Cryogenic Electronics for Very Large Liquid Argon Neutrino and Nucleon Decay Detectors

Veljko Radeka
BNL

Acknowledgements:

FNAL: G. Deptuch, R. Yarema
Georgia Tech: J. Cressler

TWEPP 2011, Vienna, Sept. 26-30
Outline:
1. Solar neutrino deficit and neutrino oscillations
2. Giant Lar facility dreams and plans
3. TPC and signal formation
4. Giant TPCs readout challenge and essential block diagram
5. CMOS properties vs temperature
6. CMOS lifetime and electronics reliability
7. ASIC design
8. ASIC results
9. Summary and future developments
1968--Ray Davis starts a fight that lasts 30 years

- Used a large vat of dry cleaning solution to look for Argon from inverse beta decay

36 Ar atoms per month.

\[
\frac{\phi_{\nu_e} (\text{Homestake})}{\phi_{\nu_e} (\text{Theory})} = 0.34 \pm 0.06
\]

- Remained mired in controversy for 30 years. Do we understand fusion? Is the experiment correct? Could it be new physics, e.g. Pontecorvo's oscillations?
The C\textsubscript{2}Cl\textsubscript{4} Tank (~400m\textsuperscript{3}) - Homestake exp., 1478m below the surface

Gas proportional counter used to count \textsuperscript{37}Ar decays by detecting 2.8 KeV Auger electrons

\~20 atoms of \textsuperscript{37}Ar extracted from 2.2x10\textsuperscript{30} atoms of \textsuperscript{37}Cl
Neutrinos and the Sun

- The source of the Sun’s energy is fusion of 4 hydrogen atoms to make a helium atom.
- Each time this reaction occurs, 2 (electron) neutrinos ($\nu$) are released.
- $1.8 \times 10^{39}$ neutrinos per second come from the center of the sun and here on Earth, $\sim 100$ billion pass through your fingernail ($1 \text{ cm}^2$) every second.
- For an average size person, an atom in the body will capture a neutrino every 70 years.

**Davis’ result (relative to the Standard Solar Model prediction):** $\sim 1/3$

This was the only experiment for over two decades searching for solar neutrinos. *It opened up a new field of particle and astrophysics …*
Super-Kamiokande solar neutrino result

\[ \nu_e + e^- \rightarrow \nu_e + e^- \]

from M. Smy (ν2002)
Resolution of Solar $\nu$ Deficit (2002)

**SNO** – Sudbury: Deep Underground: 6,000 mwe
Heavy water ($D_2O$)

Detect $\nu_e$: charged current (CC)
elastic scatter (ES)

Also $\nu_\mu$, $\nu_\tau$:
neutral current (NC)

$\nu_e$: $n \rightarrow e^- p$ CC
$\nu_e$: $e^- \rightarrow \nu_e e$ ES

Result: $\sim 1/3 \nu_e$
$\sim 2/3 (\nu_\mu + \nu_\tau)$

Neutrino oscillations

Total flux agrees with that expected from the sun
(predicted by J. Bahcall 3 decades earlier)
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1. Solar neutrino deficit and neutrino oscillations
2. Giant facility plans (and dreams!) - to study neutrino oscillations, nucleon decay, supernova neutrinos ...
3. TPC and signal formation
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Beam: 700 kW, 60-120 GeV, 5 years $\nu + 5$ years $\overline{\nu}$
on-axis, wide band, upgradable to 2.3 MW
Baseline: 1300 km FNAL to Homestake
Far Site: Underground location to facilitate broad program
Near Site: on current Fermilab property
Configurations: several options under study for beam, near, and far detectors
J-PARC to Okinoshima

Distance = 658 km
Off-axis angle = 0.76° (2.5° @ SK)
100 kton liquid Argon

Good coverage of 1\textsuperscript{st} & 2\textsuperscript{nd} oscillation maximum
Various baselines possible

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>1st oscillation</th>
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<tr>
<td>130</td>
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<td>1570</td>
<td>3.18</td>
</tr>
<tr>
<td>2300</td>
<td>4.65</td>
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</tbody>
</table>
Probability of neutrino oscillations vs neutrino energy

2300 km, $\sin^2(2\theta_{13})=0.025$

Red: $\nu$ NH, $0<\delta<180$
Dark-Red: $\nu$ NH, $180<\delta<360$
Blue: $\nu$ IH, $0<\delta<180$
Dark-Blue: $\nu$ IH, $180<\delta<360$

From: A. Rubbia, GLA2011
Cosmic Ray experiment EMMA at shallow depth

250 m long tunnel and a cavern at 1400m excavated for LAGUNA R&D

Cafeteria, meeting room and sauna at 1400 m below ground

Mobile phones work and internet available also at 1400 m
OVERVIEW: Two Far Detector Options for LBNE

200 kT water Cherenkov

34 kT liquid argon

One 200 kT fiducial WC detector
Located at the 4850 foot level

Two 17 kT fiducial LAr detectors
To be located at a new drive-in site at 800 foot level. (one detector shown here)
Hyper-K (~20xS-K)
Total (fiducial) vol. ~0.99(0.56) Mton H₂O

~99 k 20” + 25 k 8” PMs

From the Letter of Intent, Sept 2011
Giant Liquid Argon Charge Imaging ExpeRiment

A scalable detector with a non-evacuable dewar and ionization charge detection with amplification

- Single module non-evacuable cryo-tank based on industrial LNG technology
- Cylindrical shape with excellent surface / volume ratio
- Simple, scalable detector design, possibly up to 100 kton
- Single very long vertical drift with full active mass
- Double phase, large area LAr LEM-TPC for long drift paths
- Possibly immersed visible light readout for Cerenkov imaging
- Possibly immersed (high Tc) superconducting solenoid to obtain magnetized detector
- Reasonable excavation requirements (<250'000 m³)

We have developed an R&D roadmap to address this design→pto
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How Does a LArTPC Work

dE/dx of 1 MIP: 2.1MeV/cm

- Sense (anode) wires (up to ~ 10m long): ~14-31 k wires/kton
- up to 200 pF/wire
- collecting (Y)
- non-collecting (U,V)
- charge sensitivity
  - range ~300 fC
  - ENC < 1,000 e-
- sample/buffer events
  - ADC 10-12-bit, 1-2 MS/s
  - 3,000 deep buffer
- digital multiplexing
  - 128:1 to 1024:1 two-three stages
- power constraint
  - ~10 mW/wire
- operation in LAr
  - > 30 years

First proposed by C. Rubbia, 1977
First CNGS neutrino interaction in ICARUS T600

Collection view

Wire coordinate (8 m)

Drift time coordinate (1.4 m)

CNGS $\nu$ beam direction

$\nu_\mu$ CC

A. Guglielmi
Advantages of LAr TPCs

Neutrino interactions recorded in the small LAr TPC at FNAL: ArgoNeut

- Full 3D event reconstruction
- Sub-mm position resolution
- dE/dx for particle ID
  - e/γ separation >90%
- Low energy threshold <5 MeV
- Scalable to multi-kiloton size

Optimized TPC geometry
Low noise electronics
Multiplexed readout
High LAr purity
Signal Formation: 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
Bias Voltages for 3mm pitch:
\[ V_G = -480V \]
\[ V_U = -280V \]
\[ V_V = 0 \]
\[ V_X = +700V \]

For 5mm wire pitch:
\[ V_G = -690V \]
\[ V_U = -385V \]
\[ V_V = 0 \]
\[ V_X = +900V \]
Anode Plane Assembly (APA) → modular TPC in a large cryostat

~5 APAs/kton, ~4.5mm wire pitch, 3.8m drift, 2560 wires/APA

APAs are structural and electrical units containing all sense wires and readout electronics. They can be tested in LN2, stored and transported in shipping containers.
LAr40 Conceptual Design at 800L
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ICARUS 600 ton LAr TPC (pioneered by C. Rubbia)

Front-end Electronics and DAQ

54000 channels

- Liquid argon
- Sense wires (4-9m, 20pF/m)
- Twisted pair cables (~5m, 50pF/m)

Gas

H.V. (±300 V)

Decoupling Boards (32 ch.)

Front-end amplifiers (32/board); 1500 e.n.c.

10bit FADC
400ns sampling
1mV/ADC
(~1000e-/ADC)

(18 board + 1 CPU)/VME crate

Multi-event circular buffer (8x1ms)

Time

Continuous waveform Recording

To storage
Having front-end electronics in the cryostat, close to the wire electrodes yields the best SNR

Highly multiplexed circuits with fewer digital output lines not only greatly reduce the number of cryostat penetrations, but also give the designers of both the TPC and the cryostat the freedom to choose the optimum configurations.

A typical readout configuration with warm electronics: long cables connect the sense wires to the FEE, resulting in large electronics noise. To reduce the cable length, one has to implement cold feedthroughs below the liquid level, which increases the cryostat complexity.

Noise (ENC) vs Sense Wire and Signal Cable Length in relation to MIP Signal for 3x3 and 5x5 mm Wire Spacing
Readout Electronics Outline for very large TPCs

Cavern

One APA

3840 (2304) wires/APA

128 ch FE MB

128 ch FE MB

3000 x12 bit per channel

16 channel mixed signal Front End ASIC (x8)
- Charge amplifier + filter
- Charge calibration
- ADC
- Zero-suppression
- Buffering
- Token passing bus
- Register programmable

CM or LV differential digital signaling 1 Mb/s

128 channel FE Motheboard

8 Mb/s

240 Mb/s

Nx Redundancy

Optical or Copper Driver

Multiplexer/Controller ASIC

240 Mb/s

Feedthroughs

Bias Power Control

Bias Power Control

Daughterboard

N:N

30:1

30:1

16:1

8:1

Buffer

Zero Suppress

ADC

Charge amplifier + filter

Charge calibration

Charge amplifier + filter

Charge calibration

1 Mb/s

3000 x12 bit per channel

One APA

to DAQ
Outline:
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CMOS static characteristics vs T

Transconductance/drain current: \[ \frac{g_m}{I_D} \rightarrow \frac{q}{nk_B T} = \begin{cases} \approx 30 \text{ at } T = 300K \\ \approx 116 \text{ at } T = 77K \end{cases} \]

At 77-89K, charge carrier mobility in silicon increases, thermal fluctuations decrease with \( kT/e \), resulting in a higher gain, higher \( g_m/I_D \), higher speed and lower noise.
CMOS Noise Spectral Density vs T

TSMC 180nm: Noise lower by a factor of 2 at 77K across the spectrum for PMOS, only white for NMOS; (1/f further reduced at longer L)
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**Impact Ionization and CMOS *Lifetime***

*Chemistry slows down at 89K.*

*What is left of aging processes?*

- **Impact ionization**. Creation of *interface states* by (some) hot electrons causes a decrease in mobility, transconductance (gain), $f_t$, and a threshold shift.

- This limits the effective *lifetime* of the device at any temperature (defined in industry as 10% decrease in transconductance $g_m$).

- **Accelerated lifetime testing** is performed by stressing the device, at increased drain-source voltages and by measuring the *substrate current* (a very sensitive quantitative indicator).

\[
\tau \frac{I_{ds}}{W} \propto \frac{1}{\left( \frac{I_{sub}}{I_{ds}} \right)^a}
\]

\[
a = \frac{\phi_{it}}{\phi_i} \approx 2.9 - 3.2
\]

\[
\phi_i \approx 1.3\text{eV} ; \phi_{it} \approx 3.7\text{eV} - 4.1\text{eV}
\]
J. Cressler, et al. (Georgia Tech) measurements confirming:

\[
\frac{\tau I_{ds}}{W} \propto \frac{1}{(I_{sub}/I_{ds})^a}
\]

\[a \Box 3\]
NMOS 180nm TSMC lifetime vs Vds (preliminary)

Equation $y = a + b \times x$

Weight No Weighting
Residual Sum of Squares 2.32356E-5
Pearson's r 0.99999
Adj. R-Square 0.99996

Value Standard Error
D Intercept -10.44768 0.05109
D Slope 34.41767 0.15259

3.2, 3.0, 2.8V

$V_{DS}=1.6V$

$1/V_{DS}(V^{-1})$
Designing CMOS for low power = long lifetime

Design region (approx.) for low power and long lifetime at 77K (moderate inversion)

• Lifetime \( \approx \frac{1}{\text{current density}} \)

• Additional conservative guidelines:
  \( V_{DD} - 10\% \),
  \( L > 1.5 \ L_{\text{min}} \)

• Digital: clock frequency \( \ll \) ring oscillator frequency

[Graph showing measured data for CMOS018 with NMOS and PMOS for different temperatures and channel lengths.]
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• 16 channels
• charge amplifier, high-order anti-aliasing filter
• programmable gain: 4.7, 7.8, 14, 25 mV/fC (charge 55, 100, 180, 300 fC)
• programmable filter (peaking time 0.5, 1, 2, 3 µs)
• programmable collection/non-collection mode (baseline 200, 800 mV)
• programmable dc/ac coupling (100 µs)
• band-gap referenced biasing
• temperature sensor (~ 3mV/°C)
• 136 registers with digital interface
• 5.5 mW/channel (input MOSFET 3.9 mW)
• single MOSFET test structures
• ~ 15,000 MOSFETs
• designed for room and cryogenic operation
• technology CMOS 0.18 µm, 1.8 V
Cold Electronics ASIC - Front-End Detail and Calibration Scheme

\[ C_{\text{INJ}} \approx 180 \text{ fF} \]

Integrated injection capacitance \((10 \times 18 \text{ µm}^2)\)

Measured with high-precision external capacitance

Integrating pulse generators on ASICs

\[ C_{\text{INJ}} \approx \begin{cases} 184 \text{ fF at } 300K \\ 183 \text{ fF at } 77K \end{cases} \]
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Analog ASIC: Die and Packaging, Temperature Cycling

Die Photo

Package Photo

Test Fixture

Cycled (abruptly, by pouring LN over the fixture in a dewar) from 300K to 77K more than 30 times

No failure occurred
Cold CMOS: Results from FE ASIC (1st prototype cycle)

**Noise** gets better at 77K (220pF det. Capacitance):

- **Signal** after preamp+shaper changes little with temperature:

![Graph showing ENC and Peaking Time vs. Temperature](image)

**Integrated charge calibration** capacitance
- little change with temperature

Measured with high-precision external capacitance

\[
C_{\text{INJ}} \approx \begin{cases} 
184 \text{ fF at 300K} \\
183 \text{ fF at 77K} 
\end{cases}
\]
Noise vs T in CMOS:

Existing ASIC, 0.25 µm (not designed for LAr)

CMOS in LAr has less than half the (white) noise as that at room temperature, higher mobility and higher transconductance/current ratio
Signal Measurements: programmable gain, peak time and baseline

Bandgap Reference:
\[ V_{\text{BGR}} \approx \begin{cases} 
1.185 \text{ V at 300 } ^\circ \text{K} \\
1.164 \text{ V at 77 } ^\circ \text{K} 
\end{cases} \]
variation \approx 1.8 \%

Temperature Sensor:
\[ V_{\text{TMP}} \approx \begin{cases} 
867.0 \text{ mV at 300 } ^\circ \text{K} \\
259.3 \text{ mV at 77 } ^\circ \text{K} 
\end{cases} \]
\approx 2.86 \text{ mV / } ^\circ \text{K}

Programmable gain, peaking time and baseline

Maximum charge
55, 100, 180, 300 fC
Input transistor ENC optimization

ENC [rms electrons]
Gate Width [mm]

ENC = 300K, 77K

C_{DET} = 200pF
\tau_{PK} = 1\mu s
I_D = 2mA

From: G. De Geronimo
Analog ASIC: gain and waveform uniformity

Four ASICs, 4x16 channels (one lead of the 32-channel cable not connected)

Residuals from a linear fit < 0.3%
Crosstalk < 0.3%

These measurements performed with entire MicroBooNE signal chain:
Analog ASIC+cold cable+intermediate amplifier+ADC

The ASIC will be used in MicroBooNE, ~150(75) ton LAr TPC
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Front-End ASIC with 16:1 digital multiplexing

**Block Diagram**

- **Pulse generator**
- **Common register**
- **BGR, common bias, temp. sensor**
- **Control logic**

- **Channel register**
  - Test
  - Gain & mode
  - Peaking time & mode
  - Mode & coupling
  - Bypass

- **Dual-stage charge amplifier**
- **Filter**
- **Ac/dc**

- **ADC** (12-bit, 2 MS/s)
- **Compression**
- **Mux**
- **Buffer**
- **Digital interface** (LV or CM)

**Layout**

- **Chg amp**
- **Filter**
- **Ac reg**
- **Adc**
- **Mux**
- **Buffer**

- **Pulser**
- **BGR, bias, temp. sens. reg**
- **Control logic**

- **Wire**

- **16 channels**

- **Estimated size ~ 6 x 8 mm²**
- **Estimated power ~ 10 mW/channel**

- **Features**
  - 16 channels
  - Charge amplifier (progr. gain)
  - High-order filter (progr. time constant)
  - Ac/dc, progr. baseline
  - Test capacitor, channel mask
  - ADC (12-bit, 2 MS/s)
  - Compression, progr. discrimination
  - Multiplexing and digital buffering
  - LV or CM digital interface
  - Pulse generator, analog monitor
  - Temperature sensor
  - Estimated size ~ 6 x 8 mm²
  - Estimated power ~ 10 mW/channel
Summary and Future Work

- CMOS performs better at cryogenic temperatures
- CMOS technologies verified to work at 77K: IBM SiGe (Georgia Tech for Lunar Project), Chartered (FNAL) and TSMC (BNL); FPGAs (SMU, BNL); widest choice for a large project
- Defined and predictable design for 77-300K range
- Low-noise at cryogenic T demonstrated
  - ENC < 1,000 e⁻ at 200pF ~5mW/ch.
  - characterization and modeling of CMOS 180nm
- Low power design consistent with long lifetime
- Future work
  - Optimum technology node wrt dynamic range, noise, power
  - Merge separately developed ADC, zero-suppression & buffering
Backup slides
The primary science objectives of the LBNE Project are:

1. A search for, and precision measurements of, the parameters that govern $\nu_\mu \rightarrow \nu_e$ oscillations. This includes measurement of the third mixing angle $\theta_{13}$, for whose value only an upper bound is currently known, and if $\theta_{13}$ is large enough, measurement of the CP-violating phase $\delta$ and determining of the mass ordering (sign of $\Delta m^2_{32}$).

2. Precision measurements of $\theta_{23}$ and $|\Delta m^2_{32}|$ in the $\nu_\mu$ disappearance channel.

3. Search for proton decay, yielding a significant improvement in current limits on the partial lifetime of the proton ($\tau$/BR) in one or more important candidate decay modes, e.g. $p \rightarrow e + \pi^0$ or $p \rightarrow K^+ \nu$.

4. Detection and measurement of the neutrino flux from a core collapse supernova within our galaxy, should one occur during the lifetime of LBNE.

Though outside of the primary objectives, the far detector placed at the proposed depth could enable studies of atmospheric $\nu$ physics, and with additional upgrades, studies of day/night $^8$B solar $\nu$ physics and relic supernova neutrinos.
Track Waveforms on the Wires

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

Collection plane signal gives direct measurement of \( \frac{dE}{dx} \)
Signals in LAr TPC

Charge signal:

- A 3mm MIP track should create $210\text{keV/mm} \times 3\text{mm} / 23.6\text{eV/e} = 4.3\text{fC}$.
- After a 1/3 initial recombination loss: $\sim 2.8\text{fC}$
- Assume the drift path to equal the charge life time, reducing the signal to $1/e \approx 0.368$.
- The expected signal for 3mm wire spacing is then $\approx 1\text{fC} = 6250\text{ e}$, ... and for 5mm, $\approx 10^4\text{ e}$, for the “collection signal”.
- The induction signals are smaller.

- The time scale of TPC signals is determined by the wire plane spacing and electron drift velocity, ($\sim 1.5\text{ mm}/\mu\text{s}$ at 500 V/cm).

Induced Current Waveforms on 3 Sense Wire Planes:

0° track, 0.6µs rms "diffusion", 3x3 cell

Sampling rate $\leq 2\text{ Ms/s}$
Reliability of Cold Electronics (1) \(\text{wrt}\) \textit{thermal contraction-expansion}

PCB and Cold Electronics in \textbf{ATLAS}:

- ATLAS LAr Calorimeter
  - \textbf{182,468} readout channels
- EM Barrel Mother Board and Summing Board
  - EMB has \(\sim\)\textbf{110,000} detector channels read out by 896x128-ch FEBs
  - \textbf{960} Mother Boards (MB)
  - \textbf{7,168} Summing Boards (SB)
  - \textbf{20,480} resistor network chips, 0.1%
  - \(\sim\textbf{110,000}\) protection diodes on MBs/SBs
- EM Barrel Calorimeter has been cold since 2004
  - Operation: \textbf{7 years} so far
  - MB/SB will remain in operation without upgrade for super LHC

- ‘Inoperative’ channels <0.5%, as of 05/10/2011
- \textbf{Dead channels in the cryostat} \(\sim\)0.02% since 2008
Reliability of Cold Electronics (2)

Cryogenic front-end based on JFETs — NA48-NA62

- Liquid Krypton calorimeter
- JFET preamplifiers in LKr: 13,212 channels
- Operated at very high voltage
  - Tested up to 7kV, operated in 3kV
- Failures
  - ~50 because of an HV accident in 1998
  - ~25 cold electronics failures after 1998, < 0.2%
    - The last failure recorded was more than 3 years ago
- Always kept at LKr temperature since 1998
- Operation
  - 13 years so far
  - Plan to run until 2015, expected to be in operation for 17 years
ENC vs power in the input cascode

PMOS
L = 270 nm
$C_{DET} = 200 \text{pF}$
$\tau_{PK} = 1 \mu\text{s}$
$T = 87 \text{ K}$
Appendix 2

Solar hydrogen burning via the pp cycle

\[ p + p \rightarrow d + e^+ + \nu \]
\[ p + e^- + p \rightarrow d + \nu \]

\[ p + d \rightarrow ^3\text{He} + \gamma \]

85%

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p \] \( \text{pp I} \)

15%

\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]

\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu \]

99.9%

\[ ^7\text{Li} + p \rightarrow 2^4\text{He} \] \( \text{pp II} \)

0.1%

\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]

\[ ^8\text{B} \rightarrow 2^4\text{He} + e^+ + \nu \] \( \text{pp III} \)
Supernova Neutrinos

- When a star's core collapses ~99% of the gravitational binding energy of the proto-neutron star goes into ν's

- SN at galactic core (10 kpc)  
  ⇒ tens of thousands of interactions in tens of seconds

- Large detectors can discriminate between core collapse models

"You don't have to be lucky, you just have to be patient."