Worst case beam incident causes and protection

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Based largely on the work of

R.Appleby, R.Assmann, E.Carlier, A.Gomez Alonso, V.Kain, T.Kramer, R.Schmidt, J.Strait, J.Wenninger, J.Uythoven

Outline of talk

- Introduction
- Some worst case incidents….
  - during beam dump
  - during injection
  - with circulating beam
- Discussion and conclusions

This talk, by its nature, may not reassure…

What is WC and where could this happen?

- Exploring cases which have potential to stop LHC for more than 6 months
- Could be as a result of depositing a damaging beam in:
  - many arc magnets simultaneously
  - many collimators
  - a continuous cryostat interconnect
  - A DFB
  - several injection or extraction kickers
  - several RF cavities
  - an experimental beam pipe or detector
  - a triplet magnet
- Some “indirect” beam-provoked damage might also be possible
  - Large loss of vacuum plus contamination of RF cavities, injection kickers, experiment, …
  - Beam-induced quench in busbar cable?
- Collateral effects (He release, vacuum contamination) may take more time to recover from than direct beam damage

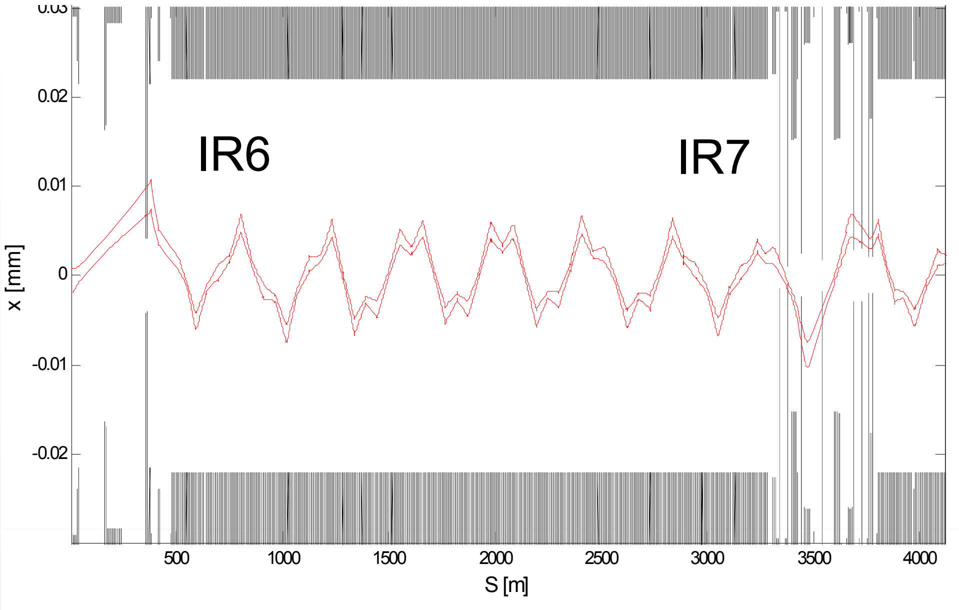
Catalogue of possible incidents and causes?

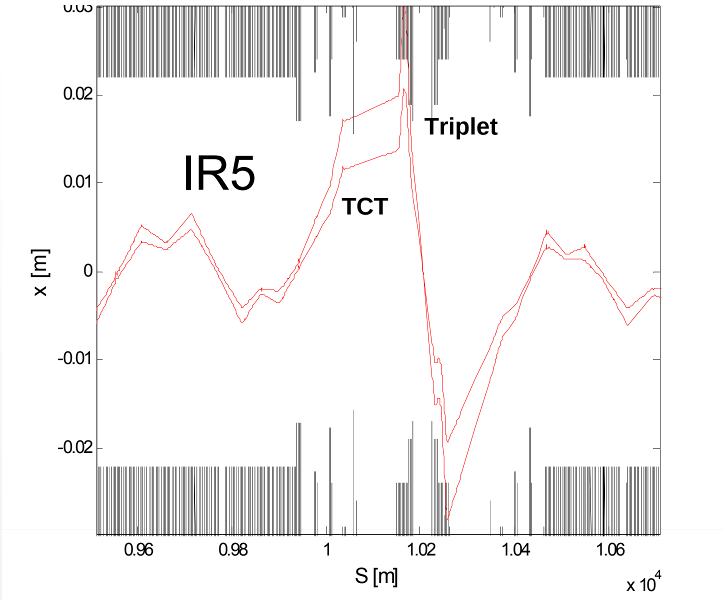
- No systematic catalogue of possible beam-induced incidents exists
  - Incidents due to single failures: already considered by individual systems designers, with lots of work on effects
  - Incidents due to multiple failures: patchy coverage, with obvious ones covered
- Should evaluate multiple failures (up to which order?!)
  - Beam dump, interlocks, BLMs, QPS, PIC & WIC, injections, collimators, operators, powering, …
- Impossible to be comprehensive – especially in a short talk
  - The incidents in the following are therefore only illustrative, concerning some of the critical elements mentioned previously

Incidents during beam abort

Dump kicker erratic **plus** failure of retriggering system

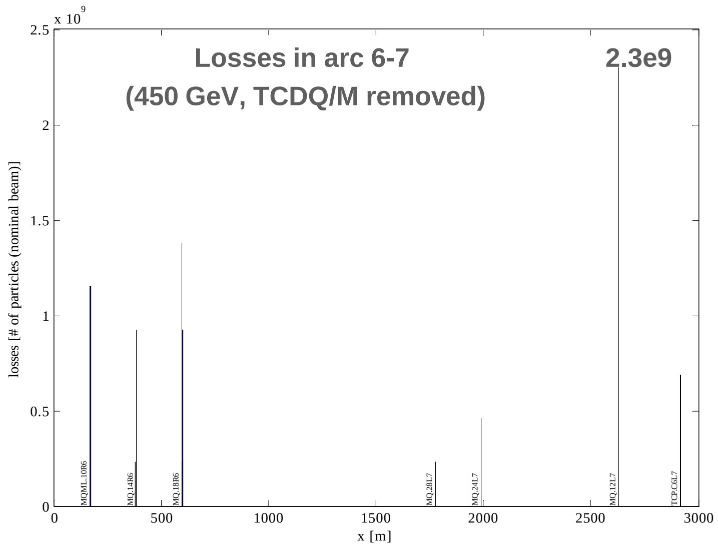
- 1/15 nominal kick - entire beam deflected by 12.1 and 17.8 σ at 7 TeV
  - Synchronous dump trigger then generated by BETs in ~5 turns
- B1: full beam impacts TCDQ and ~40% of H collimators on first turn
  - Huge beam loss and quenches - would trigger dump via BIS within 2-3 turns
  - 85% of H collimators hit within 2 turns (assuming collimators consumed piecewise)
  - Damage to elements downstream of collimators (IR6.Q4 at least 2 J/cc in coil)
- B2: If TCDQ consumed, IR5 TCTs and triplets exposed (B1 extra 5m C, 3 m W)
  - Damage extent depends on mass-transport timescale – stopping 7 TeV beam in C/W

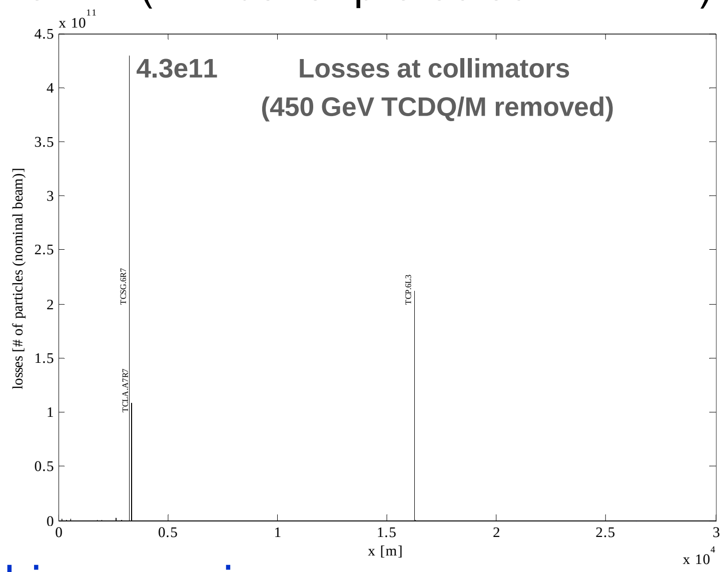




TCDQ/TCSG retracted **plus** asynchronous beam dump

- Beam swept across LHC aperture
  - At 450 GeV, fixed 2 m Fe TCDQM (and Q4) protect arc…(for well-centred beam)
  - At 7 TeV with 0.5m β*, impacts IR 5 TCTs for B2 (IR1 better protected with IR7)

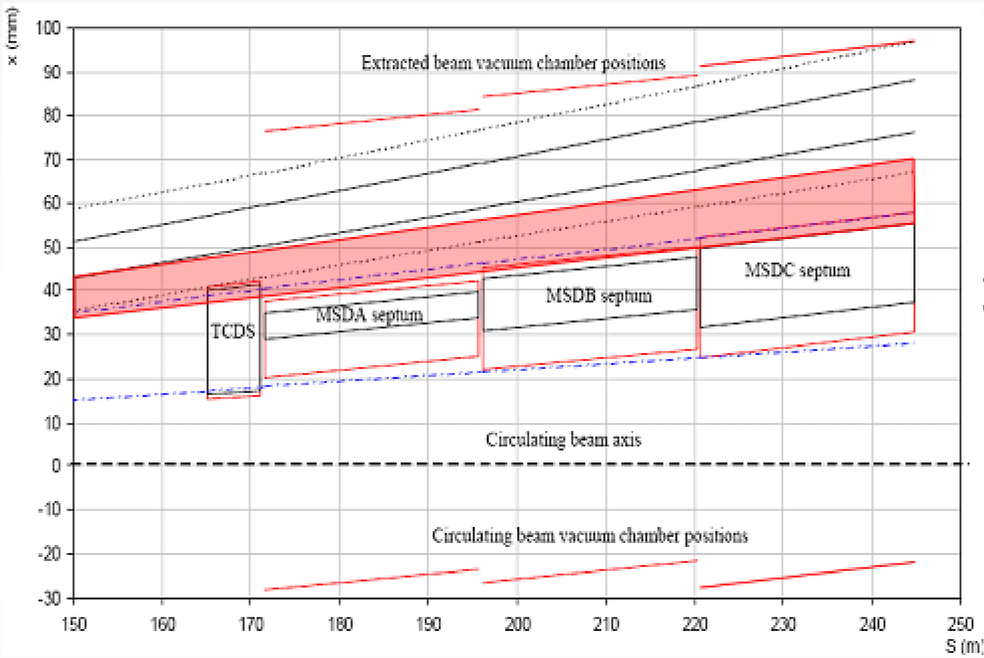


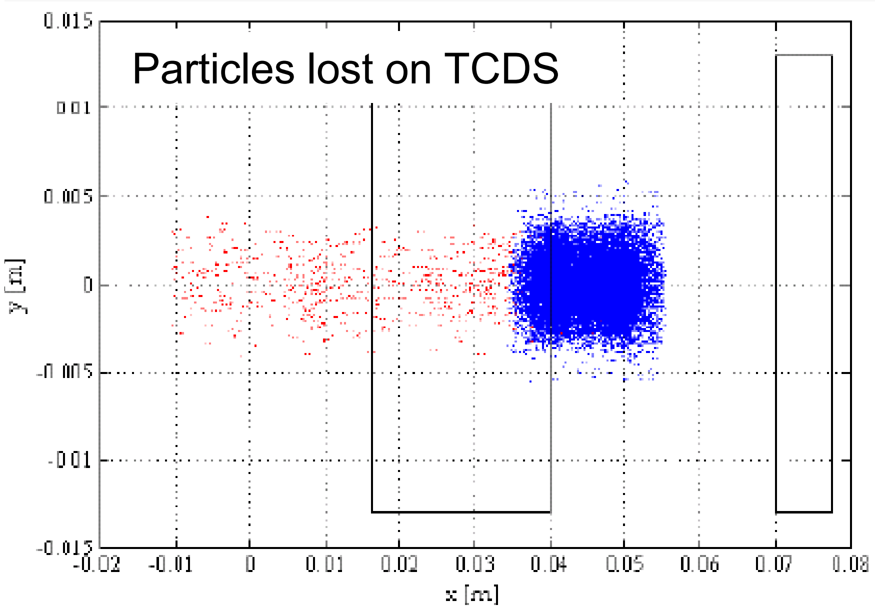


- Many concerns about protection against this scenario
  - Precision on beam position/collimator jaw specified to 0.5 σ. Adequate? Feasible??
  - TCTs are controlled and interlocked in common with TCDQ/TCSG so are there hidden common mode failures? Could then damage several of Q1, Q2 or Q3
  - Does TCT fully protect triplets? Or will swept beam (few us) penetrate?
- Similar effect to asynchronous dump if abort gap is filled

2 missing MKD kickers - switch or trigger failures

- Beam underkicked into TCDS (6m C/Ti/Fe) and MSD vacuum chamber

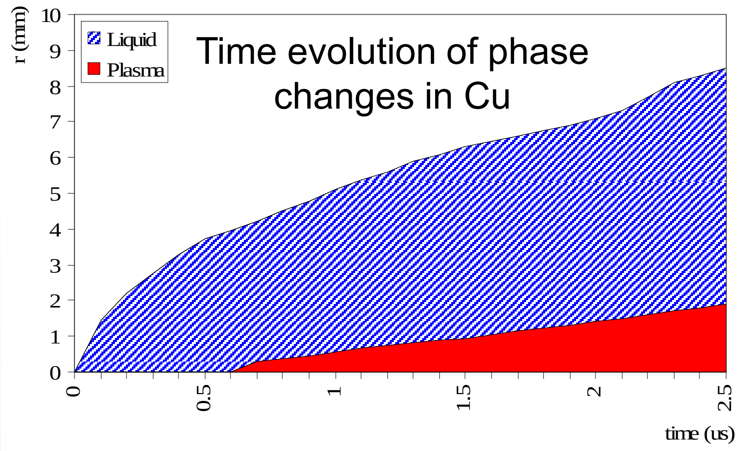


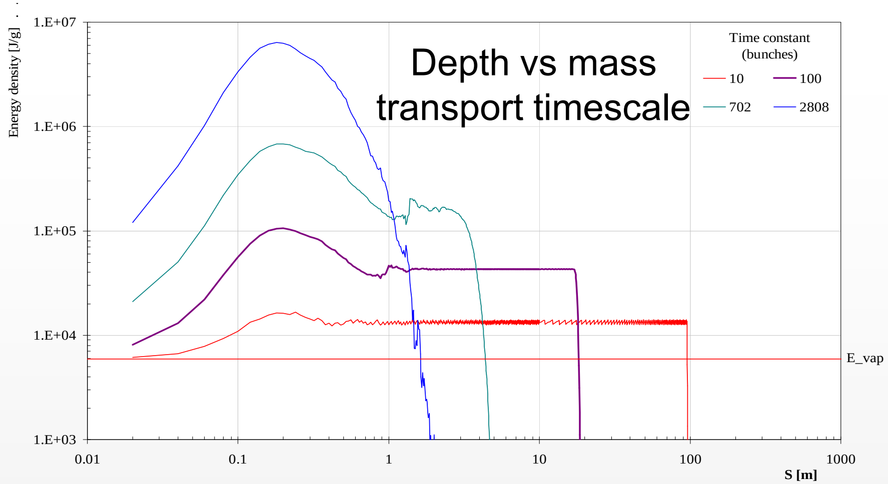


- If TCDS penetrated, damage MSDB and MSDC chambers, MSDC yokes
- Then TD vacuum line at Q4 and Q5 cryo jumpers, MKB kicker magnets, …
  – A lot of sensitive equipment here but not so much stopping power…
  – Sacrificial absorber at start of dump line?
  – Need much better knowledge on beam penetration depth and how materials fail

Penetration of 7TeV LHC beam into matter

- Simplistic energy balance estimates give 100s of metres in Cu or Fe!
- With 350 MJ 86 μs long beam, cannot assume that processes are 'adiabatic'
  - Beam modifies material properties on timescales of beam passage – drills into target
  - Huge scattering from dense target will blow up the primary beam size
- Lacking coupled nuclear – thermo-mechanical simulations
  - Basic simulations of 7 TeV impact on 7.7m C dump core showed beam not contained
  - FLUKA output in hydrodynamic code: factor 10 density reduction after 2.5 us
  - Extrapolations give penetrations of 10 - 40 m of Cu – "limited" to 3-4 SC magnets

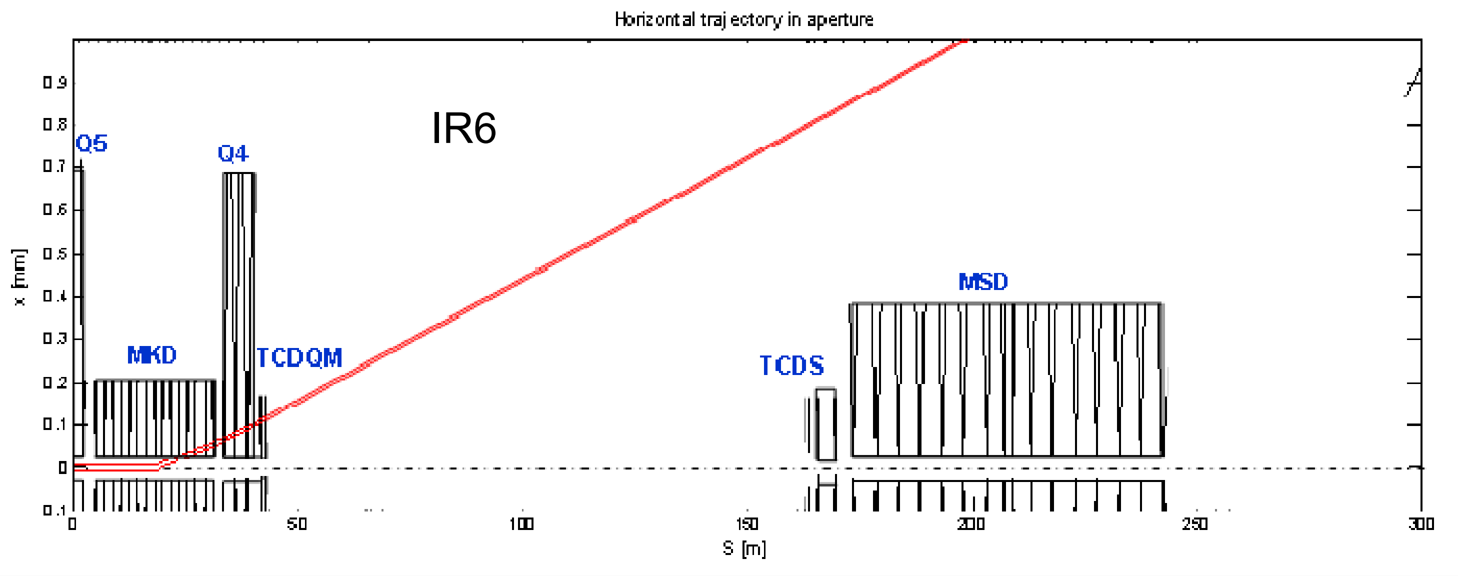




- Essential to better understand processes to estimate direct and collateral damage to machine elements and vacuum/cryo sector(s) concerned

Energy tracking failure – beam into MKD kickers

- MKD energy tracking system failure – 30 kV at 450 GeV rigidity
  - Deflects whole 23 MJ beam at 4.2 mrad instead of 0.27 mrad
  - Beam impacts ~7.5m MKD ceramic chambers, 3m MKD coils, ~5m long Q4 and 2m Fe TCDQM. Probable destruction of all these elements.
  - Showering or further penetration – e.g. into tunnel wall (via QRL for B2…)?

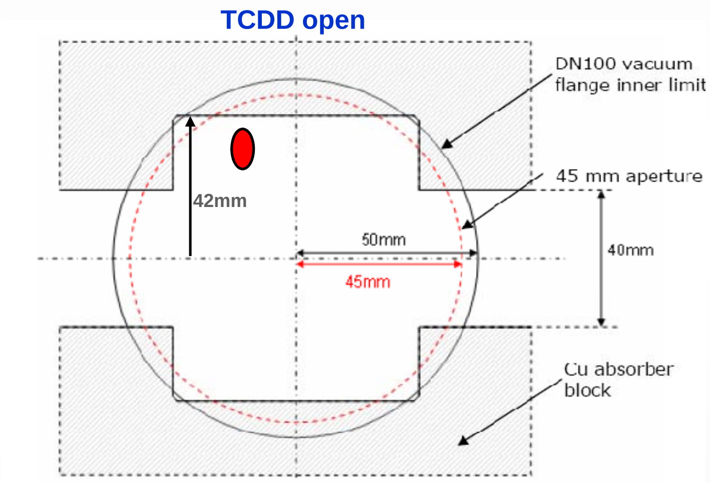


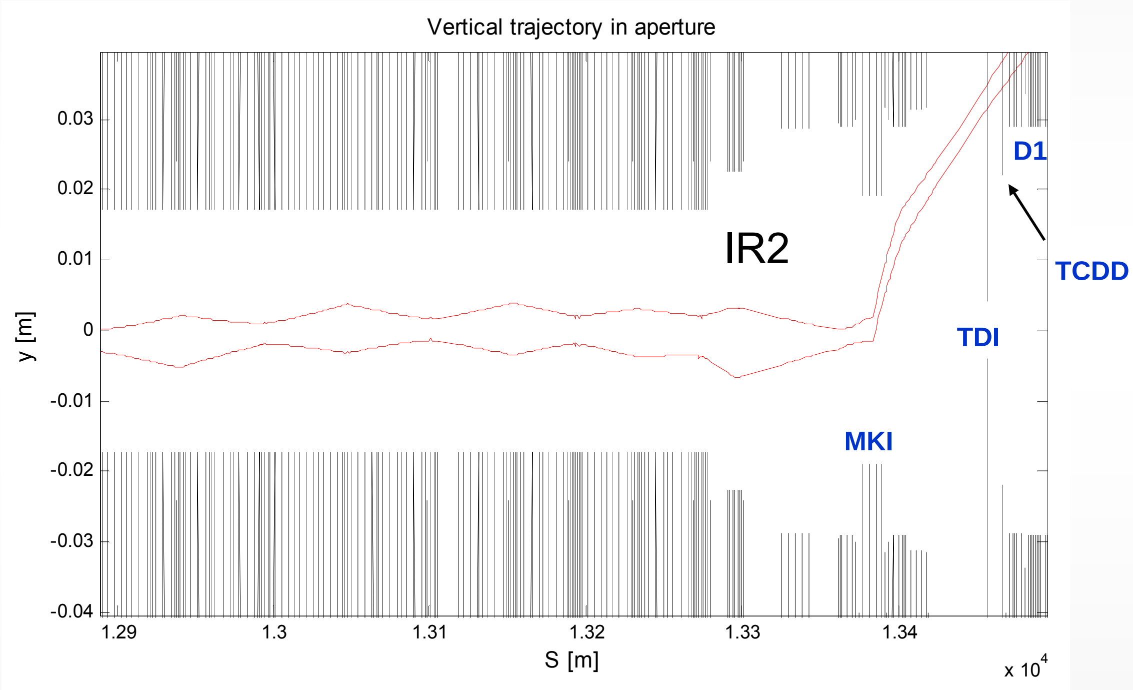
- Stopping full 86 μs long 450 GeV beam: again more data needed
  - Some suggestion from SPS experiment that mass transport can happen in ~5us
  - Experimental data could be possible at proposed HiRadMat facility

Incidents during injection

Injection kicker doesn't trigger plus TDI and TCDD out

- 0.8 mrad angle error for injected 2.3 MJ beam
- Impact ~37 mm at D1 entrance, ~40 mm at exit
  - Exactly at cold bore and coil respectively

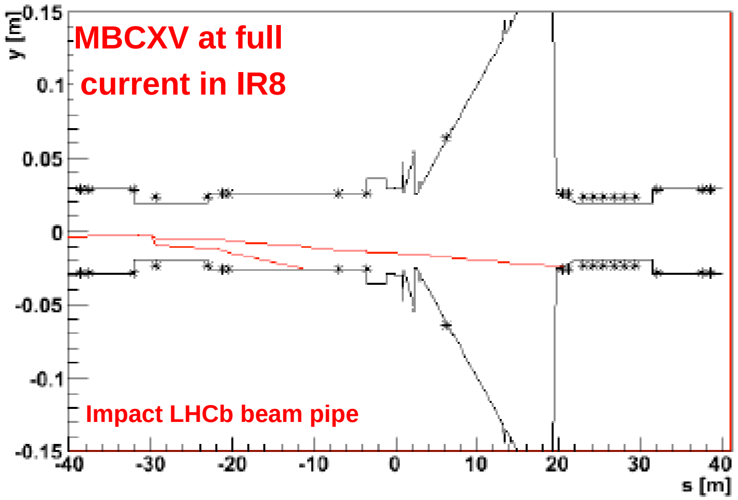




- D1 destroyed - if He into beam vacuum collateral damage probably an important issue
  - Injection kickers and experiments nearby

Injecting with (corrector) dipole field wrong

- Need Beam Presence flag failure plus PC current wrong (many sources)
  - Normal correctors ~1.3 mrad at injection…also D1, Xing/sep and compensation
- Could impact experimental beam pipes in IR2 and IR8 with 2.3 MJ beam
  - Safe limits of ~100 μrad on corrector dipoles and ~3% on D1/D2 currents



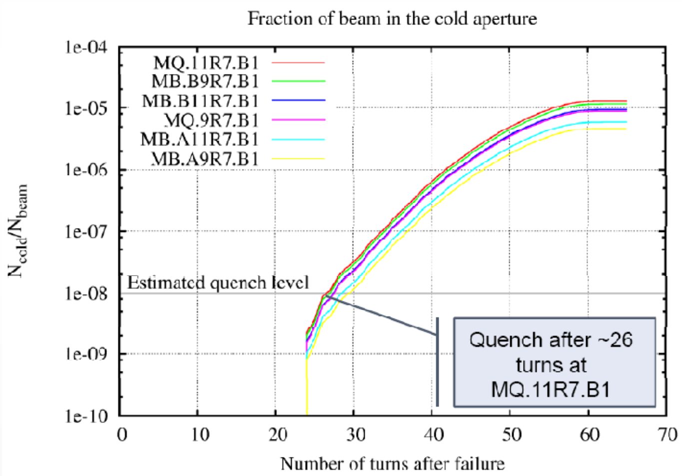
- Also could happen in arc, possibly with several grazing incidence impacts
  - In arc, cold-bore damage might leak He into beam vacuum…
- Worrying cases because of 'weak' protection and large number of sources
  - BP flag produced from "normal" BCT, many hundred unsurveyed magnet circuits

Incidents with circulating beam

"Faster" powering failures

- Effects of powering failures of separate families extensively simulated
- (In)famous warm D1 (450 GeV and 7 TeV): if collimators in position
  - ~10 turns for beam to reach jaws
  - ~25 turns to start quenching downstream magnets
  - ~30 turns to reach collimator damage level

Injection			Collision		
Magnet	t_N $[ms]$	Failure	Magnet	t_N $[ms]$	Failure
MBW	1.1	ΔV_{max}	MBXW	1.7	ΔV_{max}
MBXW	1.4	ΔV_{max}	MBW	6.5	ΔV_{max}
MCBWH/V	3.2	ΔV_{max}	MBX	8.6	Quench
MBXWT	7.9	ΔV_{max}	MCBWH/V	9.0	ΔV_{max}
MQWA	11	ΔV_{max}	MBXWT	10	ΔV_{max}
MBXWS	13	ΔV_{max}	MB	10	Quench
MBX	18	ΔV_{max}	MBRC	10	Quench
MBXWH	21	ΔV_{max}	MQXA/B	12	Quench (4mm offset)
MB	21	Quench	MBXWS	15	ΔV_{max}
MBRB	32	Quench	MBRB	16	Quench



- Correct BLM thresholds AND collimator positions critical
  - Extra protection already added to ~20 circuits in LHC/TLs

“Slower” powering failures

- Trips, quenches, loading wrong settings for one or many magnets
  - Typical timescales factor 10 longer than fastest failures
  - Some self-inflicted scenarios possible (e.g. ramp down whole machine without dumping first… a la SPS ’08)
- Danger if collimators accidentally retracted…
  - BLMs will dump in 3-4 turns when beam reaches aperture…quick enough?
  - Simulations needed…e.g. MB quench, beam moves faster nearer aperture
- Even more dangerous if BLM thresholds globally wrong
  - Beam could destroy many collimators before dump triggered
  - “losses ⇒ quench ⇒ QPS ⇒ PIC ⇒ dump” reaction time is ~150 turns
- Near-beam detectors of concern due to proximity
  - TOTEM 10 σ, VELO at 5 mm,
  - Studied extensively for 450 GeV and 7 TeV for TOTEM and LHCb VELO, for failures of linear magnetic elements
  - Protection relies on correct positioning of primary and secondary collimators with correct BLM thresholds
  - Local closed orbit bumps at detectors a danger – orbit monitoring and intlk.

BIS beam permit signal not transmitted to LBDS

- The real WC failure
- *"What do we do if the dump doesn't react to a programmed request"* is a popular question. Possible answers are
  - Call Bruno and Etienne in to fix the problem
  - Cut RF Revolution Frequency to LBDS, to provoke synchronous dump
  - Force access system door to produce asynch. dump trigger
  - Start blowing beam up slowly with tune kicker, or transverse damper
  - Scrape beam slowly away with collimators, while staying below quench limit
  - We should at least agree and maintain a procedure for the CCC…
- If dump fails to fire after an interlock, beam will probably already be long gone. How much of LHC machine will also be gone?
  - Maybe a few collimators, if losses at TCDQ provoke dump from "direct" BLM?
  - Maybe a lot more…magnets downstream of collimators
  - To date no studies have been made of this eventuality
  - Tevatron experienced something like this – lost 2 collimators and 3 corrector magnets (1.5 MJ beam energy)

Discussion and conclusions

Elements ‘most at risk*’

• IR7/IR3 collimators	(possible to damage many at once)
• TCT collimators	(exposed if TCDQ positioning bad wrt beam)
• MSD extraction septa	(extraction errors, many can be damaged)
• TCDQ/TCSG protection device	(TCDQ needs anyway upgrade)
• IR6.Q4 magnet	(if high intensity impact on TCDQ)
• TCDS protection device	(high beam load even for ‘design’ cases)
• Triplet beam screens/magnets	(if TCT damaged or out)
• MQ beam screens/magnets	(from several sources)
• MB beam screen/magnets	(from several sources)
• SC D1 beam screens/magnets	(from unprotected injection error)

* a subjective, incomplete and loose attempt at a top 10 ranking...

Concerns and ideas for follow-up

- We believe we’re well-protected against the many possible WC beam incidents
  - Hubris?
  - To date, loopholes in machine protection systems have been closed after a beam incident has occurred (see SPS in recent years)
  - Should step back and make analysis of “as built” system(s) with interdependencies
- It is presently difficult to pronounce on expected scale of damage, and very little analysis has been made of collateral effects
  - Direct and secondary consequences of these incidents must be better quantified
  - Impact on prevention/mitigation ‘weighting’, spares policy, procedures, etc
- Too easy to additionally stress Machine Protection (e.g. ramp down without dump)
  - Must define dangerous scenarios and find ways to avoid them
- “Formal commissioning of crucial MP systems essential – with procedures
  - Needs time in schedule (energy tracking in September ’08 was given no time. None)

Concerns and ideas for follow-up

- Positioning and interlocking of TCDQ/TCSG devices wrt beam
  – Rely on rather ‘soft’ concepts (SW interlocks, SMP energy via timing system)
  – Investigate e.g. TCDQ position in BETs and reduced interlock BPM thresholds?
- Collimator positioning and BLM thresholds crucial for the many slow failures
  – Collimators ARE an important part of machine protection against failures
  – Again rely on rather ‘soft’ concepts (SW intlks, shared SMP energy, LSA, …)
  – Critically verify all aspects of actual implementation?
- LBDS energy tracking and (re)triggering systems absolutely crucial
  – Continue with as-built system analysis and reliability studies…
  – Formalise acceptance testing - with a review processes at pre-defined stage?
  – Review once more connections between LBDS and BIS…
- For longer term, other more speculative studies possible
  – sacrificial absorbers to mitigate direct / collateral damage where applicable…i.e. sacrificial TCDQ which can really ‘stop’ the full beam

Main gaps in knowledge

- Need an agreed of list of damage limits for many elements
  - Design choices for protection systems and devices based on sketchy data
  - Impact on scale of a particular incident
- Need to understand development of mutual beam ↔ matter interactions at high energy density and over 100 μs timescales
  - Invaluable information (e.g. for sacrificial absorbers) but v.complicated to model
  - Coordinated R&D effort? In which framework?
  - Controlled experiment would help, possible at 450 GeV with HiRadMat
- Need a ‘full’ catalogue of multiple failures and effects
  - Could help to identify possible “birdstrikes” - single causes of multiple failures
  - Should include evaluation of elements likely to be damaged and collateral effects
  - Involves expertise from machine protection, accelerator physics, nuclear physics, materials, magnet, cryogenics, vacuum, powering, experiments, …

Fin

Machine protection strategy

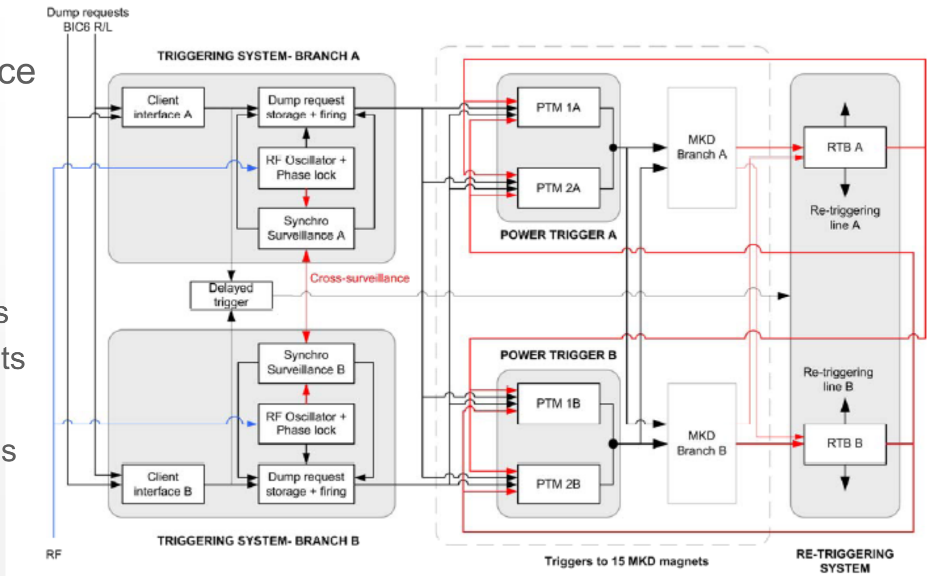
- Analysis
  - A great deal of work done in past ~5 years on protection against failures for experiments, for injection, for circulating beam and for LHC dump.
  - R.Appleby, A.Gomez Alonso, V.Kain and T.Kramer tracking studies, + R.Schmidt
- Prevention
  - Equipment design and (to a lesser extent) operational procedures made to avoid potentially dangerous situations
- Protection
  - Active surveillance and interlocking system, to detect and react to dangerous faults in time (typical reaction time of ms).
  - Explicitly stated assumption that redundancy between detection systems greatly improves coverage…
- Mitigation
  - Fixed and movable devices designed to intercept mis-steered beams, where interlocking not possible

Single "functional" failures

- Functional failures in critical MP systems could lead to WC
  - There is only one energy tracking system
  - There is only one interlock system
  - There is only one beam dump system
- Single failures are (relatively) easy to analyse and design for
  - To meet "beyond-design" criterion, reliability analyses and technical audits
  - Audits gave positive feedback on critical subsystem design
  - Safety Integrity Levels (SIL) quantified and as good as requirements
- Design reliability using fault tolerance/redundancy within a critical system

LBDS triggering uses redundancy and fault-tolerance to meet required reliability

- We can dump with 14 out of 15 MKD kickers
- each MKD kicker has 2 separate switches
- each switch has 2 redundant Power Triggers
- each Power Trigger has 2 redundant triggering lines
- each triggering line comes from 2 redundant fan-outs
- each fan out comes from 2 redundant TSUs
- each TSU gets inputs from 2 redundant permit loops



Multiple failures

- Many WC incidents possible if multiple failures “allowed” inside or across systems
- Overall, faith in LHC machine protection strategy is based on:
  - “The chance of (failure A) + (failure B) + (failure C) happening is very small”
- But…danger of using the fallacious *Argument of Personal Incredularity**
  - “I personally find it very hard to believe that these things could all fail at once. I therefore assume that they cannot all fail at once”
- Sometimes these conjunctions do occur
  - Example from 2008 in LHC: failure on beam interlocking of a vacuum valve which could only happen because of 5 *separate* faults
  - “Personally I find it very hard to believe that this could happen”.
  - But it did.
- And the more often we test (stress) the system, the more failures there will be

**as popularised by R.Dawkins*

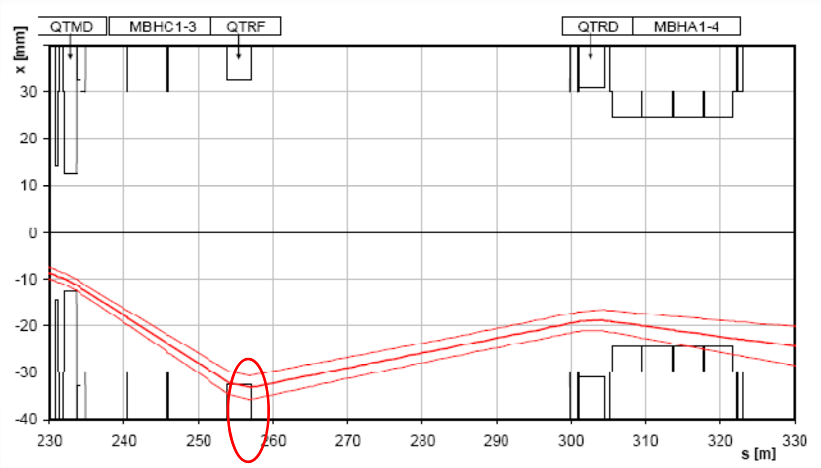
Multiple failures II

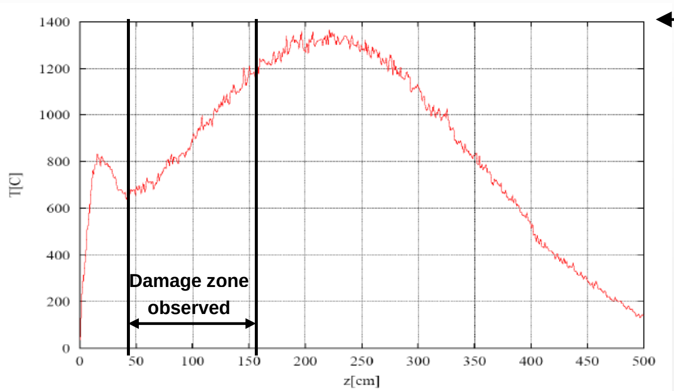
- For multiple failures, increased complexity makes failure modes much more difficult to analyse and understand
- Interdependencies between LHC systems mean that we should worry about common single causes for multiple failures (birdstrikes)
  - e.g. collimator position interlock AND BLM thresholds are “controlled” by the ENERGY value distributed over the Safe LHC Parameters system,

- Also must avoid situations where operator error makes single failure dangerous
  - e.g. an operator loads the wrong functions for extraction septum MSD - then we rely ONLY on the BEI card supplying correct MSD current to BETS

A real beam incident

- **2004 TT40 extraction of 2.3 MJ 450 GeV LHC beam from SPS**
  - Transfer line QTRF vacuum chamber destroyed in beam incident
  - Simulation very sensitive to input – no full self-consistent model found
  - Need controlled experiment!





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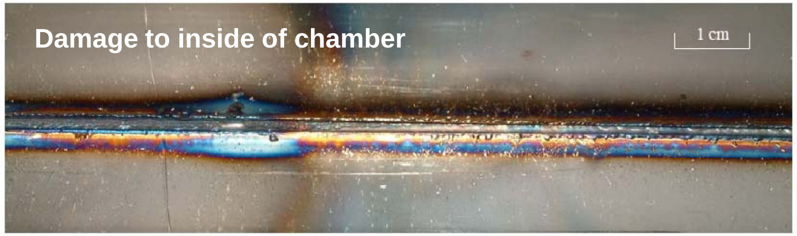
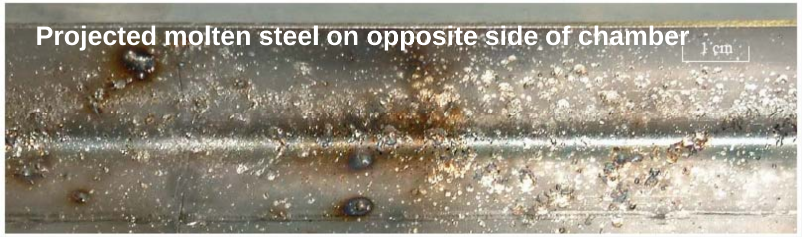


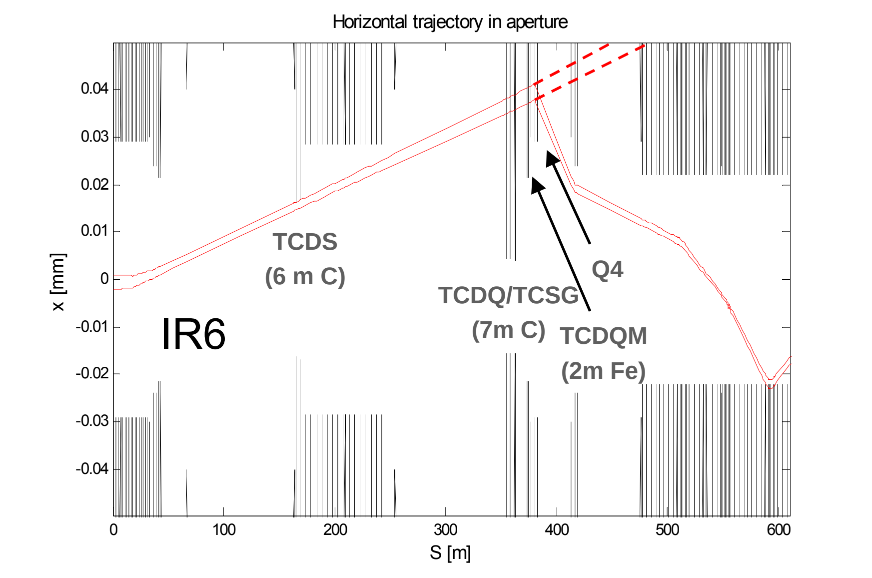


It turned out to be extremely difficult to reconstitute the observed physical damage without more accurate knowledge of the input conditions.

AB-Note-2005-014 BT

Energy tracking failure – IR6 elements

- MKD energy tracking system failure - 9 kV at 7 TeV rigidity (c.f. 30 kV nominal)
  - Whole beam deflected at ~60 sigma (misses 6m C TCDS)
  - Impacts 7m of C in TCDQ, 2m of Fe in TCDQM, 5m of Q4 coldbore/coil



  - Certainly will damage/destroy TCDQ, TCDQM, Q4
  - Possibly damage to MKDs (other beam), Q5
  - Further damage not excluded (e.g. fraction into arc?) depending on details of how beam is stopped in the first elements

Cataloging failures

Description	Failure 1	Failure 2	Protection 1	Protection 2	Protection 3	GeV	e13 p+	MJ	Direct damage	Seondary damage	Collateral damage risk	# damaged	Spares	Down time	Cost
Ansych dump + no retrigger	Erratic on MKD	Retrigger failure				7000	30	336	TCDQ		Q4	1			
									TCP		?	2			
									TCS		?	5			
									TCLA		?	3			
									TCT (b2)	TCT (b1)	Triplet	1			
										Triplet aperture	Experiment	2			
Asych dump + TCDQ out	Erratic on MKD	TCDQ position	Intlk on TCDQ pos	Intlk on energy fn	SW intlk on TCDQ/beam	7000	30	336	TCCSG		Q4				
										TCP					
										TCS					
										TCLA					
										TCT	Triplet				
										Triplet aperture	Experiment				
Asych dump + beam position	Erratic on MKD	Beam position at TCDQ	SW intlk on TCDQ/beam	BLM signal on TCSG		7000	30	336	TCP		Q4				
									TCS						
									TCLA						
									TCT		Triplet				
									Triplet aperture		Experiment				
Abort gap full + TCDQ out	Abort gap	TCDQ position	Intlk on TCDQ pos	Intlk on energy fn	SW intlk on TCDQ/beam	7000	30	336	TCCSG		Q4				
7 TeV	full		Abort gap cleaning							TCP					
			Abort gap monitor							TCS					
										TCLA					
										TCT	Triplet				
										Triplet aperture	Experiment				
Abort gap full + TCDQ out	Abort gap	TCDQ position	Intlk on TCDQ pos	Intlk on energy fn	SW intlk on TCDQ/beam	450	30	22	TCCSG		Q4				
450 GeV	full		Abort gap cleaning							TCP					
			Abort gap monitor							TCS					
										TCLA					
Energy tracking	Lookup tables		MCS	SW interlocks	Procedures	450	30	22	MKD			6			
450 GeV beam kicked									Q5			1			
with 7 TeV settings									TCDQM			1			
										QRL					
Energy tracking	Lookup tables		MCS	SW interlocks	Procedures	7000	30	336	TCDQ			6			
7 TeV beam kicked									TCP			1			
with450 GeV settings									TCS			1			
										QRL					
Energy tracking	Lookup tables		MCS	SW interlocks	Procedures	7000	30	336	TCDQ		Q4	6			
7 TeV beam kicked									TCP			1			
with 9 kV									TCS			1			
									TCLA		?	3			
									TCT (b2)	TCT (b1)	Triplet	1			
										Triplet aperture	Experiment	2			

- Considerable effort to produce – who drives it and find manpower?
  - Many possible combinations of failures
    - Beam tracking to find out impact locations and parameters
  - Evaluation of potentially damaged elements
    - Needs simulations, penetration depths, damage limits
  - Evaluation of collateral damage needs knowledge of risks for all local systems