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Project Report

Fast Timing Detectors and Applications in Cosmic Ray Physics and Medical Science

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Abstract: We use fast silicon detectors and the fast sampling method originally developed for high energy physics for two applications: cosmic ray measurements in collaboration with NASA and dose measurements during flash beam cancer treatment. The cosmic ray measurement will benefit from the fast sampling method to measure the Bragg peak where the particle stops in the silicon detector and the dose measurement is performed by counting the number of particles that enter the detector.

Keywords: cosmic ray; radiation measurement; space physics; dose measurement

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1. Introduction: Signal Amplification and Measurement

Fast silicon detectors are currently extensively used in the field of high energy physics, for example at CERN at the Large Hadron Collider (LHC) for the TOTEM, CMS, and ATLAS experiments [1–3]. The measurement of the particle time of flight allows us to know from which interaction the different particles are originating in a busy environment when up to 50 (200 at high luminosity LHC) interactions per bunch crossing can happen. The idea is to discuss two applications in medicine and cosmic ray physics that arise using this kind of detector and readout technology. We will first describe the principle and methods of the detector and readout electronics and describe in detail two applications related to in situ measurements of cosmic rays in collaboration with NASA and the measurements of the dose received by patients during cancer treatment procedures especially in flash proton therapy.

The principle behind these measurements is shown in Figure 1. A fast silicon detector is used to detect particles interacting with its medium (for instance, in the case of the TOTEM detectors at the LHC, we measure intact protons). The important point, especially for the applications that we will discuss, is to use fast silicon detectors so that the signal produced by the particle has a short time duration, typically a few nanoseconds, which allows us to reduce the probability of overlaps between the signals produced by multiple particles, for example in the cases when a new interaction between the particle and the detector occurs every few fractions of a nanosecond. We already see the advantage of these detectors, namely that we can count the particles that go through them, as well as measure the amplitude and duration of the signal.

The signal originating from the fast silicon detector is amplified with very limited shaping (so without affecting the main timing characteristics of the signal such as its duration and fast rise time). This is performed using front end electronics designed and developed at the University of Kansas using standard electronic components [4] that allow us to considerably reduce the price of the amplifier. The following step consists of performing fast sampling and digitization of the signal as shown in Figure 1. This presents two advantages. First, it allows us to obtain a very precise time stamp when the signal (or, in other words, a particle) arrives in the detector (this is used to measure the time-of-flight of particles in high energy physics with a precision of 15–20 picoseconds, the duration of the signal being only a few nanoseconds). Second, it provides a reconstruction of the full signal in terms of its amplitude and shape by performing an interpolation between the sampled points (there can be up to 64 or 256 points depending on the specific sampler [3,5]). In order to check the performance of the fast silicon detectors and their read-out electronics, we installed a full test stand at the University of Kansas that uses a laser beam or radioactive sources, and in addition, we performed some beam tests at Fermilab, Batavia, USA, and the preliminary measurements showed timing resolutions between 15 and 30 picoseconds for ultra fast silicon detectors [2]. These results were obtained during beam tests at Fermilab and at CERN, where reference timing was given using a Si photomultiplier.

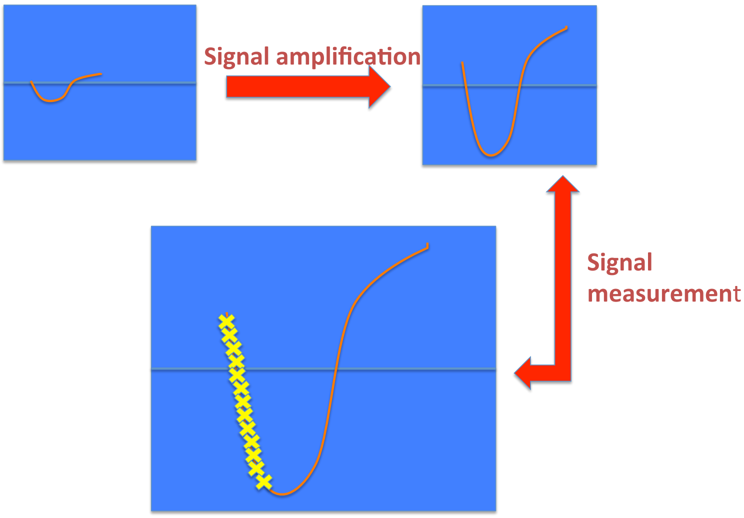

Figure 1. Principle of signal analysis originating from a fast silicon detector. A particle entering the detector medium induces a signal that is first amplified without disturbing the shape of the signal and then digitized by performing a fast (a few GS/s) sampling (yellow crosses), which allows us to measure the arrival time of the signal, its amplitude, shape, and duration. The typical duration of the signal is a few nanoseconds.

2. Measuring Cosmic Rays in Space: The AGILE Project

The first application using fast silicon detectors is the AGILE (Advanced enerGetic Ion eLectron tElescope) project in collaboration with NASA. Its main goal is to identify the kinds of particles emitted in cosmic rays originating from the sun or from space (electrons and ions H-Fe) and at the same time to measure their energies in the MeV–GeV range [4]. This should be performed directly in space using a compact, low-cost, and low-power detector installed onboard a small satellite (e.g., CubeSat) in order to reduce the cost of the apparatus. The basic idea is quite simple: we can use multiple layers of fast silicon detectors to measure and reconstruct the signal when the particle completely stops in a given layer of the silicon detector (the so-called Bragg peak) using the fast sampling technique. This approach is called pulse shape discrimination (PSD) and its simplified schematic is shown in Figure 2.

As mentioned in the previous section, the fast sampling method allows reconstructing both the amplitude and the duration of the signal. A photograph of one detector layer with the readout electronics that are part of the device to be sent into space is shown in Figure 3.

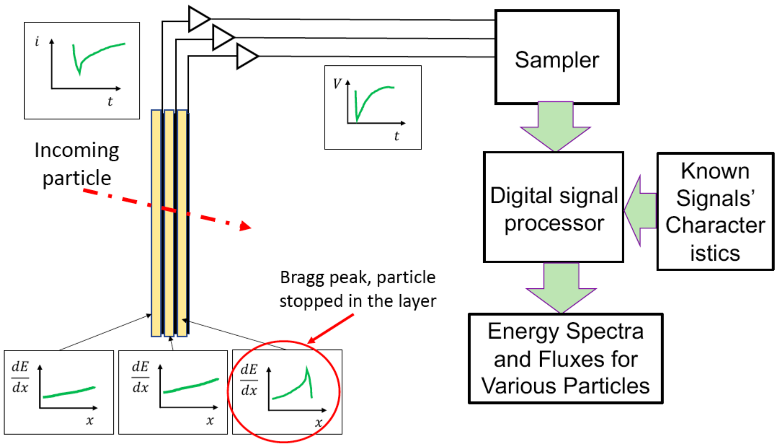

Figure 2. Simplified schematic of the PSD technique used in the AGILE prototype. We first measure the signal collected by each of the three layers of fast silicon detectors. The fast sampling method is used to sample that signal, which is then digitized. The idea is to build a database of possible types of signal parameters (rise time and amplitude) that are characteristic of the types of particles emitted in cosmic rays and their energies using beam tests that will be performed at Brookhaven National Laboratory in the US. The next iteration of the project will be using between 20 and 25 layers of the Si detector, which will allow us to measure higher energetic particles since we measure the Bragg peak when the particle stops in the detector. Figure taken from Ref. [4].

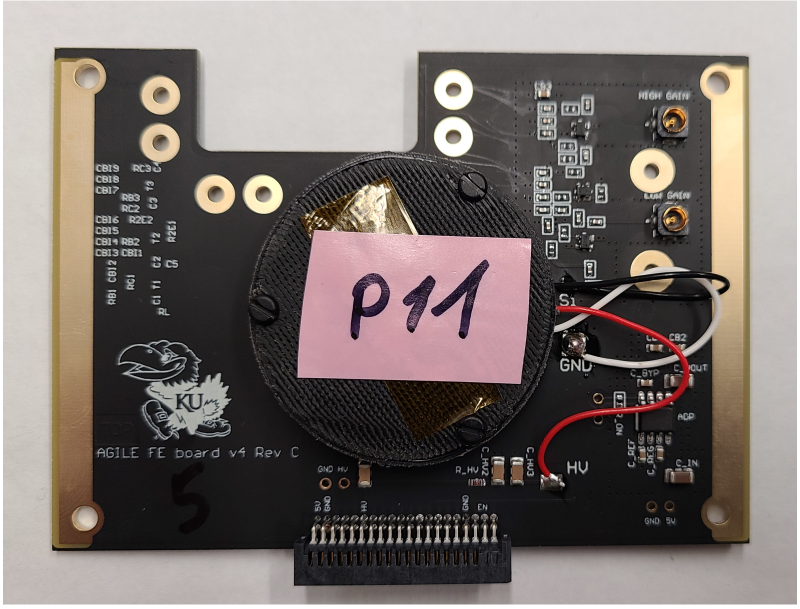

Figure 3. Photo of one layer of the silicon detector (300 μm thick and 20 mm diameter) in its protective case and its readout electronics to be sent into space in collaboration with NASA (AGILE project). The silicon is used as an absorber to detect and measure the different particles emitted in cosmic rays.

In order to identify the type of particles in cosmic rays and to measure their energy, we chose to use two estimators (we needed to select "digested" simple information on the signal in order to minimize the quantity of information to be sent back to Earth from space). The first one is the rise time (the time between 25% and 100% of the signal amplitude) and the second one is the amplitude of the signal, both measured in the layer where the particle completely stops (from the trigger point of view, we will require no signal in the next layer). These two quantities are sufficient to identify the type of the particle and to estimate its energy in most of the phase space. The amplitude as a function of rise time in the stopping layer (as put in the reference database) is shown in Figure 4 for different particles with

Z between 2 and 28 [4]. The data were obtained using a detailed simulation consisting of three main stages: simulation of the energy deposition within detector medium using GEANT4 [6], detector response simulation using WEIGHTFIELD2 software [7], and simulation of the read-out electronics (LTSPICE) [8]. The different curves (corresponding to different values of Z) do not overlap for a rise time above 6 ns. The overlapping region corresponds to approximately the initial third of the stopping range in a detector layer. It means that particle identification or in other words, the Z value, can be obtained from the measurement of the rise time and the amplitude. Once the type of the particle is known, its energy can be measured using the amplitude of the signal for all kinds of ions in space for a wide range of energies with good resolution (∼5%, which agrees with the experimental data obtained using Am^{241} α-source, see below).

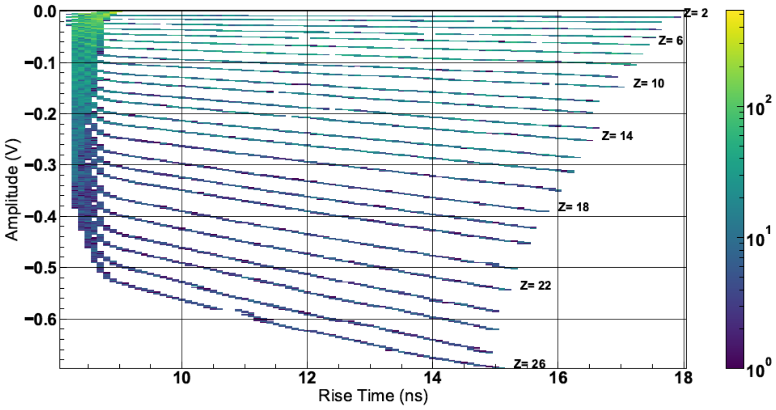

Figure 4. Simulated amplitude (in V) versus rise time (in ns) for different particles (the value of Z is indicated in the figure). Above a rise time of about 6 ns, all curves are well separated, which shows that it is possible to identify the type of particle (the Z value) using the rise time and the amplitude information.

Both measurements of the signal amplitude and rise time can be performed online onboard a CubeSat satellite using a processor or offline on Earth once raw data have been transmitted. The launch of the cube satellite is foreseen for Fall 2022 with three layers of silicon detectors only as a prototype. The goal of this prototype is to perform a successful launch, and to transmit some data to Earth. This will show that the full system is indeed working (which is called level 9 of NASA projects) and this will be the first time that the fast sampling method and PSD technique are used in space. The next step is to send a larger detector into space with more layers (up to 30) with two objectives: mapping of the cosmic rays emitted by the sun and from space can be performed using a network of satellites, and precise knowledge of the radiation between the Earth and Mars can be obtained before sending astronauts to Mars. This is obviously a high priority for NASA.

Figure 5 shows the calibration signals (10,000 events) from an Am^{241} α-source collected from one detector layer of the AGILE instrument during its preparation for launch along with the simulated signal.

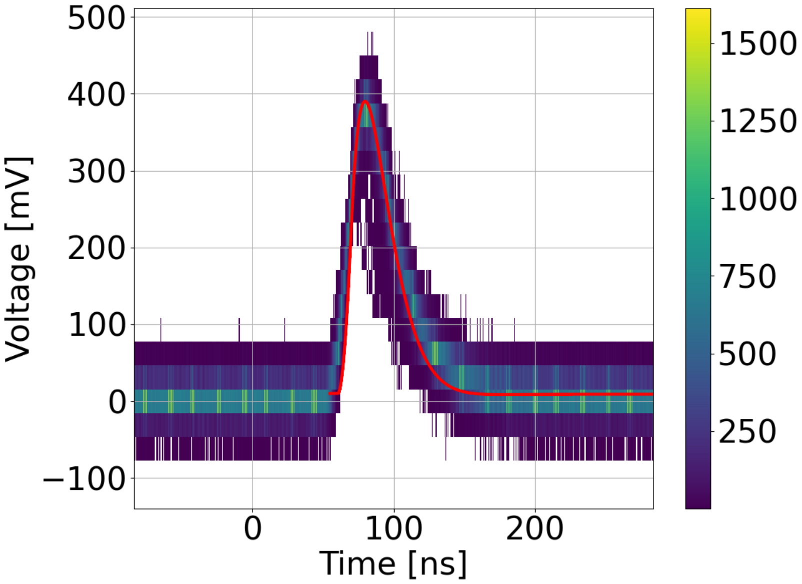

Figure 5. Two-dimensional density histogram of the signals recorded from an Am^{241} α-source (E $\simeq$ 5.5 $\dot{\text{M}}$eV). The simulated signal is plotted as a solid red line. The inverted signal polarity with respect to Figure 4 is due to the specifics of the simulation of the read-out electronics by LTSPICE software.

3. Measuring Radiation in Cancer Treatment

Another application where the same kind of fast silicon detectors can be used is the measurement of the dose delivered to patients when treated for cancer especially using flash beam therapy (e.g., with high intensity proton or photon beams) [9]. Our fast silicon detectors along with the read-out electronics were tested in an electron beam, which was previously used for radiotherapy at St Luke Hospital, Dublin, Ireland. Such a system provides a precise and instantaneous measurement of the dose without the need of calibration and with high spatial resolution (typically mm^2). The key idea here is the ability of a fast enough detector to discriminate and count every single particle (electron or proton). Figure 6 shows the results of the test at St Luke Hospital. Each spike on the plot corresponds to a signal in the detector and is considered as a particle (here an electron) crossing it. The duration of the signal is only a few nanoseconds and this fact is fundamental, especially for flash beams when the number of particles in the beam is high. In the bottom of Figure 6, we clearly see the signals above the noise that trigger our detector (red triangles) as a function of time. We notice that having both a short signal and a very fast sampling method are musts to be able to measure the instantaneous dose delivered to the patient.

Other applications of our technique in addition to the NASA and medical ones include understanding catalysis in chemistry by measuring the interface between two liquids or a liquid and a gas, beam monitoring for private or public accelerators as well as any instantaneous dose measurements that might be required.

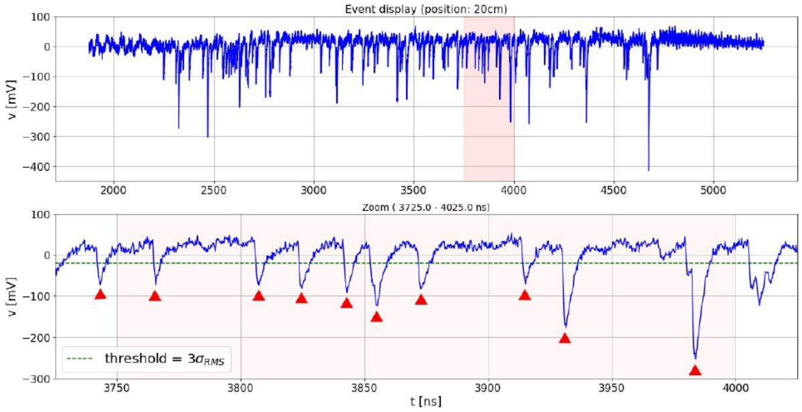

Figure 6. Silicon detector output as a function of time. Each spike corresponds to a single particle (here electrons) delivered to a potential patient. The bottom part of the plot is the zoomed red area, the red triangles shows the peaks that can be triggered using our silicon detector, allowing us to directly count the number of particles from the beam.

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