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Q-Pix: Pixel-scale Signal Capture For Kiloton Liquid Argon TPC Detectors: Charge-Quantized Waveform Capture, Free-running Clocks, Dynamic Networks

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We describe a novel ionization signal capture and waveform digitization scheme for kiloton-scale liquid argon Time Projection Chamber (TPC) detectors. The scheme is based on a pixel-scale self-triggering 'charge integrate/reset' block, free-running local clocks and dynamically established data networks. The scheme facilitates detailed capture of waveforms of arbitrary complexity from a sequence of varying time intervals, each of which corresponds to a fixed charge integral. An absolute charge auto-calibration process based on intrinsic 39Ar decay current is a major benefit. A flat electronic architecture with self-guided network generation provides very high resilience against single-point failure. The goal is optimized discovery potential. Much might be at stake.

Summary

The intrinsic quality of information inherent in a liquid argon TPC (LArTPC) is very high. Many processes of fundamental interest in the DUNE program will lead to events that display complex signal waveforms, with highly variable features in space, amplitude and time. High quality data may ultimately contain surprises whose significance may exceed what is now foreseen. The central goal is thus two-fold: to capture events in exquisite and accurate detail, and to be prepared for discovery of new physics at the threshold of detection sensitivity. We seek here to optimize discovery potential by the realization of a pixel-scale detection scheme embedded in kiloton LArTPCs such as those for the DUNE far detectors. For this goal, any such scheme must provide, a priori, exceptional resilience against Single Point Failure (SPF) in design and implementation.

The Q-Pix ASIC is likely to support between 16 and 64 pixels. Each Q-Pix pixel is equipped with a simple Charge-Sensitive Amplifier (CSA) operating in concert with a simple Schmitt trigger reset circuit. Whenever the CSA reaches a specific charge integral Q, a reset is triggered that restores the CSA to baseline. With the presumption that charge loss during reset is negligible or small and correctible, the time interval between resets provides an accurate measure of average current for a given time interval. Thus a sequence of reset time differences (RTD) provides an alternative and, as it turns out, very efficient way to capture and reconstruct, without differentiation, current waveforms of arbitrary complexity and dynamic range.

The reset times are generated by a single 32-bit local clock within each Q-Pix ASIC. The clock is driven by an oscillator running at its natural frequency F, such that 50 < F < 100 MHz. A reset signal initiates capture of the instantaneous value of the clock, which is then stored in buffer for readout when requested. Reset time differences will reflect two different current regimes: a weak average current from Ar39 decays of ~100aA, and much larger currents of ~1 nA due to ionization within minimum-ionizing particle tracks; very occasionally much larger currents may appear due to nuclear fragmentation. The long intervals (seconds) between resets due to Ar39 decays provide a statistically useful absolute calibration of charge sensitivity for each pixel. It is expected that the unwanted input leakage current in the CSA + reset will be a small fraction of this tiny current. The much shorter intervals (<1 μs) from MIPs are easy to detect, separate and convert into current waveforms.

An occasional but precisely timed interrogation by exterior DAQ leads to extraction of buffer contents and calibration of each local ASIC oscillator. The DAQ interrogation is expected to occur at about 1 Hz, requiring short-term local oscillator stability of 1 ppm. This should be easy to achieve.

The DAQ communicates to a group of Q-Pix ASICs that form a tile, on the scale of 30 x 30 cm^2. Each tile includes on the order of 100 - 200 Q-Pix ASICs as an interconnected matrix of nearest neighbors. Each Q-pix ASIC thus communicates with all four of its neighbors but not beyond. A network is dynamically established as each ASIC follows an ordering protocol such that all intact ASICs are contacted even in the presence of dead or partially unresponsive ones. An occasional failure leads to the formation of a new network pattern. The complete absence of a hierarchical structure provides exceptional SPF resilience.

In Q-Pix, we follow an electronic equivalent of the principle of 'Least Action', with an architectural approach that devolves most functions to the distal ends of a network, inspired by the Digital Optical Module of IceCube.

Q-pix is designed to capture, in exquisite detail, the high intrinsic quality of ionization information in a kiloton LArTPC. It could turn out that Q-Pix may provide an enabling technique for discovery of new physics at the threshold of detection.

Primary authors: Prof. NYGREN, David (University of Texas at Arlington); Dr MEI, Yuan (LBNL)

Presenter: Dr MEI, Yuan (LBNL)

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