Measurements of CVD Diamond properties for TESLA Beam Calorimeter

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The Beam Calorimeter (BeamCal) at the Very Forward Region of the TESLA detector will be located at very high background and requires a radiation hard sensor material. A Diamond-Tungsten sandwich calorimeter is one of the possible options for the BeamCal design, because of high radiation hardness of Chemical Vapour Deposited (CVD) diamond. During my work as a summer student in the TESLA group at DESY Zeuthen several samples of CVD diamonds produced by different manufactures have been studied.

1 Introduction

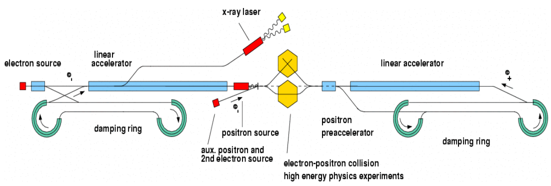

Fig. 1: Sketch of the overall layout of TESLA

Tab. 1: The basic parameters of TESLA

$\sqrt{s}$	Tev	0.5
gradient	MeV/m	23.4
Luminosity	$10^{34} cm^{-2} s^{-1}$	3.4
train/s		5
beam pulse length	μs	950
bunches		2820
bunch spacing	ns	337
charge per bunch		2×10^{10}
beam size, σ_x	nm	553
beam size, σ_y	nm	5
bunch length, σ_z	mm	0.3

Since 1992 a new linear accelerator with superconducting resonators is being developed by an international collaboration. This project is known as TESLA (TeV-Energy Superconducting Linear Accelerator).

TESLA is a project of a linear polarized electron-positron collider with a total length of 33 km and a center of mass energy between 90 GeV and 800 GeV proposed by the DESY laboratory. The high energies can be reached using techniques of acceleration based on the use of superconducting cavities [1].

A principle scheme of the planned setup is shown in Fig. 1.

2 BEAM Calorimeter

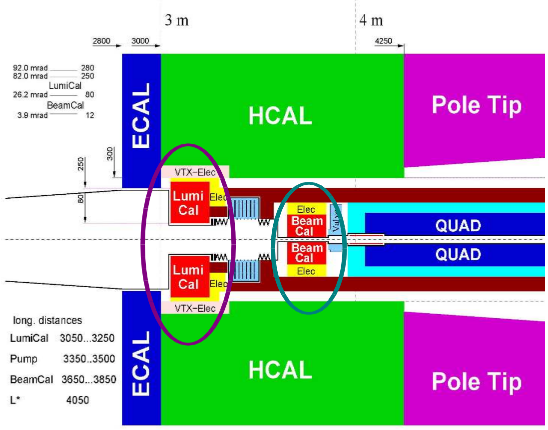

Fig. 2: Design of the forward calorimeter

A BeamCal [1] will be located at the Very Forward Region of the TESLA detector. The purpose of the calorimeter is a fast beam diagnostics and the detection of $e^{\pm}$ and γ at very low angles (5-28 mrad).

A principle scheme of the planned setup is shown in Fig. 2.

Fast beam diagnostics uses electrons and positrons resulting from beamstrahlung. Because of the small size and high charge of bunches electrons (or positrons) are accelerated in the field of an oncoming bunch and emit photons. Inspite the photons have a very narrow angular distribution and don't hit the BeamCal, they produce $e^{\pm}$ pairs which give a huge energy deposition in the calorimeter [2].

The distribution of energy deposited in the BeamCal by $e^{\pm}$ can give information on beam parameters and be used for fast beam diagnostics.

Also BeamCal gives a possibility to detect high energetic detector $e^{\pm}$ and γ at very low angles.

Under the nominal beam conditions about $3{\times}10^4 e^{\pm}$ are scattered into the calorimeter, summing up to 10 TeV of energy deposition per bunch crossing. A dose absorbed by the BeamCal cell located in the highest background region is expected to be about 10 MGy/year.

Thus the main requirement to a sensor material of the calorimeter is a radiation hardness. That is why diamond/tungsten sandwich calorimeter is considered be one of the possibilities.

2.1 Chemical Vapor Deposition of Diamond

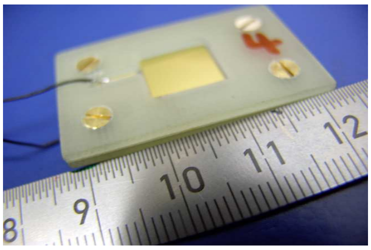

Fig. 3: Example of diamond

Future particle accelerators will produce extremely high radiation background and make the environment for particle detectors close to the beams very hostile. One promising material for future detectors [3] is CVD diamond which has been shown to be very radiation hard.

Tab. 2: General properties of diamond.

Property	Value
Hardness	10.000 kg/mm^2
Strength, tensile	> 1.2GPa
Sound velocity	17.500 m/s
Density	3.52 g/cm^3
Atom density	1.77x1023 1/cm^3
Young's modulus	1140 GPa
Poisson's ratio	0.069
Thermal expansion coefficient	1.1 ppm/K
Thermal conductivity	20.0 W/cmK
Debye temperature	2.220 K
Refractive index	2.41
Optical transparency	UV to far IR
Loss tangent at 140 GHz	< 10-5
Dielectric constant	5.7
Dielectric strength	10.000.000 V/cm
Electron mobility	2.200 cm^2/Vs
Hole mobility	1.600 cm^2/Vs
Bandgap	5.45 eV
Resistivity	10^{13} - 10^{16}Wcm
Average electron hole number for MIP	36/μm

CVD diamond [4] are grown from carbon radicals producing methan molecules in a plasma reactor. The substrate usually consists of single crystal silicon, because it has a similar lattice structure compared to diamond.

At the beginning of the growth, the whole surface of the substrate is filled hydrogen atoms. But because the binding energy of the carbon-substrate bonds is larger than the binding energy of the hydrogen-substrate bonds, the carbon atoms get accumulated on the substrate. Also the binding energy of the carbon-carbon bond is larger than the binding energy of the carbon-hydrogen bond. Therefore the carbon atoms accumulate on the other carbon atoms, which are already on the substate. When a graphite bond (sp^2 hydrid) is formed instead of a diamond bond (sp^3 hybrid), the binding energy of the graphite bond is smaller than the binding energy of the diamond bond. Therefore the graphite structure carbon atoms get transported away from the hydrogen radicals. The graphite structures get 'etched' away with the hydrogen radicals.

The diamond samples used in this work were produced by Fraunhofer Institute (Germany) - 4 samples, General Physics Institute (Moskow) - 2 samples and Element Six - 1 sample.

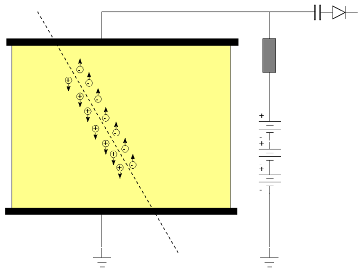

Fig. 4: Generation of a signal in a diamond detector

3 Overview of the basic operation of diamond detectors

We are concerned with the applications of diamond detectors in high-energy physics for the detection of fairly energetic charged particles. However, the response to such particles cannot usefully be discussed in isolation but should be considered in relation to the response to other types of radiation. This is desirable both to put the results obtained in context, but also because the diagnostic metods used to characterize diamond detector and to investigate their properties commonly make use of other type of radiation. In all cases we are concerned with the generation of mobile charge within the material, and its subsequent movement in response to an applied electric field. Our main concern is with the detection of individual particles; but detectors can also be used to monitor the intensity of various types of radiation through measurements of the induced conductivity. In such cases the physics of the detection process is the same, but the detecting electronics averages the signal over a timescale long compared with the response to each particle, providing a signal proportional to the incident flux.

The deposition of energy by charged particles passing through matter is of central importance to the operation of all types of particle detectors. The energy lost per unit path length decreases rapidly with increasing particle speed until this reaches roughly 95% of the speed of light. Such a particle is known is as a 'minimum ionizing particle', commonly abbreviated to 'MIP' [6], and it has a relativistic energy about 3.2 times its mass. Further increases of velocity produce a slow (logarithmic) increase in energy loss, and it is convenient to consider the response to a MIP as indicative of the characteristics of a detector.

4 CVD Diamond Measurements

4.1 Current-Voltege dependence

The Current-Voltage measurement is used to estimate resistivity of the metallised CVD diamonds. Normaly the resistivity is very high, the currents are very small. Measured currents are in the order of picoamperes at voltages up to 500 Volts.

The resistivity is a measure of quality of the diamond. The less impurities are inside the crystal, the higher the resistivity and the lower leakage currents.

It is very difficult to measure currents at this order of magnitude. A special device for current measurement is used: Keithley Amperemeter with integrated voltage source. This device measures currents with a resolution of 0.01 picoamperes. The Current-Voltage characteristics were measured at room temperature and in the darkness. The whole setup is placed in a big metal box with an outside shielding. The diamond is placed inside another small plastic box.

Before starting the Current-Voltage characteristics measurement the time dependence of the current at a constant voltage was measured. This is necessary to estimate how much time is needed for the current to settle to be able to measure in a reproduceable way. After that the voltage was varied from 0 Volts to 500 Volts and the current was measured.

The measurements were taken in the following time regime: a voltage was set and then the current was measured for 300 seconds. Then the next voltage value was set. The voltage started at 0 Volts and was ramped in 50 Volts steps up to 500 Volts and back to 0 Volts for all sensors. Measurements in this mode were done for both polarities. As it was not known, which side is the substate side and which the growth side, the frame was used as a reference. When positive high voltage was set on the top side, it was called 'normal HV' and when positive high voltage was set on the back side it was called 'opposite HV'.

I-V dependence has been measured for all the samples. The I-V behaviors of samples can be classified:

1. low currents, symmetric dependence (Sensor 3_4p)

2. relatively high currents, asymmetric dependence (Sensor 4_4p)

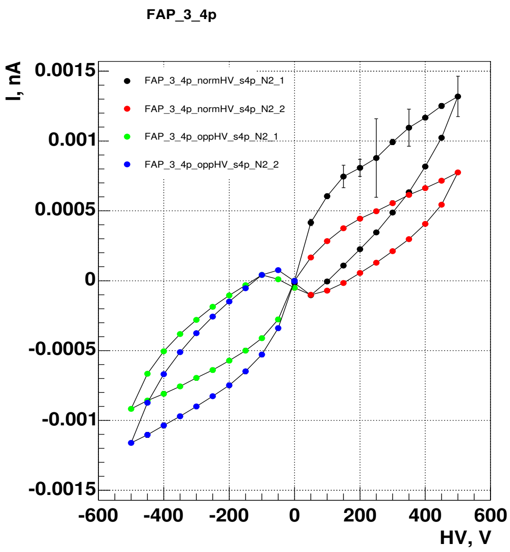

Fig. 5: Typical Current Voltage Measurement for Sensor 3_4p.

It can be seen, that most of the sensors have such a high resistivity that it is possible to apply a very high electric field to these crystals, which will be important for using it in a detector.

5 Measurement with ^{90}Sr

To be used in a BeamCal diamonds have to work as a particle detector. Therefore a sensor response to ionising particles should be studied. A ^{90}Sr source was used for the measurements. Strontium 90 decays into yttrium 90 through beta decay, with a lifetime of 28.78 years.

The diamond is placed in a small box (the mesurement setup with ^{90}Sr is presented on

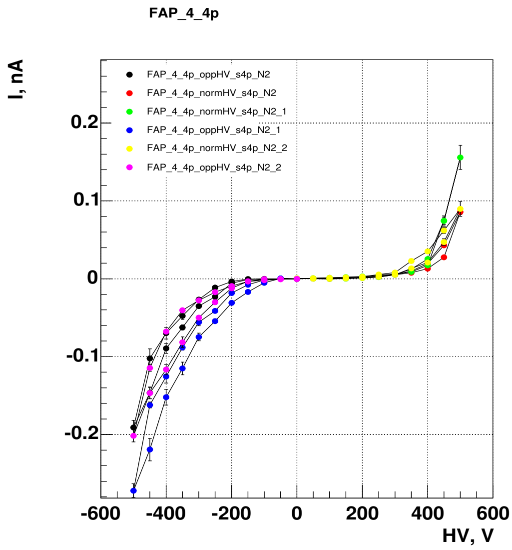

Fig. 6: Typical Current Voltage Measurement for Sensor 4_4p.

Fig. 9.) with an aluminium mylar foil on top and bottom windows to stop light coming inside the setup. The voltage is changed from 0 Volts up to 500 Volts. The strontium source is placed on top of this box. The e^- from Sr goes through the diamond and then falls on the one scintillator and only when a coincidence of the photomultiplier tube (PMT'S) takes place the signal of the diamond is amplified and read out by the ADC. For the measurements 5000 events are taken out from each diamond.

A pedestal spectrum is taken to measure the noise of the preamplifier. This is done by placing the strontium source on top the one scintiallator and the diamond is placed outside the beam line. In this way a random trigger is used to measure the pedestal of the setup. The voltage on the diamond is set to zero Volts. All those measurements are read out with a Labview program. The ADC values are saved.

The measured data are plotted in a Histogram where the ADC value is shown against the number of events taking place at this value. The plot is then fitted with a Gaussian and the standard deviation of this Gaussian Fit was estimated with a root program called ADCViewer.

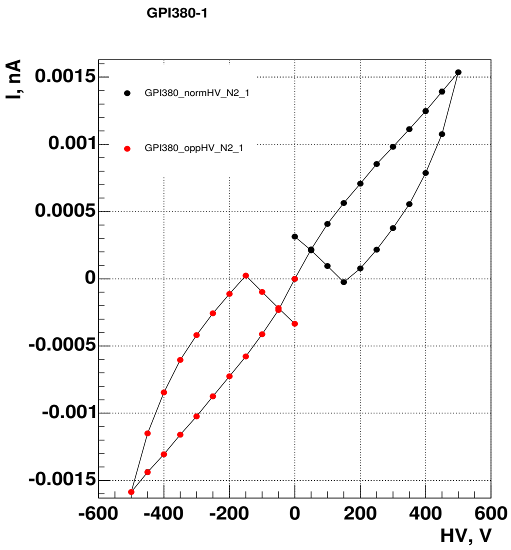

Fig. 7: Current Voltage Measurement for Sensor GPI380-1

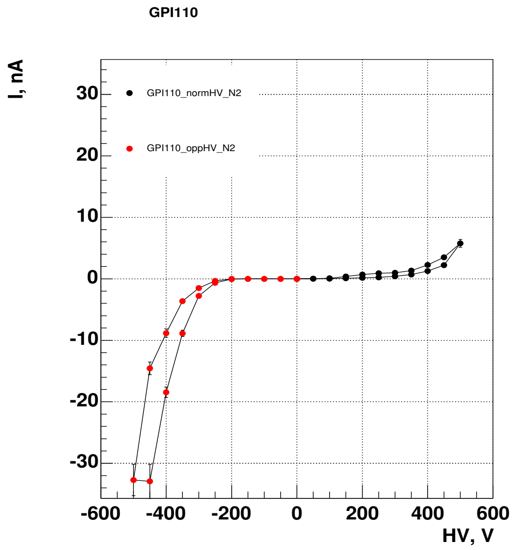

Fig. 8: Current Voltage Measurement for Sensor GPI110

6 Noise Spectra

The pedestal spectra were taken for all sensors with zero Volts applied. At the beginning it was also examined if the voltage had an influence on the noise spectra, but it has no influence, the pedestal remains the same at all voltages. Because of this reason all further noise spectra were taken with zero Volts applied. A typical noise spectrum looks like Fig. 10.

6.1 ^{90}Sr Spectra

We had measured a diamond with source, which has beta spectrum. Fig. 15 presents electronic setup for CCD measurement. ^{90}Sr is used as a radiation source. Scintillator trigger allows to register only electrons able to penetrate the diamond. As sample thickness is 100 - 500 μm, the energy of these electrons corresponds to MIP energy, which facilitates CCD measurement with help of the charge measured. When The e^- travels through both diamond and scintillator and the coincidence of the two PMT'S connected to the scintillator give the trigger. After that we had measured the signal from diamond. The presented spectra are taken during the first irradiation of the sensors. A typical spectrum is show in Fig. 11 and Fig. 12.

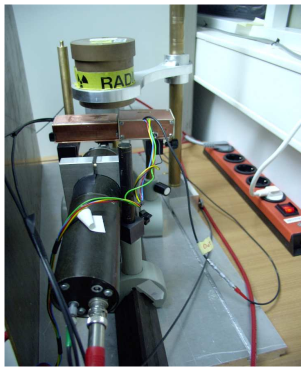

Fig. 9: Setup the measurement with Sr90

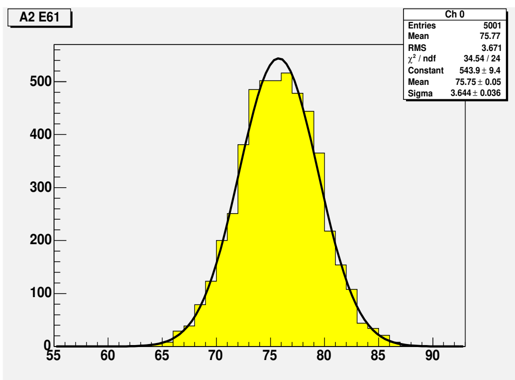

Fig. 10: Noise Spectrum of Sensor E6_1

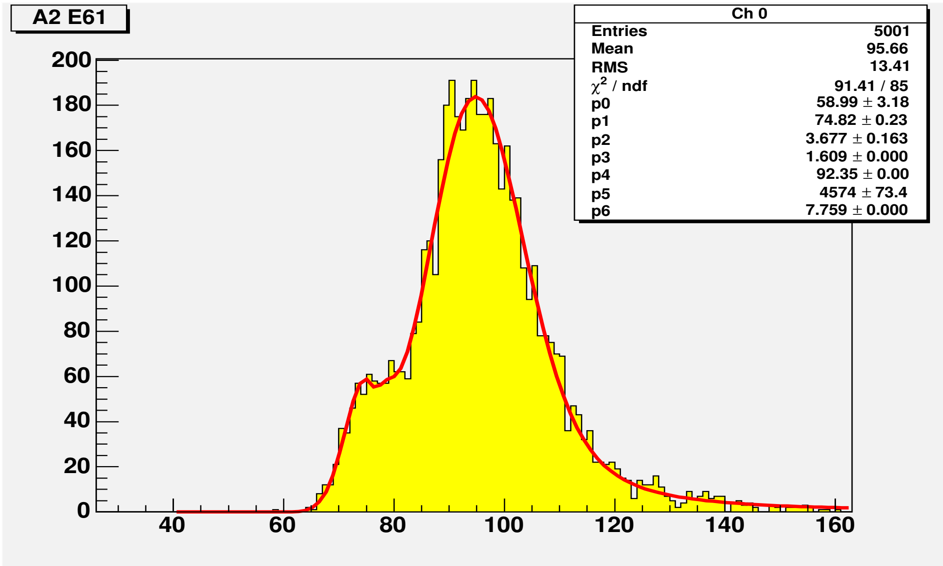

Fig. 11: Strontium Spectrum of Sensor E6_1 with 150 Volts

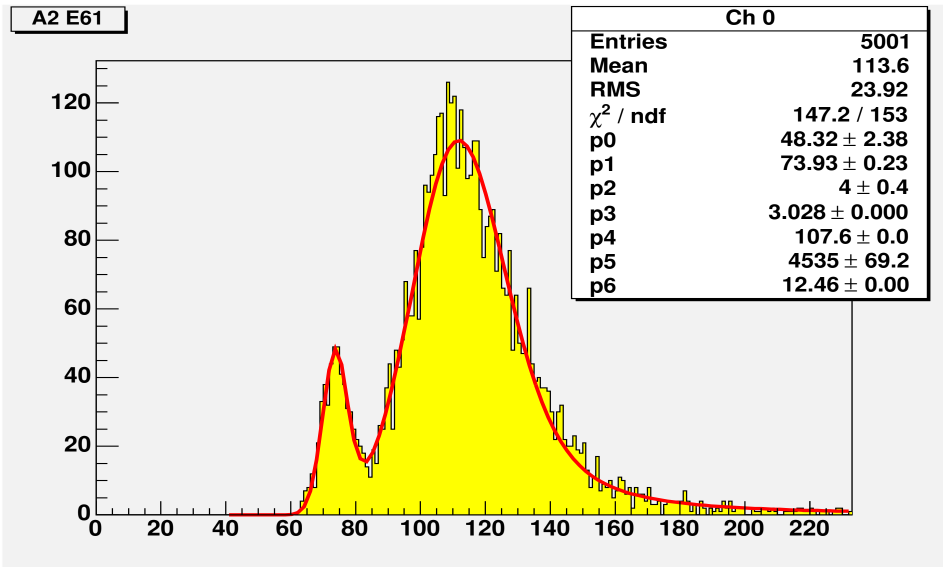

Fig. 12: Strontium Spectrum of Sensor E6_1 with 400 Volts

The data from those spectra measurements were plotted in a graph where number of the ADC value is plotted against the voltage applied to the sensor. A plot of this kind is show in Fig. 13

The error bars are very small, because of good statistics with 5000 events.

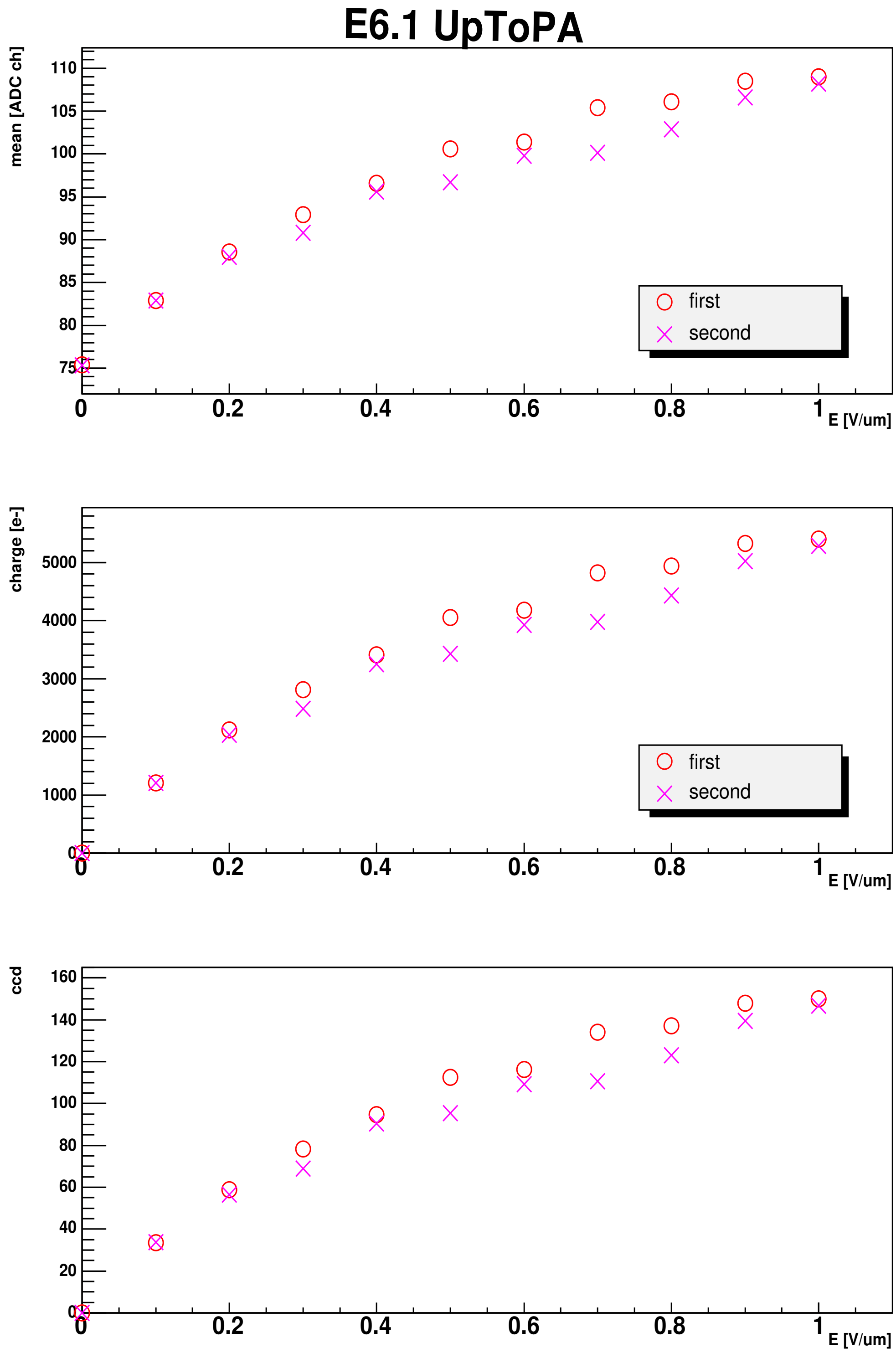

Fig. 13: CCD with the strontium 90 source.

7 Calibration

To be able to calculate the induced charge, the setup has been calibrated, to know which charge corresponds to which channel of the setup. Therefore a pulse generator is used to produce rectangular pulses with a known Amplitude and a capacitor is used to couple a definite amount of charge into the circuit.

These measurements were done with different voltages applied to six different capacitors (0pF, 1pF, 1.5pF, 2pF, 2.5pF, 3pF). The charge collected in the capacitor can be calculated by

$$Q = C \times \mathrm{U}$$

with Q – collected charge, C – capacitance of the capacitor, U - voltage applied to the capacitor. A spectrum is taken for this charge and again fitted with a Gaussian function. The number of the mean fit values of the spectrum is plotted against the charge. The plot with the data points for the capacitors is show in Fig. 14.

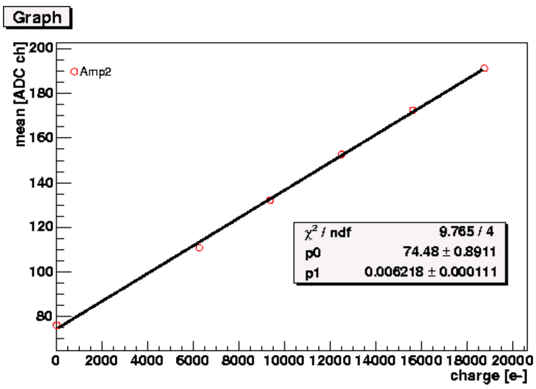

Fig. 14: Calidrashion Plot with 1 Capacitors

It is obvious, that the ADC-value to charge behaviour is linear. The curve is fitted with a linear function and the slope is calculated to be 0.006218 ADC values per electron.

7.1 Charge Collection Distance

Penetrating a bulk of diamond, ionizing particles release charge carriers. Due to presence of traps in the diamond, the created charge carriers will partially be lost during drifting to electrodes and the collected charge will be less than the charge initially induced. Charge Collection distance (CCD) is an average drift between electron and hole [8]. CCD characterize a sensor efficiency and does not depend on thickness of a sensor:

$$Q_{collected} = Q_{induced} \times \mathrm{L},$$

where $Q_{induced}$ is the charge induced in a sensor by an ionizing particle, $Q_{collected}$ is the charge collected from the sensor and L is a thickness of the sensor. For Minimal Ionizing Particles CCD can be calculated as

$$\mathrm{ccd} = Q_{collected}/36\ [\mu\mathrm{m}],$$

where 36 is the number of electrons created by a mip per 1 μm of diamond.

The setup used for measurements of CCD is shown in Fig. 15.

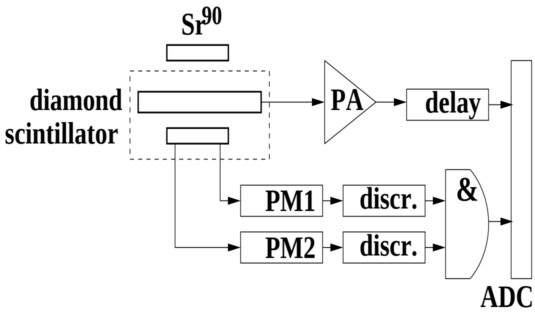

Fig. 15: Setup for the measurement of CCD

As a source of ionizing particle a ^{90}Sr beta-source was used. A scincillator bellow the diamond gives a trigger signal. Particles able to penetrate the diamond and inducing the trigger signal have energy close to the MIP energy, that allows to use the value

$$Q_{induced} = 36 \times\ e^{-}/\mu\mathrm{m}.$$

The dependence of CCD on the voltage applied has been measured for all the samples.

The induced charge can be calculated by:

$$Q_{induced} = \Delta channel/0.006218$$

with 0.006218 – the slope of the calibration curve shown in Fig. 14.

$$\Delta channel = number\ of\ mean\ fit\ channel - number\ of\ noise\ channel$$

8 Acknowledgments

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9 Conclusion

The BeamCal has to deal with a high radiation dose and large dynamic range. Hence, radiation hard sensors with linear response over a signal range of about 10^3 must be used.

Diamond is a promising material to be used in a BeamCal. Purity of the diamond produced with the CVD technigue is very good, as the Current-Voltage measurements show in 4.1.

The resistivities of the diamond are in the order of Tera Ohm, which lets us conclude that diamonds are very pure. The behaviour of most of the diamonds is ohmic. For most sensors it was possible to apply high voltages and therefore very high electric fields.

During the measurements we found out that CCD of our diamond sample is 160 μm. To provide the necessery energy resolution of BeamCal CCD should be not less than 100μm (in accordance with simulation results). So it can be concluded that the measured result satisfies requirements completely.

Diamond can be considered as a good alternative to silicon for future detector generation in high radiative environment.

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