Development of a Novel Pixelated Time Projection Chamber Detector: Q-Pix

Dissertation by

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ABSTRACT

The Standard Model (SM) of physics has proven remarkably successful in past decades, yet some measurements such as neutrino oscillations show that this model is still an incomplete description of nature. The hunt for New Physics (NP) continues at higher energies ($>> 1GeV$) with larger detectors ($\approx 10kT$); the data acquired continually hint at Beyond Standard Model (BSM) physics. One such future detector is The Deep Underground Neutrino (DUNE) detector, which has recently begun construction. This 40-kT scale detector requires high precision in both timing ($<< \mu s$) and spatial resolutions ($\approx 1mm$) for vertex reconstruction of interesting neutrino events. DUNE (as any beam detector) is a combination of two detectors, a near-detector (ND) and a far-detector (FD) for long-baseline neutrino oscillation measurements. In order to meet the required timing and spatial resolution the DUNE-FD is a Liquid Argon Time Projection Chamber (LArTPC) design. Recent work has been done to show that LArTPCs can transition from a traditional wire readout to a pixelated readout, and thus further improve vertex reconstruction. This dissertation discusses recent progress and characterizations of a novel implementation of new a pixelated LArTPC readout technology. This novel readout is based on a charge-integrate-reset circuit at the pixel level (Q-Pix). We present the basic pixel-level readout circuit and the implications such an implementation has when applied at DUNE-FD scales. Further, we demonstrate results from the first-prototype implementation based on Q-Pix has been successfully used with solely over-the-counter electronics to acquire new Liquid Argon diffusion measurements. One crucial problem of any pixelated readout is the the ability to handle a large number of unique data channels ($\approx 100k$). To address the scaling problem we developed and tested a modular digital back-end prototype, and implemented it within the first LArTPC prototype. Next, we discuss nominal DUNE-FD APA system level requirements to achieve a projected required sensitivity, remove backgrounds, pixel-level calibration techniques, and possible methods for particle-identification (PID). Simulation results are also performed based on projected background and high-energy neutrino beam-line events. Finally, based on these results of the prototypes and simulation we discuss the nominal digital back-end readout constraints of a fully realized QPix implementation for DUNE-FD APA.

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Chapter 1

INTRODUCTION

This chapter outlines and highlights useful background that will be explored in further detail in upcoming chapters as well as provides an outline for the thesis. We begin with an introduction on the standard model, and how both its success and short comings drive larger and more expensive detectors at the intensity frontier. To elucidate the issues at the forefront of the standard model we provide a brief history, with an emphasis on the detectors and experiments which lead to its formulation. Next, we become more specific and discuss DUNE which is an example of a new, large, and expensive detector which aims to push beyond the Standard Model. Finally, we relate the work presented in this dissertation is based on TPCs and how the novel readout design used here is suited for future expansion into larger detectors.

1.1 The State of Things: The Standard Model

In the history of science, it is easily argued that the most successful of all models has been the Standard Model of physics. The standard model was originally developed in mid to late 1970's, and is the model responsible for unifying the weak, strong, and electromagnetic forces together. It has been made remarkable predictions about the existance of elusive neutrinos, and an extensive number of other particles.

Yet, despite its numerous achievements in predictive power and experimental verification we know today that it has crucial shortcomings. The Standard Model (SM) has no ability to account for Dark Matter or Dark Energy in the universe, nor the distribution (or the hierarchy) of neutrino masses, nor is it able to relate how gravity interacts with the other fundamental forces of nature (Unification). It also doesn't account for some 'basic' properties it has, such as: why are there only three generations of laptonic particles (electron, muon, and tau)? These short-comings offer hints for where to search for physics. Physicists have known about these short comings from the conception of the Standard Model and have (to no avail) sought out what's next.

With a plethora of hints to search for NP, it can be useful to organize the efforts of search. In 2008 the p5 committee did just this and labeled the three frontiers of physics as the cosmological, energy, and intensity frontiers. Each of these frontiers offer different kinds of challenges and aim to search at the

The cosmological frontier aims to search for NP on extremely large time and distance scales by relying on observational techniques. Cosmological measurements have shown the that majority of the universe's matter is not visible to light, and so we call it dark matter. Additionally, the unverise is expanding at an accelerated rate, which we can tell from the blueshift of distance galaxies. Likewise, cosmologists have also discovered that the universe is expanding due to some invisible energy in the universe, and so we call it dark energy. The search for these dark causes of the universe lie within the realm of the cosmological frontier.

The energy frontier is concerned with the origin of mass. The Large-Hadron Collider experiment is the archetypal experiment aimed at solving problems within this frontier.

The third (and final) frontier to mention is the Intensity frontier. The Intensity Frontier of Physics ([4]) is one which requires very large and very precise measurements to gain the statistics to declare an observation. In order to address the issues posed within this frontier the large scale detectors hunting for New Physics (NP) have continued to grow in size, energy sensitivity, and importantly cost: [5].

1.2 How we got here.

Many times since the early 20th century it was thought that the goal of physics was accomplished. However, during each of these moments of false triumph some new detector was built to take a new measurement; thus, the door to new understanding of nature is never shut. This section provides a brief and (necessarily) incomplete history of significant measurements and detector developments relevant to particle physics. In order to clear an obstacle, it is often helpful to remember the previous ones.

A Century of new Detectors

At the turn of the 20th century particle physics was in its infancy. In 1900 Max Planck first introduces the concept of energy quanta for the first time concerning photons to eliminate the infamous ultra-violet catastrophe problem introduced by statistical mechanics. JJ Thomson used a single cathode-ray tube to discover the electron and the nucleus, and won for himself the Nobel Pize in 1906. Milikan's famous oil-drop experiment won him the Nobel Prize in 1923.

However, as each of these new discoveries solved problems only more questions were produced. Once the nucleus was discovered to contain only protons and neutrons, the natural question arose: what holds all of the positive charge together in the center. Thus, physicists cleverly named the new force which was stronger than the electromagnetic force: the Strong Force.

The bubble chamber was then invented in 1952 by Donald Glaser [6]. These detectors proved significant in the discover of the W and Z bosons and ultimately allowed the unification of the electromagnetic and weak forces to form the electroweak theory.

Next the spark chamber eventually lead to the gradual development of the wire-spark chamber. In 1968 Georges Charpak developed the Multi-Wire Proportional Chamber (MWPC) for which he (much later) won the Nobel Prize in 1992. From this key insight a new detector concept was made possible.

Time Projection Chambers

Time Projection Chambers (TPC) [7] have been shown to be extremely useful in high energy physics experiments due, in part, to their high resolution in both timing and spatial dimensions. This detector was originally used in the Position-Electron Project PEP-4 experiment which measured electron-positron collisions from the 29 GeV electron beam produced at the Stanford Linear Accelerator (SLAC). The first TPC design used high pressure gas and was able to measure 1000s of particle tracks per second (compared to 1-10) and provide full 3-D event reconstruction.

It did not take long for other experimentalists to generalize this concept to different elements or even to liquid.

Noble Gases and Time Projection Chambers

The technology of TPCs has greatly matured since their original inception. in many kinds of detectors across HEP. TPCs can also incorporate two phases of a substance (liquid and gas), called Dual Phase (DP) TPCs.

the Xenon-1T is a dark matter experiment which is a dual-phase TPC [**Aprile_2017_xenon1T**].

The LUX experiment is a single phase TPC also hunting for dark matter.

A specific kind of TCP is a Liquid Argon Time Projection Chamber (LArTPC) [8].

recent work on LArTPCs ([9], [10], [11]).

Energy resolution of the LArTPCs within DUNE are still unknown to within a factor of 4 [12].

An Escape: Catch the Neutrino

More than 100 years ago in 1899 Ernest Rutherford observed beta decay. Not too long afterward it was determined that the energy spectrum of the electrons resulting from this decay produced a spectrum. This even lead some physicists to belief that perhaps the conservation of energy was violated. However, the motivation to save this conservation law lead Wolfgang Pauli to the first prediction (1930) of the neutrino; the reason that the energy was a spectrum from the electron was that some of the energy was "taken up" by the neutrino. Finally, some 26 years later in 1956 was the first observation of the electron neutrino [13].

After this first discovery is when the the answers, and mostly the questions started to pile in.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1}, U_{e2}, U_{e3} \\ U_{u1}, U_{u2}, U_{u3} \\ U_{\tau 1}, U_{\tau 2}, U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{1.1}$$

Super-K / SNO / KamLand / NOvA / daya bay / RENO / double chooz / t2k / minos

[14–16] [17] [18] [19] [20] [21]

1.3 The Deep Underground Neutrino Experiment

The Deep Underground Neutrino Experiment (DUNE) is a long-baseline neutrino beam experiment [3, 22–24]. DUNE is composed two detectors, a near (ND) and a far (FD) which are separated by a distance of 1300 km. The ND is located at Fermilab and its purpose is to characterize the source neutrino beam created there. The FD is composed of four separate 10 kiloton modules, all of which will be a single-phase (SP) LArTPC based detector. Two of these four modules at least will use a known wire-based readout technology and a vertical drift-readout. The two remaining modules are considered modules of opportunity and their readout technology is yet unknown. A purpose of this dissertation is show the viability of a novel readout technology.

DUNE has three main science goals, all of which are geared towards pushing beyond the standard model:

- Hadron Decay
- Neutrinos from Core-collapse supernovae
- Beamline neutrino interactions.

We will discuss the relevance of each of these items, and in 2 we will further discuss how the work presented here relates to each of these topics.

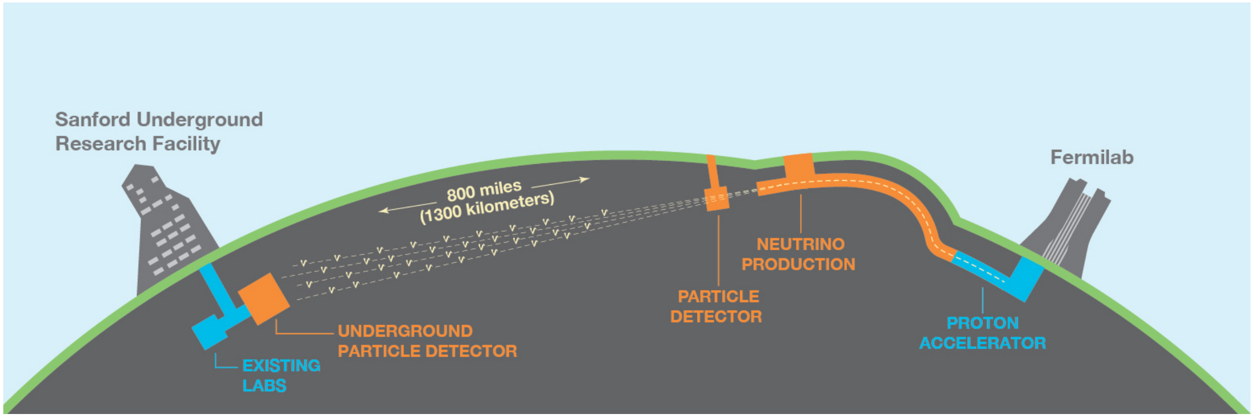

Figure 1.1: Simple Draw up of DUNE FD taken from [1]

Conventional horizontal drift detection for foreseeable DUNE modules are already considered possible for lengths up to 6.5m [25].

Hadron Decay

Second generation proton decay studies in the ICARUS experiment: [26].

Supernova Studies

The principal decay chain follows the pattern:

$$\nu_e +^{40} Ar \longrightarrow e^- +^{40} Kr^* \tag{1.2}$$

Neutrino Oscillation

Of all known particles the most elusive (hardest to detect and measure) is the neutrino. For this reason the least is known about the neutrino. What we do know about the neutrino is there are three pairs of them, associated with their leptonic partners: the electron, muon, and tau.

It came as a welcome shock that neutrino oscillation was first measured. This oscillation indicates that a neutrino as it moves through space can change its state; a electron neutrino can oscillate into a muon neutrino or even a tau neutrino. This happens because the mass eigenstate and flavor eigenstates which govern the neutrino are not equal.

Towards Understanding

1.4 Pixelated Detectors in the Current Century

Finally, in this last section we discuss recent progress of various detector technologies moving towards pixelization. There are many motivating pressures for new detectors to adopt pixelated designs. Below we discuss two contributing factors: the development of electronics and computing algorithms.

First, previously pixelated detectors have historically been more difficult because of the issues of cost and size regarding the number of readout channels. This is being addressed, in part, by the advent of newer, cheaper, and larger Field-Programmable-Gate Arrays (FPGAs). One method for reducing the electronic overhead required in pixelated detectors is to use digital multiplexing. Cheap, high channel FPGAs directly solve this problem. Other electronics development, such as the Silicon-Photomultiplier, offer much cheaper alternatives for large pixel counters compared to their historical counter-parts.

[27] Another driving factor is the the development of Machine Learning (ML) algorithms, particularly Convectional Neural Network (CNN [28]). Recent industry has driven the need for CNNs to be able to correctly identify and label 2-D images of various kinds, and thus championed much of progress in this field and spawned many kinds of CNN algorithms. Recently, it has been shown how these kinds of algorithms extend into High Energy Physics (HEP) for particle identification. A major issue at the Intensity Frontier of physics is the sheer amount of data to store and process. These ML algorithms provied a developed tool to automate the analysis of huge amounts of data ($>> 1TB$) and have been shown to be quite accurate ($> 99\%$) at particle identification in LArTPCs.

Current Pixelization Efforts in TPCs

Additional work has been performed in recent years which show that LArTPCs can also utilized a pixel-based readout [29], [30].

Comments on Other applications of Pixelization

SANDD

Another Example of a pixelated detector is [31].

The Single Volume Scatter Camera

This work is presented in greater detail in (Appendicies-A/B) and represents a substantial amount of my own individual contribution. I am the 2nd author on the the paper described in Appendix-A and the corresponding author of Appendix-B, where I also collected and analyzed all presented data therein.

Chapter 2

A NOVEL READOUT TECHNIQUE FOR LARTPCS: Q-PIX

In this chapter we introduce a novel readout technology at the pixel level for LArTPCs. The basic readout circuit was first introduced by [2].

Pixel based readouts offer several advantages over the traditional wire readout [32]. The key improvement offered is true 3-D image reconstruction. This allows for sharper vertex reconstruction, thereby improving the overall resolution of DUNE and decreasing the required time for a NP measurement. Other advantages rely on data analysis and data storage. A pixel based readout automatically records 2 of the three spatial dimensions, and thereby provides for simpler analysis. Additionally, the pixelated readout method presented here cuts the total required data storage and data acquisition rate (without loss to precision) by several orders of magnitude.

However, the advantages also come with the cost of increased design complexity as the number of readout channels increases by more than three orders of magnitude. The traditional wire based readout within a DUNE module will include hundreds to thousands of channels, whereas a full DUNE module with a pixel-based readout will have 10's of millions of channels. This number of required channels to be stably readout during DUNE's expected lifetime ($>$ 10 years), where the electronics continually operate at liquid argon temperatures is likely the largest hurtle for a pixel-based design. The aim of this dissertation is to address the channel-size problem.

2.1 Q-Pix: The Circuit Level Design

Concept of this combined ASIC and reducing the number of channels relies on digital multiplexing.

This differs from other concepts such as Genetic Multiplexing ([33]) and using only regions of interest (ROI).

2.2 System Requirements

2.3 How Q-Pix fits into a DUNE APA

DUNE Anode Plane Assemblies (APA) designs are based on [3].

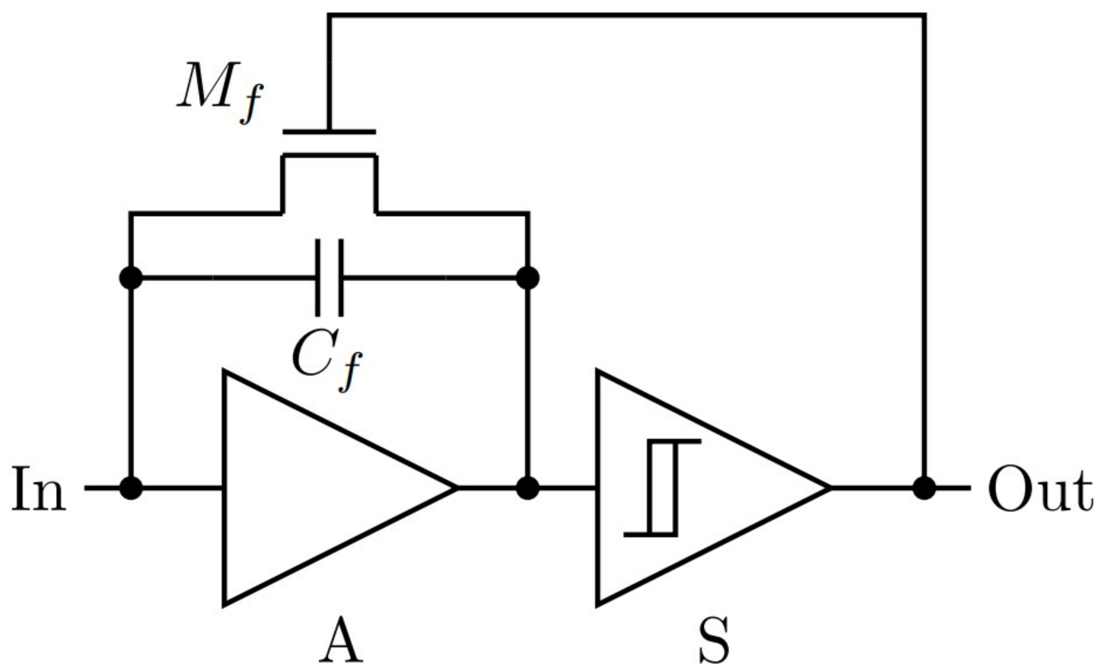

Figure 2.1: Image of Basic Q-Pix Readout circuit. Currently this is being designed within a custom analog ASIC. Image is taken from [2].

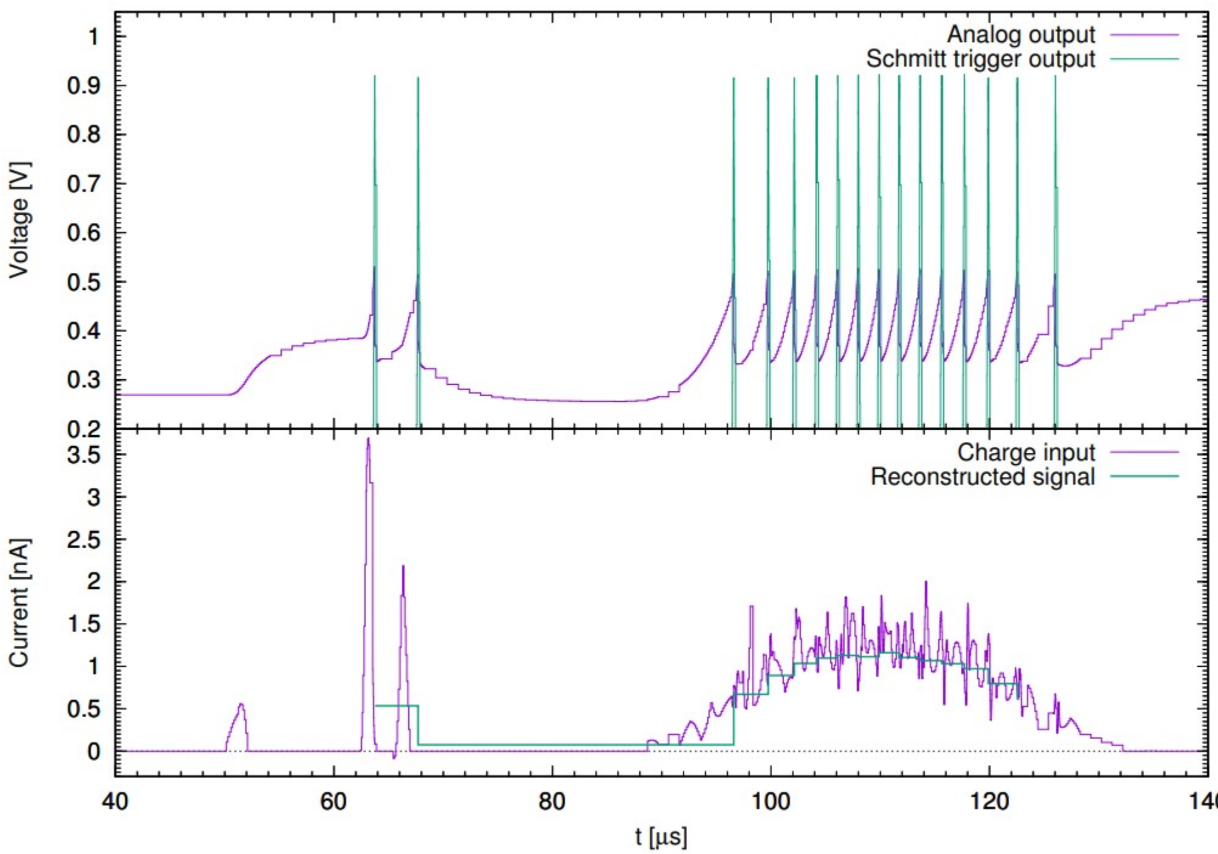

Figure 2.2: Example reconstruction of the reset time difference (RTD) based on the Q-Pix readout design. Image is taken from [2].

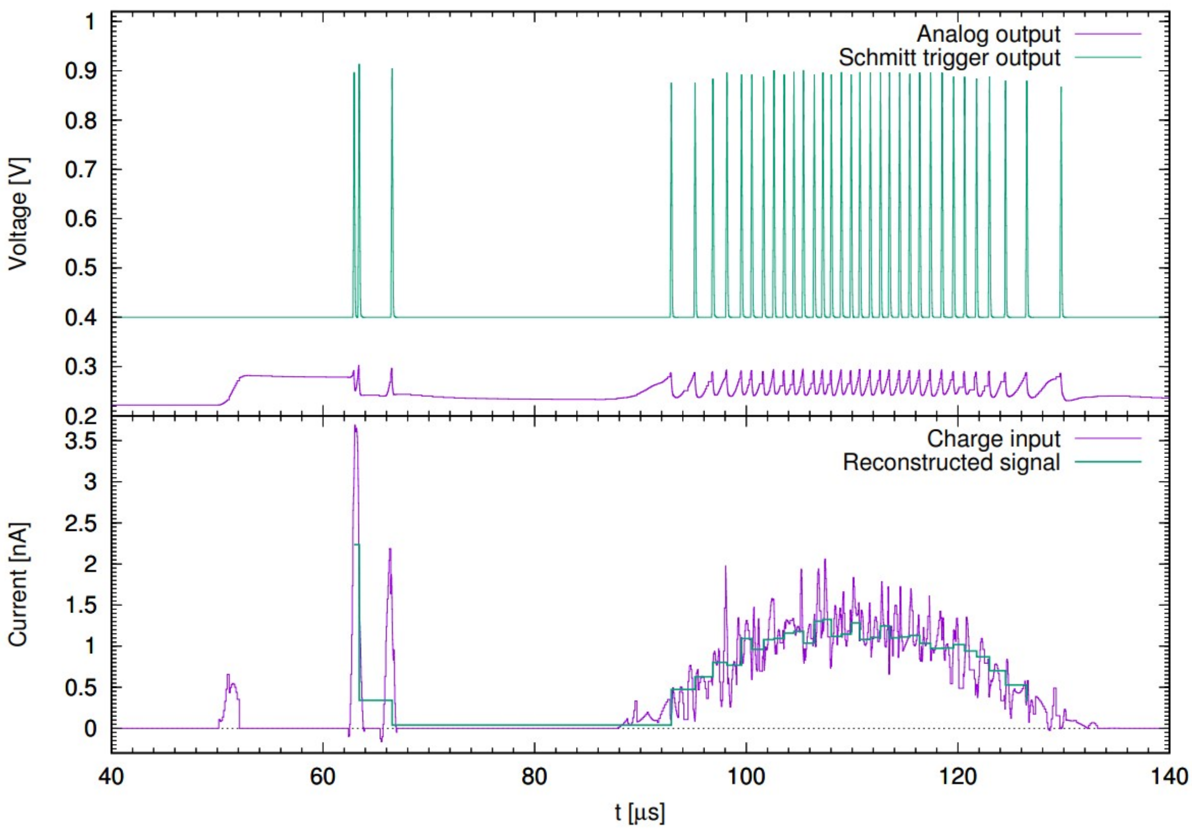

Figure 2.3: Example reconstruction of the reset time difference (RTD) based on the Q-Pix readout design. delta-Q was chosen to be $0.3fC$. Image is taken from [2].

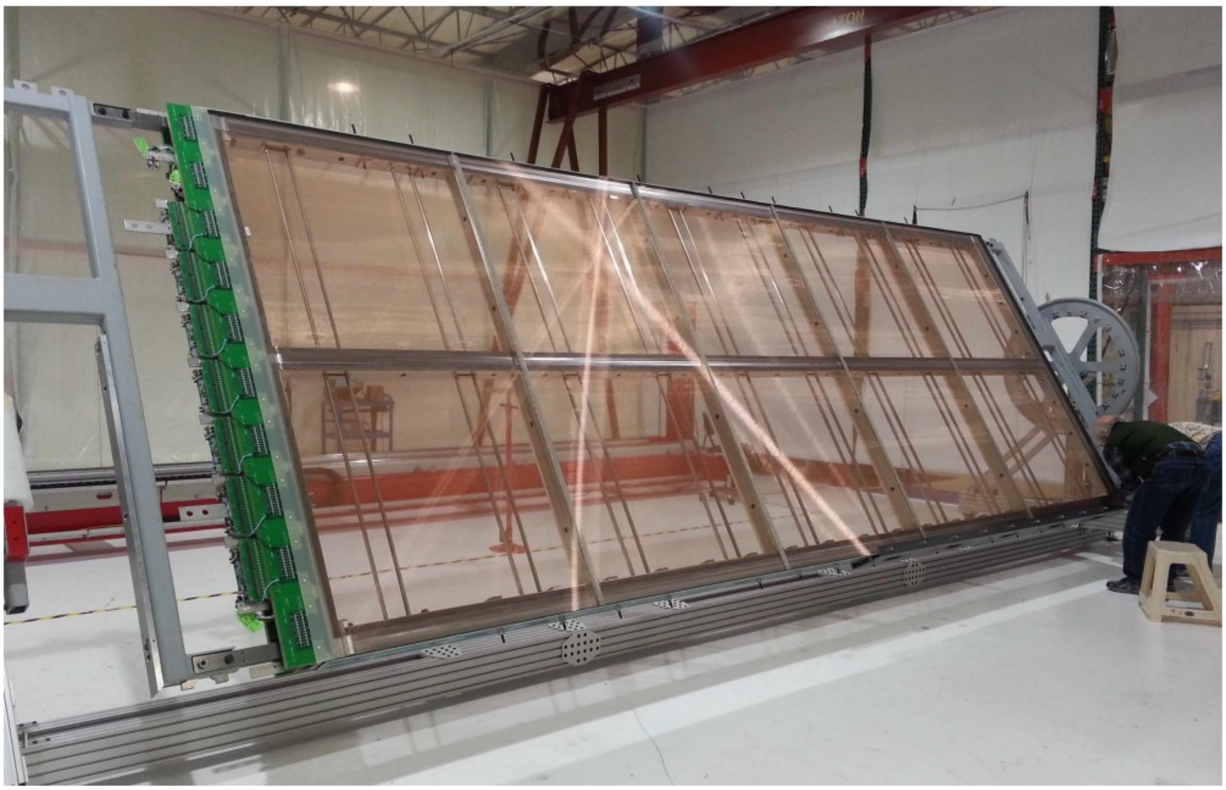

Figure 2.4: A simple caption [3]

Chapter 3

NEW DIFFUSION MEASUREMENTS: LARTPC STUDIES WITHIN SAQ

In this chapter we introduce the first implementation of the Q-Pix based design using purely "over-the-counter" electronics.

3.1 Simplified Analog Q-Pix: System Design

3.2 Leakage Current Measurements

3.3 TPC Design

3.4 Diffusion in Noble Gasses

Measurements of Transverse and Longitudinal diffusion of electrons within electric fields of strength 500 V/cm have been performed before [34].

3.5 Measurements of Drift Current

3.6 LArTPC Diffusion background

3.7 Xenon Gas Lamp Measurements

Integrating towards background Current

3.8 Results

Chapter 4

THE DIGITAL BACK-END AND VIABILITY STUDIES

In this chapter we describe the overall structure digital back-end of the Q-Pix design. We would like to take a moment here to note here that we refer to each node in the array is implemented as a lattice ice40UP FPGA

Additionally, this chapter is divided into two parts. The first part we give a detailed description of the digital-system, and its requirements to successful in a Q-Pix based detector of DUNE scales. The motivation here is to outline how the digital backend of Q-Pix based readout fits into the DUNE-FD LArTPC. The second part of this chapter is dedicated to the first evaluation boards developed and tested which are implemented in Lattice iCE40UP FGPAs [35]. The second part outlines the design of the PCB on which these FPGAs are implemented, as well as basic results of these FGPAs, which are motivated from the first part of this chapter.

The Lattice Semiconductor FPGAs [35] were selected because of the small form factor, pin out, availability, as well as lower power consumption. There are planned tests for future, but not presented here to indicate its viability of over-the-counter FPGAs in LArTPc. If such cheap and available FPGAs were shown to be reliable use in a LArTPC environment, that would greatly influence future detector development and selection for Q-Pix.

4.1 Digital Design Overview

The digital system of the entire Q-Pix design begins at the electronic collection of a recorded timestamp in respond to a reset-time-difference sent from the analog front-end. Then, all data that are recorded for each pixel, and the only data required for a full analysis of all reconstruction with a LArTPC are:

- 32 bit timestamp
- Pixel X location ($\leq$ 4 bits)
- Pixel Y location ($\leq$ 4 bits)
- APA reference number ($\leq$ 4 bits)

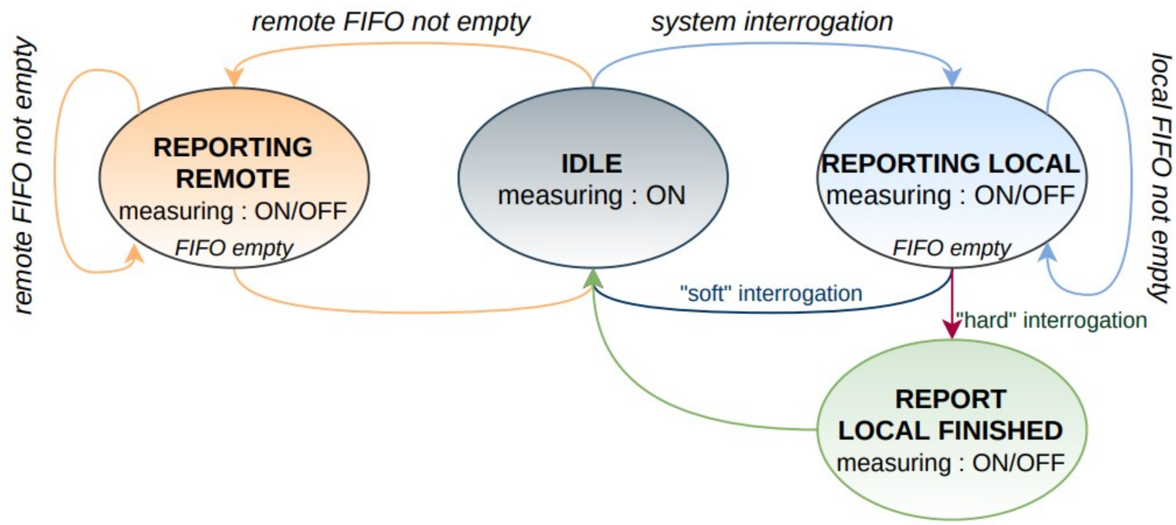

Figure 4.1: Diagram of the Digital node's FSM which determines how to respond to incoming packets.

Each of these remote ASICs are running on free-running independent clocks, with an expected frequency of $\approx$ 30 MHz.

Basic System Requirements

Reset time differences are a function of the accumulated charge compared to the integrating capacitance for this specific pixel. The sheer number of pixels required for an APA (and the entire module) require an effective means of charge and time calibration, stable buffer depths, and protection against single-point failure (SPF).

Charge Calibration of each Pixel

Natural decay products produced by ^{3}9Ar provide a continous source of incoming current across a LArTPC.

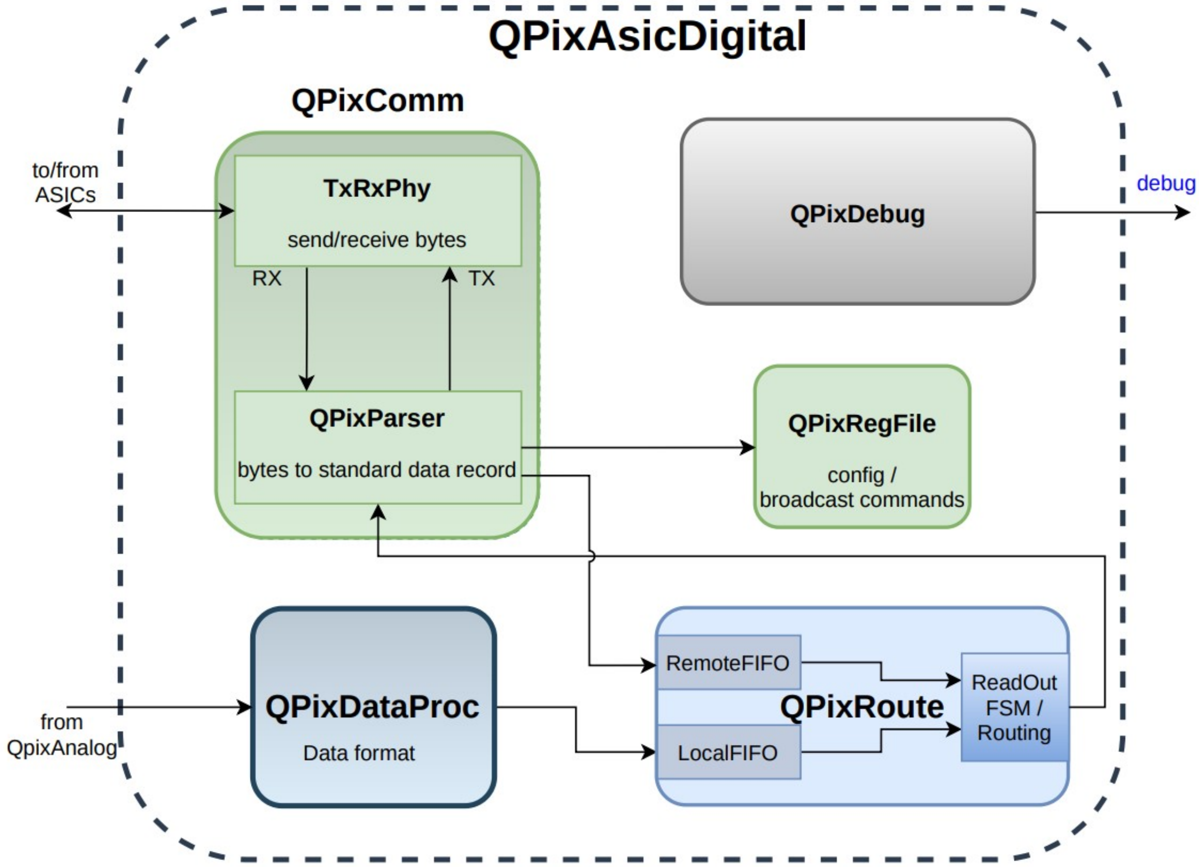

Figure 4.2: Diagram of the Digital node.

Time Calibration of each Node

Inter-Node communication via endeavor protocol

The Structure of a Data Word

Each node communicates via an entire packet, which is always 64 bits long. The communication protocol (4.1)

Comments on Data Rates and required Computing

Based on the minimum number of bits for each RTD 4.1 we can calculate minimum data rates for a full APA section and extend to this to

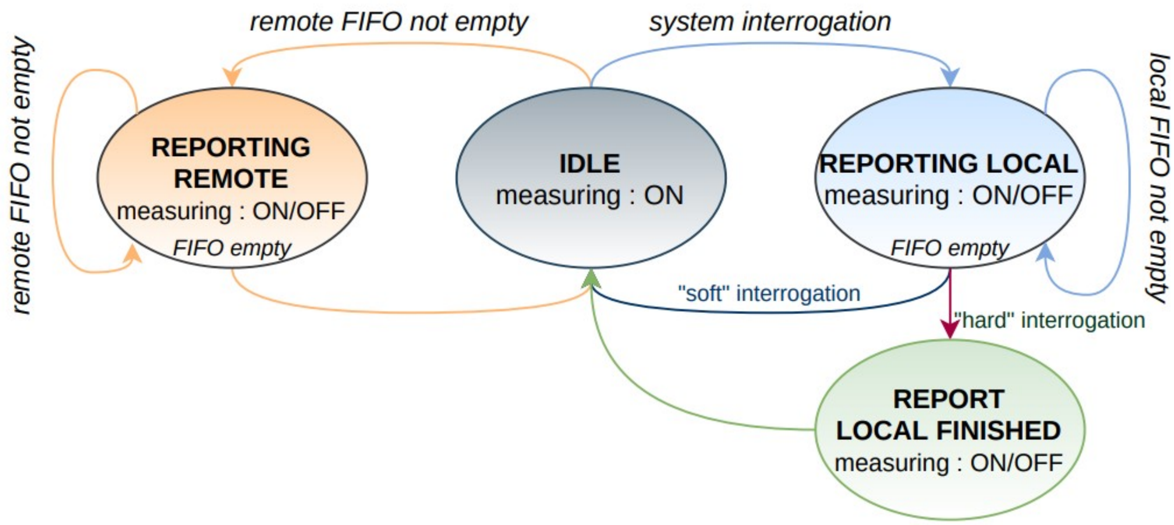

Figure 4.3: Overview of the FSM design, courtesy of Vasily Shebalin.

4.2 The Digital Finite State Machine

The Finite State Machine (FSM) of the remote digital ASIC outlines the designed behavior response to inputs from a controlling DAQ node.

- Idle, Acquisition State
- Transmit Local
- Transmit Finish
- Transmit Remote
- DONE

4.3 The Parameter Space of the Digital System

Buffer Depth Requirements

The required buffer depth of each node in an array is the maximum number of timestamps the node can store in memory before running out of room.

4.4 QDB Design Overview

4.5 Power and Current Characteristics

4.6 Timing Stability

We describe here the methods of measuring a stable time for different configurations of the nodes. We also comment on the results of the timing with resepect to the minimum required timing sensitivity in order to have accurate timestamp reconstruction.

4.7 Analysis of Systematics for Different System Implementations

4.8 Towards the Integration of a DAQ-Node

4.9 Comments on A Super-DAQ-Node

Each APA module within a larger DUNE module must ultimately be interconnected so that the entire module can be readout. As described above, a single modular tile is controlled by an individual DAQ node, where many constitute a complete APA. Therefore, we refer to the device that digitally multiplexes all of the DAQ node data as the "Super DAQ Node" (SDN). Then, we imagine the final multiplexing stage for an entire DUNE module as an array of SDNs, each of which consistute an array of DAQ nodes, where each DAQ node is a 2-D array of Q-Pix based ASICs.

The total number of request SDNs within the full dune module depends on the final size of a DAQ-node controlled tile.

4.10 Summary

Chapter 5

SIMULATION STUDIES AND FUTURE Q-PIX PROTOTYPES

5.1 Physical Simulation Studies

5.2 Background Rates and Calibration

sources of backgrounds are taken from [3]

5.3 Supernova Studies

Work has been done to understand how a Q-Pix based DUNE-FD would measure core collapse supernovae [36].

Simulation studies which involved particle interactions were based on Geant4 [37].

5.4 Looking for Hadron Decay

5.5 Neutrino Beam High Energy Studies

5.6 Further Studies

Chapter 6

SUMMARY AND OUTLOOK

Recap of Qpix Requirements for DUNE APA here.

Recap of Qpix design concept testing within SAQ here.

Recap of QDB Results here

Recap of SAQ Results here

Recap of lessons learned on pixelated detectors

Discuss how combination of simulation / qdb / saq results motivate the next stage of development for QPix and incorporating the digital / analog ASICs for round two.

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Appendix A

SVSC OS1

the work in this subsection details the work and results of [38].

Appendix B

SVSC OS2

The section lists the work detailed in [**svsc_os2_Keefe_2022**].