

# Polycrystalline CdTe Detectors: A Luminosity Monitor for the LHC

**E. Gschwendtner; M. Placidi; H. Schmickler**

## Abstract

The luminosity at the four interaction points of the Large Hadron Collider must be continuously monitored in order to provide an adequate tool for the control and optimization of the collision parameters and the beam optics. At both sides of the interaction points absorbers are installed to protect the super-conducting accelerator elements from quenches caused by the deposited energy of collision products. The luminosity detectors will be installed in the copper core of these absorbers to measure the electromagnetic and hadronic showers caused by neutral particles that are produced at the proton-proton collision in the interaction points. The detectors have to withstand extreme radiation levels ( $10^8$  Gy/yr at the design luminosity) and their long-term operation has to be assured without requiring human intervention. In addition the demand for bunch-by-bunch luminosity measurements, i.e. 40 MHz detection speed, puts severe constraints on the detectors. Polycrystalline CdTe detectors have a high potential to fulfill the requirements and are considered as LHC luminosity monitors. In this paper the interaction region is shown and the characteristics of the CdTe detector are presented.

# Polycrystalline CdTe Detectors: A Luminosity Monitor for the LHC

E. Gschwendtner<sup>a</sup>, M. Placidi<sup>a</sup>, H. Schmickler<sup>a</sup>

<sup>a</sup>CERN, SL-Division, 1211 Geneva 23, Switzerland

The luminosity at the four interaction points of the Large Hadron Collider must be continuously monitored in order to provide an adequate tool for the control and optimization of the collision parameters and the beam optics. At both sides of the interaction points absorbers are installed to protect the super-conducting accelerator elements from quenches caused by the deposited energy of collision products. The luminosity detectors will be installed in the copper core of these absorbers to measure the electromagnetic and hadronic showers caused by neutral particles that are produced at the proton-proton collision in the interaction points. The detectors have to withstand extreme radiation levels ( $10^8$  Gy/yr at the design luminosity) and their long-term operation has to be assured without requiring human intervention. In addition the demand for bunch-by-bunch luminosity measurements, i.e. 40 MHz detection speed, puts severe constraints on the detectors. Polycrystalline CdTe detectors have a high potential to fulfill the requirements and are considered as LHC luminosity monitors. In this paper the interaction region is shown and the characteristics of the CdTe detectors are presented.

## 1. INTRODUCTION

### 1.1. Requirements

At the Large Hadron Collider (LHC) the relative luminosity has to be continuously measured at the four interaction points (ATLAS, CMS, LHC-B and ALICE).

Bunch-by-bunch (40 MHz) relative luminosity measurements will be implemented to provide an adequate diagnostic tool to optimize multi-bunch beam operations. The aimed accuracy is  $\pm 1\%$ /s at  $10^{34}$  cm<sup>-2</sup>s<sup>-1</sup> design luminosity.

The measurements will be calibrated with the absolute luminosity information provided by the individual experiments. In addition, independent calibrations will be performed using the TOTEM measurements done at very low luminosity ( $10^{29}$  cm<sup>-2</sup>s<sup>-1</sup>  $\rightarrow$   $10^{31}$  cm<sup>-2</sup>s<sup>-1</sup>).

The on-line monitoring of the luminosity is needed for

- Beam finding procedures.
- Optimizing the bunch overlap.
- Cross-check luminosities at different interaction points.
- Arbitrate between discrepancies of individual experiment measurements.

### 1.2. LHC Parameters

Table 1 gives an overview of the beam parameters at the interaction points ATLAS and CMS for a nominal LHC p-p run. With the total p-p cross-section of  $\sigma_{pp} = 80$  mbarn and the nominal luminosity of  $\mathcal{L}=10^{34}$  cm<sup>-2</sup>s<sup>-1</sup>, there will be  $8 \cdot 10^8$  p-p interactions/s.

Table 1  
Beam parameters at the interaction points ATLAS and CMS.

Parameters for a nominal LHC p-p run	
Beam Energy	$E=7.0$ TeV
Lorentz factor	$\gamma=7.46 \cdot 10^3$
Revolution frequency	$f_{rev}=11.2455$ kHz
Number of protons/bunch	$N_1, N_2=1.1 \cdot 10^{11}$
Colliding bunches/beam	$k_b=2808$
Normalized emittance	$\epsilon_n=3.75$ $\mu$ m rad
IP $\beta$ -value	$\beta_x^*, \beta_y^*=0.50$ m
Bunch transv. sizes (rms)	$\sigma_x^*, \sigma_y^*=15.9$ $\mu$ m
Bunch divergence (rms)	$\sigma'^*=31.7$ $\mu$ rad
Bunch length (rms)	$\sigma_s=8.4$ cm   0.280 ns
Total crossing angle	$\theta^*=300$ $\mu$ rad
Luminosity	$\mathcal{L}=10^{34}$ cm <sup>-2</sup> s <sup>-1</sup>

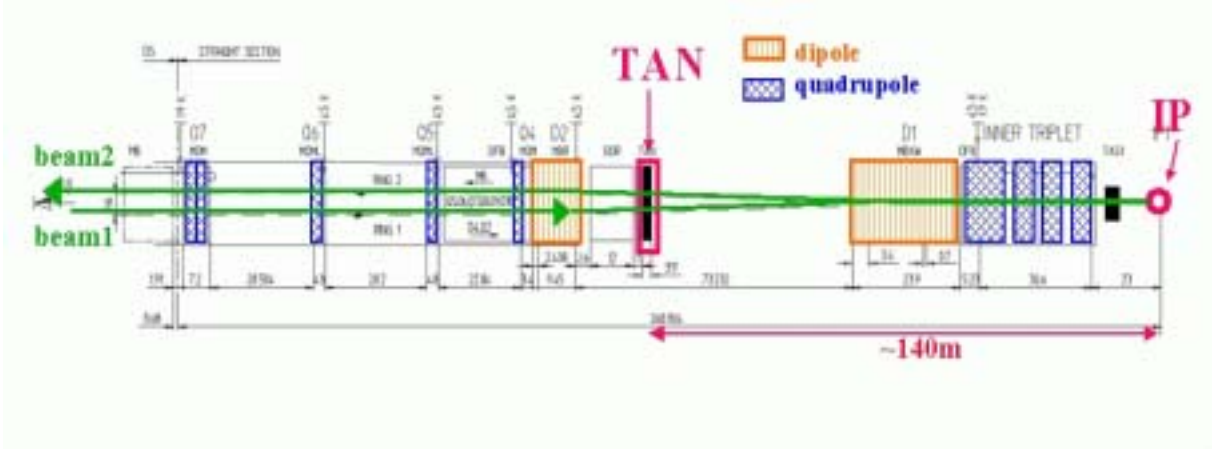


Figure 1. Layout of the LHC interaction region.

## 2. THE INTERACTION REGION

### 2.1. Layout

A schematic layout of the interaction region is shown in Fig. 1. The two beams are brought in collision at the interaction point (IP) at an angle of  $\theta^* = 300 \mu\text{rad}$ . Special purpose absorbers are designed to protect the super-conducting magnets from the interaction point radiation. The TAN absorbers are placed in front of the outer beam separation dipole D2 about 140m at each side of the IP to absorb the forward neutral collision products.

### 2.2. Particle Distributions on the TAN Absorber

The TAN absorber consists of a copper core ( $21 \times 26 \times 350 \text{ cm}^3$ ) with two 5 cm holes for the beam tubes. The copper is surrounded by massive steel shielding with a steel/marble albedo trap. The power dissipated in the core is about 200 W [1] and is caused primarily by energetic neutrals (45% neutrons and 45% photons) from the p-p interaction.<sup>1</sup>

Table 2 shows the latest simulation results [1] of the mean number of particles and the average

<sup>1</sup>All numbers are based on detailed MARS14 Monte Carlo simulations for the crossing angle of  $\theta^* = 300 \mu\text{rad}$  using DPMJET-3 as an event generator for 14 TeV p-p collisions.

energy/particles incident on the TAN absorber per p-p collision. The total particle flux  $\phi_{tot}$  [ $\text{cm}^{-2}\text{s}^{-1}$ ] at  $8 \cdot 10^8$  interactions/s is also shown.

Table 2

Average number of particles and average energy/particle per p-p collision.  $\Phi_{tot}$  is the total particle flux at  $8 \cdot 10^8$  interactions/s.

Particle Type	$\langle n \rangle$	$\langle E \rangle$ (GeV)	$\Phi_{tot}$ ( $\text{cm}^{-2}\text{s}^{-1}$ )
$n$	0.479	1516	$1.2 \cdot 10^6$
$\gamma$	301	2.2	$6.8 \cdot 10^8$
$p$	0.109	938	$2.5 \cdot 10^5$
$\pi^\pm, K^\pm$	0.875	64.8	$1.8 \cdot 10^6$
$e^\pm$	24.5	0.294	$5.3 \cdot 10^7$
$\mu^\pm$	0.006	4.87	$1.4 \cdot 10^4$

### 2.3. Shower Simulations for the TAN Absorber

Fig. 2 shows the longitudinal shower distribution at different radii initiated in the TAN absorber by a 2 TeV neutron beam with gaussian shape. We see that the shower maximum is at a depth of about 20 cm - 30 cm.

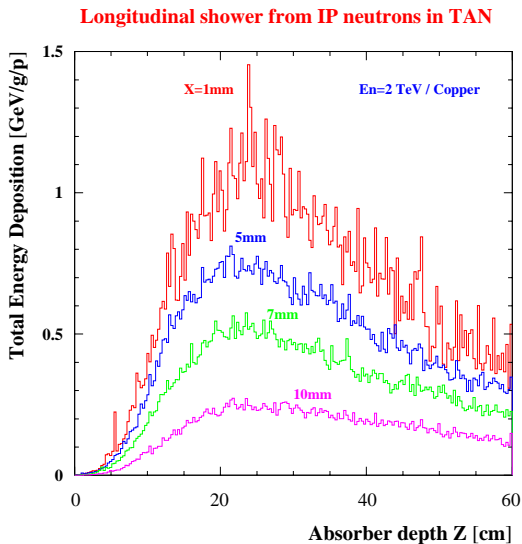


Figure 2. Longitudinal shower distribution of a 2 TeV neutron impinging on the TAN absorber.

#### 2.4. Luminosity Detectors

In order to exploit the electromagnetic and hadronic showers, luminosity detectors will be placed in the copper core of the TAN between the two beam pipes. The distance between the two pipes is at the order of 94 mm [2] which defines the space available for the detectors.

The high radiation environment ( $10^8$  Gray/yr,  $10^{17}$  n/cm<sup>2</sup>/20yr,  $10^{16}$  p/cm<sup>2</sup>/20yr), the demand for bunch-by-bunch luminosity measurements (40 MHz detection speed) and a reasonably high signal to noise ratio put severe constraints on the detectors.

At the moment there are two candidates that could meet these requirements:

##### CdTe Detector

Polycrystalline CdTe detectors from 50  $\mu$ m to 700  $\mu$ m thickness and with a pulse-width of FWHM  $\approx$  5 ns [3] have been developed at the LETI laboratories [4]. The signal yield of the CdTe detectors is very good. Hence, they can be installed inside the TAN at small absorber depths

of about 2 cm - 5 cm. There the shower has not yet reached its maximum, so the radiation requirements can be relaxed.

##### Ionisation Chamber

The chamber is pressurised with four atmospheres of Ar+1%N<sub>2</sub> and is segmented into four quadrants; each quadrant consists of 60 gaps (0.5 mm) separated by 1 mm thick Cu plates. The area of the plates is 40 mm  $\times$  40 mm.

In order to increase the signal yield, the ionisation chambers would be located near the shower maxima inside the TAN. More details of these detector can be found in ref. [5].

### 3. POLYCRYSTALLINE CdTe DETECTOR



Figure 3. Photo and geometry of the CdTe detector.

The density of CdTe is 5.83 g/cm<sup>3</sup> and the energy loss for minimum ionizing particles (MIPs) is 1.26 MeV/g/cm<sup>2</sup>. With the ionisation energy of  $E=4.43$  eV in a 300  $\mu$ m thick CdTe detector  $5 \cdot 10^4$  electrons are created. However, as we will see in section 3.1 the charge carrier lifetime is very low and only a fraction of the electrons are collected. The detectors used for the present characterisation are dies with a diameter of  $d = 1.6$  cm and a thickness of  $\approx 380$   $\mu$ m as shown in Fig. 3.

#### 3.1. Sensitivity

The sensitivity of the CdTe detectors was measured with a <sup>90</sup>Sr source. A schematic layout of

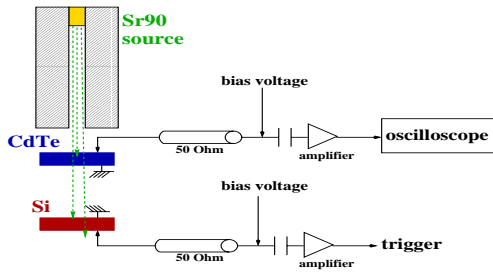


Figure 4. Test measurement set-up.

the measurement set-up and the read-out chain is illustrated in Fig. 4. The CdTe detector is connected via a 50 Ohm cable to a 2.3 GHz bandwidth fast linear amplifier (voltage gain  $\approx 500$ ). The oscilloscope is triggered by a silicon detector below the CdTe detector which assures, that low energy electrons are not measured. The signals should therefore be similar to signals from MIPs.

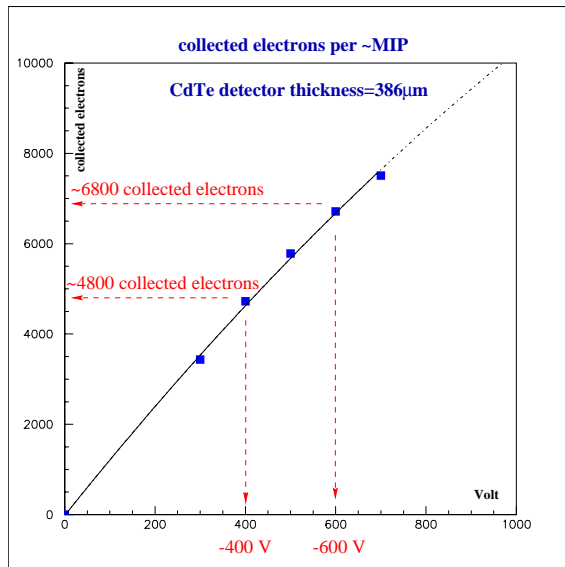


Figure 5. Collected electrons per MIP versus the bias voltage.

Fig. 5 shows the number of collected electrons versus the bias voltage. At -600 V around 7000 electrons are collected.

### 3.2. Temperature Behaviour

The luminosity monitors environment in the LHC is also 'hot' in terms of temperature. The CdTe detector have to function up to 80°C. Fig. 6 shows the dependence of the dark current on the temperature. At a voltage of -400 V the current rises from 30  $\mu\text{A}$  at 40°C up to 420  $\mu\text{A}$  at 80°C.

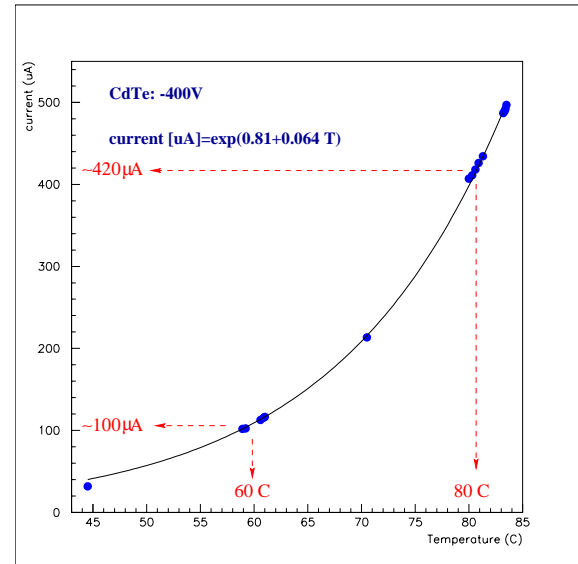


Figure 6. Dark current versus temperature at a bias voltage of -400 V.

In addition we measured the signal response to  $^{90}\text{Sr}$  electrons at different temperatures in the same set-up as described in Fig. 4. Fig. 7 shows the averaged electron signal in the CdTe detector measured at 44.5°, 61°, 70.5°, 83.3°. Although the dark current rises exponentially, the signal response stays independent of the temperature.

### 3.3. Radiation Hardness

At the TRIGA-type research reactor in Ljubljana/Slovenia a sample of CdTe detectors was ex-

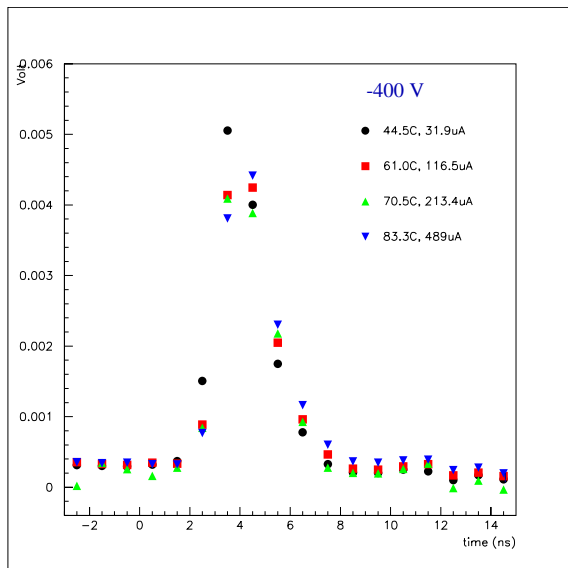


Figure 7. Average signal from  $^{90}\text{Sr}$  electrons at different temperatures.

posed to a fluence of  $10^{16}$  1 MeV neutrons NIEL in silicon equivalent<sup>2</sup>. Comparisons before and after the irradiation show that the signal decay times stays unaffected. More details can be read in [3].

### 3.4. Proposal for a Luminosity Monitor at LHC

The horizontal space between the two beam tubes in each TAN absorber is 94 mm. In order to cover this space, there will be a monitor with two arrays of five CdTe detectors, (see Fig. 8). The diameter of each detector will be  $d=1.6$  cm and the readout electrodes (gold plating) have a diameter of  $d=1.2$  cm.

## 4. SUMMARY

Instrumenting the TAN absorbers with luminosity detectors can provide a useful tool

<sup>2</sup>This means that  $10^{16}$  of 1 MeV mono-energetic neutrons would deposit the same energy with non-ionizing collisions in silicon as the neutrons to which the detectors have been exposed.

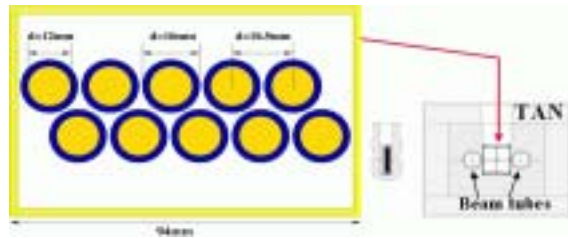


Figure 8. Luminosity monitor for the LHC with ten CdTe detectors.

for measuring and optimizing the luminosity at the LHC. Polycrystalline CdTe detectors are proposed: The signal response shows a rise-time in the sub-nanosecond range and a pulse-width of  $\text{FWHM} \approx 5$  ns. The detectors have been successfully tested to neutrons fluxes above  $10^{16}$  n/cm<sup>2</sup>. The sensitivity is  $\sim 7000$  ( $\sim 5000$ ) collected electrons/MIP/380  $\mu\text{m}$  at a bias voltage of -600 V (-400 V). Temperature tests between 40°C and 80°C show that the dark current rises from 30  $\mu\text{m}$  to 420  $\mu\text{m}$  at -400 V. However, the signal response stays independent of the temperature.

## REFERENCES

1. N. Mokhov and I.L. Rakhno, *Protecting LHC Components against Radiation Resulting from Colliding Beam Interactions*, Fermilab-Conf-01/131, 2001.
2. E.H. Hoyer and W.C. Turner, *Absorbers for the High Luminosity Insertions of the LHC*, Proc. EPAC98, 22-26 June 1998.
3. E. Rossa *et al.*, *Fast Polycrystalline-CdTe Detectors for LHC Luminosity Measurements*, Proc. IEEE Nuclear Science Symposium, San Diego, CA, 4-10 Nov., 2001.
4. LETI (Laboratoire d'Electronique, de Technologie et d'Instrumentation), CEA/Grenoble, 17 Rue des Martyrs, F38054 Grenoble Cedex, France.
5. W.C. Turner *et al.*, *Development of a detector for bunch by bunch measurement and optimisation of Luminosity in the LHC*, NIM A 461 (2001) 107-110, 2001.