Beam Dumping System – Failure Scenarios

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- How the dump system can fail
- Catalogue of primary failures
- Failure classes and protection
- Specific failures cases
  - Dilution failure (missing)
  - Extraction kicker erratic
  - Extraction kicker missing
  - Injection / dump "single turn deadlock"
- Spares policy issues

With R.Filippini, J.Uythoven, E.Carlier, V.Mertens, V.Kain, L.Ducimetiere, L.Bruno, W.Weterings, R.Assmann et al.

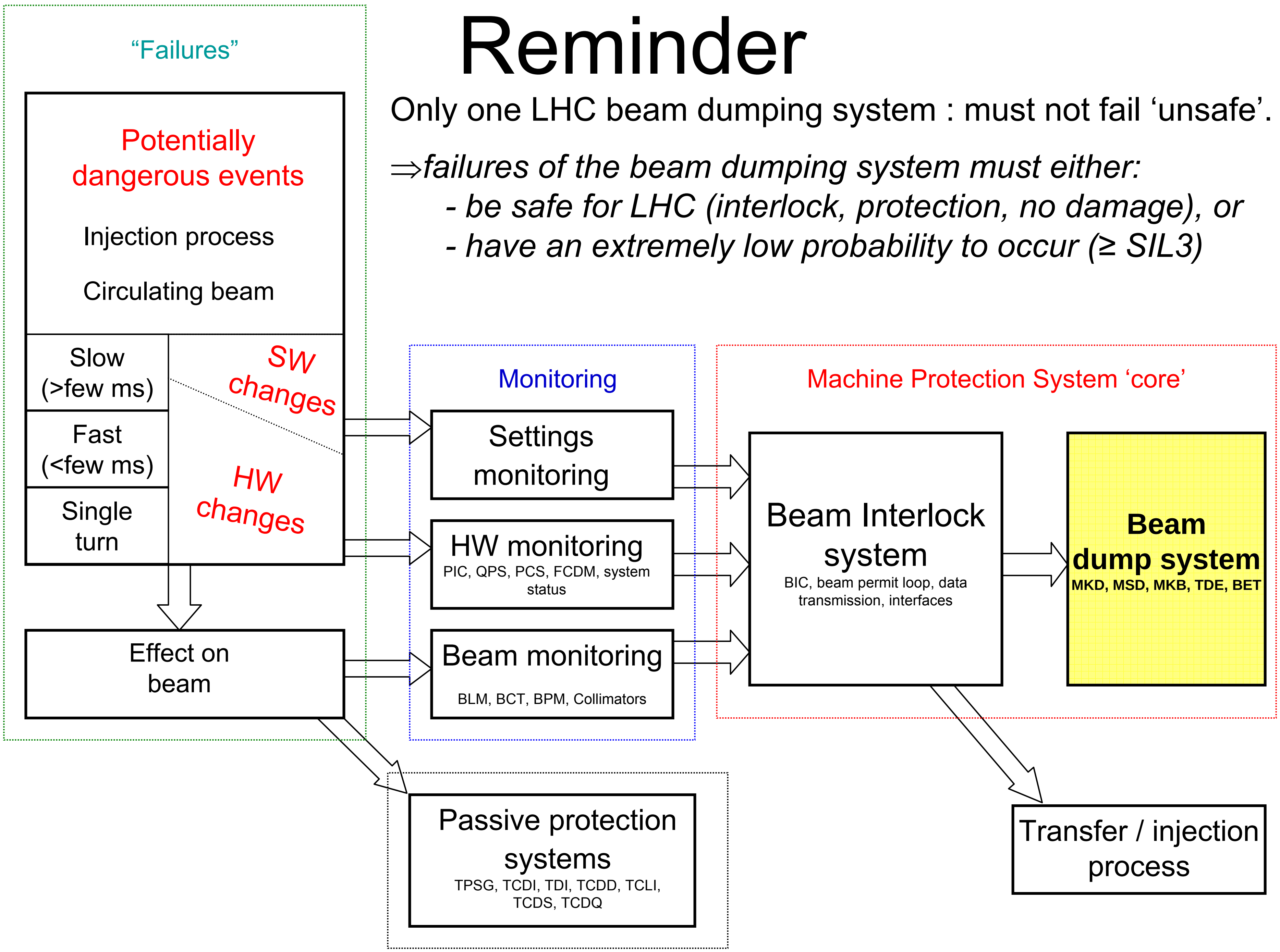
Reminder

Only one LHC beam dumping system : must not fail ‘unsafe’.

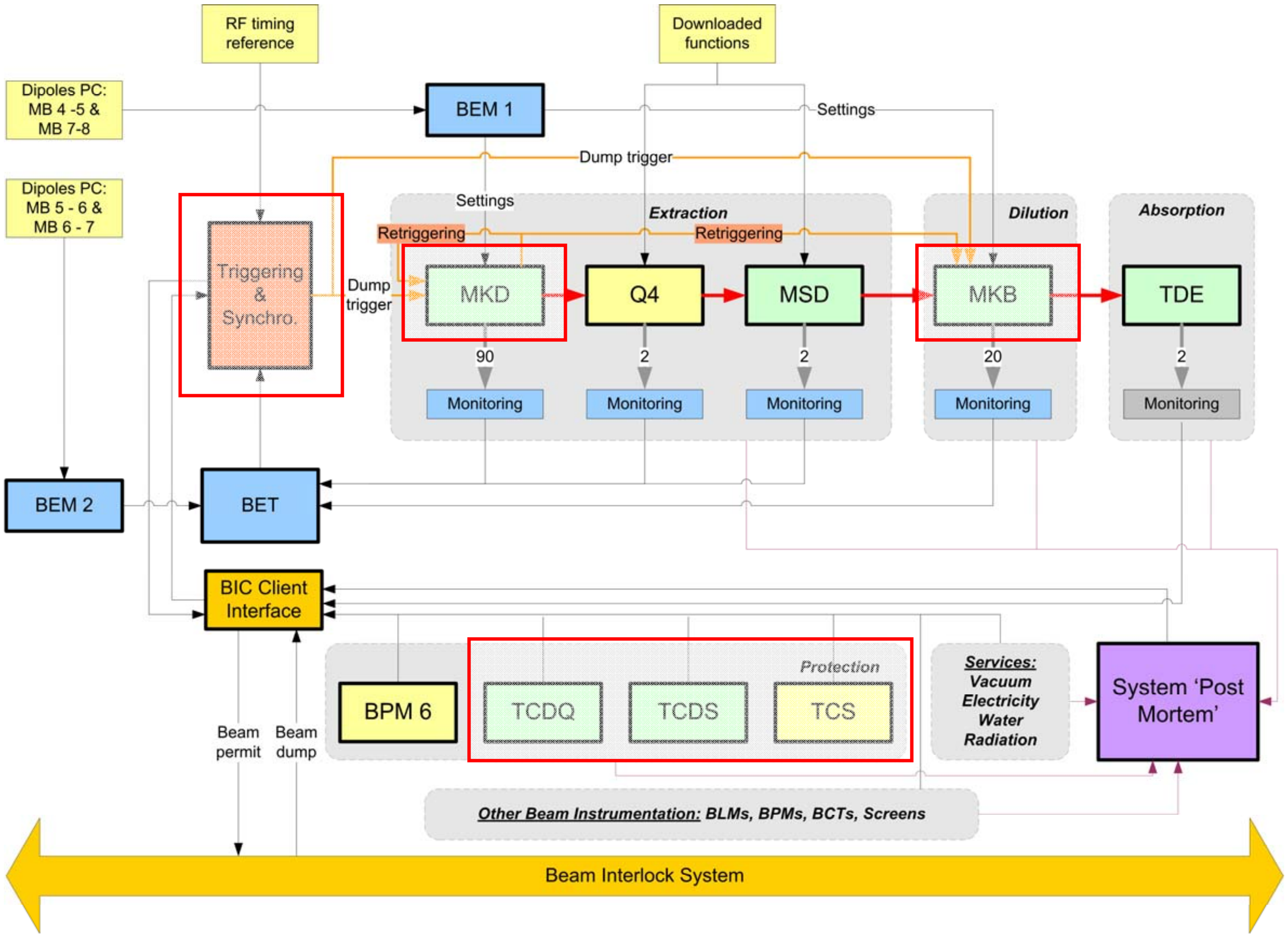
⇒*failures of the beam dumping system must either:*

- be safe for LHC (interlock, protection, no damage), or

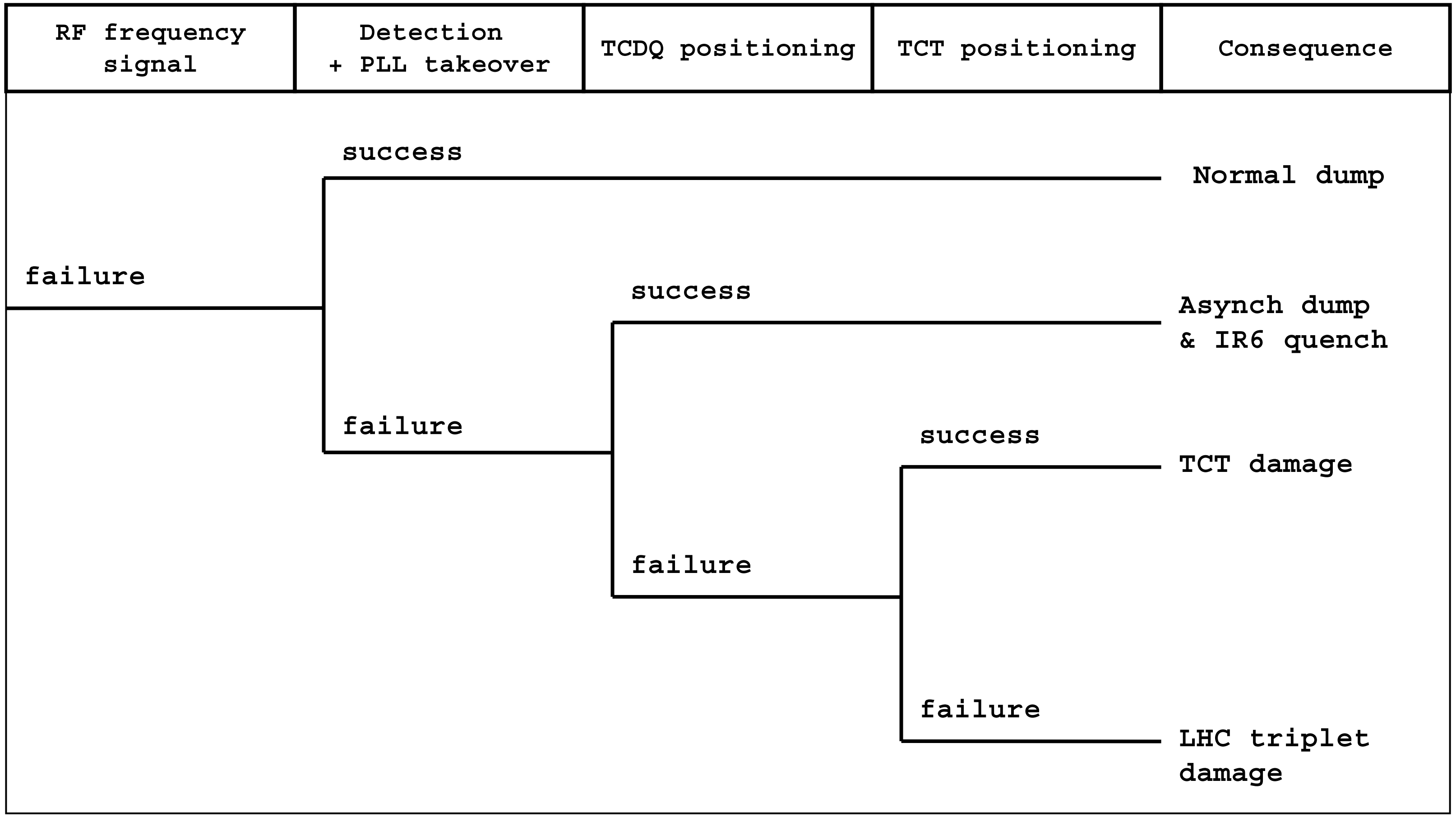
- have an extremely low probability to occur (≥ SIL3)



Dump system – functional blocks



Failures, protection and consequences



Primary failure scenarios

Category	Primary failure scenario	Main protection		Other protection		LHC consequence	SIL reqd. on failure
		Interlock	Passive	Interlock	Passive		
System status	Mobile C diluter position out of tolerance	Position		TCS BLMs			
System status	Dump block entrance window failure	TD vacuum		LHC vacuum			
System status	Dump line vacuum failure	TD vacuum		LHC vacuum			
System status	Extraction kicker system status bad	Surveillance		BETS			
System status	Dilution kicker system status bad	Surveillance		BETS			
System status	Dump block vessel N2 pressure low	Pressure					
Beam	Beam emittance out of tolerance	TCS BLMs					
Beam	Beam position out of tolerance	BPMs		TCS BLMs			
Powering	Q4 quadrupole power supply trip	PIC		FCCM/BETS			
Powering	Q4 quadrupole field out of tolerance	BETS					
Powering	Extraction septum power supply trip	PIC		FCCM/BETS			
Powering	Extraction septum current out of tolerance	BETS					
Powering	Extraction kicker charging voltage out of tolerance	BETS					
Powering	General/local power cut of dump equipment	UPS		BETS			
Abort gap	RF frequency synchronisation signal lost	Trigger unit PLL			TCDS/TCDQ		
Abort gap	Abort gap population out of tolerance	Abort gap mon.	TCDS/TCDQ		TCTs/LHC col.		
Abort gap	Synchronisation error		TCDS/TCDQ		TCTs/LHC col.	Quench	
Fast kicker	Dilution kicker erratic (spurious) trigger						
Fast kicker	<8 dilution kicker magnets missing						
Fast kicker	Extraction/Injection deadlock		TCDS			Quench	
Fast kicker	Extraction kicker erratic (spurious) trigger	Retrigger	TCDS/TCDQ		TCTs/LHC col.	Quench	
Fast kicker	1 extraction kicker magnet missing					Quench	
Fast kicker	≥8 dilution kicker magnets missing					TDE damage	SIL3
Fast kicker	≥2 extraction kicker magnets missing					**LHC damage**	SIL3
BETS	Energy tracking error					**LHC damage**	SIL3
MPS	No trigger received from Beam Interlock System					**LHC damage**	SIL3

Failure classes

1. **Should not happen in the LHC lifetime ("beyond design")**
   - Not receiving trigger from Beam Interlock System after failure in LHC
   - Failure of beam energy tracking
   - < 14 / 15 extraction kickers
   - < 3 / 10 dilution kickers

2. **Protected against by surveillance and interlocking (dump while conditions still ~ok) - majority**
   - Failures of general services (electricity, vacuum, cooling, Ethernet, …)
   - Bad beam position (BPM, BLM)
   - Magnet powering failure (PIC, FCCM, BETS)
   - Large abort gap population

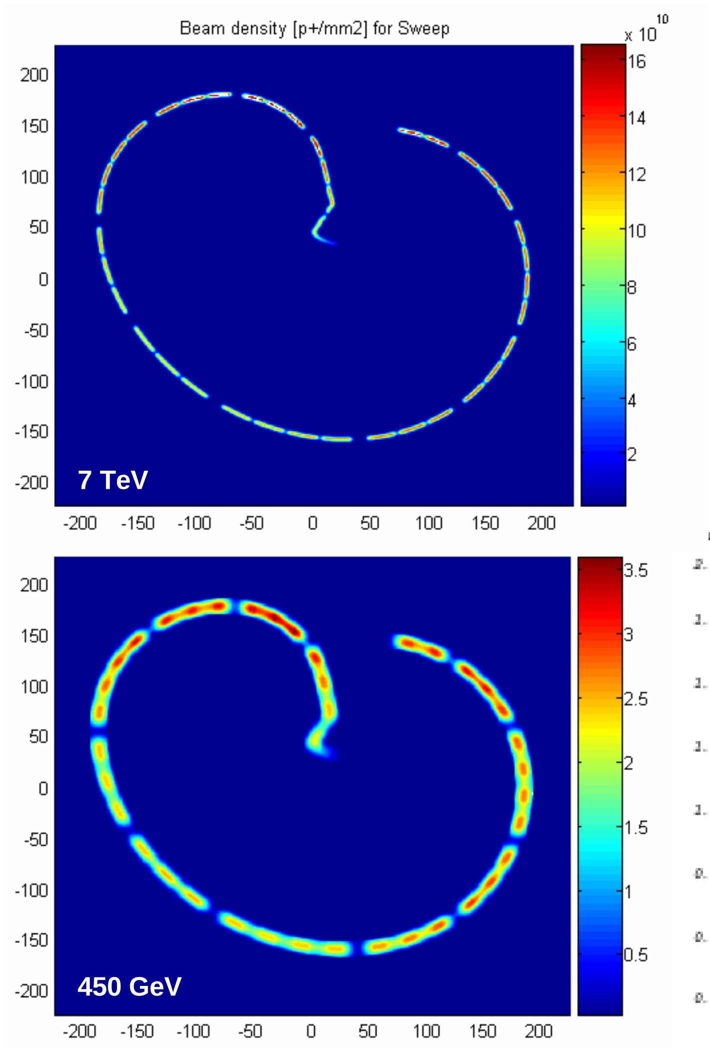
3. **Cannot be prevented by surveillance (kicker faults associated with dump action)**
   a) **Can be tolerated without damage**
   - Missing extraction kicker magnet
   - Missing dilution kicker magnet
   - Erratic dilution kicker magnet

   b) **Cannot be tolerated: rely on passive protection devices**
   - Extraction kicker erratic (spurious asynchronous trigger)
   - Single turn injection/dump deadlock

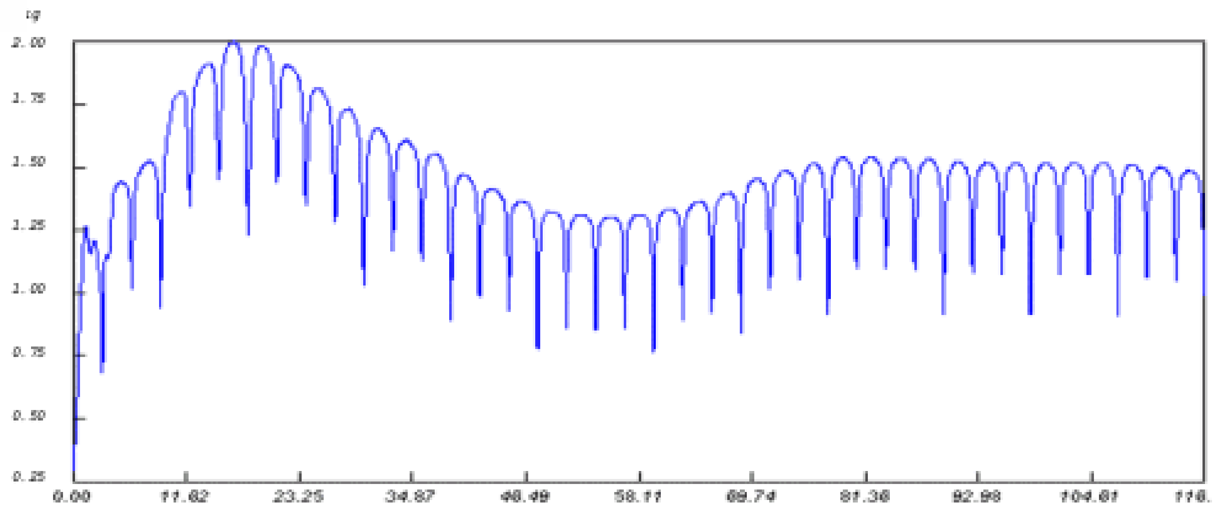
Dilution kicker failures

Normal operation: sweep beam in ‘e’ shape over the face of the dump block

4xH and 6xV kicker magnets

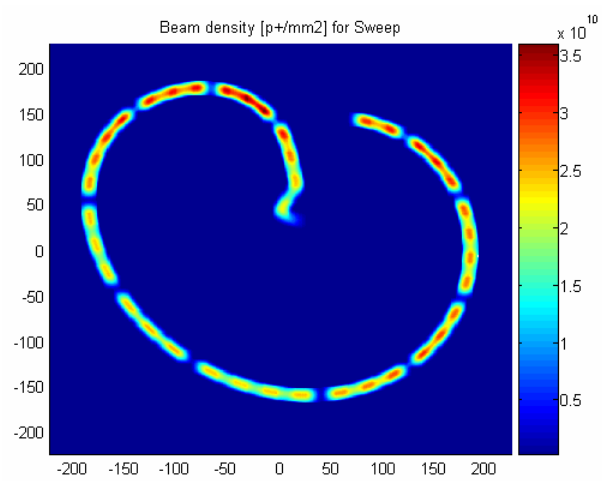


Nominal sweep profile

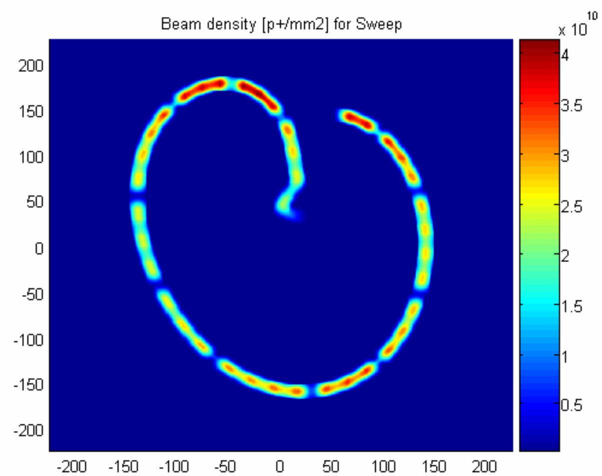


Energy deposition in C dump block (7 TeV ultimate beam)

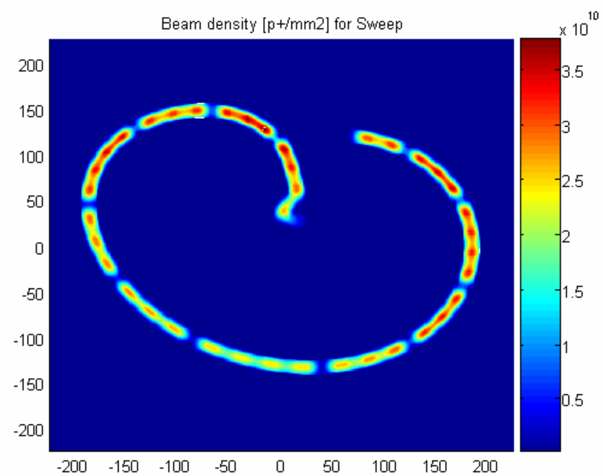
Dilution kickers failures : missing units



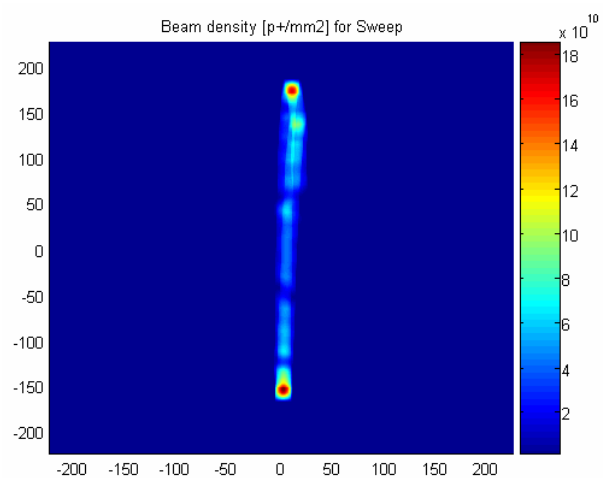
Nominal (4H, 6V)



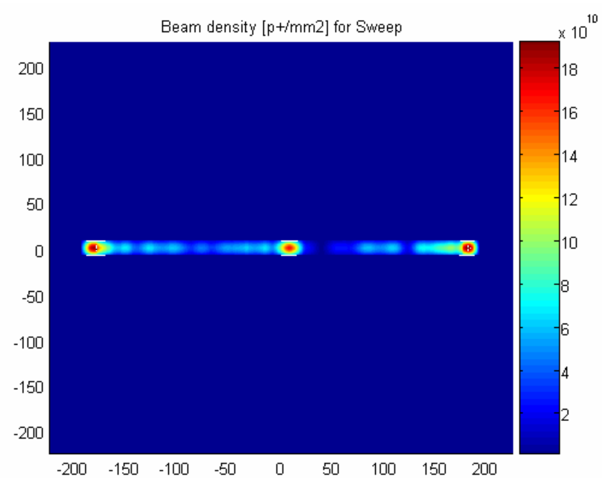
Missing 1H (3H, 6V)



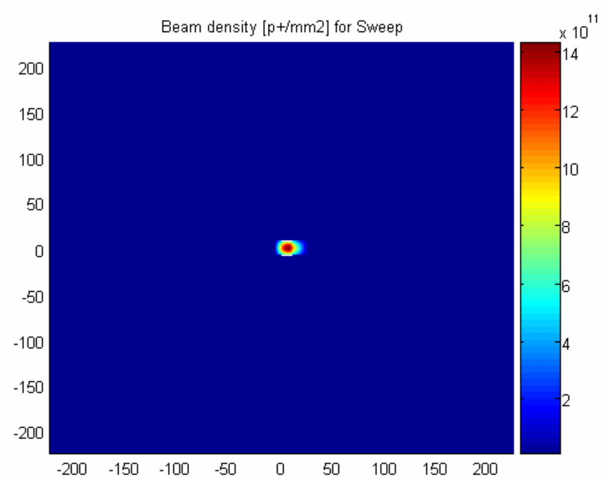
Missing 1V (4H, 5V)



Missing 4H (0H, 6V)



Missing 6V (4H, 0V)



Missing 4H, 6V (0H, 0V)

total dilution failure

Shown for 450 GeV beam spot ($\sigma \approx 6$ mm)

Dilution kickers failures : missing units

Energy deposition and ΔT

Maximum Energy Density [MJ/kg]						
		Active horizontal diluters				
		4	3	2	1	0
Active vertical diluters	6	1.96	2.32	3.18	5.29	10.5
	5	2.2	2.45	3.23	5.45	11.6
	4	2.58	2.76	3.39	5.64	13.1
	3	3.17	3.35	3.74	5.89	15.3
	2	4.17	4.41	4.8	6.36	18.7
	1	5.81	6.41	7.28	8.96	26.8
	0	10.2	11.9	14.8	21	130

Large amount of redundancy.

Values quoted for LHC ultimate (50% above the nominal)

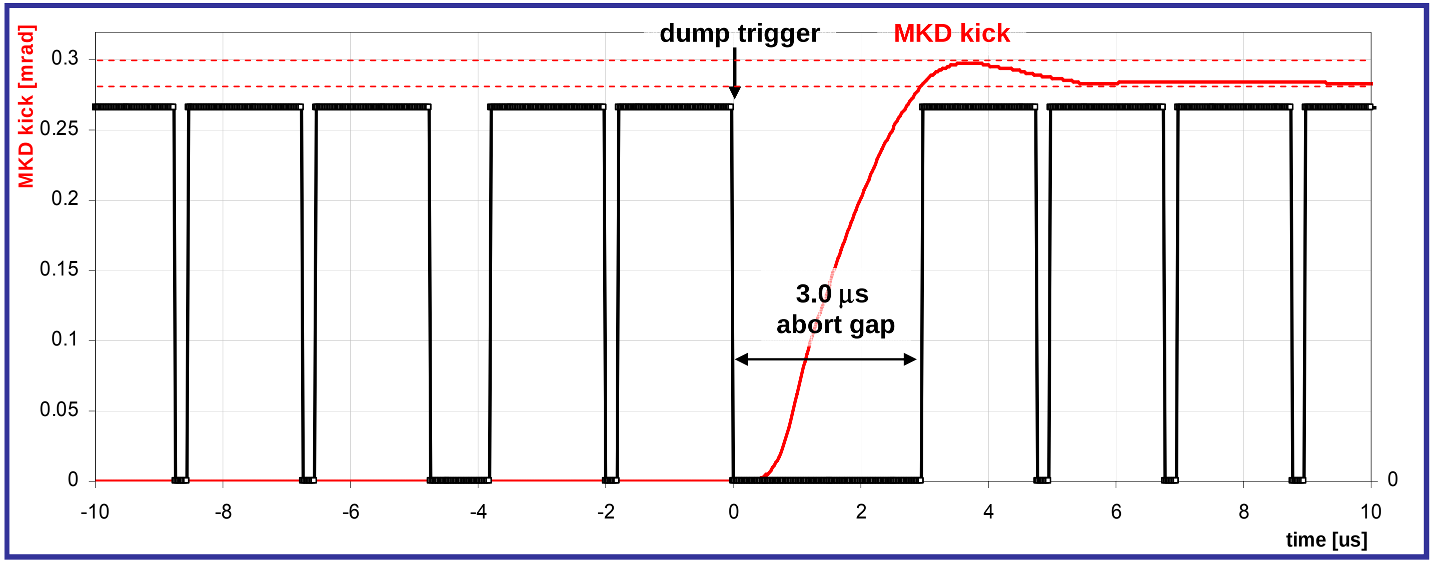
Maximum Core Temperature [°C]						
		Active horizontal diluters				
		4	3	2	1	0
Active vertical diluters	6	1241	1420	1818	2761	3727
	5	1362	1481	1839	2833	3727
	4	1545	1624	1912	2915	3727
	3	1812	1896	2071	3027	3727
	2	2262	2369	2543	3235	melt
	1	2993	3258	3642	3727	melt
	0	3727	3727	melt	melt	vapour

L.Bruno

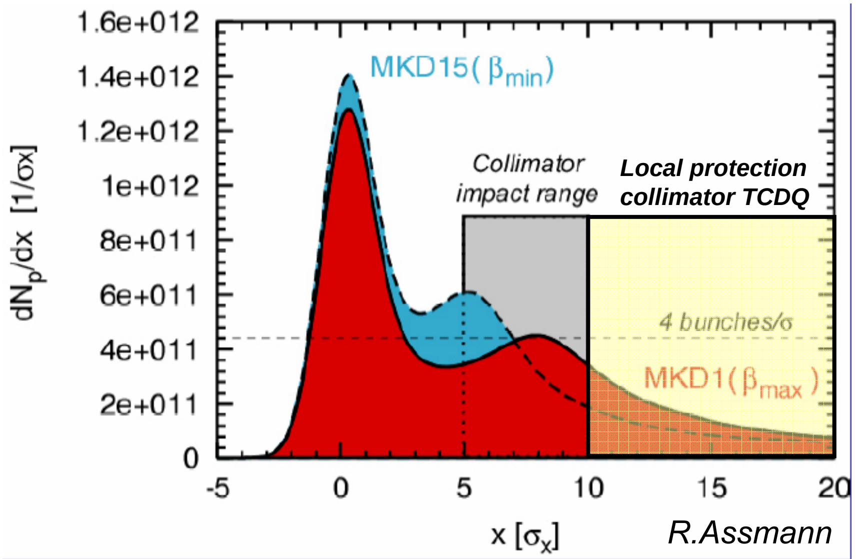
Concern is total dilution failure:

- of either H or V leads to contained dump block damage (cracks)
- of both H and V leads to perforation of dump block & exit window.

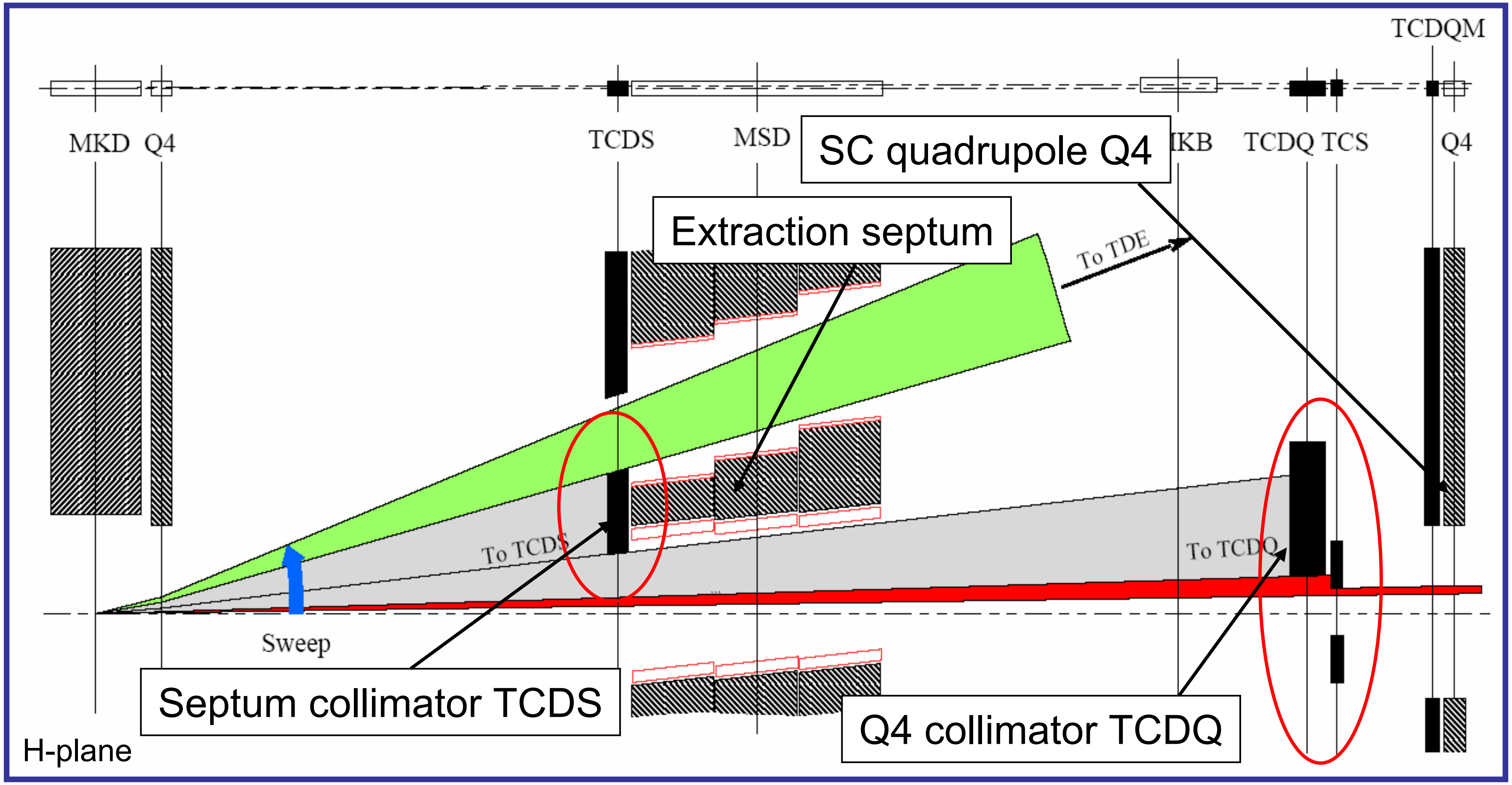
Extraction kicker failures : erratic (asynchronous dump)



- Retrigger remaining 14 kickers in ~700ns
  - Crossed and redundant retrigger lines
- ~120 bunches swept across LHC aperture
  - Local collimators protect & limit excursions

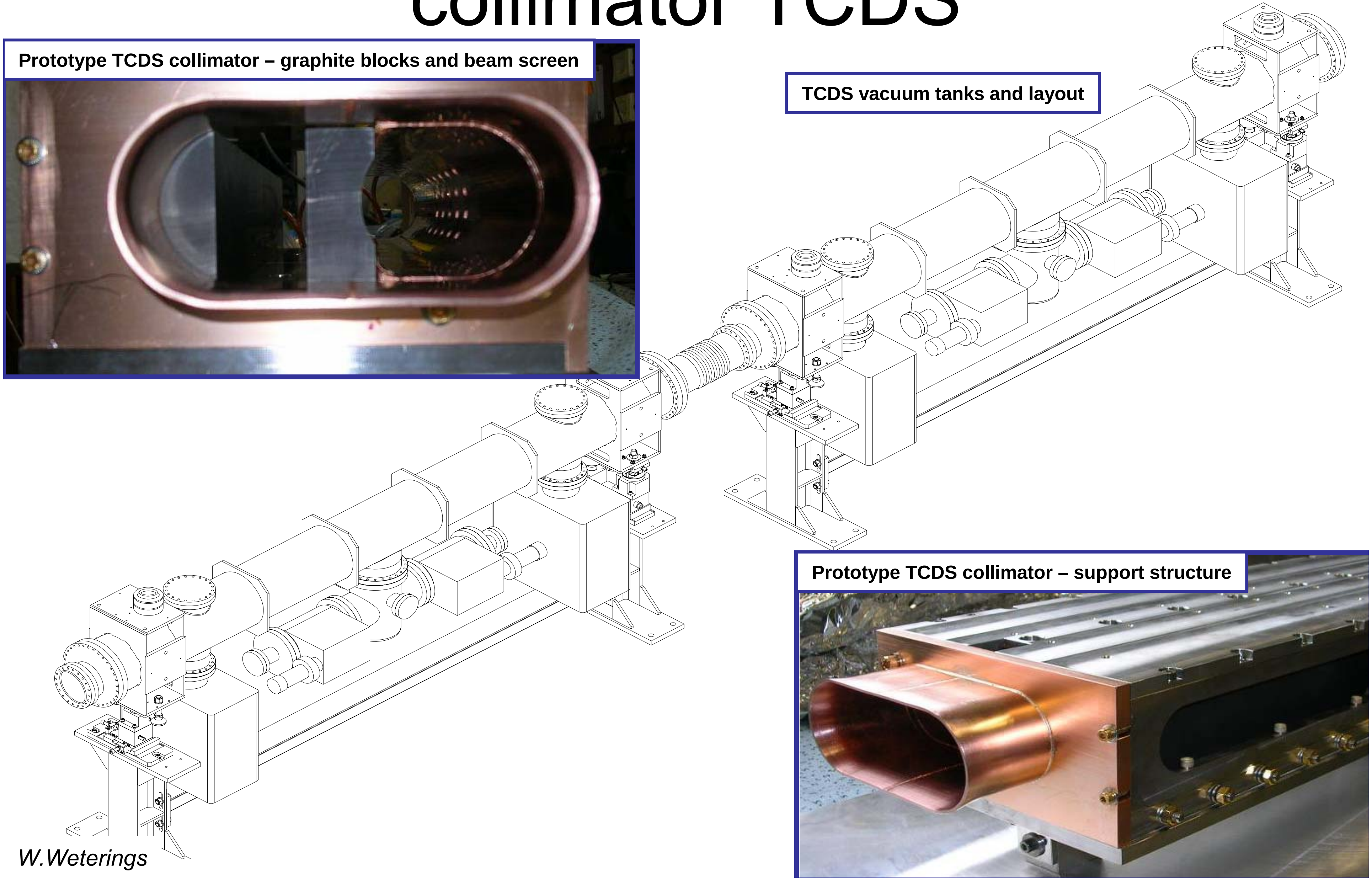


Asynchronous dump: elements at risk



- TCDS (intercepts ~40 bunches) protects the extraction septum
- TCDQ +TCS (~27 bunches) protect Q4 magnet, AND downstream LHC
  - The latter implies precise (±0.5σ) positioning of the jaw WRT beam….

Asynchronous dump : fixed septum collimator TCDS



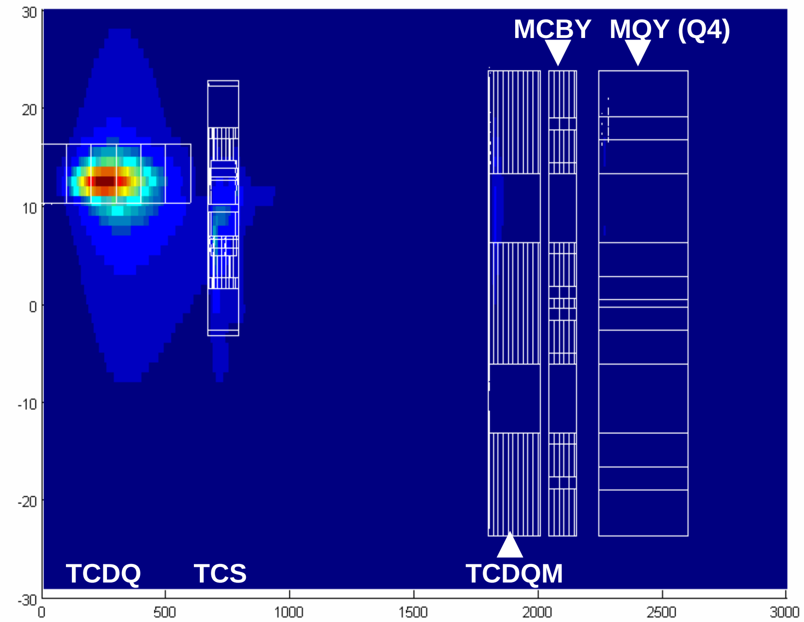
W.Weterings

Asynchronous dump – protection and energy deposition

Instantaneous loads due to asynchronous dump at 7 TeV (ultimate beam)

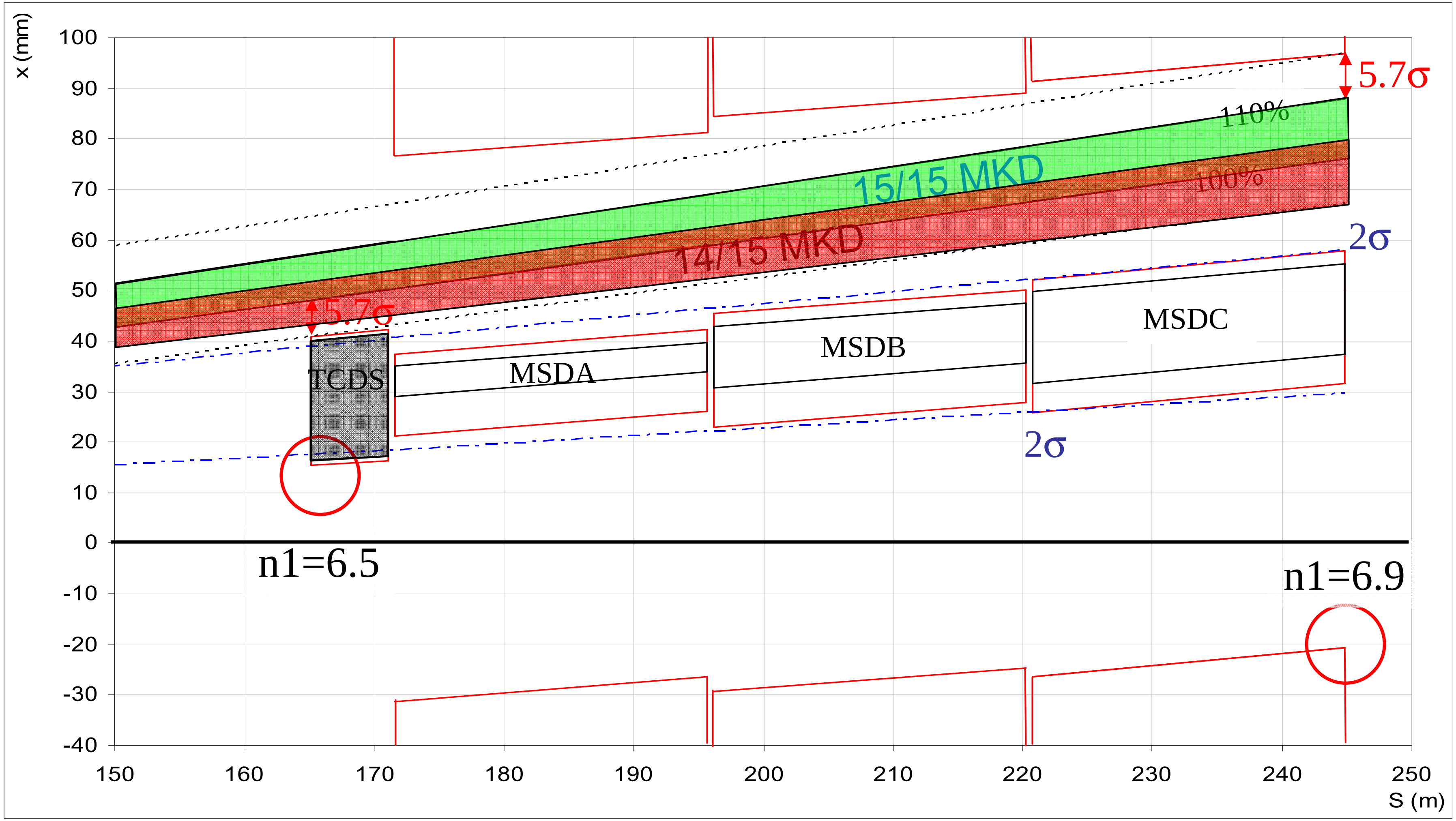
	Peak load (J/cm^3)	ΔT (K)
TCDS collimator	3121	1050
MSD septum	160	96
TCDQ collimator	2139	712
TCS collimator	2283	679
TCDQM mask	45	13
MCBY corrector	26	7
MQY Q4	38	10

- Q4 instantaneous damage limit = 87 J/cm^3 [OK]
- MSD design limit on ΔT = 100 °C [OK]
- Graphite / C-C melting point = 3700 °C [OK]
- C-C thermal shock checked [OK]



Particle fluence scoring on TCDQ, TCS, MCBY and MQY (Q4) for async dump

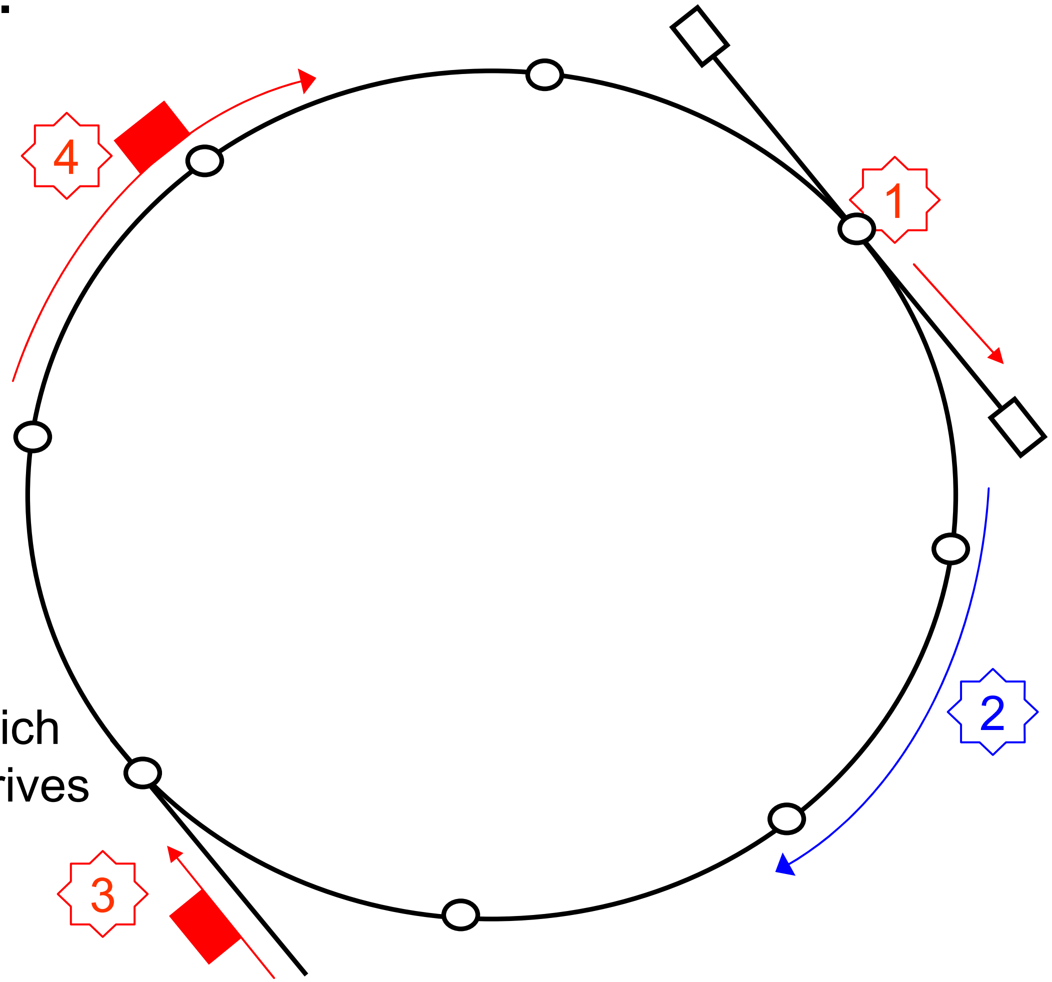
Extraction kicker failures : missing unit



- At 450 GeV, worst case with 14/15 MKD gives ~2.7σ clearance at TCDS, or ~10^{12} p+ on collimator (well below damage limit, but may cause quench)
- At 7 TeV, enough aperture (~10σ) with 14/15 MKD to avoid losses on TCDS

Special "failure" – injection / dump single turn deadlock

A potential problem….



1. Beam dump triggered
2. Injection inhibit sent to IR2
3. Injection just before signal arrives
4. Injected beam travels to dump, which is out of tolerance by the time it arrives

Injection / dump single turn deadlock

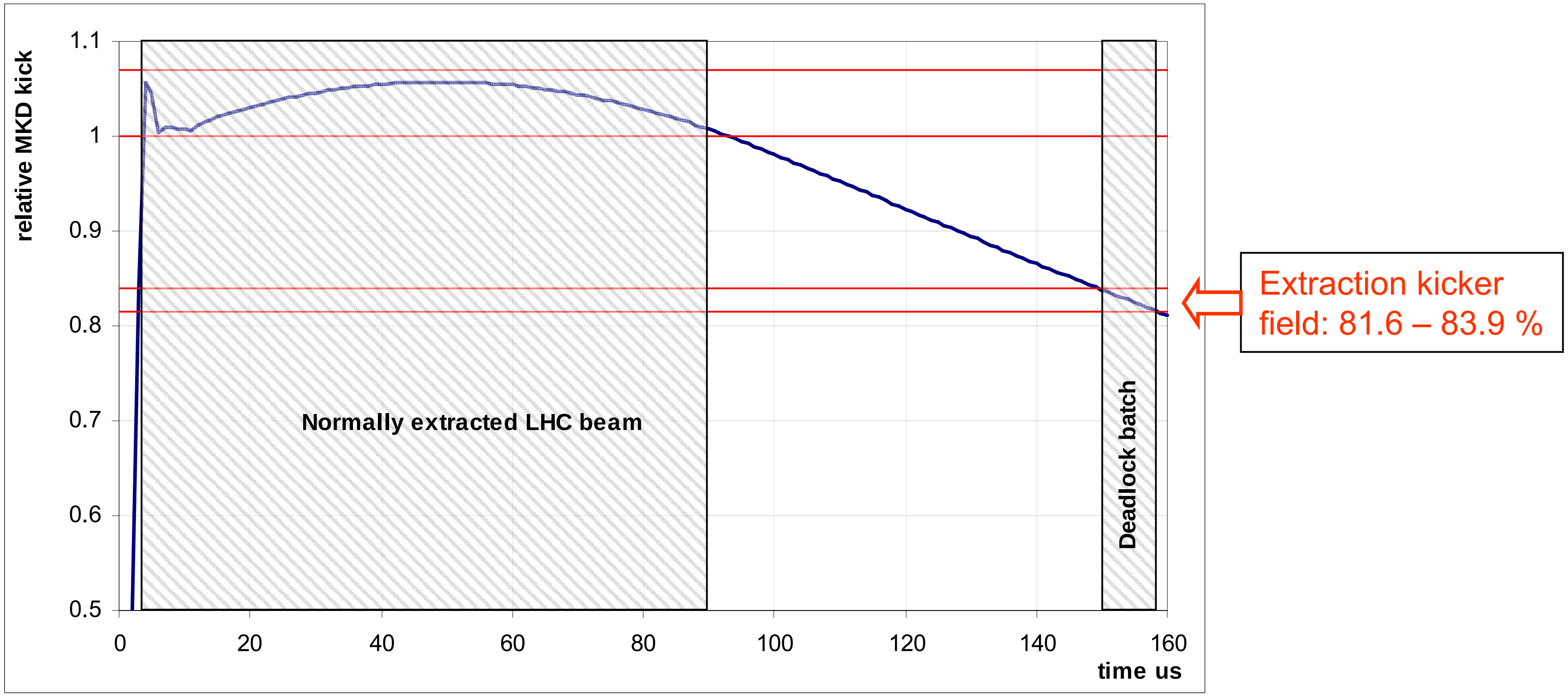
20 μs : Time to generate Injection Inhibit signal

65 μs : Time for signal to propagate 13 km from IR2 to IR6

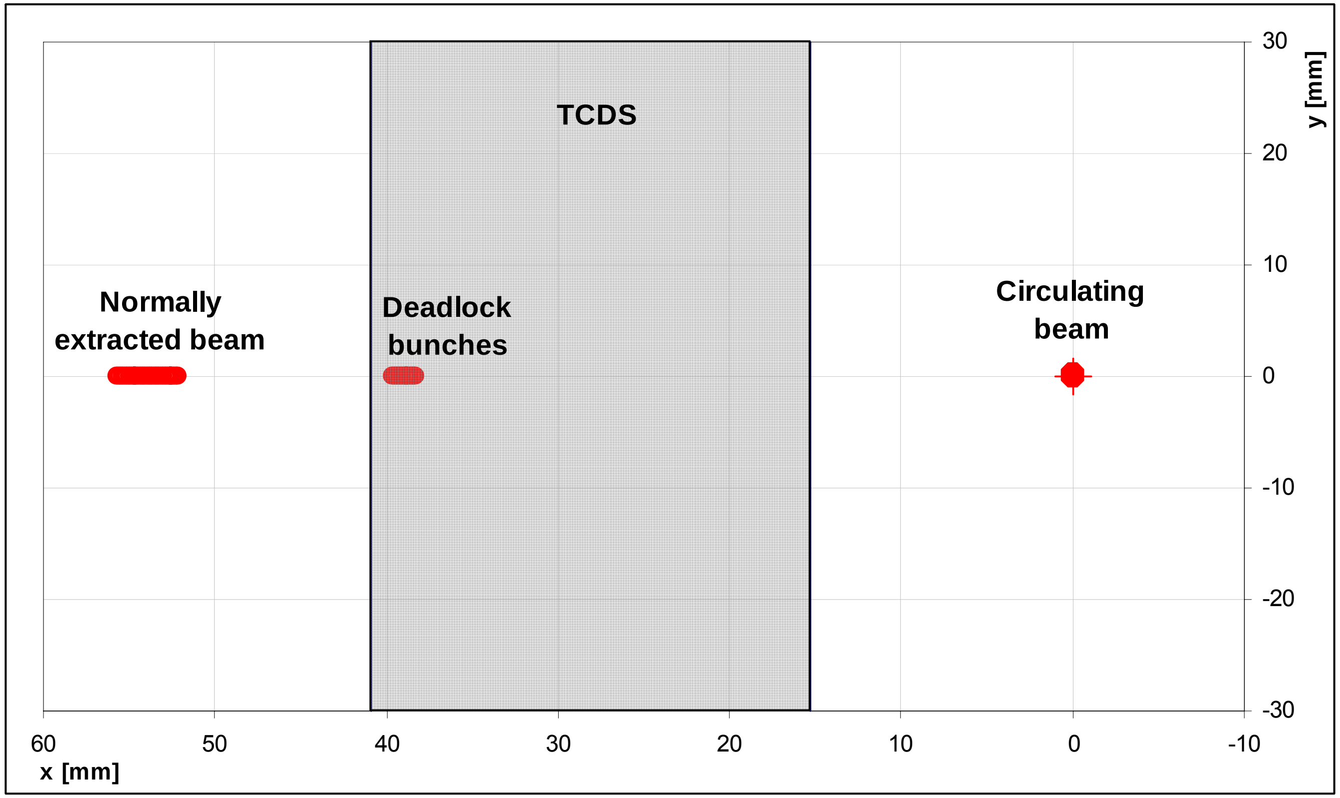
20 μs : Time for injection system to react to Injection Inhibit signal

45 μs : Time for injected batch to travel 13 km from IR2 to IR6

150 μs : Total (between beam dump trigger, and latest time an injected batch could arrive at the extraction kicker)



Injection / dump single turn deadlock



288 bunches not correctly kicked, but either all extracted or (in worst case trajectory) impact extraction septum collimator TCDS.

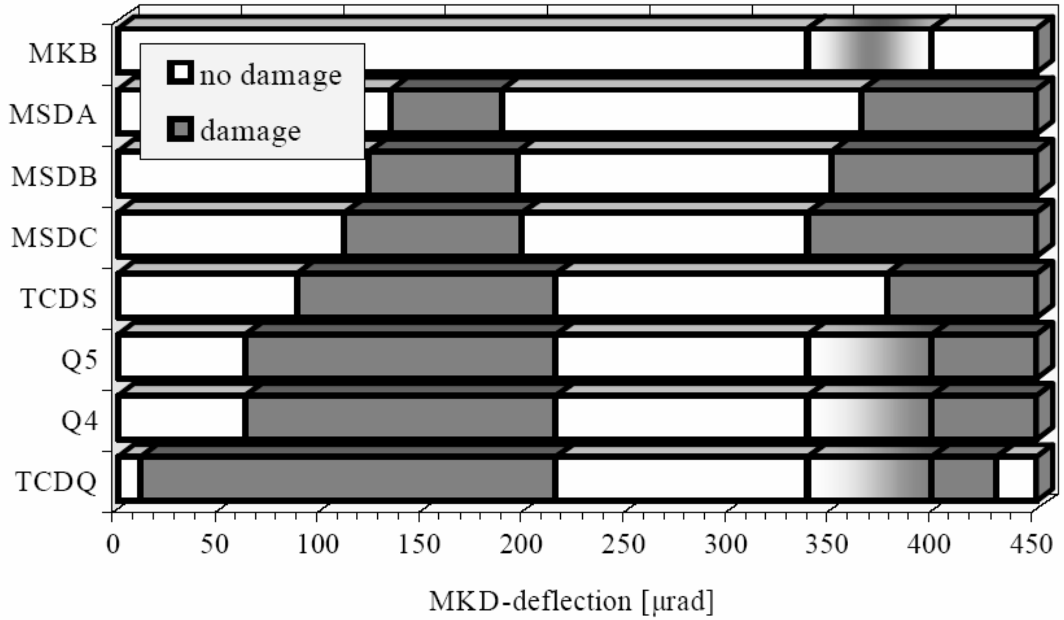
⇒ LHC is protected.

"Beyond design" failures…

Category	*Primary failure scenario*	*LHC consequence*	*Probability per year*	
			assumed	*calculated*
Fast kicker	≥8 dilution kicker magnets missing	TDE damage	1E-03	1E-07
Fast kicker	≥2 extraction kicker magnets missing	LHC damage	1E-03	1E-06
BETS	Energy tracking error	LHC damage	1E-03	?
MPS	No trigger received from Beam Interlock System	LHC damage	1E-03	3E-04

Track beam trajectory to determine elements at risk.

~straightforward in dump region: damage to extraction elements (collimators, septa, dilution kickers) and Q4, Q5 machine elements.



“Beyond design” failures and spares

- **Total dilution failure: spare dump blocks exist**
  - Will take some days to change the elements
  - Down-time probably dominated by cool-down, inquiry, system inspection, etc.
- **2-9 extraction kickers missing: TCDS and septa damaged / destroyed**
  - TCDS spares exist; for septa 3 spare magnets (1 per type) for 30 installed. Could damage 2-7 magnets (10-30m beam range) – e.g. all 5 of type A.
  - Rebuilding septa would presently take ~1-2 years. More spares? Alternatives?
- **Some beam energy tracking failures: dilution kickers also at risk**
  - 1 spare magnet per type (H/V). Rebuild ~1-2 years.
  - More spares? Low-tech, sacrificial absorber to protect magnets? Needs study
- **Asynchronous dump + mobile TCDQ collimator position failure : damage triplet collimators TCTs**
  - Presently only few (1?) spares foreseen. Foresee more? Tracking needed.
- **Worst-cases: Interlock, dump system, energy tracking failures: quantify expected damage for common initiators (trips, quenches)**
  - Tracking studies needed to determine loss locations

Unexpected failures?

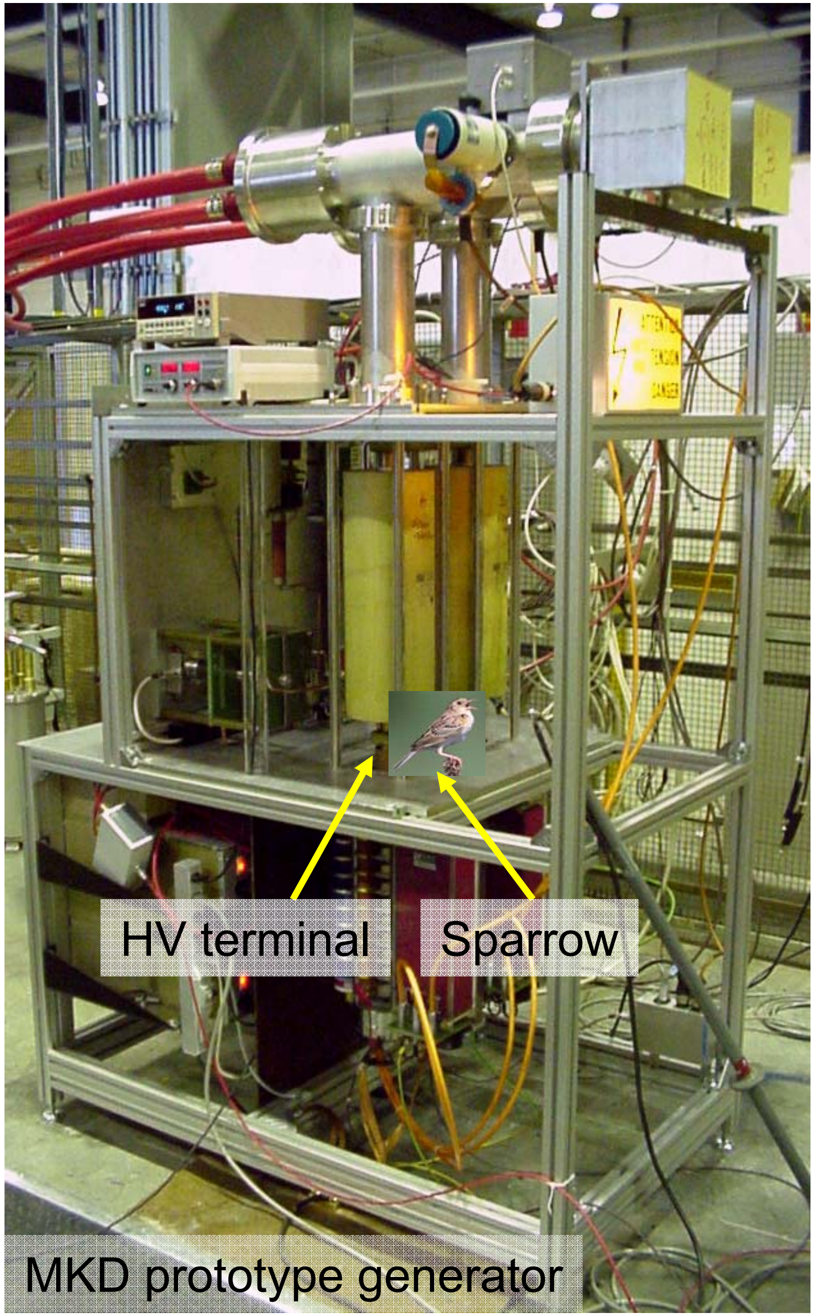
Experienced one erratic in MKD kicker testing

- 30 kV high voltage, 2 μC capacity means ~1.5 kJ energy in the capacitors
- Not very much for the kicker magnet...

  ….but more than enough for the sparrow, which acted as an unorthodox switch to earth.

(nb series generators fully enclosed)

Serious message: this 'failure' in LHC would have lead to asynchronous dump ⇒ fault - tolerant design allows some unexpected failures to be survived



Conclusions

Many possible failures for beam dumping system

- Analyses to date (and results from prototypes) have given confidence in chosen solutions
  - The identified failures are either safe for the LHC, or not expected to occur in LHC lifetime, or can be prevented with interlocking
- Some difficult aspects remain to be demonstrated
  - Safety of Beam Energy Tracking system (see next talk)
  - Positioning of mobile collimator TCDQ with respect to beam
- "Beyond-design" failures have serious consequences which could conceivably be ameliorated
  - Tracking studies needed to quantify extent of potential damage
  - Spares policy to re-examine, and/or other options to be studied (e.g. sacrificial absorbers), to reduce down-time for some cases