QPix Technology: Research and Development towards kiloTon scale pixelated LArTPC

Jonathan Asaadi
University of Texas at Arlington

Work based on original paper by Dave Nygren (UTA) and Yuan Mei (LBNL): arXiv:1809.10213
Introduction

Liquid Argon Time Projection Chambers (LArTPC’s) offer access to very high quality and detailed information. Leveraging this information allows unprecedented access to detailed neutrino interaction specifics from MeV - GeV scales. Capturing this data w/o compromise and maintaining the intrinsic 3-D quality is an essential component of all LArTPC readouts!
Introduction

- Conventional LArTPC’s use sets of wire planes at different orientations to reconstruct the 3D image
  - Challenge in reconstruction of complex topologies
- kiloTon scale LArTPC’s use “wrapped wire” geometries to reduce the number of readout channels
  - Challenging to engineer such massive structures
- Being able to readout using pixels instead of wires could off a solution
  - Comes at a “cost” of many more channels! → Requires an “unorthodox” solution
Introduction

● Kiloton scale LArTPC’s (such as DUNE) afford a huge “big data” challenge to extract all the details offered by LArTPC
  ○ 1 second of DUNE full stream data
     ~4.6 TB (for 1.5 million channels)
       ■ 1 year of full stream data ~ 145 EB (exabytes)

● However, most of the time there is “nothing of interest” going on in the detector
  ○ But you must be ready “instantly” when something happens (proton decay, supernova, beam event, etc)

● To readout such massive detectors with pixels requires an enormous number of channels
  ○ $\mathcal{O}$ (130 million) per 10 kTon at 4mm pitch
  ○ Requires an “unorthodox” solution
An “unorthodox” solution

- The Q-Pix pixel readout follows the “electronic principle of least action”
  - Don’t do anything unless there is something to do
    - Offers a solution to the immense data rates
      - Quiescent data rate $\mathcal{O}(50 \text{ Mb/s})$
    - Allows for the pixelization of massive detectors
- Q-Pix offers an innovation in signal capture with a new approach and measures \textit{time-to-charge}:(\Delta Q)
  - Keeps the detailed waveforms of the LArTPC
  - Attempts to exploit $^{39}\text{Ar}$ to provide an automatic charge calibration
- “Novelty does not automatically confer benefit”
  - Much remains to be explored
Q-Pix: The Charge Integrate-Reset (CIR) Block

- Charge from a pixel (In) integrates on a charge sensitive amplifier (A) until a threshold \( V_{th} \sim \Delta Q/C_f \) is met which fires the Schmitt Trigger which causes a reset (\( M_f \)) and the loop repeats.
Measure the time of the “reset” using a local clock (within the ASIC)

Basic datum is 64 bits
  - 32 bit time + pixel address + ASIC ID + Configuration + ...
What is new here?

● Take the **difference** between **sequential** resets
  ○ Reset Time Difference = RTD

● **Total charge for any** RTD = $\Delta Q$

● RTD’s measure the **instantaneous current** and captures the waveform
  ○ Small average current (background) = Large RTD
    ■ **Background from** $^{39}\text{Ar} \sim 100 \text{ aA}$
  ○ Large average current (signal) = Small RTD
    ■ **Typical minimum ionizing track** $\sim 1.5 \text{ nA}$

● **Signal / Background $\sim 10^7$**
  ○ Background and Signal should be easy to distinguish
  ○ No signal differentiation (unlike induction wires)
Reset Time Difference

\[ M_f \]
\[ C_f \]

Clock

32-bit Gray-code counter

32-bit latch and buffer

Background

Signal

time
$\Delta Q \approx 1.0 \text{ fC}$

($\approx 6000 \text{ e}^-$)
\( \Delta Q \approx 1.0 \text{ fC} \)

\(~1800 \text{ e}^+\)
How the time stamping works

● One free running clock per ASIC (50-100 MHz)
  ○ Required precision for DUNE $\delta f/f \sim 10^{-6}$ per second
    ■ Expect this to be easily achieved in liquid argon

● Time stamping routine has the ASIC asked once per second “what time is it?”
  ○ ASIC captures local time and sends it
  ○ Simple linear transformation to master clock synced to GMT
  ○ RTD’s calculated “off chip”

● Has this idea been realized before?
  ○ YES! In ICECUBE (by Nygren)
    ■ Oscillator precision achieved $> 10^{-10}$ /s (hard to measure)
Q-Pix ASIC Concept

- **16-32 pixels / ASIC**
  - 1 Free-running clock/ASIC
  - 1 capture register for clock value, ASIC, pixel subset
  - Necessary buffer depth for beam/burst events
  - State machine to manage dynamic network, token passing, clock domain crossing, data transfer to network (many details to be worked out)

- **Basic unit would be a “tile” of 16x16 ASICs (4092 4mm x 4mm pixels)**
  - Tile size 25.6 cm x 25.6 cm
Q-Pix Consortium

- A consortium of universities and labs has formed to realize and test the Q-Pix concept
  - Being done in close collaboration with LArPix (JINST 13 P10007) readout for the DUNE near detector

- Four central ideas being worked on
  - **Physics Simulations:** Quantify the conferred benefit of pixel vs. wire readout and the requirements of the ASIC design
  - **CIR Input:** all extraneous leakage current at the input node needs to be small (aA)
  - **Clock:** $\delta f/f \sim 10^{-6}$ per second
  - **Light Detection:** Exploring new ideas using photoconductors on the surface of the pixels
Physics Simulation

- To help quantify the range of currents the Q-Pix ASIC will need to reconstruct we are using of neutrino interactions in argon.

Focus on a 16mm x 16mm (4pixels x 4pixels) area around the vertex to get a sense of the currents that would be seen.
Physics Simulation

- We can take the charge seen by a pixel and translate this into current as a function of time.

- We can then use this simulation to set the physics requirements on the Q-Pix ASIC.
  - Allowed reset time, minimum $\Delta Q$, etc...
  - Ongoing studies exploring non-beam (supernova, proton decay, etc...) and beam related parameters.
Light Detection

- One very “blue sky” idea currently being considered is to see if the same pixels which collect ionization charge can be used to detect UV photons
  - Currently exploring different thin-film photo-conductors which may offer an opportunity
  - Exploring amorphous Selenium’s properties
    - Commonly used in X-Ray digital radiography devices
- If realized, offers a transformative opportunity in LArTPC’s
Conclusions

- Readout requirements for kiloton scale LArTPC’s offer many challenges to fully exploit the rich data they have to offer
  - We must optimize for discovery!!!
- Low threshold pixel based readout can optimize for discovery the impact of these detectors
  - Requires an unorthodox solution
- The Q-Pix concept may afford a way to pixelize a kiloton scale LArTPC and retain all the details of data
  - The devil lives in the details, but an effort is underway with promising preliminary results
  - Stay tuned for more updates!

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