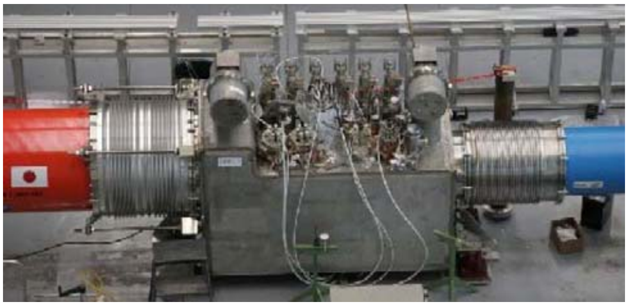

Figure 8: A DFBX.

As discussed for the main magnets, an internal electrical fault, such as a turn-to-turn short, could result in an electrical arc that could puncture the beam tube. This would, in turn, pressurize the adjacent experimental beam tube. The NEG coating, that is necessary to maintain the high vacuum required in this war section, could be compromised by soot from the electrical arc.

There are no obvious measures that can be taken to further reduce the risk of either type of event. However, several things can be done to minimize the consequences, similar to what is being done or has been proposed for the main magnets:

- Enhance the cryostat pressure relief, for example by adding a DN200 port at each interconnect. This should be done now, before there is any substantial irradiation of the triplets.
- Improve the anchoring of the triplets to the ground.
- Enhance the beam tube pressure relief in this area.
- Prompt opening of the quench valves would reduce the pressurization of the beam tube in case it is punctured.
- Unfortunately, even fast acting vacuum sector valves would not be fast enough to protect against consequences of a punctured beam tube in the triplet.

COLLATERAL DAMAGE TO SENSITIVE EQUIPMENT

Standalone and semi-standalone magnets, such as the D3 and the D4-Q5 pair in IR4, or the D2-Q4 pair and the Q5 in the experimental insertions, have smaller stored energy (~1 MJ) than the systems discussed above. Thus they are less capable of inducing large-scale damage. Nonetheless, similar considerations of beam tube contamination and spares counts mean that these devices are not risk free.

The most significant risk from these magnets is their potential to damage adjacent sensitive equipment. The D3, for example, is only about 30 m from the main RF system, and the D4-Q5 pair is only about 100 m away (Fig. 9). An electrical arc in one of these, that punctured the beam tube, would contaminate the superconducting RF cavities, requiring that they be removed from the machine for reconditioning or replacement. Since there is only one spare cryomodule, this could result in extensive down time. Similar measures to those proposed for the inner triplet could reduce the quantity of contamination. However, given how exquisitely sensitive SCRF cavities are to dust, the cavities would still, at minimum, have to be removed for cleaning and reconditioning. The only defense is to have an adequate number of spare RF cryomodules.

Similarly, the Q5 and the Q4-D2 pair are on either side of the injection kickers at IR2 and IR8 (Fig. 10). A failure in one of these magnets would contaminate the kickers, requiring their removal for reconditioning or replacement. As with the SCRF cavities, the a crucial line of defense is to have an adequate number of spare kickers.

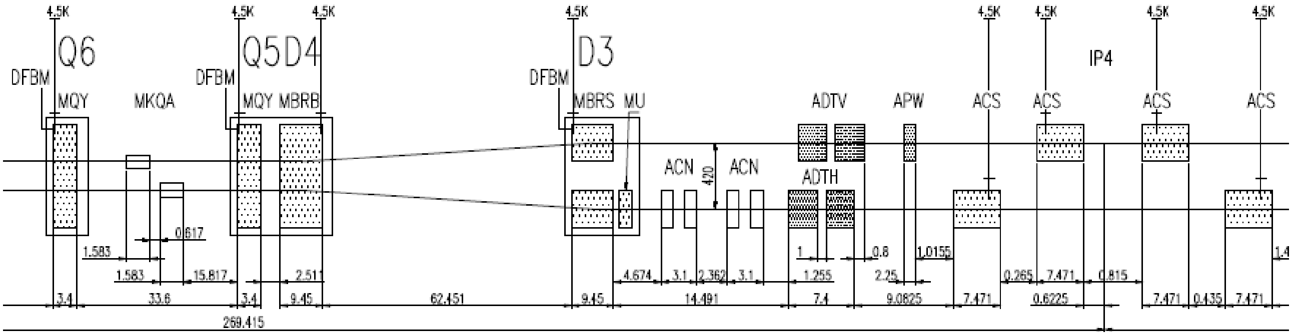

Figure 9: IR4, showing the distance between the SCRF cavities and the adjacent superconducting magnets.

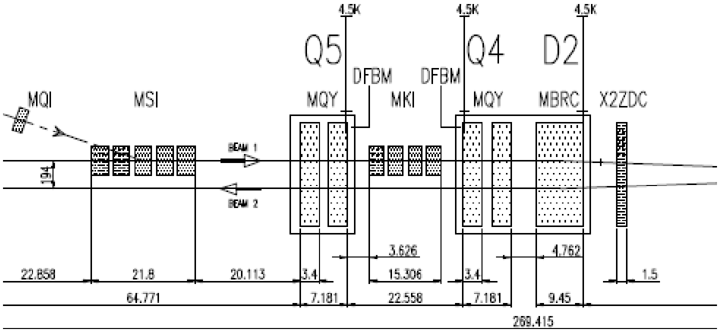

Figure 10: The injection region at IR2, showing the distance between the kickers and the adjacent superconducting magnets.

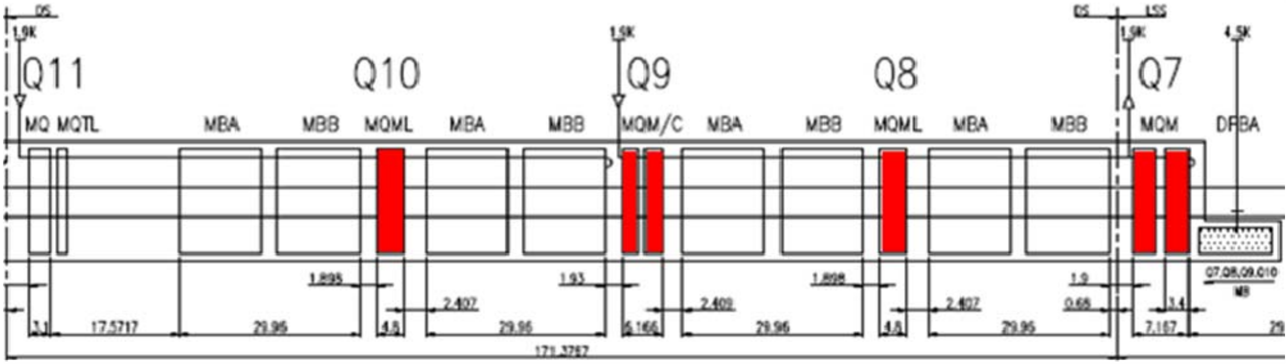

Figure 11: A dispersion suppressor sector, showing the locations of the individually powered quadrupoles.

“PRAYING HANDS” SPLICES

In half the individually powered MQM quadrupoles in the DS (Fig.11), the bus to magnet splice is made in a “praying hands” configuration, as shown in Fig. 12. In this geometry, the electromagnetic forces tend to pry the splice apart, if it is not adequately clamped. Even if the splice itself is clamped, if the adjacent conductors are allowed to flex, wires can break due to mechanical cycling, which could eventually result in an abrupt bus rupture. Experience with HERA, where a splice of this sort failed, and with the Tevatron, where buses of a different geometry failed due to mechanical cycling with magnet excitation, show that this is a real risk.

The stored energy in these circuits (0.4-0.9 MJ) is probably not enough to produce widespread damage. However, it would make a mess, and the probability of such an event is not so low. Furthermore, there are few or no spare MQM quadrupole assemblies, and the Q7 is adjacent to the DFBA, for which there are no spares. This is not likely to be a serious risk for the first year of operation, but it presents a long-term reliability issue. A careful evaluation of the support of these splice and the adjacent cables is in order, and corrections should be implemented as necessary.

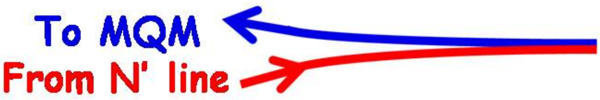

Figure 12: “Praying Hands” splice configuration.

PRIORITIZATION OF MITIGATING MEASURES

Some measures are already being taken, and others have been proposed in this paper and in [13], to reduce the likelihood of any of these “MCIs” and to reduce the impact if one should occur. These measures are summarized in Table 2, where I have also given my judgment concerning their priorities. Some are already underway (priority 0); some additional ones should, in my opinion, be done before restarting the machine (priority 1); others could be deferred until after a short engineering run, but should be done before a full year-long physics run (priority 2); still others could be safely deferred until after the first physics run (priority 3); and several need further study to determine their feasibility (priority 4) or necessity (priority 5).

Substantially improved cryostat pressure relief is being installed in the main arc cryostats in four of the eight sectors. In the other four sectors, a partial fix is being implemented now, and the full upgrade will be put in place after initial running. I recommend that the full pressure relief (DN200 on each cryostat) be implemented in <u>all</u> dispersion suppressor subsectors and in <u>all</u> DFBAs now, before the machine is restarted. Similar improvements in cryostat pressure relief should also be installed now in the inner triplet and in the matching section magnets in the RF straight section, to protect the magnet systems themselves (especially the inner triplet), as well as the adjacent sensitive equipment (experimental beam tubes and RF cavities). Improved pressure relief on other standalone magnets in the matching sections could be deferred until after an engineering run, but should be implemented before a long physics run.

Improved beam tube pressure relief should be installed, prior to any running of the LHC, in the main magnets, as well as the inner triplets, the IR4 matching section, and the magnets adjacent to the injection kickers. The necessity of this improvement for the other matching section matching section magnets should be evaluated.

The anchoring of the SSS with vacuum barriers is being strengthened in the main arcs. The need to do this also for the DFBAs needs to be studied and implemented if necessary. However, if the full pressure relief is installed in all DS and DFBAs, this is probably not necessary.

The QPS system is being substantially upgraded for the main magnets: improved bus fault detection, symmetric quench detection, and redundancy in the UPS system[17]. The need to improve the quench detection for the standalone and semi-standalone magnets in the inner triplets and matching sections should be studied, in light of the new understanding of bus fault risks and UPS redundancy issues.

Prompt opening of the quench valves (or opening at a lower pressure) in case of a bus fault could help reduce collateral damage. However, it may take some time to develop the algorithm for deciding how to trigger this action, and to ensure that it is done correctly. Therefore, this could be deferred until after the initial long physics run. However, the benefits of implementing this scheme for the inner triplets, given the spares issues and the vulnerability of the adjacent experimental beam tubes, raise the priority of implementing this now. Conversely, the operational consequences of releasing more helium into the recovery line are smaller than for the main magnets, due to the relatively small helium inventory. Thus, it would be advantageous to implement this scheme earlier in the experimental regions.

Changes in the response to bus quenches in the main magnets or in the DFBAs, involving the firing of many quench heaters, the delayed opening of the energy extraction switches, or even the non-opening of one of the extraction switches, has the potential of substantially reducing the energy available to an electrical fault in the main magnet bus bars. However, such algorithms, if not implemented properly, could have potential negative side-effects. Therefore, such systems need further study to understand if they are in fact, feasible.

Improving the clamping of the “praying hands” splices and the adjacent bus cables does not require immediate attention, but could be addressed after the first long physics run.

Finally, it is crucial to examine the spares situation, and ensure that an adequate inventory of assembled modules exist for, at least, the main RF system, and that an adequate number of parts is available to allow rapid repair or rebuild of unique devices, such as DFBs.

ACKNOWLEDGMENTS

I would like to thank numerous people for essential discussions that helped me develop this presentation. These include: Nuria Catalan Lasheras, Edmond Ciapala, Serge Claudet, Knud Dahlerup-Petersen, Lyn Evans, Sandor Feher, Bob Flora, Brennan Goddard, Miguel Jimenez, Mike Koratzinos, Philippe Lebrun, Peter Limon, Alick Macpherson, Bob Mau, Karl-Hubert Mess, Ron Moore, Ranko Ostojic, Vittorio Parma, Antonio Perin, Lucio Rossi, Rüdiger Schmidt, Andrzej Siemko, Laurent Tavian, Rob van Weelderen, Ray Veness, Arjan Verweij, Peter Wanderer, Jorg Wenninger, Rob Wolf, plus others that I’m sure I have forgotten (to whom, my apologies). While I have benefited greatly from their help, the analysis and conclusions are my own, and others are absolved of responsibility for mistakes, things forgotten, or poor recommendations I have made.

Table 2: Prioritization of Proposed Improvements.

	Main Arc	DS	DFBA	IT	MS-IR4	MS-Inj	MS
Cryostat Pressure Relief	0 / 2	0/1	1	1	1	2	2
Beam Tube Pressure Relief	1			1	1	1	5
Improve Anchor to Ground	0		5				
QPS Upgrade- bus fault detection	0			5	5	5	5
QPS Upgrade - symmetric quench	0						
Prompt Quench Valve Opening	3			2			
Complex heater/dump algorithm	4		4				
Splice clamping							3
Spares	3	3	3	3	3	3	3

0 Currently being done, prior to Fall 2009 start.
1 Strongly recommended before Fall 2009 start.
2 Could be deferred until after a Fall 2009 "engineering" run, if such exists.
3 Could be deferred until after a 2009-10 physics run, if there is no engineering run.
4 Requires substantial study and design effort to determine feasibility.
5 Requires study to determine if it is necessary or useful

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