Cadmium Telluride Sensor

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Abstract

Precision timing detectors for high energy physics experiments with temporal resolutions of a few 10 ps are of pivotal importance to master the challenges posed by the highest energy particle accelerators such as the LHC. Calorimetric timing measurements have been a focus of recent search, exploiting the temporal coherence of electromagnetic showers. Sensitive materials such as high light yield crystals are a viable detector technology as are silicon sampling calorimeters. Silicon sensors have very high efficiency for charged particles. The sensitivity to photons however is limited. A large fraction of the energy in an electromagnetic shower is carried by photons. To enhance the sensitivity to this portion of the shower sensor materias with higher atomic numbers than silicon are preferable. In this paper we present test beam measurements with a Cadmium-Tellurid sensor as an active element in a calorimeter with a particular focus on the timing performance of the detector. A Shotky type Cadmium-Tellurid sensor with an active are of $1cm^2$ and a thickness of 1 mm is used in an a rrangement with tungsten and lead absorbers. Measurements are performed with electron beams in the energy range from 2 GeV to 200 GeV. A timing resolution of 20 ps is achieved.

Key words:
Cadmium Telluride, Timing, Calorimeter

1. Introduction

There has been much recent interest in highly granular calorimeters with precision timing capability at the level of $20 - 30$ ps for the High-Luminosity LHC and future higher energy hadron colliders. In order to probe increasingly rare interactions, future hadron colliders must provide an increase in the instantaneous luminosity well above $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. With current accelerator and particle detector capabilities, such a high instantaneous luminosity will invariably result in very large amounts of pileup, exceeding several hundreds of simultaneous inelastic collisions per bunch crossing. The ability to discriminate between particles produced by different inelastic collisions will be essential for future particle detector systems. Detectors capable of measuring the time of arrival of particles very precisely can be used to discriminate between particles produced by different inelastic collisions at different physical locations along the beam axis. Taking

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the beam bunch profile of the LHC as the model for future colliders, a detector that can measure the time of arrival of a particle with a precision of $20 - 30$ ps can effectively reduce the impact of pileup by a factor of 5 to 10.

Much recent interest has focused on highly granular calorimeters based on silicon sensors as the active material [**? ?**], due to radiation hardness considerations as well as maturity of the silicon sensor technology. In this article, we propose the first studies of a calorimeter prototype using Cadmium Telluride (CdTe) sensors as the active material. CdTe has been studied extensively in the context of thin film solar cells and has become a mature and wide-spread technology [**?**]. It has also been used as a radiation detector for nuclear spectroscopy, and is known to have high quantum efficiency for photons in the x-ray range of the spectrum. This feature is of particular interest in the context of its use in calorimetery because it would be uniquely sensitive to secondary electromagnetic shower particles in the keV range. Conventional prototypes using silicon or scintillator material is not directly sensitive to such high energy shower secondaries. Therefore, the first study of electromagnetic showers using CdTe sensors has the potential to yield new insight into the behavior of secondary particles produced within an electromagnetic shower with energies in the keV range, and has the potential to yield an improvement on the energy measurement due to the additional contribution of the higher energy x-ray photons to which previous calorimeters were not sensitive.

The recent interest in precision timing capabilities has intensified the study of the timing properties of silicon sensors. They have been shown to yield 20 ps level precision given sufficiently large signal size in a variety of applications ranging from calorimetery [**?**] to charged particle detectors [**?**]. The signal formation process in CdTe sensors are very similar to the process in silicon and has similar potential to yield precise timestamps.

In this article, we study the signal response of the CdTe sensor to electromagnetic showers of varying energies and at different shower depths. We also study the timing performance of the CdTe sensors for electromagnetic showers.

2. Cadmium Telluride Sensor

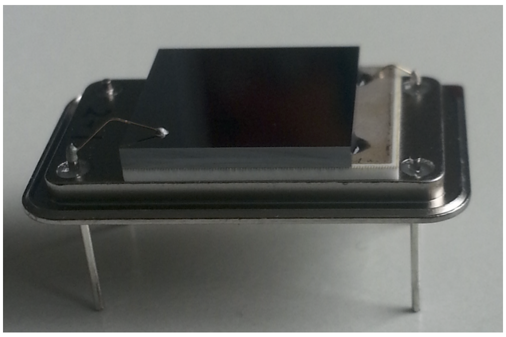

Figure 1: Cadmium-Tellurid sensor used in the setup. The sensor is a Shotky type diode with a transverse size of $1cm^2$ and a thicknees of 1 mm. It is biased at 700 V.

3. Test-beam Setup and Experimental Apparatus

We performed the test-beam measurements at the H2 beamline of the CERN North-Area testbeam facility and the T9 beamline of the CERN East-Area testbeam facility. They provide secondary electron beams from the Proton Synchrotron (PS) and Super Proton Synchrotron (SPS) of energies ranging from 2 GeV to 200 GeV. The secondary beams are composed of a mixture of electrons, pions, and muons.

Trigger counters made of photomultipliers coupled to plastic scintillators are used to initiate the read out of the data acquisition (DAQ) system. The DAQ system uses a CAEN V1742 switched capactor digitizer based on the DRS4 chip. Gas wire chambers are used to measure the position of each incident beam particle in the plane transverse to the beamline. A stack of lead or tungsten absorbers of different thicknesses are placed about 5 mm in front of the Cadmium Telluride (CdTe) sensor, which is enclosed within a metal box covered by copper foil. We amplified the size of the signals from the CdTe sensor using a Hamamatsu C5594 amplifier with a bandwidth of 1.5 GHz and providing a voltage gain of 36 dB. A micro-channel plate photomultiplier (MCP-PMT) detector is used to provide a very precise reference timestamp. At the T9 beamline, a Hamamatsu R3809U MCP-PMT is placed just upstream of the absorber material. At the H2 beamline a Photek 240 MCP-PMT is used, which contains a significant amount of absorber material (about 1.8 radiation lengths), and is therefore placed just downstream of the CdTe sensor to avoid inducing an early electromagnetic shower. The precision of the time measurement for both types of MCP-PMT's is less than 10 ps [?]. The purity of the electron beam at the T9 beamline is significantly lower than at the H2 beamline, and therefore we use a LYSO crystal optically coupled to an MCP-PMT as a means of discriminating the electrons from the pions in the beam. The schematic diagrams of the experimental setups at H2 and T9 are shown in Figure ??.

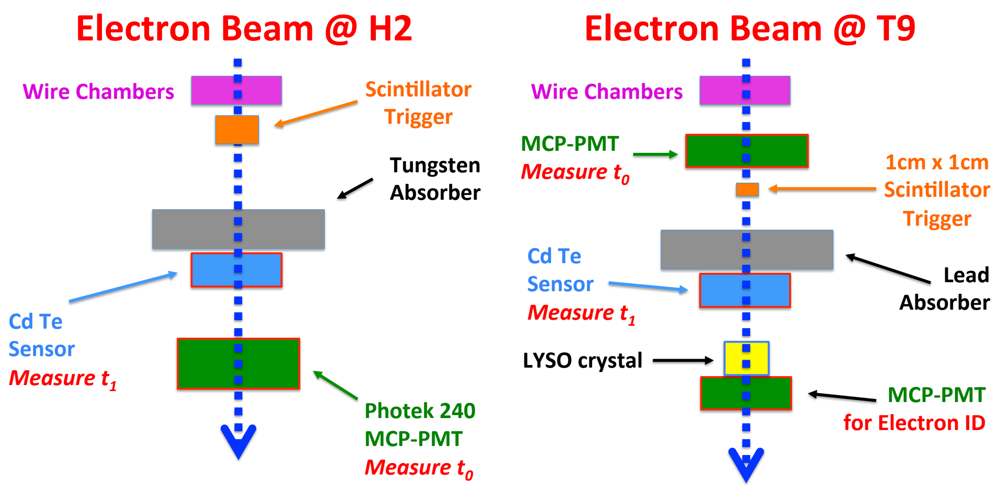

Figure 2: Schematic diagrams of the test-beam setups at H2 (left) and T9 (right) are shown. The timestamps t_0 and t_1 are defined in Section ??.

The X and Y position measurements from the wire chamber are used to determine the location of the CdTe sensor relative to the beam and to align the beam. In Figure **??**, we show plots of the average amplitude measured in the CdTe sensor as a function of the X and Y positions as measured by the wire chamber. Based on these plots, we can restrict our measurements to the electrons whose impact point is close to the center of the CdTe sensor.

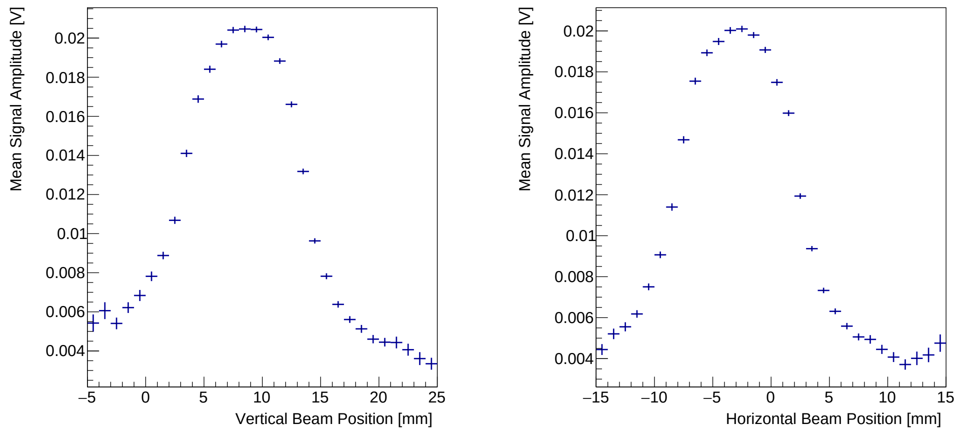

Figure 3: The average amplitude measured in the CdTe sensor is plotted as a function of the horizontal and vertical positions of the beam particle as measured by the wire chamber.

4. Event Reconstruction and Selection

Signals from each detector is recorded by the CAEN V1742 digitizer at 0.2 ns time intervals. The baseline pedestal for each channel is determined using the time samples outside of the signal window, and is subsequently subtracted from the signal pulses. Examples of recorded signal waveforms in the CdTe sensor for electromagnetic showers are shown in Figure **??**. Using randomly triggered data, we measured the RMS of the noise for the channel reading out the CdTe sensor to be about $1.2 - 1.3$ mV.

The total charge collected in each channel is obtained by computing the integral of the pulse waveform. The time stamp for each signal is reconstructed by fitting the pulse waveform with an appropriate functional form. For signal pulses from the MCP-PMT's, used as reference timers, we fit a gaussian function to a 1.5 ns window around the peak of the pulse and extract the timestamp t_0 as the mean parameter of the gaussian function. For signal pulses from the CdTe sensor, we fit a linear function to time sample points between 10% and 60% of the pulse maximum and the timestamp t_1 is assigned as the time at which the fitted linear function rises to 30% of the pulse maximum. More details of the time stamp reconstruction can be found in reference [**?**].

Based on the results shown in Figure **??**, we select events for which the incident beam particle lies within the geometric area covered by the CdTe sensor. The region with X coordinate between 2.5 mm and 13.5 mm and Y coordinate between -8.0 mm and 2.0 mm is selected. We require that the signal in the reference MCP-PMT detector

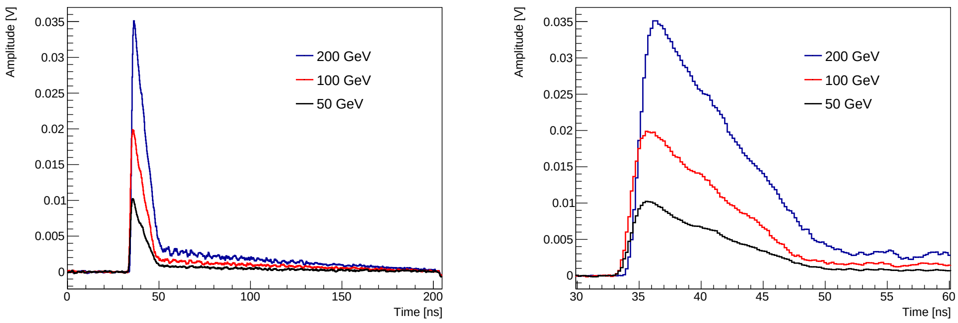

Figure 4: Examples of signal pulses in the CdTe sensor for electrons with energies of 50 GeV, 100 GeV, and 200 GeV. Right: Zoom in of the example pulses.

has an amplitude larger than 25 mV. For data collected at the H2 beamline, the MCP-PMT detector is located behind the absorbers and can disriminate between electrons that shower in the absorber material and pions that do not. We require that the signal amplitude in the MCP-PMT detector is larger than 500 mV to select a pure sample of electrons. For data collected at the T9 beamline, the electron selection is performed using the LYSO scintillating crystal placed behind the absorber material and the CdTe sensor, as shown in Figure **??**. The electromagnetic shower particles produce scintillation light in the LYSO crystal and are read out by an MCP-PMT. We require that the signal amplitude in the MCP-PMT coupled to the LYSO crystal is larger than 800 mV to select a sample of pure electrons. Furthermore, as the precision of the beam particle position measured by the wire chambers at the T9 beamline is relatively poor, we also require large signals in the 1 cm $\times$ 1 cm scintillator trigger counter, with amplitude above 150 mV, to constrain the beam to a smaller geometric region.

5. Calorimetric Measurements

To obtain a preliminary characterization of the calorimetric performance of the CdTe sensors, we measure the total charge collected out of the CdTe sensor for various incident electron beam energies. Examples of the charge distributions are shown in Figure **??** for 2 GeV and 200 GeV electrons.

We plot the mean collected charge as a function of the incident beam energy in Figure **??** and observe that the signal size scales up with increasing beam energy. The measured resolution is shown by the green error bars in Figure **??**, and is about 50% for electrons in the range of a few GeV and about 30% for electrons above 50 GeV. These resolution measurements are encouraging given that they are performed using only a single layer sample covering a relatively small transverse geometric area. In future studies, we intend to complete measurements of the longitudinal shower profile and to instrument a larger transverse geometric area to improve the transverse shower containment.

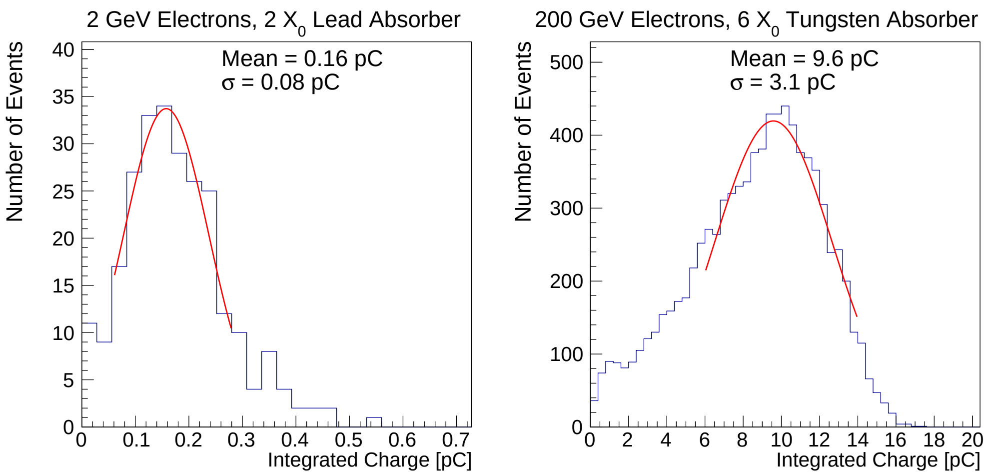

Figure 5: Distribution of total charge collected in the CdTe sensor for a 2 GeV electron after 2 X_0 of lead absorber (left) and a 200 GeV electron after 6 X_0 of tungsten absorber (right).

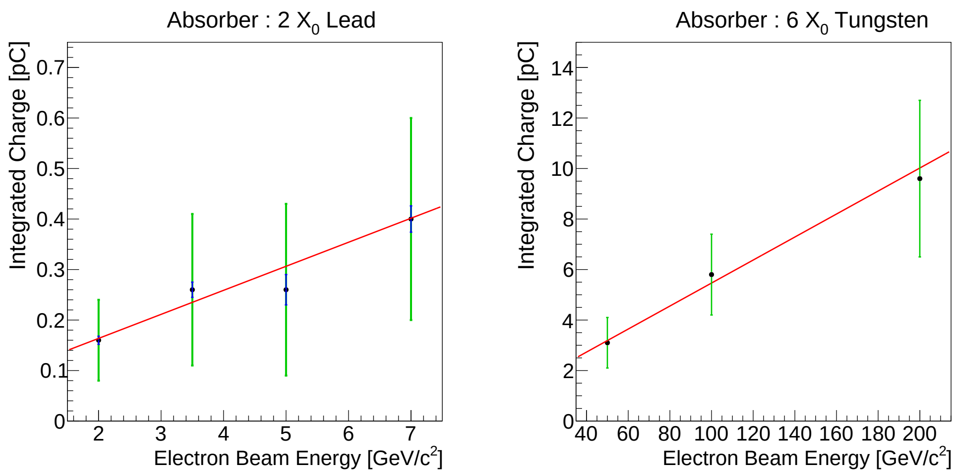

Figure 6: The mean charge collected in the CdTe sensor is plotted as a function of the electron beam energy. Left: Measurements performed at the T9 beamline with 2 X_0 of lead absorber placed directly in front of the CeTe sensor. Right: Measurements performed at the H2 beamline with 6 X_0 of tungsten absorber placed directly in front of the CeTe sensor. The blue error bars show the uncertainty on the mean integrated charge, while the green error bars show the measured resolution. The red line is a linear fit to each set of measured data.

6. Timing Measurements

We characterize the timing performance of the CdTe sensor by measuring the timestamps relative to the MCP-PMT device used as a reference timer. In Figure **??**, we show the dependence of the timestamp measurement on the amplitude of the signal, and observe no significant amplitude dependence.

Figure 7:

We also study the dependence of the timestamp measurement as a function of the geometric position of the incident beam particle as measured by the wire chambers in Figure **??**. A clear linear dependence is observed, and this geometric position non-uniformity of the time response adds significantly to the time resolution (XX ps). Performing a correction for this non-uniformity results in a time resolution of YY ps.

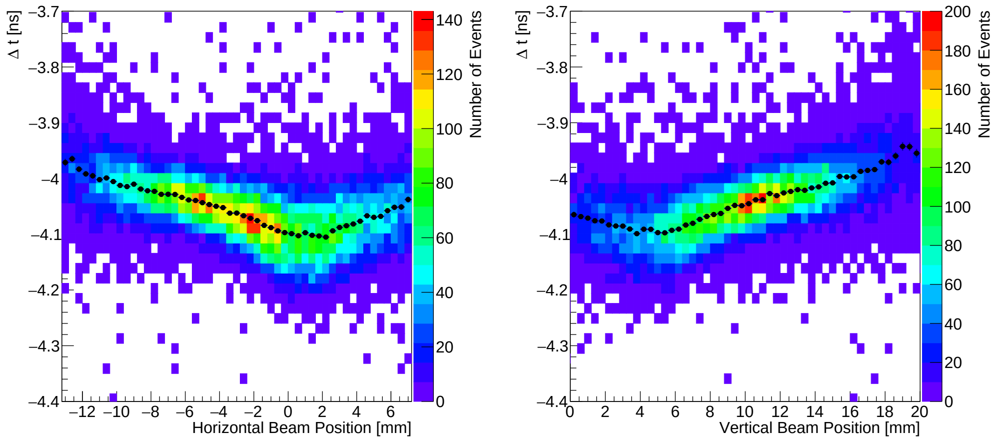

Figure 8: The distribution of the beam particle position measured by the wire chamber and the time measured in the CdTe sensor relative to the Photek reference detector is shown in the color scale. The mean value of the time measured in the CdTe sensor as a function of the beam particle position is shown in the black points.

An example of the distribution of the timestamp measurement after correcting for the beam location for 100 GeV electrons after 6 X_0 of absorber material is shown in Figure **??**. We extract the time measurement resolution from this distribution as the width parameter of a gaussian fit. The time measurement resolution has a mild dependence on the beam particle position and is shown in Figure **??**.

The same measurement is performed on various beam energies and is summarized in Figure **??**. Including the position non-uniformity correction, we obtain a time resolution of 25 ps for electrons with energy above 100 GeV.

Figure 9: Distribution of the timestamp measurement in the CdTe sensor for a 100 GeV electron after 6 X_0 of tungsten absorber.

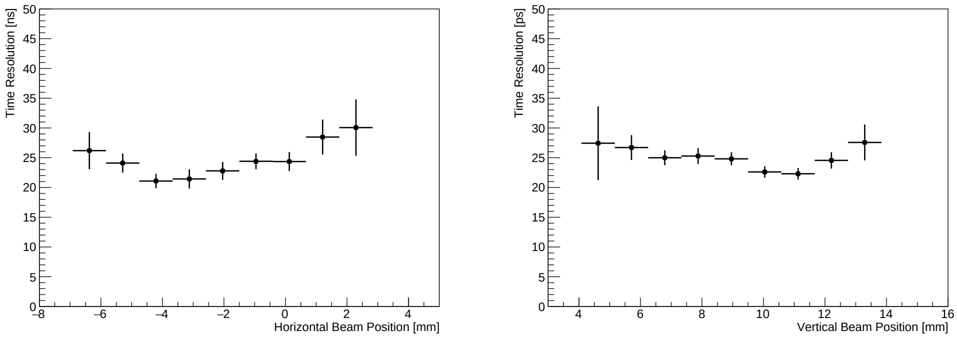

Figure 10: The time resolution is measured as a function of the horizontal (left) and vertical (right) beam position.

Figure 11: The measured time resolution of the CdTe sensor is plotted as a function of the electron beam energy.

To further characterize the timing performance of the CdTe signals, we measure the risetime, defined as the time for the signal to rise from 10% to 90% of the maximum amplitude, for various electron beam energies. The distribution of risetime for 100 GeV electrons are shown on the left of Figure **??**. The measured risetime as a function of the beam energy is shown on the right of Figure **??**. We observe a risetime that is relatively stable at around 1.3 ns.

7. Discussion and Summary

In this article, we describe the first measurement of high energy electromagnetic showers using Cadmium Telluride sensors. The signal response is consistent with expectations and show ....[to be checked more carefully]...compared to silicon. These initial results are encouraging and motivate future work on more detailed comparisons with simulation and more detailed measurements of transverse and longitudinal shower profiles.

The energy loss per g/cm^3 mass density for a minimum ionizing particle (MIP) is 1.66 MeVg^{-1}cm^2 [**?**]. For CdTe, with a density of 6.2g/cm^3, the energy loss is 1.03 keV/μm. The mean energy to produce an electron hole pair in CdTe is 4.43 eV [**? ?**], resulting in a signal size of 233 electron hole pairs per μm thickness per MIP, or 37 fC/mm per MIP. This signal size for the CdTe sensor is a factor of 2.2 larger per unit thickness than for silicon sensors.

We have measured the rise time for signals in the CdTe sensor to be about 1.3 ns, which is relatively fast and suggests that there is potential for excellent time precision. We observe dependencies of the measured time on the geometric position of the incident beam particle, which is likely due to differences in the charge collection path. More detailed studies of this aspect are needed and a more optimal design of the readout system is possible. Correcting for these dependencies yield time precision results of 25 ps for a single layer CdTe sensor of transverse area 1 cm$\times$ 1 cm sampling the electromagnetic shower of

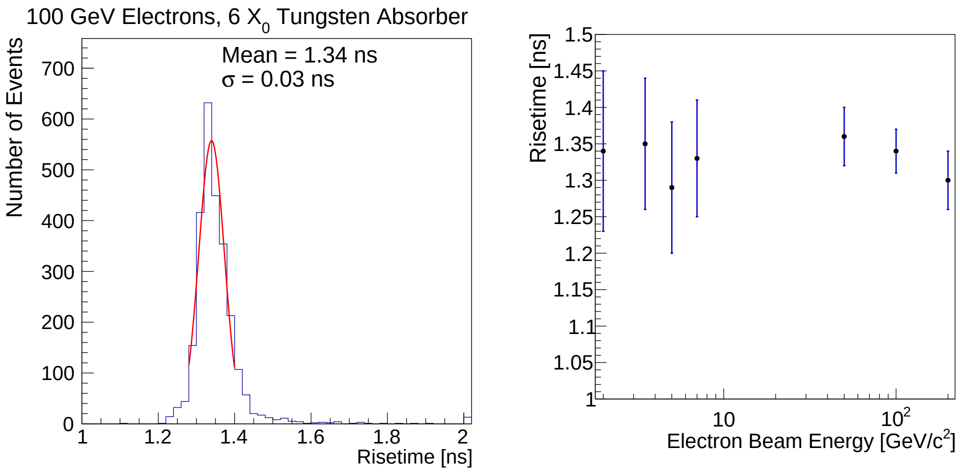

Figure 12: Left: Distribution of risetime of the CdTe signal for 100 GeV electrons. Right: Risetime of the CdTe signal is plotted as a function of the incident beam energy.

a 200 GeV electron after 6 radiation lengths. These initial results are encouraging and motivate further in-depth studies in the future.