A CdTe detector for Muon Transverse Profile Measurements

Placidi M., Rossa E., Schmickler H.

Abstract

Beam diagnostics in future High Energy Accelerators will require long lived instrumentation in high radiation environment. Detectors capable of withstanding extreme radiation levels without requiring human intervention and being operated at frontiers of radiation-resistant technology are at a prime for applications in environmental-hostile situations.

A research program has been launched at CERN in the framework of instrumentation developments for the LHC project aiming at individuating new solutions and technologies reliable under extreme operational conditions.

Preliminary ideas are presented for applications in Muon Beams Diagnostics for future Neutrino Factories of materials presently considered and tested for application in the LHC luminosity detectors.
A CdTe Detector for Muon Transverse Profile Measurements

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1 Introduction

Beam diagnostics in future High Energy Accelerators will require long lived instrumentation in high radiation environment. Detectors capable of withstanding extreme radiation levels without requiring human intervention and being operated at frontiers of radiation-resistant technology are at a prime for applications in environmental-hostile situations. A research program has been launched at CERN in the framework of instrumentation developments for the LHC project aiming at individuating new solutions and technologies reliable under extreme operational conditions. Preliminary ideas are presented for applications in Muon Beams Diagnostics for future Neutrino Factories of materials presently considered and tested for application in the LHC luminosity detectors.

2 Charge creation in semiconductor detectors

Minimum Ionizing Particles (MIP’s) create charges in semiconductor materials. While the charge production process has a linear dependence on the thickness $\tau$, the efficiency for charge collection at the detector surface decreases with it. Internal charge recombination and re-absorption processes influence the collected charge available at the detector surface for a given polarizing voltage. The multi-parameter process involves the length of the ionizing path, the geometry of the charge collecting electrode(s) which define the detector sensitive area, the polarizing voltage and the crystallographic structure of the semiconductor.

When the material budget in the beam line is an issue, as in the case of muon beam diagnostics, a good compromise between the overall sensitivity of the detector and its thickness can be achieved choosing a material offering a high specific charge production. Different materials are compared in the following Table 1 for charge production per MIP traversal for a sample thickness $\tau = 300\,\mu\text{m}$. With the symbols of Table 1 the specific charge production along the ionizing trajectory inside the detector is

\[ N_q = 10^6 \frac{\Delta E}{l_\text{o}} = - \left( \frac{dE}{dx} \right)_{\text{min}} \frac{p\tau}{l_\text{o}} \text{ (charges/MIP).} \]
<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DETECTOR</th>
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<tbody>
<tr>
<td></td>
<td>CdTe</td>
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<tr>
<td>Sample thickness</td>
<td>$\tau$</td>
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<tr>
<td>Atomic number</td>
<td>$Z$</td>
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<tr>
<td>Density</td>
<td>$\rho$</td>
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<td>Interaction thickness</td>
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<tr>
<td>Material radiation length [1]</td>
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<td>Sample radiation length</td>
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<tr>
<td>Energy loss rate</td>
<td>$-(dE/dx)_{\text{min}}$</td>
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<tr>
<td>Energy loss</td>
<td>$\Delta E$</td>
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<tr>
<td>Mean Ionization Energy</td>
<td>$I_o$</td>
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<tr>
<td>Charges/MIP (inside detector)</td>
<td>$N_q$</td>
</tr>
</tbody>
</table>

Table 1: Physical properties and charge creation per MIP for some semiconductors. Radiation length figures are derived from $X_o$ data in Ref.[1]

3 CdTe photo-conductors

X-ray detectors based on CdTe photo-conductors have been used to monitor the vertical emittance of the LEP beams [2]. This material has proved to withstand hard X-ray doses up to $10^{13}$ Gy in a synchrotron radiation energy range between 2 keV and 1 MeV.

Photon pulses or ionizing particles impinging the semiconductor material of the CdTe photo-conductors create hole-electron pairs along their trajectory in the detector. A charge flow across the semiconductor will develop as a bias voltage is applied. The rise time of the associated current pulse is defined by the transit time of the ionizing particle in the detector, while the decay time is governed by recombination processes $^1$ of the carrier.

LETI laboratories [3] have developed a deposition process of thick-polycrystalline-CdTe layers with thicknesses between $\sim$50 to 700 $\mu m$ and decay times of a few ns. These detectors are being considered for application as luminosity monitors for the LHC where a decay time of $\sim$10 ns is required to ensure the required 40 MHz acquisition speed [4].

The number of charges per MIP collected in a 470 $\mu m$, 2 cm$^2$ CdTe sample has been measured after irradiation up to $10^{15}$ n/cm$^2$ [5] providing an experimental figure for the effective charge collection at the detector surface:

$$N_{e^{\text{eff}}} = 10^4 \text{ e/MIP}.$$

$^1$Typically of the order of a few $\mu$s in mono-crystal structures, sub-picosecond decay times can be attained by proper processing of polycrystalline detectors.
4 A semi-invasive transverse profile CdTe detector

We investigate the possibility of using polycrystalline-CdTe detectors to monitor the two-dimensional transverse muon distribution in the cooling section of a typical Neutrino Factory project.

The detector consists of an array of charge sensitive elements each providing a signal with amplitude proportional to the intercepted muon beam density. Two-dimensional transverse muon profiles are obtained by a charge-position correlation from the array elements.

Industrial development of pixel-size CdTe detector arrays for medical applications is under way [3]. A ∼1 cm² granularity is adequate to the accuracy of our diagnostics. A sandwich-style detector would consists of a CdTe layer uniformly deposited on the metalized side of a 0.3 mm thin Al₂O₃ support or other light material [3] [6] which provides the common polarity of the biasing voltage and the mechanical rigidity to the wafer. A charge collecting array of 10×10 or 20×20 ∼2 cm² gold electrodes deposited on a capton thin foil facing the CdTe layer and designed to match the required granularity would constitute the detector sensitive pattern.

A single electrical connection is required per charge collecting element, to provide the biasing voltage polarity for individual calibration and to collect the charge signal. The detector dimensions should cover a ∼20 × 20 cm² muon beam cross section or larger, as anticipated in the cooling section of a Neutrino Factory facility.

The sensitivity (2) is such that no front-end electronics is needed close to the detector. This represents a remarkable advantage towards the realization of relatively large array structures, which can be directly exposed to the beam. Another evident simplification is the absence of background problems on the electronics itself and cables, originating from radiation or electro-magnetic (RF) environments.

4.1 Muon flux in the Cooling Section

An estimate of the muon fluxes expected in the cooling section of the CERN Neutrino Factory approach [7] is recalled here with the aim of evaluating the sensitivity required for a detector to measure two-dimensional transverse muon distributions.

Given the following parameter set for a proton Linac driver [7]

\[
\langle P_p \rangle_{\text{linac}} = 4 \text{ MW} \quad \text{ (Linac CW power)}
\]
\[
E_p = 2.2 \text{ GeV} \quad \text{ (proton beam Energy)}
\]
\[
\tau_b = 3.3 \mu\text{s} \quad \text{ (proton burst time length)}
\]
\[
f_{\text{rep}} = 75 \text{ Hz} \quad \text{ (Linac rep. rate)}
\]

the proton yield is, for a 10⁷ s operational year (o.y.),

\[
N_p = \frac{\langle P_p \rangle_{\text{linac}}}{10^9 e E_p f_{\text{rep}}} = 1.5 \times 10^{14} \text{ p/burst} \quad (\sim 10^{23} \text{ p/o.y.}). \quad (3)
\]

A pion/proton production efficiency \( \eta_{p\pi} \) for a 26 mm Hg target has been simulated and extrapolated to a 300 mm target length [8]. We have assumed a figure \( \eta_{p\pi} \sim 0.04 \pi/p \) to account for re-absorption effects in the target, presently being evaluated [9].
Simulated muon/pion budget $\eta_{\pi\mu}$ for both the phase rotation (RF) [10] and the Induction Linac (IL) [11] schemes, provide a consistent figure of $\eta_{\pi\mu} \sim 0.05 \mu / \pi$.

Assuming a global muon/proton budget

$$\eta_{p\mu} = \eta_{p\pi} \eta_{\pi\mu} \approx 2 \times 10^{-3} \mu / p$$

(4)

the expected average muon beam intensity in the cooling channel is

$$\langle N_{\mu} \rangle = \eta_{p\mu} N_p \approx 3 \times 10^{11} \mu / \text{burst} \ (\sim 2 \times 10^{30} \mu / \text{o.y.}).$$

(5)

4.2 Detector sensitivity, dynamic range and linearity

The intensity (5), distributed across a $\sim 500 \, \text{cm}^2$ transverse beam section, will represent an average intensity per detector element

$$\langle \Delta N_{\mu} \rangle \approx 3 \times 10^8 \mu / \text{burst/element}$$

(6)

over an array with a conservative $\sim 50\%$ active factor (sensitive area/support surface) and $1 \, \text{cm}^2$ elements.

The sensitivity in terms of collected charge per incident muon is extrapolated from the measured yield (2) obtained with a $470 \, \mu m$ thick CdTe sample. Scaling Eqn.(2) to a $\tau = 50 \, \mu m$ thickness the average number of charges at the detector surface is:

$$N_{\text{ch}}(\tau) = \frac{\tau}{470} N_{e}^{\text{eff}} \langle \Delta N_{\mu} \rangle \approx 3 \times 10^{11} \text{e/burst/element}.$$ 

(7)

We estimate the detector dynamic range assuming the transverse muon beam density can be described by a two-dimensional partially correlated Gaussian distribution function

$$N_{\mu}(x, y) = N_{\mu}(0, 0) \exp \left[ -\frac{1}{2(1-\rho^2)} \left( \frac{x}{\sigma_x} \right)^2 - \frac{2\rho x y}{\sigma_x \sigma_y} + \left( \frac{y}{\sigma_y} \right)^2 \right].$$ 

(8)

The correlation factor $|\rho| \leq 1$ accounts for the effects of the solenoidal field surrounding the proton target on the muon beam distribution in the cooling channel. Its value depends on various operating scenarios and is presently the object of simulation studies [12].

A conservative figure $\rho = 0.5$ gives for the electronic dynamic range $E_e$ required to detect muons at $\pm 2\sigma$:

$$E_e = \frac{N_{\mu}(0, 0)}{N_{\mu}(2\sigma)} = \exp \left[ \frac{2}{1-\rho^2} \right] = 14.4.$$ 

(9)

Together with the detector sensitivity (7) Eqn. (9) shows that a $50 \, \mu m$ thin CdTe element would provide a high quality measurement of the muon flux distributions down to $\pm 2\sigma$ where a collected charge in excess of $10^{10} \, \text{e/burst/element}$ is attainable.

The linearity of the response of the CdTe elements in presence of the anticipated muon intensities (6) is not presently known and has to be determined experimentally. Comparative measurements with silicon detectors are planned in the framework of the instrumentation being designed for the CNGS project [13].
4.3 Material budget

A 0.3 mm thick Al₂O₃ support represents about 6 × 10⁻³ radiation lengths and a 50 μm thin CdTe layer about 3 × 10⁻³ radiation lengths (Table 1).

The proposed semi invasive detector would represent a material budget of a few 10⁻³ radiation lengths if special light supports [3] [6] are adopted.

A remote controlled driving system is envisaged to position the detector in the beam from its rest position for data taking times of the order of seconds.

4.4 Present status and envisaged tests

The development of thin CdTe arrays is being pursued at the LETI laboratories independently from the production of thick CdTe elements for the LHC instrumentation. A prototype of the described array detector might be available in a few months.

The use of this detector in a muon cooling channel does not involve extreme radiation exposure and the sensitivity (2) measured after moderate irradiation [5] is considered appropriate.

Electro-magnetic background from the RF environment in the beam line could affect the front end electronics if closely connected to the active area of the detector. The detector itself might suffer, depending on its distance from the RF gaps, from charged particle emission from the cavity walls. The layout of a possible muon cooling experiment is not yet finalized to define in detail the position of a profile detector with respect to the cavities and to decide of their influence on its performance. Present proposals for a muon cooling experiment [14] [15] require, among other parameters, a measurement of the beam emittance before and after a modular sequence of RF cavities and absorbers. For this purpose the profile detector is not required to be installed close to an RF cavity but rather at a given distance from it, according to the extent of the absorber sections. To make this point clear, RF tests should be finalized to reproduce to the best possible way the environment in a realistic muon cooling experiment, and planned on detector prototypes close to their final configuration.

Linearity tests will be performed to verify the behaviour of the array CdTe elements as a function of the incoming beam intensity and energy.

5 Outlook

A semi invasive muon profile detector is proposed to measure two-dimensional transverse muon distributions in the cooling channel of a typical Neutrino Factory.

The material budget of the detector is of some 10⁻³ radiation lengths.

A multi element thin array of polycrystalline-CdTe semiconductor deposited on a light support would provide the desired information via a correlation between the spatial position of the charge sensitive elements in the beam and the collected charge amplitude.

The sensitivity in terms of charges produced per incident muon in a 50 μm thick CdTe sample, extrapolated from experimental data obtained from 470 μm thick elements after irradiation to a 10¹⁵ n/cm², looks promising.

This detector will obviously respond, as most similar ones, to all charged particles in the muon beam. Charge and mass discrimination will be needed to extract the required phase space information for the good muons.
References


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