Outline

• Introduction: Instrumentation and ASIC Developments at BNL

• Front-End ASIC Architectures and Examples

• Readout Electronic Examples

• Looking Forward: Information Centric Digitization?
Mission: To develop state-of-the-art instrumentation required for experimental research programs.

Instrumentation Division at BNL

Staff:
Approximately 45 total, including 14 scientists, 12 engineers, and 11 technicians.

Core Competencies:

Low-Noise Microelectronics and Cold Electronics: Low Noise ASICs, rad-hard electronics, high-throughput data acquisition, special printed circuit boards, and high-density interconnect laboratory.

Solid State Detectors Fabrication and Characterization: Silicon X- and gamma-ray detectors, silicon charged particle detectors, Si CCDs, germanium X- and gamma-ray detectors.

Gas and Noble Liquid Detectors: Micropattern gas detectors, noble liquid TPCs, noble liquid calorimetry, $^3$He based thermal neutron detectors.

Photocathodes, Lasers and Optics: Ultra-short photon and electron sources and measurements, photocathodes, optics and optical metrology.
ASIC Developments (since early 90’s)

- **RHIC/STAR**: Front-end for silicon vertex tracker
- **RHIC/PHENIX**: Front-end and flash ADC for time expansion chamber
- **ATLAS**: Cathode strip chamber, LAr calorimeter upgrades, Muon upgrades
- **Laser Electron Gamma Source**: ASIC for GEM-based TPC
- **Long Baseline Neutrino**: Cold front-end and mixed signal ASICs for MicroBooNE & LAr TPCs
- **Neutrino-less Rare Decays**: Cold charge and light ASICs for nEXO
- **Dark Matter Detection**: UNM DRIFT, OXI DRIFT II
- **Small Angle Neutron Scattering**: $^3$He neutron pad detector for SNS, ANSTO, Coded aperture
- **NSLS**: EXAFS, Powder diffraction, Inelastic scattering, CZT and Ge spectroscopy, Pixel imager
- **NSLS, CSIRO, NJIT**: High-rate x-ray fluorescence microprobe for elemental mapping
- **NSLS, SLAC**: High-voltage matrix switching, Charge-pump front-end for Active Matrix
- **NSLS, NASA**: SDD-based spectrometer for x-ray elemental mapping
- **NASA, WUSL**: X-ray polarimeter, Small pixel imager
- **NASA, SWRI**: Heavy ion sensor (HIS) for solar orbiter
- **BIOLOGY/MEDICAL**: Micro-PET for RatCAP, PET-MRI, Wrist scanner, CZT-based PET, Prostate cancer imager (Hybridyne), Eye-plaque dosimeter (CMRP)
- **NONPROLIFERATION/SECURITY**: VFG Gamma Scout, Portable Gamma Camera, 3D PSD (UM, DoD, DHS), CPG (LANL, DoD), HPGePC Neutron Detector (LBNL), Si Compton Imager for Special Nuclear Materials (NRL, DoD)
- **CRADAs**: eV Products (CZT), Digirad (Medical), CFDRC (MAPS), Photon Imaging (Si), Symbol Technologies (Wireless), Analogic, RMD, Gamma Medica, General Electric
Developing Front-End Readout ASICs: Increased Functionality and Complexity

• Low-noise low-power front-end optimized for high charge- and timing-resolution.
• High functionality integrated within front-end ASICs.
Linear Charge Amplifier:
- Pole-Zero Cancellation
- Continuous Reset

\[ Q \cdot \delta(t) \]

\[ C_F + C_A \]

\[ C_S + C_A \]

\[ \frac{4kT}{R_S N^2} \]

\[ V_G \]

\[ M_F \]

\[ R_S \]

\[ C_S \]

\[ N \times C_F \]

\[ N \times M_F \]

1st stage of filter

non-linear

linear

filter noise contribution:

Effective linear "charge amplification" by N

[Knoll_Rad. Det. 4th ed. 2010]

[De Geronimo et. al_TNS’2000]
nEXO Charge Readout Concept: Anti-Aliasing Filter

‘Anti-Aliasing’: to remove high-freq. parts which could alias into signal band after sampling

a) 12-bit ADC sampling continuously at 2MSps (into 4000 cell buffer), transfer upon trigger \( \sim 500\text{Mbits} \) to warm DAQ

b) ADC sampling continuously at 2MSps and transferring continuously \( 250\text{ Gbps} \) to warm DAQ

Slow and rare events!

induced current ... after anti-aliasing samples

Daisy chain readout of 2-4 32-channel ASICs on each tile, or more, from several tiles

Off-line waveform analysis and optimal processing of samples for charge measurement

\[\text{anti-aliasing filter (“preamp=shaper”) s/h, ADC} \sim 2\text{-drift-time buffer, serializer} \]
Very Low Noise ASIC for Germanium Point-Contact detector

- **Large gain** (~5000) of charge amplifier to lower noise contributions from later stages
- **Adaptive continuous reset** successfully avoid dead-time and switching noise in charge amplifier, and automatically adjusts to detector leakage current.
- **Large bandwidth** of anti-alias filter (AAF) to preserve 50ns pulse rise time

![Diagram](image)

### Parameters

<table>
<thead>
<tr>
<th>Cdet (fF)</th>
<th>ENC_total (e-)</th>
<th>ENC_m1&amp;lk (e-)</th>
<th>ENC_m1-1/f (e-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 (possible load)</td>
<td>5.3</td>
<td>4.8 (~82%)</td>
<td>4.5 (~71%)</td>
</tr>
<tr>
<td>100 (target load)</td>
<td>3.9</td>
<td>3.5 (~78%)</td>
<td>3.2 (~65%)</td>
</tr>
<tr>
<td>1 (without load)</td>
<td>2.6</td>
<td>2.1 (~68%)</td>
<td>1.9 (~48%)</td>
</tr>
</tbody>
</table>

**Ge Point-Contact detector C < 1 pF [P. Barton_LBNL]**
Optimizing Shaper for Low-Noise and Low-Power

Signal and noise analysis in front-end electronics

**Signal**: assuming overall pulse response $h(t)$ and transfer function $H(f)$ it follows

$$v_o(t) = Q \cdot h(t) = \int_{-\infty}^{\infty} Q \cdot H(f) \cdot e^{-j2\pi ft} df$$

Note: we measure $v_o(t_{max}) = v_{o,max}$
# Weighting Function Noise Coefficients

<table>
<thead>
<tr>
<th>Weighting function</th>
<th>Series white $A_1$</th>
<th>Parallel white $A_3$</th>
<th>Series 1/f $A_2(\text{calc})$</th>
<th>Series 1/f $A_2(\text{approx}) \approx 0.75(A_1A_3)^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>triangle</td>
<td>2</td>
<td>2/3</td>
<td>0.88</td>
<td>.87</td>
</tr>
<tr>
<td>semi-gaussian 4th order</td>
<td>2.04</td>
<td>0.90</td>
<td>1.04</td>
<td>1.01</td>
</tr>
<tr>
<td>CR-RC</td>
<td>1.85</td>
<td>1.85</td>
<td>1.18</td>
<td>1.39</td>
</tr>
<tr>
<td>trapezoidal $\Delta=1$</td>
<td>2</td>
<td>1.67</td>
<td>1.38</td>
<td>1.37</td>
</tr>
</tbody>
</table>

$$\text{ENC}^2 = \frac{1}{2} \frac{e_n^2 C_{in}^2 A_1}{\tau} + \pi C_{\text{in}}^2 A_f A_2 + q I_0 A_3 \tau$$

[V. Radeka_NSS2012]
2-D ASIC Hi-Resolution X-ray Imager

- ~700,000 transistors in CMOS 130nm technology (1.2 V supply)
- 256 hexagonal channels at 250 µm pitch
- 3-side abuttable, with 33 I/O pins only on the right side
- Each channel includes:
  - low-noise charge amplifier (adjustable gain: 0.25, 0.5, 1 V/fC)
  - shaper (adjustable peaking time: 125, 250, 500, and 1000 ns)
  - baseline stabilizer
  - discriminator and peak-detector
- ~0.6 mW/channel
- Simulated ENC: ~ 11 electrons (@ 60 fF det. cap. & 6pA leakage per pixel)

⇒ Limited area for low-noise low-power readout chain
⇒ No direct address control of each pixel, relying on token passing

[S. Li & G. De Geronimo, IEEE NSS 2017]
**FE-SOC: ASIC for ATLAS Muon Spectrometer**

**New Small Wheels:** 2.3M channels, 2pC @ < 1fC rms, 100ns @ < 1ns rms, 30pF-2nF

- 64 channels: low-noise amplification, peak, timing, discrimination, 3 ADCs, timestamp, FIFO, L0 handling
- real-time address, sub-hysteresis, direct outputs, fully digital interface
- CMOS 130nm, 13.5 mm x 8.4 mm,
- transistor count/ch.: > 100,000

G. De Geronimo et al._TNS’2013
Analog 3D PSD Technique - H3D ASIC

- H3D ASIC measures peak amplitude and relative timing on each signal (Prof. Z. He)

[G. De Geronimo_TNS2008]
Digital 3D PSD Technique - H3DD ASIC

- H3DD ASIC measures **whole waveform** on each signal
- Waveforms are analyzed with powerful signal processing techniques, thus achieving **higher resolution** (Prof. Z. He)
DUNE LAr TPC Cold Readout Electronics

- Front end ASIC: ~5mW/ch.
- ADC ASIC: ~5mW/ch.
- FPGA (COTS): ~8mW/ch.
- Voltage regulation (COTS) (<100mV dropout)

Overall 128:4 multiplexing

R&D produced key components to form a complete cold front-end readout chain for LAr TPC experiments

Front end mother board assembly serving 128 wires ~2.4 W + LDO inefficiency
Possible Zero suppression for LBNE

- **Simple**: sending data of channels that are over a threshold level
- **Involving more than one sensor wire**:
  - Need to collect pre and post triggered data
  - Neighbor triggering up to the second order (Neighbors can be located on adjacent PCB)
  - Non trivial mapping of anode wires to ASIC channels
  - If more than 80 channels need to be readout zero suppression does not pay

Not including Header OR 8B/10B overhead

<table>
<thead>
<tr>
<th>Description</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>(12bit ADC) *(128 CHN) * 2MHz</td>
<td>3.072Gb</td>
</tr>
<tr>
<td>(12bit ADC + 7bit ADDR) * 128 CHN</td>
<td>4.864Gb</td>
</tr>
<tr>
<td>(12bit ADC + 7bit ADDR) * 80 CHN</td>
<td>3.04Gb</td>
</tr>
</tbody>
</table>
Silicon pixel sensors bump-bonded to 2-D ASICs

- Global peak-found signal triggers the FPGA and turns all channels into global read-out mode.
- FPGA assigns a token to pass along all 256 channels.
- Once receiving the token, a channel outputs its stored value to the external ADC.
- By counting the token, the FPGA corresponds the peak information to the channel which detected it.
Two-Dimensional, Pad Detector for Neutron Scattering

$^3\text{He} + n \rightarrow ^3\text{H} + p + 764\text{keV}$ ($\sim 5 \text{ fC}$, or $\sim 30\text{k electrons}$)

Array of $4 \times 4$ pad boards, comprising $37 \text{ k}$ independent channels. Operation in ionization mode, i.e. unity gas gain, would not be not feasible without ASICs

PAD side

24 cm $\times$ 24 cm anode pad board, with 5mm $\times$ 5mm pads $\rightarrow$ 2304 pixels

ASIC side

SNS ASIC

64 channel

2mW/ch

Neutron beam, $\sim 1 \text{ mm}^2$, over pad# 20-53

2 $\mu$s shaping, 3 bar $^3\text{He}$ / 2 bar $\text{C}_9\text{H}_8$

1 m $\times$ 1 m Detector for ANSTO
Looking Forward: Information-Centric Digitization?

[Murmann_HEPIC’2017]
Backup Slides
<table>
<thead>
<tr>
<th>Year</th>
<th>ASIC Families</th>
<th>Collaborator</th>
<th>Publications</th>
<th>Impact areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996-1999</td>
<td>ATLAS family</td>
<td>ATLAS</td>
<td>*</td>
<td>Particle Physics</td>
</tr>
<tr>
<td>1996-1999</td>
<td>RHIC family</td>
<td>RHIC</td>
<td>*</td>
<td>Nuclear Physics</td>
</tr>
<tr>
<td>1997-2001</td>
<td>CreV family</td>
<td>eV Products</td>
<td>*</td>
<td>Nonproliferation, Medical Imaging</td>
</tr>
<tr>
<td>2000-2004</td>
<td>HERMES family</td>
<td>NSLS</td>
<td>*</td>
<td>Energy Sciences, Light Sources, Medical Imaging</td>
</tr>
<tr>
<td>2001-2009</td>
<td>PDD family</td>
<td>eV Products</td>
<td>*</td>
<td>Energy Sciences, Light Sources</td>
</tr>
<tr>
<td>2002-2003</td>
<td>CPG1 ASIC</td>
<td>LANL</td>
<td>*</td>
<td>Nonproliferation</td>
</tr>
<tr>
<td>2003-2004</td>
<td>LEGS TPC ASIC</td>
<td>Physics</td>
<td>*</td>
<td>Nuclear &amp; Particle Physics</td>
</tr>
<tr>
<td>2005-2008</td>
<td>CPG2 ASIC</td>
<td>eV Products</td>
<td>*</td>
<td>Nonproliferation</td>
</tr>
<tr>
<td>2005-2007</td>
<td>SNS He3 ASIC</td>
<td>ORNL</td>
<td>*</td>
<td>Energy Sciences</td>
</tr>
<tr>
<td>2005-2007</td>
<td>Multiwindow ASIC</td>
<td>eV Products</td>
<td>*</td>
<td>Nonproliferation, Medical Imaging</td>
</tr>
<tr>
<td>2005-2008</td>
<td>RATCAP ASIC</td>
<td>Medical</td>
<td>*</td>
<td>Medical Imaging, Neuroscience</td>
</tr>
<tr>
<td>2006-2011</td>
<td>H3D family</td>
<td>DoD, UMich</td>
<td>*</td>
<td>Nonproliferation, Medical Imaging</td>
</tr>
<tr>
<td>2006-2009</td>
<td>Compton Imager ASIC</td>
<td>NRL, NASA</td>
<td>*</td>
<td>Nonproliferation, Energy Sciences</td>
</tr>
<tr>
<td>2006-2010</td>
<td>LUNAR family</td>
<td>NSLS, NASA</td>
<td>*</td>
<td>Energy Sciences, Light Sources</td>
</tr>
<tr>
<td>2010-</td>
<td>DUNE front-end ASIC</td>
<td>Physics</td>
<td>*</td>
<td>Particle Physics</td>
</tr>
<tr>
<td>2011-</td>
<td>DUNE ADC ASIC</td>
<td>Physics</td>
<td>*</td>
<td>Particle Physics</td>
</tr>
<tr>
<td>2011-</td>
<td>ATLAS VMM family</td>
<td>Physics</td>
<td>*</td>
<td>Particle &amp; Nuclear Physics</td>
</tr>
<tr>
<td>2014-</td>
<td>MARS family</td>
<td>NSLS</td>
<td>*</td>
<td>Energy Sciences, Light Sources</td>
</tr>
<tr>
<td>2014-</td>
<td>HEXID 2D family</td>
<td>NSLS, NASA, SBU</td>
<td>*</td>
<td>Energy Sciences, Light Sources</td>
</tr>
<tr>
<td>2015-</td>
<td>Ge family</td>
<td>LBNL, LANL</td>
<td>*</td>
<td>Particle Physics, Energy Sciences, Nonproliferation</td>
</tr>
<tr>
<td>2015-</td>
<td>H3DD family</td>
<td>DoD</td>
<td></td>
<td>Nonproliferation, Particle &amp; Nuclear Physics</td>
</tr>
<tr>
<td>2015-</td>
<td>ATLAS HLC ASIC</td>
<td>Physics</td>
<td>*</td>
<td>Particle Physics</td>
</tr>
<tr>
<td>2016-</td>
<td>SAR ADC ASIC</td>
<td>Physics</td>
<td></td>
<td>Particle Physics, Energy Sciences</td>
</tr>
<tr>
<td>2016-</td>
<td>LDO regulator</td>
<td>Physics</td>
<td></td>
<td>Particle Physics, Energy Sciences</td>
</tr>
</tbody>
</table>
ASIC for High Resolution X-ray Spectrometers

Improving Radiation Resistance:
- Radiation degradation due to leakage current of NMOS↑
- ENC degradation: peak at around 2 Mrad
- Modified design to improve radiation resistance: replacing NMOS switch with PMOS switch; insert PMOS switch between NMOS current source and charge amp. input; increase device length; gate-enclosed layout.

~11 e⁻ resolution (93 eV) with 20 mm² SDD pixel

[S. Li, de Geronimo, et al., IEEE TNS 2013]
Cryogenic Analog Front-End ASIC

- 16 channels - charge amplifier, filter, buffer
- Adjustable gain: 4.7, 7.8, 14 and 25 mV/fC
- Adjustable filter time constant: 0.5, 1, 2, 3 μs
- Selectable collection/non-collection mode
- Selectable DC/AC (100 μs) coupling
- Band-gap referenced biasing
- Temperature sensor (~3 mV/°C)
- 5.5 mW/channel (input MOSFET 3.6 mW)

Adopted in MicroBooNE, DRIFT, Argontube, CAPTAIN, LArIAT, LBNF 35T, LAr1-ND, ICARUS (CERN), candidate for nEXO

G. De Geronimo et al., IEEE TNS 58 2011
HLC1 FE ASIC

Outputs
- 16 x front-end channels
  - High gain, low gain output x 8 channels
  - Low-noise preamplifier
  - Programmable (25/50) internal termination
  - Differential output with ADC drivers
- 3 x summing channels
  - 2 x four-channel summing
  - 1 x eight-channel summing
  - Differential output with ADC drivers

Power Consumption
- 880 mW @ 1.2V => 733 mA

Configuration Interface
- 4 x 1.2V CMOS, SPI, 143 registers;

Package
- 128 LQFP

Other Features
- Pulse generator;
- Temperature sensor, biasing circuitry;
- 65 nm TSMC CMOS process;

[G. De Geronimo et al. IEEE NSS 2017]