Instrumentation Technologies
Enabling Current and Future Science

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Outline

- Instrumentation’s core technologies and BNL programs
- Solid-state Detectors – Si, diamond
- Liquid-based detectors – liquid argon (LAr)
- Gas-based Detectors – $^3$He
  \[ \text{ASICs in all applications} \]
- Detectors for Medical Applications
- Laser/Photo Cathode Studies
- Wrap-up
Instrumentation Division
Core Competencies ↔ Program Areas Roadmap

Mission:
"To develop state-of-the-art instrumentation required for experimental research programs at BNL."

R&D Facilities
- Semiconductor Detector Laboratory
- Gas & Noble Liquid Detector Laboratory
- Hybrid Circuit Laboratory
- Monolithic Circuits Laboratory
- Computer-Aided Circuit Layout
- Multilayer Printed Circuits
- Laser Laboratory
- Optical Metrology Laboratory
- Micro/Nano Fabrication Laboratory
- Vacuum Deposition Laboratory
- Solid State Irradiation Facility

Staff (41)
- Scientific: 16
- Professional: 11
- Technical: 10
- Administrative: 4

Publications
- Annual: ~50
- Cumulative: 1370

Patents: 18

Future Research Areas: Nano-electronics, Si - Detectors Integrated with Microelectronics.

BNL Science Area or Directorate

Instrumentation's Core Competencies

GARS

BES &PS
Core Competencies in IO

Future Research Areas: Nano-electronics, Si - Detectors Integrated with Microelectronics.
Mission: “To develop state-of-the-art instrumentation required for experimental research programs at BNL”

Our goal: to make the Lab scientists and science programs more competitive by development of enabling technologies.
Summary of $w_i$ for Key Detection Media

$w_i$ is energy required to create an electron ion/hole pair

<table>
<thead>
<tr>
<th>Material</th>
<th>$w_i$ (eV)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconducting Tunnel Junction (STJ)</td>
<td>~2.5. $10^{-3}$</td>
<td>X-ray, eV resolution</td>
</tr>
<tr>
<td>Semiconductor Microcalorimeter</td>
<td>2.9</td>
<td>$\gamma$-ray</td>
</tr>
<tr>
<td>Si</td>
<td>3.6</td>
<td>Tracking; X-ray</td>
</tr>
<tr>
<td>CdTe &amp; CZT</td>
<td>5.2</td>
<td>$\gamma$-ray</td>
</tr>
<tr>
<td>Diamond</td>
<td>~13</td>
<td>High temp detectors, Flux Measurement</td>
</tr>
<tr>
<td>Xe</td>
<td>22</td>
<td>$\gamma$-ray, X-ray</td>
</tr>
<tr>
<td>Kr</td>
<td>24</td>
<td>$\gamma$-ray, X-ray</td>
</tr>
<tr>
<td>Ar</td>
<td>26</td>
<td>GeV, TeV calorimetry</td>
</tr>
<tr>
<td>$^3$He</td>
<td>40</td>
<td>Neutron</td>
</tr>
<tr>
<td>Se</td>
<td>~50</td>
<td>X-ray radiography</td>
</tr>
<tr>
<td>NaI (+PM)</td>
<td>200</td>
<td>SPECT</td>
</tr>
<tr>
<td>LSO (+APD)</td>
<td>~100</td>
<td>PET</td>
</tr>
<tr>
<td>PbWSO$_4$</td>
<td>~$2\times10^5$</td>
<td>TeV calorimetry</td>
</tr>
</tbody>
</table>
Solid-State Detectors
Solid State Detectors for Synchrotron Radiation

NSLSII will require advanced photon detectors, particularly for extremely high photon rates and dynamic studies on time scales of \(10^{-9}\) s and shorter, which can be solved only by novel detector concepts. Key areas at include:

- X-ray Fluorescence and X-ray Microprobe: Si diode arrays, Si Drift Detector arrays
- Powder Diffraction: One dimensional microstrip arrays
- Soft X-ray Microscopy: Multi-element Si detector with custom pads

Other key areas:
- Small and Large Angle Scattering
- X-ray Protein Crystallography
- Biological and Biomedical Imaging

**Thrust of our R&D efforts is planned to be on:**

- Si Diode Arrays - integrated with ASICs and wire bonding
- Silicon Drift Detectors - arrays, excellent energy resolution
- Silicon Pad Detectors - integrated with ASICs and wire bonding
- Germanium Detectors - higher Z than Si: higher photon energies
- X-ray Active Matrix Pixel Sensors - large area coverage with \(n^2\) pixels, but only \(n\) readout channels (XAMPS).
- Strong Collaboration with NSLS/Peter Siddons’ group
Backscattering Geometry for Fluorescence Microprobe – Maia Detector

- Backscattering geometry allows close approach to sample
- Provides significant solid-angle even for small area detector
- Sensor with many channels increases global count rate
Maia Detector - Microprobe for Elemental Mapping

**HERMES** chip developed for NSLS, adopted by industry

**SCEPTER** chip developed for industry, adopted by NSLS

384-pixel Si detector die, fabricated in the IO Si-Lab; 20mm by 20mm, 384 pads, each 1mm^2 & ~ 1pF
**Hermes chip:**

**ASIC (Application Specific Integrated Circuit)**

32-channel ASIC, BNL IO

*Size: 3.7 x 6.3 mm²*

- amplifier
- filter
- discriminator
- counter
- 8 mW/channel

**ASICs make possible multi-channel detectors such as Maia**
Wire (~1/2 human hair) bonding of silicon detector pixels to ASICs

Assembly of microcomponents to 12-layer circuit board

Computer-aided design of multi-layer circuit boards

Assembly and x-ray checking of Ball-Grid-Arrays (several hundred contacts)
Microprobe for Elemental Mapping

MAIA microprobe elemental imager
NSLS and CSIRO, 2011 R&D 100 award

Rembrandt
“old man with a beard”

copper  iron  lead  mercury
Silicon Drift Detector (SDD)

The silicon drift detector is a product of R&D in detectors and widely regarded as one of the most significant developments in silicon detector technology:

- Invented in 1983 by Emilio Gatti and Pavel Rehak – thought by many at the time to be technically unachievable

- Novel principle: charge carriers drift in a long, narrow channel in the plane of the wafer (solid state equivalent of gas drift chamber) – device provides excellent timing and low capacitance

- Solved long-term problem of accurate position/energy measurements with reduced number of readout channels count

- Successful concept and development has led to other novel devices, e.g., deep depletion CCDs (flown on XMM mission).

Major impacts in Office of Science research interests:

- Used in both fundamental and applied research, for particle tracking and X-ray spectroscopy

- Position-sensing element in high energy and heavy ion experiments:
  - CERES experiment at CERN; ALICE experiment at CERN
  - STAR experiment at RHIC (Silicon Vertex Tracker)

- 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
Silicon Drift Detector (SDD) for X-rays

Schematic of cylindrical version of SDD

Example of excellent spectroscopic resolution of SDD, from irradiation with $^{55}$Fe. Typically 120-160eV FWHM @5.9keV

64 channel array of SDDs for fluorescence studies on NASA planetary missions

15mm FWHM
For Mn:
- K shell binding energy = 6.54 keV
- L shell binding energy = 0.64 keV
- M shell binding energy = 0.05 keV

1. K electron captured by Fe (Z=26) nucleus – becoming a Mn (Z=25) nucleus

2. L electron fills K hole, fluorescence occurs, $K_\alpha = 5.90$ keV

3. M electron fills K hole, fluorescence occurs, $K_\beta = 6.49$ keV (~12% prob. of #2)
Energy Resolution for X-rays

\[ \frac{\Delta E}{E} = 2.35 \left( \frac{\sigma_p}{P} \right) = 2.35 \left[ (\frac{\sigma_N}{N})^2 + (\frac{\sigma_e}{N})^2 + \text{others} \right]^{\frac{1}{2}} \]

where \( (\frac{\sigma_p}{P})^2 \) is relative variance on the signal amplitude

\( N \) is the number of electrons created by the x-ray

\( \sigma_e \) is the rms electronic noise

No. of electrons created is given by:

\[ N = \frac{E}{w} \]

where \( E \) is X-ray energy, \( w \) is the average energy to create an electron/ion pair.

Since creation of secondary ion pairs cannot be considered as a series of independent events, these fluctuations are smaller than expected from (random) Poissonian statistics. In fact the variance of \( N \), \( \sigma_N^2 \), is given by:

\[ \sigma_N^2 = FN \]

where \( F \) is the Fano Factor

Fano factor limit at 6keV ~ 1.8%
**55Fe Energy Spectra Comparison**

- **Proportional Counter**
- **Silicon Drift Detector**
- **Microcalorimeter**

Spiro et al, NIM A461 (2001) 304-310
Diamond Detectors for Synchrotron Radiation

- Require intensity, timing and position information for synchrotron X-ray beams (white and monochromatic)
  - White beam position monitors (BPMs) are a very useful tool for commissioning, maintaining and troubleshooting critical beam-line alignments
  - Monochromatic BPMs will allow for alignment and sample positioning, along with (potentially shot-to-shot) flux measurement

- Why Diamond?
  - High thermal conductivity and low coeff of thermal expn: can tolerate heat
  - High transmission for manageable thicknesses; vacuum-compatible, compact
  - Wide band gap: can operate in the light at room temp. with no noise penalty
  - High speed capability (compared to a gas-filled ion chamber)
    - electrons and holes have saturation $v_d \sim 0.2 \mu m \text{ ps}^{-1}$
**Diamond Detectors for Synchrotron Radiation**

**Calibrated X-ray flux monitors**
- Linear over 12 orders of magnitude

![Graph showing calibrated X-ray flux monitors]

**Fast Timing**
- Resolving time structure of storage ring current

![Graph showing fast timing]

**Diamond Beam Position Monitors**
- Position resolution down to 20 nm (X15A)
- High flux white BPM (X25, 310mA)

![Graph showing diamond beam position monitors]

**NSLS X-ray ring (25 of 30 buckets filled), ~1 ns pulse width at 52.88 MHz**

\[
\begin{align*}
    d_x &= G_x \cdot \frac{(A + C) - (B + D)}{A + B + C + D} \\
    d_y &= G_y \cdot \frac{(A + B) - (C + D)}{A + B + C + D}
\end{align*}
\]
Liquid-based Detectors
Liquid Argon (LAr) Time Projection Chamber (TPC) for a Booster Neutrino Experiment (MicroBooNE)

Collaboration between:
BNL, Columbia, FNAL, Kansas State, LANL, MIT, Michigan State, New Mexico State, Princeton, St Mary’s, Syracuse, U. of Cincinnati, UT @ Austin, U. of Bern, INFN, Yale.

• The experiment will measure low energy neutrino cross sections and investigate the low energy excess events observed by the MiniBooNE experiment.

• The detector serves as the necessary next step in a phased program towards the construction of massive kiloton scale LArTPC detectors.

• Detector R&D: LAr TPC for larger scale detectors (DUSEL)

• Builds on our expertise with cold electronics/ASICs
Main Components in the MicroBooNE TPC

TPC active volume:
- Length: 10.37m
- Height: 2.33m
- Width (drift length): 2.56m
Number of Wires:
- Y: 3456
- U, V: 2400 each
- Total: 8256
Weight: ~ 5 tons
- ~ 100 tons LAr active volume
Large Volume LAr TPC

- Full 3D event reconstruction, sub-mm position resolution
- \( \text{d}E/\text{d}x \) for particle ID, \( e/\gamma \) separation >90%
- Low energy threshold particle energies \( \rightarrow 1 - 2 \text{ MeV} \)
- Scalable to multi-kiloton size

[Diagram of Liquid Argon TPC]

- Optimized TPC geometry
- Low noise electronics
- Multiplexed readout
- High LAr purity
LAr TPC - Charge Signal Formation

Induction by electrons on wires
and Collection of (by a track at 0 degrees and perpendicular to the wire planes)

Drift Distance (cm)

Time (µs)

U Induction (small, bipolar)

V Induction (small, bipolar)

Y Collection (large, unipolar)

Current Out of Wire
Gas-based Detectors
Multi-Node Centroid Readout

Block diagram for multi-wire neutron detector and data acquisition at a spallation source
Multi-node Charge Division: node samples vs position
Thermal Neutron Detectors Based on $^3$He:

120° curved detector (~ $\frac{1}{4}$ million resolution elements)

LANSCE, Los Alamos National Laboratory

Installation: January 2002

Detector is part of the OBER-funded Protein Crystallography Station (PCS) at LANSCE:

First user of HIPD – magnetic powder diffraction of Pr, Lu, Mn,Ge alloy, showing structural change as a function of temperature

ANSTO, Australia

Installation: January 2007

Detector is a key component of the High Intensity Powder Diffractometer (HIPD), one of several new instruments on the recently commissioned OPAL reactor:

Typical diffraction spectrum from protein crystal – detector’s novel internal electrode design results in continuous coverage over the 1.5m × 20cm area
About the 120° detector:

- Uninterrupted operation since installation in 2002
- Position res$^n \sim 1.2$ mm (FWHM)
- Global rate $\sim 500$kcps
- Sensitive area: $150\text{cm} \times 20\text{cm}$
- Radius of curvature: 70cm
- Picture elements: $2 \times 10^6$
- Resolution elements: 250 k
- Low Gas Gain $\sim 50$
- Absolute position stability ($\sim 50 \mu$m)
- Long term elec. stability (10yrs +)
Wombat Instrument at ANSTO’s Opal Reactor
(HIPD: High Intensity Powder Diffractometer)

- One of the most powerful high intensity powder diffractometers in the world
- rapid crystal structure determination for phase transitions, chemical reactions and rapid kinetic measurements
- Analysis of very small samples (down to 10mg)
- Complex sample environments, e.g. pressure cells

- 120° detector installed in 2007
- Has operated very stably, without interruption, for these last 5 years
- Prolific publication output
Two-Dimensional, Pixel Detector for Neutrons

Operation in ionization mode, i.e. unity gas gain, with electronics channel on every pad. Such a detector is not feasible without ASICs.

24 cm × 24 cm anode pad board, with 5mm × 5mm → 2304 pixels

Weighting potentials for a single pad in a parallel plate geometry

64 channel 2mW ch⁻¹

ASIC side

Pad side
Thermal Neutron Response, Pixel Detector

$^3\text{He} + n \rightarrow ^3\text{H} + p$ (+764 keV)

(≈25-30k electrons, or ~5 fC)

Completely assembled detector
Readout ASICs in the vessel; power dissipation <10W total

Intensity response to illumination with point source of neutrons.
Boundaries in green represent pads read out by one 64 channel ASIC - there are 36 ASICs in total, 2304 pads.

Presently preparing a contract with ANSTO for a 1m × 1m detector based on this pad technology for SANS. Value ~ $1.8M (Work for Others)
# Instrumentation Radiation Detector Development

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<th>Medium</th>
<th>Detector Type</th>
<th>Application</th>
<th>Directorate/Competency</th>
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<tr>
<td>Semiconductor</td>
<td>Si: X- &amp; γ-ray Detectors</td>
<td>X-ray Detectors for Light Sources</td>
<td>BES and Photon Sciences</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PET/MRI Imaging</td>
<td>Env. &amp; Life Sciences</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X-ray Detectors</td>
<td>Other Labs (+WFO)</td>
</tr>
<tr>
<td></td>
<td>Si: Charged Particle Detectors</td>
<td>RHIC, ATLAS, Other HENP Expts</td>
<td>Nuclear and HE Physics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Polarimetry at RHIC</td>
<td>Accelerator Development</td>
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<td></td>
<td>CFN Technology Support</td>
<td>BES and Photon Sciences</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Biomedical Detectors</td>
<td>Env. &amp; Life Sciences</td>
</tr>
<tr>
<td></td>
<td>Si: CCDs</td>
<td>LSST and Astrophysics</td>
<td>Nuclear and HE Physics</td>
</tr>
<tr>
<td></td>
<td>Ge: X- &amp; γ-ray Detectors</td>
<td>X-ray Detectors for Light Sources</td>
<td>BES and Light Sources</td>
</tr>
<tr>
<td></td>
<td>Diamond: X-ray Detectors</td>
<td>X-ray Monitors/Det. for Light Sources</td>
<td>BES and Light Sources</td>
</tr>
<tr>
<td>Liquid</td>
<td>Noble Liquid TPCs</td>
<td>Neutrino and Special Detectors</td>
<td>Nuclear and HE Physics</td>
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<tr>
<td></td>
<td>Noble Liquid Calorimetry</td>
<td>RHIC, ATLAS, Other HENP Expts</td>
<td>Nuclear and HE Physics</td>
</tr>
<tr>
<td>Gas</td>
<td>Gas Detectors (Wire, Micropattern, Ionization)</td>
<td>X-ray Detectors for Light Sources</td>
<td>BES and Photon Sciences</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Neutron, X and γ ray Detectors for HS</td>
<td>GARS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Neutron Detectors</td>
<td>Other Labs (+WFO)</td>
</tr>
</tbody>
</table>
Detectors for Medical Applications
Small Animal PET (RatCAP) and MRI (at 9T)

12 modules
384 pixels
4mm²

12 output lines

511 keV

511 keV

e⁺
e⁻

Small Animal PET (RatCAP) and MRI (at 9T)
Laser/photocathode Studies
Need for *high QE-long life-low thermal emittance* cathode for ERL, FEL applications recognized in ~2001. Research started soon after ...

**Cathode Fabrication for ERL:**

Recent Result with Cathode Fabricated @ BNL, tested @ JLab

- Current density of 166 mA/mm²
- Thermal emittance measurement in progress

*Unique project to understand basic science of the evolution of cathode fabrication at NSLS, CFN, IO*

Cathode evolution measured with XPS in CFN
Wrap-up
Current and Future R&D and Projects

- State-of-the art Microelectronics essential everywhere; integration with detectors (includes WFO)
- Large Synoptic Survey Telescope (LSST) – Sensor development: BNL entry into astrophysics
- X-ray detectors for photon sciences, and space experiments (WFO)
- Laser applications, photoemission, optics and opto-electronics, ultra short pulse generation and measurement - toward ERL
- Unique contributions to beam diagnostics at RHIC and NSLS-II (e.g., beam position monitor)
- Diamond detectors for use at NSLS-II
- Medical imaging technology (PET, MRI), with Stony Brook
- Neutron detectors for NNS, SNS, LANL, ANSTO (WFO) – BNL a leader in the field
- Long Baseline Neutrino Experiments (LBNE) – Liquid argon time projection detector development: BNL key role in future neutrino experiments
- ATLAS Detector upgrades (e.g., recent CERN tests, V Polychronakos)
- Detectors for RHIC upgrades and e-RHIC
- Optical metrology and Nanofabrication applications
- How to develop high technology contributions to growing applied programs, e.g. energy issues – collaborative efforts with a key scientist are essential.
Two dominant research activities on “exotic” transistors, that promise higher speed and higher circuit density

**Looking far ahead, ?? years**

1. **Single electron transistor:**

The gate voltage controls the tunneling current through a quantum dot (QD) (since mid-1980s).

C = 1aF, Q = 1.6 × 10^{-19} C, V = 160 mV

1.5 nm QD operation demonstrated

2. **Carbon Nanotube Transistor:**

Graphene rolls up to form a cylindrical channel with improved charge transport properties (since mid-1990s).

Uniformity and reproducibility have not yet reached levels required by microelectronics
Acknowledgements to the excellent team we have in the Division, and to our collaborators
Back-up
Examples of “Return on Investment”

A key element: in most cases: at the time of an investment in instrumentation R&D, the science program or project that made use of the development had not been initiated

- **Liquid Argon Calorimetry (1973)**
  Has become a high resolution calorimetry technique for HEP. Used in many experiments at CERN, DESY, SLAC. This development significantly increased BNL role in LHC/ATLAS, and will lead to a role in future neutrino detectors.

- **Low Noise Techniques (1975)**
  Fundamental studies for optimized front-end electronics; circuit techniques now utilized in all ASICs for detectors; numerous ASICs for most science areas.

- **Optical Metrology (1983)**
  Critical, non-contact, measurement techniques for precision aspheric optics for NSLS

- **Silicon Drift Detectors (1983)**
  Seen as one of most dramatic developments in Si detectors; immense impact in X-ray science, HEP/ NP

- **Interpolating Cathode Strip Chambers, CSCs (1984)**
  Developed for multi-wire x-ray detectors, resulted in increased BNL role in PHENIX and ATLAS

- **Micro/Nanofabrication (1990)**
  MEMS and EM development, expertise used in clean room design for CFN

- **Photocathodes (1990)**
  The highest current electron sources for accelerator research and FELs

- **Microelectronics (1990-2010) – a critical enabling technology for many programs**
  Examples of detectors not possible without ASICs: Si dets. for NSLS, LEGS TPC, RatCAP, new neutron dets., CZT detectors, Proxiscan, LAr neutrino detectors, …

- **Beam Diagnostics (2006-):**
  Novel beam profile measurements for RHIC and other accelerator facilities
Ingredients for success: Collaboration with lead scientists

Key to a successful collaboration/project are the lead scientist(s) in the field, and the diverse expertise from within the Division

Examples of successful collaborations:

- **Development of RatCAP**
  Medical Dept: David Schlyer, Paul Vaska; Physics: Craig Woody + 9 Instr. staff

- **Development of ATLAS detectors**
  Physics Dept: Francesco Lanni, David Lissauer, Vinnie Polychronakos + 11 Instr. staff

- **Advanced X-ray detection techniques**
  NSLS Dept: Peter Siddons + 11 Instr.

- **Optical metrology of grazing incidence mirrors**
  NSLS Dept: Beamline scientists + 2 Instr.

- **X-ray detectors for soft x-ray microscopy**
  NSLS Dept / SBU/ANL: Chris Jacobsen + 9 Instr.

- **Position-sensitive thermal neutron detectors for homeland security**
  NNS Dept: Peter Vanier + about 6 Instr. personnel + microelectronics

- **LSST focal plane sensors:**
  Physics Dept: Morgan May (Sam Aronson) + 7 Instr.

- **DOE’s OBER: neutron detectors for protein crystallography**
  LANL: Benno Schoenborn, Paul Langan + 9 Instr.

- **DOE’s BES: neutron detectors for SNS**
  ORNL/SNS: 6 Instr.

- **LBNE/μBoone Lar neutrino detectors**
  Physics Dept, Columbia, Yale, FNAL + 5 Instr.

Some more examples: