CHAPTER 17

BEAM DUMPING SYSTEM

17.1 SYSTEM AND MAIN PARAMETERS

17.1.1 Introduction and System Overview

IR6 of the LHC [1] is dedicated to the beam dumping system. The function of the beam dumping system will be to fast-extract the beam in a loss-free way from each ring of the collider and to transport it to an external absorber, positioned sufficiently far away to allow for appropriate beam dilution in order not to overheat the absorber material. A loss-free extraction will require a particle-free gap in the circulating beam, during which the field of the extraction kicker magnets can rise to its nominal value. Given the destructive power of the LHC beam, the dumping system must meet extremely high reliability criteria, which condition the overall and detailed design. The system is shown schematically in Fig. 17.1 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 ~750 m from the centre of the septum magnets;
- The TCDS and TCDQ diluter elements, immediately upstream of the MSD and Q4 respectively.

Nominal system parameters are given in Tab. 17.1, with details of the equipment subsystems in Section 17.3. The MKD kickers will 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.

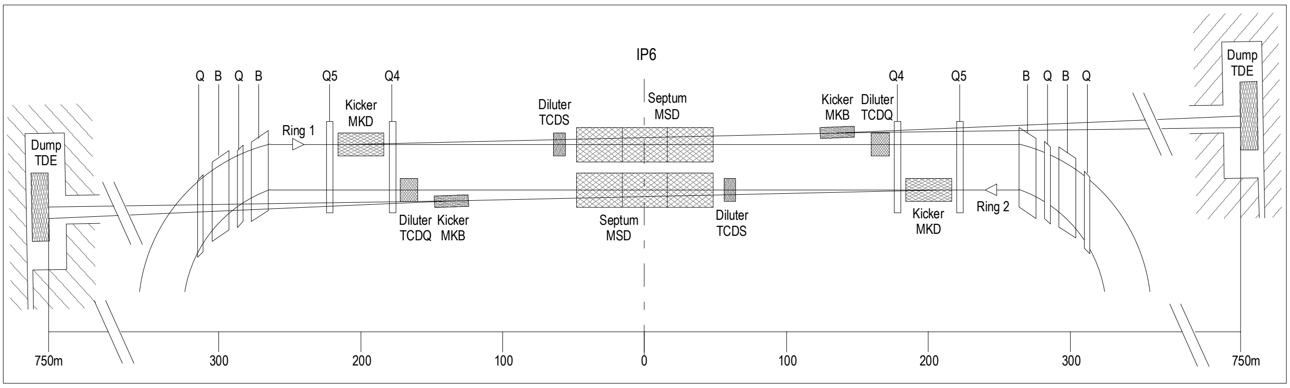

Figure 17.1: Schematic layout of beam dumping system elements around LHC point 6.

17.1.2 Assumed Worst-Case Beam Characteristics

The beam dumping system must be able to accept LHC beams with well-controlled parameters (e.g. during a planned abort at the end of a physics run) and also beams with off-normal parameters (e.g. as arising from an equipment failure or beam instability), in addition to variations imposed by optical effects (beta-beating, power supply ripple, allowed tuning range). The relevant worst-case beam characteristics that can be accommodated [2] by the dumping system are given in Tab. 17.2 for the various LHC beams considered.

Table 17.1: 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 17.2: Assumed worst-case LHC beam characteristics for dumping system design.

Beam	Max ε_n 450 GeV [μm]	Max ε_n 7 TeV [μm]	Total Orbit [mm]	Beta variation [%]	Total p+ 10^{14}
Commission	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

17.1.3 Operational Assumptions

For the purposes of estimating radiation and heat loads for the TDE, TCDS and TCDQ and also for the purposes of the reliability analysis, the assumptions shown in Tab. 17.3 were used concerning the operational parameters, dump and fault frequencies [3, 4]. Note that these are generally worst-case assumptions so as to ensure that there is an inherent safety factor in the subsequent calculations.

Table 17.3: Assumptions for activation calculations and reliability.

Number of years of LHC operation	20
Number of days 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 modules 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

17.2 RELIABILITY AND FAULT CASES

17.2.1 System Reliability

A fault with the beam dump system could lead to severe damage to the dumping system itself, to the LHC machine or to the LHC experiments, due to full or partial loss of the beam onto machine components. (The beam dumping system is not, however, formally considered as a critical element of the safety systems, since from the state of the system one cannot determine the presence or absence of beam in the LHC.)

It is assumed that a total beam dump failure (i.e. a failure to execute a correct beam dump upon receipt of a dump request) will not exceed 1 failure in 10^6 hours [5, 6], or roughly one failure in 100 years. Obtaining (and even quantifying) lower failure rates than this (already ambitious) value is very difficult and would be likely to reduce the availability of the beam dumping system. The low assumed failure rate has to be obtained by using high quality components, introducing redundancy for the most critical elements, provision of redundant signal paths, use of fault tolerant subsystems, continuous surveillance, rigorous follow-up and the imposition of a check list of validation tests before injecting beam in the LHC. It has to be noted that this failure rate needs to be obtained for the complete system, comprising the beam dumping sub-system elements together with the LHC Beam Interlock System (Sec. 15.5), the LHC Beam Energy Meter and the associated signal transmission [7].

The Beam Energy Meter will be one of the critical elements in the chain of equipment required to dump the beam [8], since underestimating the beam energy could send the full LHC beam into one of the arcs adjacent to the beam dump insertion. Severe malfunctioning of the very complex extraction kicker magnets could also result in similar disastrous scenarios and the MKD will therefore also be one of the critical reliability elements in the system.

17.2.2 System Design Regarding Reliability

MKD

First estimates from reliability calculations [5] 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: the beam can safely be extracted (albeit with the risk of beam losses on the TCDS) with only 14 out of 15 kicker magnets pulsing [9].

The following additional measures are incorporated in the MKD design specifically for reliability reasons:

- Each MKD generator will consist of two parallel discharge circuits, including two switches, with failsafe triggering [10]. In case of failure to start of one switch, the other will take the full current;
- The switches [11] will use Fast High Current Thyristor (FHCT) solid-state technology which is much more reliable than using conventional gas discharge switches;
- The energy needed for the kickers will be stored in local capacitors of which the voltage will be constantly monitored. If one voltage is outside the specified value, the beam will be dumped immediately (self triggering);
- If a switch closes when not demanded (erratic), a re-trigger system will immediately close all the other 14 switches with a maximum delay of 700 ns (for beam energies above 3 GeV/c). Note that this action will not be synchronised with the abort gap and will therefore produce losses at the LHC collimators, the TCDS and TCDQ;
- A redundant UPS system will ensure that a dump action is correctly triggered and executed in the event of a general power cut;
- All trigger and re-triggering lines will be doubled.

MKB

The diluter kickers MKB will not be critical items from a reliability viewpoint because of the redundancy present [31] and because extraction of the beam from the LHC machine will not rely on their correct operation. Triggering lines will, however, be doubled, since a total dilution failure could lead to damage of TDE core.

MSD

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

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, since a loss of TD vacuum or loss of TDE pressure can be detected well in time; in any case the beam can still be dumped under degraded vacuum conditions of these components without risk to the LHC machine proper. The risk of a damaging loss of containment of the TDE will be dealt with by over-pressuring the core with inert gas.

Post-mortem

High reliability will be maintained by performing and analysing a post-mortem of every beam dump. A dump action without beam will take place if the last post-mortem was too long ago, e.g. after a technical stop. 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 was satisfactory.

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.

Energy Tracking

The beam energy tracking system will bind the deflection strength of the MKB and MKD kicker magnets and the MSD septum magnets to the measured beam energy in order to get the correct extraction trajectory (the tolerances on the kick angles for the MKD and MSD elements are below one percent). The beam energy tracking system will have two main tasks:

- The generation of the strength reference signals for the power-supplies of the kickers and MSD;
- The verification of the output voltages of the kicker power-supplies and the MSD current.

The measured levels must follow the required levels for the inferred beam energy, within a predetermined tolerance window; otherwise a synchronous beam dump request is issued. 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 IR6. The BEM will convert a physical measurement, current or voltage, into a value proportional to the beam energy and will therefore not be a real beam energy measurement.

A BEM Transmitter (BEM_T_x) will be installed in the standard AB/PO main bend power converter function generator controller, in the MSD power converter and in the MKD high voltage generators for monitoring of the equipment settings. The BEM_T_x will send out the measured DCCT value for magnet power converters or the capacitor charging voltage for the kicker as well as 1 mV and 10 V constant reference voltages at 1 kHz. The current measurement signal will be provided by a ±0.1% accuracy DCCT and the capacitor charging voltage by a ±0.1% accuracy high voltage divider. Each data frame sent out by the BEM_T_x will contain the 16 bit measurement signal, the two calibration signals and system status information.

The data frame will be received by the BEM Receiver (BEM_R_x) that will convert the measurement signal to an absolute energy value reconstructed from an internal look-up Table. Different tables will exist for the different types of power converter (main bends, septa or kicker). The frame will then be re-emitted by the BEM_R_x with the two calibration signals, some status bits and the absolute beam energy with an accuracy of 0.2%.

Finally, signals emitted by the different BEM_R_x modules will be received by the Beam Energy Tracking (BET) module and the absolute energy value measured for each equipment will be compared. If one signal falls outside a predefined tolerance window, a dump request will be sent to the Beam Interlock System.

It should also be noted that the MKD power trigger primary voltage will also be connected to the BEM system in order to compensate dynamically the FHCT switch turn-on delay described in 17.3.1.

The RF central frequency and integrated orbit corrector fields will affect the beam energy and possibly need to be taken into account, either via the BEM or via interlocking.

Other Protection

Local damage to components in case of certain fault scenarios will be avoided or reduced by the absorbers TCDS [12] and TCDQ [13]. 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 tolerable limits to permit a successful abort. Sacrificial absorbers in the TD lines are also possible if the reliability analysis shows a necessity.

17.2.3 Acceptable (Design) Fault Cases

Despite the precautions listed above, certain faults of the dumping system are nonetheless expected to occur and are therefore foreseen in the design of the system and in the load cases for other systems, in particular the LHC collimators. They may result in a loss of efficiency for operation but should not result in equipment damage. These faults are termed acceptable faults and are as follows:

- One missing extraction kicker (MKD). A correct beam dump can be performed with 14 out of the 15 kicker magnets functioning correctly. If this fault occurs simultaneously with other acceptable faults (such as an orbit error of several mm) this can affect the machine operation by producing a quench in the downstream superconducting elements;
- Asynchronous dump. This could be caused by a spontaneous trigger of one of the MKD kickers followed by a re-triggering of the other magnets, or by a fault in the synchronisation with the abort gap [14]. In both cases the majority of the beam swept over the machine aperture will be intercepted by the TCDS and TCDQ absorbers and should not cause any damage, although several superconducting elements in IR6 will probably quench [13];
- Missing diluter kickers. Only one MKB magnet of each type will need to be operational to prevent damage to the beam dump block for nominal beam intensity. In the case of missing MKB magnets a longer cool-down period of the TDE needs to be envisaged before beam can be re-injected. This effect will be exacerbated by the staging of the TDE cooling;
- Self triggering of the system. If the beam dumping system detects an internal fault, like a tracking error of one of the voltages or a fault on one of the generators, the system will be triggered to cause a synchronous beam dump.

17.2.4 Unacceptable (Beyond Design) Fault Cases

The following system faults are unacceptable and could possibly lead to damage to the LHC since they are not foreseen in the design:

- The MKD kickers do not fire when a dump request is made by another system (e.g. the beam loss system). This potentially catastrophic failure could be caused by an undetected fault of the Beam Interlock System or by problems in signal transmission / reception;
- Receiving the wrong energy information, caused by an error in the beam energy system. It is expected that an energy error of more than a few percent for the complete system or for one of the subsystems can lead to severe equipment damage (a detailed analysis of the tolerances and consequences on energy errors remains to be performed). Wrong energy information in one of the sub-systems could be caused by problems in the look-up tables that relate energy to specific equipment settings;
- 13 or fewer out of 15 MKD extraction kicker magnets pulsing correctly. This may result in equipment damage, the extent of which would depend on the number of missing kicker magnets;
- Q4 field out of tolerance. The defocusing Q4 magnet is downstream of the extraction kickers and contributes about 20% of the total deflection angle. If Q4 is out of tolerance by more than about 1%, it is possible that the beam will not be properly extracted from the machine (losses or damage);
- MSD septum magnet field out of tolerance. If the septum field is more than about 0.5 % out of tolerance, losses or damage to the septum magnets, the MKB dilution kickers and the TD vacuum system could result. In addition the containment of the TDE could be threatened;
- If none of the MKB magnets pulse the dump block could be damaged, depending on the beam intensity.

17.2.5 Expected Fault Frequencies

The reliability of the complete beam dumping system remains to be calculated. Initial estimates have been made regarding the MKD generator, which is one of the most critical items. According to [6] an obtainable failure rate of 10^{-4}/h/kicker branch per year results in system failure rate (i.e. fewer than 14/15 generators working) of 1.1×10^{-11} /h. This assumes a fill duration of 10 hours and an ‘as good as new’ status after maintenance tests, to be made before each beam dump. This is better than the required Safety and Integrity Level (SIL) 4 [15] and much better than the assumed 10^{-6} hours mentioned in Section 17.2.1. Without a redundant MKD system, the failure rate calculated for 14/14 generators is only 1.4×10^{-6} /h, which conforms only to SIL 1 and is therefore inadequate. Full calculations will be made for the complete system, including the beam energy meter, Beam Interlock System and signal transmission systems.

17.2.6 Reliability Run

After the hardware commissioning of the beam dumping system a 'reliability run' without beam of about three months is planned. This test period should eliminate any teething problems of the system, show up unforeseen faults scenarios and confirm the calculated reliability figures.

17.3 EQUIPMENT SUBSYSTEMS

17.3.1 Fast-Pulsed Extraction Magnets MKD

Two sets of 15 fast-pulsed extraction magnets MKD will form part of the beam dumping system. A pulse generator will power each magnet via a low impedance transmission line. There are several basic design requirements for the MKD system:

- At least 14 out of the 15 kicker magnets must operate simultaneously on request;
- The kicker system field rise time must be at most 3.0 µs and the kicker field 'flat-top' must be at least 90 µs. The current pulse is shown in Fig. 17.2;
- Any spontaneous triggering of one of the pulse generator-magnet systems must be detected and trigger the other generators within 700 ns at energies above 3 TeV;
- The kicker field must track the energy as provided by the Beam Energy Meter to better than ±0.5 %.

The unipolar system voltage will be 30 kV. The individual magnet current pulse (Fig. 17.2) will have 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. Tab. 17.4 summarises the main parameters of the MKD kicker system.

Table 17.4: 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
Magnet field overshoot at 7 TeV	≤7.9	%
Magnet field overshoot at 450 GeV	≤10.0	%
Field flat top duration	≥ 90	µs
Effective magnet length (magnetic)	1.421	m
Yoke length (mechanical)	1.348	m
Magnet vacuum length (mechanical)	1.583	m

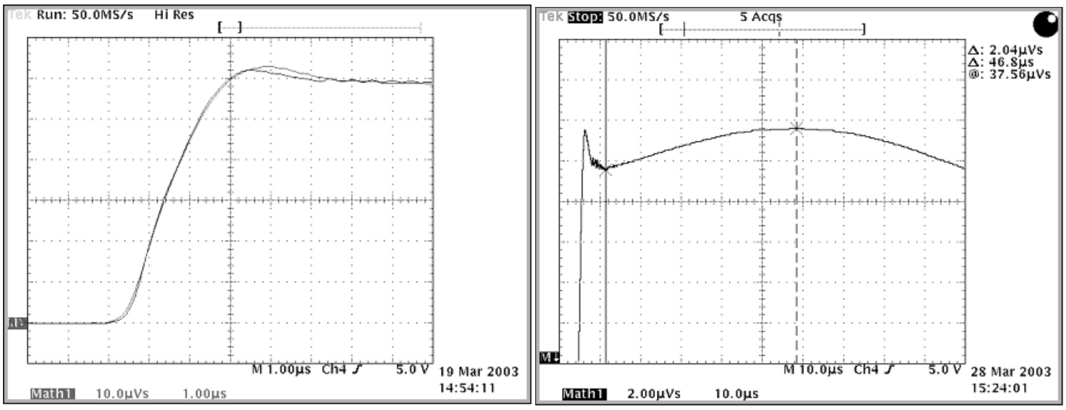

Figure 17.2: Start of MKD magnet current pulse at 450 GeV and 7 TeV with overshoots of 7.5% and 5.2% respectively (left); MKD magnet current pulse over 100 µs at 7 TeV with flat top overshoot of 5.6% (right).

The MKD magnets will consist of a steel yoke with a one-turn HV winding. A mechanical frame will surround the yoke for support and location of the individual components. A metallised ceramic chamber will be placed in the centre of the magnet. The cross-section of the MKD magnet is shown in Fig. 17.3. The service life of the magnets will be at least 20 years and during this period the magnets will be exposed to an estimated integrated radiation dose of 10^6 Gy (10^8 rad), which conditions the choice of materials. The magnet and its excitation coil can be opened horizontally in order to insert a ceramic vacuum chamber, with its two large vacuum flanges at both ends.

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

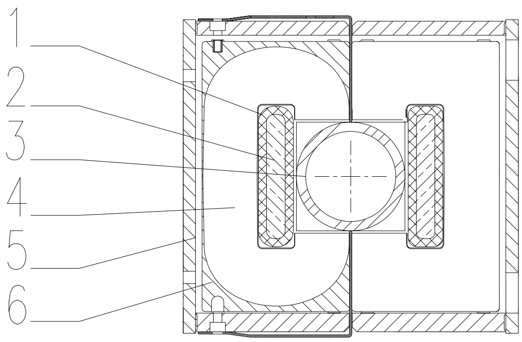

Figure 17.3: Cross-section of the MKD magnet

Y*oke*

The yoke will be composed of tape-wound C-shaped cores of thin gauge steel in continuous tape form, produced from a cold-rolled grain oriented silicon-iron alloy of at least 3% Si content. Once wound, heat-treated and vacuum impregnated, one leg of the core will be cut to create a gap. Short circuits between adjacent layers are then removed. Two C-cores with insulating sheets will be vacuum moulded in charged epoxy resin to provide mechanical stability and to allow mounting. During the assembly of a magnet, these individual assemblies will be stacked longitudinally.

Conductor

The one-turn coil will be composed of two insulated conductor bars of quasi-rectangular cross-section, with a minimum insulation thickness of 5 mm. The conductors will be made of high conductive electrolytic copper OFE, with hot-pressed mica tapes with a glass carrier and pre-impregnated with an electrically high-grade epoxy resin as insulation. This tape has excellent high voltage properties and adequate radiation resistance. The extremities of the conductors will be epoxy vacuum moulded using a dolomite charged epoxy compound. The surface of the insulation will be coated with a semi-conductive layer and connected to earth.

Vacuum Chamber

The magnets will be equipped with ceramic vacuum chambers, forming part of the vacuum system which will operate in the 10^{-11} mbar range. The ceramic chamber will be composed of a monolithic, isostatically pressed cylindrical Al_2O_3 tube. Fe-Ni-Co alloy sleeves with ceramic back-up rings will be brazed onto both ends of the ceramic tube and stainless steel Ultra High Vacuum (UHV) flanges welded to these sleeves. The total length of the brazed assembly will be 1583 mm. In order to maintain the impedance of the kicker magnets as low as possible [38, 39], the ceramic chamber will be coated on the inner surface of the tube with a thin sputtered titanium layer [41].

The 15 magnets will be divided into 3 vacuum sectors of 5 ceramic chambers each. This sectorisation, which requires 2 additional valves per MKD zone, will limit the extent of failures of the very fragile ceramic vacuum chambers in case of problems during the 24 hour bake-out at 150°C. During bake out the magnets will have to be opened to allow access to the ceramic chamber and installation of the heating jackets. The temperature rise and decrease will be limited to 20°C/h to avoid damaging the chambers.

The circulating beam will pass through a standard copper chamber (ID 80 mm, 2 mm thickness) coated with Non-Evaporable Getter (NEG) and baked up to 250°C. Two 60 l/s ion pumps per vacuum sector mounted on standard pumping ports will ensure the required pressure.

Generator

The generator will consist of a discharge capacitor in series with a solid-state switch operating at 30 kV [16]. In combination with a parallel diode stack, this generator produces the current pulse shown in Fig. 17.2. 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.

For reliability reasons each generator will have a redundant second, parallel branch. The circuitry of the dual branch generator is shown in Fig. 17.4.

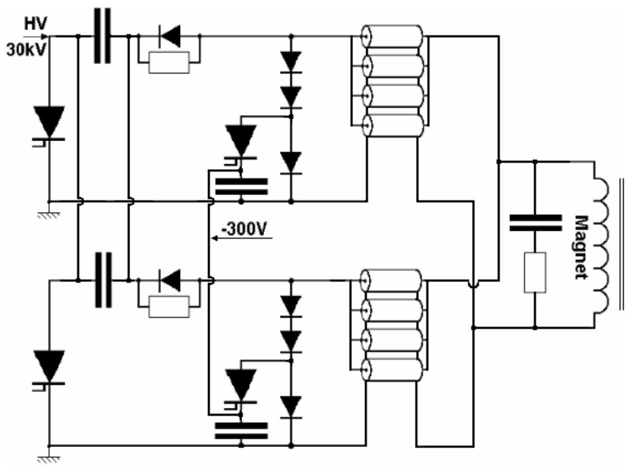

Figure 17.4: Dual branch generator circuit layout.

When both branches operate, each branch will supply only half the current, although in the event of a switch failure each branch will be capable of supplying the nominal current. Before each physics run both branches will be tested. If they are found to be working correctly, the probability that a magnet fails to pulse at the end of the physics run will thus be low enough to meet the reliability requirements.

The system is designed such that the expected failure behaviour of components should not cause a spontaneous trigger. Any spontaneous trigger will be detected using several detectors built into the generator on crucial points and a re-trigger will be immediately forwarded to the other 14 kicker magnet systems.

Due to the low level of the current in the dual main switch branches at 450 GeV (614 A) the anode delay of each switch will be almost 300 ns shorter than at 7 TeV. By decreasing the gate trigger voltage of the switch at 450 GeV, the turn-on speed will be reduced and synchronised with the turn-on at 7 TeV as shown in Fig. 17.2. This means that the voltage of the trigger unit has to be variable and will be a function of the beam energy.

After the magnet current has reached its full amplitude the polarity of the generator will inverse and the freewheel diode stacks, each consisting of two 13.5 kV multi-chip avalanche diodes and one very fast recovery 4.5 kV diode, will start to conduct the magnet current. Simultaneously the 2.5 kV FHCT switch, connected in series with a 3.25 mF, -300 V pre-charged low inductance (<200 nH) self-healing capacitor, will be closed and the current in the fast recovery diode commutated. The capacitor will then be connected in series with the magnet inductance and the current will oscillate with a superimposed half-sine wave. The initial capacitor voltage is determined so that it will compensate the resistive losses of the magnet current freewheel circuit.

The total stray inductance of each freewheel branch has to be kept very low (about 75 nH). This will limit the initial magnet current overshoot to 5.2% at beam energy of 7 TeV, which means a total system overshoot of about 7.5%, when all uncertainties such as charging voltage stability, temperature effects, interpolation errors, differences between generators etc. are included. At 450 GeV the dynamic current conduction and the sum of the threshold voltages of the freewheel diode branch will have a greater influence on the initial magnet current overshoot, which will increase to 7% (corresponding to a system total of 10%). There are two compensation circuits to minimise the magnetic field overshoot.

The generators will be air-insulated and only the capacitors will be impregnated with liquid dielectric. Therefore no significant amount of dielectric fluid will be present in the underground generator areas.

Transmission Lines

In order to respect the 2.85 μs rise time required for each individual magnet, the total inductance of the transmission line between magnet and generator should not exceed 250 nH. This will be achieved by connecting 19 m long, 18 Ω coaxial cables with an inductance of 104 nH/m, in parallel. In order not to influence the droop by more then 30%, the cable resistance will be kept to 3 mΩ. The inner conductor will be a Cu-tube with an outer diameter of 15 mm and a wall thickness of 1.5 mm. The dielectric will be low-density polyethylene of high purity with semi-conducting layers. A number of constraints are imposed on the design of the outer conductor, like low voltage drop between magnet and generator (<100 V), limited free-wheel droop of the current pulse and maximum temperature rise of the cable to about 30 K at a repetition period of 20 s. The outer conductor will comprise 74 spiral-wound Cu-wires of 1 mm diameter. To keep the circular wires in place and to improve the fire barrier, two layers of 40 μm wrapped Cu-foil will be applied over the spiral wires. The cable will be flame retardant and free from halogens and sulphur according to CERN Safety Instruction IS23. It can be exposed to an integrated radiation dose of at least 10^6 Gy without loss of performance. Simplified high voltage connectors that do not require moulding will terminate the cable ends.

Regular Maintenance

Regular maintenance will be concentrated on the generator side, mainly consisting of dust removal and contact cleaning. Regular control of the shape of the pulse will also be required.

17.3.2 Fast-Pulsed Dilution Magnets MKB

For each extracted beam, a set of four horizontal and six vertical dilution fast-pulsed magnets MKB will be used to 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. Each magnet will be sinusoidally powered by a pulse generator via a low impedance transmission line. Tab. 17.5 summarises the main parameters of the beam dump dilution kicker system.

The MKBH and MKBV magnets will be based on the same technology, using similar C-cores to the MKD, although no ceramic vacuum chamber will be required for the magnet which is installed directly in a vacuum tank.

Initially only 2 of each type of magnet will be constructed and installed on each extracted beam. The construction of the remaining staged equipment will take at least two years, installation not included and will be started at a later date.

Table 17.5: 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

The main elements of the horizontal MKBH circuit will be pre-charged oscillating capacitors coaxially connected to the magnets. The capacitors will be discharged through solid-state closing switches to produce an attenuated sinusoid. The vertical MKBV circuit will be more complex because it will require a current phase shift of 90° with respect to the horizontal system for a simultaneous trigger of the two systems.

Fig. 17.5 shows the attenuated discharge currents of both systems. The duration of the resulting "*e*"-shape beam spot, Fig. 17.6, corresponds to one revolution of the beam in the LHC.

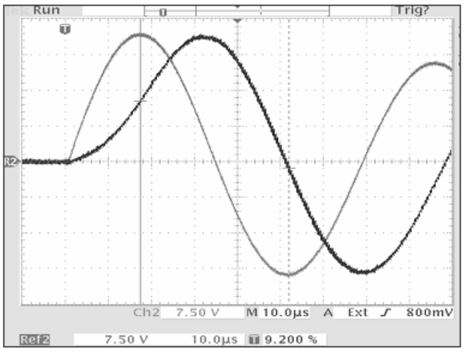

Figure 17.5: Discharge currents of horizontal and vertical (bold) generators (7.5 kA per vertical division).

Generator

The generators [17] will consist of a discharge capacitor in series with a solid state closing switch and completed by auxiliary circuits as shown in Fig. 17.7.

The MKBH system will comprise a pre-charged oscillating capacitor, CH, coaxially connected to the magnet inductance, LMH. The capacitor, CH, will be discharged through a solid state closing switch, SH. The discharge pulse will be an attenuated sinusoidal oscillation of 25 kA maximum amplitude with a period of 70 μs. The required damping coefficient of the magnet current is adjusted with the resistor RH.

The oscillation in the MKBV vertical magnet system is started by resonantly charging capacitor, CV2, from capacitor, CV1, via the fast solid-state closing switch, SV, diode, DV and charging inductance, LV. The resonant charging time is 26 μs. The circuit LMV-CV2 can then swing freely with attenuated oscillations.

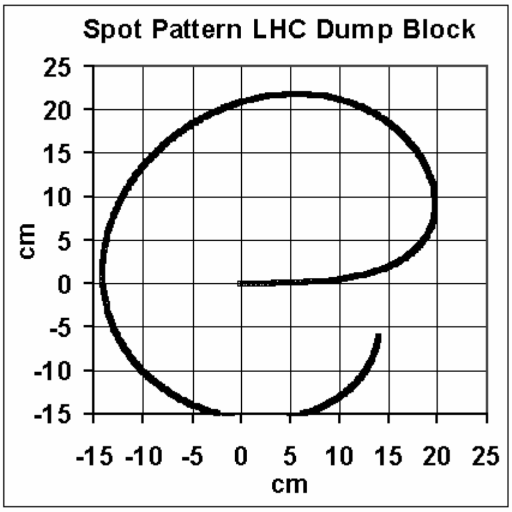

Figure 17.6: Beam spot figure on absorber block.

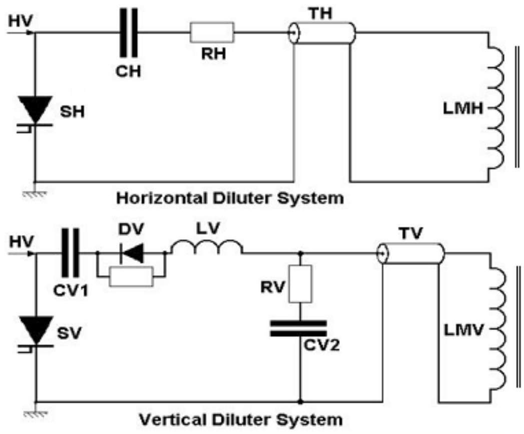

Figure 17.7: Basic circuit diagram for MKBH and MKBV systems.

The damping coefficient of the magnet current will be adjusted with the resistor, RV. The main advantage of the circuit of the MKBV system is the absence of a switch in the oscillation between CV2 and LMV. A current amplitude of 25 kA and a maximum hold off DC voltage of 27 kV will be required. The fast 30 kV solid-state switches, developed for the LHC beam extraction generator, will be used.

All switches and damping diodes will be mounted with grounded cathodes. This will permit the remote checking of the state of each complete stack of FHCTs and diodes by comparing the voltage over the first device at earth potential with the voltage of a separate divider over the complete stack.

Transmission Lines

The low inductive cable link between generators and magnets will use a specially developed coaxial cable. The construction mixes the inner conductor of an RG-220/U cable and the outer conductor of an RG-218/U with two braids of bare copper wires without joints. Each braid will have an optical coverage of 90 %. Two layers of PETP foil are wrapped between the braids. The dielectric is low-density polyethylene of high purity with semi-conducting layers. The cable is flame retardant and free from halogens and sulphur according to CERN Safety Instruction IS23 and must retain its performance after exposure to an integrated radiation dose of 10^6 Gy. Simplified high voltage connectors that do not require moulding will terminate the cable ends.

Regular Maintenance

Regular maintenance will be concentrated on the generator side, mainly consisting of dust removing and contact cleaning. Regular control of the shape of the pulse will also be required.

Vacuum System

The pumping of each tank will be ensured by two 400 l/s ion pumps. Two magnets will be installed per vacuum tank, with no bake out foreseen. The magnets, containing a non negligible amount of organic material, will outgas strongly and the large installed pumping speed (600 l/s effective) will allow operation in the 10^{-5} mbar range, to maximise the lifetime of the ion pumps in this potentially radioactive region.

Differential pumping will be installed between the extraction septa (MSD) and the diluters (MKB) to reduce the gas load onto the NEG coated chambers.

The two circulating beams will pass just below the MKB tanks and a permanent bake out will be installed to reduce personnel radiation exposure in case of intervention. The chambers will be standard copper chambers (ID 80 mm, 2 mm thickness) coated with NEG and baked up to 250°C. The chambers will be supported directly on the ground, independently from the MKB tanks.

17.3.3 Extraction Septum Magnets MSD

The 30 MSD septum magnets [18] will be laminated iron-dominated magnets built using an all welded construction. There will be 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. Transverse and longitudinal sections of the MSD magnet are shown below in Figs. 17.8 and 17.9. The installation of the magnet in the LHC tunnel will be complicated because the magnets will be placed back-to-back (Fig. 17.10). Moreover, access to the magnets for maintenance in the non-tunnel passage side will be limited by the cryogenic feed line (QRL), which will be near the connection box of the magnet. A modification to the connection box shown in Fig. 17.8 will be necessary to avoid an interference with the QRL in this region. The supply of the septum magnets is part of the CERN collaboration with IHEP (Protvino) in Russia. The main parameters of the magnets are shown in Tab. 17.6.

Table 17.6: 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

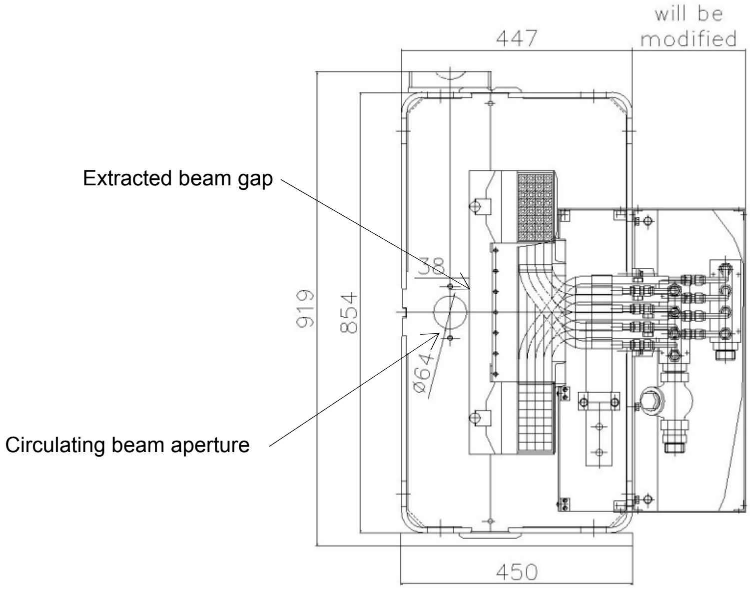

Figure 17.8: Connection end view of an MSIA magnet

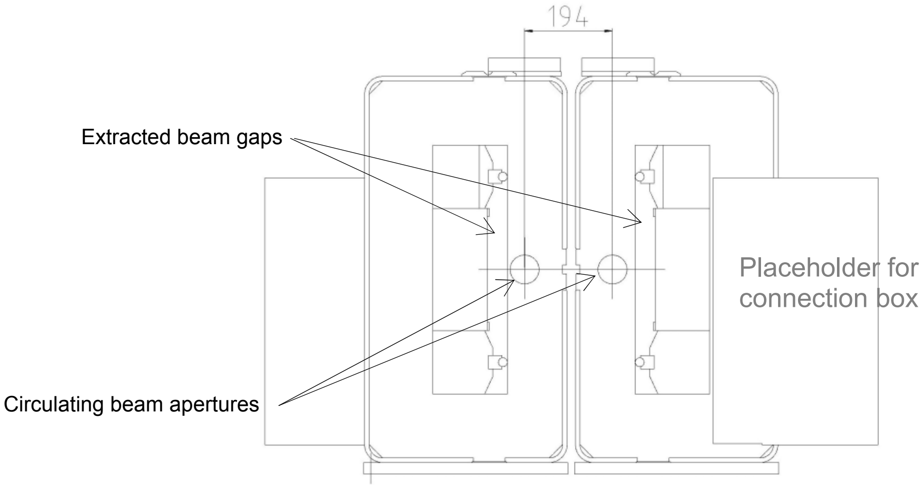

Figure 17.9: MSD in installed positions for Beam 1 and Beam 2.

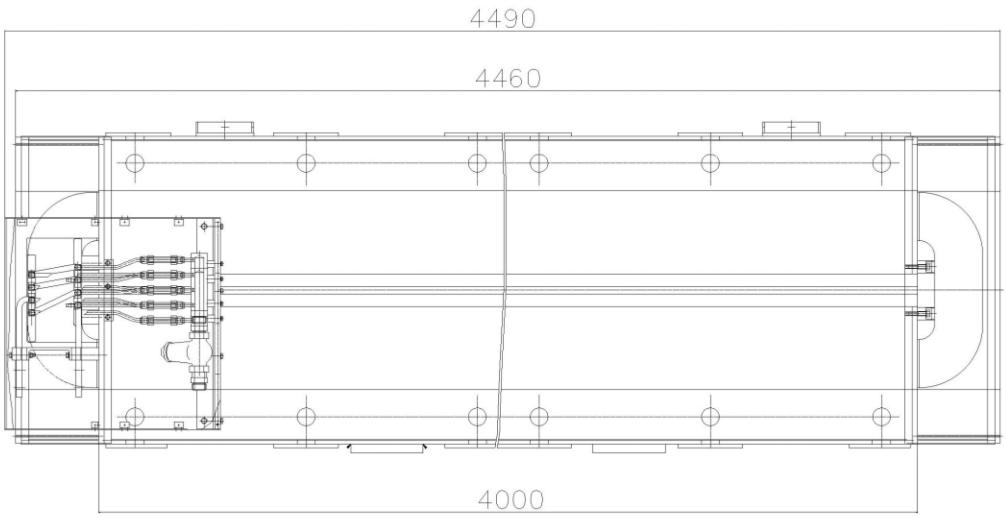

Figure 17.10: Side view of an MSDA magnet

Laminations

The laminations will be made of 1.0 ±0.02 mm steel, with a 10 μm thick Fe_3O_4 layer as electrical insulation, a maximum permeability of 4600±80 and a coercivity of 60±12 A/m. The circulating beam holes will be punched into the individual laminations, to avoid the careful alignment needed for wedge-shaped septum blades as used in classical Lambertson magnets.

Yoke

The yoke will be an all-welded construction made from two half-cores, the coil- and septum cores. The coil-core will contain the single pancake coil; the septum-core will contain the circular hole for the circulating beams. The septum core will be longer than the coil core in order to minimise the stray field extending from the field gap to the circulating beam holes. A μ-metal layer on the vacuum chamber will shield the beam from the residual field in the circulating beam hole [19], such that the residual field level will be lower than 0.5 Gauss.

Coil

The racetrack coils will be made from rectangular OFHC square copper conductor of 15×15 mm section, with a circular cooling hole 7.0 mm in diameter for the MSD. Each layer corresponds to one cooling circuit with a pressure drop of 5 bar and a temperature increase of 20°C. A 0.5 mm thick glass fibre tape, treated with amino silane, will be used as inter-turn and ground insulation. The vacuum impregnation of the coil will be made using radiation-hard epoxy resin. A thermo-switch will be placed to protect against cooling faults on each coil water outlet.

Vacuum and Alignment Issues

The vacuum system for the MSD magnets [20], similar to the one of the injection septa (MSI) described in 16.2.4, will have to fulfil several stringent requirements. With the septum beam hole diameter of 64 mm, the mechanical vacuum system tolerances including their alignment and the alignment of the magnet in general must be such as not to reduce significantly the available aperture. The circulating beams must be shielded against the stray field leaking from the core into the septum holes, which has a measured dipole component on the order of 10 Gauss [21]. The vacuum chambers for the circulating beams should be bakeable in situ (after installation) to 250°C without heating the magnet yokes to more than 120°C.

To fulfil these requirements, a vacuum chamber in 0.9 mm thick μ-metal will be used with a 0.5 mm copper coating [22,23] for impedance reasons. The compilation of all the constraints (magnet and chamber alignment tolerances, angle of tilt of the magnets, aperture requirements) gives an inner diameter (beam stay-clear) of 52.4 mm with a total wall thickness of 1.4 mm. The stray field in the shielded vacuum chamber will be of the order of 0.1 Gauss [24].

The μ-metal vacuum chambers equipped with the heating and insulating elements will be fitted at both ends with DN200CF flanges, welded after insertion in the magnet. The chambers will be centred using stainless steel rings. To reduce the outgassing rates of the vacuum chambers, a bake out at 250°C for at least 24 hours will be made [25]. This will use special heaters developed at CERN [26], which comprise a resistive stainless steel heating strip in the centre surrounded by two insulating polyimide films, wrapped around the tube with a total thickness of 0.3 mm. A reflective aluminised polyimide film will be wrapped on top of the bake out sandwich and special thermal insulation precautions are foreseen to reduce the heat load on the magnet yoke.

The copper coating of the inner surface of the μ-metal vacuum chamber will be made using the electrochemical deposition process. Due to the ~5 m length of the tubes, the deposition will be made using a fluid circulation electrolytic technique [22]. Finally, the circulating chambers will be NEG coated to improve the pressure and to avoid the electron cloud build up.

The extraction beam line chambers will be made from stainless steel with an inner diameter of 41 mm and a wall thickness of 1 mm. Alignment in the gap will be achieved by special form pieces along the gap and welded strips at the ends. The injection chambers will be baked at 85°C using the special sandwich heaters described above to minimise the outgassing flux onto the circulating chambers coated with NEG.

All the 450 mm inter-magnet gaps will be fitted with special modular pumping ports. These will be specific to each gap with a length of 300 mm, equipped with a 60 l/s ion pump to provide the required differential pumping between the chambers for the circulating beams in the order of 10^{-11} mbar and the chambers for the extracted beam ~10^{-8} mbar, while permitting a reasonably fast exchange of a magnet in case of failure

17.3.4 TCDS Diluter

A fixed diluter block TCDS will be installed immediately upstream of the MSD septum magnets in order to protect them from destruction in the event of an asynchronous firing of the MKD kickers [12, 14]. The TCDS must intercept about 40 LHC bunches (1.7% of the beam) containing about 6.1 MJ of energy and must provide enough dilution such that the temperature in the MSD vacuum chambers does not exceed 300°C and so that the temperature in the MSD yoke does not exceed 100°C.

Several scenarios have been studied [26] for the configuration of the TCDS and a 6m long wedge shaped model has been chosen to optimise the aperture for the extracted beam and to provide adequate protection for the MSD magnets, with a sandwich construction of 1m Graphite (1.77 g/cm^3), 2m C-C composite (1.4 g/cm^3), 1.5m Graphite (1.77 g/cm^3), 1m Aluminium nitride (3.31 g/cm^3) and 0.5m Titanium (4.5 g/cm^3).

A parallel row of diluter blocks, the outer jaw, giving a clear aperture of 30mm, are also envisaged to protect the MSD magnets from bunches with large excursions to the outside. Figure 1. 17.11 shows a schematic of the layout and function of the TCDS absorber system.

The RF heating due to circulating beam will result in a power deposition estimated at about 40W/m. A 1 kW water cooling system is designed to absorb this power. Temperature sensors, flow-meters and temperature gauges for the cooling system will be required.

The diluter and surroundings will be subject to irradiation by protons or heavy ions. The estimated contact radiation dose levels after an asynchronous dump and a cooling period of 1 day reach 3mSv/h. After a cooling period of 30 days these radiation dose levels are estimated to go down to a level of 0.035mSv/h [12].

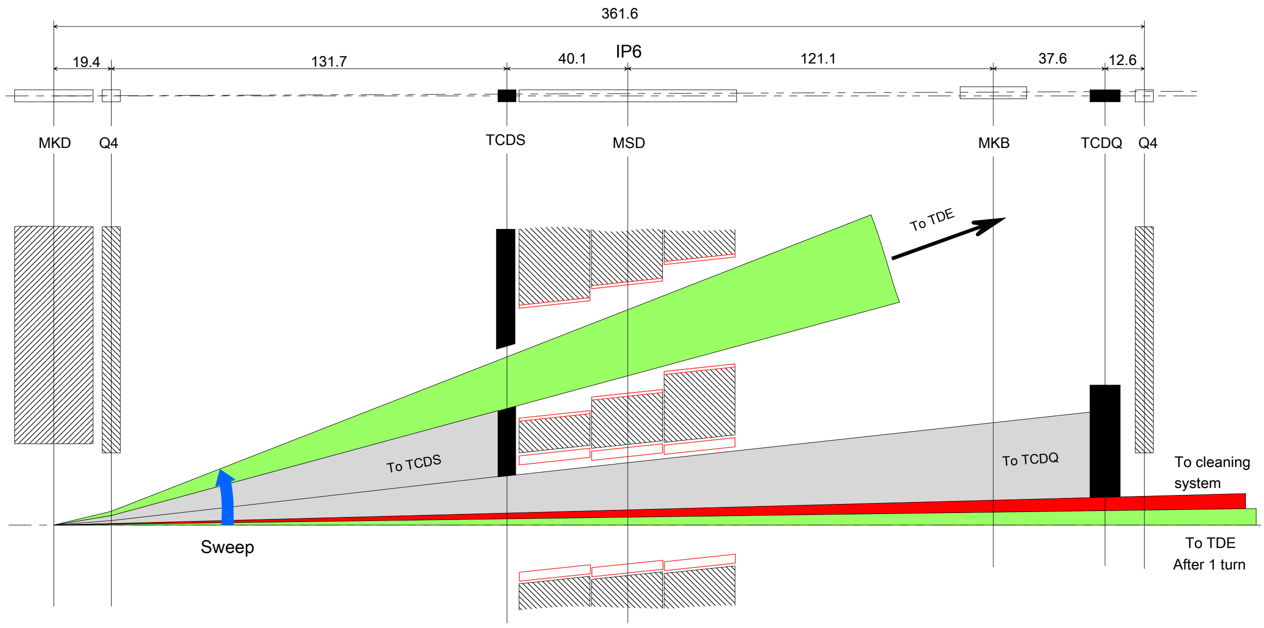

Figure 17.11: Schematic and functional layout of TCDS and TCDQ diluter systems.

Vacuum

The beam gas scattering and the operating pressure in the TCDS must be kept small for beam lifetime issues and also to avoid the saturation of the adjacent NEG coated chambers. Two 400 l/s ion pumps and two 1000 l/s Ti sublimation pumps will provide an effective pumping speed of 1600 l/s. The expected residual pressure inside the beam screen will be 10^{-8} mbar during normal operation after a 24 hour in situ bake out at 250°.

Prior to mounting, the graphite and Carbon-Carbon materials must undergo a heat treatment at 1000°C under vacuum. After installation and any intervention, the tanks will be baked out at 250°C using heating jackets. The vacuum system has been design to cope with the outgassing during normal operation, i.e. with the jaws between 20 and 35°C. For a temperature increase of 50°C the thermal outgassing increases by a factor of 10 to a point where the gas density levels will be too high for the required beam lifetime.

17.3.5 TCDQ Diluter

In the event of a beam dump that is not synchronised with the abort gap, or after an asynchronous firing of MKD kickers, a part of the beam will not be absorbed by the TCDS and could impact on the Q4 coils [13]. In order to protect these magnets against damage a mobile diluter block TCDQ will be installed immediately upstream of Q4. The TCDQ will also protect the downstream arc at 450 GeV and low β insertion triplets at 7 TeV and will reduce the number of bunches impacting on the LHC collimators [12].

The preliminary TCDQ design is based on nuclear simulations, with 8m of graphite (1.77g/cm^3) followed by 1.5m Aluminium (2.6g/cm^3). The required jaw width was found to be 40 mm. A single jaw configuration will fulfil the protection objectives although for machine protection issues and orbit control, an additional short two-sided collimator may be considered.

The TCDQ will be mobile, to guarantee the nominal setting of 10±0.5σ at injection (450GeV) as well as collision (7TeV). The TCDQ will be at a phase advance of 87° from the MKD kicker magnets. Precise control of the orbit at the TCDQ will be very important to ensure correct protection of the downstream machine elements. A movement of about 30 mm will be required, with a resolution of below 100 µm.

The vacuum considerations are identical to those described above for the TCDS.

17.3.6 Beam Dump Absorber Block TDE

For each ring, the LHC beam dumping system will direct the extracted and diluted beams onto an external beam dump TDE [28]. Approximately 2×10^4 beam aborts at 7TeV and full beam intensity are assumed during an operational lifetime of 20 years. As the TDEs will be permanent fixtures of the accelerator, the LHC ultimate beam intensity (4.69×10^{14} protons per beam) was considered as the reference load case in the design study. Under this ultimate load, about 80% of the corresponding total beam energy (i.e. 428 MJ out of 534 MJ) must be safely absorbed into the dump core. For safety reasons the core must be solid and it must keep its structural integrity under normal operating conditions over the dump lifetime.

TDE Core Design

The TDE design [40] has been substantiated by Monte Carlo energy deposition simulations [29], heat transfer analyses [30] and the structural assessment of the off-normal operating conditions [31]. Carbon was chosen as the most suitable absorbing material for the LHC main beam dump, with highest melting (sublimation) temperature and best thermal shock resistance of the investigated materials.

Localised fracture in the graphite core will not be a concern for the absorber block, as the dump will not lose its absorbing function: fractured graphite will continue to intercept the incident particles exactly as solid graphite does. Optimisation of the design, however, has led to adopting the very conservative constraint of avoiding not only any thermal, but also any mechanical degradation.

Based on numerical analyses, the ambitious goal of preventing fracture within the carbon core can been achieved by carefully selecting the grades of carbon material. The absorber block will be made of consecutive Polycrystalline Graphite (PG) cylinders with 1.73 g/cm^3 density and Flexible Graphite (FG) plates with 1.1 g/cm^3 density. A 0.7 m long section of PG will be followed by 3.5 m of FG and again by 3.5 m of PG. The maximum temperature increase will be limited to 1250 °C in the FG and to less than 1050 °C in the PG [31] under normal beam dilution conditions at ultimate beam intensity.

Based on these requirements, each beam dump core was designed as a segmented carbon cylinder of 700 mm diameter and 7700 mm length, shrink-fitted in a stainless steel jacket (Fig. 17.12). The jacket will incorporate welded tubes for cooling water. The core assembly will be connected upstream to the beam dumping line by a DN700 quick-disconnect flange, while a leak-tight titanium window will close the downstream end.

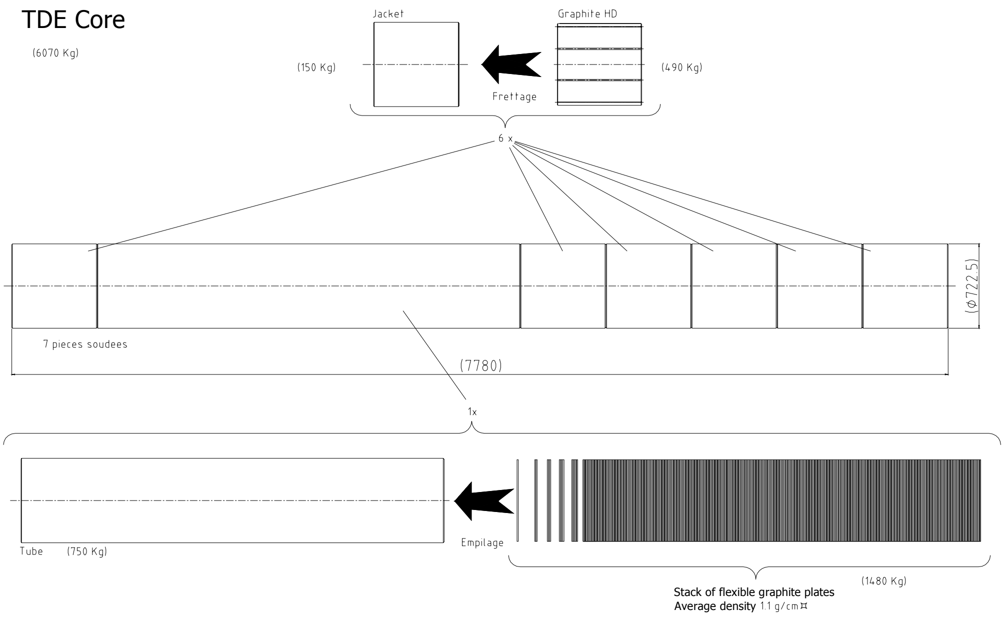

Figure 17.12: Side view of the TDE core.

Shielding

Each dump will be surrounded by ~900 tons of radiation shielding blocks, which have been constructed using decommissioned ISR dipole-yokes, partially filled with concrete [32]. Each block is 1298×1088×2440 mm and weights 24 tons. Thirty-five blocks in total are required per dump, Fig. 17.13.

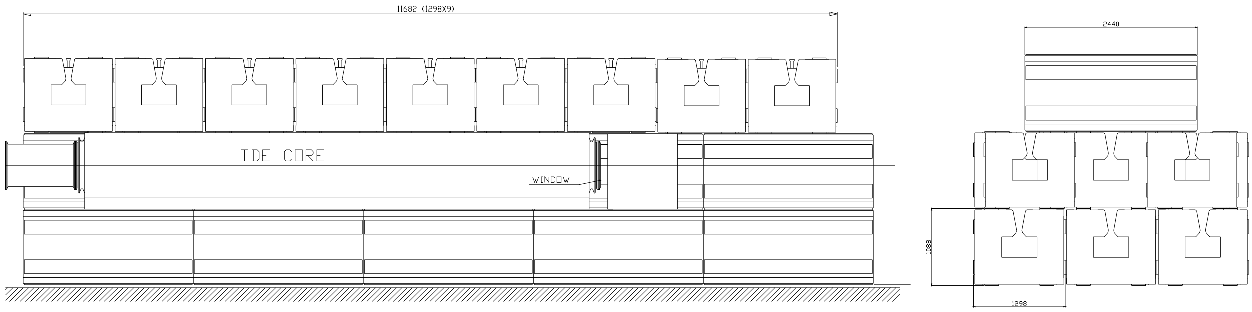

Figure 17.13: Installed TDE core and shielding blocks.

Water Cooling

The dump core has been designed to be actively water-cooled and the core will be equipped with the cooling tubes, but the external cooling circuit will be implemented at a later date as part of the staged equipment. During LHC commissioning, therefore, thermal inertia, conduction and natural convection will define the temperature evolution of the TDE, which will be permanently monitored. The most sensitive elements of the TDE will be the helicoflex joints of its end-flanges. If the temperature approaches the maximum allowable temperature (250°C), an interlock will prevent further operation of the LHC.

Steel Jacket

The steel jacket will be made of a duplex stainless steel tube Ø724/700×710 mm, which will be shrink fitted onto a polycrystalline graphite cylinder Ø700×700 mm. The jacket's functions are: *1*) to provide a beneficial pre-stress; *2*) to better disperse the energy of stress waves; *3*) to protect the lateral surface of polycrystalline graphite; and *4)* to build a vacuum tight containment for the carbon core. Six of these sections (also called *segments*) will be needed for the 7.7 m-long dump core. In the remaining 3.5 m-long section containing flexible graphite no shrink-fit will be possible. A steel tube Ø724/700×3500 mm will nevertheless be used, which will act as a container for a Ø700×3500 volume of the low-density carbon, providing the necessary mechanical rigidity and ensuring stable shape and dimensions.

Failures

Under almost all conditions and fault scenarios the structure of the graphite block and its concentric steel jacket will remain intact. The 700 mm diameter dump is designed to accept a total offset (misalignment) of the diluted beam of ±50 mm. An optical transition radiation (OTR) beam monitor located in front of the dump [33] will detect off-normal dilutions. Only if the beam was kicked very badly and exceeded the alignment limit, could the steel jacket be damaged. If the risk of this failure mode is found to be non-negligible, a sacrificial absorber placed some distance upstream of the dump and outside the beam pipe could be implemented as a safety upgrade to deal with this scenario.

In case of a total dilution failure (no active dilution kicker), the downstream window of the dump could be penetrated when operating with normal or ultimate beam intensities. From detailed numerical analysis, the central graphite blocks will fail extensively due to tensile unloading. In addition, the graphite density will reduce considerably due to vaporisation along the core axis. However, this failure will remain laterally contained within the steel jacket, with only a negligible amount of graphite material failure in the upstream segment, which will not suffer complete perforation from either mechanical failure or phase transition. The consequences of such a total dilution failure will not, therefore, be catastrophic for the LHC or its environment.

Containment

The initial dump design was based on a vacuum-tight core operating under high vacuum. However, if a massive air entry were to occur in the 6 minutes following a high intensity dump, the graphite could burn releasing a thermal power of up to 2 MW. To avoid this risk, the option of permanently filling the dump with an inert gas with sufficient supply to stop a fire will be implemented. The window at the end of the extraction line, before the dump block, will be able to withstand this differential pressure and the gas pressure in the TDE will be slightly above atmospheric. Monitoring connected to the machine interlock system will dump the beam (or inhibit injection) if the pressure begins to drop and simultaneously cut the ventilation in the beam dump cavern affected.

Activation

From the radiological viewpoint, total activities in different parts of the dump, activities in the surrounding air, rock and ground water, dose-rates close to the core and different parts of the dump have been estimated [40]. For general access to the dump-caverns with all the dump-shielding in position, total dose-rates from all sources (dump, air and walls) 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.

17.3.7 Special Vacuum Systems

The vacuum system for the two beam dump lines TD62 and TD68 between the MKB and TDE, each about 630 metres in length, is described in Chap. 12 of this report.

17.3.8 Beam Instrumentation

The beam instrumentation of the dump extraction lines [34] must ensure that the relevant characteristics of the extracted beam and its impact on the machine components can be properly determined and also must allow correct setting up and commissioning of the extraction system with beam.

The position of the extracted beam must be adjusted inside the extraction channel to ensure the best possible transmission efficiency to the dump block. Beam profile (BTV) and position (BPM) monitors will be placed at strategic positions around the extraction septa, after the dilution kickers and in front of the dump block to monitor the trajectory along the entire path of the beam. Commissioning will be performed using both profile and position monitors, while for high intensities most of the profile monitors must be retracted (with the exception of the monitor in front of the dump block) to avoid damage due to the large amount of energy deposited.

Beam loss monitors (BLM) [45] will be installed around the septa and along the extraction line to monitor the quality of the extraction and localise aperture restrictions. The loss monitors are mainly concentrated near known aperture limitations.

Two redundant beam current transformers (BCT) will be used to cross-check the intensity of the extracted beam with respect to the circulating beam before dump extraction. The accuracy of the cross calibration is expected to be in the range of 1-2% for nominal filling, which should be sufficient to prove that the beam was indeed correctly extracted from the ring. Due to the limited accuracy of the BCTs, beam loss recordings over the last machine turn and in the extracted channel must be used to verify that the dump action was clean.

An undiluted beam could damage the dump block. It will therefore be mandatory to determine the sweep trace of the beam on the front face of the dump block. The sweep must be recorded by a very large profile monitor in front of the dump block. High resolution will not be critical since no attempt will be made to measure the beam sizes, only the trace of the beam produced by the dilution kickers must be monitored. For redundancy, the bunch-by-bunch position measured by a BPM installed a few meters downstream of the dilution kickers could be used to verify the correct functioning of the dilution kickers.

To ensure clean dumps without losses in the extraction channel, the circulating beam position should not deviate from its nominal position at the MKD kicker and MSD septum by more than 4 mm. To enforce this tolerance under all circumstances, 4 dedicated BPMs will be installed on the IR side of the Q4 quadrupoles (2 per quadrupole and per beam). These BPMs will be dedicated to a position interlock system that will monitor the position on a bunch by bunch and turn by turn basis and which will dump the beam if the threshold is reached.

Finally, all beam instruments must provide post-mortem data. This data must be analyzed to establish that dump action was performed correctly before any beam can be re-injected into the ring and in addition the dumped beam intensity will be logged.

17.3.9 Equipment State Control

The MKD state control entity will be based on a SIEMENS S7-400-F master Programmable Logic Controller (PLC), which interfaces 15 independent PROFISAFE sub-segments through a single PROFISAFE master segment. Each sub-segment will be attached to a single high voltage generator and will be controlled by a SIEMENS S7-315-F slave PLC. The interface between PROFISAFE segments will be based on PROFIBUS DP/DP couplers.

Failsafe PLC technologies will be used to ensure that any failures, hardware or software, occurring in the state control entity will generate a dump request. The state control entity will be in conformity with IEC 61508 International standard for electrical/electronics/programmable electronics safety related systems.

The master PLC will use the Ethernet TCP/IP network for communication with the application layer, but the design will be such that failures in the application layer and Ethernet network will not compromise the safety of the operational behaviour.

The state control entity will be responsible for the control of equipment state (ON, OFF, STANDBY…), the surveillance of the FHCT switches, the generation of the kick strength reference voltage accordingly to the beam energy and personnel safety aspects of the installation. Typical response times will be ~5 ms.

17.3.10 Synchronisation, Trigger and Re-trigger Control

Dump requests will come from different sources including the machine protection system for emergencies, the machine timing system for scheduled dumps and the LBDS itself for internal failures.

The LHC revolution frequency pulse train will have a fixed phase offset relative to the abort gap in the circulating beam and this will be used to synchronise spontaneous requests with the abort gap. Once synchronised, dump requests will be distributed to the power trigger system (PTS) for firing of the kicker pulse generators. In addition, a re-trigger system (RTS) will be used to increase reliability and protect the machine against spontaneous firing.

The beam dump triggering system will be based on a redundant fail-safe logic [10] up to the beam abort gap synchronisation unit and then on a redundant fault tolerant system up to the high voltage generator power trigger unit, in order to avoid asynchronous beam dumps.

Synchronisation

Locked to the LHC revolution frequency, two independent quartz controlled oscillators (QCO) will continuously produce dump trigger pulses synchronised with the gap in the circulating beam. The distribution of these pulse trains will be inhibited until a beam dump is requested. The pulses which pass the inhibit stage will be then sent via a fan-out system to all power trigger modules. In this way the first pulse after the reception of a dump request will synchronously trigger the system. The time of flight of the circulating beam through the magnets, as well as electronic and high voltage turn-on delays, will be compensated for each kicker magnet individually with the trigger distribution cables.

In case the revolution frequency pulse train is lost for more than one turn, an internally synchronised direct digital synthesiser (DDS), precisely locked on the revolution frequency, will issue a dump trigger, which is still synchronous with the particle free gap in the circulating beam. This mechanism reduces the probability of non-synchronised dumps to almost zero. If the synchronisation of only one of the oscillators fails, a synchronous dump trigger is forced by the redundant system.

In addition, any dump request also generates a dump trigger, delayed by just over one turn, via the re-trigger system to the power trigger modules. This third trigger path guarantees that at least an asynchronous beam dump is initiated, even when both principle systems fail. It has to be mentioned that in the case of spontaneous firing of one of the generators no synchronisation is possible.

The duration of the particle free gap is 3.0 μs and just covers the rise of the magnetic field in the magnets. The tolerance available for the synchronisation at the extraction kicker will be approximately 100 ns. Any delay or jitter in the transmission of the revolution frequency therefore has severe consequences for the synchronisation of the extraction process. For that reason it will be necessary to verify continuously the phase between each revolution frequency pulse and the structure of the circulating beam.

Re-triggering

The main task of the re-triggering system (RTS) will be to immediately re-distribute a trigger request issued from a spontaneous firing of one generator to the remaining 14 generators.

A redundant chained input/output system has been chosen for the RTS. Each pulse generator will have several re-trigger source sensors with enough powering capabilities to trigger all power trigger modules of the other 14 high voltage generators. Due to the architecture of the system, an avalanche mechanism is started after a detection of a spontaneous firing. Since there is no stored energy in the system itself it is difficult to create spurious triggers, neither can a disconnected cable nor a defective trigger source cause triggers. The typical reaction time between detection of a spontaneous firing of one pulse generator and re-triggering of the 14 other generators is 700 ns for energies above 3 TeV.

Trigger

The normal trigger distribution system will be based on two redundant fan-out units triggered independently. The output driver circuit of each fan-out unit will be based on a blocking oscillator circuit with one primary input for 30 circuit secondary outputs.

The dump request distribution will be based on redundant chains of stages using the “domino effect” strategy to trigger the next stage in the chain. The energy required to propagate the trigger request up to the kicker high voltage generator will be stored within capacitors at each stage of the triggering chain. This energy will be used to trigger the next stage of the chain and its level is checked before a beam permit signal is issued.

17.4 PERFORMANCE AND OPERATIONAL ASPECTS

17.4.1 Controls Issues

Triggering and Internal Monitoring

The external signals such as beam loss monitors, quench detectors etc. which can generate a beam dump trigger are listed in Section 15.5. These signals will trigger the Beam Interlock System which will then pass on the dump request. In addition the beam dumping system will continuously monitor its own status [35] and will trigger a synchronous dump if one of the following faults is detected:

- Error in the energy tracking of the MKD, MKB or MSD;
- Beam Energy meter: inconsistency between the two branches;
- Incoherence of one of the two synchronisation systems with the Radio-Frequency system;
- Out of specification of vacuum of the TD lines, overpressure of TDE, or high temperature of TDE;
- Temperature of the absorbers TCDS, TCDQ too high;
- Fault in the water flow of the different cooling circuits;
- Incorrect general status of the beam dumping system (status of the power converters, slow controls, Programmable Logic Controllers).

Post-mortem

A system post-mortem will have to be performed after every beam dump. It is planned that at least the following signals will be recorded and an automated comparison made relative to reference signals:

- Shape of figure on the beam dump block;
- Beam position on pick-ups in TD dump line;
- All MKD and MKB current wave forms;
- Check of redundancy of circuit paths: they should all carry current;
- Comparison of circulating beam currents and current in TD dump lines;
- Radiation levels in the beam dumping system elements (check synchronisation) and behind the TDE block.

After every beam dump the system will pass from a ‘ready’ state to a ‘not ready’ state. Only after successfully passing the post mortem tests described above can the system status pass back to ‘ready’. The time necessary for the beam dumping system to perform the internal post-mortem analysis is expected to be shorter than 10 seconds.

An ‘external post-mortem’ will also take place at every beam dump. It should identify the source of the beam dump request and log certain key machine parameters before, during and just after each beam dump request. The time stamp of the beam dump request as generated by the Beam Interlock System will be compared with the time stamp of the beam dump request as received by the beam dumping system.

Logging

Like many other signals in the machine, a number of beam dump signals will be logged continuously:

- Voltages of the different circuits of the MKD and MKB generators;
- Currents in the MSD septa;
- Different temperatures and pressures of the system;
- Beam instrumentation data (profile on the TDE, dumped intensity, …).

17.4.2 Apertures

The MSD septa and TCDS diluter will be aperture limiting elements for both the circulating and extracted beams. The layout of the TCDS and MSDC vacuum chamber have been optimised [9] according to the allowed LHC beam parameters (Tab. 17.1) and the allowed beam dumping system failure modes (Sec. 17.4.8). The MSD chambers must be shielded by the TCDS in the event of an unsynchronised MKD pre-trigger, which constrains the possible positions of these elements. The maximum aperture for the overall system (considering the circulating plus extracted beam) is obtained with the TCDS positioned as close as possible to the circulating beam axis.

Circulating Beam Aperture

With a ±4 mm orbit, the nominal TCDS position (upstream) will be set to +16.3 mm, which corresponds to an acceptable *n1* [36] of 6.5. At the MSDC the aperture in terms of *n1* will be 6.9. The plots of available aperture versus orbit at the upstream end of TCDS and the downstream end of the MSDC5 vacuum chamber are shown in Fig. 17.14 for the limiting 450 GeV beam.

Extracted Beam Aperture

For the extracted beam aperture calculation the total overshoot of the MKD kicker waveform is taken to be 10%. For the nominal case with all 15 MKD kickers pulsing correctly, the extracted beam will be centred in the septum gap. The same kick of 0.27 mrad will be imposed from 450 GeV to 7 TeV beam energy, which will ease setting up, post-mortem and energy-tracking. The available aperture at 450 GeV and 7 TeV as a function of orbit is shown in Fig. 17.15. Assuming that for 'loss free' extraction an aperture of 4σ will be sufficient at 450 GeV and 6σ at 7 TeV, the orbit should stay within about ±4 mm and ±7.3 mm, respectively. The control of the orbit in point 6 to better than ±2 mm will be achieved using a feedback system and will provide an essential operational margin in the event of failures.

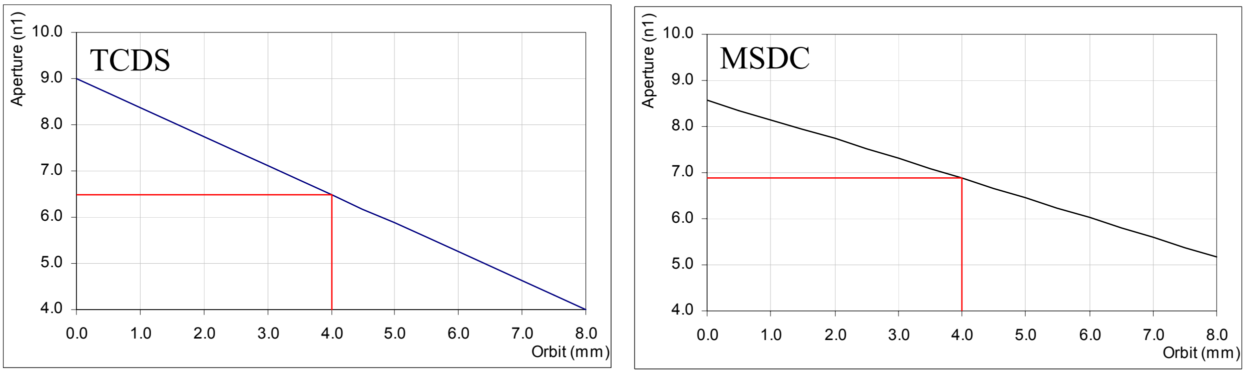

Figure 17.14: Aperture in *n1* at TCDS and MSDC5 for circulating beam as a function of local horizontal closed orbit excursion (±4 mm vertical orbit assumed) for the limiting 450 GeV beam.

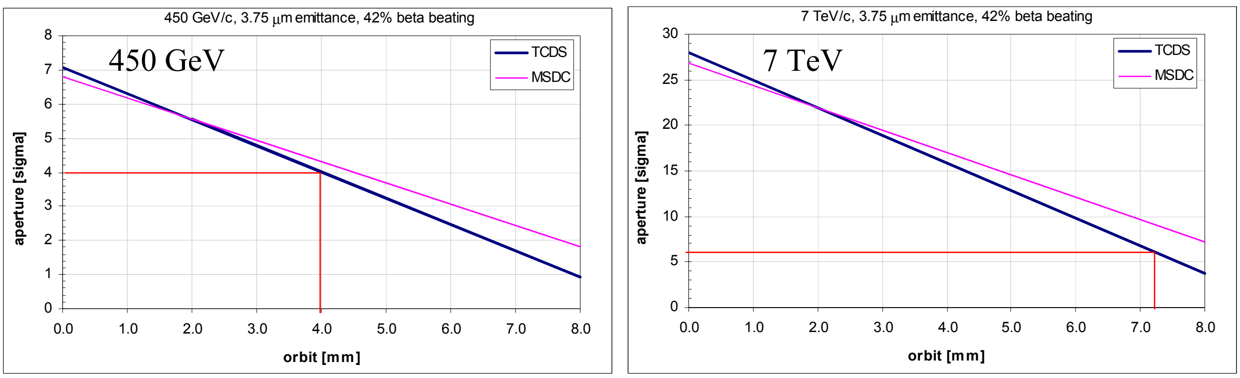

Figure 17.15: Aperture in beam □ at 450 GeV and 7TeV for extracted beam as a function of the orbit in the nominal 15/15 MKD case.

An allowed failure case is where one of the MKD magnets does not pulse. The worst of these modules to miss firing will be MKD1; in this case the effective deflection at the TCDS will be 91.96% of the total and the beam will approach the TCDS. The available apertures at 450 GeV and 7 TeV as a function of orbit are shown in Fig. 17.16. At 450 GeV, even for moderate orbit excursions, the TCDS will receive some beam, with the attendant risk of quenches in downstream superconducting magnets.

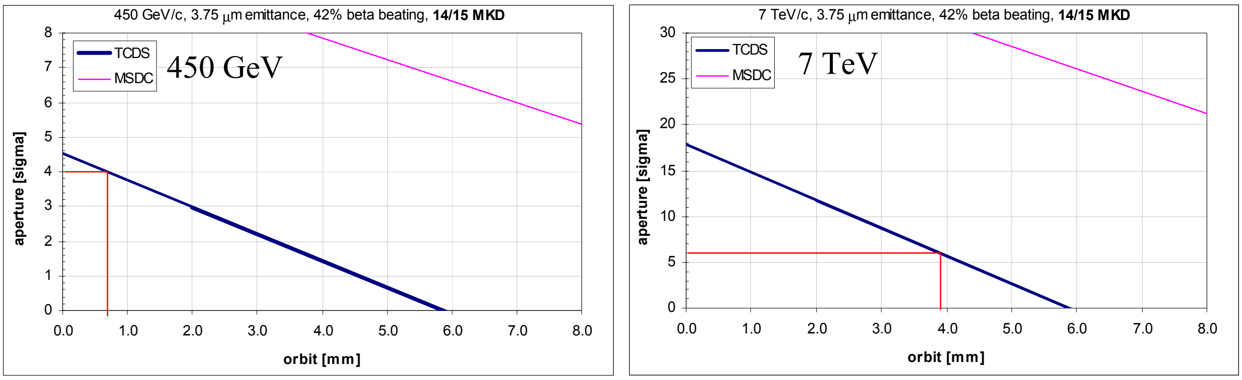

Figure 17.16: Aperture in beam σ at 450 GeV and 7TeV for extracted beam as a function of the orbit in the 14/15 MKD case.

For normal operation, with realistic failure cases, orbit excursions of up to ±4 mm should be tolerable without damage to any elements, up to nominal intensities. In addition, emittance increases of ×2 / ×4 will not result in equipment damage at 450GeV / 7TeV respectively. However, these may produce Q4 quenches at low energy for large orbit excursions. The 14/15 MKD case will produce losses on the TCDS and Q4 quenches but should not result in damage, again provided the orbit is held to better than ±4 mm. To ensure that the dumping system can safely extract the beam, reliable interlocking of the local beam position at a level of ±4 mm in point 6 will be absolutely necessary. The required response time of this interlock and the exact threshold margin will depend on the maximum rate at which the beam will move after an LHC fault, which has been shown to be ~60 μm per turn [37].

17.5 SPECIFIC REQUIREMENTS PLACED ON OTHER MACHINE SYSTEMS

Many of the following items have already been treated in the above; here a summary is given of the specific requirements placed on other LHC machine systems by the beam dumping system, apart from the general services which are not considered here.

- Powering (MSD powering): the MSD current must follow the LHC energy with a tolerance of 0.5%;
- Radio-Frequency (synchronisation): the beam dumping synchronisation will rely on a revolution frequency signal for each beam from the RF system; if this signal is interrupted the beams will be dumped immediately after a few turns using an internally generated synchronisation which will stay in phase with the abort gap;
- RF (abort gap cleaning): the abort gap should be as free as possible of spurious particles in order to minimise the activation of the TCDS, TCDQ and collimators during regular dump actions. If the abort gap population becomes too high, a normal dump could result in a Q4 quench, which is unacceptable from an availability viewpoint. The abort gap population must therefore be kept below 0.3×10^7 protons per m [44] which will require active cleaning using the damper [42];
- Controls (settings, alarms, timing, post-mortem and logging): the logging and post-mortem will be essential to provide the assurance that dump actions have been correctly executed. The relevant data must be available to enable the beam permit;
- Safety (fire detection, access zoning, emergency stops): the availability of standard safety systems will be required for tests and conditioning. In the case of the emergency stop system, it is clear that the beam dump action must be triggered before any power supplies are cut;
- Collimators: there will be a fundamental interdependence of the TCDQ settings with LHC collimation system settings [43], since the TCDQ must be positioned so as to reduce the number of bunches impacting the primary collimators in the event of an asynchronous dump and also because in the planned second phase of the collimation system, the TCDQ must act as a tertiary collimator and completely protect the metallic secondary collimators;

- Machine protection (beam permit): the Beam Interlock System will pass on a dump request generated by other critical systems such as the beam loss monitoring. To ensure the required reliability level for the beam dumping system as a whole, the Beam Interlock System must also meet stringent requirements, concerning the correct transmission of the dump request and its internal status;
- LHC magnets: the tolerance on the Q4 current will be about 1% and for the MSD about 0.5% - beyond these limits an abort signal should be generated. The detection of a short-circuit between MSD coils may require an additional protection, e.g. based on voltage surveillance;
- Localised orbit feedback and position interlock: the beam position in IR 6 should be stabilised to ±2 mm using orbit feedback and a separate interlock system must dump the beam if the orbit exceeds ±4 mm.

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