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Timing performance of a double layer diamond detector

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ABSTRACT: In order to improve the time precision of detectors based on diamonds sensors we have built a detector with two scCVD layers connected in parallel to the same amplifier. This work describes the design and the first measurements of such a prototype performed on a particle beam at CERN. With this different configuration we have obtained an improvement larger than a factor of 1.6–1.7 for the timing precision of the measurement when compared to a one layer scCVD diamond detector.

KEYWORDS: Diamond Detectors; Electronic detector readout concepts (solid-state); Performance of High Energy Physics Detectors; Timing detectors

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1 Overview

Diamond detectors are presently used extensively in many LHC experiments ([1–4]) and by HADES in the GSI ion facility [5, 6] to monitor beam condition and rates.

The TOTEM collaboration exploits the diamond detector good timing capabilities to measure with the utmost precision the arrival time of the leading proton in a scattering event and has recently installed in the LHC a set of timing detectors on each side of the interaction point IP5. The detectors are installed in the very small space inside a movable section of the vacuum pipe of the CERN LHC, the Roman Pot (RP); details are described in [7].

As expected, tests show that improving the S/N of the amplifier is one of the key element together with the rise time to obtain a better time precision and in the case of TOTEM, a better longitudinal precision in the determination of the interaction vertex, given by $z = c \Delta T/2$ where ΔT is the difference of the arrival time of the protons in the left and right RP, c is the velocity of light.

For a given amplifier to have larger signal one should increase the primary charge collected by the scCVD diamonds. For a larger charge collection one may increase the detector thickness, at the expense of a longer collection time. In this article we will instead use two separated scCVD diamonds read out in parallel by the same amplifier in order to double the collected charge while keeping the collection time constant.

2 Principle

In 2004, in order to improve the signal amplitude of a pCVD beam monitor detector, H. Pernegger tested a configuration of sensors such that the charge released in two sensors traversed simultaneously by the same charged particle is read out by the same amplifier input: the “double-diamond assembly” (DD) [8]. Later also Benardzick [9] and Cardarelli [10] tried a similar configuration.

Applying this idea to the precise measurement of the time from the signals of n diamond pixels traversed by the same particle and connected in parallel to the input of the same amplifier

should improve the time precision by a factor greater than \sqrt{n} , which is the combined time precision expected from the signals of n pixels each measured independently with their amplification chain. Indeed, thanks to the small dielectric constant of the diamonds, the capacitance of pixels of area $1 - 2 \text{ mm}^2$ is only about 0.2 pF, still smaller than the input capacitance of the preamplifier ($\approx 0.4 \text{ pF}$ see [7]) therefore more than one diamond sensors can be connected in parallel to one amplifier without degradation of the timing performance if the leakage current of the single crystal diamond sensor is negligible when compared to the noise current of the amplifier. The negligible shot noise due to the leakage current of the sCVD diamond sensor with respect to the series noise of the amplifier is indeed a decisive aspect towards the interest in a parallel connection of two diamonds. In conclusion, more than one sensor can be connected in parallel to the same amplifier with a negligible effect on its performance; since the collected charge is double on average and even if the rise-time of the signal is the same as for a single sensor, we expect an improvement of the time precision of almost a factor 2 with respect to the one obtained from a single measurement.

Note that in the context of a time measurement the connection of two sensors in parallel is different and gives better results than simply doubling the thickness of the sensor: for the same “volume” of sensor two separate parallel sensors will provide on average the same amount of charge to the input of the amplifier with approximately half the collection time.

Besides, if the space available is limited (usually as in our case the thickness per layer of detector is dominated by the electronic board) it may be more interesting to increase the number of diamond sensors per detector layer, obtaining with the same amount of sensors and half the number of boards a better time precision than the one that could be obtained from $2n$ independent diamond boards in the same space. This connection scheme brings also advantages on the overall system aspects, reducing the total number of channels to acquire for a certain overall thickness of the detectors and the total amount of heat dissipated by the system.

We noticed that several undesired factors can lead to a loss of time resolution with respect to the ideal behaviour described before. The mechanical alignment of the two sensors (see section 3) has a precision of 100-200 μm in both the X and Y directions. Therefore a fraction of the signals is not generated by both diamond sensors. This is a weak point of the system, as it can easily results in about 20% of the double diamond signals which actually come from a particle traversing only one crystal. A better mechanical solution for the alignment will be developed for future measurements. Moreover a fraction of about 5% of the largest double diamond signals cannot be used for the analysis as they saturate the amplification chain. These signals, that would be the most precise ones generated by the double diamond detector, cannot be properly included for the measurement of the time precision of the detector. The impedance of the connection between the sensor and the amplifier is usually negligible as the bonding wire is short (less than 2 cm, with $R=0.01\Omega/\text{mm}$ and $L=0.731 \text{ nH/mm}$). In the discussed layout the bottom layer has to be connected using a via in the PCB which increases the impedance of the connection, but also in this case, being $R=2\text{m}\Omega$ and $L=0.3 \text{ nH}$ the delay of the signal coming from one of the sensors is negligible. A numerical simulations that takes into account the primary shape of the signal generated by the diamonds gives the same result. Assuming a 1.3 mm path difference of the signals due to the board thickness, and assuming the permittivity of Rogers fiberglass 3.5 and the signal speed $1.3 \cdot 10^8 \text{ m/s}$, the time difference of the two signals is about 10 ps. The measured rise time of the single diamond pulse is 1.5 ns. The time difference between the 2 signals is therefore negligible with respect to the rising

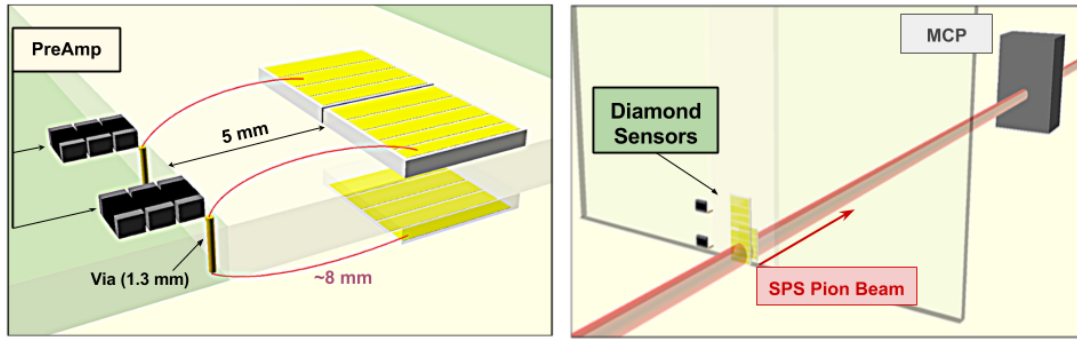


Figure 1. Left: PCB board with a 4-strips and a 5-strips diamond glued on one side and the other 5-strips diamond glued on the other side. The drawing includes a sketch of the connections of the sensors to the corresponding amplifier using a via in the PCB. Right: arrangement of the PCB diamond board in the test beam together with the MCP. The SPS pion beam is also indicated in red. To minimize the delay between the two paths of the double diamond signals, the detector is oriented such that the beam hits first the diamond connected through the via.

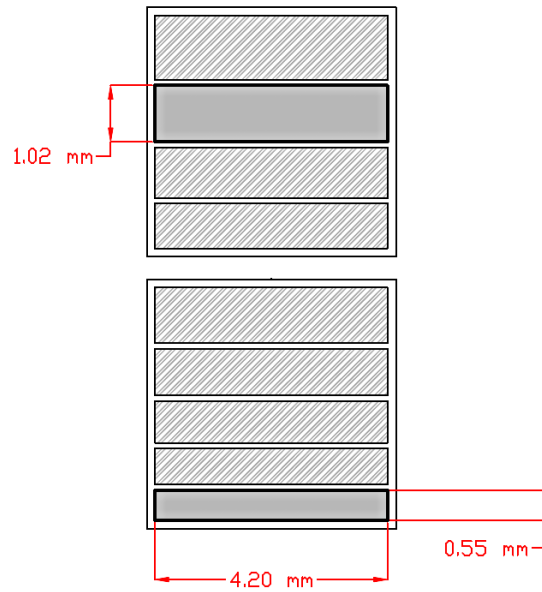


Figure 2. Sketch of the two diamond geometry used in this work, with 5 and 4 strips. The electrodes connected to the amplifier are reported with a solid color and the corresponding dimensions are shown.

edge. The same conclusion applies even if a difference of the bonding wire length of about 1 mm (see section 3) is taken into account. Diamond single crystal sensors are now easily available with a thickness of $500\ \mu\text{m}$, larger thickness with good quality crystals are difficult to obtain and this reflects also on the cost per unit volume.

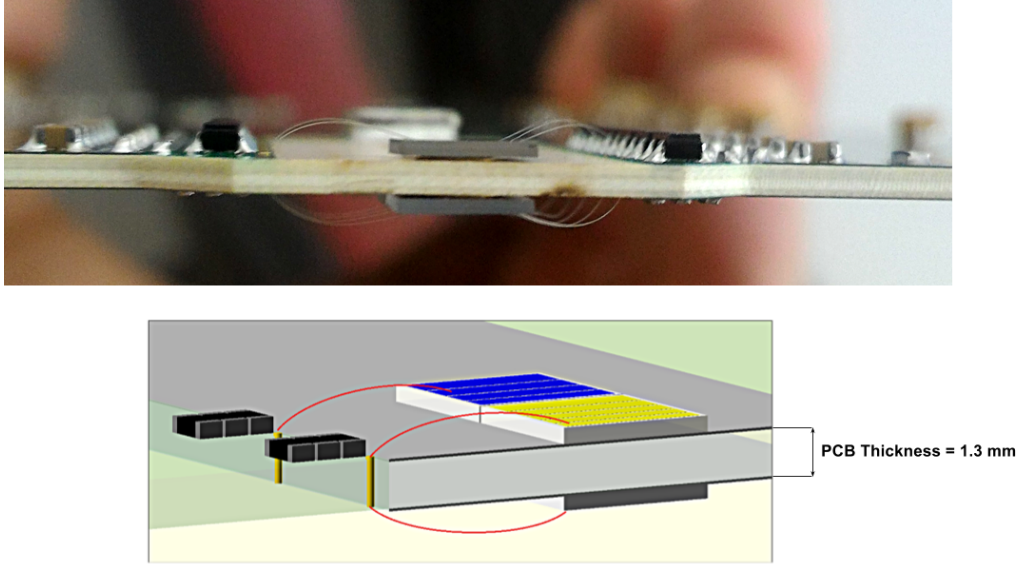


Figure 3. Top: picture of the edge of the prototype showing the two 5-strips diamonds connected to the same amplifier. Bottom: sketch of the PCB board showing the double diamond system. The diamond on the top layer far from the edge is used for performance comparison.

3 Description of the detector

Two scCVD diamond sensors of $4.5 \times 4.5 \text{ mm}^2$ area and $500 \mu\text{m}$ thick are aligned and glued with conductive epoxy to the HV contact present on each side of a slightly modified hybrid board developed by TOTEM. A sketch of the PCB board showing the two aligned diamonds and the single one used for comparison can be seen in figure 1(left). The setup used to perform the measurement at the SPS beam is shown in figure 1(right). The two diamonds used for this measurement are segmented into five pixels. The pixel used for the measurement has $0.55 \times 4.20 \text{ mm}^2$ hence for 2 pixels in parallel the area and the capacity is doubled (see figure 2). The DD signal is compared with a signal obtained from a single scCVD diamond of similar total area (pixel area $1.02 \times 4.2 \text{ mm}^2$), with a capacitance equal within 10% to the double one. A picture showing the edge of the detector with the two diamonds connected to the same amplifier is shown in figure 3. The signal electrodes of the double diamond are bonded with standard $25 \mu\text{m}$ diameter Al wire to the input of the same amplifier, which will now receives in input the charge released in the two sensors. In figure 1 the relevant lengths of the connection path are reported, with an error (dominated by the bonding wire) of about 1 mm. During the test the detector was oriented such that the beam crossed the diamond connected to the PCB via first.

Having developed a new fast and performing electronics to measure timing with a precision down to less than 100 ps we decided to test it with a double-diamond assembly; the amplifier is described in details elsewhere [7] and its schematics reproduced in figure 4.

3.1 The amplifier chain

Table 1 gives the main parameters of the electronics [7] and figure 4 shows the schematic diagram of the amplifier.

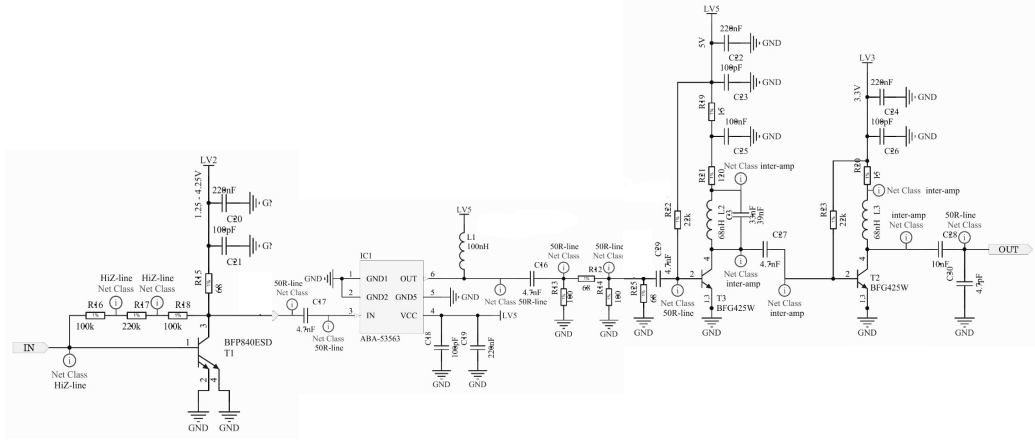


Figure 4. Schematic of the TOTEM amplifier used for the measurements.

Table 1. Characteristics of the TOTEM amplifier.

Number of stages	4	
	transconductance amplifier	
	flat freq response amplifier (ABA)	
	10 dB attenuator	
	booster-shaper	
	at DC	at 200 MHz
Input impedance	10 kOhm	1.5 kOhm
Current gain		93 dB
Current gain 1 st stage	45 dB	30 dB
Power gain 2 nd stage		21 dB
Attenuation 3 rd stage		10 dB
Power gain 4 th stage		52 dB
Power dissipated	0.3 W/ch	

4 Measurements

The measurement was performed using a 180 GeV pion beam at the CERN SPS. A Micro Channel Plate (MCP) PLANACONTM 85011-501¹ detector used in previous measurements was aligned with the detector and used as a time reference as indicated in figure 1. From measurements performed with a UFSD, the time precision expected from the MCP is of the order of 40 ps [11].

¹LANACONTM photomultiplier tube assembly 85011-501 from BURLE.

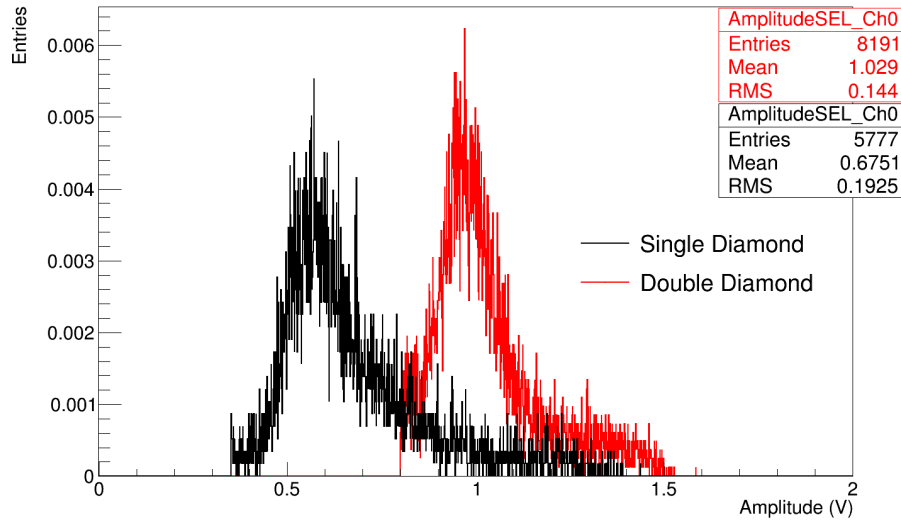


Figure 5. Comparison of the measured pulse height for a detector with one 500 μm crystal (black), and one which mounts two 500 μm crystals mounted back to back on the same amplifier (red).

The flux of particles traversing the detector was about 1 kHz/mm²/spill. Signals are recorded with an Agilent DSO9254A oscilloscope (8 bits, 20 GSa/s) and an off-line constant fraction discriminator analysis is used to measure the time difference between the MCP and the diamond signal.

In this first measurement to compare the performance of the two connection schemes implemented on the same board the gain of the DD preamplifier has been reduced to have a low amount of the DD signal saturated (about 5%).

Figure 5 shows the comparison of the signal maximum amplitude as measured for a single and a double diamond mounted on the same hybrid. The average values are 0.67 V for the single diamond and 1.03 for the double. The DD rise time was ~ 1.5 ns, which is compatible with the single crystal one.

The RMS of the noise V-amplitude was 22 mV for the channel connected to the two different diamonds, while the noise was 24 mV for the channel connected to the one-layer diamond used for comparison. The difference of the two values is compatible with the variation of the noise and gain measured channel-by channel on the hybrid board and is mainly due to the tolerances on the value of the discrete components used in the amplification chain. Indeed, even for a board without the diamond sensors connected, the noise measured on 12 channels varies within 2-3 mV. The ENC computed with respect to the charge released by the most probable values of figure 5 is found to be $(0.024/0.67) \times 2.9\text{fC} = 650e^-$ for the single-diamond channel, and $(0.022/1.03) \times (2.9 \times 2\text{fC}) = 770e^-$ for the channel with two diamonds.

Figure 6 shows the arrival time difference between the double diamond and the MCP. The standard deviation of the Gaussian distribution is 62 ps which means, assuming the MCP time precision of 40 ps, a time precision of the double diamond below 50 ps. The small non-Gaussian tail at larger ΔT values contains $\sim 5\%$ of the events of the plot. Therefore an improvement of the time precision of about 1.6-1.7 is obtained with respect to the single diamond, which was measured to be ~ 80 ps for a sensor with the same capacitance.

Time difference distribution between double diamond detector and MCP

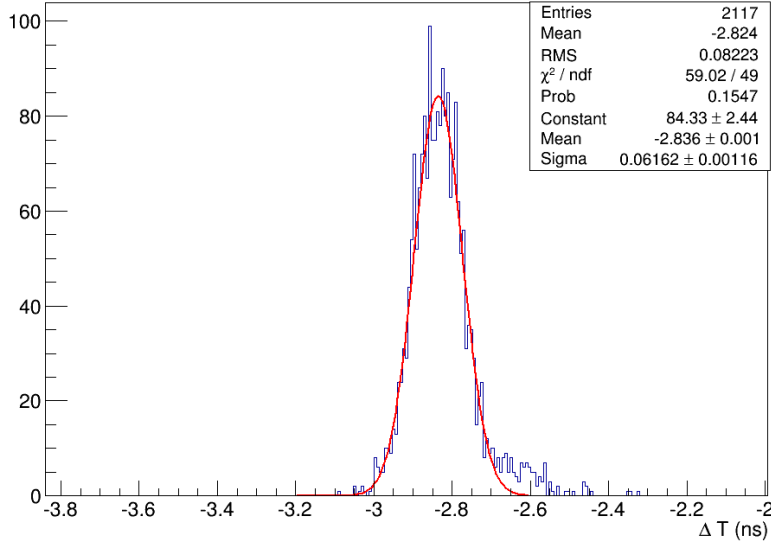


Figure 6. Time precision of a double diamond detector: the time difference between the time measured by the MCP and the time measured by the double diamond detector is shown.

The perfect alignment of the sensors on the sides of the board is of great importance to ensure a good measurement of the time resolution by the DD. This may be one of the reasons why the DD time precision measured here is not exactly equal to half of the single diamond time resolution, which is anyway better than the one expected for measurements performed simultaneously on two independent diamonds. This can be improved by modifying the way the double diamond sandwich is realized and it will be a subject of further developments.

5 Conclusions

The TOTEM TOF diamond detectors for the upgrade of the vertical RPs has been operated successfully in the LHC. Here we have presented a way to improve the timing precision by reading simultaneously two sensors with the same amplification chain that had been developed for the TOTEM upgrade.

A time precision improvement of a factor 1.6-1.7 has been measured for a double diamond setup when compared to the single plane detector used in the TOTEM upgrade.

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