Chapter 10

Detector infrastructures and safety systems

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The common term *infrastructures* includes very different systems, ranging from basic site facilities to more detector-specific and safety-related services. In this section, the main general systems are described.

10.1 Detector powering

CMS, like any other modern particle physics detector, needs considerable electrical power for its front-end electronics (FEE), for electronics racks in counting rooms and in site control centres, and finally for auxiliary services (cranes, ventilation and cooling stations, lifts and access facilities, etc.). Different power sources are available on site. Uninterruptible Power Systems (UPS), for valuable equipment that must stay on in case of power disruption, secure power for specific users for a short period, before being backed-up by a diesel engine. Common users are connected to standard network power. Table 10.1 gives an overview of the power requirements for CMS.

With the exception of the cooling stations, the racks system is the most important client in

Table 10.1: Power requirements for CMS.

System	Power (kW)
General site services	2200
Electronics racks	2300
Low voltage to front-end electronics	1000
Magnet and cryogenics	1250
Ventilation stations	1250
Surface cooling stations	4000
Underground cooling stations	1500
Total steady-state consumption	9000

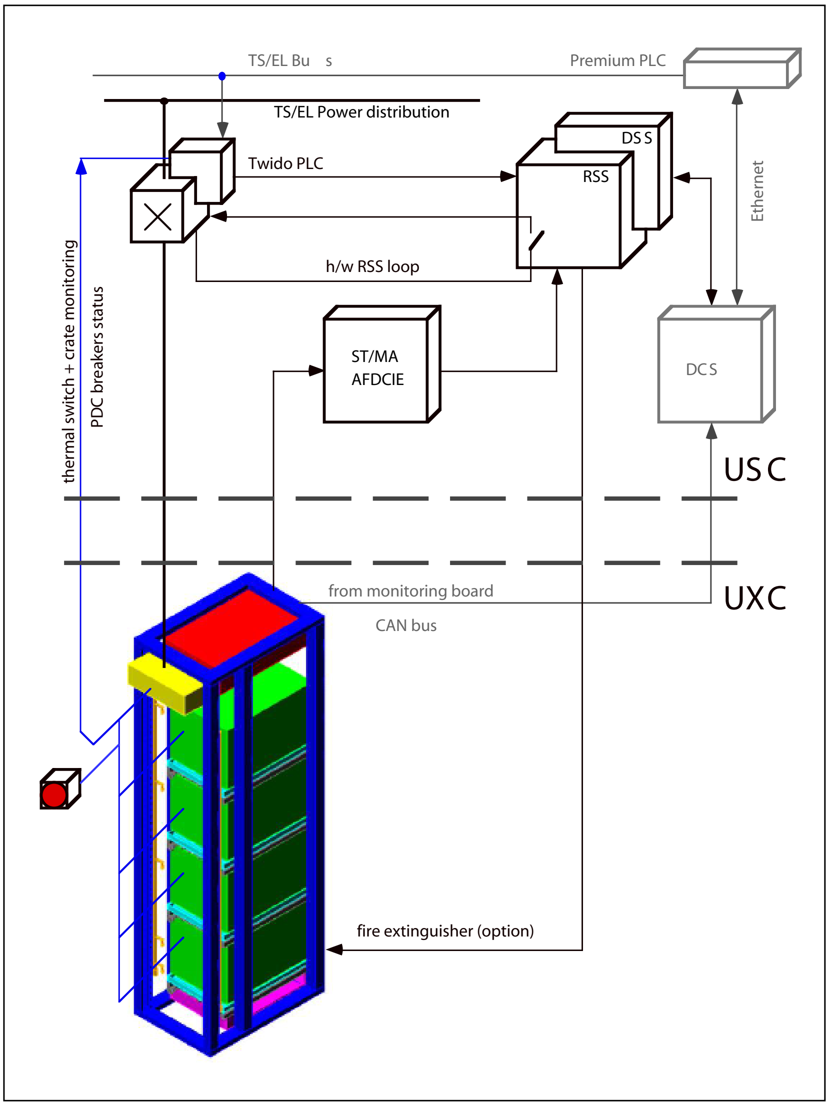

Figure 10.1: Control loops for rack powering.

terms of power. Rows of racks are fed by power bus-bars. Each single rack has a main breaker piloted by a dedicated PLC, the whole system being located in a box attached to the bus-bar. A power and a control cable run from this box to the power distributor cabinet inside each rack. Cabinets provide single-phase, three-phase or three-phase + neutral current distribution. The breaker PLC is controlled by the Detector Control System (DCS) via a network connection. Single racks can be switched on-off upon DCS request and the status of each breaker is known by DCS as well. Moreover, a hardwired connection to the Detector Safety System (DSS) secures the system in case of smoke or a high temperature is detected inside a rack. Figure 10.1 describes the logic behind the power controls.

Table 10.2: Cooling power for different sub-systems.

System	Power (kW)
Muon Endcaps	100
Muon Barrel	50
HCAL and Yoke Barrel	60
ECAL	300
Rack system	1600
Tracker, Pixel, Preshower	150

10.2 Detector cooling

10.2.1 Front-end electronics cooling

The CMS front-end electronics dissipates some 800 kW in the experimental cavern. This huge amount of heat is intercepted by cooling water at 18°C for the ECAL, HCAL and Muon systems, and by C_6F_{14} fluid at temperature ranging from -15°C to -25°C for the Preshower, Pixel and Tracker systems. In addition, some 1600 kW are dissipated by the rack system. Table 10.2 shows the power dissipated by each system.

Chilled water at 14°C is produced at the surface in the SU5 building and then transferred to the USC55 cooling plant, where five independent water circuits, each one with its own heat-exchangers, pumps and controls, produce and distribute water at 18°C to the experiment cavern. The Tracker, Pixel, and Preshower systems have on their primary side chilled water at 6°C, and they have their own cooling cabinets in UXC55 to shorten the transfer lines. Cooling status is monitored by the central DCS via ethernet connection to TS/CV control units. The DSS monitors crucial parameters such as flow rate, temperature, and dew point, in order to take actions in case of need. Loss of coolant is detected by measuring the fluid level in the expansion tanks of every cooling loop.

10.2.2 Cryogenics

The cryogenic plant at the CMS site has the function to cool down and keep at 4.7 K the 230 t of the CMS superconducting coil. The refrigerator system can deliver a cooling power of 800 W at 4.7 K, plus 4500 W at 60 K to cool the coil's thermal screens, in addition to the 4 g/s of liquid helium used to cool the 20 kA coil current leads. Cooling the coil down from room temperature takes 3 weeks, with a maximum thermal gradient inside the cold mass of 30 K. In case of a quench, the temperature rises to 70 K and 3 days are necessary to bring the cold mass down to 4.7 K. A 6000 l liquid helium storage tank sits close to the coil cryostat to allow a slow discharge from full current without warming up the coil.

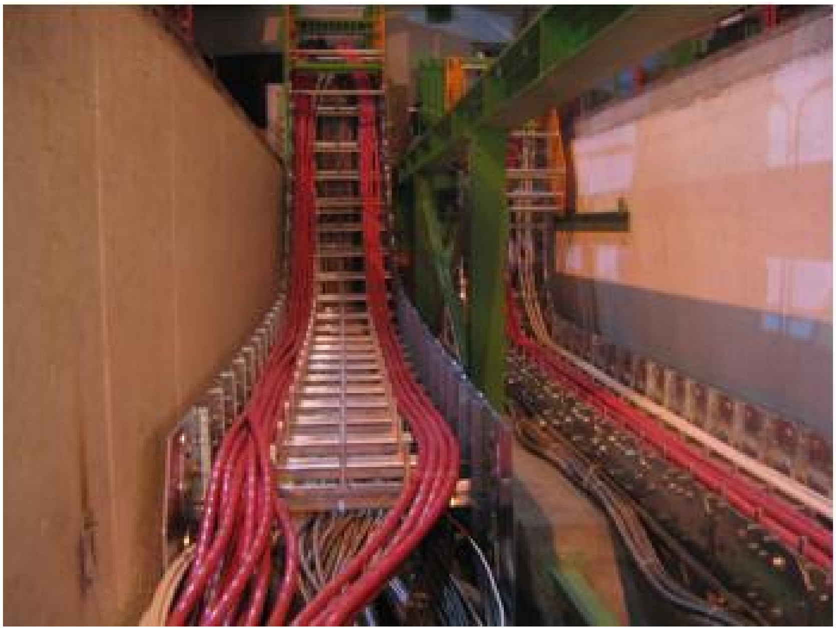

Figure 10.2: YB+2 and YE+1 cable-chains in UXC55 basement trenches.

10.3 Detector cabling

Due to the specific CMS design, with one central element (YB0) that is fixed and 6 mobile elements for each side moving on the cavern floor during shut-down periods, power cables, coolant, gas and optical fibres have to run through huge cable-chains in order to open and close the detector without disconnecting everything (figure 10.2).

Cables are labeled and stored in a database with web interface, that allows identification of each cable by sub-system, type, length, starting point, endpoint and routing. The main cable types can be summarised as follows:

- HV cables;
- LV cables for DC power to FEE;
- FEE read-out cables;
- optical fibres read-out;
- monitoring and control (DCS) cables;
- general pourpose power cables (230-400 V AC);
- safety system cables (DSS) for hard-wired signals and interlocks.

The cable-trays include also the gas-sniffer soft-pipes. Some 30 000 cables are referenced in the data-base.

10.4 Detector moving system

The CMS moving system has been designed according to the following criteria: affordability, robustness, preciseness, easyness in handling and compactness. The boundary conditions have been determined on the one hand by the weight and dimensions of the assemblies and on the other hand by the friction, the slope and the size of the cavern.

10.4.1 Sliding system

In order to limit friction and thus the power of the pulling system, CMS has chosen a heavy duty air pad system for the long movements (10 cm to 10 m) and a flat grease pad system for the final approach (up to 10 cm). In addition, these systems allow, without any additional structure, movement perpendicular to the beam. The air pads (figure 10.3) have rubber sealing rings that prevent air losses. The system can be used with compressed air bottles only. At the same time, this sealing increases somewhat the friction factor, which lies around 0.8% before moving and goes down to around 0.4% once moving has begun. The grease pad system produces a final approach with practically no friction.

10.4.2 Pulling system

The pulling system consists of a hydraulic strand jack system and includes 6 jacks with strands (of which the two in the center are pivotable) and a strand storage mandrel. Taking into account the slope of the cavern (1.234%) and the friction of the airpads and cable chain, the system must be capable of safely pulling uphill 2.5% of the maximum load, which is 2600 t (3 endcaps together). Whereas going uphill is a pure pulling, going downhill needs a retaining force in order to produce a smooth, constant movement of the load. This was integrated into the design of the hydraulic control unit.

10.5 The Detector Safety System

The Detector Safety System (DSS) is a common development carried out by the 4 large LHC experiments together with the CERN IT department. The purpose of the DSS is to protect the detector and the experimental equipment from hazards. The DSS works complementary to the Detector Control System (DCS) and the CERN Safety System (CSS) (figure 10.4).

Normal operation of the experiments proceeds with the DCS which monitors and controls any deviation from normal operation or the occurrence of anomalies. In this respect, the DCS is ensuring a safe operation of the experiment. The DCS is designed such as to monitor and react up to a very detailed level and in a highly granular way, a necessary feature which on the other hand makes the system quite complex and thus vulnerable.

For emergency situations though, the LHC experiments are equipped with the CERN Safety System. The CSS is designed to reliably detect the main hazards, like smoke, flammable gas, oxygen deficiency, etc. that could endanger the human life, and will transmit a corresponding alarm to the CERN fire brigade. The CSS, however, does not foresee immediate actions for the protection of the equipment.

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Figure 10.3: A transport beam for barrel rings with 4 air pads fixed on it.

Equipment protection is the purpose of the DSS which triggers automatic actions in order to avoid or to reduce eventual damage to the experimental equipment when it detects abnormal and potentially dangerous situations. The DSS is designed to be simple and reliable and consequently the DSS actions have to be fast and quite coarse, e.g., cutting the power to the entire cavern in the case that smoke is detected. In order to do so, the DSS partially recuperates signals from the CSS (e.g., smoke detection) and triggers actions on the main infrastructure, as cutting the 18 kV supply. DSS actions thus will in general disrupt the data taking, but in the long run, by avoiding damage to experimental equipment, will increase the overall data taking efficiency of the experiment.

10.5.1 DSS Requirements

In order to fulfill its purpose, the DSS has the following characteristics:

- high reliability and availability to make the system simple and robust;

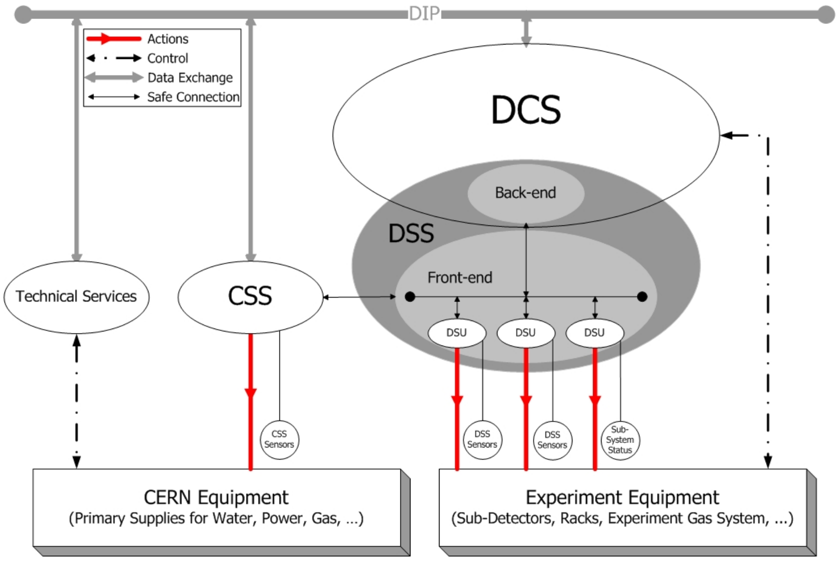

Figure 10.4: Context diagram of the DSS system, showing its rôle with respect to the CERN Safety System (CSS), the Detector Control System (DCS) and other technical services. The interconnection network is provided by the Data Interchange Protocol (DIP).

- operational independence of all other systems, running in stand alone system mode;
- autonomy from outside services, especially power supply and computer network;
- input from its own sensors and actuators (nevertheless some are owned by the CSS);
- capability of immediate and automatic actions;
- flexibility to be adopted and configured in order to adapt to the evolving needs of the experiments;
- full integration into the DCS.

10.5.2 DSS Architecture

The DSS consists of two main pillars: the front-end and the back-end.

The front-end is a redundant array of two Siemens S7-400 H PLCs. These PLCs interpret the signals coming from the connected sensors according to a programmable alarm-action matrix. Actuators, attached to the output of the PLCs trigger actions. The PLCs are scanning all input channels, processing the alarm-action matrix and modifying the state of the outputs accordingly. Such a cycle will take about 500 ms, allowing the DSS to react to any hazardous situation with a response time below one second. Different type of sensors can be connected to the DSS that are digital inputs, analogue inputs (4–20 mA) and PT100 temperature probes. The front-end can operate completely independent from the back-end and is thus the safety relevant part of the DSS. It is also connected to an uninterruptible power supply which gives the DSS autonomy of several hours.

The back-end of the DSS consists of a standard PC running the PVSS software. It serves as interface between the front end and the operator. The back-end provides tools for post mortem and data analysis, e.g. the possibility to retrieve and display data based on user-defined selection criteria, trending tools and the possibility to filter alarms according to criteria such as time, origin, alarm priority. However, it is not necessary for the user to initiate any DSS actions, as these are all performed as automated actions in the DSS front-end.

10.5.3 CMS Implementation of DSS

Due to the rather large number of input channels for the CMS experiment, the DSS is split into two completely separate entities. One entity collects input channels from the equipment housed in the USC cavern and the surface buildings and one entity for the UXC cavern. Both systems, each equipped with a set of redundant PLCs, are stand alone and communicate only via hard wired input and output. The USC/surface system consists of 6 Detector Safety Units (DSU) each housed in a rack, where the UXC system consists of 10 DSU's. A typical DSU is made of 224 digital input channels, 64 analogue or PT100 input channels and a few digital output channels. The bulk amount of signals originates form the 230 V rack power distribution system and from the low voltage system. The about 200 racks in the USC cavern produce each an individual smoke detection alarm and an alarm from the power distribution box (TWIDO). The about 200 racks in the UXC cavern will give as additional signals the status of the electrical breaker inside the TWIDO box and a signal in case of an electrical fault since the racks in the UXC cavern are not accessible during the LHC operation. Concerning the low voltage supply for the UXC racks, the DSS receives about 180 status- and electrical-fault bits, and it is able to cut the low voltage power supply to each rack individually.

In addition to the protection of the racks, the DSS also directly safeguards the sub-detectors via a number of sensors. These are temperature sensors placed directly on the sub-detector or in the vicinity of them, flow meters measuring their cooling circuit, water leak detectors inside the vacuum tank of the solenoid, etc. Since the functioning of the DCS is mandatory for the operation of the DSS, every sub-detector shall send a status bit to DSS, such that DSS can take appropriate actions in case the DCS of a sub-detector or the central DCS is not functioning. The typical DSS action is to cut the power to part of the detector equipment, but other actions can be taken as, for example, triggering the CO_2 rack extinguishing system, as well as the water mist system.

10.6 Beam and Radiation Monitoring systems

10.6.1 Introduction

The Beam and Radiation Monitoring systems (BRM) [227] perform both a monitoring and a protection function for CMS. To this end, multiple and redundant systems have been installed, some of which can be used to initiate LHC beam aborts and/or CMS equipment control, others of which can be used for fast beam/detector optimisations. All systems will provide long term monitoring of the received radiation dose in various regions of the CMS detector.

The CMS experiment sits in an unprecedentedly high radiation field for a HEP experiment and much effort has gone into the design and construction of systems with very high radiation tolerance. Nevertheless, the LHC is designed to run with 362 MJ of stored energy in one beam and with proton intensities in excess of 10^{14} per beam. Even very small fractional losses of this beam risk causing serious damage to detector elements. Whilst the LHC itself has extensive instrumentation designed for machine protection, CMS requirements dictate that CMS must be able to detect beam-related problems as they develop and to assert beam aborts if required. In addition, CMS must be able to log data and perform post-mortem analyses in the case of accidents and understand the accumulated dosage and potential longer term damage to the detector elements. To this end CMS has implemented the BRM systems.

While radiation damage can lead to long term effects, the most likely damage scenarios involve very fast bursts of radiation/energy-dissipation in detector elements. Thus the protection systems must be sensitive to very fast changes in beam conditions; the BRM systems can detect changes at the 25 ns level, though the initially deployed protection systems will react in times of order 3–40 μs. Additionally, the BRM systems provide monitoring and tuning data to permit operator intervention to diagnose and improve beam conditions. In addition, all BRM systems can be used to monitor integrated dose and detector component aging over the years of LHC operation.

In designing the BRM, CMS imposed several design constraints; namely to implement systems which can stay alive at any time when beam may be in the LHC independently of the state of CMS operations; that have readout and post-mortem capabilities extremely close to those of the LHC machine protection systems; and that offer a high degree of redundancy and a wide dynamic range for protection and monitoring scenarios. Given these constraints, the BRM protection system, summarised in table 10.3, has been implemented. The BRM system, its nomenclature and sub-system locations in CMS are also represented in figure 10.5.

10.6.2 Protection systems

The protection systems are based on chemical vapour deposition diamond detectors [228] similar to those that have been widely used in recent collider experiments [229, 230] where they have proven to be radiation hard [231], fast enough to match beam abort scenarios, and small enough to be inserted into areas close to key detector components without adding substantial material or services.

In CMS there are two protection systems foreseen for initial LHC operation. The first is the BCM1L made of four polycrystalline diamonds, each $10 \times 10 \times 0.4$ mm^3, positioned on either side of the IP at z values of $\pm$ 1.8 m, close to the beam pipe and the inner-tracker pixel detectors (chapter 3) at a radius of 4.5 cm. The second protection system is the BCM2L. This is a set of twelve polycrystalline diamonds, each $10 \times 10 \times 0.4$ mm^3, on either side of the IP behind the TOTEM T2 detector at a z position of $\pm$ 14.4 m. On each side of the IP, a set of eight sensors are deployed at an outer radius of 29 cm and an additional four at an inner radius of 5 cm. Here BCM refers to Beam Conditions Monitor, the index 1 or 2 refers to the two locations in z and L indicates that these detectors are used in a leakage current measurement mode as relative flux monitors, typically integrating the leakage current over μs time scales. The BCM1L diamonds are arranged on the x and y axes. The BCM2L comprise eight diamonds at 45° intervals at large radius

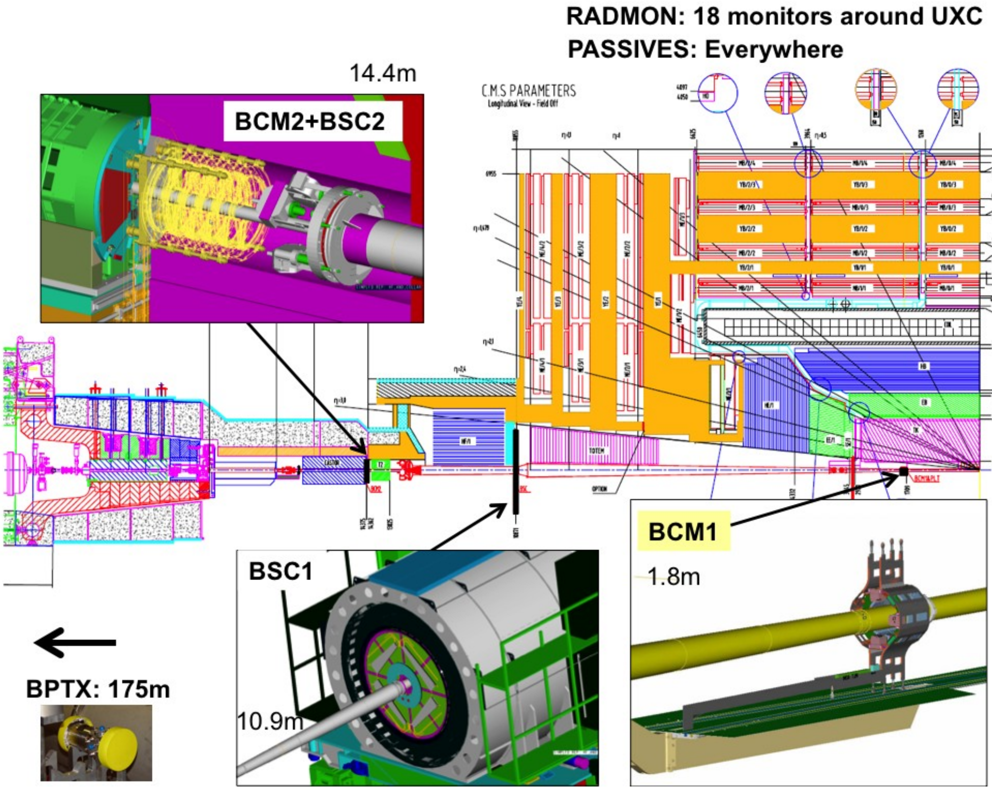

Figure 10.5: Layout of CMS BRM sub-systems.

and four on the x, y axes at small radius. The BCM1L and inner BCM2L diamonds measure a rate which is dominated by pp interactions at the IP. The outer BCM2L diamonds are hidden from the beam-spot and are expected to be largely sensitive to beam-halo rates.

The diamonds used for BCM1L and BCM2L are essentially identical, but the two systems differ in the readout methods adopted. The BCM2L uses a standard LHC Beam Loss Monitor (BLM) electronics and data processing [232, 233] that is read out asynchronously with respect to the LHC machine with 40 μs sampling. The BCM1L readout uses the same LHC BLM back-end electronics, but uses an additional mezzanine card to provide sub-orbit sampling. The readout is synchronized with the 89-μs LHC orbit, allowing user-configurable sampling, so that the sampling can be matched to the LHC bunch trains. In addition the BCM1L allows sampling of the LHC abort gap, which must be kept empty to avoid a spray of particles being directed at CMS during a beam dump.

Using a set of thresholds in the readout systems and a combinatorial logic to reduce sensitivity to individual noise events, a hardware beam abort signal can be generated and transmitted to the LHC machine via the Beam Interlock System [234], leading to the dumping of the beams within 3 orbits. A lower threshold value can be used to send hardware signals to CMS sub-detector clients to initiate high and/or low voltage ramp-downs.

In the event of a beam abort initiated by CMS, or by any of the other LHC (or experiment) protection systems, a full history of the BCM1L and BCM2L signals is produced and transmitted to the LHC control room.

Table 10.3: The sub-systems to be deployed as part of the initial BRM. The table is ordered from top to bottom in increasing time resolution.

sub-system (Sensor type)	Location Distance from IP (m)	Sampling Time	Function	Readout + Interface LHC or CMS type	Number of Sensors
Passives (TLD+Alanine)	CMS and UXC	$\sim$ months	Monitoring	N/A	Many
RADMON (RadFets+SRAM)	CMS and UXC	1 s	Monitoring	Standard LHC	18
BCM2L (Polycrystalline Diamond)	Behind TOTEM T2 z=$\pm$14.4 m	40 μs	Protection	Standard LHC	24
BCM1L (Polycrystalline Diamond)	Pixel Volume z=$\pm$1.8 m	5 μs	Protection	Standard LHC	8
BCM2F (Polycrystalline Diamond)	Behind TOTEM T2 z=$\pm$14.4 m	$\sim$ns	Monitoring	CMS Standalone	8
BSC (Scintillator Tiles)	Front of HF z=$\pm$10.9 m	$\sim$ns	Monitoring	CMS Standalone	32
BCM1F (Single Crystal Diamond)	Pixel Volume z=$\pm$1.8 m	$\sim$ns	Monitoring	CMS Standalone	8
BPTX (Button Beam Pickup)	Upstream of IP5 z=$\pm$175 m	200 ps	Monitoring	CMS Standalone	2

10.6.3 Monitoring systems

Several monitoring systems are listed in table 10.3: the BCM1F and BCM2F are also based upon diamond sensors, but with readouts able to resolve the sub-bunch structure, the Beam Scintillator Counters (BSC) are a series of scintillator tiles designed to provide hit and coincidence rates, the Button Beam Pickup (BPTX) is designed to provide precise information on the bunch structure and timing of the beam, and the RADMON and Passives systems give calibrated information on the radiation field within the CMS cavern.

The BCM1F, BSC and BPTX are sensitive to time structure below the 25-ns level; as such they also provide technical trigger inputs into the global CMS trigger. In particular, the inputs from the BPTX and BSC provide zero- and minimum-bias triggers, respectively. Additionally, all three of these systems are sensitive to all foreseen beam intensities including the LHC pilot beam, where a single low intensity bunch is injected for studies or to confirm parameter settings prior to full intensity injection.

The BCM1F consists of four single crystal diamonds, each $5\times5\times0.5$ mm^3, positioned on either side of the IP at z values of $\pm$ 1.8 m at a radius of 4.5 cm, in close proximity to the BCM1L detectors. The BCM1F is used as a diagnostic tool to flag problematic beam conditions resulting in "bursts" of beam loss over very short periods of time. Such beam losses are expected to be one of the principle damage scenarios for the CMS detector systems. The location of the BCM1F is close to the optimal position in terms of timing separation between ingoing and outgoing particles from the IP (i.e. 6.25 ns from the IP). The gated rate information from the BCM1F should therefore give a very good handle on the comparative rate of background from beam halo to that from lumonisity products. The sensor is connected to the JK16 radiation hard amplifier [235], after which the

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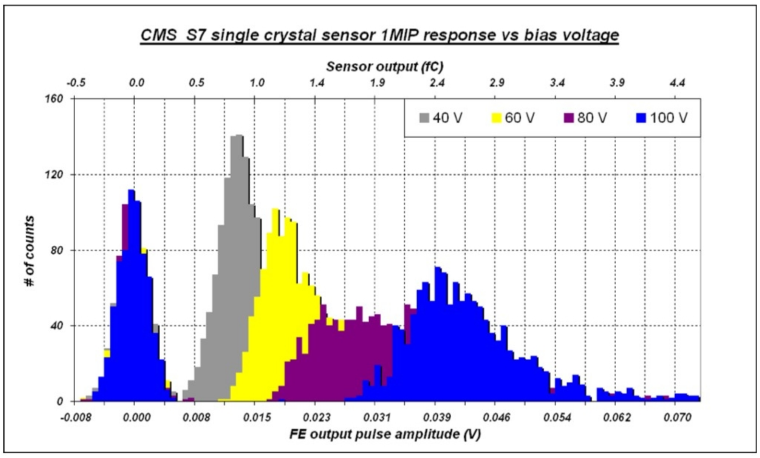

Figure 10.6: MIP response of BCM1F single-crystal diamond with front-end electronics, as a function of bias voltage of the sensor. The superposition of histograms around 0-V output amplitude indicates the noise.

signal is transmitted to the counting room over an analog optical link built from the tracker optical components [236].

The detector is sensitive to one MIP and has a timing resolution for single hits of a few ns. The performance of the front end electronics is shown in figure 10.6. Good separation can be seen between the signal and the noise. The pulse height was found to saturate at 100 V bias voltage across the sensor. The back-end readout produces rate, multiplicity, timing and coincidence information independently of the CMS DAQ. However, there is the possibility to feed information into the event stream via a standard CMS SLINK.

In a similar vein to the BCM1F, the BCM2F is composed of four diamonds at the BCM2L location, read out by a fast digitiser. The aim of this system is to provide additional diagnostic information at this location, as the digitiser can sample at 1 GHz, giving information on the sub-bunch level [237]. Whilst this will not be MIP-sensitive, it will help resolve the timing structure of periods of enhanced background.

The Beam Scintillator Counters (BSC) are a series of scintillator tiles designed to provide hit and coincidence rates, with a design similar to those used at previous experiments [238]. The scintillators and PMTs used for the BSC are recycled from OPAL [239]. The layout and geometry of the scintillator tiles are shown in figure 10.7. The BSC1 is located on the front of the HF, at ± 10.9 m from the IP, and consists of two types of tiles. Next to the beampipe are the disks, segmented into 8 independent slices in ϕ, with an inner radius of 22 cm and an outer radius of 45 cm. The primary function of the disks is to provide the rate information corresponding to the beam conditions. In addition, there are four large area "paddles" further out, at a radial distance of between ≈ 55 cm and ≈ 80 cm, which in addition to providing rate information, will also provide coincidence information which can be used to tag halo muons passing through the detector, for calibration purposes. The area covered by the BSC is about 25% of the tracker; therefore these tiles can be indicative of activity within this bunch crossing, and can be used to provide a minimum-

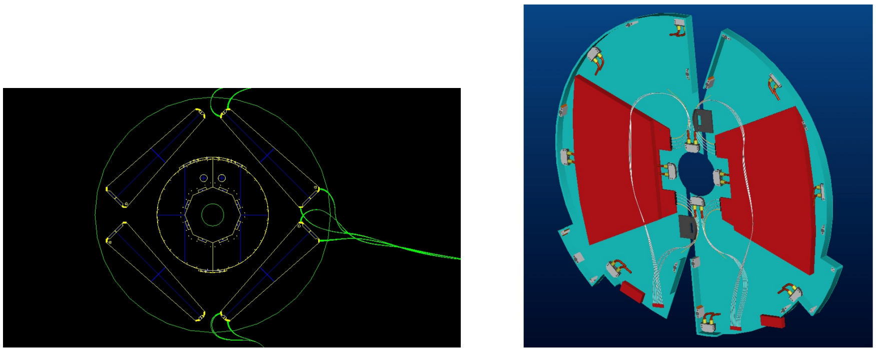

Figure 10.7: Layout of the Beam Scintillator Counters tiles. The left-hand panel shows the layout for BSC1, the right-hand panel for BSC2. The locations of the BCM2 sensors can also be seen in the right-hand panel.

bias trigger for commissioning and systematic studies. The BSC2 is located behind TOTEM T2 at ±14.4 m from the IP. The BSC2 consists of two tiles on each side of the IP, with a minimum inner radius of 5 cm and a maximum outer radius of 29 cm. The primary function of the BSC2 is to distinguish between ingoing and outgoing particles along the beamline, as there is a 4-ns timing difference between them. The rates at this location can therefore be tagged as to whether they are incoming (beam halo only) or outgoing (collision products and beam halo).

The Beam Timing for the experiments (BPTX) is a beam pickup device specifically installed to provide the experiments with the timing structure of the LHC beam. This beam pickup is a standard button monitor used everywhere around the LHC ring for the beam position monitors. Two are installed for CMS: 175 m left and right upstream of the IP. At this location there are two beampipes, and therefore the timing measurement is only of the incoming beam. To optimise the timing measurement, the four buttons (left, right, up, down) of the pickup have been electrically connected together. This is done to maximise the signal strength and hence the resolution on the timing, at the price of loosing the position information.

An oscilloscope-based read-out was chosen for the BPTX and developed in common with ATLAS [240]. The BPTX will provide accurate information on the timing and phase of each bunch and its intensity. The phases of all the experimental clocks can be compared to the measured phase of each bunch with a precision better than 200 ps. This will also allow the interaction-point z position to be calculated from the relative phases of the BPTX measurements on opposite sides of the IP. The BPTX can also detect problems with the bunch structure, and measure the proportion of beam which has drifted into the neighbouring RF bucket.

In parallel to the oscilloscope based read-out, the signals from the BPTX will also be discriminated and sent as three technical trigger inputs to the CMS global trigger. This will provide three flags on each bunch crossing as to whether: a) bunch in beam 1 is occupied; b) bunch in beam 2 is occupied; c) both beams are occupied. The flag where both beams are occupied is indicative of whether collisions can occur in this bunch crossing, and therefore provides a zero-bias trigger for commissioning of the trigger system.

At 18 locations around the CMS cavern, RADMON [241] detectors are installed. The RADMON detectors each provide well calibrated measurements of: a) the dose and dose rate using

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RadFETs; b) the hadron flux with energies above 20 MeV and the single event upset rate using SRAM; c) the 1-MeV-equivalent neutron fluence using pin diodes. RADMON detectors are installed all around the LHC ring, and in the experimental insertions. The RADMON detectors at CMS will be integrated into and read out via the accelerator-wide RADMON system.

The integrated radiation dose throughout the CMS cavern will be measured during each run period with passive dosimetry. This allows to map the radiation field throughout the cavern and will be used to validate the simulations of the anticipated doses. This gives an absolute scale to the other measurements. The dosimeters chosen are TLDs and Alanine.

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