Integral Concept of Sensors and Electronics – Past to Future

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Caveat  ...

... about any historical account given by a participant:

“History will be kind to us …
... I intend to write it”

( W.C. ~1945)
Limited Selection of significant events in Detector Technology

• **Germanium p-i-n detector**, Tavendale, Ewan (1963-4), gamma-ray and x-ray spectroscopy; first cold front end JFET (1965)
• **Liquid Argon Ionization Calorimetry**, Willis, Radeka (1972) → CERN ISR → ATLAS
• **TPC**, Nygren (1974), lasting impact through gas and later noble liquid TPCs
• H. Chen, C. Rubbia, independently propose **TPC with LAr** (1977) → leads to ICARUS
• H. Chen, (1985) proposal for a large LAr TPC
• Uranium-LAr hadron calorimeter (...), first use of cold electronics (JFETs),(1986)
• Major realizations at FNAL(D0), HERA(H1), SLAC(SLD), (1985-1993)
• LKr EM calorimeter for CERN NA48-NA62 (1997-today)
• MAPS and active Si-pixel detectors 2000 -
• **ATLAS LAr EM calorimeter** (2004 -); high speed-high precision; highest confidence limit on Higgs (2012)
• MicroBooNE(MB) proposal (2007) with **cryogenic electronics** (JFETs); In 2009 decision to go with cold CMOS; MicroBooNE starts operation in 2015 -
• Technology selection for LBNF(DUNE) in 2011: LAr TPCs
• MB in operation for 7 years; protoDUNE rapid realization and successful test in 2018. Technology path open for DUNE ...

3
1962 - Spark Chambers in the Muon Neutrino Experiment

Spark chambers also used in CP violation experiment (Fitch and Cronin, 1964)

Two Nobel Prizes with such detectors!
1963 Germanium Detector Breakthrough

A. Tavendale, G. Ewan, NIM 25 (1963)185

Coaxial det.contacts
Ge-crystal ~50-100 cm³

Large Ge detectors 1966 -
First cryogenic JFET on a detector
Comparison of Germanium with Sodium Iodide for gamma-ray spectrometry (~1968)

Low noise electronics and signal processing (for gamma ray energy resolution of ~0.1%) developed for germanium detectors in ~1965-1972 provided the basis for later use of these techniques in particle physics, solar neutrino detection, x-ray and neutron detectors ... in LAr calorimeters and later in noble liquid TPCs ... and ... in AGATA, LEGEND

1821.2 keV
2015: Germanium detector with p+ point contact and cryogenic CMOS

Charge collection to p+ point contact

Low capacitance → low noise

ENC = 5.6 electrons-rms

P. Barton et al., NIMA812(2016)17
Jan-Apr 1973: Design and build the first LAr sampling electromagnetic calorimeter

20 radiation lengths, 200 steel 1.6 mm plates with 2 mm LAr gaps; \( \Delta E/\Delta x \approx (11.6 + 2.1) \) MeV/cm, or 0.1 \( X_0 \)

Charge Collection and Drift Velocity Studies in LAr
Only electrons induce a signal in the time of interest <1 \( \mu s \); mobility \( \mu_{\text{electron}} \gg \mu_{\text{ion}} \)

2 mm electrode spacing \( \rightarrow \sim 400 \) ns at 10kV/cm

W.J. Willis and V. Radeka, NIM 120 (1974) 221
ATLAS LAr Calorimeter Readout $\rightarrow$ Faraday Cage with Cryostat

- Electrodes
  - Calibration resistors, 0.1%

- System crate: on detector electronics, Faraday cage

- An integral system design approach - from detector electrode to readout electronics. This approach was followed later in MicroBooNE and protoDUNE

Accordion Sampling

EM calorimeter by Daniel Fournier in 1990
Higgs Discovery in **2012**

- **2012**: ATLAS and CMS find evidence of Higgs-like events
- ATLAS LAr calorimeter provides more than 5σ confidence level
- Mass resolution of ~1% for the Higgs between 100 and 200 GeV
- Calibration and stability of response <0.1 %
1974: David Nygren introduces Gas Time Projection Chamber (TPC)

STAR TPC at RHIC: Au on Au (2000)

Challenges: Positive ion pace charge vs gain

Interpolating anode pad plane with front end ASICs

Digital readout board

Double GEM planes

Deep learning (convolutional neural network) methods
1977: H.H. Chen and C. Rubbia introduce LAr TPC ... leading from ICARUS to MicroBooNE, Protodune, eventually to DUNE ... 

\[
\text{dE/dx of 1 MIP: 2.1 MeV/cm}
\]

Animated illustration by Bo Yu
Signal Formation in LAr TPC: Induced Signals from a Track Segment

LBNE style wire arrangement: 3 instrumented wire planes + 1 grid plane
Raw current waveforms convolved with a 0.5μs gaussian (~1/2 drift length) to mimic diffusion

Time scale of signals determined by wire plane spacing and electron drift velocity ~1.6 mm/μs
2008: CMOS at 77K: low power = long lifetime

At 77-89K mobility increases, thermal fluctuations decrease with $kT/e$, resulting in:

- higher $g_m/I$
- higher speed
- lower noise.

2015: MicroBooNE – First LAr TPC with cryogenic CMOS ASIC

LAr 170 tons (86 tons active)
8256 sense wires


### Waveform Type

<table>
<thead>
<tr>
<th>Data Type</th>
<th>U Plane PSNR</th>
<th>V Plane PSNR</th>
<th>Y Plane PSNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Data</td>
<td>6.6</td>
<td>5.7</td>
<td>19.5</td>
</tr>
<tr>
<td>After Noise Filtering</td>
<td>22.3</td>
<td>16.2</td>
<td>37.9</td>
</tr>
</tbody>
</table>
**2018: Integral system design concept for LAr TPC with cryogenic electronics in ProtoDUNE (prototype for DUNE module 1)**

ProtoDUNE

- LAr 770 tons (420 tons active)
- 15600 sense wires

**Cold electronics (CE) module and its attachment to the APA frame**

A. A. Abud, et al., JINST 17 (01) (2022) P01005
3-ASICs design allows optimal choice of CMOS nodes and supply voltages to minimize power dissipation for the large dynamic range. (An FPFA used in place of COLDATA in ProtoDUNE).
Giant LAr TPCs: The Challenge of Capacitance Noise (ENC) vs TPC Sense Wire and Signal Cable Length for CMOS at 300K and 89K

DUNE with warm electronics (300K) ENC~6x10^3 e^− rms!

ProtoDUNE ENC~660 e^− rms

MicroBooNE ENC~400 e^− rms

Signal for (1/e drift) 3x3 5x5 10^4 e
The times are changing ... ... and so are interests and activities ...
AI/ML methods will be dominant activities in producing *new science results* in the future, while the *ultimate detector sensitivity* will depend on *integral design* of sensors and electronics.

- neural networks...
- deep learning (convolutional neural network) methods...
- data healing algorithms...
- neuromorphic...
- autonomous experiments...
- quantum...
- .........
Thank You!