Beam dump dilution failure

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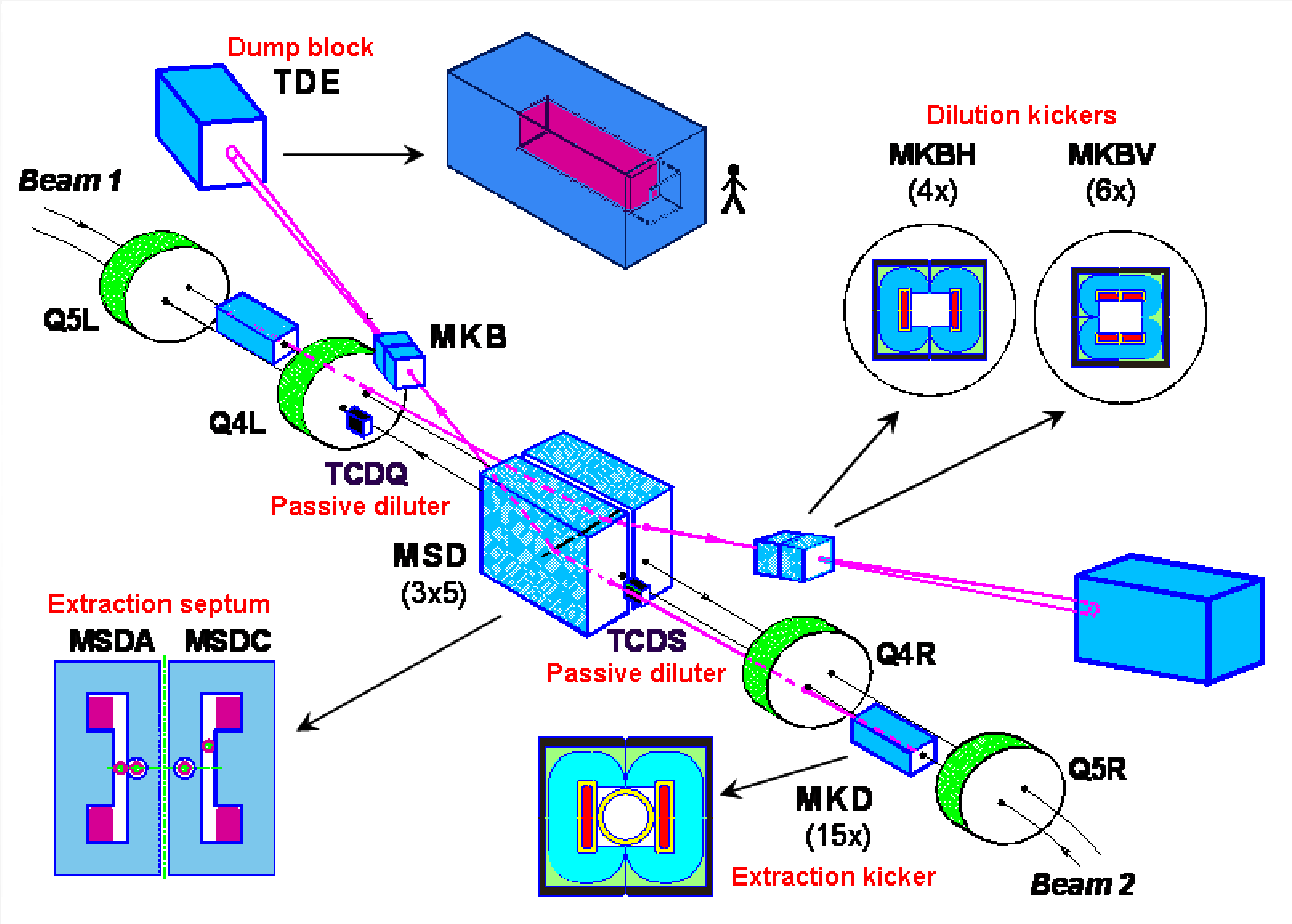
On behalf of the LHC Beam Dump project team

Outline

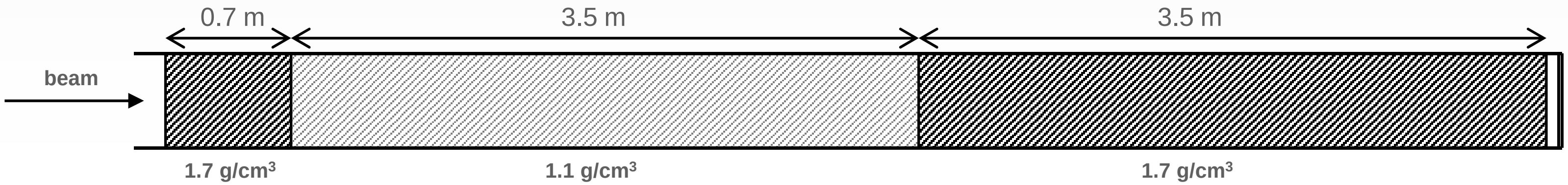
- Brief overview of LHC beam dump system
- Beam dilution
- Consequences of total dilution failure
- Expected activation levels
- TDE exchange procedure and downtime estimate
- Spares
- Summary

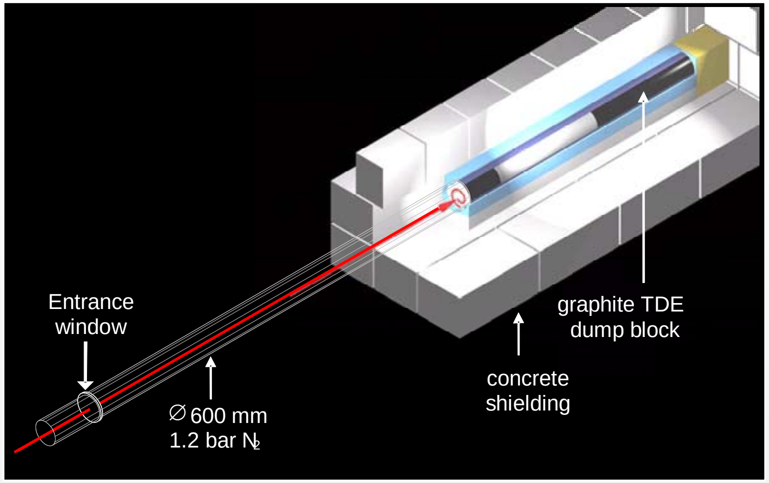
LHC beam dump principle (and acronyms)



Beam dump core (TDE)

- 7.7m long, 700 mm ∅ graphite core
- Graded density of 1.1 g/cm^3 and 1.7 g/cm^3
- 12 mm wall, stainless-steel welded pressure vessel, filled with 1.2 bar of N_2
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks

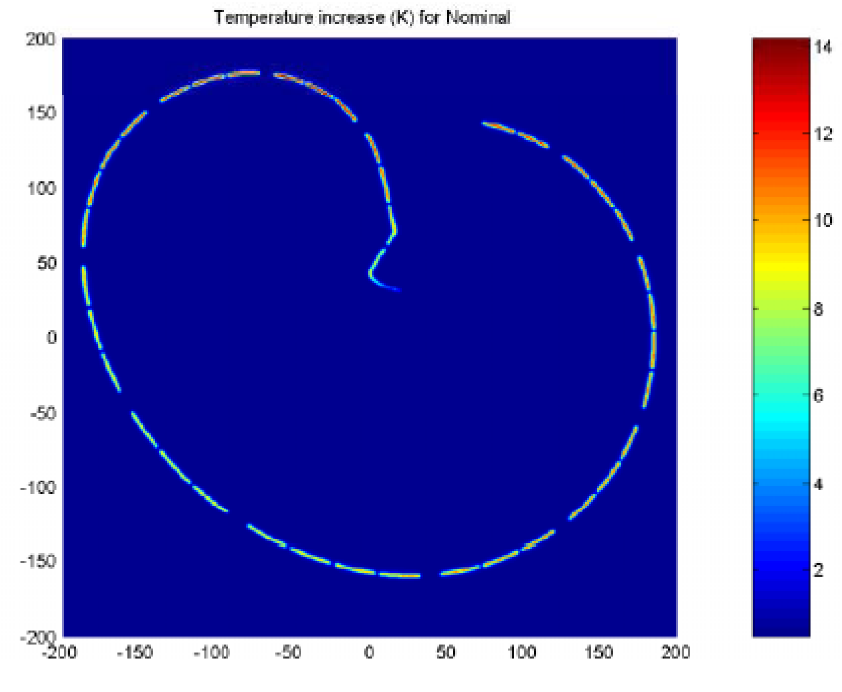




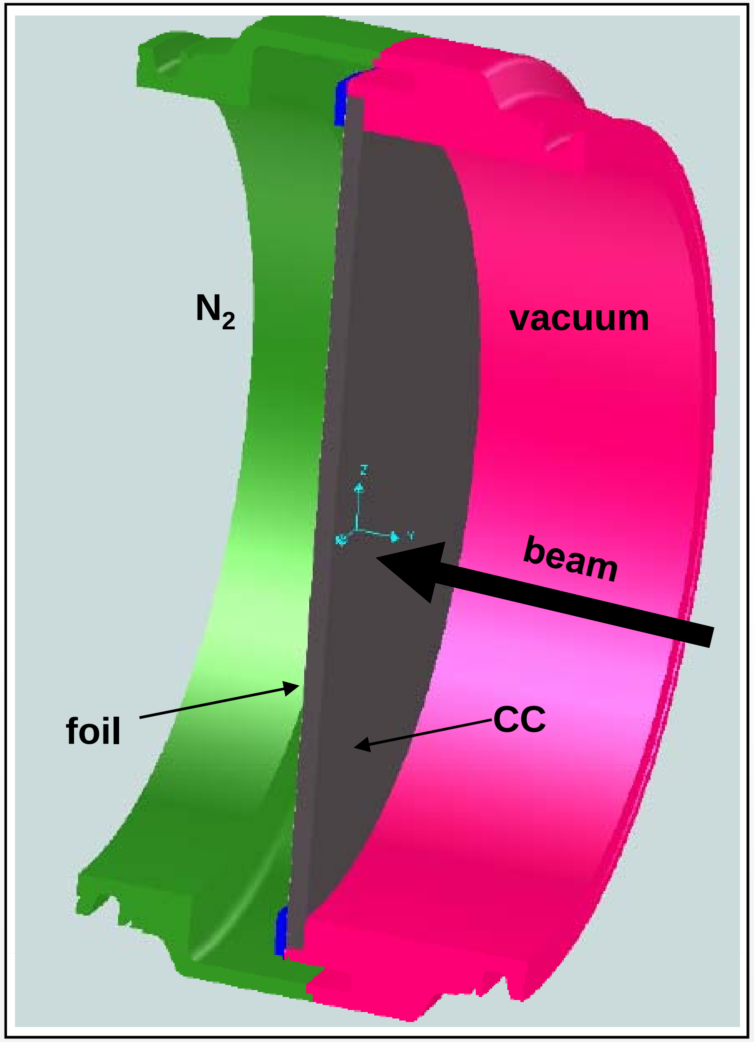
Dump block entrance window

- 15 mm thick, 600 mm ∅ CC composite window separating vacuum line from beam dump block
- 0.2 mm stainless steel backing foil

ΔT in CC for nominal beam impact
on entrance window

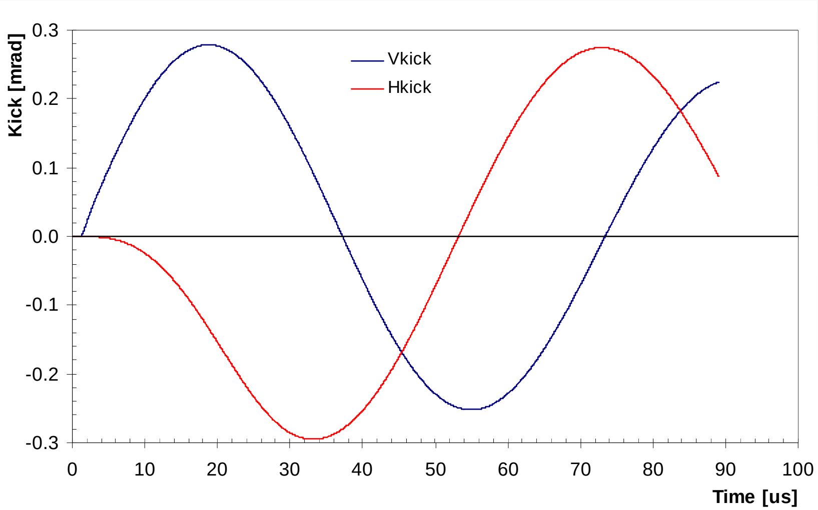


ΔT_{max} = 15K

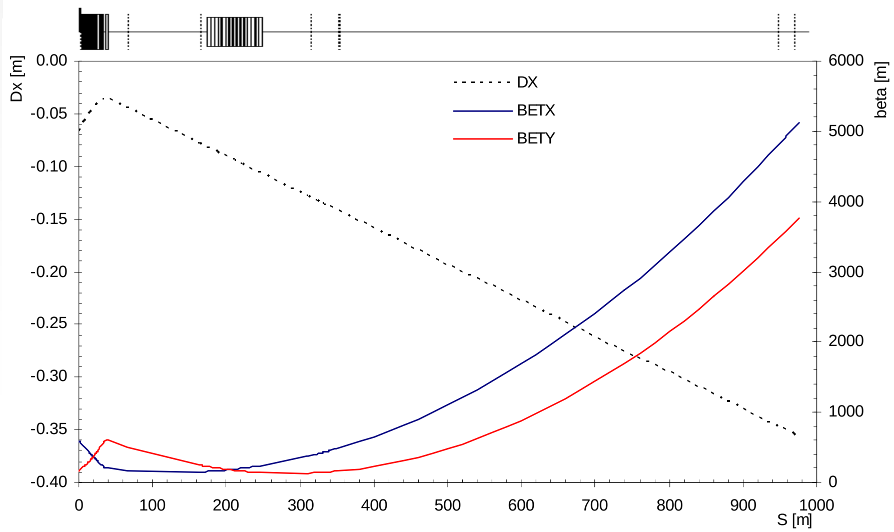


Beam dilution – drift length and sweep

Reduce beam density from ~10^{15} p+/mm^2 to ~10^{11} p+/mm^2...



Dilution kicker waveforms



β and D_x functions for dump line (TD62)

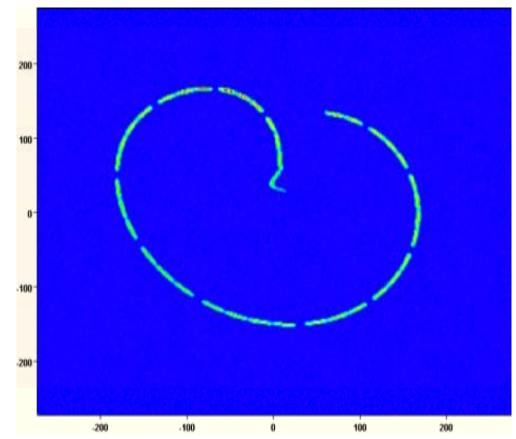
~900 m drift → 4-5 km $\beta_{x,y}$ at dump → σ ~ 1.5 mm

Dilution → 1200 mm sweep length, ∅ ~400 mm

⇩

Peak p+ density is ~1.2×10^{11} p+/mm^2

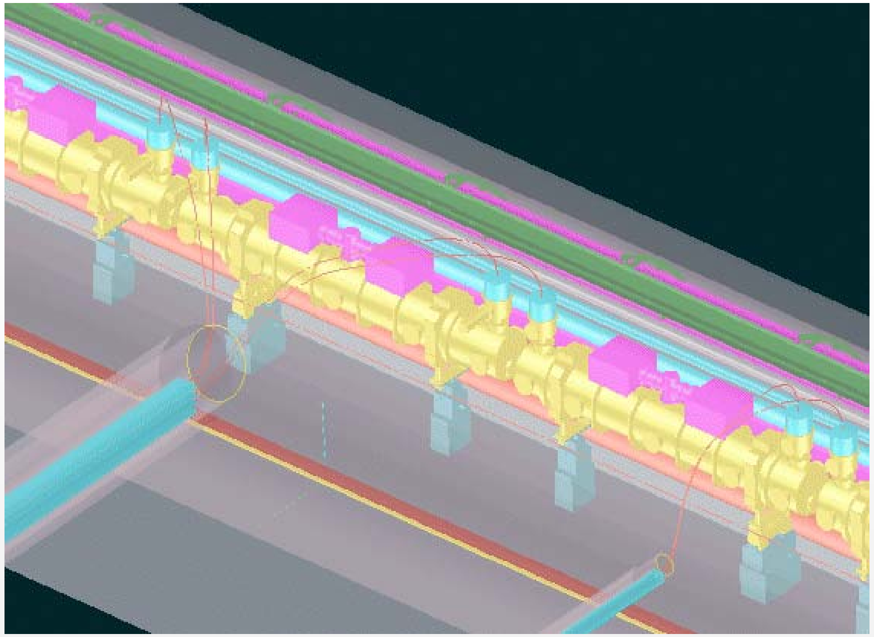
(cf 6.8×10^{14} p+/mm^2 for undiluted beam, $\beta_{x,y}$ ~150 m)

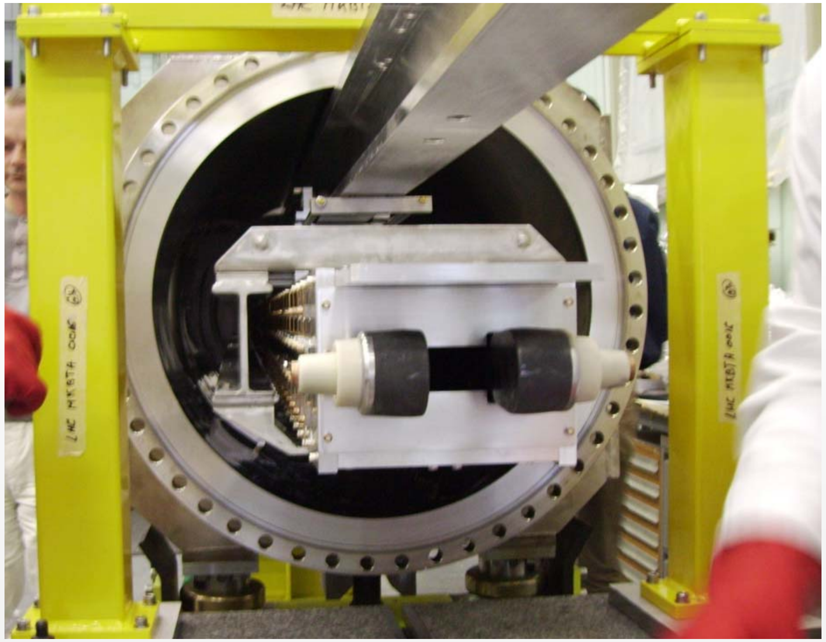


Dilution kickers (MKB)

- **Large redundancy (can dump with several missing magnets)**
- **Generators with single switch (less redundancy c.f. extraction kickers)**
- **Similar/identical technology to extraction kickers**
  - Check correct operation after triggering (redundant branches, triggering, current waveforms, sweep shape, losses…)
- **Analyses showed MKB within specified reliability (SIL4)**
  - 6% contribution to total unsafety risk of 2.4×10^{-7} per year (<1 kicker per plane)

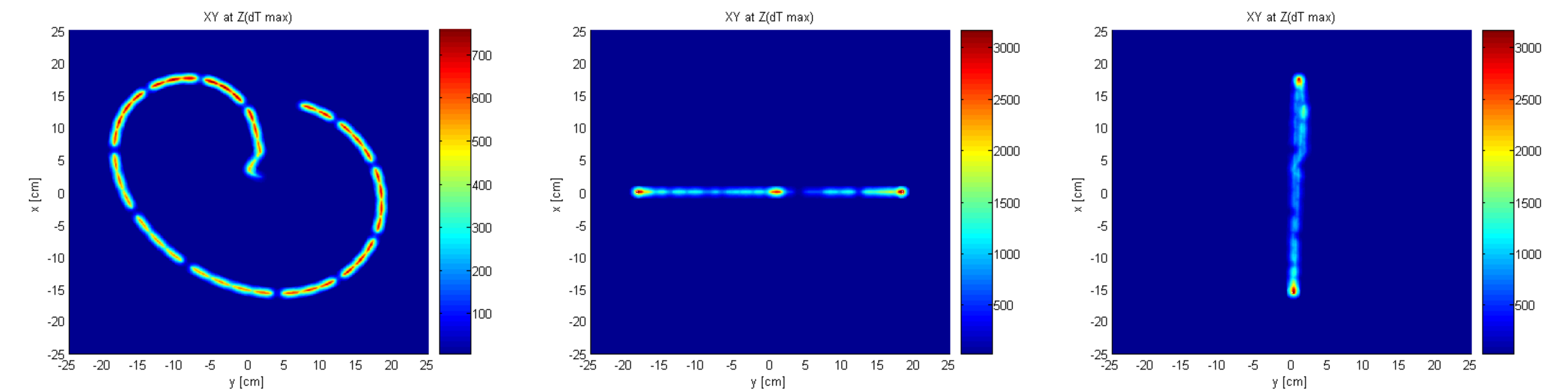
See talk by J.Uythoven





Beam dump core with dilution failures

Nominal | *0/6 vertical diluters* | *0/4 horizontal diluters*



Nominal beam intensity (3.2×10^{14} p+)

Maximum energy density in dump block

		number active MKBV						
	kJ/g	6	5	4	3	2	1	0
number active MKBH	4	1.09	1.17	1.28	1.65	2.44	4.25	7.96
	3	1.33	1.38	1.45	1.67	2.43	4.32	8.98
	2	1.74	1.75	1.85	2.01	2.50	4.50	11.30
	1	2.74	2.89	2.87	2.99	3.36	4.74	16.03
	0	6.67	7.56	8.41	9.90	12.70	17.44	53.29

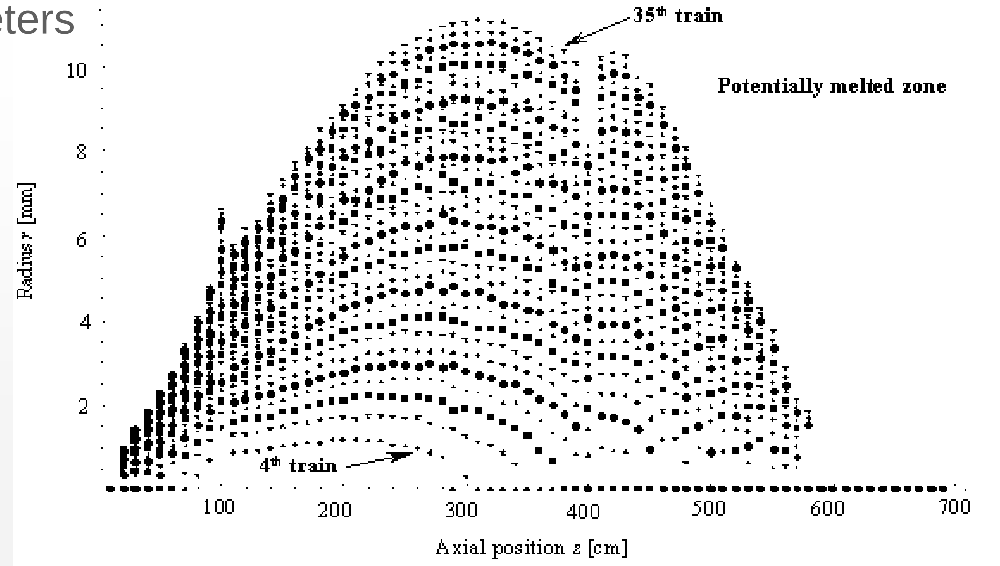
Maximum temperature rise in dump block

		number active MKBV						
	K	6	5	4	3	2	1	0
number active MKBH	4	761	804	867	1060	1455	2308	3727
	3	894	919	954	1069	1451	2340	3727
	2	1105	1110	1164	1244	1482	2425	3727
	1	1603	1670	1661	1720	1895	2534	3727
	0	3397	3727	3727	3727	3727	3727	Vapour

31 kJ/g for onset of sublimation, 60 kJ/g for complete vaporization

Dump core damage extent for total dilution failure

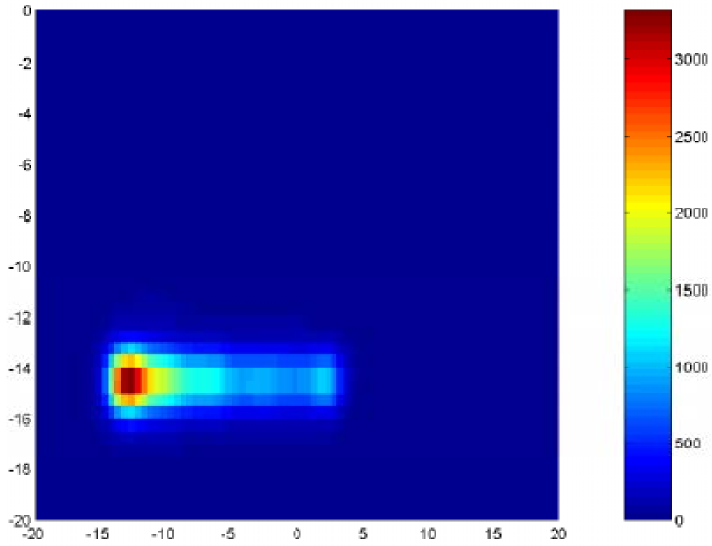
- **Detailed study made in 2000-2002 for total dilution failure, with pessimistic assumptions on mass transport**
  - Dump integrity preserved for all partial dilution failures – energy density <31 kJ/g
  - Total dilution failure (ultimate intensity) could perforate TDE core from s=1m to s=5m but without containment loss (pessimistic assumptions on mass transport)
  - For nominal intensity could damage TDE core over about 2m $\Rightarrow$ exchange of TDE necessary as preventive measure
  - Similar analysis made by UK company using different code
- **Coupling FLUKA to hydrodynamic code being explored**
  - Preliminary results encouraging with penetration of <8m for very pessimistic parameters
  - Planned extension to realistic LHC dump core (maybe results in 2010)



Entrance window and BTVDD with dilution failures

Load case Ultimate intensity	ΔT (K) CC	SS	Stress (MPa) CC
one bunch	1	3	0.2
nominal sweep	15	38	-
no MKBH	116	335	-
no MKBV	166	537	-
no MKB	891	3580	294

ΔT in steel foil for total dilution failure

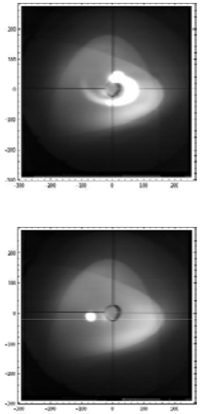


ΔT = 3580K

CC survives all failure cases.

0.2 mm thick steel backing foil will be damaged for total dilution failure ⇒ exchange window if leaking

Steel sheet survives either MKBH/V total failure

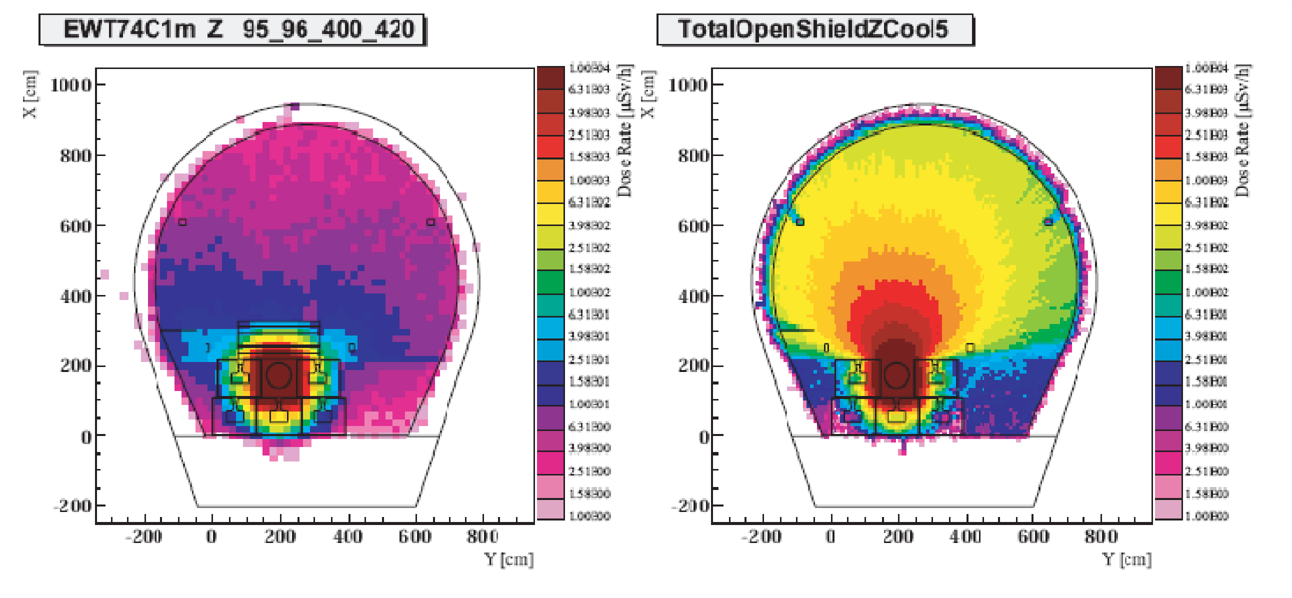


Large screen upstream of TDE core

Will also be damaged by total dilution failure – central portion designed to be "easily" replaced.

Beam dump and cavern expected activation

- **Detailed analyses made of expected activation for "pessimistic" operating conditions, for different cooldown times (1d, 1w, 1m, 1y)**
  - With shielding blocks in place, around 90 μSv/h max in the cavern after 1w
  - With blocks removed, up to 18 **m**Sv/h in ~contact with core after 1w



Dose rate maps in UD cavern (after 1 month of cool down) with Shielding closed (left) and shielding open (right)

  - Remote handling of shielding and dump core via cranes installed in UDs

Dump block exchange

- **Exchange procedure worked out in detail with RP and tested in 2007 with a real core exchange**
  - 1 week of cooling down gives 230 μSv collective dose
  - Damaged core left in UD for 1y as transport gives big dose (still 1.7 mSv collective)

Doses for TDE core exchange

Worker	Dose in μSv		
	1 week	1 month	4 months
V1	8.3e+00	4.5e+00	2.4e+00
T1	6.2e+01	3.6e+01	2.0e+01
T2	6.2e+01	3.6e+01	2.0e+01
P1	6.2e+01	4.3e+01	1.2e+01
P2	4.4e+00	3.2e+00	1.2e+00
RP	3.2e+01	2.2e+01	1.0e+01
Collective dose	2.3e+02	1.4e+02	6.6e+01

Doses for TDE core transport

Worker	Dose in μSv			
	1 week	1 month	4 months	1 year
D1	6.1e+03	3.1e+03	1.5e+03	7.3e+02
D2	4.4e+03	2.5e+03	1.1e+03	5.3e+02
P1	1.8e+01	1.0e+01	4.1e+00	3.1e+00
RP	3.1e+03	1.6e+03	7.5e+02	3.7e+02
Collective dose	1.4e+04	7.2e+03	3.4e+03	1.7e+03

Step	Intervention	Persons	Position	Time (s)	Configuration
1	RP measurement in the UD cavern	RP	UD		1
2	Release of the nitrogen overpressure	V1	5	10	1
3	Padlock between the core and the CL to be opened	V1	2a	20	1
4	Chain clamp between the core and the CL to be opened	T1 & T2	2a & 2b	60	1
5	Compression of the downstream bellow	T1 & T2	2a & 2b	60	1
6	Compression of the upstream bellow	T1 & T2	6a & 6b	60	1
7	Connecting the palonnier for the shielding blocks to the crane	P1 & P2	7 & 8	60	1
8	Removal of the top shielding blocks	P1	7	1300	1-2
9	Exchange of "Palonnier"	P1&P2	4 7 8	90 @ 4, 90 @ 8	2
10	Catching the dump core	P1	1 &7	20	2
11	Moving the dump core to the storage area	P1	7	60	2-3
12	Catching the spare core	P1	7	60	3
13	Installing the new core in the shielding	P1 & P2	1 & 7	20	3-4
14	Removing of the palonnier for the core	P1 & P2	4 & 7	60	4
15	Connecting the shielding blocks palonnier to the crane	P1 & P2	7 & 8	60	4
16	Installation of top shielding blocks	P1	7	1300	4-5
17	Put a new joint between the core and the CL	T1 & T2	2a & 2b	60	5
18	Release of the bellow upstream of the CL	T1 & T2	6a & 6b	60	5
19	Release of the downstream bellow	T1 & T2	2a & 2b	60	5
20	Closing the chain clamp	T1 & T2	2a & 2b	120	5
21	Rigidifying the bellow	T1 & T2	3	20	5
22	Pumping of the core and the CL	V1	5	240	5
23	Filling the CL with a nitrogen overpressure	V1	5	240	5
24	Releasing the threaded stem	T1 & T2	3	20	5
25	Putting the padlocks in place	V1	2	20	5
26	Parking the crane in the upstream part of the cavern	P1	7		5
27	Pumping the beam line upstream of the carbon window	V1	TD / 7		5
28	Evacuating material and persons				5

Overall downtime

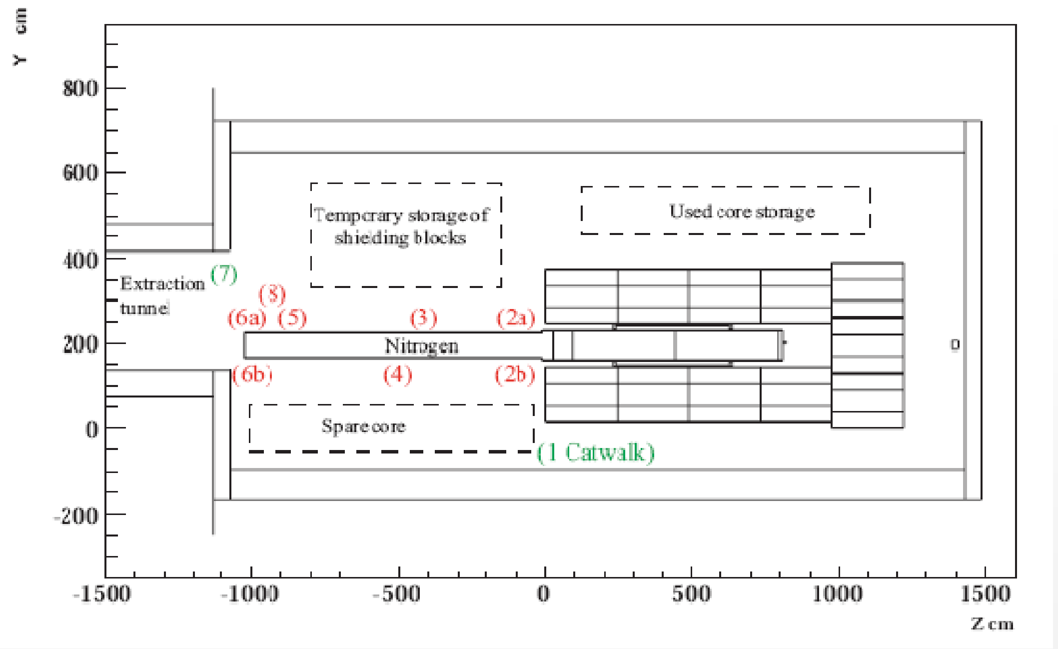
- **Overall downtime for total dilution failure estimated assuming:**
  - TDE core is damaged and exchanged.
  - VDWB backing steel foil is damaged and VDWB is exchanged.
  - BTVDD insert is damaged and exchanged.
- **Total downtime is about 4 weeks**
  - Dominated by 1 week cooling time and 2 weeks repumping of TD dump line vacuum (only 7-10 'working' days needed)

Activity	days	
Dump core cooldown time	7	
Repressurisation of dump line	0	Done in shadow of cooling time
RP inspection and intervention authorisation	1	
Exchange of dump core	2	
Exchange of VDWB window	2	
Exchange of BTVDD central insert	2	
Dump line pumpdown and leak testing	14	
Total	**28**	

Spares

- 2 complete spare TDE dump cores exist and are stored in the UD caverns
- 1 complete spare VDWB window exists
- Spare components for one BTVDD screen and several spare central inserts exist

Cavern layout with spare core, space for shielding blocks and damaged core storage



Summary

- **A total dilution failure not expected to happen during LHC lifetime**
  - Reliability run gave confidence in reliability figures for triggering and switches
  - But unexpected things can still happen: e.g. simultaneous MKB flashover (addressed with new vacuum interlocking, new HT insulator design, reduction of conductance between tanks).
- **If a total dilution failure happens, a full intensity 7 TeV beam may cause damage to several components at end of beam dump line**
  - Beam dump core TDE could be damaged over several metres
  - Dump entrance window VDBW could lose vacuum tightness
  - Central insert of BTVDD screen could be damaged
- **Total LHC downtime for a total dilution failure with beam at full intensity and 7 TeV would be ~4 weeks**
- **Replacement of TDE core is critical because of activation (~18 mSv/h after 1w) and has been extensively studied and optimised**
  - Checked with “dry-run” in 2007 where a core was exchanged

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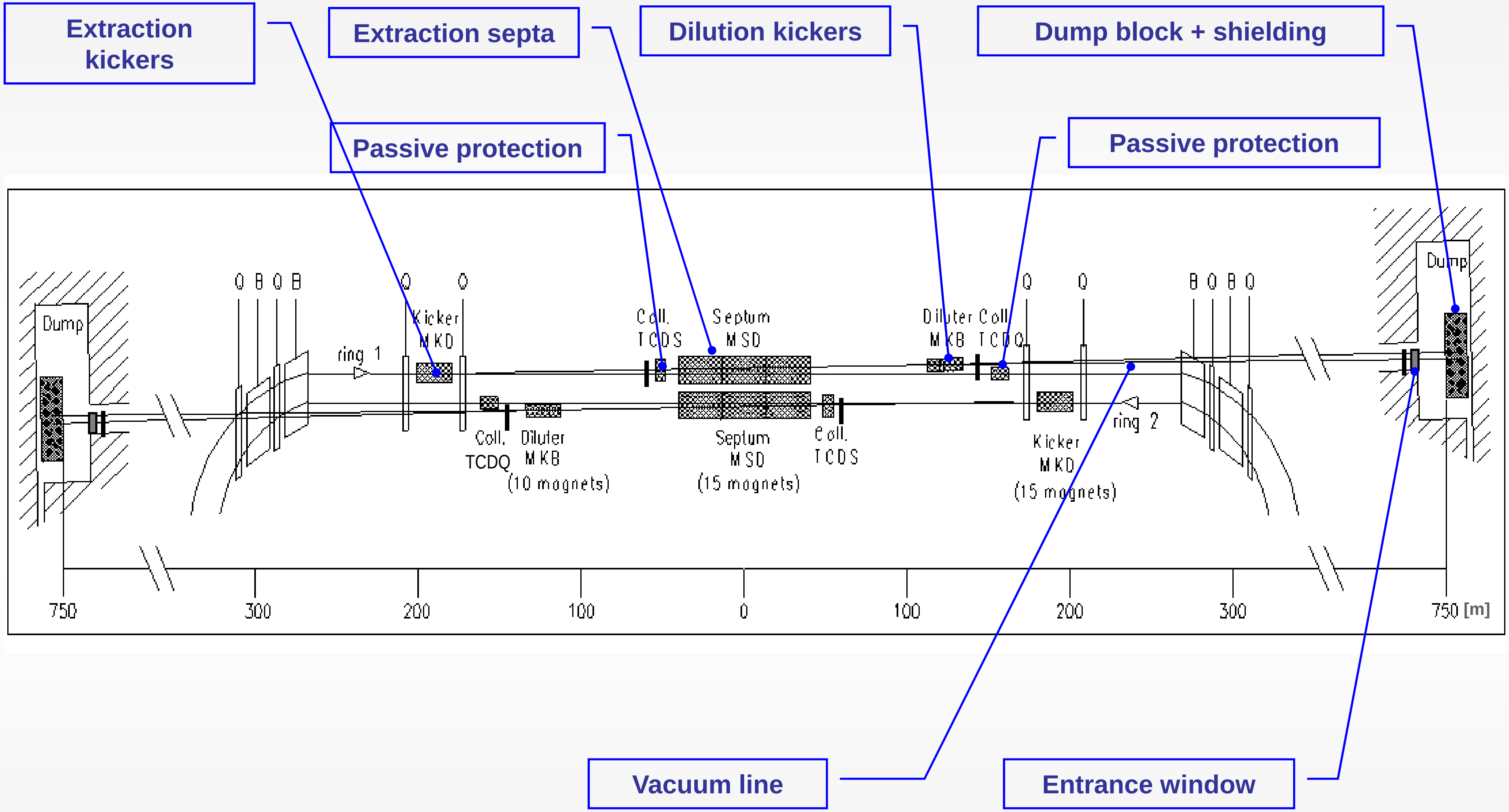
Main subsystem performance characteristics

Parameter	Unit	Value
Extraction kicker (MKD) horizontal deflection	mrad	0.28
MKD ∫B.dl at 7 TeV	T.m	6.53 ***15 magnets of 1.4 m***
Total horizontal deflection (MKD + Q4)	mrad	0.33
Extraction septum (MSD) vertical deflection	mrad	2.40
MSD ∫B.dl at 7 TeV	T.m	56.0 ***15 magnets of 4.5 m***
Dilution horizontal deflection (MKBH)	mrad	±0.28 ***4 magnets of 1.9 m***
Dilution vertical deflection (MKBV)	mrad	±0.28 ***6 magnets of 1.3 m***
Total beam line length (start MKD – end TDE)	m	975
Required particle-free abort gap length	μs	3.0
System Safety Integrity Level (SIL)		Three

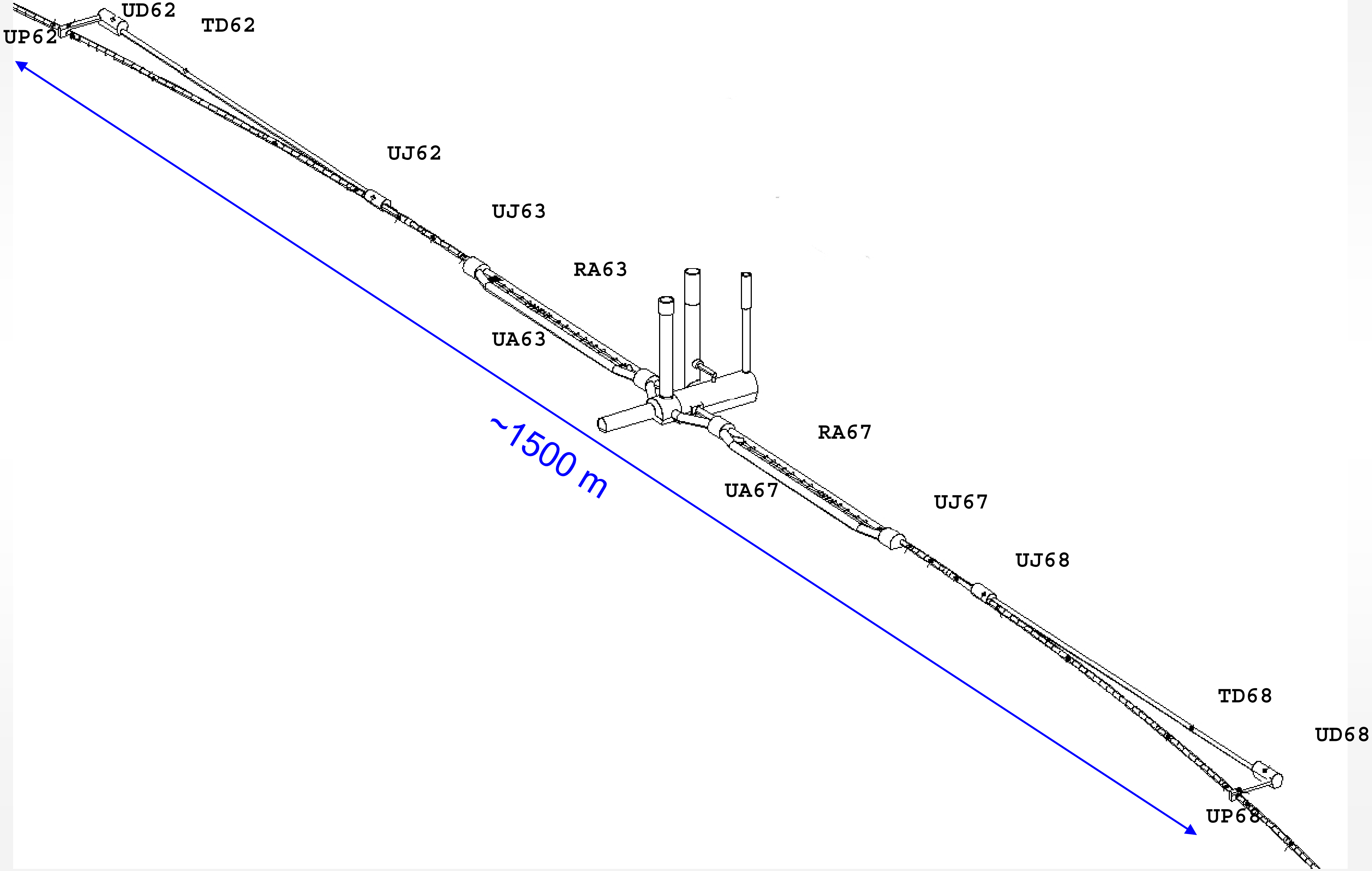
Note that fixed extraction angle requires active energy tracking for extraction and dilution kickers, and extraction septum

Layout of components

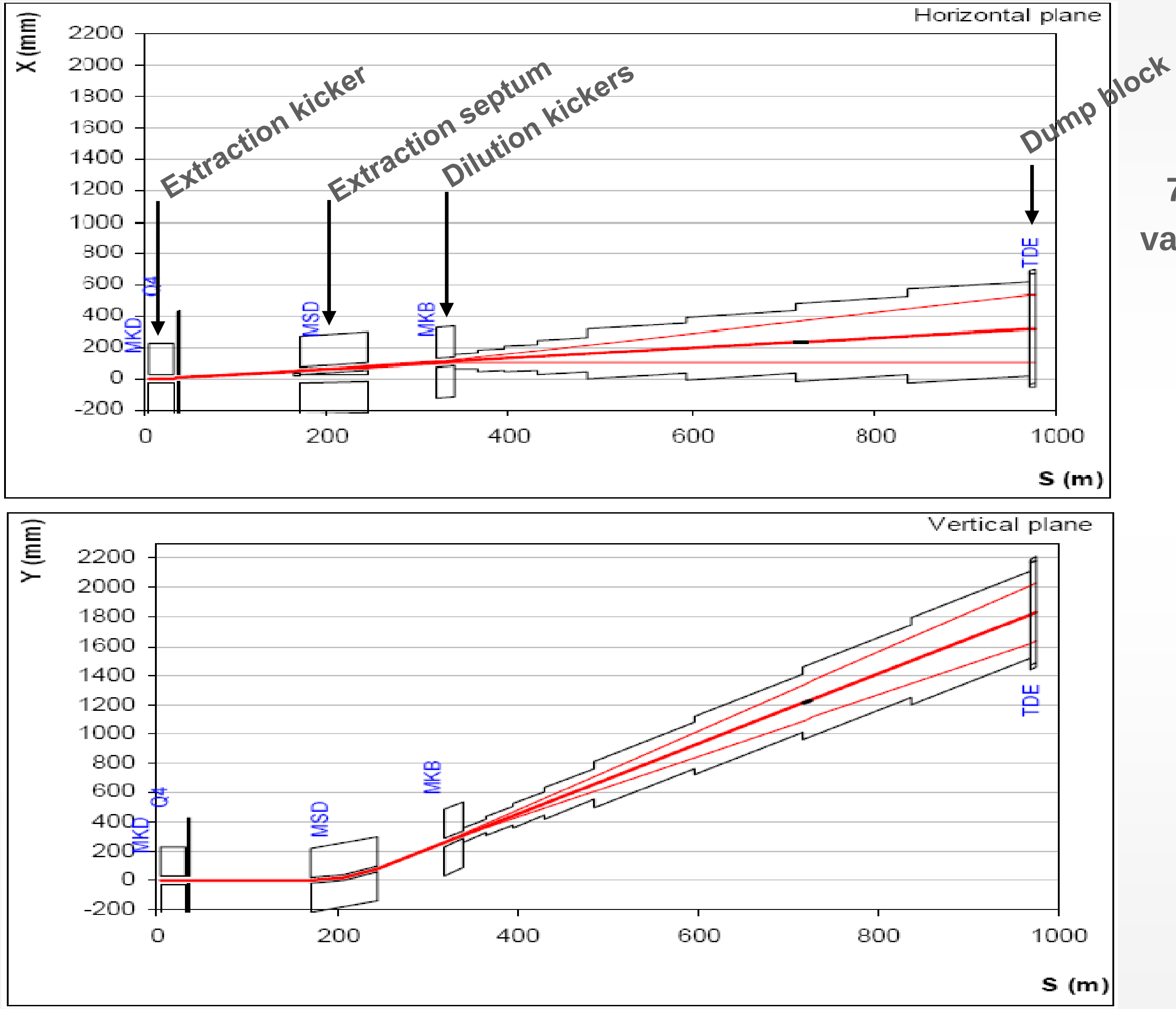


Plus beam position and loss monitors, and dedicated interlocking (not shown)

Underground structures



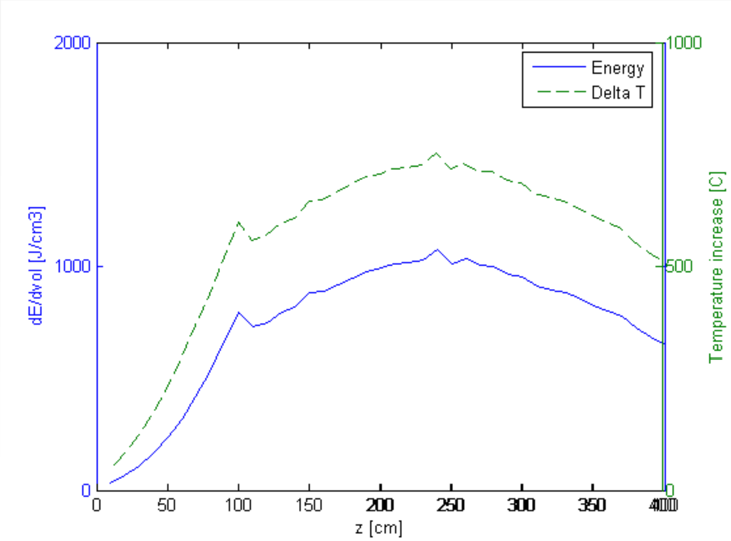
Central and extreme particle trajectories



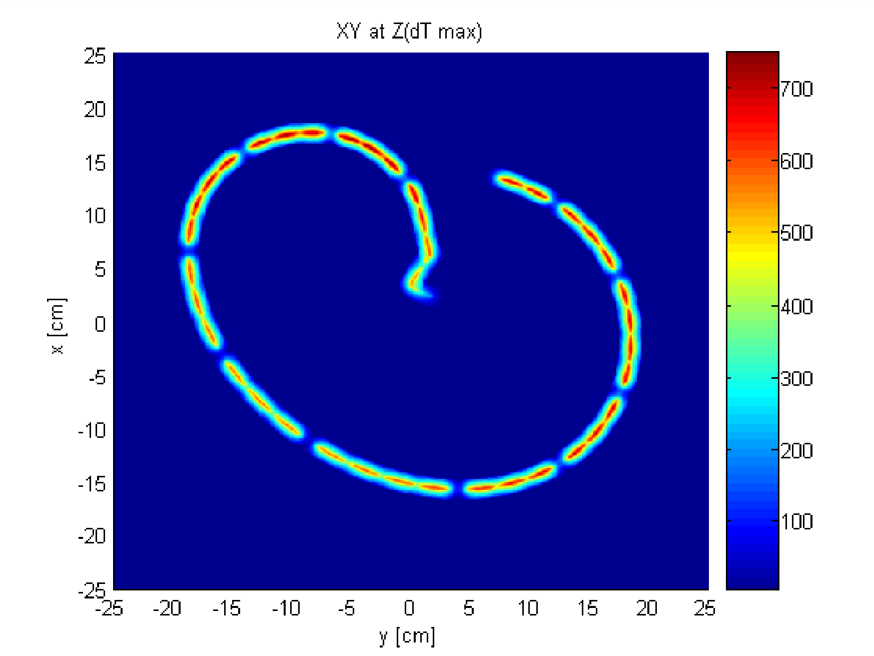
750 m long separate beamline
vacuum chamber up to ∅600 mm

Temperature rise in dump block

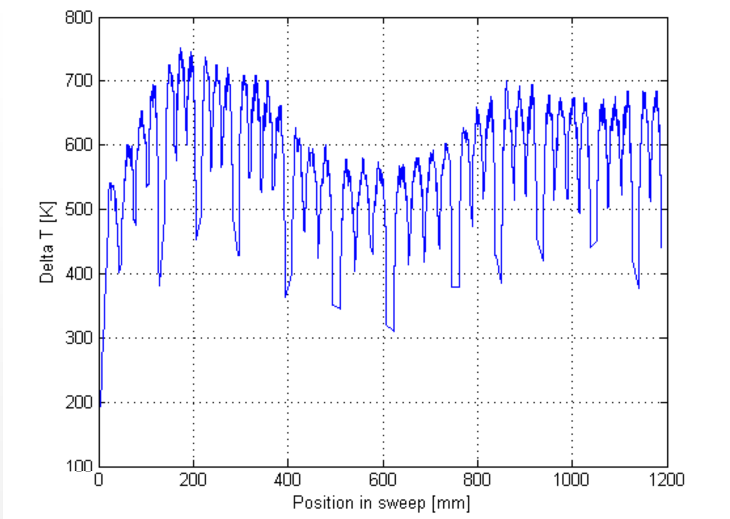
FLUKA calculations made to give energy deposition for single bunches, then superimposed according to bunch pattern and ΔT calculated by integrating temperature dependant heat-capacity



Temperature profile along dump block length



Temperature profile through dump block at Z=250 cm



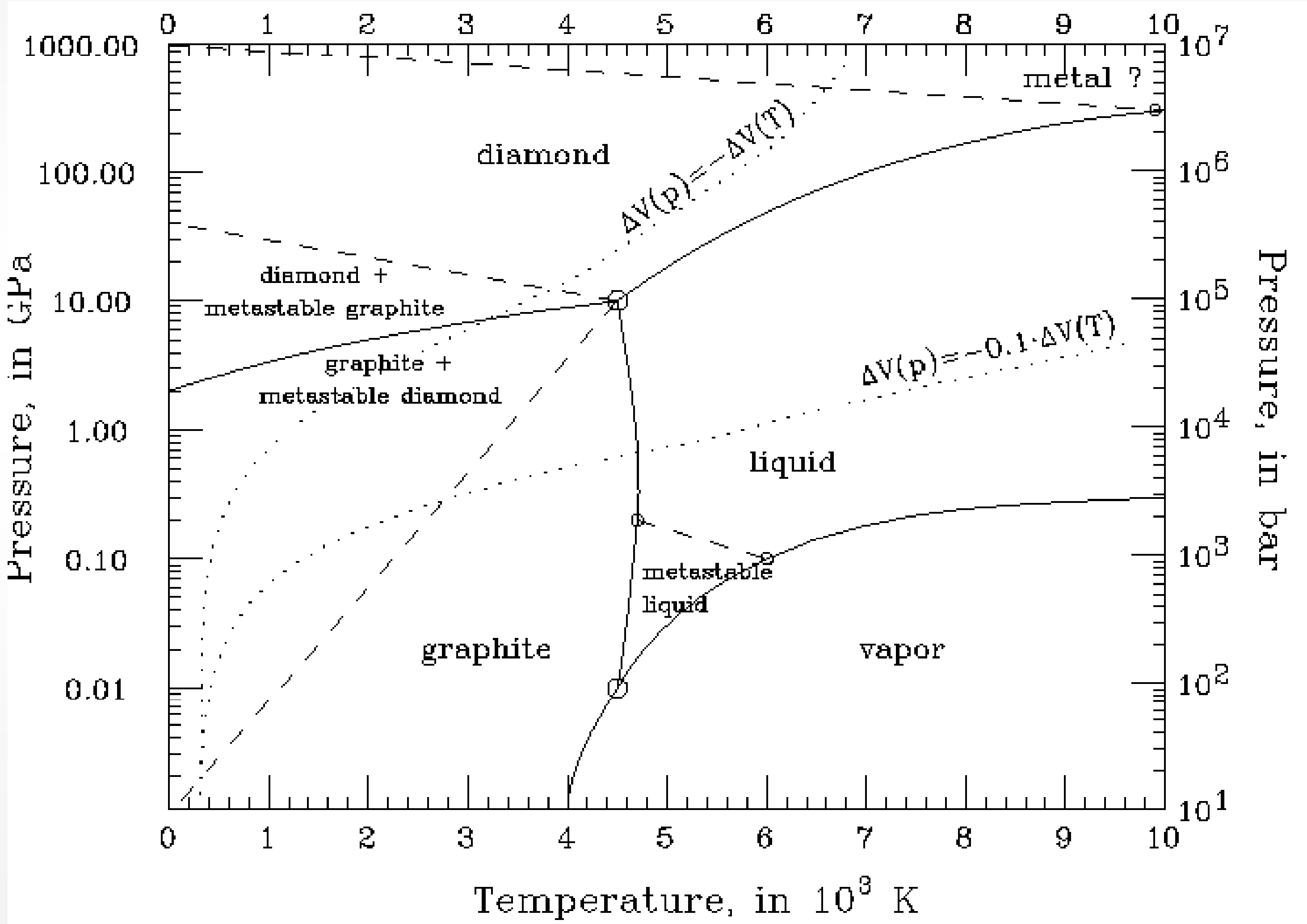
Temperature profile along sweep path at Z=250 cm

Dump block damage extent for total dilution failure

- **Main concern about penetration through core, exit window and into shielding**
  - Several estimates made – the most recent indicate that the dump should survive without a loss of containment even for LHC ultimate intensity
  - Mitigating actions anyway taken to ameliorate effects of loss of containment (TDE core kept at 1.2 bar N_2 to avoid air inrush, smoke/fire detection in UD, ventilation cut if fire alarm)
- **Full simulations a difficult undertaking**
  - Mutual dependence of energy deposition and material properties in poorly known domains with phase changes, plasmas, matter-transport, massive beam scattering, …) over 100 μs timescales
  - Would require coupling of e.g. FLUKA and ANYSIS, with material phase changes included….not presently feasible
- **Alternative simulations being made with GSI (N.Tahir)**
  - Using FLUKA output and 2D hydrodynamic code BIG2, for full, undiluted LHC beam.
  - Predicts stopping distance of about 8 m in high-density C, for much more pessimistic conditions (no sweep from extraction kicker waveform, 0.2 mm transverse σ c.f. 1.5 mm)
  - Will apply this to TDE core geometry and beam input conditions

Reliability analyses results

- **Reliability of full system was analysed (recent PhD R.Filippini)**
  - Detailed analysis of subsystems
  - ‘Quantitative’ numbers on safety and availability
  - Also partly extended to LHC machine protection system as a whole
- **Safety**
  - Critical subsystems (triggering, energy tracking) looked at in great detail
  - Figures confirm that dump should reach SIL4 as required
    - Dump ‘unsafety’ 4.8×10^{-7} per year of operation
    - Increases to 2×10^{-4} per year without post-mortem diagnostics
  - Several design choices made using results of reliability analysis
  - Some highlighted areas will still be worked on
    - Redundancy in link from beam permit (interlock) loop
- **Availability**
  - Expected number of false dumps from dump system seems reasonable
    - 8 ±3 false dumps per year (41 ±6 from whole MPS)



0 1 2 3 4 5 6 7 8 9 10
1000.00
100.00
10.00
1.00
0.10
0.01
Pressure, in GPa
10^7
10^6
10^5
10^4
10^3
10^2
10^1
Pressure, in bar
metal ?
diamond
ΔV(p)=−ΔV(T)
diamond +
metastable graphite
graphite +
metastable diamond
ΔV(p)=−0.1·ΔV(T)
liquid
metastable
liquid
graphite
vapor
0 1 2 3 4 5 6 7 8 9 10
Temperature, in 10^3 K