Investigation of a direction sensitive sapphire detector stack at the 5 GeV electron beam at DESY-II

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***Abstract*– For detectors in particle physics experiments and at accelerators extremely radiation hard sensors are needed in the region near the beam pipe. We designed and built a multichannel detector using metallised single crystal sapphire plates. The detector allows to register single minimum ionising particles, with enhanced sensitivity to trajectories parallel to the plate surface. The charge collection efficiency of the sensors was measured in a test-beam as a function of the bias voltage. It rises with the voltage, reaching about 10% at 950 V. The signal size at this voltage was equivalent to about 22000 e^-. The detector was operated together with EUDET beam telescope, which allowed the reconstruction of the position of the hits at the detector, allowing to measure the signal size as a function of the position with respect to the metal electrodes. A dependence on the electrical field direction was found. The data confirms the prediction that mainly the electrons contribute to the signal. Also evidence for the presence of a polarization field was observed. Future plans for a next generation sapphire based detector will be also presented.**

INTRODUCTION

For the operation in the harsh radiation environment, typical for near-beam detectors e,g. at LHC or other accelerators, extremely radiation hard sensors are needed. CVD diamond sensors are an option used for beam conditions and instant luminosity measurements. Regardless of the excellent radiation hardness and low noise at room temperature, high production costs, small size and a low manufacturing rate limit larger scale applications. As an alternative, the use of sapphire sensors is suggested. Optical grade single-crystal sapphire is industrially grown as large-size wafers for relatively low cost. Earlier tests showed excellent radiation hardness of sapphire sensors [1], very low leakage current at room temperature, but small charge collection efficiency. Nevertheless, sapphire sensors have been already used for beam-loss measurements, when many particles hit the sensor simultaneously, at FLASH, and are planned to be installed at FLASH-II and XFEL [2]. Here we present a new detector for single particle detection of about 0.3 cm^2 sensitive size using sapphire plates of 0.5 mm thickness, forming a stack. Its performance was investigated in a 5 GeV electron beam at DESY. Results on the signal size as functions of the bias voltage and the impact point are presented.

I. THE DETECTOR

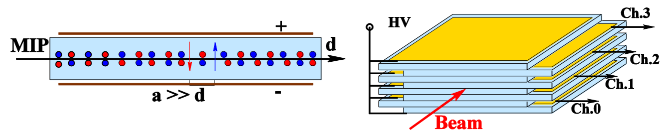

Fig. 1: The sapphire detector stack. Left: operation principle of a single sapphire sensor, right: stack of eight sapphire sensors.

In Fig. 1 (left) a single metallised sapphire plate is sketched. Since due to the relatively low charge collection efficiency of industrially produced sapphire the signal for minimum ionising particles crossing the plate perpendicular to its surface is very low, only about 1000 e^-, the orientation of the plates was chosen to be parallel to the beam. Such the track length for the generation of charge carriers is larger, and the signal size depends on the direction.

A stack as shown Fig.1 (right) was built. Eight plates metallised on both sides were assembled together. To allow wire bonding connections to the HV circuit and to readout channels, the plates were alternatively shifted to both sides. Each readout channel served two plates. Signals were amplified and shaped by a charge sensitive frontend amplifier and sampled by a CAEN v1721 ADC. The detector was mounted inside the EUDET Telescope [3] and positioned in the 5 GeV electron beam at the DESY II synchrotron. Using the telescope data the particle trajectories have been reconstructed using three telescope planes up- and three planes

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downstream of the detector. The resolution of the impact point position at the detector was about 10 μm.

II. CHARGE COLLECTION EFFICIENCY

Events with tracks pointing into the corresponding detector plate were used to determine the average signal amplitude using the ADC data readout in coincidence. To obtain the correspondence between the signal amplitude and the charge collected by the preamplifier, the full readout chain was calibrated injecting a known charge via a capacitance into the preamplifier.

The energy loss of 5 GeV electrons inside the sapphire was determined by a simulation using GEANT. To obtain the expected amount of electron-hole pairs the average energy loss was divided by the energy needed to create an electron-hole pair. The latter was estimated from the sapphire band-gap [4]. The charge collection efficiency CCE was calculated as the ratio of the measured and expected charges.

The CCE was measured as a function of the bias voltage. The result is shown in Fig.2 for four plates separately. The dependence on the bias voltage is practically linear in the investigated range. The CCE approaches between 9 and 11% at 950 V.

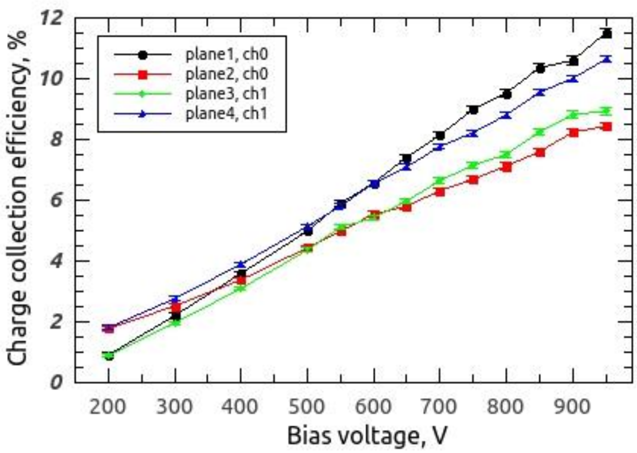

Fig. 2: The charge collection efficiency of four sapphire plates. Among the other four plates one has similar efficiency, while three plates show worse performance (see Table 1).

Table 1: Results for single plate charge collection efficiency measurements at the highest applied bias voltage 950 V. Listed are average values over the sensitive detector volume.

Plate number	1	2	3	4	5	6	7	8
CCE, %	11.5	8.4	8.9	10.6	9.1	5.8	3.9	2.9
stat. error	0.14	0.1	0.13	0.11		0.08	0.06	
syst. Error	0.6	0.4		0.5		0.3	0.2	

Since there was no preselection of sapphire plates before detector construction, the measured CCE indictes possible variation of the substrate quality. Mean values of the CCE obtained for all plates at a bias voltage of 950 V are listed in Table 1. It is seen, that 5 out of 8 plates have a relatively high and similar CCE of 10% within a spread of 1.5%, while three other plates have lower efficiency.

III. SIGNAL SIZE AS A FUNCTION OF PLATE DEPTH

To evaluate the relative contribution of electrons and holes to the collected charge and to see indications for a polarization field, the signal size was studied as a function of the position between the electrodes, referred to hereafter as plate depth. Each plate was subdivided into 50 μm slices and for each slice the average signal was measured selecting events with track pointing inside the slice.

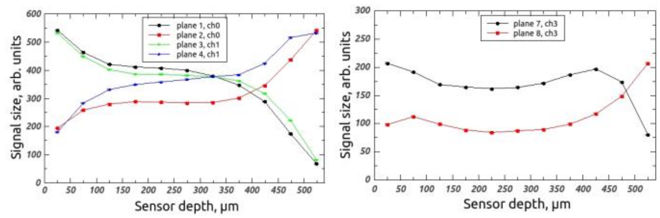

Fig. 3: Signal size as a function of plate depth for plates 1-4 (left) and 7-8 (right) at 950 V. The electrical field direction is opposite for neighbouring plates.

For all plates the signal is reduced in the vicinity of positive electrode and has the maximum at the negative electrode, as can be seen in Fig.3. For plates 7 and 8 that have lower CCE, a second local maximum is seen in Fig.3 (right) at a distance ~100 μm from the positive electrode. The signal drop near the positive electrode points to a dominant contribution of electron drift to the CCE. This result is expected from the theoretical prediction that the effective mass of holes is larger than the electron effective mass [5]. The maxima seen in Fig.3 point in addition to the presence of a significant polarization field.

IV. CONCLUSIONS AND OUTLOOK

This paper presents results on the performance of a direction-sensitive sapphire detector stack designed for single particle detection measured in a 5 GeV electron beam. The charge collection efficiency is linearly dependent on the bias voltage and approaches 11% at 950 V, being sufficient for single particle counting. A detailed study of position-resolved response indicates the dominant contribution of electrons to the charge collection in sapphire as well as a visible polarization effect. The design of a next-generation sapphire strip detector with intrinsic non-uniformity compensation for high energy particle tracking purposes is ongoing and will be presented at the conference.

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