Chapter 10

Beam dumping

2008 JINST 3 S08001

10.1 System and main parameters

The dedicated beam dumping system of the LHC is sited in Point 6. The system is able to fast-extract the beam from each ring in a loss-free way, to an external absorber positioned sufficiently far away to allow for beam dilution, so as not to overheat the absorber material. A loss-free extraction requires a particle-free gap in the circulating beam, during which the field of the extraction kicker magnets can rise to the nominal value. Given the destructive power of the LHC beam, the dumping system must meet extremely high reliability criteria. The system is shown schematically in figure 10.1 and will comprise, for each ring:

- 15 extraction kicker magnets MKD located between the superconducting quadrupoles Q4 and Q5;
- 15 steel septum magnets MSD of three types MSDA, MSDB, and MSDC, located around IP6;
- 10 modules of two types of dilution kicker magnets between the MSD and Q4;
- The beam dump proper, comprising the TDE core assembly and associated steel and concrete shielding, situated in a beam dump cavern $\sim$750 m from the centre of the septum magnets;
- The TCDS and TCDQ diluter elements, immediately upstream of the MSD and Q4, respectively.

The nominal system parameters are given in table 10.1. The MKD kickers deflect the entire beam horizontally into the high-field gap of the MSD septum. The MSD will provide a vertical deflection to raise the beam above the LHC machine cryostat before the start of the arc sections. The dilution kickers will be used to sweep the beam in an '*e*' shaped form, and after the appropriate drift distance the beam will be absorbed by the TDE assembly. The TCDS and TCDQ will serve to protect machine elements from a beam abort that is not synchronised with the particle-free beam gap.

The beam dumping system must also be able to handle beams that are outside normal parameters, due to equipment failure or abnormal optics settings in the rings. The relevant worst-case

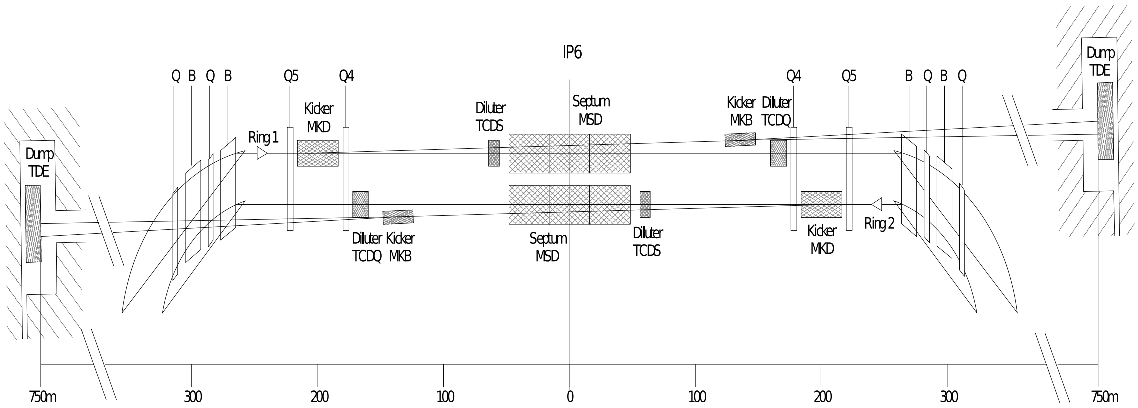

Figure 10.1: Schematic layout of beam dumping system elements around LHC Point 6 (distances in m).

Table 10.1: Overall beam dumping system parameters.

Parameter	**Unit**	**Value**
Total horizontal deflection (MKD + Q4)	mrad	0.330
Total vertical deflection (MSD)	mrad	2.400
Dilution horizontal deflection (MKBH)	mrad	±0.14
Dilution vertical deflection (MKBV)	mrad	±0.14
Total beam line length (start MKD – end TDE)	m	975
Required particle-free abort gap length	μs	3.0
System Safety Integrity Level (SIL)		3
Beta function at TDE entrance	m	4990 (H), 4670 (V)

Table 10.2: Assumed worst-case LHC beam characteristics for dumping system design.

Beam	**Maximum ε_n**		**Total Orbit [mm]**	**Beta modulation [%]**	**Total p+ 10^{14}**
	450 GeV [μm]	7 TeV [μm]			
Commissioning	6.0	12.0	±4	42	0.3
Initial	6.0	12.0	±4	42	0.8
Nominal	7.5	15.0	±4	42	3.1
Ultimate	7.5	15.0	±4	42	5.3

beam characteristics that can be accommodated are given in table 10.2 for the various LHC beams considered.

For the purposes of estimating radiation and heat loads on the TDE, TCDS, and TCDQ, and also for the purposes of the reliability analysis, the assumptions shown in table 10.3 were used for the operational parameters, dump and fault frequencies. In general, these are worst-case assumptions, so as to ensuring that there is an inherent safety factor in the subsequent calculations.

Table 10.3: Assumptions for activation calculations and reliability.

Number of years of LHC operation	20
Number of days of operation per year	200
Number of 7 TeV fills dumped per day (at nominal current)	2
Number of 450 GeV fills dumped per day (at nominal current)	2
Number of dumps at full intensity per beam in LHC operational lifetime	2×10^4
Number of dumps with a missing MKD module per year	1
Number of asynchronous dumps per year	1
Number of total dump system failures per 100 years	1
Total intensity until staged equipment operational (MKB and TDE cooling)	50% of nominal

10.2 Reliability

A fault in the beam dump system could lead to severe damage to the system itself, to the LHC machine, and/or to the LHC experiments, due to uncontrolled beam losses on equipment. It is desired that total beam dump failures will not exceed a rate of 1 failure in 10^6 hours, or roughly one failure in 100 years. This requires the use of high quality components, the introduction of redundancy for critical elements, the provision of redundant signal paths, fault-tolerant subsystems, continuous surveillance, rigorous follow-up, and finally the mandatory use of a check list of validation tests before injecting beam in the LHC. It has to be noted that this is the failure rate for the complete system, comprising the beam dumping sub-system elements, together with the LHC Beam Interlock System, the LHC Beam Energy Meter, and the associated signal transmission. The Beam Energy Meter will be one of the critical elements in the chain of equipment required to dump the beam, since a false estimation of the beam energy could send the full LHC beam into one of the arcs adjacent to the beam dump insertion. Similarly, the extraction kicker magnets, MKD, will also be one of the critical elements in the system.

10.2.1 MKD

First estimates from reliability calculations for the extraction kicker system, MKD, have shown that the reliability requirement can only be obtained with full redundancy of one complete MKD kicker and its generator. Thus the beam can safely be extracted, albeit with the risk of beam loss on the TCDS, with only 14 out of the 15 kicker magnets. In addition, each MKD generator will consist of two parallel discharge circuits, including two switches, with failsafe triggering. The switches will use Fast High Current Thyristor (FHCT) solid-state technology, which is more reliable than conventional gas discharge switches. The energy needed for the kickers will be stored in local capacitors whose voltage will be constantly monitored. If one voltage is found outside the specified value, the beam will be dumped immediately (self-triggering). If a switch closes when not requested, a re-trigger system will immediately close all the other 14 switches with a maximum delay of 700 ns. A redundant UPS system will ensure that a dump action is correctly triggered and executed in the event of a general power failure and all triggering and re-triggering lines will be doubled.

10.2.2 MKB

The dilution kicker, MKB, will not be critical items from a reliability point of view. However, triggering lines will be doubled, since a total dilution failure could lead to damage of the TDE core.

10.2.3 MSD

The reliability of the DC septum magnets, MSD, is also not regarded as critical, since the magnets are based on conventional technology (with current decay constants in the order of seconds). The current in the magnet can be constantly monitored, as could the voltage drop across the magnet if required.

10.2.4 Vacuum system and TDE

The vacuum system of the TD dump line and the pressure vessel of the dump block, TDE, cannot fail in such a way as to threaten the safety of the LHC machine in general. The vacuum systems give adequate warning of degradation, and the beams can still be dumped without risk to the LHC machine proper.

10.2.5 Post-mortem

High reliability will be maintained by performing a post-mortem on every beam dump. A dump action without beam shall take place if the last post-mortem was too long ago, for example after a shutdown. It will only be possible to inject beam in the LHC if the post-mortem of the last beam dump and the beam dump status are satisfactory.

10.2.6 Synchronisation

The synchronisation between the RF and the beam dump kickers will be a redundant system, and the loss of the synchronisation of one of the two systems will launch a synchronous beam dump. Transmission is via a direct fibre-optic link.

10.2.7 Energy tracking

In order to get the correct extraction trajectory, the beam energy tracking system will determine the deflection strength of the MKB and MKD kickers and the MSD septa according to the measured beam energy. The tolerances on the kick angles for the MKD and MSD elements are below one percent. The beam energy reference information will be obtained through two redundant Beam Energy Meter systems (BEM), connected to the two main bend power converters located left and right of Point 6. The RF central frequency and integrated orbit corrector fields will affect the beam energy and may need to be taken into account, either via the BEM or via interlocking.

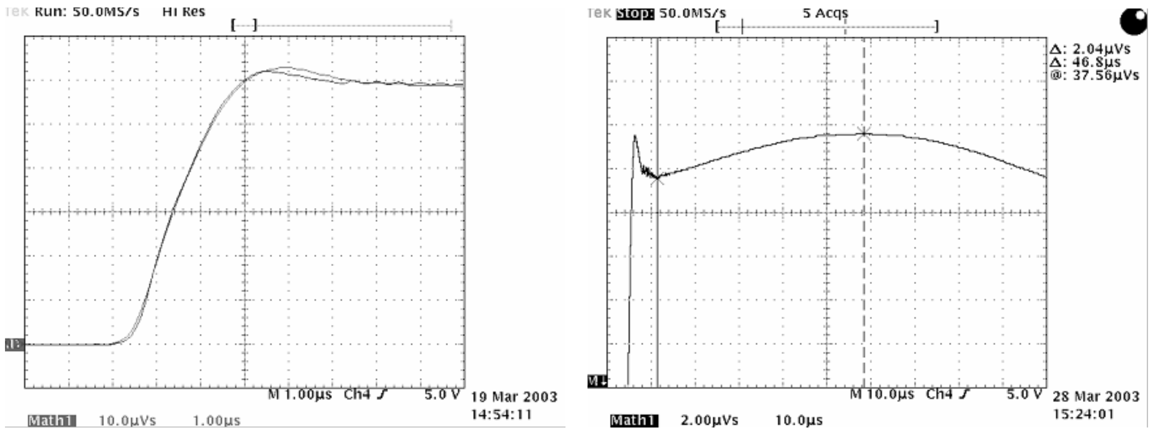

Figure 10.2: Start of MKD magnet current pulse at 450 GeV and 7 TeV with overshoots of 7.5% and 5.2% respectively (left); MKD magnet current pulse over 100 μs at 7 TeV with flat top overshoot of 5.6% (right).

10.2.8 Other protection

Local damage to components in case of certain fault scenarios will be avoided or reduced by the absorbers TCDS and TCDQ. The local orbit feedback will stabilise the beam in the extraction channel, and an interlock on the orbit position will ensure that the beam position remains within specified tolerances to permit a successful abort. Sacrificial absorbers may also be placed in the TD lines.

10.3 Main equipment subsystems

10.3.1 Fast-pulsed extraction magnets MKD

The beam dumping system has two sets of 15 fast-pulsed extraction magnets, MKD. A pulse generator will power each magnet via a low impedance transmission line. At least 14 out of the 15 kicker magnets must operate simultaneously on request. The kicker field rise time is specified as $\leq 3.0\ \mu$s and the kicker field ‘flat-top’ $\geq 90\ \mu$s. The current pulse is shown in figure 10.2. Any spontaneous triggering of one of the pulse generators must be detected and trigger the other generators within 700 ns at energies above 3 TeV. The kicker field has to track the energy as indicated by the Beam Energy Meter to better than $\pm 0.5\%$.

The unipolar voltage is 30 kV. The individual magnet current pulse (figure 10.2) has an amplitude of 18.5 kA with a rise time of 2.85 μs (to which 150 ns total jitter between magnets must be added), and a ‘flat top’ duration of 90 μs, followed by an approximately exponential decay of 1900 μs. This current corresponds to a magnetic field in the gap of 0.34 T, with up to 0.35 T in the steel. Table 10.4 summarises the main parameters of the MKD kicker system.

The MKD magnets have C-shaped cores made of thin gauge steel in continuous tape form, produced from a cold-rolled grain-oriented silicon-iron alloy of at least 3% Si content. The single-turn HV winding is composed of two insulated OFE copper bars of quasi-rectangular cross-section, with a minimum insulation thickness of 5 mm. The conductors are insulated with hot-pressed

Table 10.4: MKD system parameters.

Number of magnets per system	15	
System deflection angle	0.275	mrad
Kick strength per magnet	0.428	Tm
Vacuum chamber clear aperture (inner diameter)	56	mm
Operating charging voltage range	2 to 30	kV
Magnetic field overshoot at 7 TeV	$\leq$ 7.9	%
Magnetic field overshoot at 450 GeV	$\leq$ 10.0	%
Field flat top duration	$\geq$ 90	μs
Effective magnet length (magnetic)	1.421	m
Yoke length (mechanical)	1.348	m
Magnet vacuum length (mechanical)	1.583	m

1. Insulation of high voltage coil
2. Conductor of high voltage coil
3. Ceramic vacuum chamber
4. C-core
5. Mechanical frame
6. Epoxy moulding

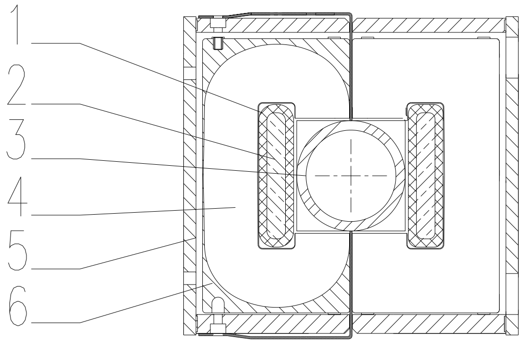

Figure 10.3: Cross-section of the MKD magnet.

mica tapes with a glass carrier and pre-impregnated with an electrically high-grade epoxy resin. Figure 10.3 shows a cross-sectional view. The service life of the magnets will be $\geq$ 20 years, and during this period the magnets will be exposed to an estimated integrated radiation dose of 10^6 Gy (10^8 rad). The magnet and its excitation coil can be opened horizontally in order to insert the metallised ceramic vacuum chamber. The vacuum system operates in the 10^{-11} mbar range.

10.3.2 Generator

The generator consist of a discharge capacitor in series with a solid-state switch operating at 30 kV . In combination with a parallel diode stack, this generator produces the current pulse shown in figure 10.2. The circuit will be completed with a flat top current droop compensation network, consisting of a low voltage, low stray inductance, high current discharge capacitor. To improve reliability, each generator has a redundant second, parallel branch. The circuitry of the dual branch generator is shown in figure 10.4. Normally, both branches will supply half of the current, but in the event of a switch failure each branch will be capable of supplying the full nominal current.

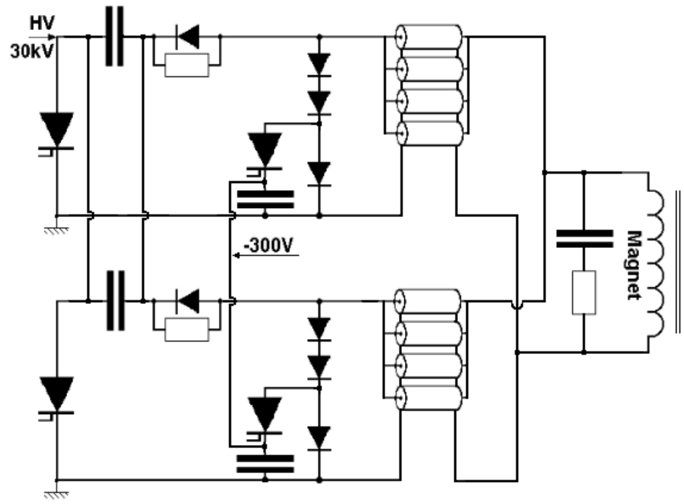

Figure 10.4: Dual branch generator circuit layout.

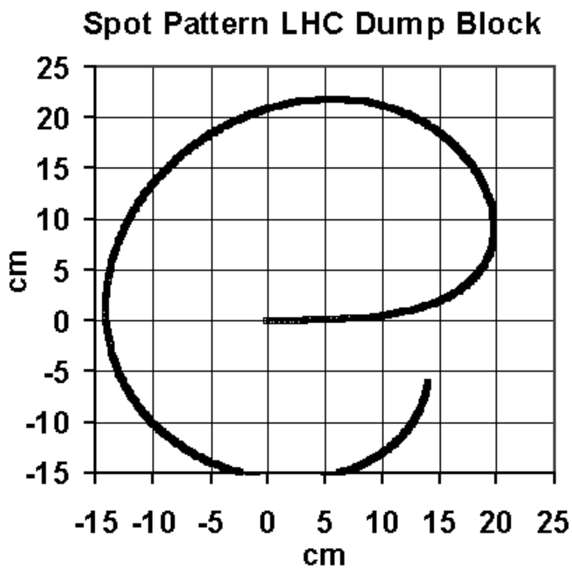

Figure 10.5: Beam spot figure on absorber block.

10.3.3 Fast-pulsed dilution magnets MKB

For each extracted beam, a set of four horizontal and six vertical fast-pulsed dilution magnets (MKB) will sweep the beam along an "*e*"-shape path on the upstream face of the absorber graphite core, with a minimum velocity of 10 mm/μs during the dumping process. The MKBH and MKBV magnets will be based on the same technology as the MKDs, using similar C-cores, although no ceramic vacuum chamber will be required for the magnet, which is installed directly in a vacuum tank. Each magnet will be sinusoidally powered by a pulse generator via a low impedance transmission line. Table 10.5 summarises the main parameters of the beam dump dilution kicker system, and figure 10.5 shows the trace of the beam spot on the dump block.

Table 10.5: MKB System parameters.

Horizontal diluter magnet system MKBH		
Number of magnets per system	4	
Max. system deflection angle	0.278	mrad
Kick strength per magnet	1.624	Tm
Magnet beam aperture — horizontal	58	mm
Magnet beam aperture — vertical	32	mm
Operating charging voltage	16.4	kV
Field rise time	18.9	μs
Field oscillating frequency	14.2	kHz
Effective length (magnetic)	1.936	m
Yoke length (mechanical)	1.899	m
Vacuum length (mechanical), 2 magnets	4.582	m
Vertical diluter magnet system MKBV		
Number of magnets per system	6	
Max. system deflection angle	0.277	mrad
Kick strength per magnet	1.077	Tm
Magnet beam aperture — horizontal	66	mm
Magnet beam aperture — vertical	36	mm
Operating charging voltage	22.3	kV
Field rise time	34	μs
Field oscillating frequency	12.7	kHz
Effective length (magnetic)	1.267	m
Yoke length (mechanical)	1.196	m
Vacuum length (mechanical), 2 magnets	4.076	m

2008 JINST 3 S08001

10.3.4 Extraction septum magnets MSD

The 30 MSD septum magnets are modified Lambertson-type septa with an all-welded construction. The yoke lamination is 1.0 ± 0.02 mm thick steel, with a 10 μm Fe_3O_4 layer as electrical insulation, a maximum permeability of 4600 ± 80, and a coercivity of 60 ± 12 A/m. There are 3 magnet types, MSDA, MSDB, and MSDC, differing in the number of coil layers and the distance of the circulating beam hole from the pole face. A transverse section of the MSD magnet is shown in figure 10.6 and the main parameters are shown in table 10.6.

10.3.5 Beam dump absorber block TDE

For each ring, the extracted and diluted beam will be directed onto an external beam dump, TDE. The TDE is designed for 2×10^4 beam aborts at 7 TeV with full beam intensity (4.69×10^{14} protons per beam) during an operational lifetime of 20 years. The TDE design has been checked by Monte Carlo energy deposition simulations, heat transfer analyses, and structural assessment at off-normal operating conditions. Carbon was chosen as the most suitable absorbing material for the

Table 10.6: The main parameters of the MSD magnets.

	MSDA	MSDB	MSDC	
Septum core length	4460	4460	4460	mm
Coil core length	4000	4000	4000	mm
Core width	447	447	447	mm
Core height	854	854	854	mm
Gap height	44	44	44	mm
Septum thickness	6	12	18	mm
Number of coil turns (total)	32	40	48	-
Number of coil layers	4	5	6	-
Number of turns per layer	8	8	8	-
Electrical coil resistance at 20 °C	27.1	33.9	40.7	mΩ
Inductance	36	56	79	mH
Dissipated power	22.7	28.3	34.0	kW
Water flow per coil	16.5	20.7	24.8	l/min
Coil water pressure drop	5	5	5	bar
Design current	880	880	880	A
Nominal magnetic field in the gap	0.80	0.99	1.17	T
Magnet weight	10500	10600	10700	kg

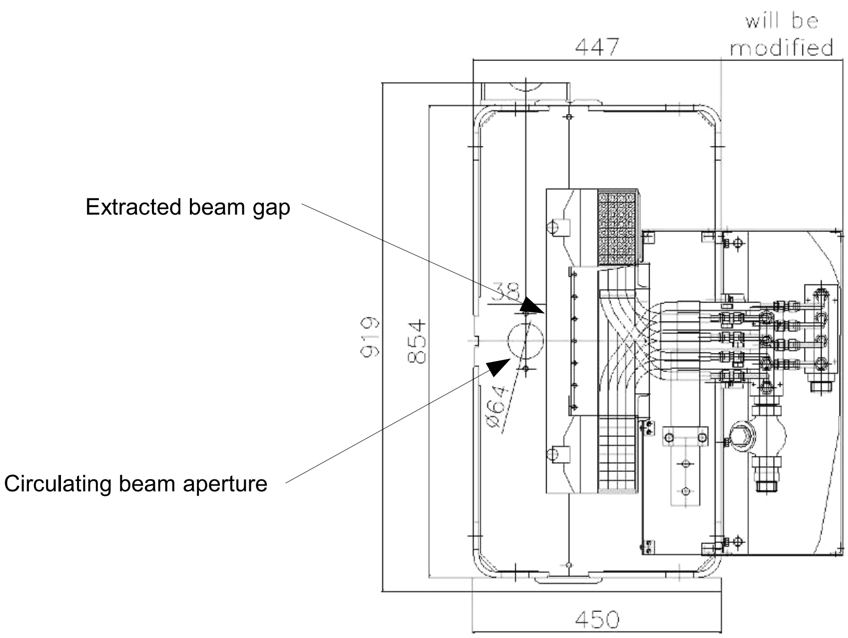

Figure 10.6: Connection end view of an MSD magnet (dimensions in mm).

dumps, with the highest melting (sublimation) temperature and the best thermal shock resistance of the investigated materials. The dump core is a segmented carbon cylinder of 700 mm diameter and 7'700 mm length, shrink-fitted in a stainless steel jacket. The jacket incorporates welded tubes for cooling water. Each dump is surrounded by $\sim$900 tons of radiation shielding blocks constructed from decommissioned ISR dipole-yokes, partially filled with concrete. Each block is 1'298$\times$1'088$\times$2'440 mm and weights 24 tons. Thirty-five blocks in total are required per dump.

10.3.6 Activation

Activation in the surrounding air, rock, and ground water, and dose-rates close to the core and in different parts of the dump, have been estimated. For general access to the dump-caverns with all the dump-shielding in position, total dose-rates from all sources will be at relatively low levels. Only 1 hour after dumping the beam, the dose-rates will be typically below 300 μSv/h. However, most of this will be due to the ^{24}Na in the concrete shielding and walls, so allowing several days for this to decay would be preferable. The dismantling of the dump to exchange the core will require strict control and remote handling.

2008 JINST 3 S08001