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Picosecond timing resolution with 3D trench silicon sensors

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Summary. — In the high luminosity LHC phase, the collider will operate at a luminosity of 1.5×10^{34}/cm/s and strict requirements will be posed on subdetectors capabilities. Concerning the LHCb Upgrade2 VELO, to guarantee a good detector performance, the additional information of the hit time stamping with an accuracy of at least 50 ps is needed. A very promising option today to achieve this level of timing precision is the 3D trench silicon pixel, developed by the INFN TimeSPOT collaboration. This kind of sensor would allow to build a 4D tracker, capable of excellent resolution in both space and time measurements. The latest beam test with the 3D trench sensors has been performed at the CERN SPS/H8 in 2021. By means of low-noise custom electronics boards featuring a two-stage transimpedance amplifier, it was possible to test silicon pixels and strips made with the 3D trench technology. To extrapolate the sensor time resolution, the crossing time of a particle was estimated using two MCP-PMTs as time tag, with an accuracy of approximately 7 ps. The beam-characterization was performed for both non-irradiated and irradiated ($2.5 \cdot 10^{16}$ 1 MeV n_{eq}/cm^2) devices. Preliminary results show that the standard deviation of the core of the pixels time distribution is about 10 ps and the tilted sensor has shown an efficiency close to 100%.

1. – Introduction

Looking at the future of LHC, the instantaneous luminosity will increase by a factor five with respect to the LHC nominal value, and this will imply a degradation of the detectors performance due to the very large pile up. Concerning the LHCb Upgrade2, 2000 tracks from 40 pp interactions will cross the vertex detector (VELO) at each bunch crossing. To guarantee good detector performance, the additional information of the hit time stamping with an accuracy of at least 50 ps is needed [1]. A viable option to

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obtain such a challenging time resolution is the 3D trench silicon pixel developed by the INFN TimeSPOT Collaboration. In the following, the results obtained from the beam-characterization of these sensors at CERN SPS/H8 are presented, for both non-irradiated and irradiated ($2.5 \cdot 10^{16}$ 1 MeV n_{eq}/cm^2) devices.

2. – The TimeSPOT 3D sensors

Within the TimeSPOT (Time and SPace real-time Operating Tracker) project, 3D silicon sensors with trench-shaped electrodes were designed, fully simulated and characterized [2, 3]. Unlikely planar sensors, with 3D technology the electrodes of both doping types are penetrating partially or entirely through a high-resistivity silicon substrate, perpendicularly to the wafer surface. As a consequence, the electric field is parallel to the wafer surface, starting from one electrode type going to the other. This design allows having extremely fast signals and robustness to bulk damages thanks to the short inter-electrode distance [4].

For the TimeSPOT silicon sensors, the shape of the electrodes was chosen in order to maximize the timing performance: the goal is going towards uniformity in both the weighting field and the charge carriers velocity, aiming at the saturation regime thanks to the high and uniform electric field. The TimeSPOT sensors are $55\,\mu$m $\times$ $55\,\mu$m pixels with an active thickness of $150\,\mu$m; the substrate is made of p-type silicon.

3. – Devices under test and the SPS/H8 beam test setup

The devices under test (DUT) are pixels and triple strips (three strips made of 10 pixels read out together). The characterization was performed both for sensors irradiated with neutrons up to $2.5 \cdot 10^{16}$ 1 MeV n_{eq}/cm^2 and non-irradiated ones. To read out the fast current signals, all the sensors are connected to custom front-end electronics based on a trans-impedance amplifier (TIA) scheme with two amplification stages.

These sensors were characterized with a 180 GeV/c pion beam with 8 mm of transverse size at the CERN SPS/H8. A scheme of the setup is displayed in fig. 1 (left). Two sensors were placed in a Radio-Frequency shielded box: the device upstream was fixed to a support with piezo-electric stages ("sensor 1" in fig. 1 (left)), that allowed moving the board in the transversal plane with respect to the beam. The DUT was mounted on a fixed support that could be rotated ("sensor 2" in fig. 1 (left)). Moreover, this second sensor could be operated down to -40°C by means of a polystyrene box filled with dry ice: in this way, it was possible to test the irradiated devices as well. The time-tag of the setup was provided by two MCP-PMTs, placed outside the box; their average time resolution is approximately 5 ps.

The full setup was read out with an 8 GHz analog bandwidth, 20 GSa/s 4-channel oscilloscope (the Rhode&Schwartz RTP084). The two silicon sensors and the two MCPs waveforms are recorded and analyzed in order to determine the time of arrival of the crossing particle. The trigger of each data acquisition is the logic AND of the upstream sensor and the two MCP-PMTs waveforms.

4. – Waveforms analysis and results

In order to determine the time of arrival of the particles crossing both 3D silicon devices and the MCP-PMTs, different algorithms are considered. Namely, the *Spline* method (interpolating the rising edge of the pulse, taking as the reference time the one corresponding to the 20% of the signal amplitude), the *Leading Edge* method (taking the reference time as the one corresponding to a threshold of 15 mV), and the *Reference* method (subtracting from each waveform a delayed copy of itself, then taking the 50%-amplitude time as the reference one).

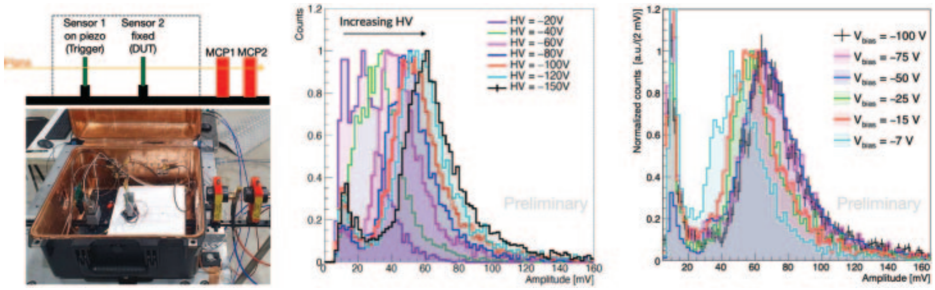

Fig. 1. – The setup in the SPS/H8 experimental area (left). Maximum amplitudes distribution for the irradiated pixel (centre) and the non-irradiated pixel (right) for different bias voltages.

4·1. *Amplitude distributions.* – The trend of the maximum amplitudes of the pixel waveforms as a function of the bias voltage is a useful observable in order to check the charge collection performance of the sensors. In the case of the non-irradiated sensor (fig. 1, right), the Landau-shaped distribution is well distinguishable from the noise peak even for low bias voltages, ensuring a good sensor performance in a wide range of bias voltages.

Regarding the irradiated pixel (fig. 1, centre), a higher bias voltage is necessary to recover the expected amplitude distribution of the non-irradiated sensor, which is however recovered for bias voltages higher than 100 V in absolute value.

4·2. *Detection Efficiency.* – The TimeSPOT 3D sensors have a geometrical efficiency of approximately 80% due to the trench-shaped electrodes which are inactive volumes. Thus, it is relevant to check the dependence of the efficiency on the tilt angle with respect to the normal incidence.

A single pixel is placed centered and upstream with respect to a triple strip: the detection efficiency is estimated counting how many events triggering a signal in the pixel would generate a signal in the triple strip as well. To do so, the distribution of the time of arrival of the triple strip with respect to the two MCP-PMTs is considered. Fitting the distribution with a double gaussian and a constant term (fig. 2, left), efficiency is evaluated as the number of events populating the peak over the total number of triggering events. The efficiency at normal incidence is compatible with the expected geometrical calculations, and at tilt angles larger than 10° the efficiency is close to 99% for -100 V bias voltage (fig. 2, right). The irradiated triple strip fully recovers the efficiency performance for a bias voltage of -130 V.

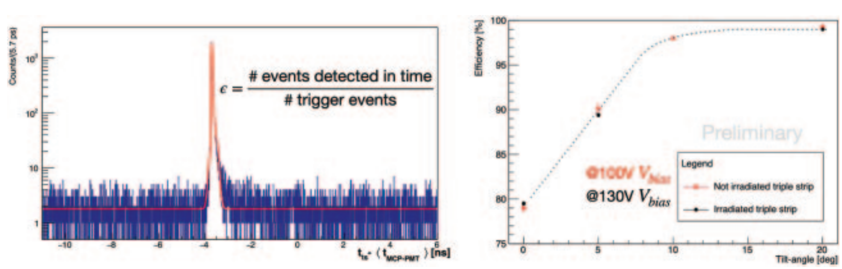

Fig. 2. – Time of arrival of the triple strip with respect to the two MCP-PMTs for the non-irradiated pixel at normal incidence (left). Detection efficiency as a function of the tilt angle for the irradiated and non-irradiate triple strip (right).

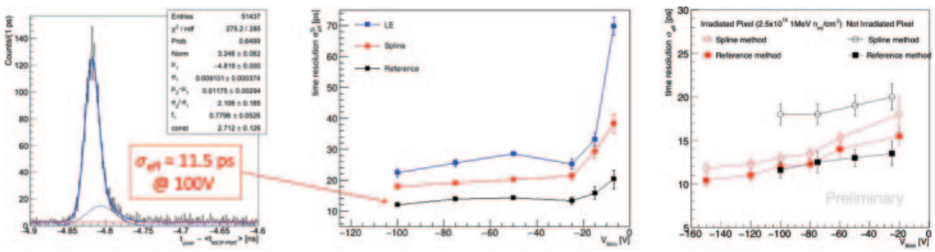

Fig. 3. – Distribution of the time of arrival of the non-irradiated pixel with respect to the average of the two MCP-PMTs (left). Time resolution of the non-irradiated pixel as a function of the bias voltage (centre). Comparison of the time resolution of the irradiated and non-irradiated pixel as a function of the bias voltage (right).

4·3. *Timing performance.* – In order to extrapolate the time resolution, the difference of the time of arrival of the particle in the pixel under test and the average of the time of arrival in the two MCP-PMTs is considered. As it is possible to notice in fig. 3 (left), where a typical time distribution for the non-irradiated pixel is displayed, the distribution is not perfectly symmetric and the sum of two gaussians was chosen as the fit function to include the contribution of the tails. The effective time resolution is obtained by properly weighting the standard deviations of the two gaussians. The time resolution as a function of the bias voltage for the three different analysis methods is displayed in fig. 3 (centre). The best result obtained is 11 ps with a bias voltage of -100 V with the *Reference* method. Also, the *Spline* and *Leading Edge* methods show promising results, all below 30 ps.

The irradiated sensor shows excellent time resolution as well, reaching the result of approximately 10 ps at a -150 V bias voltage. Figure 3 (right) displays the comparison between the time resolution obtained with the irradiated and non-irradiated sensor as a function of the bias voltage.

Concluding, in both the irradiated and non-irradiated pixels there is no dependence of the time resolution on the bias voltages below -20 V.

Moreover, a study was performed considering two neighbouring pixels tilted in order to have tracks crossing both. It was observed that combining the contributions of the two pixels it is possible to recover the time resolution expected for a single pixel at normal incidence.

5. – Conclusions

The high luminosity conditions in future hadron colliders pose strict requirements to the detectors performances. Concerning tracking detectors, the TimeSPOT 3D sensors have all the characteristics to overcome such challenges, with a time resolution of the order of 10 ps and a detection efficiency close to 100% for both the irradiated and non-irradiated sensors.

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