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Development of Time-of-Flight System for an Energetic Particle Spectrometer in Space

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We present the development of a 30 cm long Time-of-Flight (ToF) system targeting 30 ps timing resolution for charged particle detection. The system as part of a miniaturized charged particle spectrometer enables the extension of energy measurement to 2 GeV/n without using a magnet. Each of the two ToF channels integrate a plastic scintillator coupled to a silicon photomultiplier (SiPM), custom readout electronics, and a Constant-Fraction Discriminator (CFD). A Tapped-Delay-Line (TDL) Time-to-Digital Converter (TDC) with dynamic range of 2.5ns and LSB ˜3.8ps implemented in FPGA digitizes the time difference between the trigger signals. A reference detector has been characterized.

Summary (500 words)

Space radiation is one of the main health risks for human exploration of the Solar system. Risk estimation continues to have large uncertainties, despite years of research. The complete description of the local radiation field provided by the fluence spectrum as a function of charge and energy of the impinging particles is the sought input to risk assessment algorithms either existing or new. A possible solution for compact and lightweight particle telescopes which serves the extension of the charged particle kinetic energy measurement beyond the limit posed by the energy deposition of minimum ionizing particles in Si is the use of time-of-flight (ToF) in combination with Si active pixel sensors. It has been estimated with Monte Carlo studies that kinetic energies up to 2 GeV/n could be measured without incorporation of a magnet with an instrument of 30 cm length, provided time of flight resolution ≤30ps is achieved.

The laboratory prototype ToF system consists of two subassemblies placed 30cm apart. Each of them comprises i) a 50×50x5 mm3 EJ232 plastic scintillator coupled to fast SiPM, ii) custom-designed readout electronics, with a 2-stage non-inverting amplifier, based on a high bandwidth (2GHz) RF monolithic amplifier. The subassemblies are connected via coaxial links to two FPGA mezzanine cards (FMC). Constant-Fraction Discriminators (CFD) are implemented on the FMC cards, using passive attenuation and on-board delay lines to generate a time-walk-corrected trigger. High-speed comparators detect the zero-crossing points, yielding a jitter-limited digital trigger (<10 ps RMS). The FMC cards plug into the KC705 evaluation board hosting an FPGA-based TDC.

For the initial characterization of the system a 3 x 3 x 3 mm3 reference plastic scintillator was irradiated with a Sr-90 source. 10000 amplified SiPM waveforms were recorded using an oscilloscope-and constant fraction discrimination was performed off-line. A time resolution of 67 ps was measured. The oscilloscope trigger mechanism induces extra error. To overcome this source of error and to advance the development towards the full prototype we proceeded with the development of the TDC.

The TDC timing core is a Tapped-Delay-Line (TDL) implemented in a Xilinx Kintex-7 FPGA using four parallel delay lines (200 stages each) constructed from CARRY4 primitives. The non-uniform propagation delay within the FPGA TDLs, which impacts timing linearity, was addressed (a) by scanning multiple FPGA regions and selecting one with optimized behavior and (b) by confining the TDC in a single clock region. Furthermore, a calibration correction procedure which compensates for measured non-uniformities across the TDC dynamic range, significantly improves effective linearity and minimizes timing biases. Linearity tests using a programmable delay generator showed an LSB of ˜3.8ps with a maximum absolute error less than 14ps, for a dynamic range of 2.5ns.

Once individual subsystems are fully validated, the resolution of the reference detector will be re-evaluated and end-to-end testing of the complete ToF prototype will commence.
The ToF system could be part of low footprint payload which will provide energetic particle data listed by the ESA in its product specification document or measure flux near to an astronaut.

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