Cross-Disciplinary Research: From Nuclear Physics to Cosmic Ray Detection and Medical Applications

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After a short introduction about the Large Hadron Collider at CERN, Switzerland, we will discuss briefly the fast timing detectors built to measure intact protons. The applications of these detectors concerning cosmic-ray detection and medical applications will be described.

The Large Hadron Collider and Timing Measurements

The Large Hadron Collider

The Large Hadron Collider (LHC) located close to Geneva at the border between Switzerland and France collides protons with a centre-of-mass energy of 13 TeV, making it the highest energetic collider in the world. The idea is twofold: a better understanding of the proton structure in terms of quarks and gluons and reproducing conditions as close as possible to the big bang where new particles might be produced. The LHC energy allows getting similar conditions at the particle level at about 10^{-13} seconds after the big-bang. In most cases, the interacting protons are completely destroyed after interactions and general purpose detectors such as ATLAS[1] and CMS[2] have been built to identify and measure all kinds of particles that are produced after the interaction. Since particles need more or less material to be absorbed in a material according to their type and energy, the structure of such detectors is always made of different layers dedicated to measure successively photons, electrons and positrons, pions, protons, neutrons and finally muons that need a lot of material to be absorbed. Only neutrinos cannot be directly measured and appear as missing energy in the detector. Detectors such as ATLAS and CMS are large and heavy; for example, the site of the ATLAS detector being of the same magnitude as Mount Rushmore in the USA and the weight of the CMS detector being larger than the Eiffel Tower in Paris. In addition to these two main experiments, smaller, more dedicated experiments exist such as LHCb, ALICE, TOTEM, MOEDAL...

Recently, some "strange" events were observed at the LHC where protons are found to be intact after interacting. An everyday analogy would be one gets an accident between two trucks (the protons) and both trucks are intact after the accident and, in addition, some small cars (additional particles) are produced during the collision. The two trucks will however be slower: the protons "donate" part of their energy to create the additional particles. The LHC magnets are used as a spectrometer to measure the intact protons in the final state. Namely, the radius of curvature of the intact protons in the final state is smaller than for the beam protons since they lost part of their energy. This clearly means that it is possible to detect these intact protons after interaction by installing detectors very close to the beam. This is why both ATLAS and CMS-TOTEM[3] Collaborations installed detector in so-called roman pots, at few mm from the beams, about 220 m downstream the interaction point, to measure the intact protons scattered at very small angles. A scheme of the proton detectors in the case of the CMS-TOTEM collaboration is shown in Figure 1 as an example.

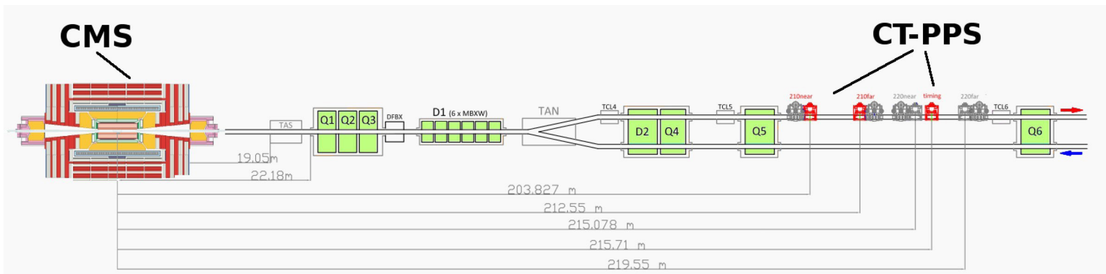

Figure 1. Schematic view of the CMS detector and the roman pot detectors from TOTEM. Only one side is shown.

Measuring proton time-of-flight at the LHC

The LHC collides clouds of hundreds of billions of protons together; this means that there are multiple proton collisions occurring within the same bunch crossing. What we are interested in, as an example, is the production of two photons or two *W/Z* bosons together with two intact protons that could be a sign of extra-dimensions in the universe, composite Higgs bosons or axion-like particles[4, 8].The issue is that the two photons or the two *W/Z* bosons can originate from a different interaction than the two protons as shown in Figure 2. In order to reject these uninteresting events (called background), it is possible to measure precisely the time of the protons interaction. Namely, we can constrain the protons to originate from the same interaction point as the two photons or *W/Z* bosons. Since particles at the LHC travel at the speed of light, time needs to be measured with high precision, of the order of ten picoseconds (1 ps=10^{-12} s). Fast silicon detectors together with their readout electronics have been developed in order to achieve this goal.

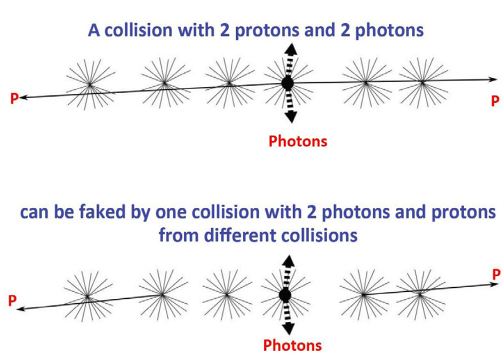

Figure 2. Pile up processes at the LHC.

Performance of Timing Detectors at the University of Kansas

At the University of Kansas (KU), we designed a multi-purpose electronics board to read out silicon or diamond detectors to measure precisely the time at which particles cross the detector, as well as a test-stand in order to test the full chain from the detector to the read-out electronics. The test-stand is equipped with a laser or a radioactive source in front of the silicon detectors (see Figure 3). The system is highly adaptable to different kinds of sensors (diamond or Silicon) and only requires a power supply to operate. The read-out electronics produces a signal that can be analysed using a digital scope or some waveform signal analyser, such as SAMPIC[5, 6, 7]. The amplifier was designed at the University of Kansas and can be used for a full range of detectors and applications.

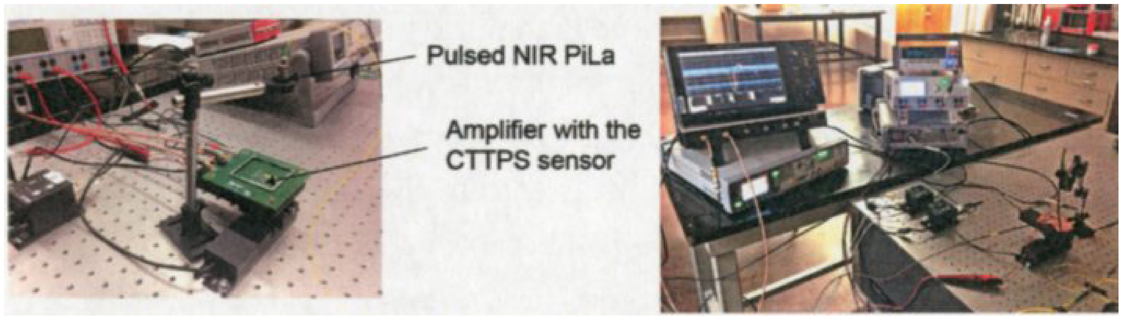

Figure 3. Timing detector test stand at the University of Kansas.

The performance of the timing detector and its amplifier is shown in Figure 4. In order to test the full system in real conditions for nuclear and particle physics, we used a test using a particle beam at Fermilab, Batavia, USA. Using a single layer of silicon sensor, we obtained a resolution of about 39 picoseconds, which means that a resolution better then 15 picoseconds can be achieved with 8 layers of these detectors. In particular, the sensor technology that was used is often referred as Low Gain Avalanche Detectors (LGAD), or Ultra Fast Silicon Detectors. On Figure 4, we can see a photo of the board designed and built at the University of Kansas. The idea was to build a "plug-and-play" amplifier that can be used to test different kinds of sensors for different applications. The performance of the amplifier is similar or even better than commercial ones with a cost about two orders of magnitude lower.

Possible Applications of Timing Detectors and Analysis Techniques

In this section, we will discuss three possible applications using Ultra Fast Silicon detectors and the electronics that was developed at KU, namely the measurement of cosmic rays in collaboration with NASA, of doses applied for cancer treatment in collaboration with KU Medical Center and a better understanding of catalysis in chemistry.

Measuring signals of a diamond or Ultra Fast Silicon detector

All applications that we are going to discuss rely on the same principle: we

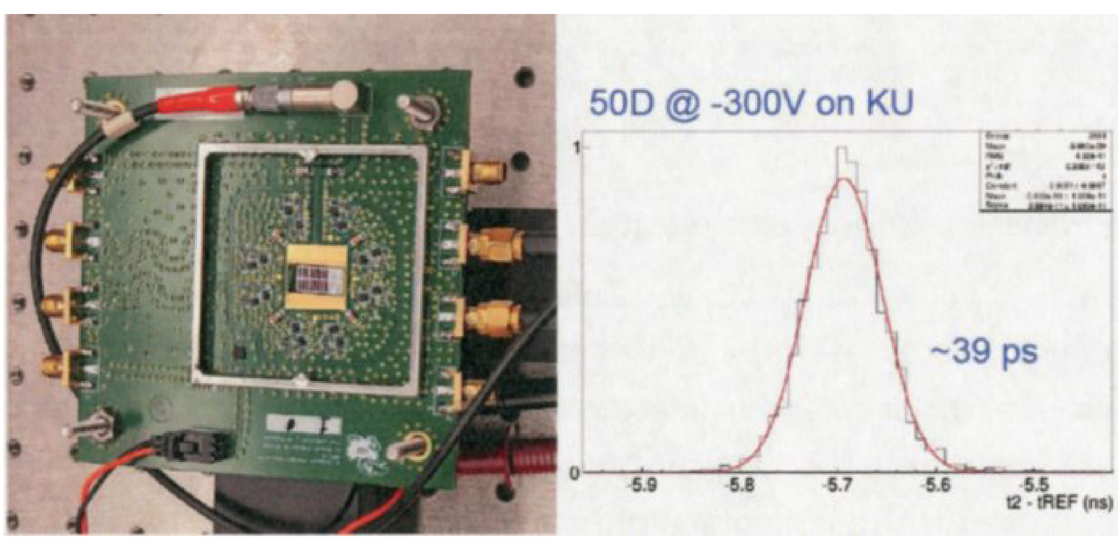

Figure 4.Timing board made at the University of Kansas.

need to analyse the full signal produced by a sensor at the passage of a particle. The applications do not rely too much on timing measurements (as in high energy particle or nuclear physics) but in the measurement of the number of particles or charge that crosses the detector. The idea is similar and it is illustrated in Figure 5. When a particle (for instance a proton) crosses a detector, some pairs of electrons and "lack of electrons", called "holes", are formed and drift slowly for the ions or fast from the electrons towards the electrodes because of the electric field. Detecting the proton passing through the detector is thus possible measuring the signal induced on the electrodes using dedicated electronics.

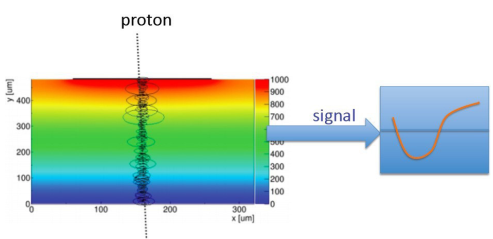

Figure 5. Scheme of signal induced in a silicon detector at the passage of a particle.

Since we want some automatic method to detect particles or to measure deposit charges, a dedicated electronics system was delayed at KU as we mentioned already. The next steps are illustrated in Figure 6. Signals directly read out from a detector need to be amplified. The first step of the KU circuit is then to amplify these signals without affecting too much the properties of the signals, like shape and amplitude with respect to the noise. In order to measure the signal, a very fast digitization is performed (taking as an example 64 measured points in a few nanoseconds). A mathematical interpolation between the different measured points allow then a smooth reconstruc-

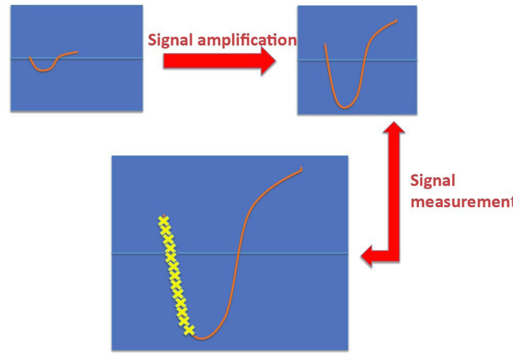

Figure 6. Scheme of amplification of a signal coming out of a Silicon detector.

tion of the full signal. The method allows the precise measurement of the time of crossing of the particle and, at the same time, the signal amplitude and other signal characteristics, like the rise time and the duration.

Application 1: Measurement of cosmic rays with NASA[10]

The idea for this project in collaboration with NASA is to measure the type and energy of cosmic ray particles originating from the sun for a range between keV to GeV as illustrated in Figure 7.

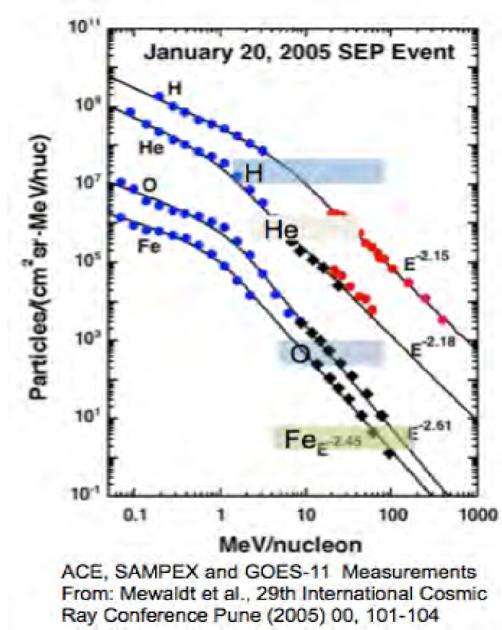

Figure 7. Spectrum of solar cosmic rays.

In order to do so, build a detector made of sandwiches between active layers of Si detectors and absorbers that allows the measurement of different kinds of particles with different energies. Using the very fast digitization described above, it is possible to reconstruct fully the signal in the different Si layers. Since different kinds of particles deposit their energies in the different layers differently, also depending on their energies, it will be possible to reconstruct the full properties of the comic ray radiation analysing the digitized signals. This project aims at preparing a prototype of a cube sat in collaboration with NASA (the AGILE project, shown in Figure 8) in the next

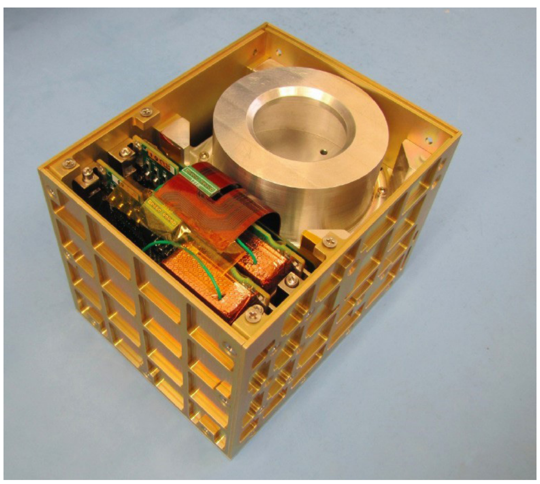

Figure 8. The AGILE project with NASA.

three years and will eventually help with the precise measurement of radiation between the Earth and Mars needed in order to send astronauts to Mars.

The inconvenience of digitizing the signal in each Si layer is that the amount of data originating from the detector will be quite high. This is needed to pre-process data before sending them back to Earth. Advanced analysis techniques have been developed successful in high energy physics to discover the Higgs boson, as an example, or to look for physics not explained by the standard model. The amount of data accumulated by the LHC experiments is very large and requires neural networks or other advanced techniques in order to analyse them. For this application, advanced techniques will be needed to filter and optimize the relevant important data that will be sent back to Earth.

Application 2: Measuring radiation in cancer treatment[9]

The second application deals with the precise measurement of radiation accumulated by the human body during cancer treatment using photon (radiotherapy) or proton (hadrotherapy) beams. The idea is to measure the amount of radiation delivered by the medical particle accelerators with millimetre precision. Furthermore, present techniques are not able to count exactly the number of particles produced, but they measure the average charge deposited inside the sensor. A more precise method consists in counting the number of photons or protons that pass through the sensor. This project is being developed in collaboration with KU Medical Center and, if successful, it will allow a more optimized dose absorbed by the patient during cancer treatments.

Another possible medical application deals with PET imaging. Usually, patients absorb radioactive material that interact with electrons inside the tumour, emitting photons that can be measured and that can be used to create an image of the tumour. The problem is that the human body emits naturally lots of photons and in average, 1 pair on photon originates from the tumour out of 10,000. An advanced analysis is then needed in order to isolate the interesting photons. In order to preselect the photons originating from the tumour, it is possible to measure the time of detection of the photons and require them to originate from the tumour itself. This would allow to produce a more effective and faster image of the tumour. This development would be a fundamental application as well and has been the interest of many private companies in the world.

Application 3: Understand better catalysis in chemistry

The third application deals with a better understanding of catalysis in chemistry with the application of reaching better methods to desalinize sea water, as illustrated in Figure 9. The idea is to understand better how an interface between two liquids, a solid and a liquid, or a gas and a liquid vary as a function of time when catalysis occurs. Using interferometry technics, we can measure how the interface varies as a function of time by measuring a snapshot every 20 or 30 picoseconds. This will lead to new insights in the mechanism of catalysis and thus in a better understanding of applications where catalysis is needed. This could also have implications on the way medicine is absorbed by human body by improving the interface between human cells and medicine.

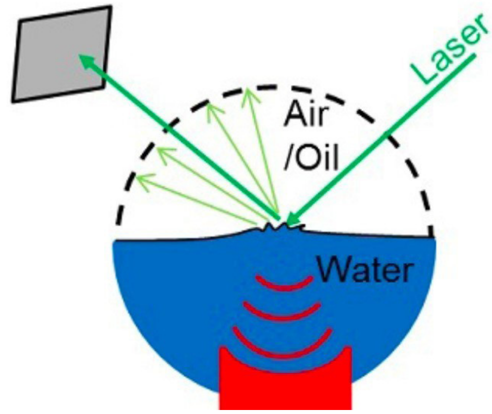

Figure 9. Catalysis measurements in chemistry.

Conclusion

In this short report we describe the fast timing detectors and their electronics developed originally for high energy and nuclear physics as well as the potential applications in cosmic ray measurements, medical analysis and chemistry performed at the University of Kansas.

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