Overview of BNL's Instrumentation Division

David M. Asner
Deputy Associate Laboratory Director
Head, Instrumentation Division
Nuclear & Particle Physics Directorate

70 YEARS OF DISCOVERY
A CENTURY OF SERVICE

U.S. DEPARTMENT OF ENERGY
BROOKHAVEN NATIONAL LABORATORY

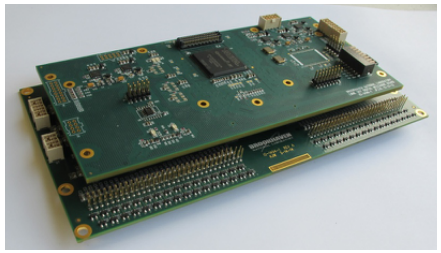
Nearly seven decades of detector and instrument development…

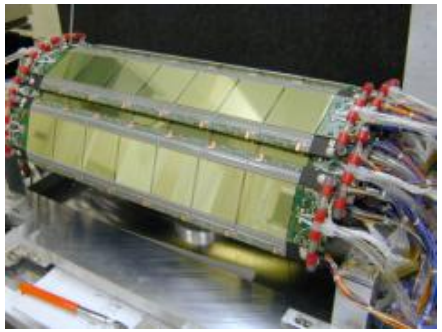
Mission: to develop state-of-the-art instrumentation required for research programs at BNL and to maintain the expertise and facilities in specialized high technology areas

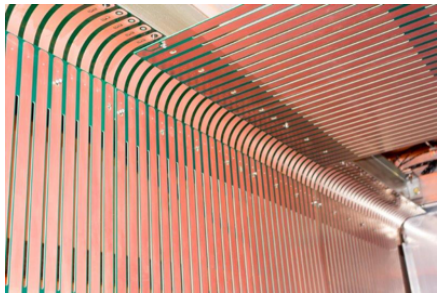
Instrumentation Division's research efforts also have a significant impact on programs elsewhere in the world that rely on advanced radiation detectors and their associated readout electronics and data acquisition.

Strong collaboration with University partners is sought to develop, design, prototype, and construct detector systems to realize the science goals of the Electron Ion Collider.

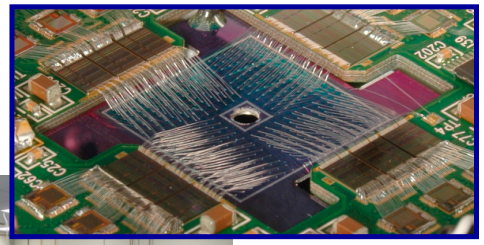
Capabilities Stewarded by Instrumentation Division







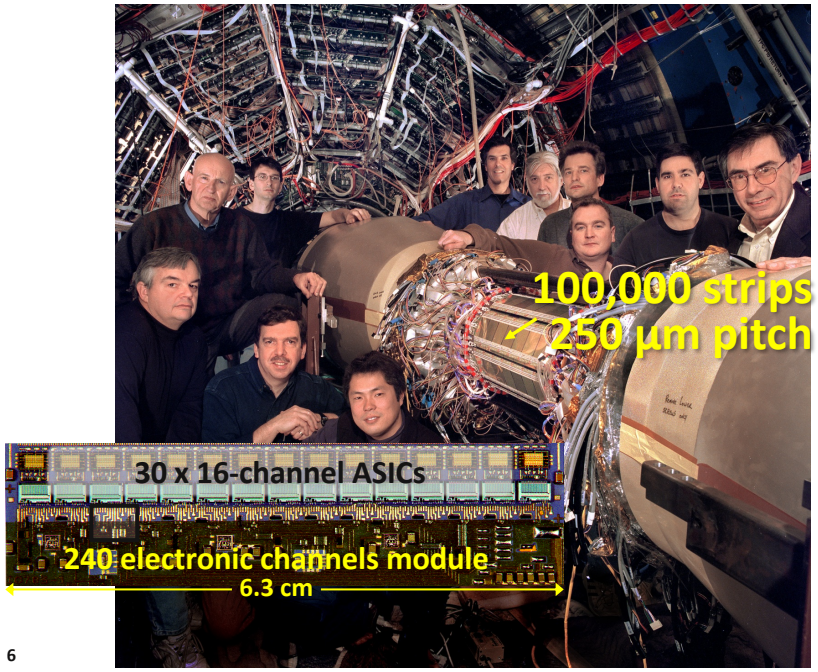
- Low Noise Microelectronics and Cold Electronics
- Solid State Detectors Fabrication and Characterization
- Noble Liquid Detectors
- Gaseous Detectors
- Photocathodes, Lasers and Optics
- High Throughput Data Acquisition
- Irradiation Facilities



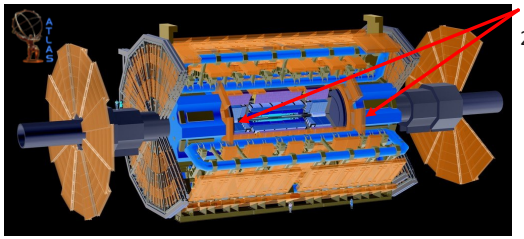
Capability: Low Noise Microelectronics & Cold Electronics

- ASIC and PC design experts, test engineers, design & integration tools
- Devices that can measure small signals, have very low noise, low power consumption, compact, light weight, and operational over a wide temperature range, from ambient to cryogenic.
- High Density Interconnect and Electronics Assembly Laboratory
- Cryogenic ASICs and Analog Front End electronics
- Our ASIC designs include:
  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.
  Neutrino Experiments: Cold FE and mixed signal ASICs for MicroBooNE & LAr TPCs cold ASICs for nEXO for charge and photon detection

ASICs for RHIC: STAR Silicon Vertex Tracker

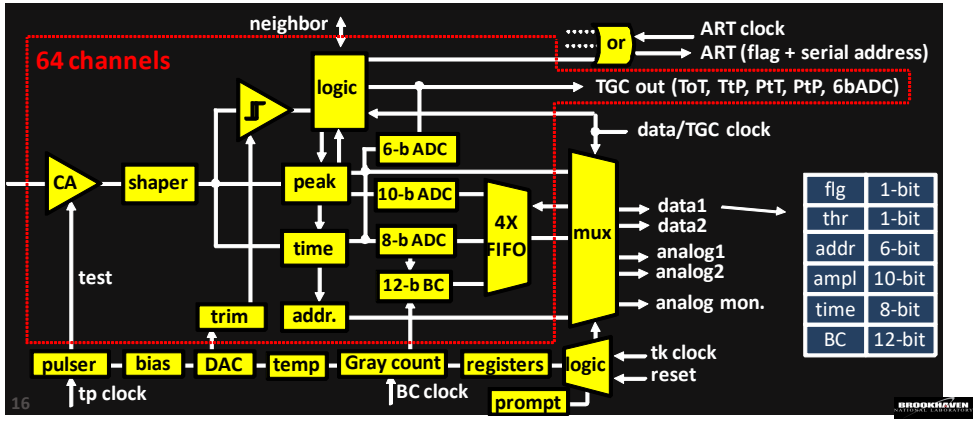


ASIC for ATLAS Muon Spectrometer



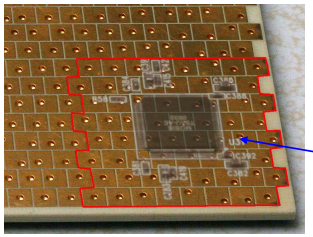
New Small Wheels: 2.3M channels,
2pC @ < **1fC** rms, 100ns @ < **1ns** rms, 30pF-**2nF**

- 64 channels: amplification, peak, timing, discrimination, 3 ADCs, FIFO, timestamp
- real-time address, sub-hysteresis, direct outputs, fully digital interface
- CMOS 130nm, 13.5 mm x 8.4 mm,
- transistor count/ch.: > 80,000

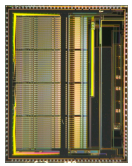


ASIC for Neutron Imaging / Nonproliferation

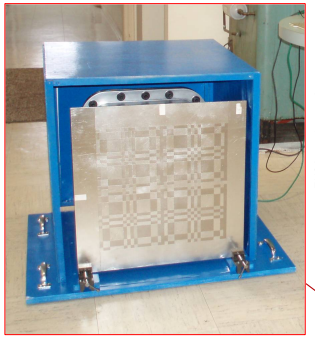
^{3}He detector for Small Angle Neutron Scattering Experiments at SNS

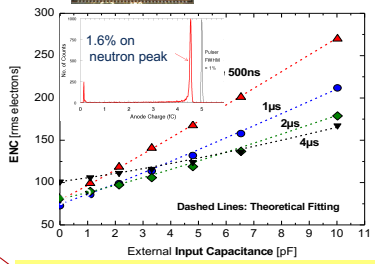


- Low-noise front-end with unity gas-gain
- Single-pad induction (small-pixel effect)
- Full size: 196 x 196 pad array (10^8 n/s) - very high neutron rate
- Pad 25 mm^2, 5 pF, rate 5 kHz / pad



- 64 channels - mixed signal
- low-noise charge amp.
- current-mode 6-bit ADC
- 18-bit timestamp
- 110 e$^-$ resol., 1.5 mW/ch.
- sparse readout and FIFO





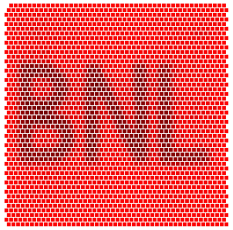


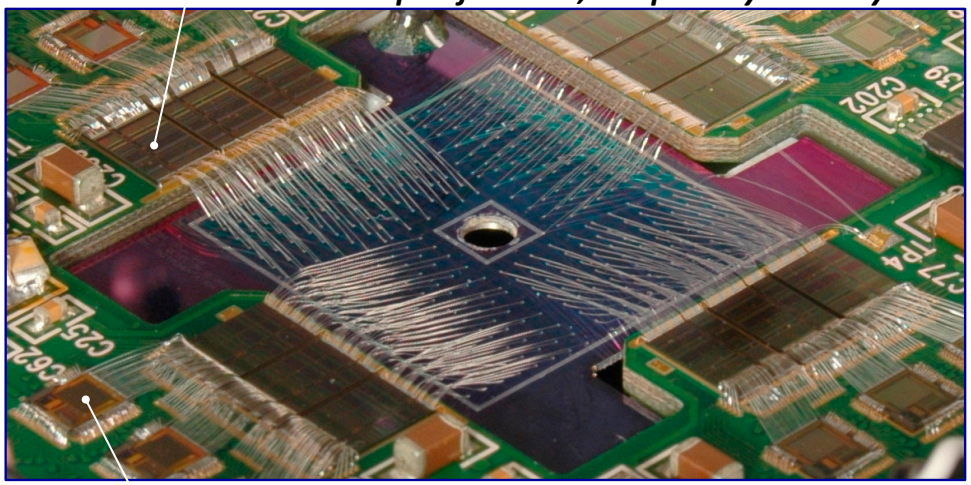
Image from Cd foil, 48x48 pad array

- *Coded aperture version for Nonproliferation*
- *Large 1 m^2 version being developed for ANSTO*

ASICs for Light Sources: Maia

R&D 100 Award

Hermes - developed for NSLS, adopted by industry



Scepter - developed for industry, adopted by NSLS

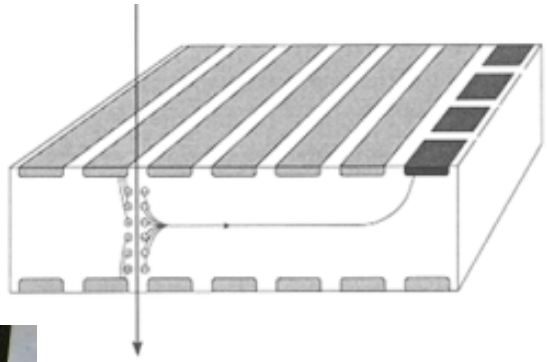
High Density Interconnect and Electronics Assembly Laboratory

Capability: Solid State Detectors Fabrication and Characterization

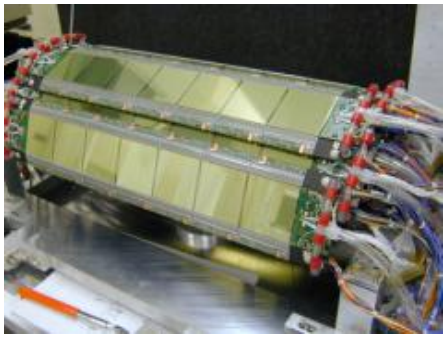
- Clean rooms for semiconductor detector processing, class-100 CR for silicon processing, static and dynamic testing of semiconductor detectors.
- Ability to detect X-rays over a wide energy range, and charged particles in high radiation environment with in-house fabricated detectors. High sensitivity, low noise photon detection using CCDs and SiPMs. LGADs development.

Silicon Drift Detector (SDD):

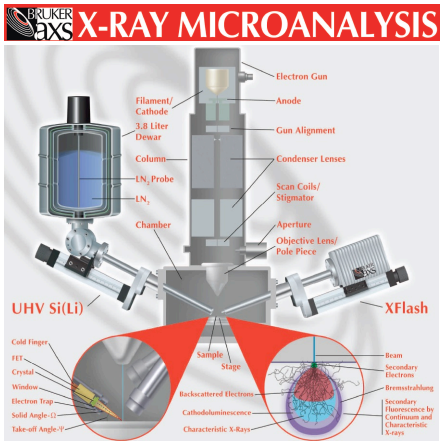
particle tracking and x-ray spectroscopy for fundamental and applied research



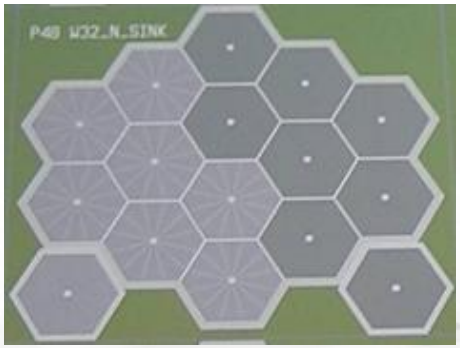
- Position-sensing element in high energy and heavy ion experiments
  - CERES experiment at CERN;
  - ALICE experiment at CERN
  - STAR experiment at RHIC
- SDD arrays used in high rate, high resolution fluorescence in synchrotron science
- Growth of SDDs as high resolution x-ray detectors in commercial electron microscopes
- Space science applications – low power, large angular coverage



STAR Silicon Vertex Tracker



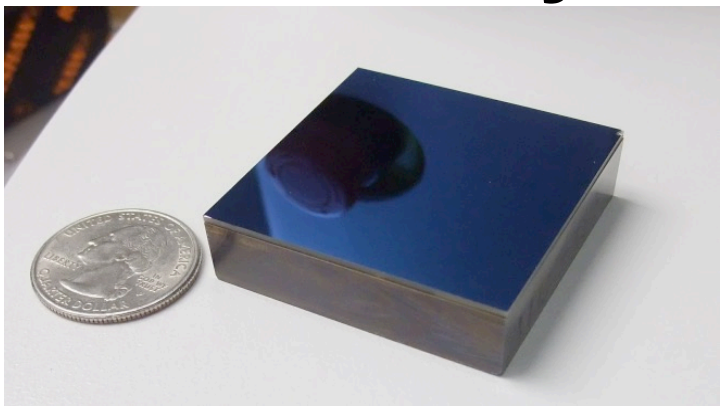
SDDs now used in commercial EMs

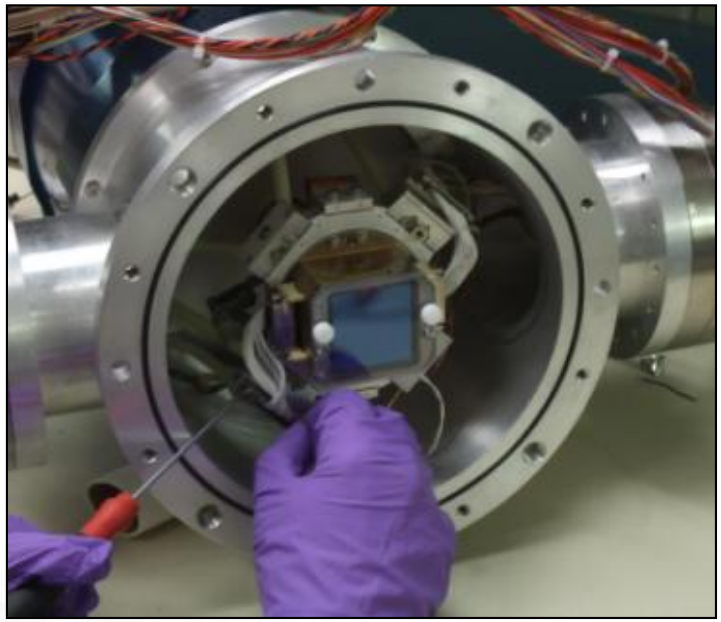


SDD array for NASA

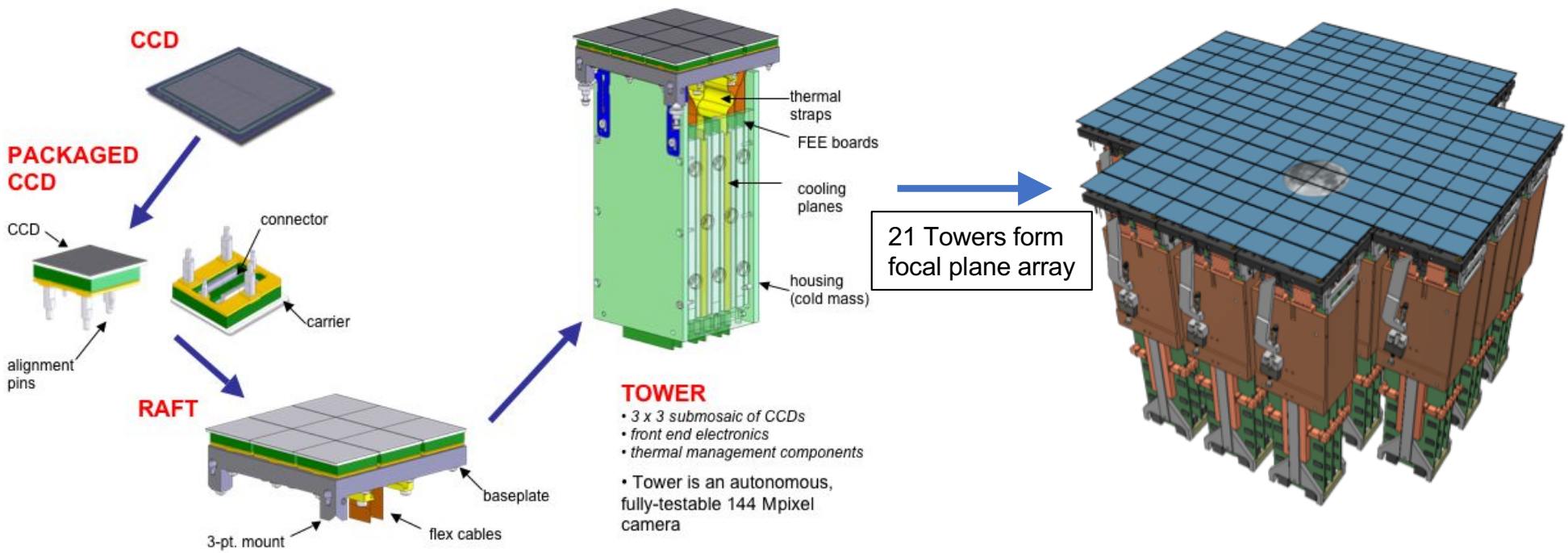
LSST: New generation CCD sensor optimized for WIDE, DEEP, FAST survey

- 100μm-thick, high resistivity silicon CCDs, fully-depleted with transparent conductive window and AR coating
  - *for broadband QE and small PSF*
- 4K x 4K format
  - *4 die sites/6"wafer*
- 16-fold parallel output
  - *for low noise readout at 2s frame read time*
- 10μm pixels
  - *for optimum sampling at LSST plate scale*
- Buttable, thermally-matched packaging
  - *>92% fill factor*
- Flatness and alignment tolerance to bring image surface of all CCDs coplanar to ±9μm
  - *for use in fast f/1.2 beam*
- Operating temperature -100C
  - *Suppress dark current to negligible levels*





BNL constructs & qualifies LSST Science Rafts, which are sent to SLAC, to be integrated into the LSST Camera



First LSST science raft delivered to SLAC in November 2017: one of BNL's Top Ten "Discoveries and Scientific Achievements" for 2017

Instrumentation Division Scope

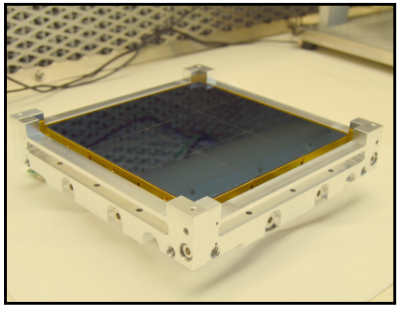
Science Raft is comprised of:

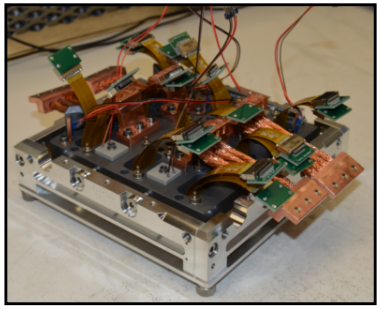
- 9 CCDs (Sensors)
- 3 "Raft Electronics Boards" (each synchronously controlling 3 CCDs)

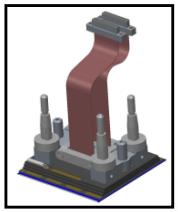
22 Science Rafts

RTM Construction/Qualification

Raft Sensor Assembly





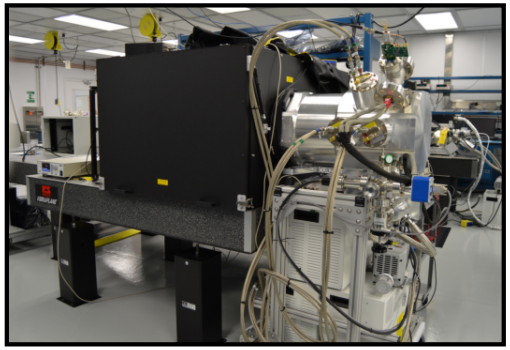


Sensor Qualification

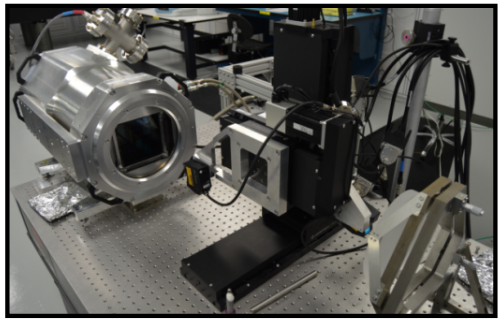
Assembly & Test Facility at BNL

- Electro-Mechanical Assembly
- Metrological Tests
- Electro-Optical Tests

Full Raft EO Testing



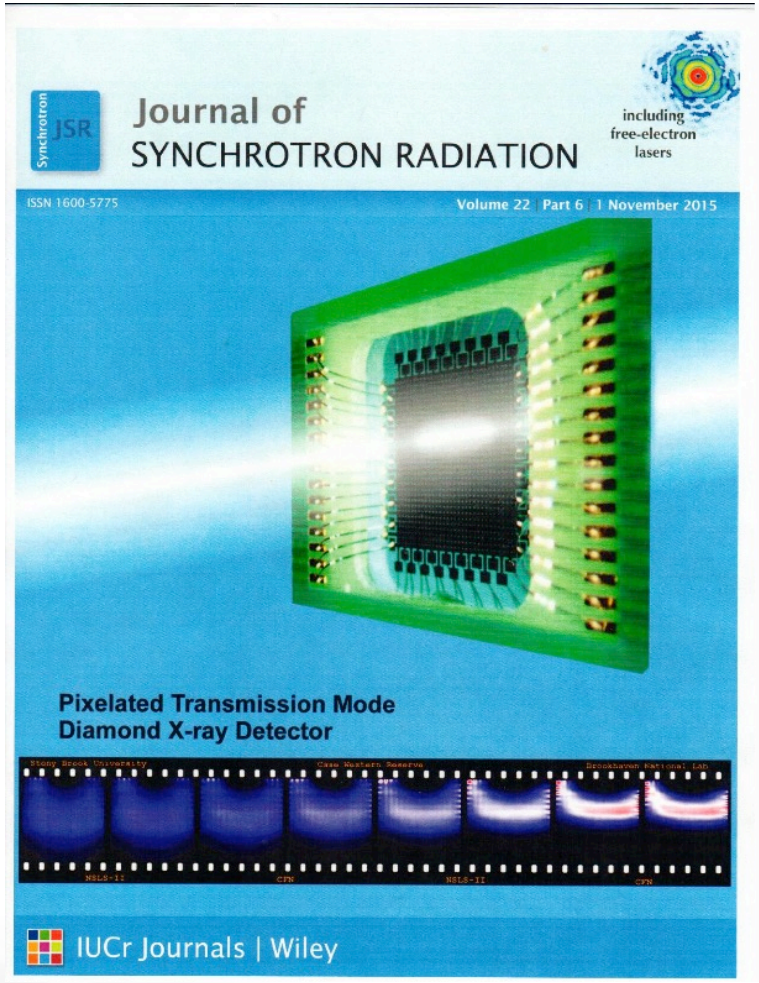
Warm/Cold Metrology



Single CCD Testing

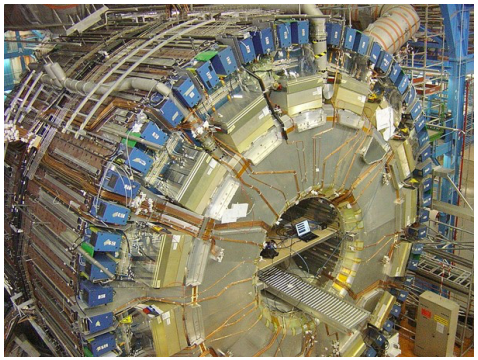
Pixelated Diamond X-ray Detector

- Fabricated and tested transmission-mode pixelated diamond X-ray detector
- Lithographically patterned vertical stripes (front) and horizontal stripes (back) on electronic-grade chemical vapor deposition single-crystal diamond
  - pitch size 60–100mm
  - simultaneously and in real time measure flux, position & morphology of an X-ray
  - 1 kHz sampling ➔ 30 Hz image rate



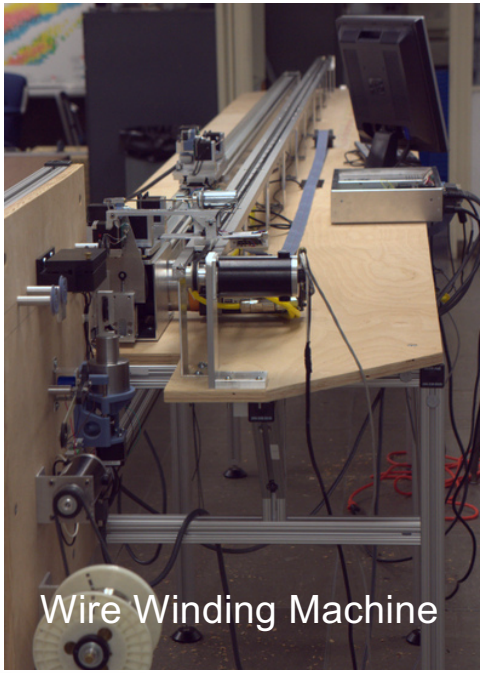
Capability: Noble Liquid Detectors

- Cryogenic detector systems using liquid argon, krypton and xenon
- Particle and photon detection with Time Projection Chambers and calorimeters
  - Conceptual → final detector design
  - Development of wire carrier boards; wire selection, testing & termination
  - Design & construction of wire winding machines
  - Design, prototyping, testing and installation of the cold front-end ASIC, mother boards, & cold cables
  - Design, construction & installation of TPC signal feedthroughs and warm interface electronics



Pioneering R&D for ATLAS Liquid Argon Calorimeter

Liquid Argon TPCs
ν cross sections,
ν oscillations,
proton decay

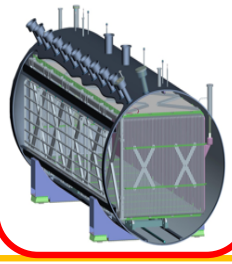


Wire Winding Machine

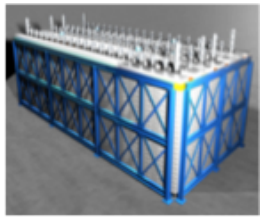
ProtoDune Field Cage

Landscape of LArTPCs (recent/planned)

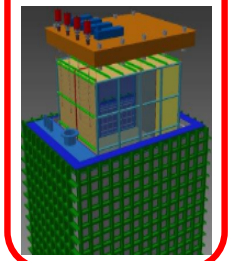
MicroBooNE, 80t



ICARUS 600t



SBND, 110t



SBN Program

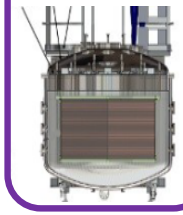
Bo TPC

LAPD

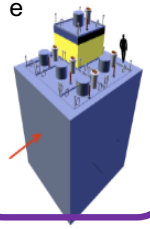
ArgonTube

LArIAT, 0.3t

CAPTAIN, 5t



ArgonCube



Detector R&D Program

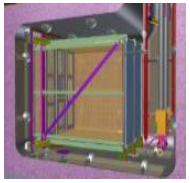
BNL's contributions:

Supply electronics

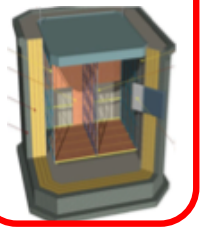
TPC + electronics design & construction

LBN Program

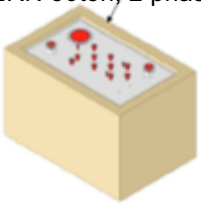
LBNE 35ton, 10t



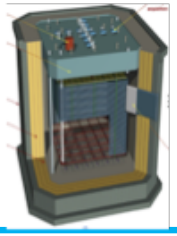
CERN NP04, 300

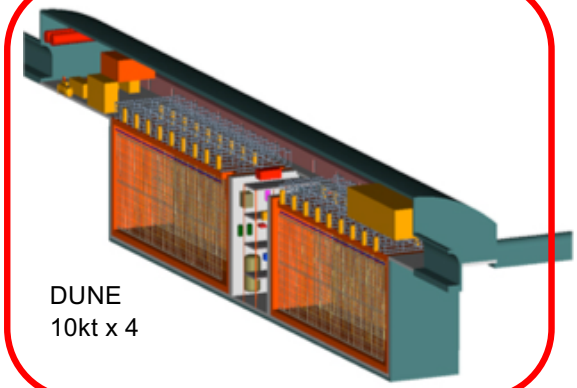


CERN 50ton, 2 phase



CERN NP02, 2 phase





DUNE
10kt x 4

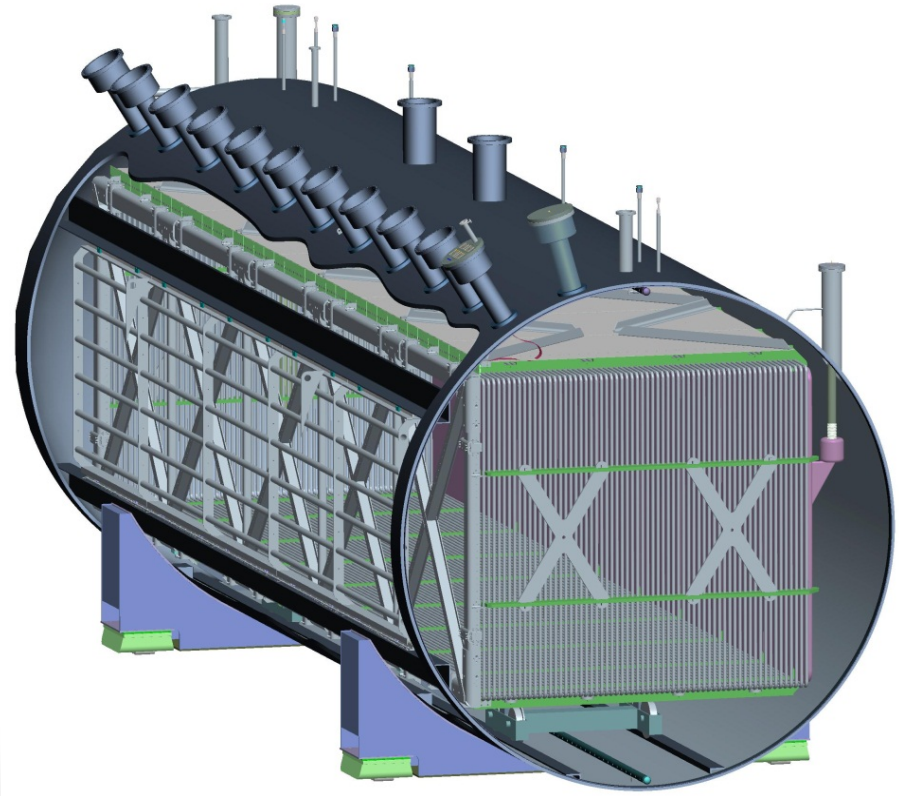
2016 → 2020

The MicroBooNE TPC

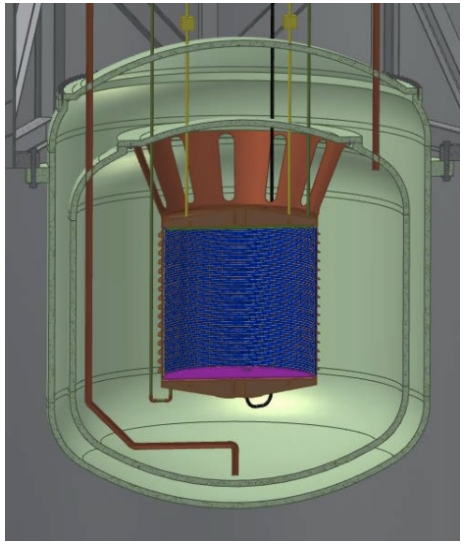
TPC active volume:
- Length: 10.37m
- Height: 2.33m
- Width(drift length): 2.56m

Number of Wires:
- Y: 3456, vertical, collection
- U, V: 2400 each, ±60°induction
- Total: 8256 readout channels

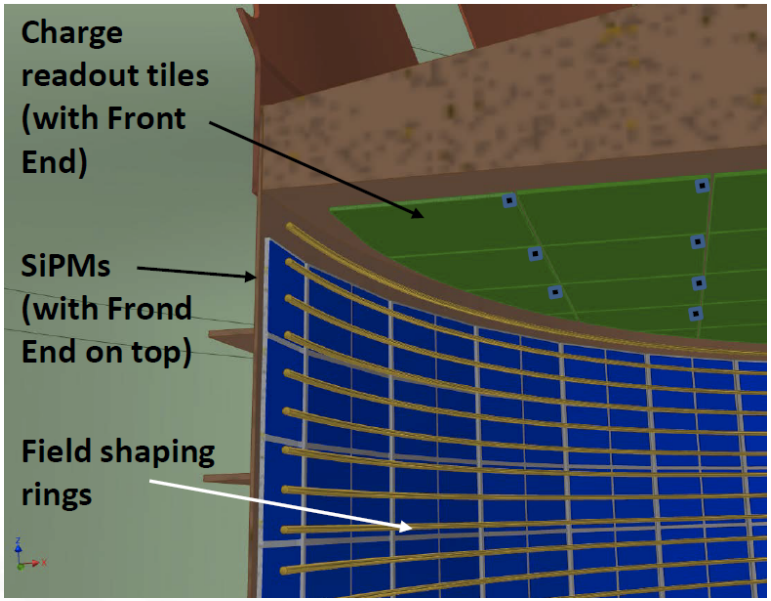
MicroBooNE Cryostat:
- 4m diameter, 12m long, 170 tonnes LAr
- Passive insulation, no evacuation



nEXO – Enriched Xenon Observatory

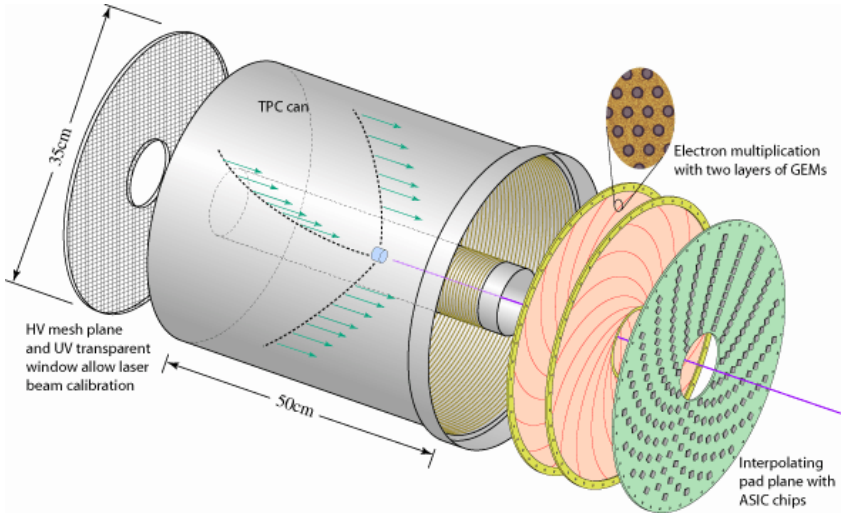


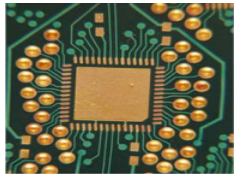
- Five tonne liquid xenon (^{136}Xe enriched) TPC to search for neutrino-less double beta decay
- Technology that BNL is contributing to nEXO includes:
  - Development of cold readout system for light detection in TPC
  - Optimization of the charge readout electrode design and radiopure interconnects
  - SiPM characterization

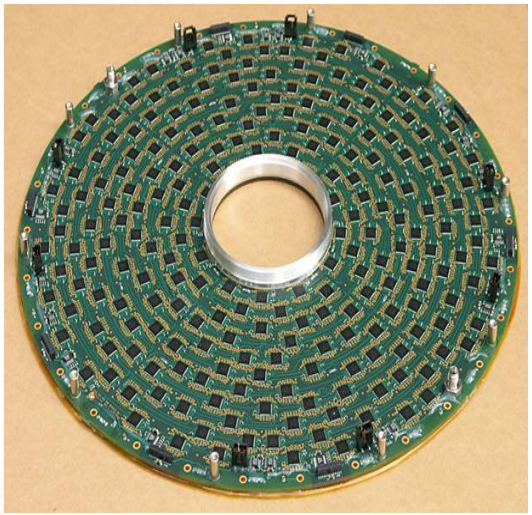


Capability: Gaseous Detectors

- High pressure design, chamber fabrication, testing and integration capability
- Particle and photon detection with time projection chambers and calorimeters
- Neutron detectors for worldwide user facilities
- Neutron detectors for national security programs

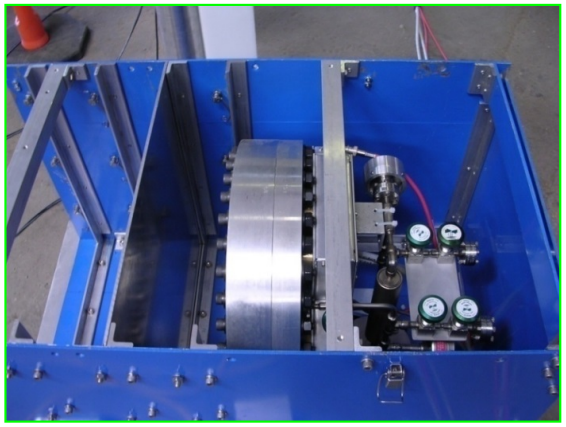


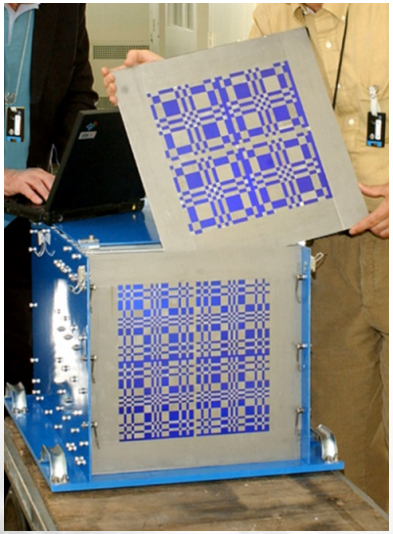




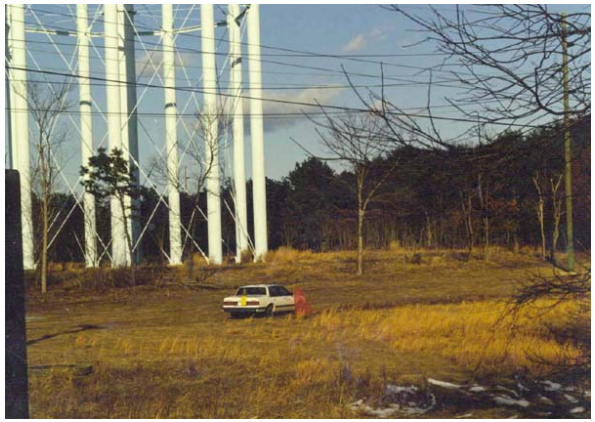
Neutron Detectors: Coded Aperture Imaging of Non-focusable Radiation

Coded-aperture imager hardware

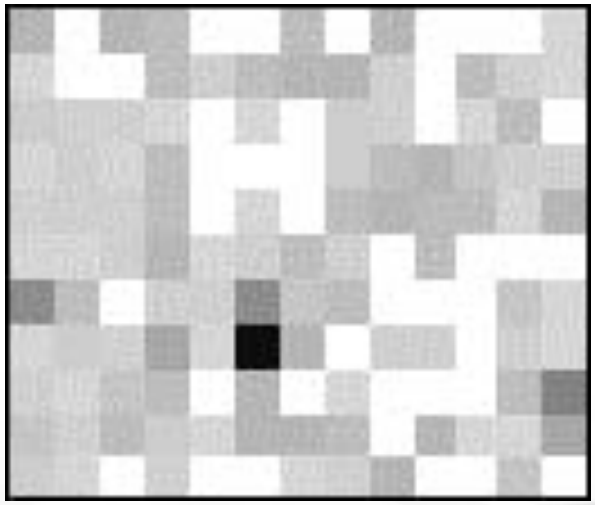




Coded aperture masks



Cf source in trunk of car

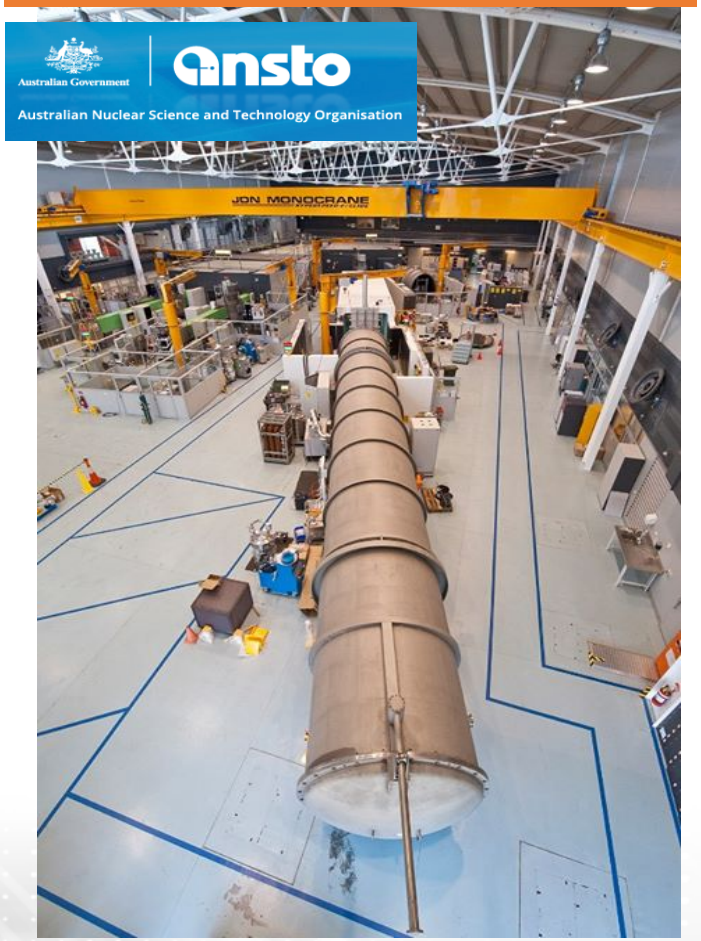


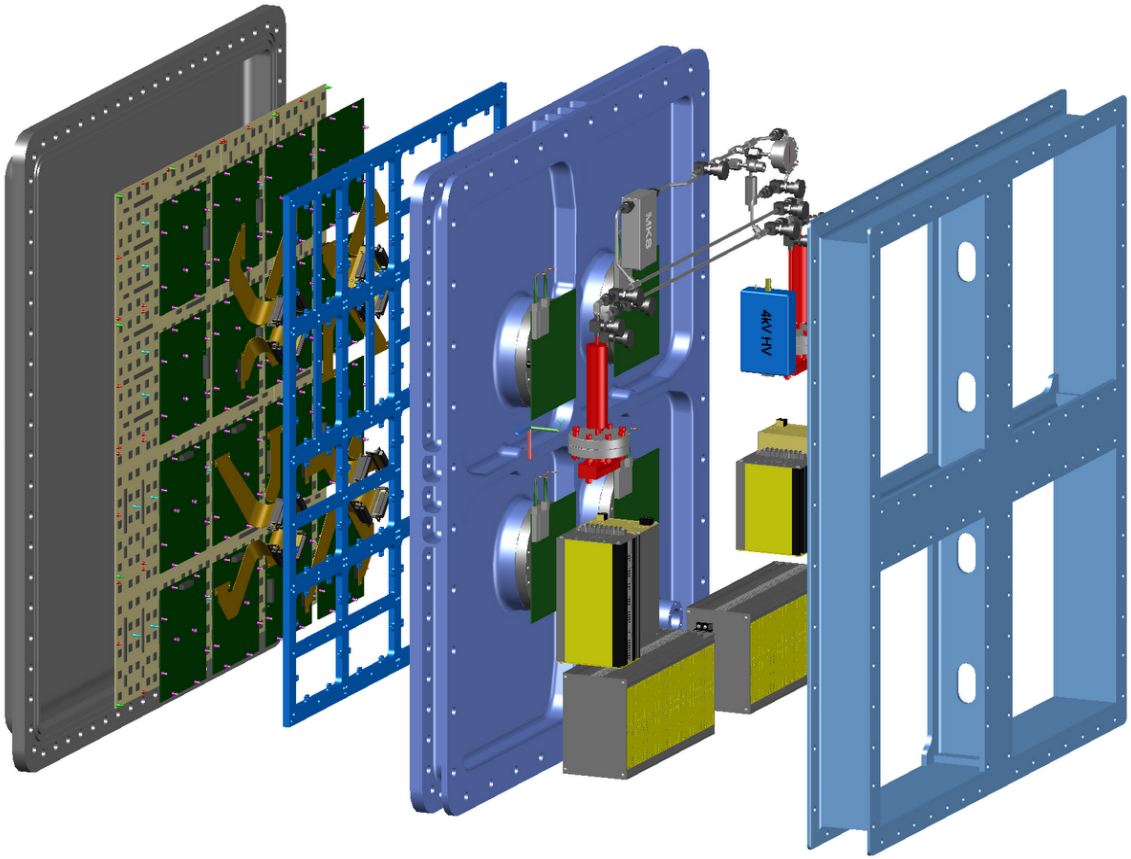
Thermal Neutron Image

1m × 1m Neutron Pad Detector @ ANSTO

First Ionization Mode Neutron Detector at a User Facility

Quokka 20m long x 2m diam. vacuum tank

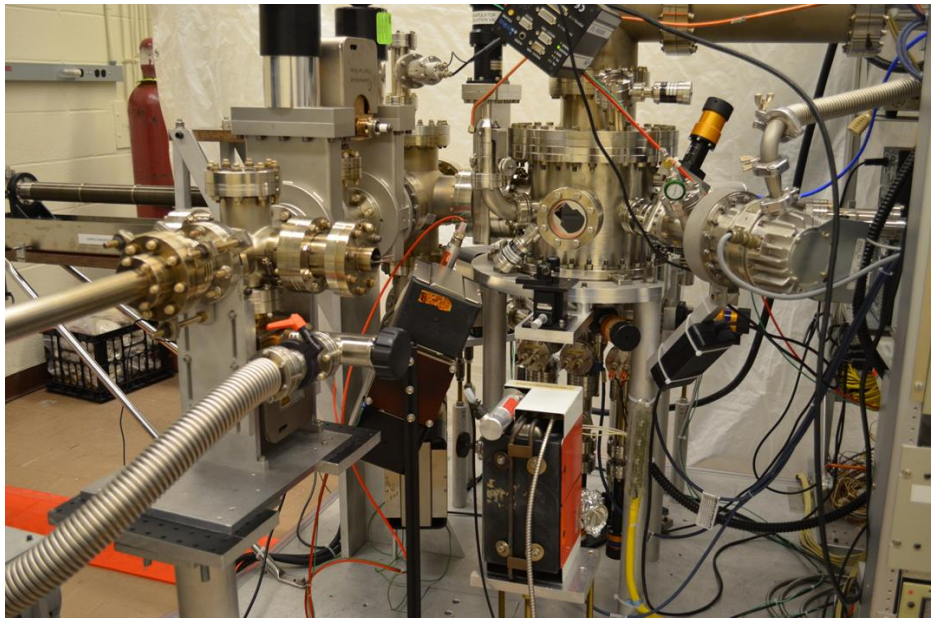




Exploded view of pad detector currently under development

Drawing by Bo Yu

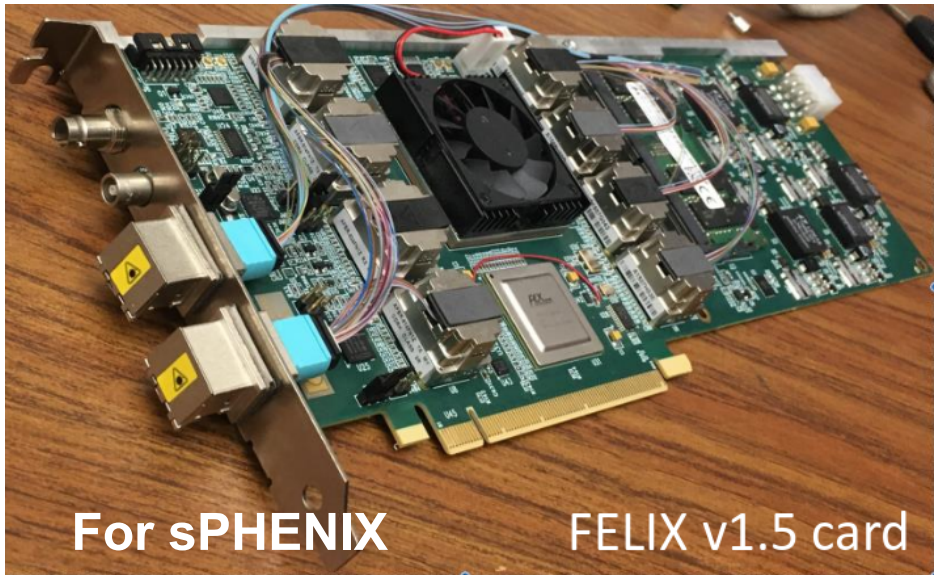
Capability: Photocathodes, Lasers, Optics



- Photocathode Production for RHIC
  - Coherent electron cooling
  - Low energy electron cooling
- Photocathode R&D relevant to EIC
  - surface charge limit of GaAs
  - novel materials for generating polarized electron beams
- Lasers with wavelength ranging from infra-red to ultraviolet, pulse duration ranging from CW to femtosecond, optical design tools
- Ability to produce and characterize electron and photon beams down to fs, generate coherent VUV and XUV radiation, modify and characterize materials with lasers, ability to design and implement complicated optical systems

Capability: 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



ATLAS FELIX module, repurposed for SPHENIX TPC Data Aggregation Module, and other sPHENIX detector sub-systems. 48 -12Gbps fiber optic links, PCIe x16, 100Gbps throughput, Xilinx Kintex7 Ultrascale FPGA

Germanium strip detector Readout Module. Xilinx Zynq FPGA with dual ARM-A9 processors, 2 – 12Gbps high speed links, 24 channels of 25MSPS ADC's. Processes 20M photon events/sec from 384 strip detector

Capability: Irradiation Facilities

- Intense gamma and neutron sources, located in Bldg 356 (dedicated)
- Sources operated in concrete-shielded room with multiple interlocks
- Major activities:
  - Ionizing radiation testing for ATLAS upgrade components
  - Neutron displacement damage in electronic components & sensors
  - Some proprietary, commercial radiation testing

Thermo-Electron Energized Neutron Source

Based on D-T reaction producing 14 MeV n, ~10^8 n/s max

^{60}Co source

1.1 & 1.3 MeV gamma
20 kCi when purchased,
~ 700 Ci at present

~ 5× 10^4 rad/hr on contact
~ less than 10^4 rad/hr outside collimator

Track record of collaboration across the lab, the country, the world

- Development/construction of SVT for STAR at RHIC
- Development/integration of ATLAS Detectors at CERN
- Silicon polarimeter detectors for RHIC
- Advanced x-ray detectors for NSLS-II
- Focal plane sensors for LSST
- Liquid Ar detectors for neutrino program at Fermilab
- Diamond detectors for photon science
- Neutron detectors for Spallation Neutron Source
- Neutron and x-ray detectors for National Security

Near future collaborations

- Neutrino oscillations/cross sections – DUNE et al.
- Neutrinoless double beta decay - nEXO
- Direct detection of dark matter - DarkSide
- Relativistic heavy ion physics - sPHENIX
- Future cosmology experiments – 21cm, CMB-S4
- Precision heavy flavor physics – Belle II
- **Detectors for Electron Ion Collider**

Summary of Instrumentation Division Capabilities

Capability	Infrastructure	Uniqueness
Low Noise Microelectronics and Cold Electronics	ASIC and PC design experts, test engineers, design and integration tools	Devices that can measure small signals, have very low noise, low power consumption, compact and light weight, and are operational over a wide temperature range, from ambient to cryogenic. High Density Interconnect Laboratory
Solid State Detectors Fabrication and Characterization	Clean rooms for semiconductor detector processing, class-100 CR for silicon processing, static and dynamic testing of semiconductor detectors.	Ability to detect X-rays over a wide energy range, and charged particles in high radiation environment with in-house fabricated detectors. High sensitivity, low noise photon detection using CCDs and SiPMs. LGADs development.
Noble Liquid Detectors	Systems for fundamental measurements using liquid argon, krypton and xenon	Particle and photon detection with Time Projection Chambers and calorimeters
Gaseous Detectors	High pressure design, chamber fabrication, testing and integration capability	Particle and photon detection with time projection chambers and calorimeters Neutron detectors for worldwide user facilities Neutron detectors for national security programs
Photocathodes, Lasers and Optics	Lasers with wavelength ranging from infra-red to ultraviolet, pulse duration ranging from CW to femtosecond, optical design tools	Ability to produce and characterize electron and photon beams down to fs, generate coherent VUV and XUV radiation, modify and characterize materials with lasers, ability to design and implement complicated optical systems
High Throughput Data Acquisition	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 Photon Sciences and Particle Physics.
^{60}Co Irradiation	Gamma & neutron radiation sources	Capability to irradiate samples over a large dosage range

Thank you