Diamonds as timing detectors for MIP: The HADES proton-beam monitor and start detectors

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Abstract

This paper gives an overview of a recent development of measuring time of flight of minimum-ionizing particles (MIP) with mono-crystalline diamond detectors. The application in the HADES spectrometer as well as test results obtained with proton beams are discussed.

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1. Introduction

Diamond detectors are well known for their radiation hardness and high drift speeds of both electrons and holes, making them ideal not only as timing detectors placed in the beam\textsuperscript{\[1,2\]} but also as luminosity monitors\textsuperscript{3}. However, due to the large effective energy needed to create electron-hole pairs (13 eV) the charge created by minimum-ionizing particles (MIP) traversing the diamond is marginal (8000 pairs for a 300\,$\mu$m thick diamond)\textsuperscript{8}. Taking into account that the poly-crystalline texture of CVD-diamond material leads to losses in charge collection these sensors can not be used for the detection of MIP because signals are too small to be registered by state-of-the-art electronics. Instead, the recently developed technology of producing a mono-crystalline diamond material, which is almost free of structural defects and

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chemical impurities and thus provides very high charge collection efficiency, allows for building detectors for MIP based on diamond material. In the following a dedicated, low-noise readout scheme is described as well as its application as a start detector for proton beams in the HADES experiment [4].

2. Diamond Readout

Mono-crystalline diamonds with two different detector sizes of 3.5×3.5 mm$^2$ (4 pixel) and 4.7×4.7 mm$^2$ (8 pixel) with thicknesses of 300 µm and 500 µm, respectively, were used during the test. For both our detectors a capacitance of a single segment was 0.25 pF only, which was defined by the geometry of the detectors. The front-end electronics has been build using RF transistors with low input capacitance (0.2 pF) which were placed close to the diamond (see Fig. 1, 2). The bias current was reduced to an extremely small value leading to a relatively large input impedance of about 2 kΩ. This results in an integration of the primary charge signal. Final shaping is done by an external booster amplifier resulting in rise-times (10% – 90%) of 1.2 ns (300 µm) and 1.35 ns (500 µm), respectively. The booster amplifier contains a 56 Ω pullup resistor to 5 V at the input to provide the bias voltage as well as proper termination of the signal line. It should be mentioned that for such a front-end design it is necessary to keep the stray capacitances at a minimum [5]. In our

![Figure 1: Schematics of the front-end amplifier.](image1)

![Figure 2: PC board ($\phi = 50$ mm) with the diamond (4.7×4.7 mm$^2$) in the centre surrounded by 8 amplifiers.](image2)
case this was realized by the bias current which is provided via 3 resistors in series in order to reduce their capacitive coupling below 0.1 pF. The power consumption of a single amplifier amounts to slightly less than 5 mW at a 5 V supply allowing for operation in vacuum which is an important issue for the foreseen application as a beam detector.

The base plate containing a diamond (4.7×4.7 mm²) surrounded by 8 amplifiers is shown in Fig. 2. The PC board material is Rogers 4003C TM utilizing a low dielectricity constant of 3.4.

3. Results

The diamond detectors were exposed to proton beams with kinetic energies from 1.2 GeV to 3.5 GeV and rates of up to $3 \times 10^6$/s/10 mm². Several detector samples with different metallizations were tested to achieve stable operation of the detector at high beam intensities. As a result the high-rate capability could be reached only after applying a metallization procedure which includes passivation in an oxygen plasma, ”baking” at 500°C in an Ar atmosphere and depositing a 50 nm Cr layer followed by a 150 nm Au layer. Otherwise, a constantly increasing leakage current appeared at intensities above several $10^5$/s which finally resulted in a rapid discharge. A data acquisition system of the test setup was built based on the TRB [6], a stand-alone DAQ board, which employs the HPTDS [7] chips for time measurement. The analog signal from the detector, after amplification, was sent to the signal discrimination circuit with the signal integration functionality. The integrated signal was converted into pulse width of the timing output of the discriminator which allowed for pulse charge measurement. Fig. 3 shows the signal charge distribution of a single segment measured for 1.8 GeV protons (MIP). Zero charge results in a minimum width of 14 ns (arrow in Fig. 3). The visible tail at small signal charges (small signal widths) is dominated by cases where the beam particle hits the detector at the edge of the segment and in this case charge is shared between neighbored segments of the diamond.

To determine the time resolution of the detectors, two diamonds were put into the proton beam with a distance of 10 cm between them. As shown in Fig. 4 the time resolution measured with leading edge discriminators between two segments of diamond is of the order of 165 ps. This gives a single segment time resolution of 117 ps. Based on the signal to RMS-noise ratio of about 23 (300 µm) and 27 (500 µm) one expects a intrinsic time resolution of
about 65 ps for both detector thicknesses which clearly gives room for further improvements.

The detection efficiency of the device was measured with a well focused proton beam centered in the middle of the diamond detector. The diameter of the beam spot at the focal point (center of the diamond) was below 2 mm and the halo of proton beams is typically below 1%. As a reference, a plastic, segmented detector, located 7 m downstream, where the beam was defocused (beam spot diameter about 30 mm), was used. By comparing the rates measured in the reference detector with the rates seen by the diamond detector, the diamond detection efficiency was determined to be \( \geq 95\% \).

4. Outlook

Due to continuous progress in the development of low-noise transistors, the signal to RMS-noise ratio can be improved by nearly 50% at 10% shorter rise-time based on up to date SiGe:C technology. In particular, tiny housings provide less stray capacitance (E.g. BFR705L3RH). The power consumption per channel can be reduced to below 2.5 mW and the total area of all components of such an amplifier amounts to only 2 mm\(^2\). First results with a Sr\(^{90}\)
source confirmed these improvements, but no in-beam tests were performed so far.

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