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Fast Polycrystalline-CdTe Detector for LHC Luminosity Measurements

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Abstract

Beam diagnostics in future high-energy accelerators will require long lived instrumentation in highly hostile radiation environments. A research program aiming at individuating new solutions and testing them under extreme operational conditions has been launched at CERN in the framework of developments for the LHC instrumentation. Its outcome might be used in future accelerator projects, in industry or in physics applications. The detectors which will be adopted for the LHC luminosity monitoring and optimization will be installed close to or inside copper absorbers specifically designed for radiation protection of the accelerator magnetic elements in the interaction regions. These detectors will have to withstand extreme radiation levels and their long-term operation has to be assured without requiring human intervention. Polycrystalline-CdTe detectors have demonstrated their radiation hardness against extreme doses of X-ray exposure in the LEP collider and are considered as good candidates for LHC luminosity monitoring applications. After recalling a series of measurements obtained on CdTe samples exposed to different sources to study their time response and sensitivity we present results on their performance after irradiation at doses of 10^16 neutrons/cm^2. This is a preliminary step in the program intended to test the samples during and after irradiation up to levels of 10^18 neutrons/cm^2 and 10^16 protons/cm^2 comparable to those anticipated at the detector locations over ten years of operation of the accelerator.

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I. INTRODUCTION

The possibility of using the forward flux of neutral secondary particles produced at each proton-proton collision in the LHC Interaction Points (IP) has been suggested in [1]. This flux carries information about the interaction rates and the actual luminosity available to the experimental detectors.

TAS and TAN absorbers are installed at both sides of the high luminosity IP's (IP1 and IP5) to protect the super-conducting accelerator elements from quenches caused by deposited energy from this flux. The hadronic and electromagnetic showers initiated in the absorbers are proportional to the collision rate and can be exploited with an appropriate detector for a continuous monitoring and optimization of the LHC luminosity.

A bunch-by-bunch luminosity measurement, as required for the continuous optimization of the LHC operation, involves a 40 MHz detection speed in order to cope with the 25 ns time interval between successive proton-proton collisions at each Interaction Point (IP).

The extremely high environmental radiation doses associated with the operation of the accelerator in IP1 and IP5 (up to10^8 Gy/year at the LHC design luminosity) impose the adoption of radiation hard detectors materials. In addition, their operation should not require any human intervention for maintenance and/or repair.

Detector sensitivities must allow a reasonably high signal to noise ratio (S/N) in order to provide separation of multiple- from single-events per bunch interaction.

II. POLYCRYSTALLINE-CDTE DETECTORS

X-ray detectors based on Cadmium Telluride (CdTe) photo-conductors have been used to monitor the vertical emittance of the LEP beams [2]. This material has proven to withstand hard X-ray doses up to 10^{14} Gy in a 2 keV to

1 MeV energy range. Ionizing particles traversing the semiconductor material create electron-hole pairs along their trajectory and a charge flow will develop across the detector as a bias voltage is applied.

LETI laboratories [3] have developed polycrystalline CdTe detectors up to 700 µm thick and with decay times of a few ns. These devices are presently considered, together with radiation hard ionization chambers developed at LBNL [4], for application as luminosity monitors for the LHC as their fast response meets the detection speed requirements mentioned above. CdTe pixel detector arrays are of great interest in Muon Beams Diagnostics [5] as well as in Medical and Industrial imaging [6], and Space instrumentation.

The samples used for the present characterization consist of polycrystalline CdTe elements (typically 8 mm x 8 mm surface, 300 µm thick) with a gold electrode on each side.

The physical properties of some semiconductors used in particle detector techniques are summarized in Table 1. A Minimum Ionizing Particle (MIP) creates about $5x10^4$ electron-hole pairs in a 300 µm thick CdTe detector. For comparison, about $5.3x10^4$ electron-hole pairs are created in GaAs-detectors of the same thickness, $3.22x10^4$ in Si and $1.44x10^4$ in Diamond.

TABLE 1: PHYSICAL PROPERTIES AND CHARGE CREATION PER MIP FOR SOME TYPICAL SEMI-CONDUCTING MATERIALS USED IN PARTICLE DETECTION TECHNIQUES.

PARAMETER			DETECTOR			
			CdTe	GaAs	Si	Diamond
Thickness	l	[µm]	300	300	300	300
Atomic Nr	Z		48/50	31/33	14	6
Density	ρ	[g/cm^3]	5.83	5.32	2.33	3.51
Int. thickness	ρτ	[g/cm^2]	0.18	0.16	0.07	0.11
Rad. Length	X_0	[g/cm^2]	8.90	12.21	21.82	42.70
Sample r.l.	X_0^{eff}	[10^{-3} Xo]	20.2	13.1	3.2	2.6
-(dE/dx)		[MeV/g/cm^2]	1.26	1.40	1.66	1.78
Energy loss	ΔE	[MeV]	0.221	0.224	0.116	0.187
Ion. En.	I_0	[EV]	4.43	4.20	3.61	13.0
Ch/MIP	**Nq**	**[10^3]**	**50.0**	**53.3**	**32.2**	**14.4**

III. PULSE CHARACTERISTICS

The response of a CdTe polycristalline detector to MIP was measured with a 2.2 MeV ^{90}Sr beta-source. The experimental set-up is shown in Fig. 1.

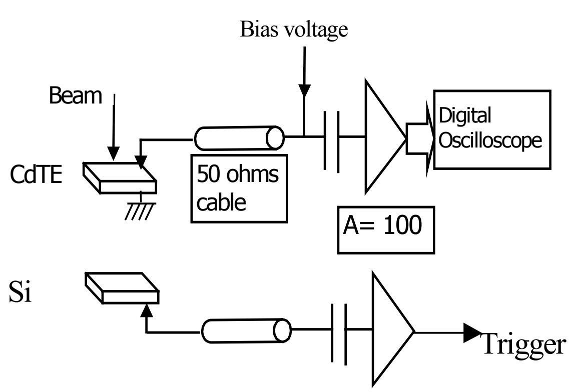

Fig. 1. Experimental set-up for the measurement of the response to MIP

The detector is connected via a 50 ohms cable to a 3 MHz - 2.3 GHz bandwidth fast linear preamplifier and to a digital oscilloscope. The signal of the detector is triggered by a silicon detector in order to reject the pulses corresponding to the low energy particles of the ^{90}Sr source. A typical pulse shape of the source is shown in Fig. 2, from which a promising S/N ratio can be derived.

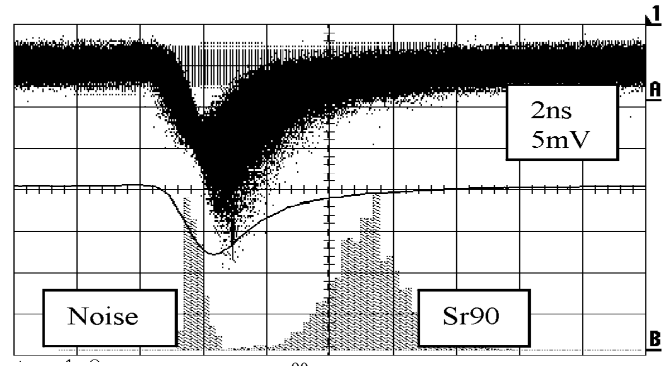

Fig. 2. Typical pulse shape of ^{90}Sr electrons. The noise level is well below the signal level.

The large pulse amplitude, comparable to the response of a silicon detector, is significative of a high mobility combined with the large applied electric field. Due to the poor transport properties of holes in this kind of material the main contribution to the measured transient signal is given by the collection of electrons. Assuming the electron mobility μ_e and the distribution of the applied electric field E_b are uniform across the thickness l of the detector, the transient properties are defined by the time dependence $n(t)$ of the electrons and the bias voltage $V_b = l\, E_b$

$$I(t) = \frac{en(t)}{l}\mu_e E_b \qquad (1)$$

Considering an initial charge equivalent to 170 electron-hole pairs/µm for a MIP, the electron mobility can be deduced from the amplitude of the current pulse. For CdTe polycrystalline detectors the mobility is found to be in the 400-700 cm^2/V/s range, while it reaches 1000 cm^2/V/s for a single-crystal CdTe structure.

The pulse shape is essentially governed by the time dependence of the number of charged in the sample. For a uniform generated charge distribution across the detector thickness we have:

$$n(t) = n_0\left(1 - \frac{\mu E_b}{l}t\right)e^{-\frac{t}{\tau_e}} \qquad (2)$$

where the exponential factor corresponds to the finite carrier lifetime τ_e. In practice the time behavior of the pulse can differ from this simple description if, for example, the charge mobility or the electric field are not uniform across the detector thickness. The carrier lifetime deduced from these measurements is typically 2.5 ns, leading to a pulse duration far below the 25 ns time interval between consecutive bunch crossings at the LHC interaction points. The product $\mu\tau_e$ reaches a comfortable value in the range of 1.7×10^{-6} cm^2/V.

IV. Detector Sensitivity

The detectors were exposed to a ^{90}Sr source in order to measure the sensitivity of the material. For this purpose close to the detector, a classical charge sensitive amplifier with a shaping time of 2 µs was used. The set-up is described in details in [7]. Well above 10^4 electrons per incident particle were detected for 470 µm thick detector [8] [9]. This was a very encouraging result, unfortunately the charge sensitive preamplifier must be used very close to the detector to obtain good signal to noise ratio. Such electronic cannot withstand extreme radiation level.

Therefore we have done a beam test using the set-up of Fig. 1. The detector was connected with few meters of 50 ohms cable trough AC coupling to the (2.3 GHz-50 ohms) linear amplifier [10]. The amplifier gain was about 100. The amplified detector current was analysed on-line with a digital oscilloscope triggered by a coincidence signal of 2 detectors in the beam.
Test results with 120 GeV pion beam are shown in Fig. 3 where the average number of electrons collected per incident particle is given as a function of applied electric field.

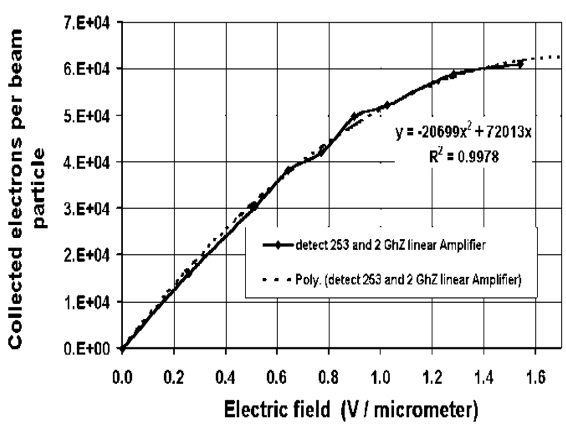

Fig. 3: Display of the charges collection measured with 120 GeV pion beam as a function of applied electric field. The detector thickness is 470 µm.

V. Radiation resistance tests

A first irradiation campaign up to 10^{15} n/cm^2 was performed at a reactor in Valduc, France. No significant modification in the sensitivity of the CdTe detector was observed [8].

More recent irradiation tests were undertaken at a TRIGA-type research reactor in Ljubljana, Slovenia. The detectors were connected to the digital oscilloscope via 10 m long, SiO_2-isolated, 50 Ohm stainless steel cables. The CdTe detector picture of Fig. 4 shows the 16 mm diameter sample assembled in its support and mechanically hold in place by a Beryllium-Copper spring .

The detector response was monitored during the irradiation by measuring the signal induced by the high energy gamma-ray flux present in the reactor. The electronic set-up used for the measurement is identical to the one described in section III. Due to the random energy deposition of the gamma rays in the detector absolute calibration of the pulse amplitude could not be performed. However the time dependency of the measured pulses is representative of the response to MIP.

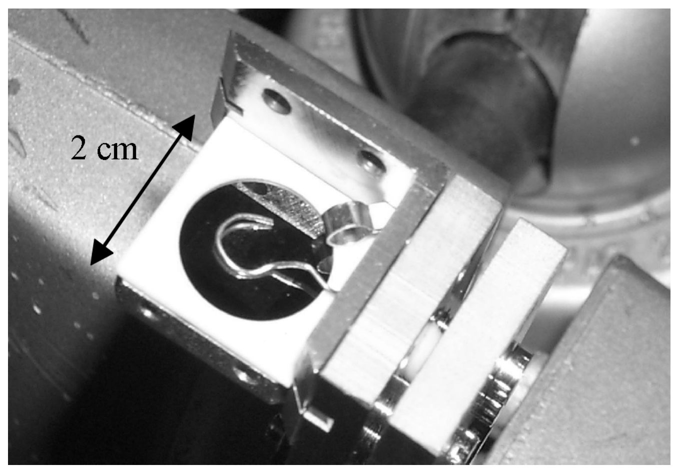

Fig 4. One of the CdTe detectors used in the irradiation tests campaign shown assembled in its support.

As the decay time is governed by the carrier lifetime, it is the only parameter of the output signal which qualifies the detector in terms of radiation resistance of its rapidity. The front-end rise time is only determined by the rapidity of the electronics involved in the tests (cables, amplifier, oscilloscope) and does not enter in the sample characterization procedure.

As shown in Fig. 5 the decay time of the current signal appears unaffected by a neutron irradiation up to a 10^{16} neutron/cm^2 level.

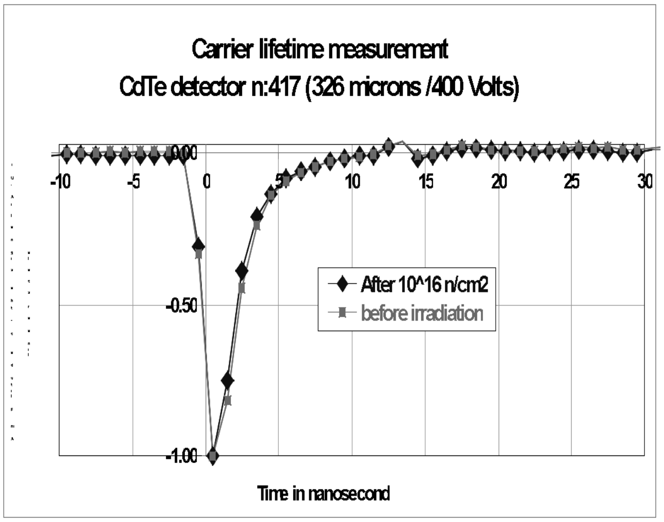

Fig. 5. Pulse shape of the current from the CdTe sample before and after neutron irradiation.

More insight into the velocity dependence of the CdTe sample on the neutron exposure is given in Fig. 6. The pulse decay-time shows a slow and a fast component practically identical before and after irradiation.

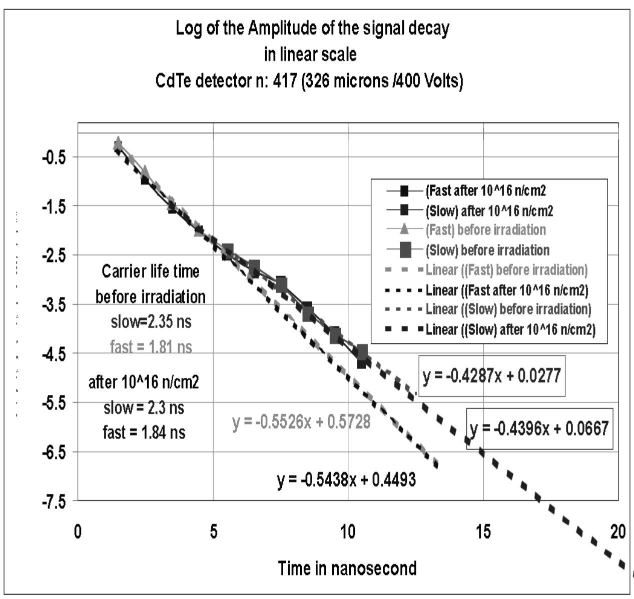

Fig. 6. The fast and slow components of the current pulse decay-time for a 300 μm polycrystalline-CdTe sample before and after irradiation.

Other parameters like the amplitude of the dark current, for a given bias voltage normalized to the thickness of the sample, are of great importance to qualify the radiation hardness of the detector to meet the criteria dictated by the specific use as the sensitive component of the LHC luminosity monitor. At present no further measurement has been perfomed due to the strong activation of the material present in the detector housing. The response to MIP will be measured as soon as the activity has decreased to acceptable levels.

VI. Outlook

We have presented the results of measurements intended to qualify polycrystalline-CdTe detectors for possible application in the monitoring of the LHC luminosity.

The time response of 300 μm thick polycrystalline-CdTe samples to a sub-nanosecond laser source showed a FWHM pulse width of a few nanoseconds adequate for the 40 MHz acquisition rate required by the 25 ns time interval between successive proton-proton collisions at the LHC.

A sensitivity in excess of 10^4 collected electrons per incident MIP was measured with a 300 V polarizing voltage. This will generate signal amplitudes easily measurable after a fast 50 Ohm preamplifier.

Preliminary irradiation tests up to 10^{16} neutrons/cm^2 have demonstrated no significant modifications in the sensitivity or in the decay-times of the current pulse.

Irradiation tests at 10^{18} neutrons/cm^2 are in preparation.

VII. Acknowledgments

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