Graduate Instrumentation Research Award Proposal

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Introduction For the upcoming international program in neutrino physics, including the Deep Underground Neutrino Experiment (DUNE), the liquid argon time-projection chamber (LArTPC) is a primary detector technology [1]. The ground-breaking ICARUS [2] experiment showed that LArTPCs could be made large enough to detect neutrinos. Further research and development has demonstrated that the various engineering challenges involved in expanding a LArTPC to a multi-kiloton scale can be addressed [3,4]. However, the readout schema that have been employed thus far rely on the use of projective wire planes to collect track information. Wire planes have a number of drawbacks, most notably in the reconstruction of particle interactions in a high-rate environment. This is particularly problematic for the high-rate environment of the DUNE near detector (ND). Two-dimensional pad-based systems, such as have been demonstrated in liquid argon by the LHEP group at the University of Bern [5], promise a TPC that is free from these same reconstruction ambiguities. In order to utilize these systems in a large-scale detector, low-power electronics must be developed. We are pursuing a cryogenic integrated circuit and a printed circuit board sensor plane (LArPix) that meets the requirements of a multi-ton TPC with true 3D charge readout.

Working with a mentor at LBNL, I am driving a research and development effort to design, test, and demonstrate the LArPix concept in a full-scale detector. Since the initial LArPix chip design began in December 2016, excellent progress has been made to test and integrate the LArPix chip in a small LArTPC demonstrator. All but one of our initial demonstration goals have be met. A publication on the LArPix-v1 chip is forthcoming, however there remains considerable research and development work beyond our initial demonstration goals. Namely, very little experimental work has been done to determine an ideal sensor design, including pad geometry, for a pad-based LArTPC with electrostatic focusing, also referred to as a *pixelated* LArTPC. The pad geometry will play a significant role in TPC angular resolution, calorimetry, track separation, and other critical detector performance characteristics. **The aim of this research project will be to characterize a variety of sensor designs to optimize the overall performance of a true 3D LArTPC.**

Motivation A time-projection chamber (TPCs) consists of a volume filled with a suitable detector material, such as a noble liquid or gas, and a uniform electric field. When a charged particle passes through the chamber, it ionizes the detection medium along its path. If a large electric field is applied, the electrons will drift through the gas or liquid at a constant rate towards the maximum potential. Traditionally, a series of parallel wire planes, oriented at different angles with respect to one another, are placed near the maximum potential and along the path of the drifting electron cloud. The presence of the electron cloud can then be detected either by inductive coupling as the cloud passes the wire plane or by directly collecting the charge on the wires. The three-dimensional particle track can then be reconstructed by using wire position and the electron drift time, and the total charge of the track can be used to infer the kinetic energy of the particle. Further particle identification can be performed either through the dE/dx of the particle track or by using curvature in a magnetic field.

Gas TPCs have been widely used for particle tracking [6]. The LArTPC is an emerging technology, favored by neutrino experiments for its high density and excellent background rejection. The future DUNE experiment plans to build four 10-kiloton LArTPCs far detectors to measure δ_{CP} and the neutrino mass-splitting Δm^2_{32} [7], however in order to achieve DUNE's physics goals, beam uncertainties must be constrained to the percent level. To reduce the analyses' dependence on beam models, a neutrino flux measurement near the beam source will be performed. In particular, a liquid argon near detector (ND) allows for an analysis that is also nuclear model-independent. Therefore, the DUNE collaboration has concluded that a liquid argon component to the ND is necessary to accomplish the experiments' physics goals [8].

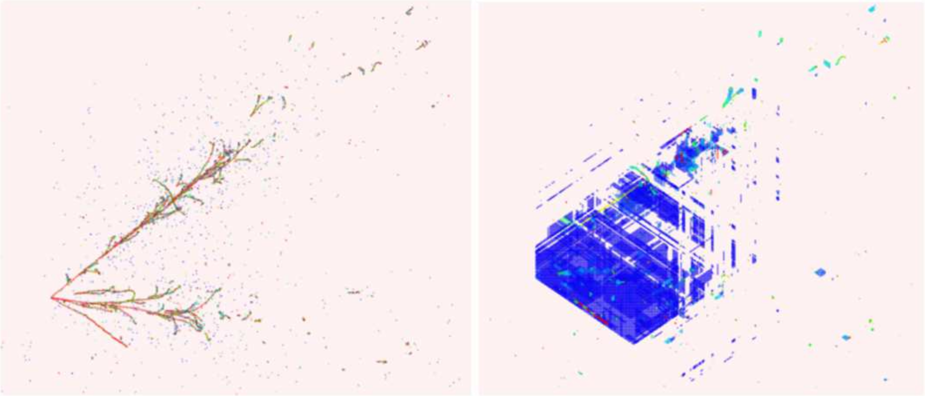

Figure 1 Left, charge distribution of an example GeV-scale neutrino event in liquid argon. Right, the charge distribution of the same neutrino interaction as observed in a wire-based TPC, illustrating ambiguities that are typical of wire-based readout.

The DUNE near detector environment at the multi-megawatt Long Baseline Neutrino Facility (LBNF) is expected to have a neutrino flux on the order of 10^{10} ν/GeV/m^2/yr [9], leading to approx. 10 neutrino interactions in liquid argon per beam spill. Limited by the electron drift velocity and length, a meter-scale LArTPC ND will experience significant pile-up. Using projective wire-planes, pile-up leads to reconstruction ambiguities that significantly impact the detector's performance, as in Figure 1. A pad-based TPC has access to the full 3D information of the neutrino interaction, thereby eliminating the ambiguities present in a wire-plane TPC.

Implementing a pad-based LArTPC is not without challenges—what is gained in reconstruction simplicity, is lost in an increased channel number. A meter-scale pad-based TPC would contain 100,000s of channels, as opposed to the 1000s in traditional wire-plane TPCs. A high channel number introduces new complications in the amplification and digitization of the signal. In order to preserve the 2D information of a pixelated TPC, each channel must be amplified and digitized independently. Additional electronics adds heat load on the cryogenic cooling system and additional heat-carrying penetrations to the cryostat. The University of Bern group was able to overcome these thermal challenges by utilizing a multiplexed readout that repurposes cold application-specific integrated circuits (ASICs) originally developed for wire-based TPCs [5]. However, this multiplexing scheme does not preserve the full 3D track information and thus is still susceptible to reconstruction ambiguities. LArPix will build on the success of the University of Bern group, but meets the thermal constraints and can record complete 3D track information.

LArPix LArPix consists of two primary components: first, a low-power cryogenic ASIC capable of handling charge amplification and digitization for up to 32 channels per chip; and second, a pixelated PCB sensor plane that is manufactured according to industry-standard PCB printing techniques.

In order to satisfy the required low-power, high-channel-number requirements, the LArPix ASIC is a CMOS IC that includes a charge-sensitive amplifier (CSA) front-end, a discriminator, and an analog-to-digital converter (ADC) for each of 32 channels. The chip contains a first-in-first-out (FIFO) memory buffer, which allows for low-power buffering and transmission track data. Communication is handled via a daisy-chained serial communication network, reducing the number of cryostat penetrations. To further reduce power consumption, the chip is designed to be fully operational down to a core digital voltage of 1V and communication voltage of 1.5V. Finally, LArPix is based on data-driven sampling and readout. While in operation, a LArPix channel only preforms an ADC conversion when the signal passes an adjustable channel threshold or when an external trigger is issued, thus dramatically reducing digital power usage.

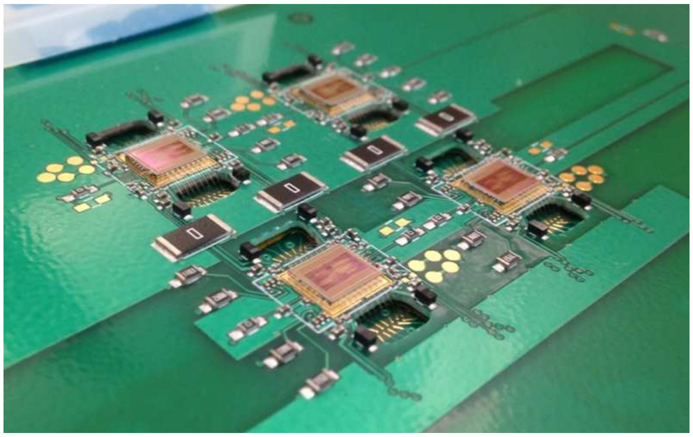

Figure 2 An example 4-chip / 128-channel digital board epoxied and wire-bonded to a sensor plane.

The LArPix sensor plane uses industry-standard PCB printing techniques to reduce production cost and improve scalability. The collection-side of the PCB consists of vias with a focusing grid of copper traces. As the electron cloud drifts towards the sensor plane, the negatively biased grid focuses the charge onto the pixel via, improving the charge collection efficiency. The back-side of the sensor plane has short traces to a cluster of 16 bonding pads at the center of each 8x8 pixel square. The complete assembly of the LArPix sensor and LArPix ASIC is performed by aligning and epoxying the two circuit boards together. Wire-bonds are then created between the chip and the pixels through a 3mm cavity in the digital board, see Figure 2.

Since initial testing of LArPix ASIC began in September 2017, all of the primary performance metrics have been measured and are well within the limits required for large-scale instrumentation. In particular, the front-end amplifier noise is much less than the 1500 e- noise eq. allowed, the total power consumption is approx. half of the 100μW/channel required, and the chip is fully operational at liquid argon temperatures. Additionally, preliminary results from the complete LArPix system suggest successful charge collection and track imaging. Combined, these indicate that the LArPix approach is technically feasible for a full-scale LArTPC.

Research plan Now that my work has demonstrated that LArPix can perform low-power 3D readout, I would like to begin comprehensive characterization and optimization of the LArPix sensor. The end goal of this effort would be a publication describing the performance characteristics for various sensor layouts and geometries along with recommendations for a sensor optimized for DUNE ND physics.

Utilizing a small demonstrator TPC that was built for the initial LArPix testing, I will explore the resolution and noise performance of a variety of pixel geometries. To this end, we have designed the first prototype sensor PCB with a variety of pixel pad sizes and shapes, enabling a direct comparison of pixel performance across individual particle tracks. With this sensor, I will explore three different geometric features that may affect pixel performance. First, the sensor has 448 triangular pixels and 448 square pixels of the same 3mm pitch. Triangular pixels will enhance charge-sharing between adjacent pixels, theoretically improving track resolution, but may experience drawbacks, such as increased leakage current or poor electron focusing. Second, the collection vias are surrounded by pads of various sizes. With variety of pad sizes, I will experimentally test electron-cloud transparency conditions and noise performance. Finally, roughly half of the sensor is left without a focusing grid to examine the grid's ability to shield the CSA from inductive signals induced by drifting electrons and its influence on pixel transparency. Informed by this study, I will design and fabricate additional sensor planes to test alternative sensor layouts and new pixel geometries not exclusively limited to these three parameters.

In tandem, I will construct a GEANT4 [10] simulation of a full-scale pixelated TPC. Demonstrator-measured sensor characteristics will be incorporated into the simulation to base the predictions in observational data. This simulation will provide an important handle on the baseline LArPix system performance in a full-scale detector. Verification of these predictions will be performed through cosmic ray and radioactive source data from our TPC. Once I have a verified simulation and have a strong understanding of how pixel geometry and sensor layout influences high-level detector performance, I will begin extrapolating to untested sensor designs, optimizing for the DUNE ND requirements. During this process, I will select a few of the best performing sensors to fabricate and characterize in a real TPC. This testing will initially be carried out in our small TPC with plans to instrument a larger TPC, such as our collaborators' at the University of Bern.

Based on the results of these studies, I will prepare a publication documenting the prominent aspects of pixel geometry and sensor layout that determine overall TPC performance. This document will also include recommendations on a sensor design for further testing in a large-scale detector such as LArIAT at Fermilab or ArgonCube at CERN. My previous experience working on miniCAPTAIN [11] and in developing muon detectors for LBNF [8] has involved extensive modelling of detector performance with both simulation and data and leaves me well prepared for this task.

Figure 3 The demonstrator TPC that will be used for this research. The TPC has a 10cm drift length and a 10cm diameter sensor region. Equally spaced field circular rings provide a uniform electric field across the drift dimension.

Resources To execute this research plan, I will use our 1 liter demonstrator TPC, see Figure 3, for much of the data collection. This TPC is modeled after the demonstration TPC described in [5]. The TPC is operated while submerged in a high-purity liquid argon chamber, suspended within a cryostat containing a moderate-purity argon gas. Purity is achieved through a single-shot fill process using an activated copper and molecular sieve filled purifier. The warm cryostat is rapidly filled with the high-purity liquid argon from the purifier, quickly purging the cryostat volume with pure argon gas and providing a purity- and temperature-maintaining buffer gas around the high-purity inner volume. This method has enabled us to achieve adequate purity and liquid argon for more than 4 hours with a single fill. Two such systems will be available for my use – the first has been lent to the neutrino group at LBNL by the LUX/LZ group for the initial LArPix testing; the second is our own dedicated system that is currently under construction. An external muon telescope consisting of two scintillator paddles instrumented with photomultiplier tubes can be easily installed in either system to provide an external cosmic ray tag.

The computational aspects of this project will be accomplished via the NERSC computing center [12] and readily-available, open-source software.

Timeline This project is anticipated to take 1 year. A sketch of the expected research progress is as follows:

June 2018-Aug 2018: Write simulation code building on existing GEANT4 frameworks and measure pixel characteristics in demonstrator TPC

Sept 2018: Verify simulation with demonstrator TPC data and predict full-scale detector performance

Oct 2018-Dec 2018: Optimize pixel geometry using verified simulation and begin design and fabrication of test sensors

Jan 2019-Mar 2019: Compare performance of test sensors with predictions from simulation and instrument the Bern TPC

Apr 2019-May 2019: Synthesize results and prepare publication

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