Pixel Instrumentation for Neutrino Detectors

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Snowmass Community Summer Study (Seattle)
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Neutrino Instrumentation Challenge

Deliver mm-scale spatial granularity for stadium-sized detectors.

Example: DUNE

- DUNE consists of four Far Detector modules, with a total volume on the order of 50,000 cubic meters.
- To achieve the required precision, a spatial granularity of ~4mm is required over this volume.
- Corresponds to a detector with a total of ~1 trillion spatial voxels.
Neutrino Pixels

Benefits:
- True 3D imaging
- ‘Triggerless’, 100% uptime

Science Gains:
- Improved signal fidelity, S/B
- Enhanced low-energy program

\( \text{JINST} \, 15 \, P04009 \)
\( \text{arXiv:2203.12109} \)

Challenge:
Very high channel counts
\( O(100k) \) channels/m\(^2\)

Requires:
- Very low power
- Minimal cabling
- Cryogenic robustness
- Scalable production

Raw 3D Cosmic Ray images in LArPix prototype LArTPC
R&D on Feasibility: LArPix-v1 System

LArPix-v1: 2016-2018

Complete 3D Pixel System for LArTPCs:
- Custom ASIC with amplifier, digitizer, multiplexer
- Integrated Pixelated Anode w/ASICs
- Control electronics and software (outside cryo)

Key R&D Achievement:
Demonstrated technical feasibility
--> Successfully imaged cosmic rays in LArTPC

ASIC:
- Cryogenic-compatible
- Low-power: 62 uW/channel
- Low-noise: 275 e- ENC @ 87K

Pixel Anode:
- Cryogenic-compatible
- Low Digital-Analog cross-talk
- O(1k) channel readout via 2 wires

Control electronics:
- Fieldable system: noise-isolated and wifi accessible

Main drawback:
Difficult to scale above O(1k) pixels
- Anode requires manual assembly, bare chip wirebonding
R&D on Scalability: LArPix-v2 System

**LArPix-v2: 2019-2021**

Substantial Design Evolution:

**ASIC Improvements:**
- 64 channels/ASIC (twice channel density of v1)
- Hydra-I/O: Dynamic routing, robust to chip failure
- Cryogenic-compatible custom SRAM memory
- Improved tunability, testability
- Packaged to facilitate commercial mass production

**Pixel Anode Design Overhaul:**
- ‘Tileable’ design to cover anodes of arbitrary scale
- 32cm by 32cm pixel anode PCB tile
- Frontside: 4900 square pixels, 4.4 mm spacing
- Backside: 10x10 grid of ASICs
- Enable fully-commercial mass production and assembly

**Warm Controller (PACMAN) Redesign:**
- Noise-isolated, compact, flange-mounted

**Key R&D Achievement:**
Demonstrated robust and scalable pixel anode
- Fast (~few weeks) fully-commercial production/assembly
- Robust to repeated cryogenic cycling
- Successfully imaged cosmic rays in LArTPC on first try

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**Production-scale LArPix-v2 Pixel Anode**

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**Raw 3D images of cosmic rays from initial single-tile test**

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“LArPix-v2: a commercially scalable large-format 3D charge-readout scheme for LArTPCs” publication in preparation
Prototyping: ArgonCube 2x2 LArTPCs

Four ton-scale Prototype TPC Modules to validate DUNE Near Detector Design

Each TPC Module:
- Active Size: 0.7m x 0.7m x 1.25m
- 16 pixel tiles, with ~80k pixel channels total
- 16 light collection modules, with 96 light sensors (SiPMs)
- Resistive-film-on-fiberglass field cage

Progress @ Univ. of Bern:
- TPC Module 0:
  Run 1 (Demonstration): Apr. 1-10, 2021
  Run 2 (Extra Cryo-test): Jun. 21-26, 2021
- TPC Module 1 Operation:
  Feb. 5-13, 2022

Achievements:
Demonstrated fully-integrated prototype detector module at a scale relevant to the DUNE Near Detector
Prototyping: ArgonCube 2x2 LArTPCs

Verified design meets technical requirements:
- Collected $>10^7$ cosmic ray events
- Stable HV at $\sim$30kV ($\sim$1 kV/cm drift, 2x target)
- Stable purity at $>2$ms (>4x target)
- MIP Charge Signal-to-Noise $>20$:1 (at target)

Continuous readout:
$\sim$100% live, independent of light system
Low data rate due to self-triggered design

Arguably the most performant ton-scale LArTPC to date.
LightPix: Scalable Cryogenic SiPM Readout Electronics

• Readout Electronics Needs:
  - Low-power cryogenic-compatible scalable SiPM readout electronics at very low system cost

• R&D Plan:
  - LightPix:
    • Adapt existing LArPix ASIC to provide scalable readout for many (e.g. >10^6) Silicon Photomultipliers
    • Reuse all of LArPix system architecture (low-power, cryo-compatible, scalable, O($0.10)/channel system cost)
    • Provide a path for highly-granular photodetection systems for very large detectors

Rough concept: Replace LArPix charge-collection pixels with SiPMs

Why LightPix:
Existing readout electronics are either too high power or too high cost for our cryogenic detector needs.

Looking ahead:
Personally, I think LightPix fits some specific near-term HEP needs (next 5yrs). In the long-term (5-10yrs), my guess is that digitally-integrated SiPMs may eventually provide better performance at lower cost.
**LightPix ASIC**

**LightPix-v1:**
- Develop and test dedicated time-to-digital converter (TDC) to provide < 10ns time resolution
- Add multi-channel coincidence triggering mode to suppress excess data from dark noise at room temp

**Progress:**
- Received Aug. 2021
- Power-up, configuration successful
- TDC meets design targets

**Next Steps:**
- LightPix-v2:
  - Provide both TDC and ADC functionality
  - Deployment and testing of light detector system in prototype LArTPC
  - Exploration/optimization of light detector formats

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**Very-low-power TDC achieves ~ns-scale precision in response to external pulse**

**Offset between external pulse and TDC stop signal**

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LightPix-v1b ASIC
QPix: Concept and Progress

Concept: arXiv:1809.10213

Report ‘time between resets’ instead of digitizing charge

Distribution of reset times proxy for signal current on pixel

Front-end Prototype ASIC
(180nm, UPenn)
QPIX Layout: Integrator + Amplifier + Comparator
Size: 350um x 90 um

Front-end Prototype ASIC
(130nm, UTA)

Digital Back-end Prototype
(FPGA-based, U-Hawaii)
QPix: Light-sensitive Pixels

**Concept:**
Add photoconductive (ASe) film to pixel anode to make pixels sensitive to both TPC charge and scintillation light.

**Prototype PCBs with biased traces coated in ASe**
- 127 um trace spacing, 5V/um max field, UTA/ORNL
- 127 um trace spacing, 5V/um max field, UTA/ORNL
- 25 um trace spacing, 40V/um max field, UCSC/UTA/FNAL

**Example signal traces in response to light pulses**

![Graph showing example signal traces in response to light pulses](image_url)
**Concept:**
Achieve Dual-phase TPC 3D readout by imaging electroluminescence in THGEM with fast optical cameras.

**Advantages:**
- Low noise via optical-only readout
- Low threshold due to gas amplification
- Accessible/upgradeable: Cameras outside cryostat

**Disadvantages:**
- Only viable in a dual-phase TPC
  - High cathode voltage
  - High-field e- extraction region
  - THGEM amplification
- Scattered/indirect light

**Example 3D cosmic ray imaged in prototype**
R&D Collaboration

**Snowmass LOI:**

“Continued development of scalable pixelated detector systems could benefit from a structured method for supporting detector R&D collaborations within the US DOE system. Such an approach can be seen in the CERN RD Collaborations, which have been essential for delivering the technologies used by the current generation of large high-energy physics experiments.”

*e.g.* RD-50 (Rad-hard semiconductors), RD-52 (MPGDs), RD-53 (Pixel Tracker ICs)

“The DOE, through the national laboratories, could provide a similar shared infrastructure for supporting these R&D collaborations amongst a large number of university and laboratory partners.”

“The scalable pixelated detector R&D proposed here could serve as a test case for this model within the US.”

**Potential Future R&D:**

- Finer detector granularity
- Embedded detector logic
- Increased system reliability
- Advances in commercial mass production.
- Adaptations:
  - Higher-bandwidth detector systems
  - Adaptable readout logic
  - Large-area photodetection.

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Snowmass2021 Letter of Interest: An R&D Collaboration for Scalable Pixelated Detector Systems


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**Thematic Areas:**

- IF7: Electronics/ASICs
- IF8: Noble Elements
- IF9: Instrumentation Science: Cross Cutting and Systems Integration
- NF10: Neutrino Detectors
- UF06: Underground Detectors

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**Introduction**

Frontier experiments in neutrino and dark matter physics typically rely on large detectors, in the ton to many kiloton regimes. Achieving high-granularity readout in detectors at these scales requires new techniques in instrumentation design and production. Specific areas of development are large-area low-noise mixed-signal detector anode designs, system reliability (in the billion-channel regime), scalable and robust I/O architectures, and leveraging commercial methods for mass production. Recent advances in pixelated readout for large liquid argon time-projection chambers (LaTPCs) provide a concrete example of progress in this field [1, 2]. However, much development is still needed, and as the scale of that development necessarily increases, so do the required resources. Establishing a mechanism for coordinated R&D in this area that allows pooling of resources, similar to the CERN RD Collaboration model, would enable the required scale to meet the needs of future experiments.
Summary: Neutrino Pixels

LArPix:
- True 3D pixelated charge readout for LArTPCs
- Low-noise, low-power, cryogenic-compatible
- Self-triggering, 100% live
- Scalable anode design leverages commercial production
- Two recent 80k-pixel ton-scale prototype exceeded expectations
- Baseline technology for the DUNE Near Detector

LightPix:
- Highly-scalable readout for cryogenic SiPMs
- Reuses much of LArPix system design

QPix:
- Record trigger time distribution instead of digitizing charge
- R&D on ASe coating to make pixels light-sensitive

ARIADNE+:
- Optical 3D readout for dual-phase TPCs
- Successful mid-scale prototyping at CERN

Potential technologies for future highly-granular detectors