Test beam & time resolution analysis for UFSD and CVD diamond detectors

Stefano Scali
Department of Physics and Advanced Technologies,
University of Siena, Siena, Italy
CERN Summer Student Programme 2017
(Dated: September 2, 2017)

The ever-increasing luminosity in particle physics, aimed at seeking new phenomena, has led to the need for radiation-hard detectors with a remarkable time resolution. To reach the goal several tests and data analysis has been performed but further development is still required. During my internship I have participated to the test of new sensors. After an introduction to the theoretical framework this report describes the data taking procedure using SPS beam at the H8 site in Prevessin. The second part describes the data analysis and extrapolation of the time resolution for many boards.

During the *Summer Student Programme* I took part in the TOTEM experiment that studies *diffractive physics* events. TOTEM experiment aims at a deeper understanding of the proton structure and at the research for new physics. The collaboration with the CMS experiment, which lead to the CT-PPS joint detector, allows to perform high precision measurement in CD processes (see sec.I). The project make use of timing detectors (UFSD or diamonds) installed in the TOTEM Roman Pots to reconstruct the longitudinal vertex of the interaction and thus to assign the proton vertex to the correct central CMS tracker vertex in presence of event pileup. Therefore the vertical Roman Pots will be equipped with timing detectors with $\sim$30$\div$50 ps resolution, depending on the running scenarios.[1]
The goal of this report is to elucidate the steps followed to test and analyze silicon and diamond detectors in order to achieve the time resolution aspired.
Section I delivers a basic introduction to the physics programme followed by TOTEM experiment. Section II describes the experimental setup for the test beam at H8 site with SPS beam. Section III presents the results of the test beam. Section IV provides a conclusion with future considerations for further test beams.

I. THEORETICAL FRAMEWORK

Diffractive physics has been studied since 60's when the first accelerators comes to life. Due to the similarities with the optical diffraction, the research for a similar theory that could explain the experimental data started. Tullio Regge developed his theory which explains diffractive processes through the exchange of "objects" called Reggeons. The most important one is the *Pomeron*, that determines the hadron-hadron cross section behavior at high energies. Afterward a connection between the Pomeron and the *glueball* has been found opening the way to many questions to which TOTEM experiment is trying to answer.[2]
A diffractive process can be defined as an high energy process where no quantum numbers are exchanged between the colliding particles.

Diffractive physics includes a specific event topology, called *Central Diffractive events*, where both protons survives the interaction and a central system is created with rapidity gaps in the final state particle distribution. The CD processes effectively turns LHC into a gluon-gluon collider and provides an excellent opportunity to search for glueball candidates. Glueballs are predicted by QCD as bound gluon states with no valence quark content. QCD lattice calculation foresee a $J^{PC} = 0^{++}$ ground state and a 2^{++} state followed by a spectrum of excited states. Scalar and tensorial f states in the 1.5 to 2.5 GeV mass region are generally regarded as potential glueball candidates. The absence of valence quarks, in combination with the $J_z^{PC} = 0^{++}$ selection rule, makes exclusive CD reactions an ideal place to search for them. The hypothesis, whether a resonance is a glueball or not, can be studied by measuring its exclusive CD production cross-section as well as its decay modes and their branching ratios. The full TOTEM physics program can be found elsewhere[3].

II. EXPERIMENTAL SETUP

I have participated to the test beam started on 2017 July, 17 and ended on July, 22. The test beam was performed in H8 site in Prevessin where SPS beam is extracted to allows experiment groups to test their detectors. During the test beam I had align the detectors in the test bench station and to set-up all the equipment needed, starting from the low voltage and high voltage power supplies, through cabling and the the oscilloscope (see Figure 1). Here a list of the instrumentation used:

- Keithley 2410-C High Voltage SourceMeter
- Aim-TTi PL303QMDP Programmable Power Supply
- Aim-TTi TSX1820P Programmable Power Supply
- Agilent DSO9254A Oscilloscope
- SMP, SMA, BNC cables and adapters

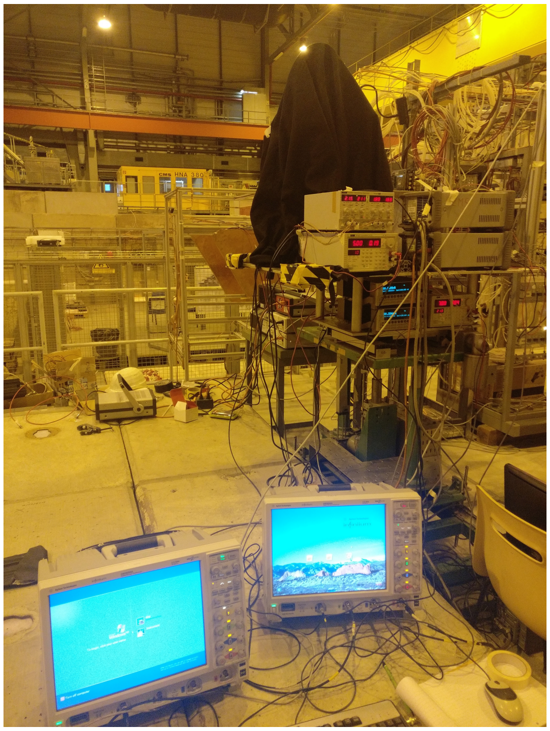


FIG. 1: In the image the setup for the test beam. The detectors are under the black cloth to protect the light-sensible UFSD sensors.

After that, I set up the remote control of the oscilloscope from the H8 control room. Thank to the remote desktop I learned to start the data acquisition through a Python script. The latter script can take as input parameters the maximum number of waveforms to be acquired before starting a new file. This avoid to create large output files but introduce the need for a proper tool to offline merge the data. The other parameters like the trigger threshold, channels acquired, the samples frequency and the acquisition segmentation are set via the oscilloscope interface. To collect the data we chose different segmentation between 5000 and 8000 events to optimize the files dimensions. At the end of the runs we collected 350 GB of data containing information about the following boards:

- 1 new Ultra Fast Silicon Detector (UFSD) (see figure 3)
- 1 UFSD (already tested to be used as reference)
- 2 ultra pure single crystal CVD diamond detector
- 1 ultra pure double crystal CVD diamond detector (see figure 4)

CVD diamond detectors are consisted by pure diamonds metallized on the two faces. Diamonds are normally considered as one of the best insulators but when a high difference of potential is created between the two metallized faces, the diamonds can be treated as a semiconductors. Therefore the ionization created by a particle create a small signal than amplified through the different steps.

UFSD detectors are thin (typically 50 μm thick) silicon Low Gain Avalanche Diodes (LGAD) that produce large signals showing hence a large dV/dt, a characteristic necessary to measure time accurately. An high difference of potential is applied to the sensor so that charge multiplication happens when the charge carriers drift. Under this condition the drifting electrons acquire sufficient kinetic energy to generate additional e/h pairs and generate a sufficient signal that can be detected[4].

The set-up of the test beam started with the alignment tests to find as much coincidences as possible between the boards hosting the sensors. Due to the relatively small sensor (max area: 4.5x4.5 mm^2) the first steps consisted in find the raw alignment. We started using a laser level passing through the *wire chambers*[5]. After we optimized it changing the currents of the last bending magnets of the beam line. In this way we could limit the data taking interruptions caused by the accesses in the experimental area.
To organize and collect the information of the test beam I created a *logbook* template to take account of the oscilloscope parameters and the setup tested (see Figure 2 in the other page). This files helped to reconstruct the data through the analysis program.

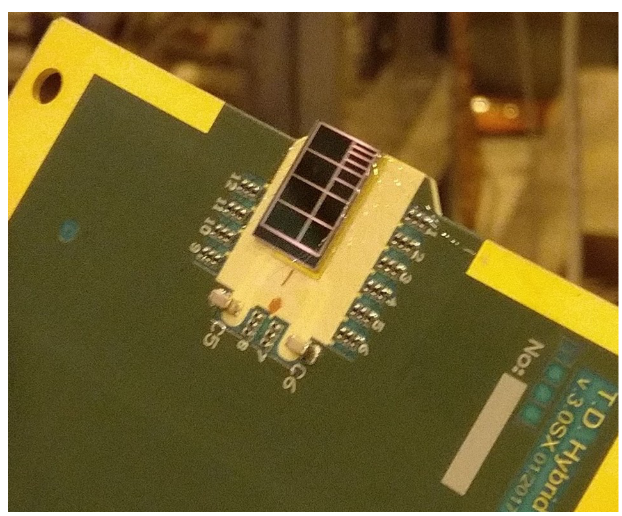
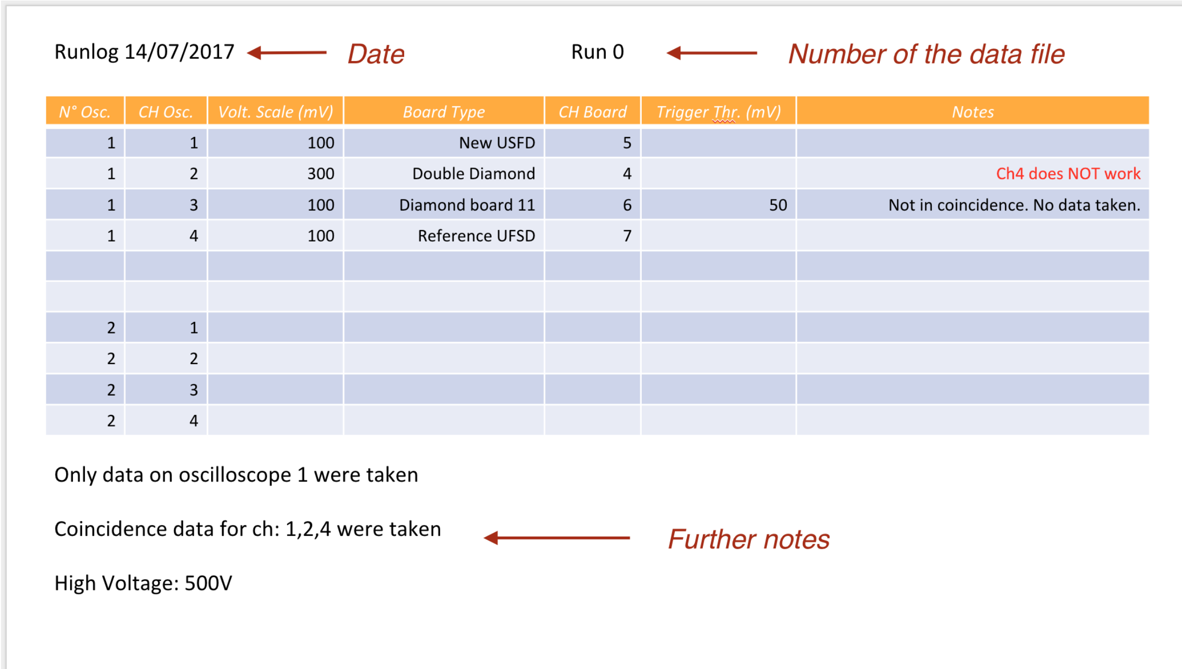


FIG. 3: New UFSD sensor. In the image we can see the segmentation of the device, optimized for TOTEM needs.



Runlog 14/07/2017 ← *Date* Run 0 ← *Number of the data file*

N° Osc.	CH Osc.	Volt. Scale (mV)	Board Type	CH Board	Trigger Thr. (mV)	Notes
1	1	100	New USFD	5		
1	2	300	Double Diamond	4		Ch4 does NOT work
1	3	100	Diamond board 11	6	50	Not in coincidence. No data taken.
1	4	100	Reference UFSD	7		
2	1					
2	2					
2	3					
2	4					

Only data on oscilloscope 1 were taken

Coincidence data for ch: 1,2,4 were taken ← *Further notes*

High Voltage: 500V

FIG. 2: The runlog model helped to organize the parameters used during the test beam. In the first line we can see the cells dedicated to the board type, the channel analyzed and the threshold used together with other important notes.

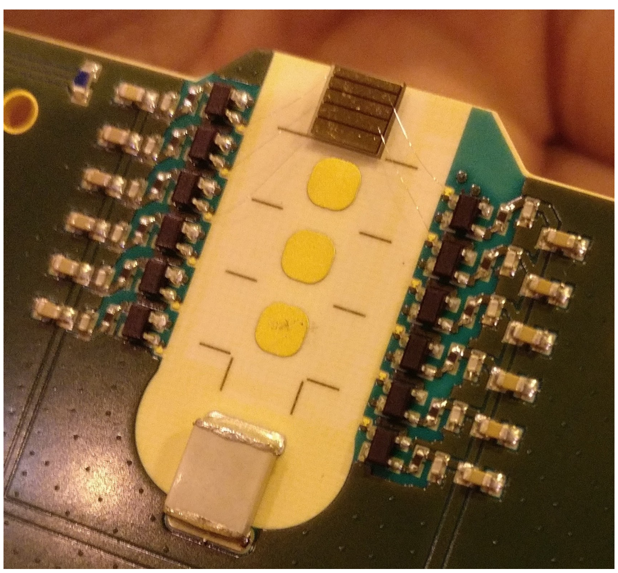


FIG. 4: Double diamond sensor. On the opposite side the board hosts 3 diamonds.

III. DATA ANALYSIS

After the data taking I started converting the *binary* files created by the oscilloscope to *Root trees* to let the analysis program interpreting them. After the first files conversion, I found useful to write down a Python script to organize and reconstruct all the files in a raw. The script organizes all the binary files, and launch the command to convert the format from *binary* to *Root trees*. The code take account of the sequential numbering automatically introduced by the oscilloscope acquisition software, organizes all the necessary directories, convert the files of the same run and move the converted files in the right folders. The code is now available and used by the TOTEM collaboration.
The next step has been to use a C++ program (*readOscilloscope.C*) to process the waveforms and extrapolate the time resolution of the boards (in Figure 5 an example of UFSD signal). To reach the goal I have optimized the program to display the raw waveforms taken at the test beam. This work helps the user, in this case me, to better choose the right analysis parameters.

The number of coincidences between the reference board and the channels tested ranged considerably because the fixed support table does not help in the detector alignment. That slowed down the data analysis forcing us to use large dataset and consequently several files to reach a sufficient statistic.

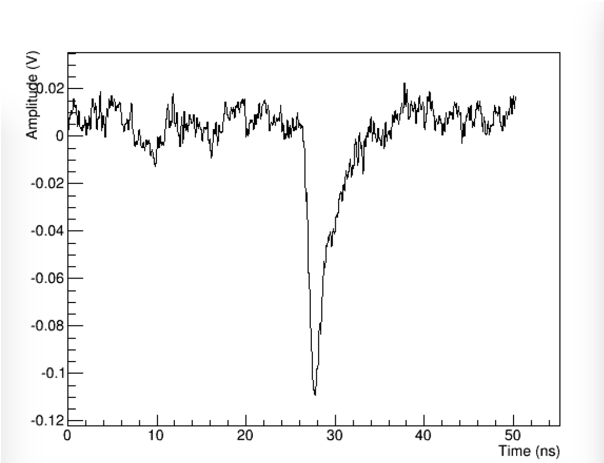


FIG. 5: Example of new UFSD signal extrapolated by the *readOscilloscope* program.

For each channel, the raw data collected were analyzed removing the noise pedestal and selecting a population of waveform with similar *Signal to Noise Ratio*(SNR). The similar SNR in the two boards let us calculate in a simple way the approximate time resolution of the channels. The event selection is done rising the offline trigger threshold of the channel while the right SNR selection was performed changing the data taking range of the reference channel. With a comparable SNR we can calculate the sensor resolution dividing by $\sqrt{2}$ the σ of the Δt distribution between the analyzed sensors (e.g. new UFSD and reference board). Here an example of the parameters used to analyze the signals.

Variables needed to start the Loop method:

```
$ void Loop(int initevent, int numevent, bool
    applyFilter, bool cuthighrisetime, double
    THE_FCut_MHz_Input, string extrastr, bool
    displayFIT0, bool displayFIT1, bool
    EVTDISPLAY, int ChosenCh_0, int ChosenCh_1,
    double AmpliThr_0, double AmpliThr_1, int
    EventualChFilter, double EventualChFilterThr,
    bool cutsaturation, bool help, bool
    useAutoTHR)
```

Example of parameters :

```
$ .L SPS2015August.C+
$ SPS2015August
    s1("/tmp/sscali/run43_file0.root")
$ s1.Loop(0, 20000, false, false, 1400,
    "Osc1450V_A", false, false, false, 1,
    3, -0.06, -0.09, -1, 0, false, false,
    false)
```

IV. CONCLUSION

Improvements can be made for future experimentation. Possible improvements would optimize the speed of the set-up to leave more space to different measurements and increase the number of coincidences allowing the analysis code running on less files to reach a sufficient statistic. This improvement would include: a more sophisticated method to choose the right parameters inside the analysis program and a mobile station where to install the detectors to let the user moves the detectors remotely.

Concerning the time resolution analysis, after a gaussian fit done on *Root* (Fitting parameters on Table I), the board have presented an average time resolution of $\sim 70 ps$ (in Figure 6). Have to be noted that with 4 boards in one single *Roman Pot* unit we can reach ~35 ps thanks to 4 different independent measurements. This result should be further improved to fulfill the future timing requirements of the TOTEM experiment (<30 ps).

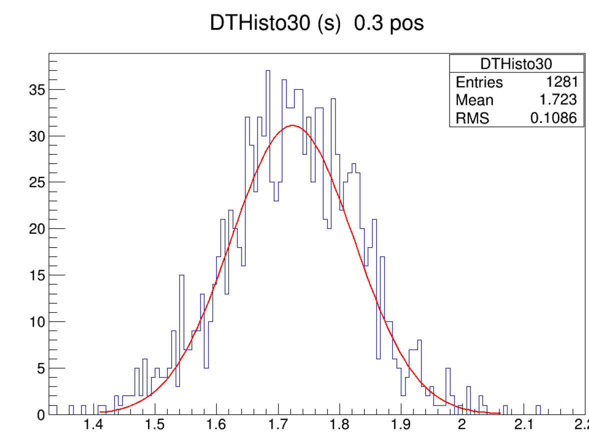


FIG. 6: DT Histo 30 - CH1 new UFSD. Here one of the histograms used to extract the time resolution. In red the gaussian fitting through which we obtained ~70 ps of time resolution

TABLE I: Fitting parameters.

NAME	VALUE	ERROR
Constant	$3.13e+01$ ns	$1.19e+00$ ns
Mean	$1.72e+00$ ns	$3.042e-03$ ns
Sigma	$9.89e-02$ ns	$2.52e-03$ ns

[1] Tommaso Isidori. *Diamond detectors for proton Time of Flight in CT-PPS and TOTEM experiments.* (English) Università di Pisa, 2017.

[2] Edoardo Bossini. *Development of a Time Of Flight diamond detector and readout system for the TOTEM experiment at CERN.* (English) CERN-THESIS-2016-137, 2016.

[3] TOTEM Experiment. *Timing Measurements in the Vertical Roman Pots of the TOTEM Experiment Technical Design Report*. (English) CERN-LHCC-2014-02 TOTEM-TDR-002, 2014.
[4] TOTEM Experiment. *Test of UFSD Silicon Detectors for the TOTEM Upgrade Project*. (English) arXiv:1702.05180v1
[5] *Wire chambers are gas detectors part of the test beam facility, used to locate and monitor the beam position.*