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MINIMUM IONIZING PARTICLE TIMING WITH GRAZING DIAMOND[*]

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The authors discuss a possible technique to measure the arrival time of minimum ionizing particle with tens of picosecond resolution using diamond detector parallel to tracks and show preliminary testbeam results obtained with 5 GeV electrons and polycrystalline diamond strip detectors.

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1. Introduction

The commercial availability of wafer size high quality polycrystalline diamond based on Chemical Vapour Deposition (CVD) has increased the interest in the applications of synthetic diamond for ionizing radiation detectors.

The most interesting features related to the use of this material are its very high tolerance to high radiation doses, the intrinsic speed of the collected signal (related to the high mobility of the free charge carriers), its low thermal noise, which makes these devices suitable for being operated at room temperature, the possibility to produce strip or pixel-segmented electrodes in order to obtain position detectors with high spatial resolution and fast response.

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The physicists working at CERN, particularly with the LHC high-luminosity upgrade plans, showed great interest in the diamond detector technology in recent years. The applications which have stimulated major interest are the ones connected to the use of the detector close to particle beams, therefore in an environment with high radiation level (beam monitor, luminosity measurement, detection of primary and secondary-interaction vertices).

Our aim is to extend the studies performed so far by developing the technical advances which are needed to prove the competitiveness of this technology in terms of time resolution, with respect to more usual ones, such as Cherenkov radiator coupled to a Micro Channel Plate, which does not guarantee the required performances and working stability in the presence of high integrated radiation doses.

The performance goals to be reached are well set within the experimental framework related to a system of forward detectors proposed for the phase-1 upgrade of the ATLAS detector at the LHC [1], named AFP (ATLAS Forward Physics). The AFP project means to extend the ATLAS scientific plan (study of anomalous gauge couplings, search for monopoles, diffractive Higgs production) by increasing the detector coverage in the small-angle region close to the proton beams, in order to allow the identification and the reconstruction of double-diffractive events in which the two protons emerge intact from the inelastic collision. Each proton is identified in one arm of the AFP system, which must measure its momentum and the time-of-flight difference dT from the measurement of the momentum lost by the two protons, it is possible to determine the mass of the centrally-produced particle system, which is recorded by the present detectors in ATLAS, while a measurement of dT with a precision of the order of 10 ps allows the association of the two protons to only one among the tens of pp interactions occurring in every collision between the two beams (pile-up events), thanks to the primary-vertex identification.

CVD diamond detectors are already successfully used in nuclear physics for time-of-flight measurements of relativistic ions (atomic number $Z > 1$) where the signal intensity is high, reaching time resolutions of the order of tens of ps [2]. The same results show the limitation of using diamond detectors for time-of-flight applications for minimum-ionizing particles, for which, due to the small amplitude of the signal or, better, to the signal-to-noise ratio (S/N) of the front-end electronics, the present time resolution is limited to about a hundred ps, for mono-crystalline diamond, or to about half ns, for poly crystalline diamond.

Assuming a readout electronics chain capable to correct the time walk error and with a negligible time digitization error (employing, for example, very fast constant fraction discriminators and TDCs, for on-line corrections, or very fast waveform digitizers, for off-line corrections), then the time resolution is dominated by the signal jitter [3]. Under these circumstances, we can naively estimate a time resolution given by the formula

$$\sigma_t = \frac{N}{\frac{dS}{dt}} \approx \frac{t_{\mathrm{rise}}}{\frac{S}{N}}\,, \tag{1}$$

where N is the electronic noise, which for diamond is just due to the front-end noise because the leakage current is negligible, dS/dT the signal slope at the electronics threshold, t_{rise} is the signal rise time, and S is the signal amplitude. In order to improve the time resolution, it is necessary to act on one of the following conditions: decrease the signal rise time, decrease the noise and increase the signal. Such goals require the development of low-noise and high-speed front-end electronics and the use of innovative geometrical and circuital configurations for the diamond sensors.

2. Grazing diamond layout

Two innovative solutions have been recently proposed in literature. In the first solution, a Multi-Layer-Crystal-Detector (MLCD) concept is proposed using M layers of thin diamond sensors (fast collection time independent from M) readout in parallel (signal increased M times) by a fast charge sensitive amplifier realized by bipolar transistors [4]. The MLCD idea relies on a custom made front-end electronics, featuring a low and constant electronic noise for input capacitance up to few nF, thanks to a new design solution. In the second solution, a sensor with 3D electrodes is proposed [5]. In such electrodes configuration, the charge is collected very fast for small pitch electrodes but with the signal still proportional to the thickness of the sensor, allowing a reduction of the collection time without compromising the signal level. The 3D diamond sensors have been successfully built and extensively tested [6].

This paper suggests a more conservative approach, proposing a solution that could be built with the existing technology. The idea is to strongly boost the signal, without affecting the noise and the collection time, by placing several diamond layers parallel to the tracks, one on top of each other (see figure 1). Such a configuration can be built with diamond sensors because the electrodes thickness is not bigger than few hundred nm, resulting in a negligible dead area. In this proposal, we consider only polycrystalline diamond, for which 6 or 8 inches wafers are commercially available, in contrast to mono-crystalline diamond having a size limited to about 4.5×4.5 mm^2. In polycrystalline diamond, the collection time is given by the charge collection distance (CCD $\approx$ 200 μm) times the drift velocity $v_{\mathrm{D}} \approx 100$ μm/1 ns for both free carriers in saturation conditions, a working condition easy to achieve in planar geometry. For MIP particles orthogonal to the sensors, this is parallel to the free carrier drift paths, the induced signal is given by about 36 e^-/μm times the charge collection distance. Instead, for MIP particles parallel to the sensors, this is orthogonal to the free carrier drift paths, the induced signal is boosted by the ratio L/d, where L is the length and d the thickness of the sensor. This ratio for polycrystalline diamond can be as large as 50 times and with a corresponding time resolution improvement of up to tens of ps. A further advantage in the grazing diamond geometry is the reduced signal induced by secondary particles which stays below the electronic threshold. In fact, these particles are produced in the interaction with the material and are expected to cross the active layers with a larger angle with respect to the primary particles coming from the interaction point.

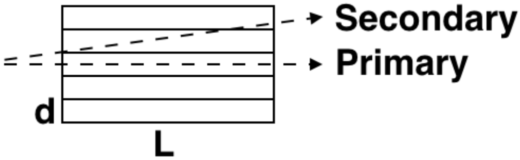

Fig. 1. Grazing diamond detector layout with five adjacent layers parallel to the primary particles.

3. Testbeam at DESY

We began to study experimentally the time resolution limit achievable with the grazing diamond concept by carrying out a testbeam at the Deutsches Elektronen SYnchrotron (DESY) in Hamburg, Germany [7]. Figure 2 shows schematically the setup used along the TB22 beam line, which provided

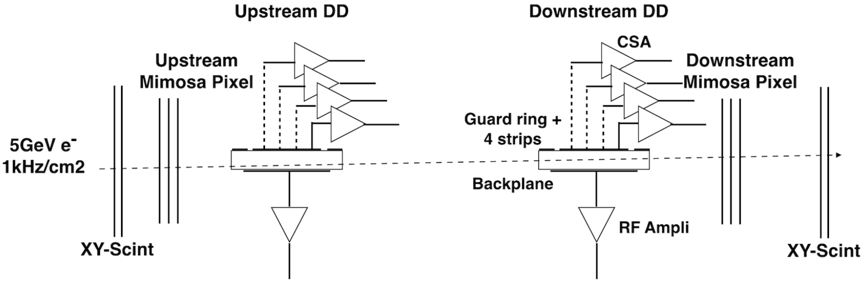

Fig. 2. Experimental setup used to measure the time of flight between two diamond detectors placed parallel to a 5 GeV electron beam at DESY.

5 GeV electrons with small divergence. The main test consisted in the measurement of the time of flight of single electrons with two polycrystalline diamond detectors parallel to the beam and extract the time resolution for a MIP-like particle crossing the sensor along the long dimension.

We used two polycrystalline diamond detectors to measure the single electron time of flight: the first one provided a start signal and the second one the stop signal. The diamond detectors consisted of $10 \times 10 \times 0.5$ mm^3 sensors with four metalized strips on the front-side, 6.5 mm long and 1.5 mm pitch, and a metalized pad on the back-side. The strip electrodes were connected to SMA connectors and the signal directly amplified by a fast charge amplifiers of 100 MHz bandwidth and 8 mV/fC gain (CIVIDEC C6). The eight analogue signals were digitized by a 17 channels digitizer having a 12 bit ADC resolution, a 20 GS/s sampling rate (CAEN DT5742) and controlled by a USB cable connected to a near-by laptop driven by a remote connection. The digitized waveforms were dumped into an ASCII file and analyzed off-line by ROOT software [8].

The back-side pads of the two diamond detectors were also connected to SMA connectors but the signals were amplified by broadband amplifiers of 2 GHz bandwidth, voltage gain 100 and input terminated at 50 Ω (CIVIDEC C2). The high voltage was applied by the broadband amplifiers and set to a value of -350 Volts. The back-side signals were discriminated by two constant fraction discriminators and put in time coincidence with four plastic scintillators provided by the test beam facility. The obtained coincidence signals were used as the trigger signal for two independent acquisition systems: the fast waveform digitizers for the diamond detectors and the EUDET DAQ for the pixel telescope. The pixel telescope was fully provided and supported by DESY and it was made by two stations of three planes of MIMOSA monolithic pixel sensors.

We could build pixel tracks using EUTELESCOPE software [9] and verify the event synchronization between diamond detectors and pixel telescope by measuring the spatial coincidence between pixel hits and strip signals.

4. Testbeam preliminary results

In the analysis presented here, the eight charge sensitive amplifiers were cross-calibrated using a reference voltage pulse and assuming a global gain equal to the nominal one. This is compatible with the signal pulse size measured with the diamond detector placed orthogonally to the beam, after being removed from the trigger, and assuming a charge collection distance of 200 μm, which corresponds to a collected charge of about 6200 e^-.

An example of a recorded waveform is visible in figure 3. For each event and recorded waveform, we made an interpolation with the following formula

$$V(t) = \begin{cases} V_0 & \text{if } t < t_0 \\ V_0 + V_1 \frac{t-t_0}{t_1} e^{-\frac{t-t_0}{t_1}} & \text{if } t \geq t_0 \end{cases} , \qquad (2)$$

where V_0 is the baseline offset, V_1/t_1 is the initial pulse slope, t_0 is the arrival time and t_1 is the rise time. We evaluated the arrival time from the fit parameter t_0 by stopping the interpolation to about 70% of the amplitude and the signal amplitude by the difference between the pulse peak and the fit parameter V_0.

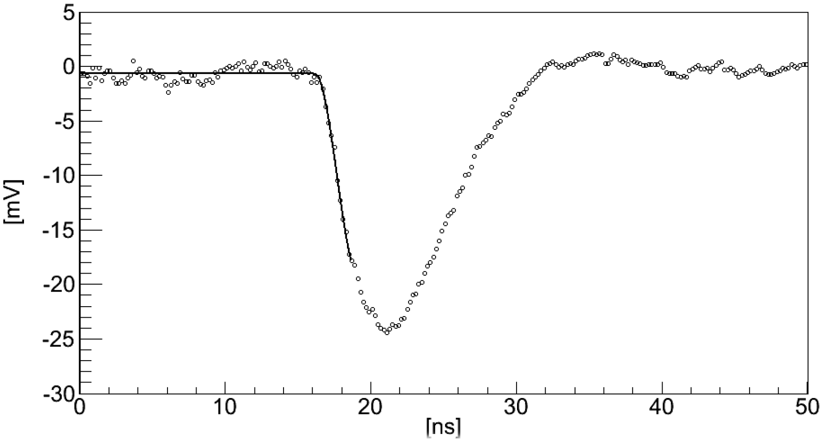

Fig. 3. Example of the signal output from a 500 μm thick polycrystalline diamond detector placed parallel to a 5 GeV electron beam amplified by 100 MHz bandwidth charge sensitive amplifier and digitized at a rate of 5 GS/s (open circles). The pulse function interpolating the signal up to the 70% of the amplitude is superimposed to the waveform (continuous line).

In figure 4 one can see the correlation between the time of flight of the two diamond detectors with respect to the amplitude Q_1 of the first one under the condition that the two amplitudes do not differ more than the threshold ($|Q_1 - Q_2| < Q_{\text{threshold}}$). The signal is normalized to the value expected for a minimum ionizing particle incident orthogonally on a diamond detector and having a charge collection distance of 200 μm. From this scatter plot it is possible to estimate a threshold of about 2.5. It is clear from the measurements that the time-of-flight spread decreases for increasing amplitude, reaching quite small value for signals above 26 where the statistics is very limited.

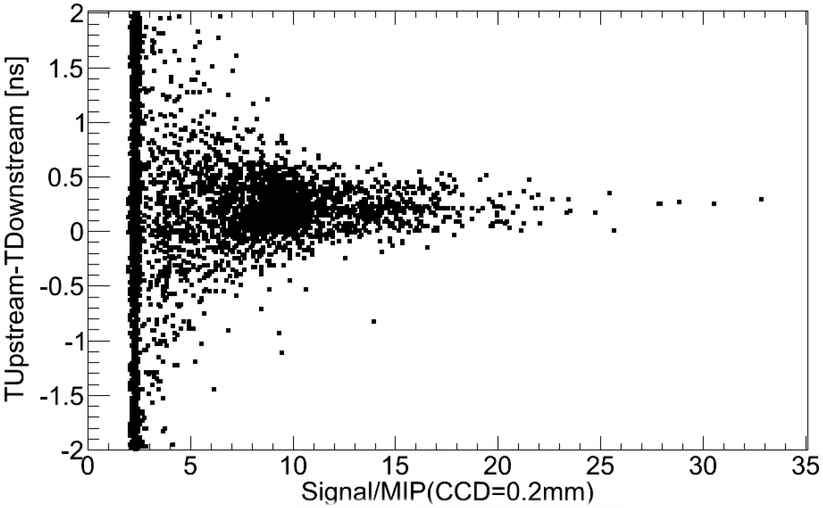

Fig. 4. Scatter plot of the time of flight between two 500 μm thick polycrystalline diamond detectors placed parallel to a 5 GeV electron beam as a function of the signal amplitude. The high voltage value was -350 V.

In Table I we report the time resolution measured by the standard deviation of the time-of-flight distribution divided by $\sqrt{2}$, because the time spread of the two diamond detectors are assumed to be equal. The time resolution is evaluated for different ranges of the signal values reported in the table with an estimate of the signal-to-noise ratio.

TABLE I

Preliminary estimate of the time resolution achieved with 500 μm thick polycrystalline diamond detector placed parallel to a 5 GeV electron beam as a function of the signal amplitude. The high voltage value was -350 V.

Signal/MIP [CCD = 0.2 mm]	Signal/Noise	Time resolution [ps]
7.5 ± 2.5	47	230 ± 40
$15. \pm 2.5$	94	110 ± 30
22.5 ± 2.5	140	84 ± 40
> 22.5	> 140	60 ± 40

5. Conclusions

In this paper, we suggested a grazing diamond layout to boost the time resolution of a MIP-like particle crossing the sensor along its full lenght perpendicular to thickness in order to maximize the released charge without increasing the collection time. It is apparent from the measurements that the time resolution decreases almost proportionally to the increasing signal. Nevertheless, the time resolution obtained is not really great with respect to the prediction of equation (1). The reasons of this discrepancy are likely related to charge fluctuation inside the diamond sensor related to the track impact point and to the multiple scattering of the 5 GeV electrons through the diamond sensor (2 cm) and the aluminum enclosure (5 mm) thicknesses. Currently, we are studying geometry effects using the tracks reconstructed with the pixel telescope and preparing a testbeam at CERN to reduce strongly the multiple scattering by using 120 GeV hadrons.

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[7] Additional information on the DESY TestBeam facilities can be found at `http://testbeam.desy.de`

[8] `http://root.cern.ch`

[9] `http://eutelescope.web.cern.ch`

[10] `https://aida.web.cern.ch/aida/index.html`