From Concept to Field Deployment of Advanced Instrumentation for National Security

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Overview

R&D capabilities, synergistic developments, unique opportunities

**Sensor Development:** Solid State (Silicon, Germanium, Diamond, Room Temperature Semiconductors), Noble Liquid & Gas, Liquid Scintillator

**Integrated Electronics:** ASIC Development, Signal Processing & Electronics, DAQ & Control Systems, PCB Design, High Density Interconnects

**Systems Development:** Mechanical (Engineering, Fabrication, and Integration), Electrical (Engineering, Assembly, and Integration), Cryogenic & Quantum, Photocathode Systems and Electron Source Development

**Infrastructure & Facilities:** Sensor Fabrication & Semiconductor Processing Clean Rooms, Crystal Growth, Irradiation Sources, Ultrafast Lasers, Microscopy, Quantum Lab
Silicon sensors

*Design, simulation, fabrication, testing, analysis*

- SDDs: single element and arrays.
- Strips and microstrips.
- Pixel Array Detectors (square, hexagonal, etc.)
- Active/monolithic pixel detectors (XAMPS, monolithic-SDD, LGAD, etc)
- Low Gain Avalanche Detectors (LGAD)
- Active edge sensors
- Engineered entrance window (nanostructure)

![LGAD simulation]

*Pictures of the class-100 Clean room for the silicon processing.*
Other sensor materials

*Design, simulation, fabrication, testing, analysis*

Germanium: strip and pixel
Diamond: quadrant and pixel
Room Temperature
Semiconductors: CdZnTe
Amorphous Selenium

384-strip germanium detector wire-bonded to 12 MARS ASICs

Left: Integrated 10-module CdZnTe calorimeter prototype
Right: CdZnTe detectors in a radiation beam line at NSRL
Application Specific Integrated Circuit (ASIC)

Expertise in low-noise, low power, large mixed-signal designs
- hand-in-hand work with in-house TDAQ, PCB, Sensors groups

Design tools and methodologies
- industry-standard tools for interoperability between analog and digital designs for final tape out (analog on top or digital on top)
- **analog, digital RTL2GDS, library characterization** (customs standard cell libraries for handling designs for extreme environments, i.e. cryogenics and radiation), verification, device modeling
- foundry PDK’s: standard and specialized processes
- access to foundries via services and directly

Low-noise and low-power
- custom analog front-end matched to a specific sensor
- front-end circuits optimized for amplitude & time-resolution
- data, event driven or zero-suppressed readouts

Cryogenic operation
- liquid Noble gasses TPCs readouts
- long lifetime reliability

Radiation-Hard
- immunity to TID, NIEL and SEE effects

Collaborations with academia, national labs, and industry

![TID Effects on an Inverter (Typical Corner)](image-url)
Hybrid-pixel detectors
• counting and spectroscopic detectors for BES photon science, NNSA applications

3D-IC and High-Density Interconnect
• edgeless and gapless, highly granular pixel detectors with extended functionalities

Monolithic Active Pixel Sensors
• on HR, thick substrate with full CMOS capability and built-in charge-signal processing

Emerging technologies
• Quantum Information Science and Technology
  • Control and readout electronics
• High speed electronics for optoelectronic applications
  • High speed switches, DACs and high voltage amplifiers
• AI, Machine Learning for Neuromorphic computing
  • On detector imaging extraction
  • Towards non Von-Neumann architecture
Controls and high throughput data acquisition

- Factorize front-end electronics from data handling with compact, high-density, scalable, low maintenance, easily upgradeable, commodity-based solution
- Field Programmable Gate Array (FPGA) and system integration experts, highly integrated system level data acquisition systems.
- High performance data acquisition, digital signal processing and data collection. Advanced applications for Nuclear Physics, Particle Physics, & Photon Sciences

eBPM & xBPM electronics

VIPIC readout concepts

@ NSLS-II
Examples of advanced control boards

**DUNE Warm Interface Board**

- Data streaming and control board for DUNE liquid argon based Time Projection Chamber (TPC)
- Xilinx Zynq Ultrascale+ ZU9EG
- Quad-Core A53 and Dual-Core R5 processors
- Four bidirectional optical links up to 40Gbit/s
- Sixteen 1.25Gbit/s links with external adaptive equalization
- Two TCP/IP Gigabit Ethernet for system diagnostics and control
- Twenty DC/DC converters with voltage and current monitoring for DUNE cryostat electronics power

**Xilinx Zynq UltraScale+ RFSoC ZCU111 board**

- Eight 12-bit 4.096GSPS ADCs and Eight 14-bit 6.554GSPS DACs.
- Quad-Core A53 and Dual-Core R5 processors.
- Xilinx XCZU28DR-2FFVG1517E FPGA.
- Flexibility of sampling the ADCs either using the external Phase Locked Loop (PLL) or internal PLL.
- 1GbE and 100 GbE UDP Ethernet Interface.
2-dimensional neutron detectors

Inside the Detector – the Pad Board

- Pad size: 5mm x 5mm
- Pad board: 24cm x 24cm
- # pads: 48 x 48 = 2304
- # layers: 11
- Board thickness: 2.8 mm (0.011"
- ASIC: 64 channels
- # ASICs: 36

There are 16 of these boards, in a 4 x 4 array, in the final detector. This represents a 192 x 192 array, or 36,864 channels.

16 pad array: heart of 1m x 1m detector

Channels: 16 x (48 x 48) = 1024 x 192 = 36,864

Assembled Detector

Front of detector

Several hours of operation in absence of neutron source. Full 1m x 1m area, 192 x 192 pads

Possible phenomena:
- He recoils
- C recoils
- Pn(p,e) reactions

Rear of detector

Quokka 20m long x 2m diam. vacuum tank
Thermal Neutron Imaging concept for National Security

- Fast neutrons are emitted by neutron sources
- Some neutrons are moderated close to the source
- Un-scattered thermal neutrons can be used to form an image of the moderator, using a pinhole
- Many pinholes can be combined to increase efficiency in a Coded Aperture

\[ n^+ \, ^3\text{He} \rightarrow p^+\, ^3\text{H} + 764 \text{ keV} \ (25 \times 10^3 \text{ electrons}) \]

Fission source

\[ \text{Moderator} \]

\[ \text{He-3 chamber} \]

Coded aperture imaging of non-focusable radiation


Position-sensitive \(^3\text{He}\) wire or pad detector

0.4 mm thick Cd masks on Al
Thermal Neutron Imaging concept for National Security

**Multi-view imaging in warhead counting**

Sketch of a missile with warheads

- Multiple view (stereo or higher order) has higher accuracy and less uncertainty in resolving complicated structures
- It can resolve neutron sources which are blocked on one view only

Four Cf-252 sources embedded in polyethylene blocks

Stereo images
Quantum Networks

MOTIVATION: secure communication

• A quantum network provides the basis for:
  • trading, personal data handling, transport and power grid security
  • secure position tracking
  • Quantum internet and the future of cybersecurity
• Disruptive technology with tremendous scientific and economic impact.
An elementary 158 km long quantum network connecting room temperature quantum memories

- LONG DISTANCE QUANTUM INTERFERENCE EXPERIMENTS
  - SINGLE PHOTON (SP) MACH-ZEHNDER INTERFEROMETRY
  - TWO-PHOTON (TP) HONG-OU-MANDEL INTERFEROMETRY
Free Space Optical Link for Entangled Photon Distribution Over Long Distances

Quantum Receiver

Entanglement detection (left) and source (right)

Quantum Transmitter

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN
NATIONAL LABORATORY
A tour of the QIST lab

- Quantum network
- Quantum lidar
- Quantum astrometry

- Deployable entanglement source

- Portable laser rack with master and locking lasers
Summary

- *Instrumentation Division is a vibrant organization*
- *Broad set of capabilities*
- *Diverse portfolio*
- *Natural set for collaborations and internships*

Questions?