Snowmass2021 - Letter of Interest

Q-Pix: Kiloton-scale pixelated liquid noble TPCs

Topical Group(s):

☑ (IF07) Electronics/ASICs

☑ (IF08) Noble Elements

☑ (NF10) Neutrino detectors

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Abstract:

The Q-Pix concept proposes a continuously integrating low-power charge-sensitive amplifier viewed by a Schmitt trigger. When the trigger threshold is met, the comparator initiates a ‘reset’ transition and returns the CSA circuitry to a stable baseline. This is the elementary Charge-Integrate / Reset (CIR) circuit. In practice, the circuitry may more accurately represent a classical charge pump to avoid losses during the instant of reset. The instant of reset time is captured as a 32-bit clock value in a register and the cycle begins again. What is exploited in this new architecture is the time difference between one clock capture and the next sequential capture, called the Reset Time Difference (RTD). The RTD measures the time to integrate a predefined integrated quantum of charge (Q). Waveforms are reconstructed without differentiation and an event is characterized by the sequence of RTDs. In quiescent mode the RTDs will be spaced with varying time intervals of seconds between RTDs, Whereas an event is signaled by the appearance of a sequence of multiple RTDs in microseconds. This technique easily distinguishes the background RTDs due to ^{39}Ar decays and signal RTD sequences due to ionizing tracks. Q-Pix offers the ability to extract all track information providing very detailed track profiles. Q-Pix also utilizes a dynamically established network for DAQ enabling exceptional resilience against single point failures. Q-Pix naturally allows a large fraction of the entire detector to have very low detection thresholds, enabling discovery of new physics at the very limit of detection.

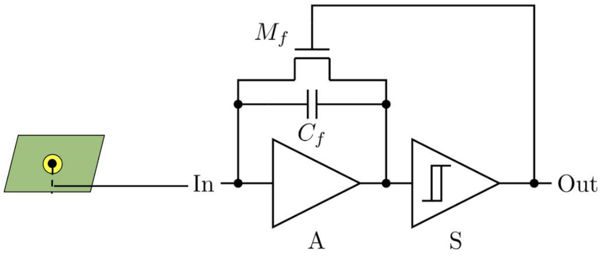
Large scale noble element time projection chambers (TPC's) play a central role in many aspects of high energy physics experiments. The TPC provides a fully active tracking detector with calorimetric reconstruction capabilities without instrumenting the bulk volume of the detector. The standard method for reading out the ionization charge relies on the use of consecutive planes of sensing wires to measure two of the three space coordinates. This method has been used for numerous liquid argon TPC's (LArTPC's), and was also adopted as a baseline configuration for the Deep Underground Neutrino Experiment (DUNE) far detector. Although the concept has precedence in the community, it has intrinsic limitations resolving ambiguities and poses difficult and costly engineering challenges. Clearly, a non-projective readout could provide a remedy.

Such a readout scheme has been utilized in many gas based TPC but was not considered viable for LArTPC's because of the number of readout channels and power consumption requirements. The number of pixels for equal spatial resolution will be two or three orders of magnitude higher than the number of corresponding sense wires, with an analogous increase of the number of signal channels, data rates and power dissipation. This would make such a solution untenable except for very small detectors. A truly transformative step forward for future LArTPCs is the ability to build a fully pixelated low power charge readout. The endeavour to build a low power pixel based charge readout for use in LArTPC's has independently inspired two research groups to pursue complementary approaches to solving this problem.

The LArPix and Q-Pix consortia have undertaken the challenge of the R&D necessary to realize a pixel based readout. The LArPix design has been constructed to target the DUNE near detector and is currently in an advanced prototyping stage. The operating conditions of the LArTPC in the DUNE near detector are much different than that of the far detector. The high intensity neutrino beam seen by the near detector means there will be multiple overlapping neutrino interactions within the liquid argon volume. Thus a smaller, segmented, and modular TPC design with optically isolated modules and pixel based readout is envisioned. This is in stark contrast to the operating conditions of the LArTPC far detector which expect to see ~4 beam-events / day / 10-kTon module. This suggests a design of large uninterrupted modules with long drifts and maximal coverage for the pixel design. Moreover, the performance of the pixels in terms of energy threshold and retaining the detail of the LArTPC will need to be more dynamic to be maximally sensitive to natural neutrino sources (e.g. solar, atmospheric, and supernova) as well as beam related neutrino sources and to optimize for potential discovery of beyond the standard model physics (e.g. baryon number violation and exotic physics channels). It is to these challenges that the Q-Pix design for pixel readout is targeted.

The fundamental idea of the Q-Pix readout scheme is to use pixel-scale self-triggering `charge integrate/reset' blocks with local clocks running with unconstrained frequencies and dynamically established data networks robust against single point failure (SPF). This pixelization concept is targeted as a `technology of opportunity' for the multi-kiloton DUNE far detector (FD). In the DUNE FD, high-quality capture of data across all spatial and energy ranges is desired for true signal events, but most of the time nothing of interest is occurring and thus the data acquisition scheme should be doing as little as possible until something happens.

The basic concepts of the Q-Pix circuit begins with the Charge-Integrate/reset (CIR) circuit. A charge sensitive amplifier continuously integrates an incoming signal on a feedback capacitor until a threshold on a Schmitt trigger (regenerative comparator) is met. When this threshold is met, the Schmitt trigger starts a rapid ``reset" which drains the feedback capacitor



and returns the circuit to a stable baseline and the cycle is free to begin again. This ``reset" transition pulse is used to capture and store the current value of a local clock within one ASIC. This changes the basic quantum of information for each pixel from the traditional ``how much charge per unit time" to the difference between one clock capture and the next sequential capture, referred to as the Reset Time Difference (RTD). This new unit of information measures the time to integrate a predefined charge ΔQ with RTDs from true signals expected to be represented by a sequence of short (O(μs)) RTDs and in the absence of a signal the quiescent input current from backgrounds (^{39}Ar, cosmogenic, and radioactivity) would be minuscule and the expected time between RTDs expected to be of the order of seconds. An alternative scheme is to the "reset" function is to replace the ionization charge in units of Q each time the sensed ionization signal exceeds the thresholded "Q" value for replacement. This scheme has the potential to exactly record the ionization signal without the losses that occur during more intense current from multiple charged particles at event vertexes.

Signal waveform reconstruction occurs by exploiting the fact that the input current and the RTD are inversely correlated (I $\propto$ 1/RTD), where I is the average current over an interval ΔT and thus I x ΔT = $\int$ I(t) dt = ΔQ. The signal currents are captured with fixed ΔQ, determined by the charge integrator/reset circuit, but with varying time intervals. An initial study of the exact requirements for the minimum ΔQ for the Q-Pix circuit (~5000 electrons) as well as the range and precision of ΔT has been carried out using simulated signals from neutrino interactions, however the ultimate limit of how low in threshold this technology can achieve is yet to be determined. Early simulation suggests thresholds <1000 electrons is feasible with the actual limit possibly down at O(100) electrons.

The time stamping architecture currently envisioned for the Q-Pix readout will utilize a local clock based on a free-running oscillator within the ASIC is used and its value captured in a buffer register when a ``reset" transition occurs. The string of ``reset" times are transmitted periodically out of the cryostat and a linear transformation from local clock frequency to central master clock allows one to recover the universal time RTDs. The interrogation of the local clock by surface systems need only occur as necessary to monitor and correct for oscillator drift.

While the Q-Pix chip itself represents the smallest quantum for the system, a more useful architecture which is resilient against single point failure is to define a tile as an array of NxN Q-Pix chips making up an array of a 64x64 = 4096 pixel block, as the fundamental unit of the system. The number of Q-Pix ASICs, N, per tile and exact dimensions of the tile will be determined by the pixel pitch and number of channels per ASIC. These quantities themselves need to be studied to ensure the maximum physics reach for the given readout design, but will likely result in a tile size O(625 cm^2). Preliminary studies suggest the power consumption of such a readout per channel is quite low (~20μW) and the quiescent data rates for kiloton scale detectors to be <100 Mb/s

The Q-Pix technology affords a way to instrument a noble element TPC with a pixel based readout at very large scales and achieve a readout threshold at very low energies. Such an enabling technology opens the door to thinking about a new design for an integrated readout capable of sensing both charge and light from a single sensor.

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