Q-Pix:
Pixel-scale 3-D Signal Capture for the DUNE Far Detector

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Q-Pix: Pixel-scale Signal Capture for Kiloton Liquid Argon TPC Detectors: Time-to-Charge Waveform Capture, Local Clocks, Dynamic Networks

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Abstract

We describe a novel ionization signal capture and waveform digitization scheme for kiloton-scale liquid argon Time Projection Chamber (TPC) detectors. The scheme is based on a pixel-scale self-triggering 'charge integrate/reset' block, local clocks running at unconstrained frequencies and dynamically established data networks. The scheme facilitates detailed capture of waveforms of arbitrary complexity from a sequence of varying time intervals, each of which corresponds to a fixed charge integral. An absolute charge auto-calibration process based on intrinsic ^{39}Ar decay current is a major benefit. A flat electronic architecture with self-guided network generation provides exceptionally high resilience against single-point failure. Integrated photon detection, although highly speculative, may also be possible. The goal is optimized discovery potential. Much might be at stake.

Keywords: Pixel, Charge sensor, Readout, LAr, TPC

1. Introduction

1.1. Context

The DUNE project is the flagship enterprise of US HEP[1]. Definitive results are expected for neutrino mass ordering, with high sensitivity to CP-violation in the lepton sector, supernova dynamics, other neutrino topics and the search for baryon decay. The DUNE neutrino physics program depends on many things, but accurate classification of events is the one big thing: is the apparent single electron in this event really caused by neutrino flavor change, or is that track a misidentified π^0 or γ? For CP-violation studies, discrimination among various neutrino flavor interactions and nuclear/hadron/electron recoils is of paramount importance. In the end, after several years of running, the number of true events is likely to be measured in tens to a few hundred.

Many processes of fundamental interest lead to events that display complex signal waveforms with highly variable features in space, amplitude and time. As the intrinsic quality of information inherent in a kiloton liquid argon TPC (LArTPC) is very high, the central technical goal must be to capture these events with high efficiency, and in exquisite detail. High quality data may ultimately

unexpected phenomenon, however subtle but above intrinsic sensitivity threshold, be recognized as new physics, be dismissed as artifact, or just not seen? We seek here to optimize discovery potential.

In the era of DUNE operation as a full system, however, much more will have become known about primary goals from other experiments. The mass ordering of light neutrinos is likely to have been well clarified, and no follow-on experiment based on a particular value of CP-violation is apparent. The enormous investment, with sustained effort for two decades by thousands of people, is likely to exceed US\$2 $\times 10^9$. From this mixed perspective, how should the DUNE program be viewed?

We believe an obligation exists within the HEP community to ensure that data extracted from the DUNE FD is captured with the highest quality to the extent possible within constraints of time, resources, and our capacity to innovate, so that any subtle new phenomena near the limit of detection may be revealed. A search for an optimal, intrinsically 3D signal capture approach with low signal threshold seems accordingly very well motivated. Dwyer et al.[2] have recently demonstrated a true 3D pixelized information capture technique, proposed for the DUNE near detector. That work provides evidence that impres-

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- Goal: Optimized discovery potential !
- LAr TPC: information quality is very high
  → Technical pathway must:
    - capture information without compromise !
    - maintain intrinsic 3-D quality !
- Aspiration: complete pixelization of DUNE FD
- Immense FD scale → unorthodox solution
  →Electronic principle of "Least Action"
  →New approach: measure time-to-charge: ΔQ

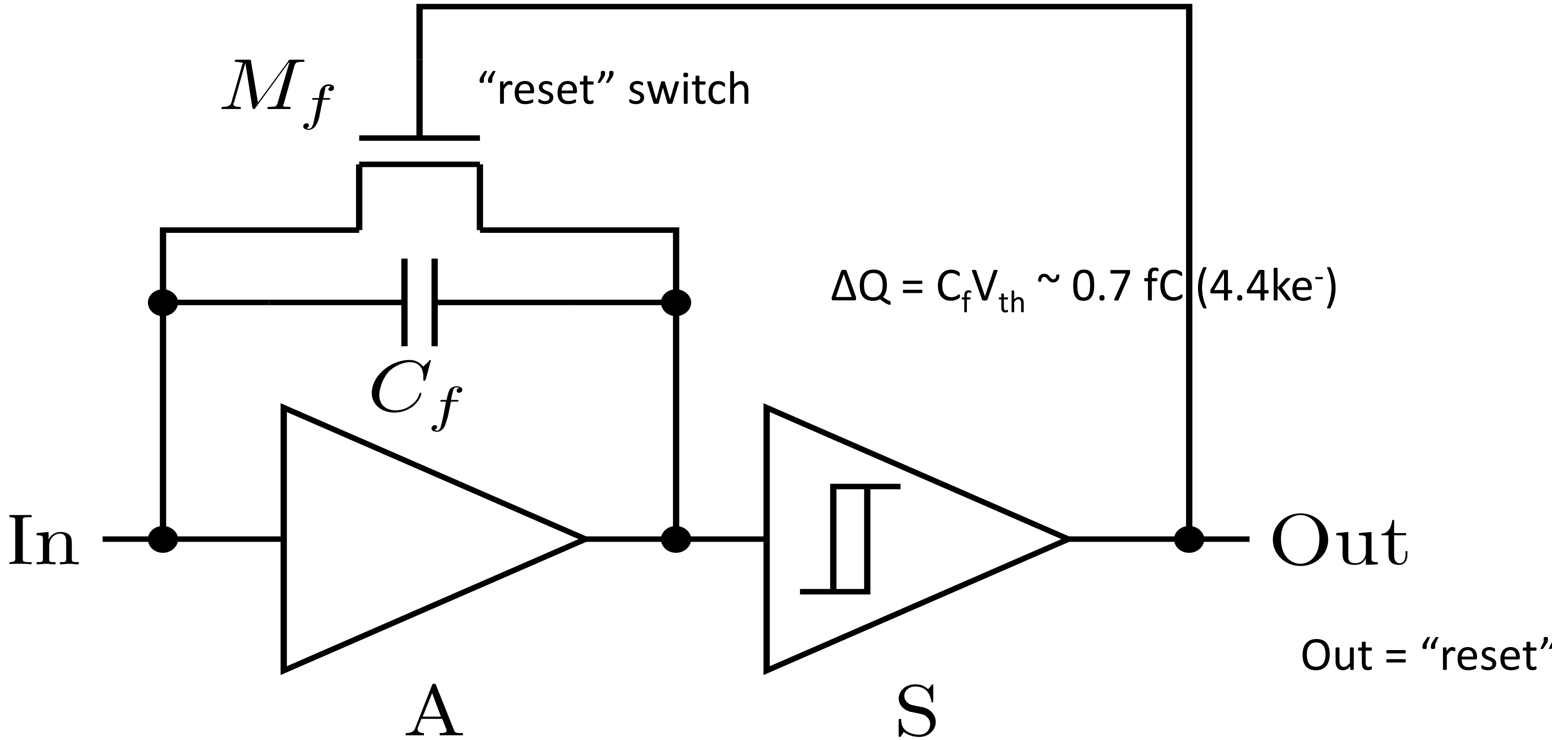
Q-pix

- A genuine innovation for signal capture:
  - Detailed waveforms provide:
    - track profiles, track continuity, dE/dx, …
  - Exploit ^{39}Ar decays to provide:
    - automatic absolute charge-energy calibration
- High intrinsic *single-point-failure* resilience

  → Electronics permanently immersed in LAr

  → Allows maximal functional devolution
- Novelty does not automatically confer benefit!
  - Much remains to be explored…
  - LArPix (D. Dwyer) show great promises

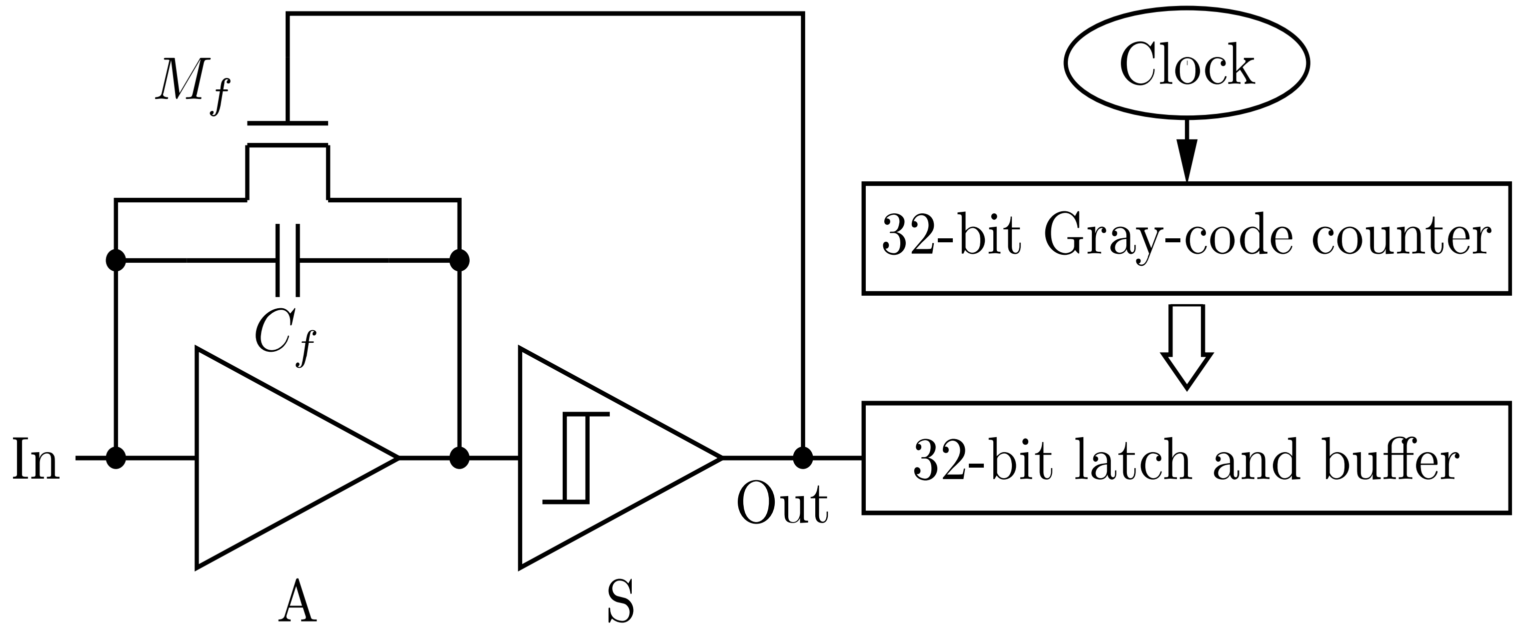
The Charge Integrate-Reset (CIR) Block



A = Charge sensitive amplifier

S = Schmitt trigger
V_{th} = threshold

Measure time of “reset”



Clock: local (within ASIC) oscillator free-running at 50 – 100 MHz

Basic datum is 64 bits: 32 bit time, pixel addresses, ASIC ID, …

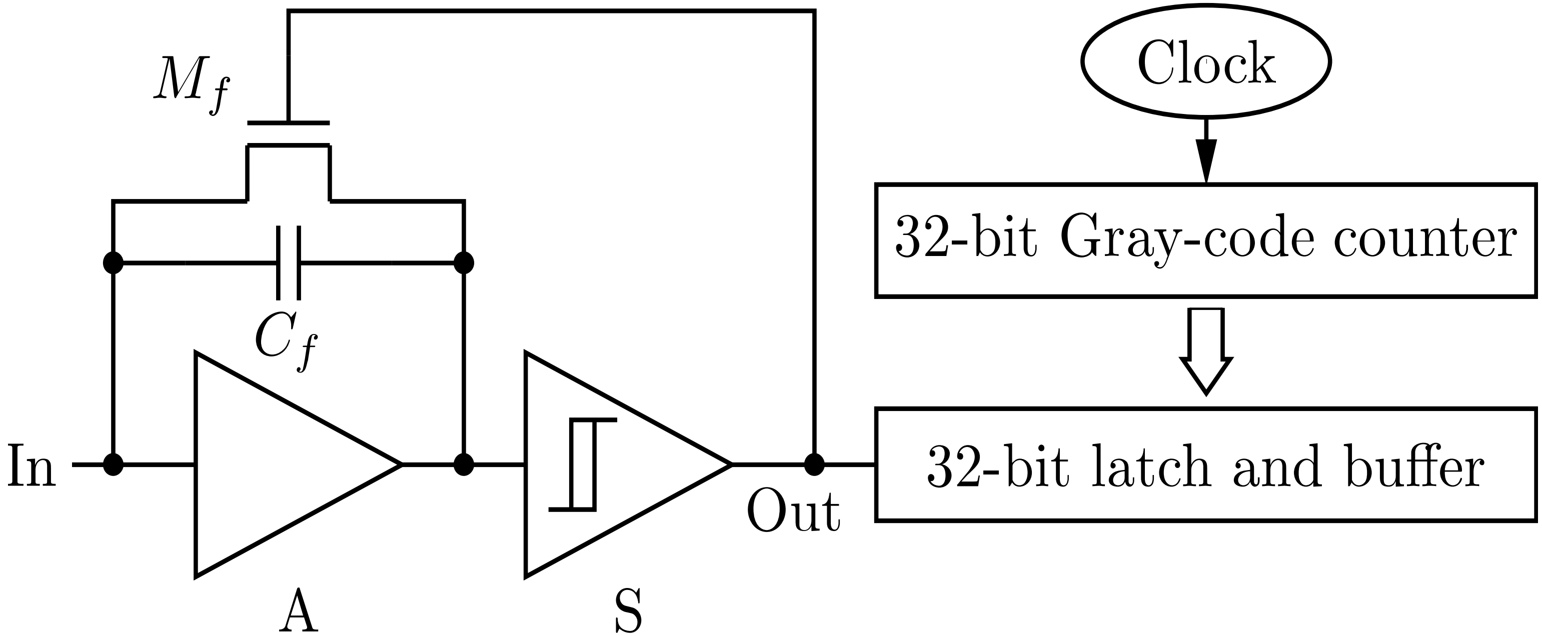
What's new here?

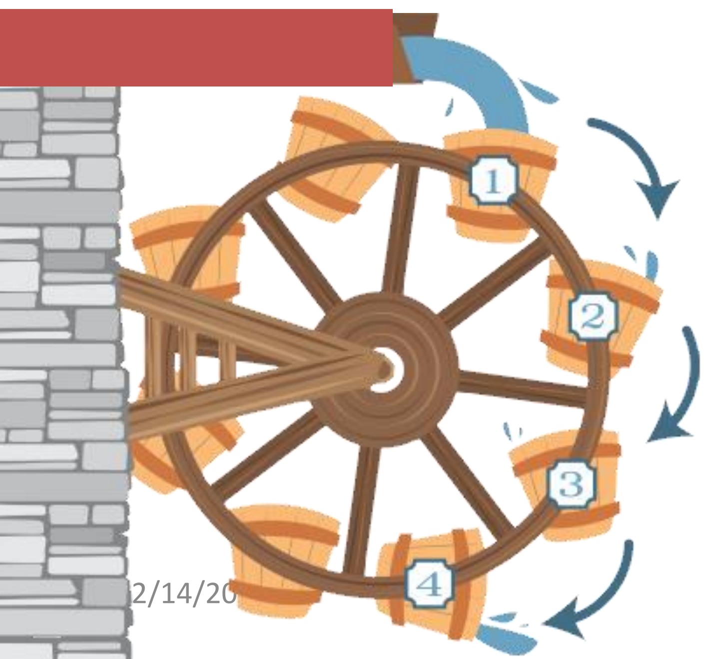
- Take the difference between sequential resets

This is the **Reset Time Difference = RTD**

Total charge for any **RTD = ΔQ**

- **RTDs** are not generated at ASIC level;
- **RTDs** are computed off-detector


M_f
C_f
Clock
32-bit Gray-code counter
32-bit latch and buffer
In
Out
A
S


1
2
3
4


Background
Signal
time

RTDs capture the waveform !

- **RTD** measures instantaneous current
  - Small average current (background): Large RTD
    - "Background" current from ^{39}Ar is ~100 aA
  - Large average current (signal): Small RTD
    - Typical track current from min-I is ~1.5 nA

S/B ~ 10^7

Background and signal are easy to distinguish

The two RTD patterns

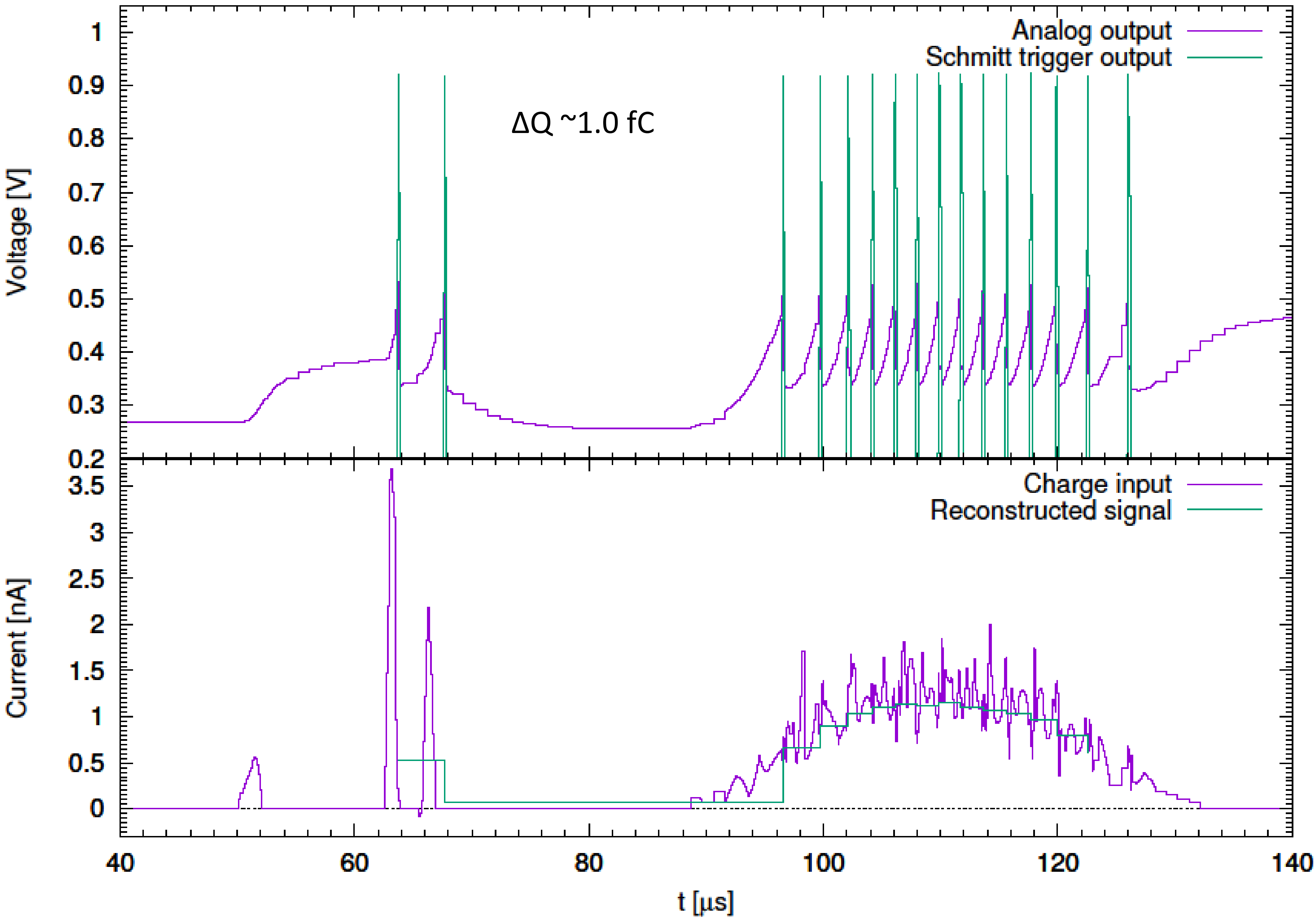
Signal Characteristics

- Choose ΔQ such that Min-I track will cause several resets during one track arrival:

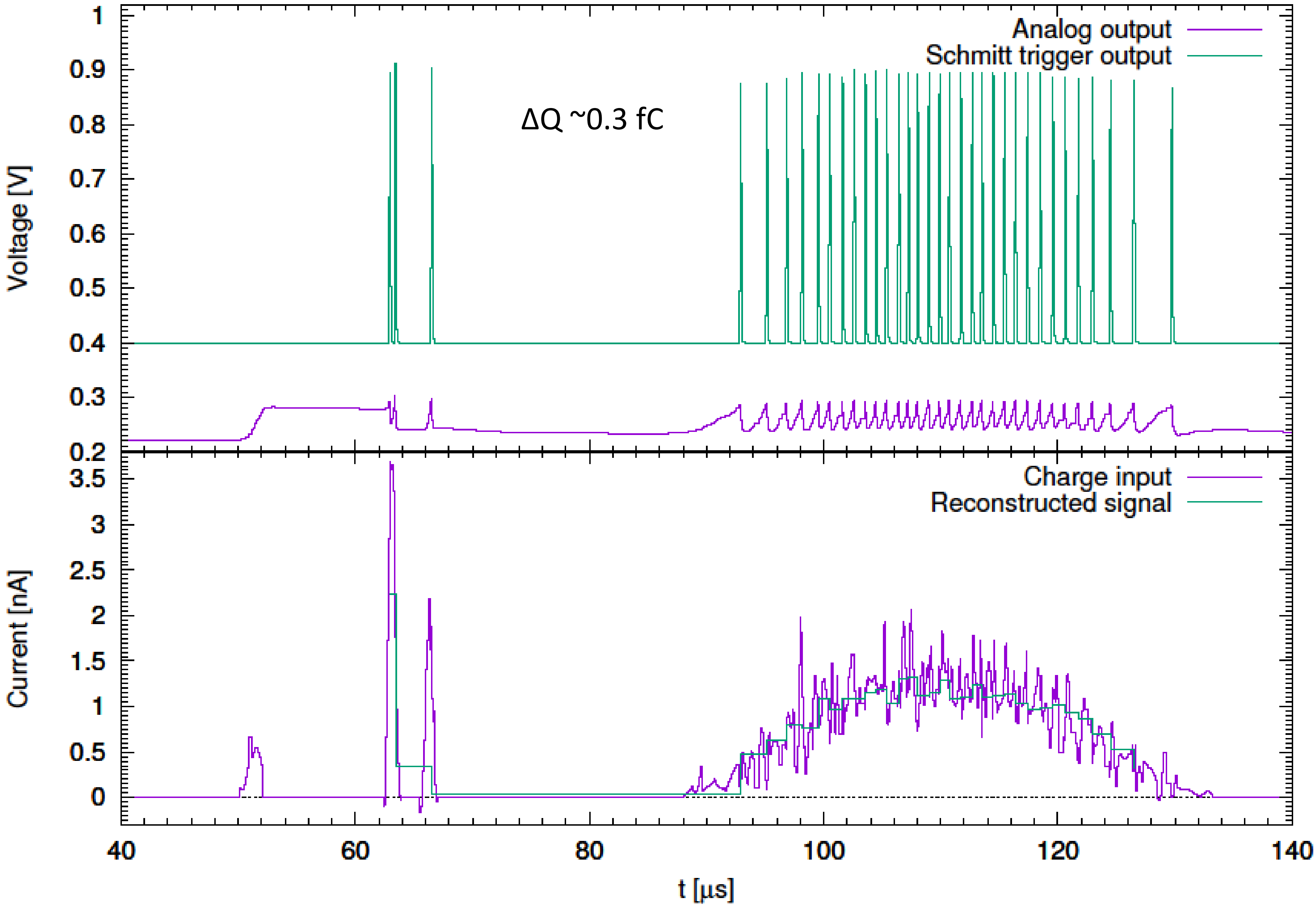
Choose ΔQ = 0.7 fC

Signal: a contiguous sequence of small RTDs

A conventional current waveform of arbitrary length and complexity can be reconstructed from the RTD sequence.



ΔQ ~1.0 fC
Analog output
Schmitt trigger output
Voltage [V]
Charge input
Reconstructed signal
Current [nA]
t [µs]



Analog output
Schmitt trigger output
ΔQ ~0.3 fC
Voltage [V]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Charge input
Reconstructed signal
Current [nA]
3.5
3
2.5
2
1.5
1
0.5
0
40
60
80
100
120
140
t [µs]

Signal capture: summary

- RTD = inversely proportional to input current
- Background: ^{39}Ar decays lead to 'heartbeat'
  - heartbeat RTD ~11 seconds
  - automatic absolute charge calibration
- Signal: typically a few nA, → RTD < 1 μs
  - Five or more contiguous small RTDs
  - Easy to recognize signal against background!
  - No signal differentiation! (unlike induction wires)

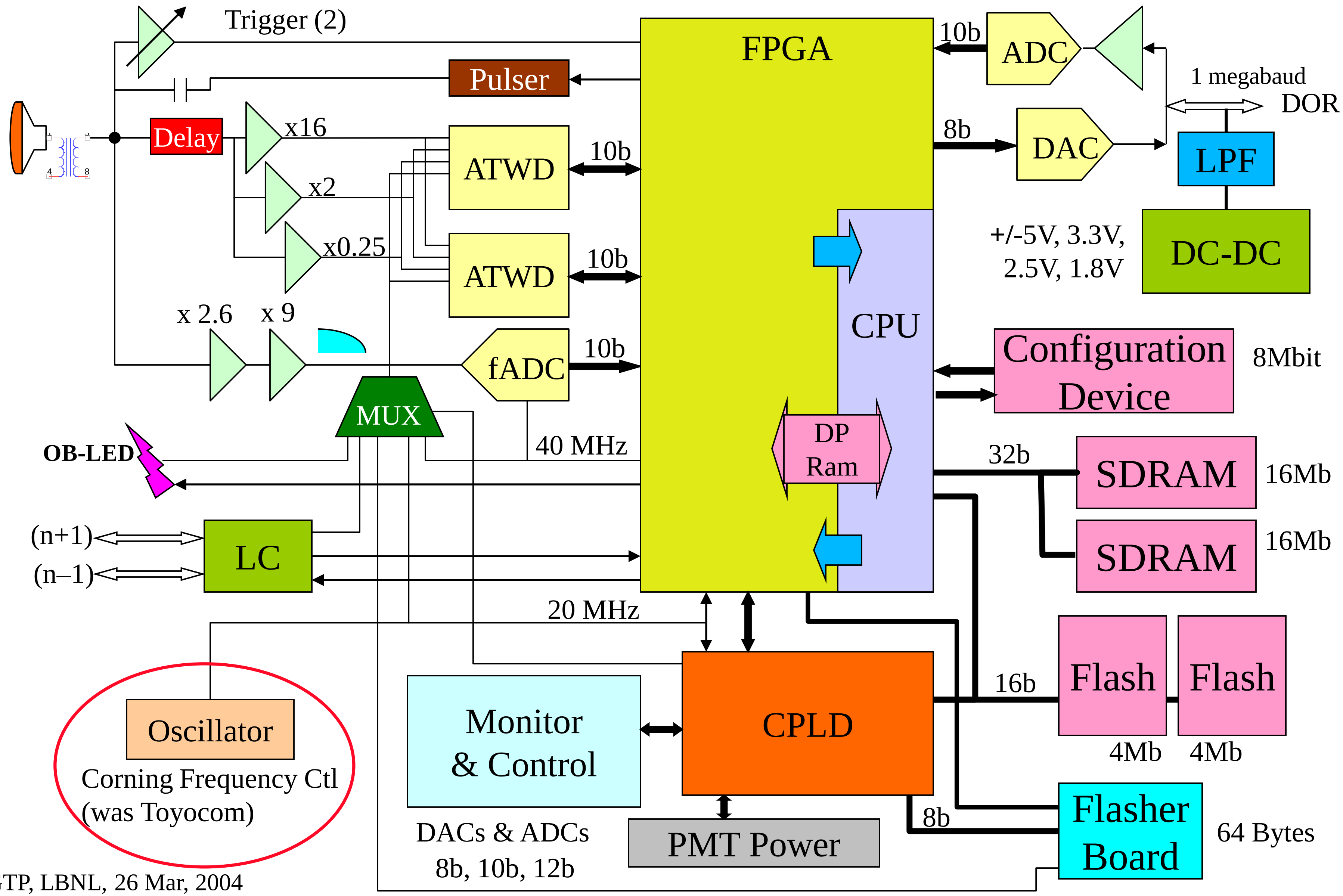
Time-stamping: how does that work?

- One clock per ASIC, runs freely at f ~50 - 100 MHz
  - No phase-locked loop
- Requirement: Local clock must be stable:
  - $\delta f/f < 1 \times 10^{-6}$ per second
- Time-stamping routine:
  - Once a second, ask ASIC "What time is it?"
  - ASIC captures local time and sends it @ ~1Hz
  - Simple linear transformation: $T = A \bullet F/f + B$
  - F is master clock synched to GMT

This method is proven to work !

- Where has this idea been realized?
- **IceCube**: ±2 ns rms within 1 km^3 of ice!
  - works flawlessly and invisibly
- Oscillator precision in IceCube is ~1 x 10^{-10}/s
  - hard to measure
- DUNE: ±1 μs precision
  - requires $\delta f/f < 1 \times 10^{-6}$ per second for local clock
  - This is probably easy to achieve in LAr

IceCube: Digital Optical Module Block Diagram



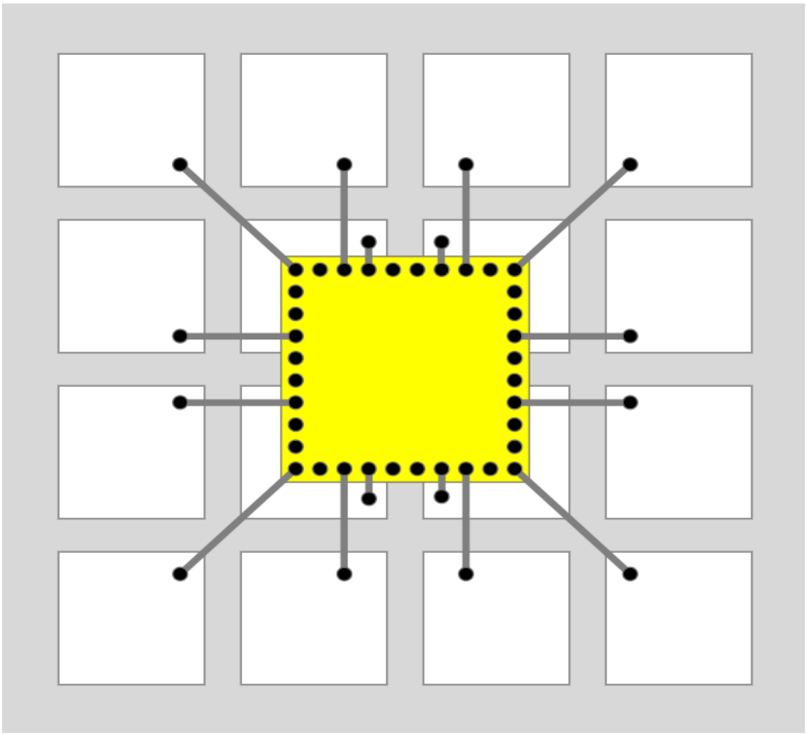
GTP, LBNL, 26 Mar, 2004

ASIC concept

- 16 -32 pixels/ASIC
- 1 free-running clock/ASIC
- 1 capture register for clock value, ASIC, pixel subset,
- Buffer depth as needed to store beam, SN event…
- State machine to manage:
  - dynamic network,
  - token passing,
  - clock domain crossing,
  - data transfer to neighbor in network,
  - exception states (devils in the details)

16-Pixel ASIC

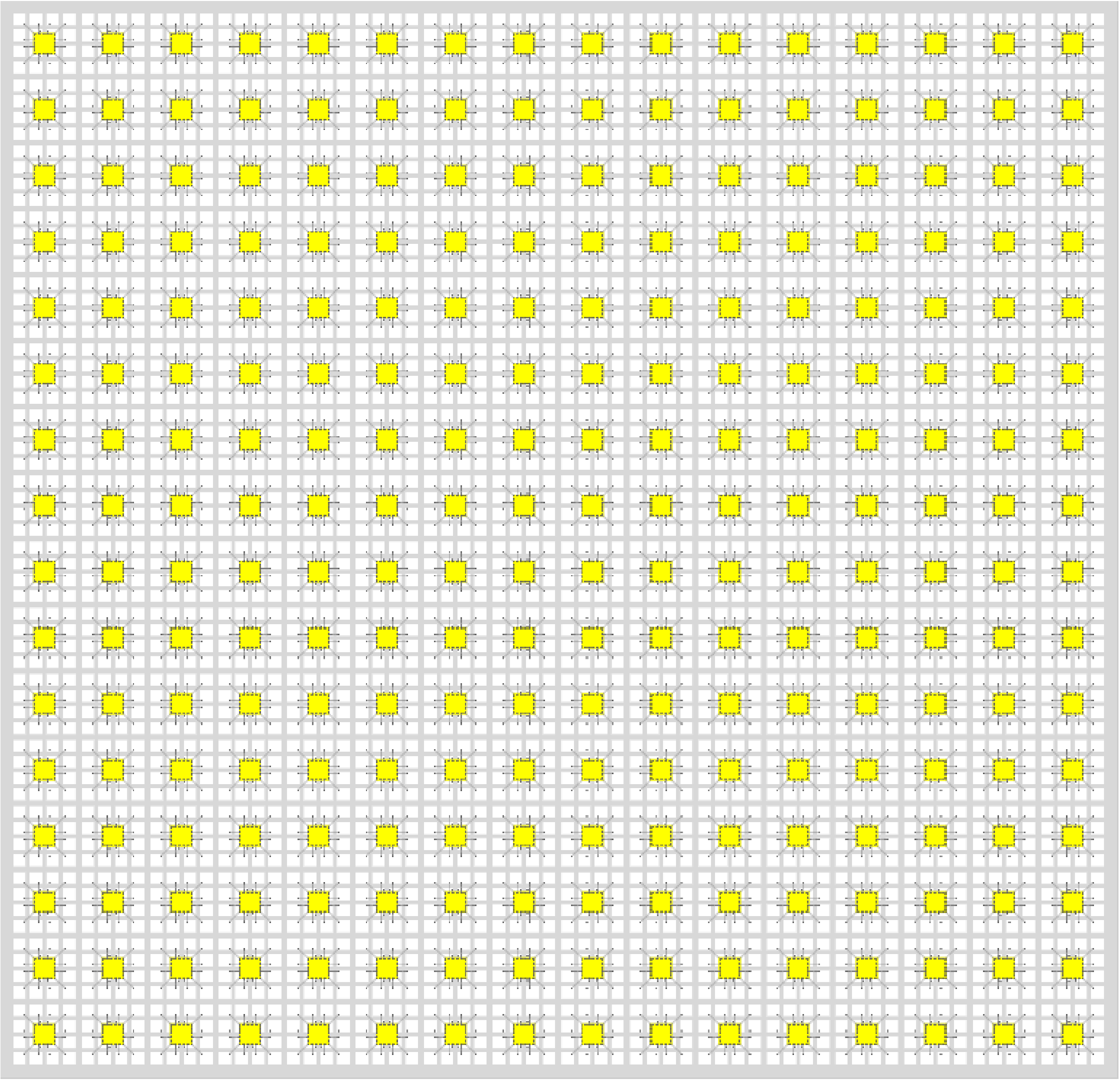
The local clock serves all pixels in one ASIC



<u>View from inactive side</u>

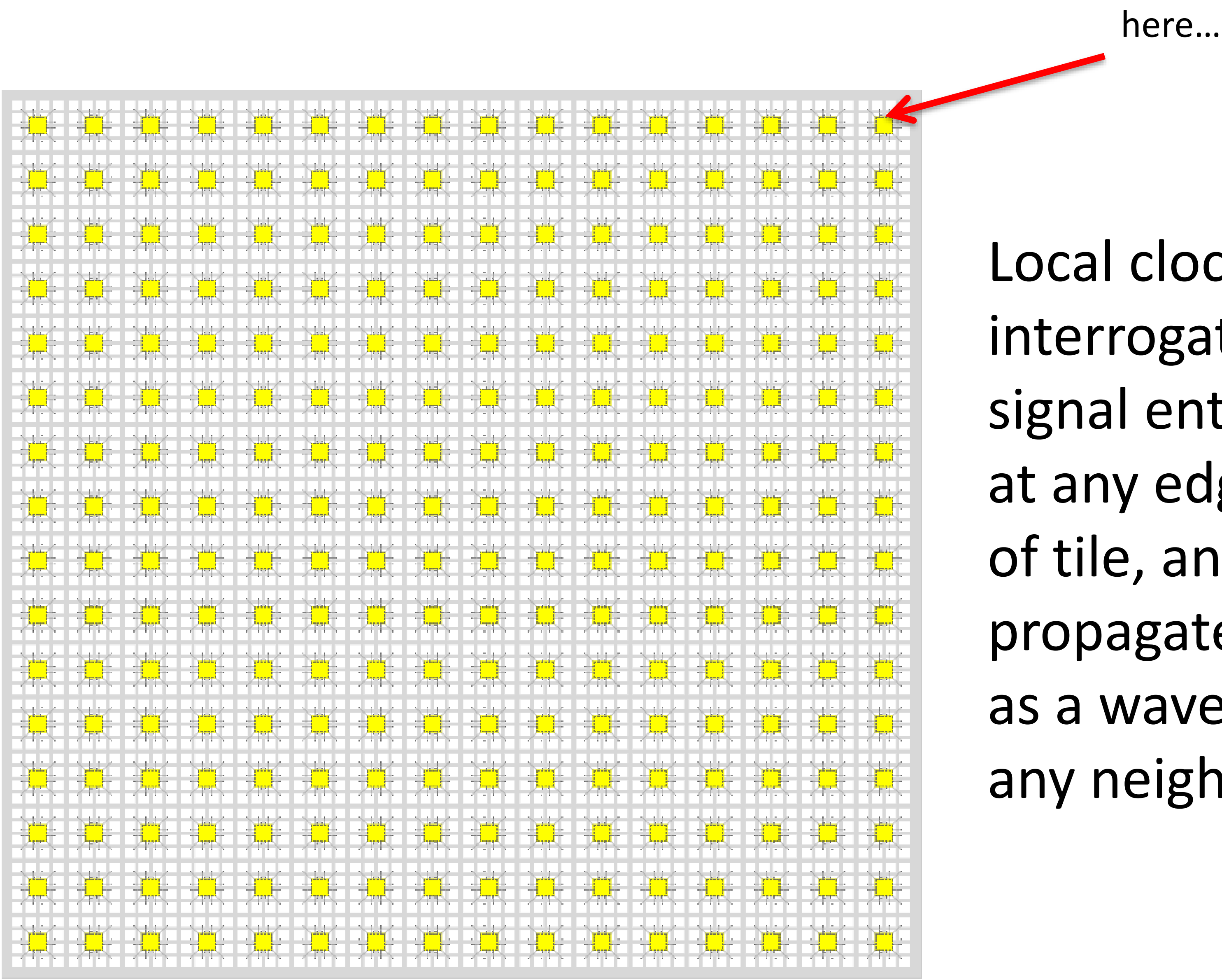
Wire-bonds connect each pixel to ASIC; via connects to small button on active side, minimizing capacitance and noise.

Pixels are 4 x 4 mm^2

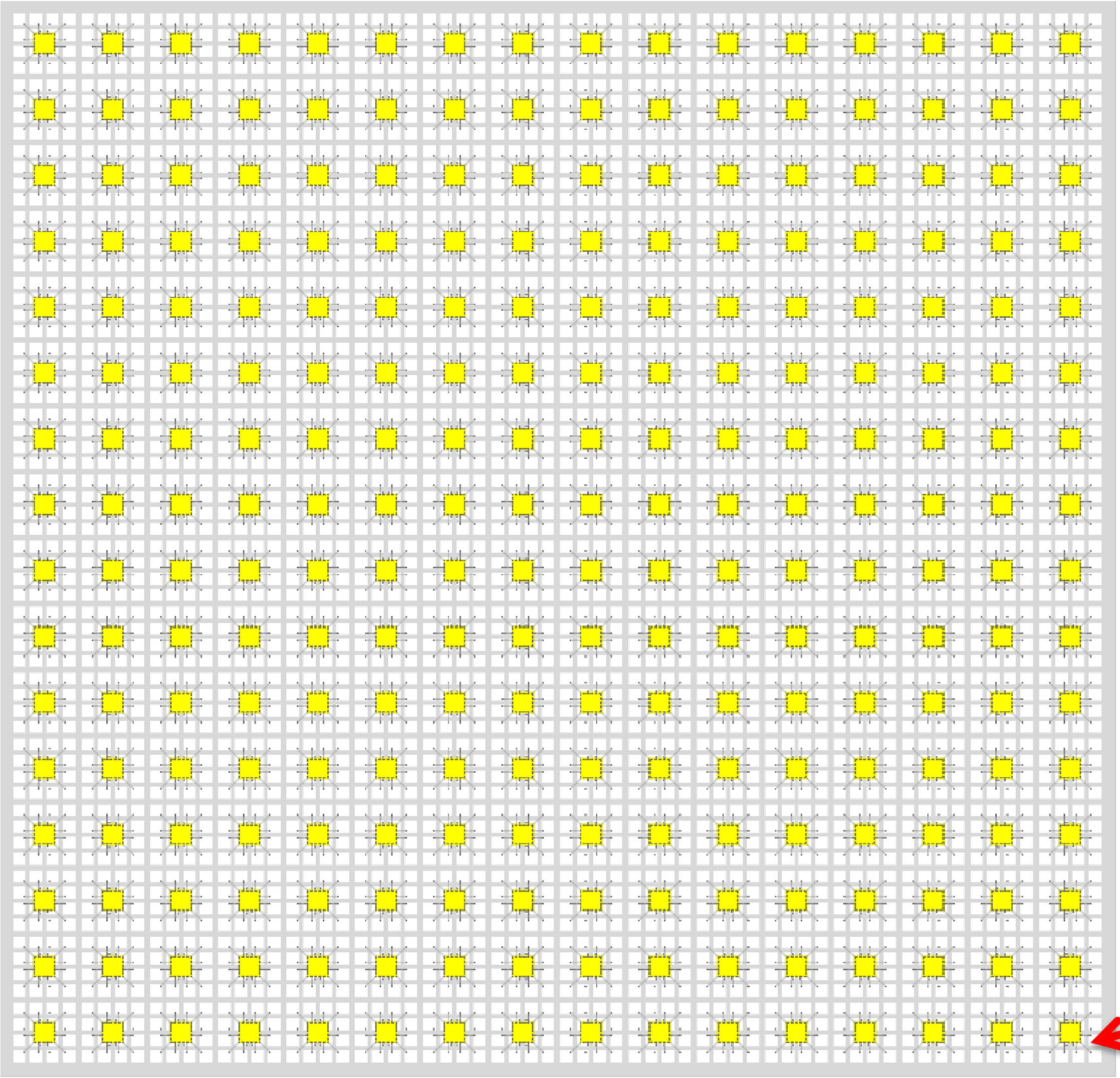


16 x 16 **Tile** of 256 ASICs, = 4092 pixels

Tile size: 256 mm x 256 mm



Local clock interrogation signal enters at any edge of tile, and propagates as a wave to any neighbor



Local clock interrogation signal enters at any corner of tile, and propagates as a wave to any neighbor

Or here…
or any edge

DAQ Concept

- Once per second, introduce “time token” at one ASIC somewhere on the tile periphery
- ASIC accepts token & offers it to all neighbors
- ASICs remember who gave them a token
- Wave propagates across tile and establishes a network for reverse data push
- Dead or defective chips are bypassed by encircling wave of DAQ
- No master clock distribution + flat architecture

→ Very high resilience against single-point-failure

Data Flow

- Clock calibration: once per second

  → 16,384 bits/tile
- Assume 20,000 tiles/10 kton module

  →~40 MB/s per module

Easily digestible by commodity computer to transform data to global time frame & prepare histograms.

Very little data corresponds to real event data

Three Central Technical Issues

- CIR Input:
  - all extraneous leakage currents at the CIR input node are small compared to ^{39}Ar current
    - This must be tested in a realistic setup…
- Clock:
  - Must be stable: $\delta f/f < 1 \times 10^{-6}$ per second
    - I think this will be easy…
- Surface Charge Creep:
  - Must be negligible relative to ^{39}Ar current
    - This may require surface physics expertise…

Perspective

- IceCube demonstrated that it is rational to embed complex electronics in perpetuity
  - care taken in design phase to avoid bleeding edge
  - care taken in qualifying parts list
  - care taken in fabrication & test
- IceCube demonstrated that unorthodox time-stamp method meets high performance goals.

Summary

- **Q-pix** extracts energy, spatial and time information with high precision, exquisite detail and appropriate dynamic range.
- The Q-Pix scheme, however unorthodox, to realize a fully pixelized DUNE FD might offer a unique advantage for discovery of new physics at the threshold of detection.

Thank you

Photon detection ?

- Can the pixel surface also detect photons?
- Wild speculation: coat surface with a-Se
  - a-Se is a photoconductor (old copiers had it)
  - VUV photon might liberate free electrons…
  - Some avalanche gain will trigger some pixels that are near trigger point.
  - Look for clustering of Hits in time → S1 signal
- Far-fetched, but would be fabulous if real

The 64-bit datum

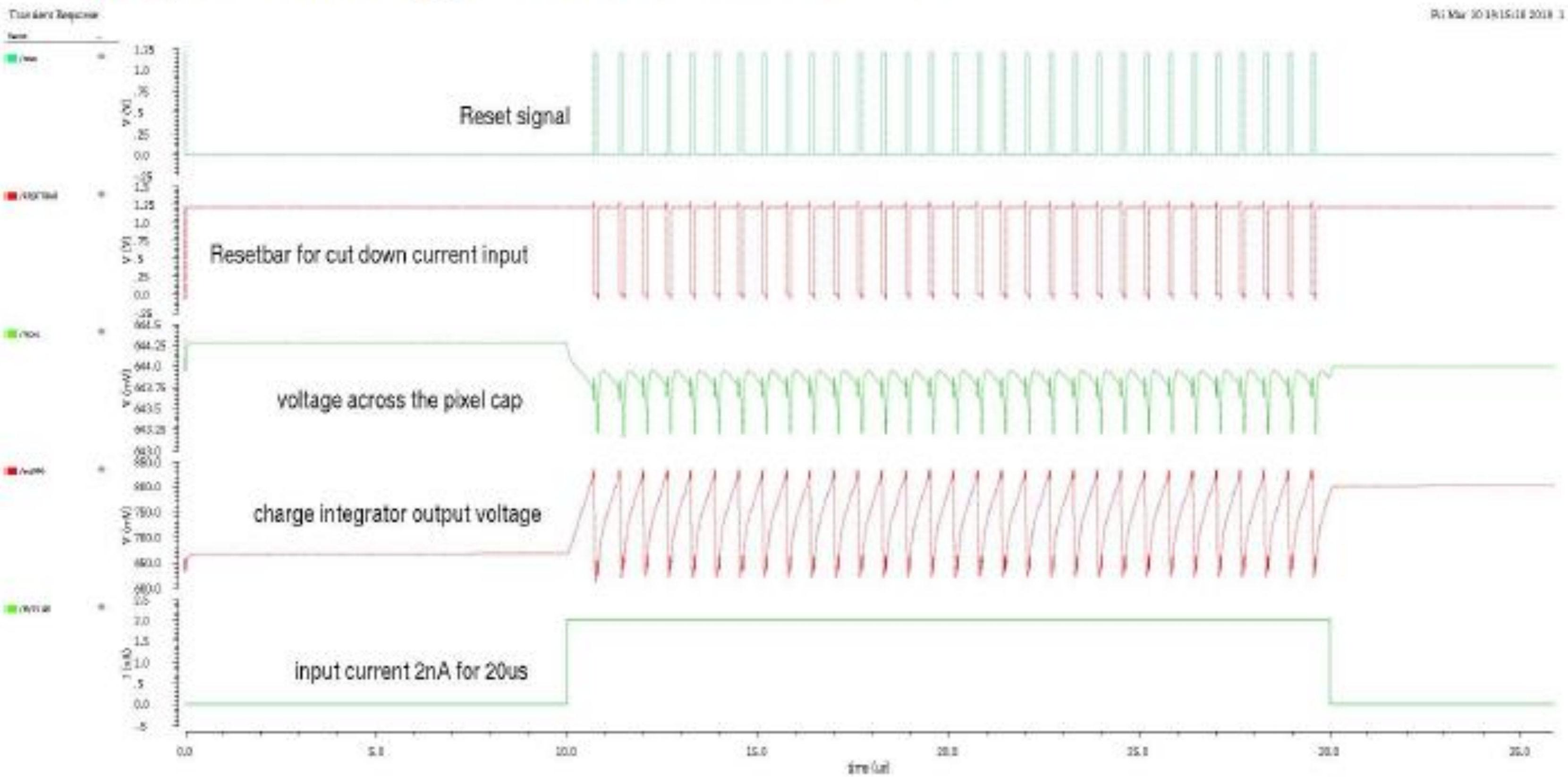
• Clock value	38 bits
• ASIC location	8 bits
• Pixel address	16 bits
• Flags	2 bits

Total: 64 bits

Datum is always the same format

Simulation of this idea at U Penn – Mitch Newcomer et al

Input charge 2nA for 20uS



The pixel “button”

- The pixel must be a small button exposed to LAr active volume, not a space-filling square
- The dielectric surface exposed to LAr active volume will automatically ‘heal” to create the desired electrostatics: “all charge to button”
- → Dielectric properties of first dielectric surface are important: teflon, …