Maximum Credible Incidents

LHC Performance Workshop - Chamonix 2009
4 February 2009

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The Title

Maximum

- Defined for the purpose of this talk to be any incident which results in substantial loss of capability of LHC:
  - Extended down-time, ending a physics run whenever it occurs.
  - Extended running with reduced performance.

Credible

- Computation of probabilities is not possible => judgment as to whether or not it is plausible that such an incident could occur during the lifetime of LHC.

Incident***s***

- 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.

Scope of the Talk

This talk is “limited” to incidents involving hardware failures in the superconducting magnet system.

- Faults initiated by the SC magnet system which “maximally” damage itself, e.g 19 September.
- Faults initiated by the SC magnet system which “maximally” damage other systems.
- Faults initiated by another system, e.g. the beam, to which the SC magnet system does not respond appropriately, resulting in “maximal” damage to itself or others.

General Considerations

"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 arc)
- The cryogenic system (high forces from high pressures, thermal damage due to rapid temperature changes)
- The beam (360 MJ per beam at nominal energy and beam current)
  - Outside the scope of this talk => See Brennan's talk later in this session.

Other Considerations

- The machine can induce "collateral damage" in the experiments
- When implementing mitigating measures, need to take account of their effects, for example:
  - improved pressure release => more rapid release of cold helium into the tunnel
  - reinforcing a weak point => what is the next "fuse"?

Disclaimer

Any effort to catalog the "worst possible cases," especially one developed by one person, is bound to miss possible events.

What actually happens is likely to be something not foreseen.

Still, planning for the foreseen cases can help deal with the unforeseen!

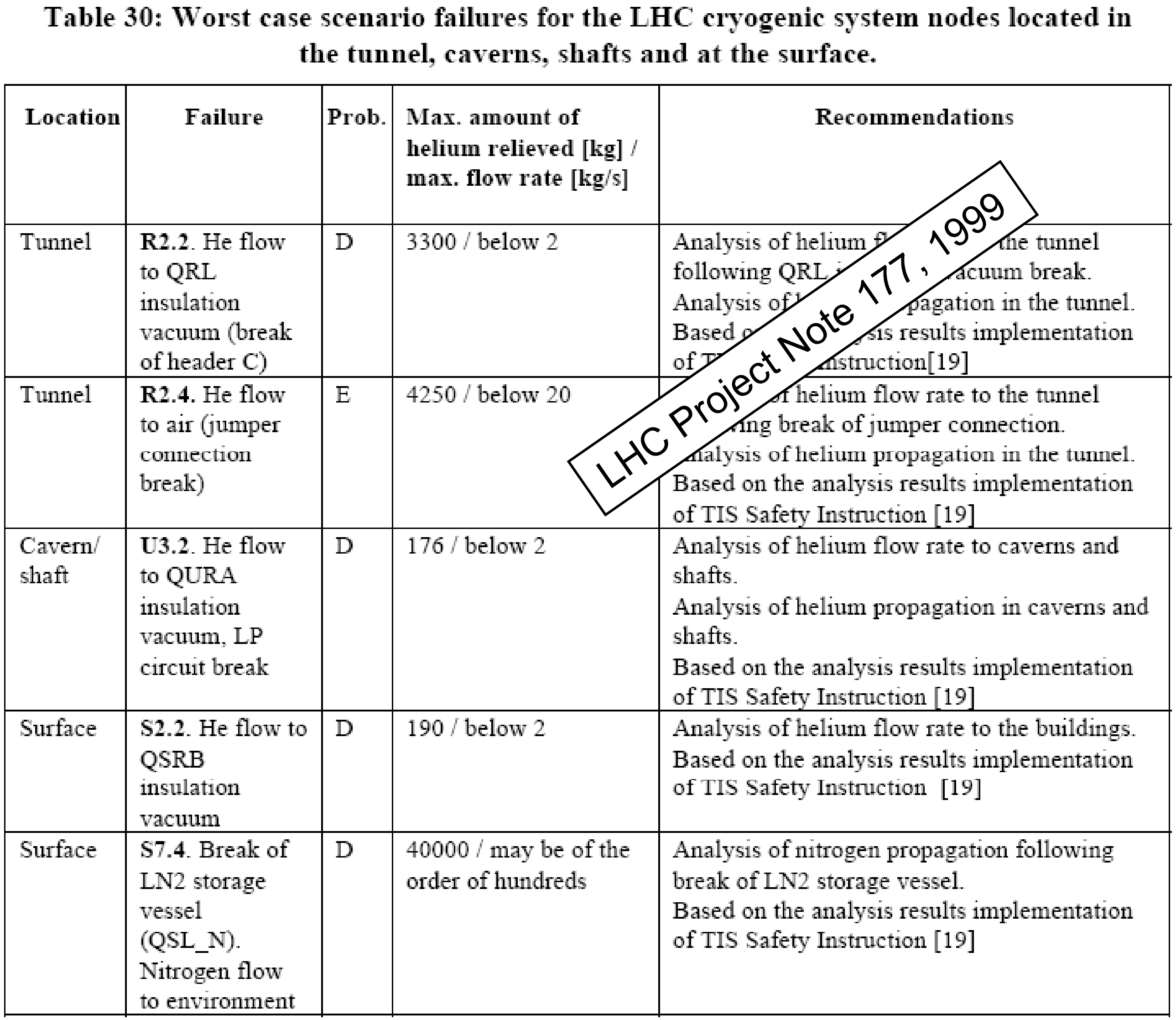


Table 30: Worst case scenario failures for the LHC cryogenic system nodes located in the tunnel, caverns, shafts and at the surface.

Location	Failure	Prob.	Max. amount of helium relieved [kg] / max. flow rate [kg/s]	Recommendations
Tunnel	**R2.2.** He flow to QRL insulation vacuum (break of header C)	D	3300 / below 2	Analysis of helium f[illegible] the tunnel following QRL i[illegible]acuum break. Analysis of [illegible]pagation in the tunnel. Based o[illegible]sis results implementation of T[illegible]nstruction[19]
Tunnel	**R2.4.** He flow to air (jumper connection break)	E	4250 / below 20	[illegible]f helium flow rate to the tunnel [illegible]ing break of jumper connection. [illegible]nalysis of helium propagation in the tunnel. Based on the analysis results implementation of TIS Safety Instruction [19]
Cavern/ shaft	**U3.2.** He flow to QURA insulation vacuum, LP circuit break	D	176 / below 2	Analysis of helium flow rate to caverns and shafts. Analysis of helium propagation in caverns and shafts. Based on the analysis results implementation of TIS Safety Instruction [19]
Surface	**S2.2.** He flow to QSRB insulation vacuum	D	190 / below 2	Analysis of helium flow rate to the buildings. Based on the analysis results implementation of TIS Safety Instruction [19]
Surface	**S7.4.** Break of LN2 storage vessel (QSL_N). Nitrogen flow to environment	D	40000 / may be of the order of hundreds	Analysis of nitrogen propagation following break of LN2 storage vessel. Based on the analysis results implementation of TIS Safety Instruction [19]

LHC Project Note 177, 1999

Magnet Systems with Largest Stored Energy

Classify magnet systems by “quench protection unit,” that is the effective circuit once the quench protection system has triggered.

Circuit	Type	E (MJ)	
MB-bus	bus	1157	
MQ-bus	bus	43	[1]
MB	Dipole	7.5	
MQXB (Q2)	Quad	2.4	[2]
MQXA (Q1, Q3)	Quad	2.0	
MQY	Quad	1.9	[1,2]
MQM	Quad	0.9	[1,2]
MBRC/B/S (D2,D4,D3)	Dipole	0.8	
MQ	Quad	0.8	[1]
MBX (D1)	Dipole	0.4	

[1] Individually powered apertures - energy summed due to coupling between circuits

[2] two magnets powered in series

Sector 34 Type Incident – ***The*** MCI

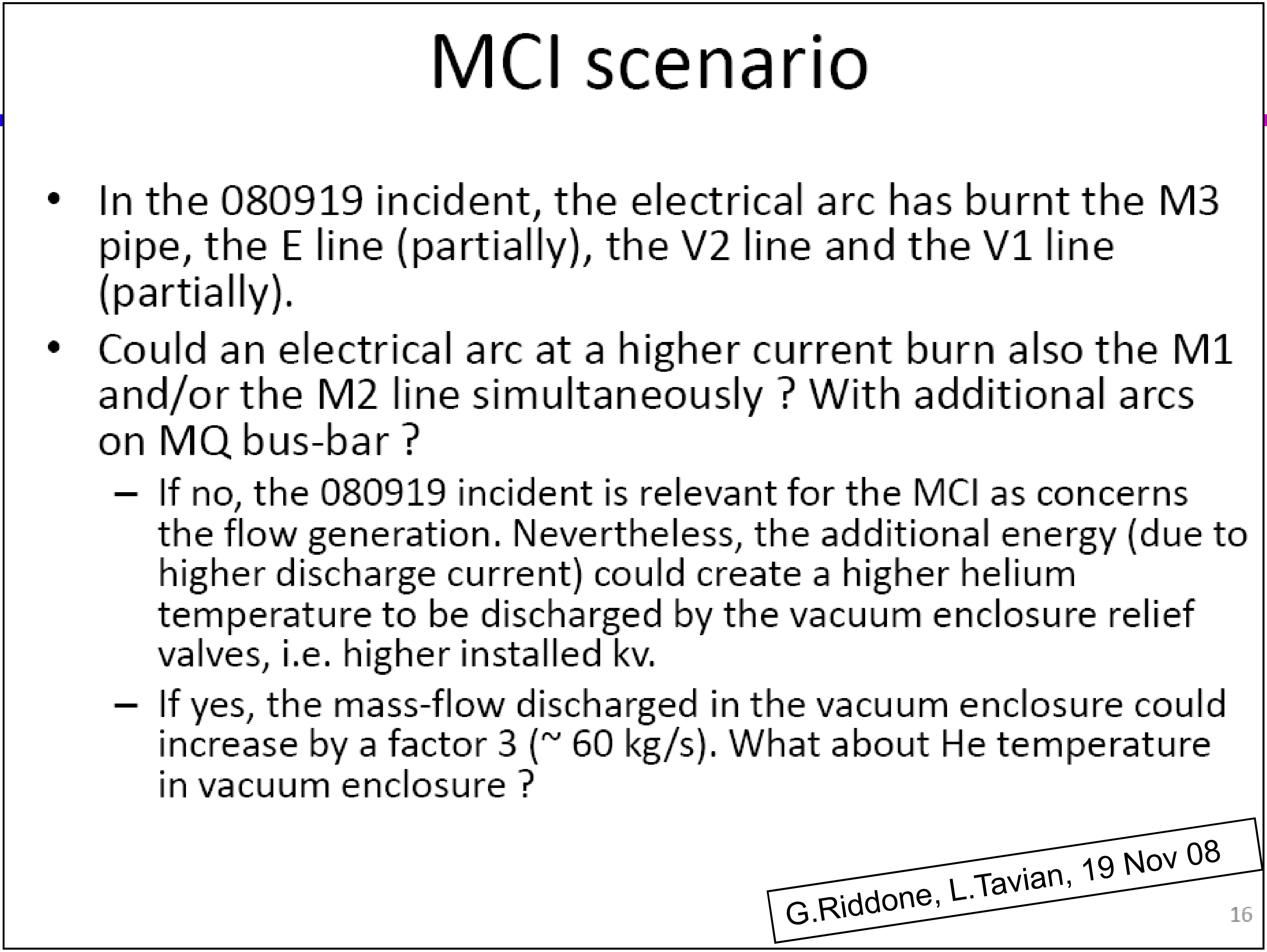
An incident, such as that of 19 Sep, is probably THE Maximum Credible Incident involving a hardware failure, since it involves:

- the electrical system with the largest stored energy – the whole dipole circuit,
- the largest single volume of helium in the tunnel – one cryo sub-sector which is up to 300 m long.

What could be worse??

- An electrical arc in the dipole bus, which breaches one or both of the quadrupole bus lines, creating arcs in the quad busses also.
- "Only" 4% more stored energy available in the quad circuits . . . "merely" 43 MJ.
- Yields at least twice the helium flow into the cryostat.

The new cryostat relief system is designed to deal with this scale event.

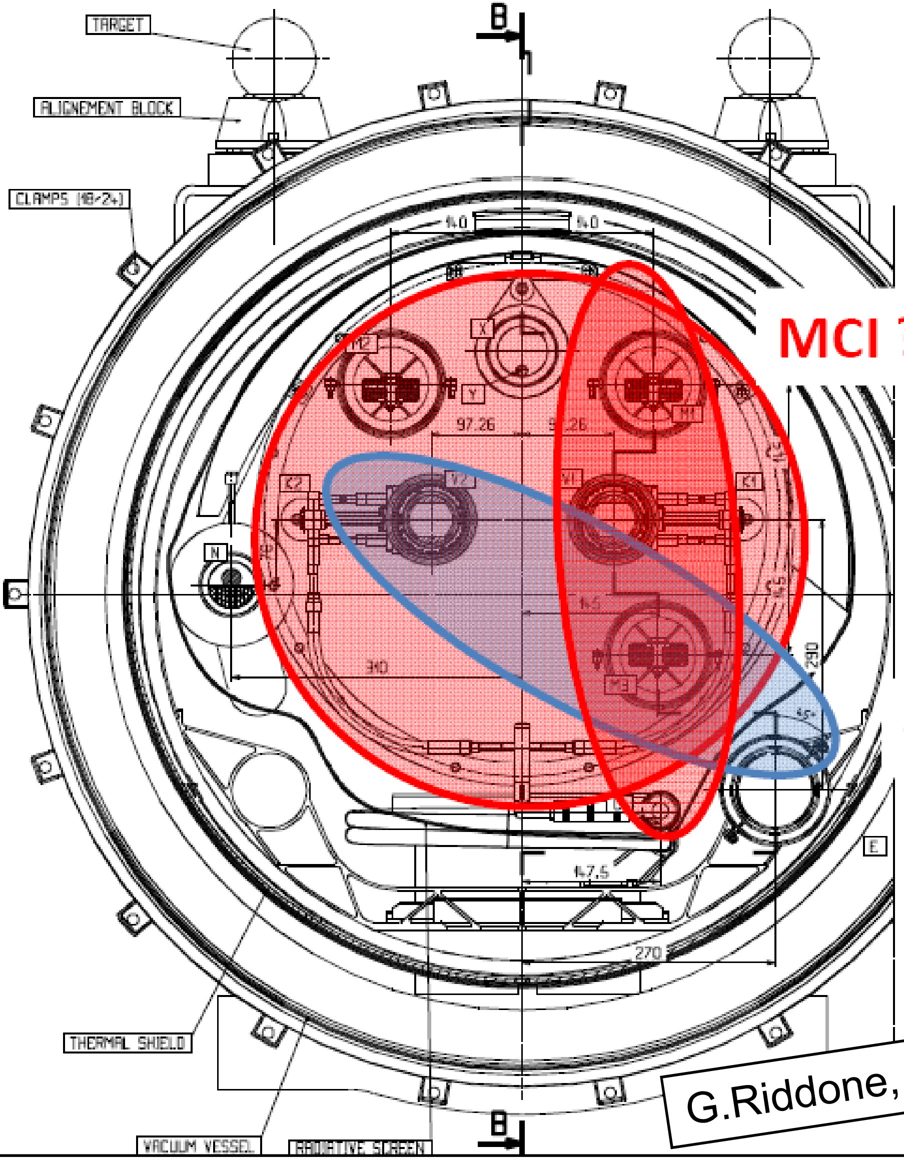


MCI scenario

- In the 080919 incident, the electrical arc has burnt the M3 pipe, the E line (partially), the V2 line and the V1 line (partially).
- Could an electrical arc at a higher current burn also the M1 and/or the M2 line simultaneously ? With additional arcs on MQ bus-bar ?
  - If no, the 080919 incident is relevant for the MCI as concerns the flow generation. Nevertheless, the additional energy (due to higher discharge current) could create a higher helium temperature to be discharged by the vacuum enclosure relief valves, i.e. higher installed kv.
  - If yes, the mass-flow discharged in the vacuum enclosure could increase by a factor 3 (~ 60 kg/s). What about He temperature in vacuum enclosure ?

G.Riddone, L.Tavian, 19 Nov 08

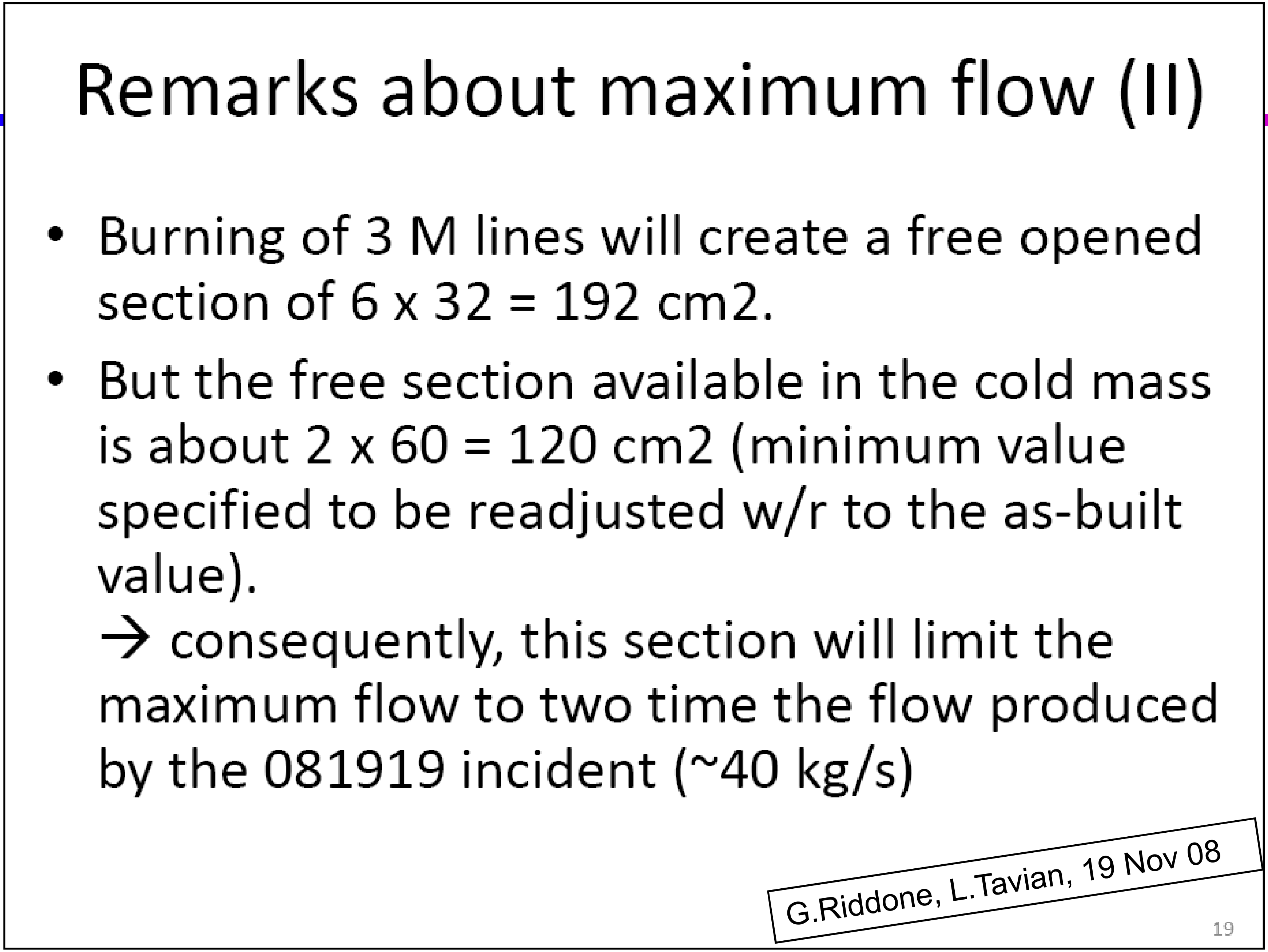
Possible MCI arc damage ?



MCI ?

080919 incident

G.Riddone, L.Tavian, 19 Nov 08



Remarks about maximum flow (II)

- Burning of 3 M lines will create a free opened section of 6 x 32 = 192 cm2.
- But the free section available in the cold mass is about 2 x 60 = 120 cm2 (minimum value specified to be readjusted w/r to the as-built value).
  → consequently, this section will limit the maximum flow to two time the flow produced by the 081919 incident (~40 kg/s)

G.Riddone, L.Tavian, 19 Nov 08

19

Sector 34 Type Incident – ***The*** MCI

- Measures being taken to minimize changes for such an event and minimize damage should one nonetheless occur:
  - Vastly improved bus fault detection.
  - Systematic survey for resistive joints at the 10 nΩ level.
  - Vastly improved cryostat pressure relief.
  - Improved anchoring of SSS to the floor.

Sector 34 Type Incident – ***<u>The</u>*** MCI

- A sector 34 type event, although credible, is much less likely in the future due to vastly improved bus fault detection system.
  => Abrupt rupture of bus or short circuit between buses, with no precursor signal above 0.3 mV.

- Direct and collateral damage would still be significant.
  - Severe damage to the two affected magnets (dipoles or SSS)
  - High helium mass flow likely at least to disrupt MLI throughout the affected subsector => up to 24 (long sub-sector) magnets to remove and re-cryostat
  - Substantial contamination of beam tubes and risk to bellows.

Electrical Fault in DS or DFBA

- Situation could be worse if the fault occurred in a DS with only the first phase pressure relief improvement.
  - Square cryostat vulnerable to internal pressure.
  - Anchors to floor may not be adequate for 2.5 bar.
  - HTS leads and chimneys could be damaged.
  - No spares* => 6 months to a year to build a replacement.
- Electrical fault in the DFBA itself could be even worse.
  - All circuits potentially involved.
  - Bottlenecks make relief path to magnet cryostat problematic.

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* There are 16 DFBA of 16 different variants.
There are 28 DFBM+DFBL of 15 different variants.

Electrical Fault in DS or DFBA

- How to protect the DFBs?
  - Consider adding DN200 ports to all DS.
  - Improve pressure relief on the DFBs themselves.
  - Ensure anchoring to floor is adequate.
  - In case of bus fault in DFBA, do ***not*** open dump switch adjacent to it => limit voltage across electrical fault.
  - Open quench valves early.
  - Fire many quench heaters away from DFBA/DS.

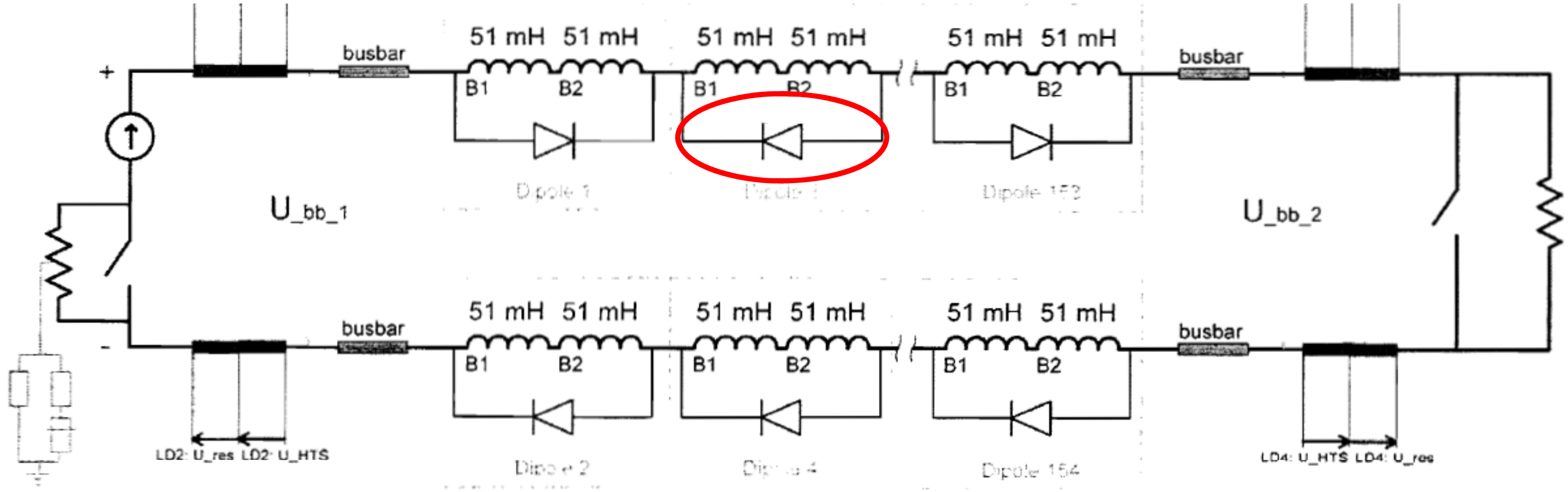
Individual Dipole Failure

- Arc inside a dipole (or quadrupole)
  - Inter-aperture or inter-pole splice opening
  - Inter-turn short
- Fault is behind the diode => only the stored energy in one dipole is involved ~1% the stored energy of 19 September.
- QPS will fire quench heaters, dissipating the stored energy within <1 sec => ~1% the time constant for a bus event.
- The available energy (even for a quadrupole) is more than sufficient to breach the helium containment or the beam tube.
- Leak to cryostat << "new MCI" => properly handled.
- If arc punctures the beam pipe, it could be pressurized up to the 17 bar opening pressure of quench valves. => widespread damage of PIMs and nested bellows.
  - => need substantial improvement in beam vacuum pressure relief.
  - => if arc can be distinguished from quench, could mitigate by opening the quench valves early.

Diode installed backwards?

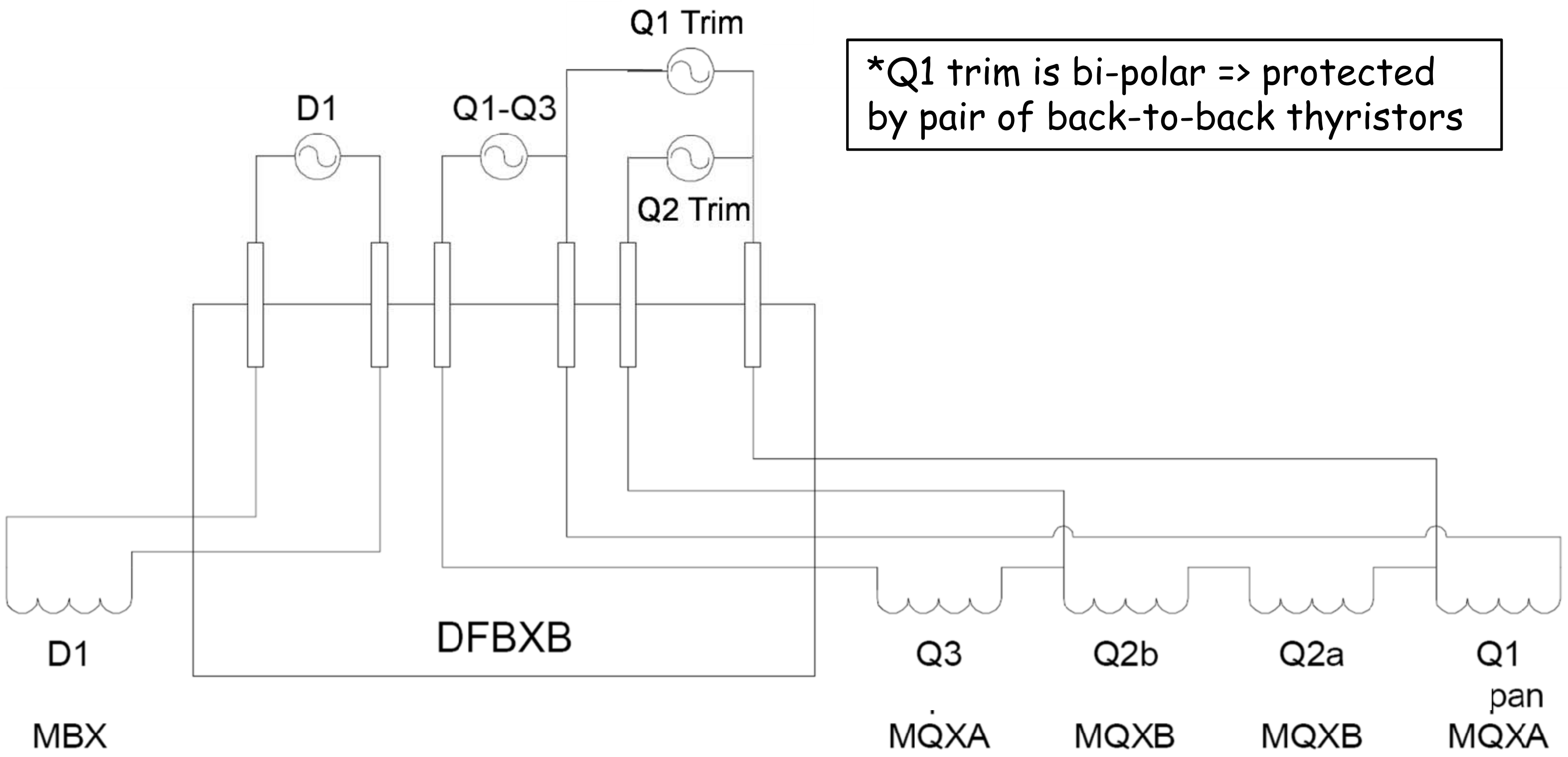
- I don't know if this is "credible," but the consequences could be substantial.
- Quench in dipole with diode installed backwards
  => Current from the rest of the dipole circuit flows through quenching magnet, not diode => gross overheating and maybe electrical arc, with potential similar to a bus rupture.

  Probably saved by failure of diode due to high reverse voltage,
  . . . unless diode fails open!



Inner Triplet

- The stored energy in the triplet (6.5 MJ) is almost as large as one main dipole (7.5 MJ).
- Complex powering scheme with 3 power converters.
- Diodes* across each PC divide the triplet into 3 circuits once a quench occurs: Q1, Q3 - 2.0 MJ each; Q2 - 2.4 MJ.



*Q1 trim is bi-polar => protected by pair of back-to-back thyristors

Inner Triplet

Specific points about the Inner Triplet system.

- Quench protection:
  - Voltage taps cover the bus bars together with the magnets.
  - Any quench => fire quench heaters in all triplet magnets.
- IT bus bars are very different from main magnet bus:
  - One 13 kA SC cable soldered to Cu-only cable of same geometry.
  - Designed so quenches propagate and can be detected.
  - Can carry current during the detection and current decay time.

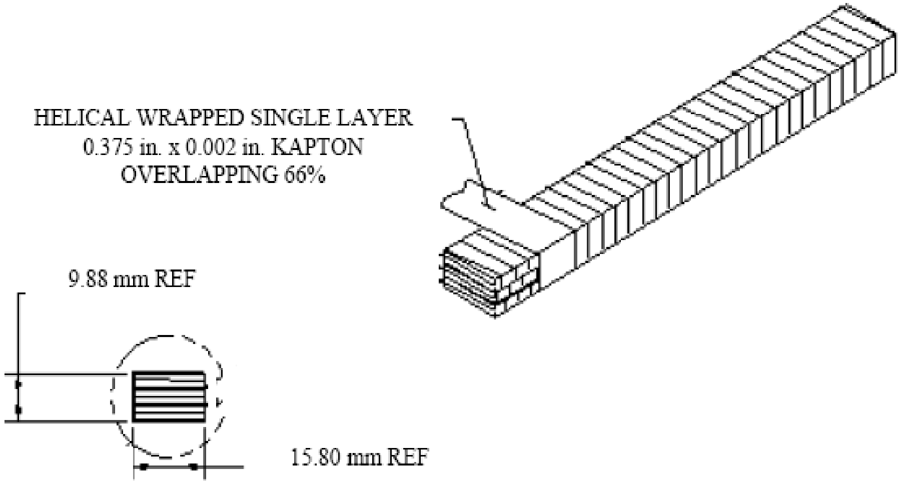
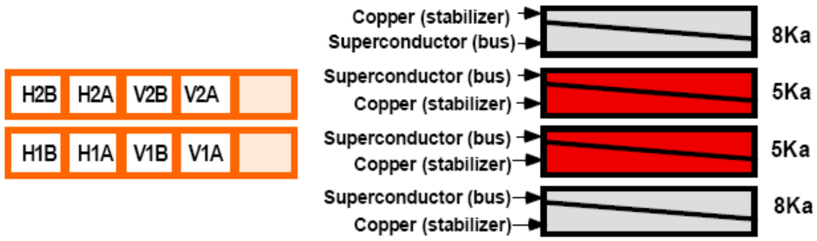
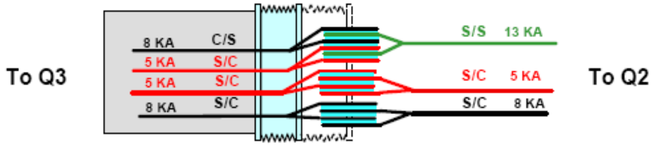


Figure 4. **Main buswork in LQXB, before packaging in housing.**



View A-A (Q3 Lead Configuration)



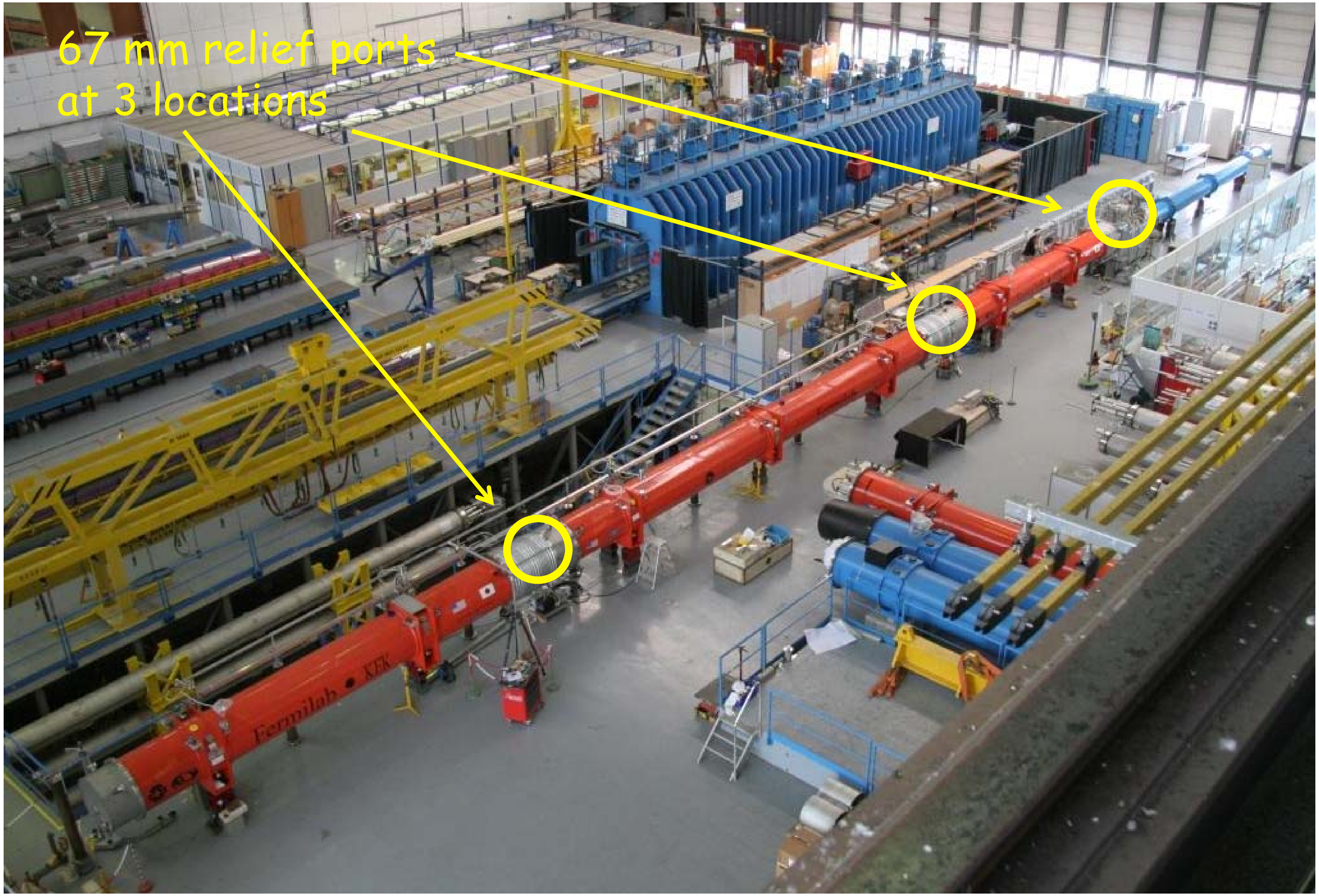
Section B-B (Magnet Lead Configuration)

Inner Triplet

Specific points about the Inner Triplet system.

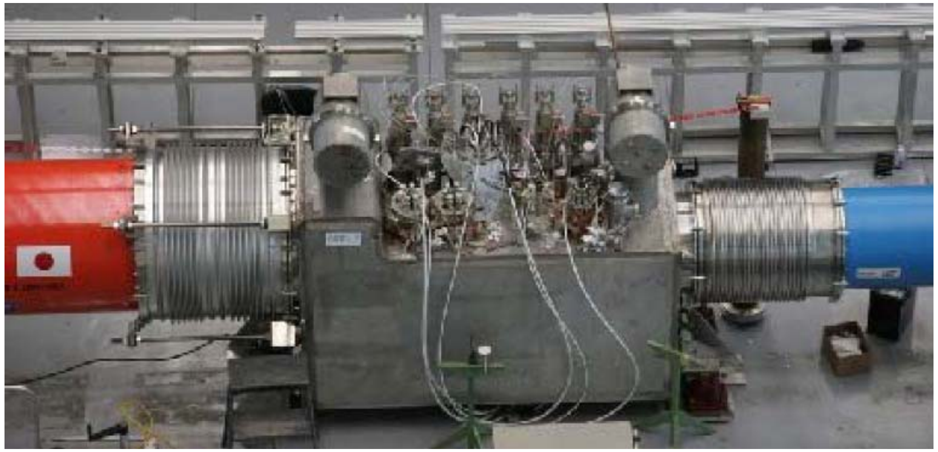
- Risk of bus failure is low, **but** . . .
- Bus splices are inside thin-walled (0.25 mm) bellows
  => vulnerable to puncture/rupture in case of an electrical arc
- Rupture of an interconnect bellows could release helium at a peak rate similar to 19 September.
- Existing cryostat relief system is three 67 mm ports, covering triplet, DFBX, and D1 => capacity of 1~1.5 kg/s

Inner Triplet


67 mm relief ports at 3 locations

Inner Triplet - MCIs

- Bus fault rupturing interconnect bellows:
  - Up to 20 kg/s helium flow into cryostat.
  - Cryostat pressurized to many bar, similar to 19 Sep event.
  - Anchors to floor will break for P > 1.5~2 bar.
  - Superconducting D1 could also be pushed off its stands.
  - DFBX (square cryostat) could be severely damaged by internal pressure.
    No spare DFBX* => 1-2 years to build new from scratch.



- Inter-turn short puncturing/rupturing cold bore tube.
  - Scaling from a similar incident with an SSC R&D magnet, such an event could create a 20-30 mm diameter hole in the beam tube.
  - Up to 10 kg/s high pressure helium released into vacuum tube, adjacent to experiments, in presence of electrical arc.

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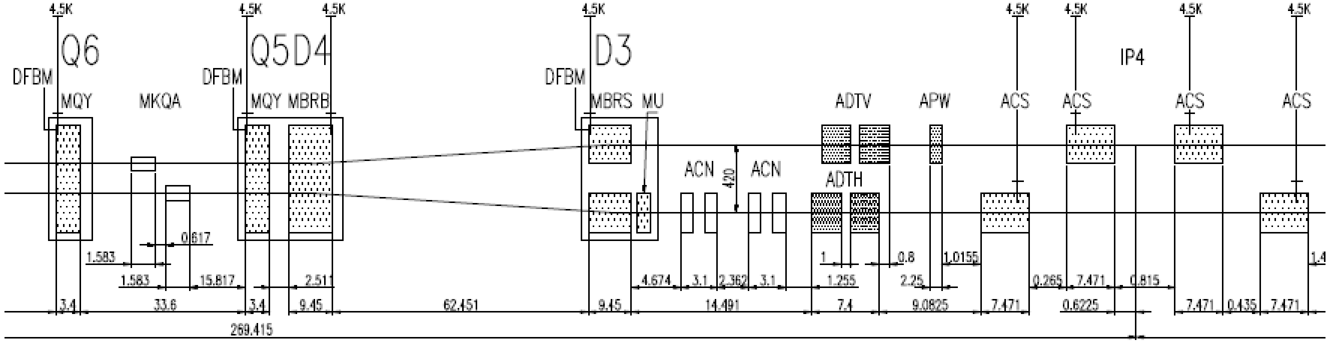
* There are 8 DFBX of 6 variants

Inner Triplet – MCIs – What can be done?

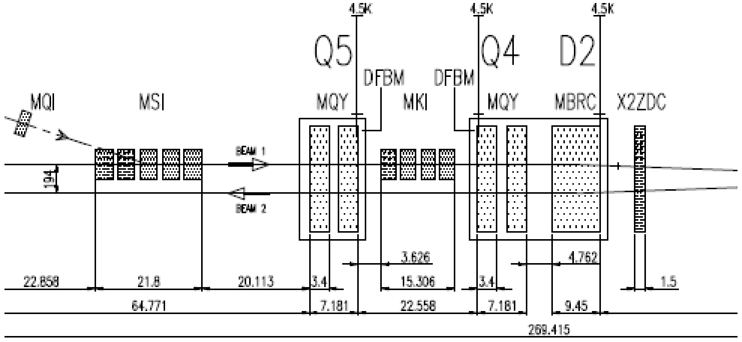
- No obvious measures to further reduce risk of either case.
- Can do more to mitigate consequences.
- Rupture of interconnect M-line:
  - Substantially enhance relief capacity, e.g. adding several DN200 to each triplet.
  - Should be done now, before irradiation of magnets. Can be done for all triplets this year, if started now.
  - *Difficult to strengthen anchors to ground, given specific tunnel floor conditions in some areas.*
- Rupture of beam tube
  - Pressure could be minimized by early opening of quench valves.
  - Enhance pressure relief on beam tube in inner triplet and experimental region.
  - Should be done now, before irradiation of the region.
  - *No fast acting gate valve is fast enough to protect the experimental beam tube.*

Collateral Damage Risks to Other Sensitive Equipment

- Inter-turn short in D3, D4, Q5, . . . (~1.0 MJ stored energy each) could puncture the beam tube and contaminate the SCRF cavities, for which there is only one spare cryo-module.



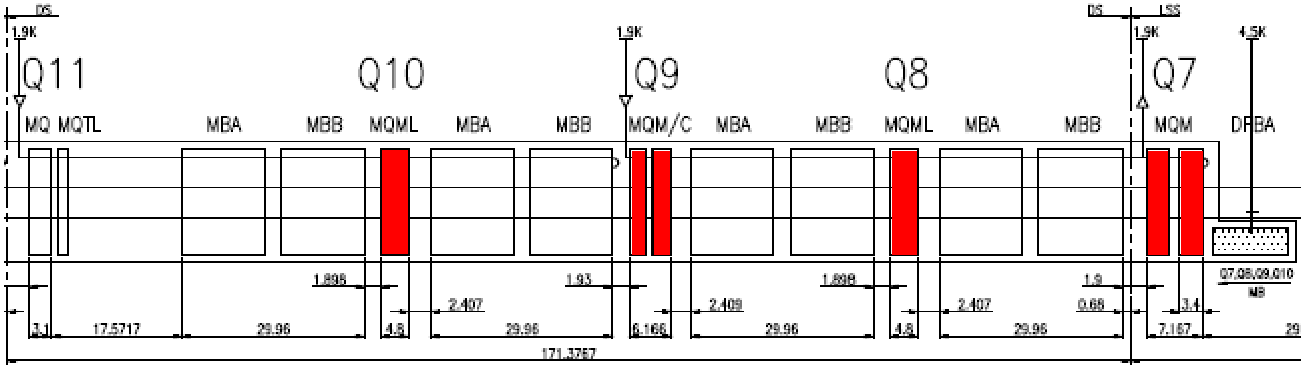
- Or fault in Q5, Q4 (1.9 MJ each) or D2 (0.8 MJ) could contaminate the injection kickers.



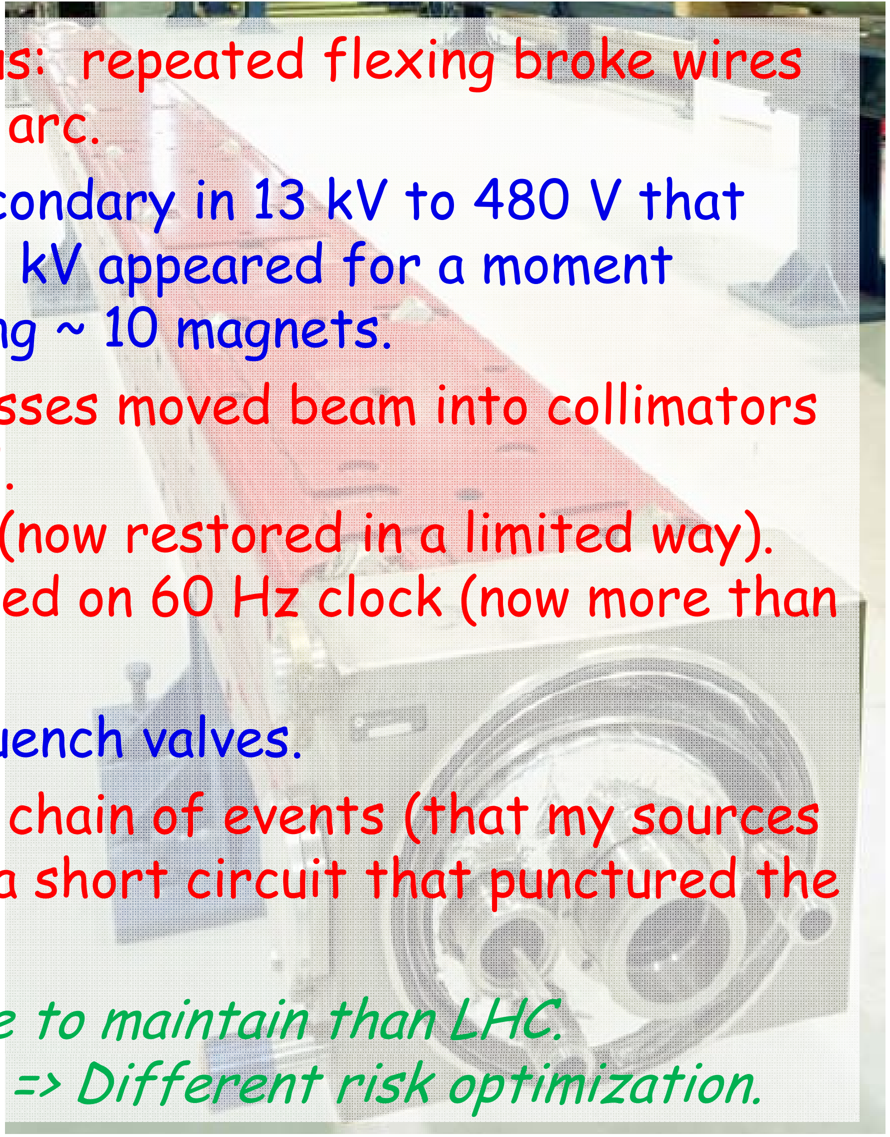
MQM bus splices

- In half the individually powered quads in the DS, the bus to magnet splice is made as shown here.

- EM forces tend to pry such a splice apart, if not well clamped.
- Repeated flexing can break wires, eventually resulting in abrupt rupture of the joint and an electrical arc.
- Experience with Tevatron and HERA suggest that this risk is real.
- 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. And Q7 is adjacent to the DFBA. . . And few or no spare MQM . . .



Short list of some bad things that have happened to the Tevatron



- Poorly restrained inter-magnet bus: repeated flexing broke wires until bus abruptly broke, creating arc.
- Electrical arc from primary to secondary in 13 kV to 480 V that fed a Tevatron power supply => 13 kV appeared for a moment across the magnet string, damaging ~ 10 magnets.
- Fast quench due to heavy beam losses moved beam into collimators before beam abort was requested.
  - Beam loss monitors masked out (now restored in a limited way).
  - Quench protection system worked on 60 Hz clock (now more than an order of magnitude faster).
- Pressure damage due to broken quench valves.
- Mouse in AC electrical box set up chain of events (that my sources can't remember) that resulted in a short circuit that punctured the beam tube.
- *Tevatron is a much easier machine to maintain than LHC.*
  => Relatively short recovery time. => Different risk optimization.

Summary and Conclusions

- A bus failure, such as the 19 September event, remains the most serious SC magnet system failure that anyone can think of.
  - Could be worse if 2 or 3 M-lines were ruptured.
  - Could be worse if it happened in a DFBA or a DS.
- The failure of the diode protection of a dipole, e.g. a diode installed backwards or one that fails open, could be a result in serious damage.
- A bus failure in the inner triplet could rupture a M-line and severely damage the whole system, including the DFBX for which there are no spares.
- Single magnet inter-turn short could puncture the beam tube, contaminating it and pressurizing it to 17 bar.
- Such an event could damage nearby sensitive equipment, such as the SCRF cavities, injection kickers, or experiment beam tubes.
- “Praying hands” splices in MQMs are a problem waiting to happen.

Summary and Conclusions

Additional measures that could be take to reduce the impact of possible future incidents.

- Improve cryostat pressure relief for
  - DFBAs and DS
  - Inner triplet
  - Matching section magnets
- Ensure adequate anchoring of DFBA to the floor
- Improve beam vacuum relief
  - Burst discs at on SSS pumping ports in the main arc.
  - Around inner triplet, experiments, RF, and kickers.
- Prompt opening of quench valves
  - for bus faults in main magnet circuits
  - for quenches/faults in magnet adjacent to sensitive components.
- Develop more sophisticated quench heater and dump switch algorithms in response to bus faults.

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, Rudiger Schmidt, Andrzej Siemko, Lorent 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.