BNL 66826 rev -03

Instrumentation Division

R&D Programs
Facilities
Staff

BROOKHAVEN
NATIONAL LABORATORY

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April 2003

http://www.inst.bnl.gov

This work was sponsored by the U.S. Department of Energy under Contract No. DE-AC02-98CH10886.

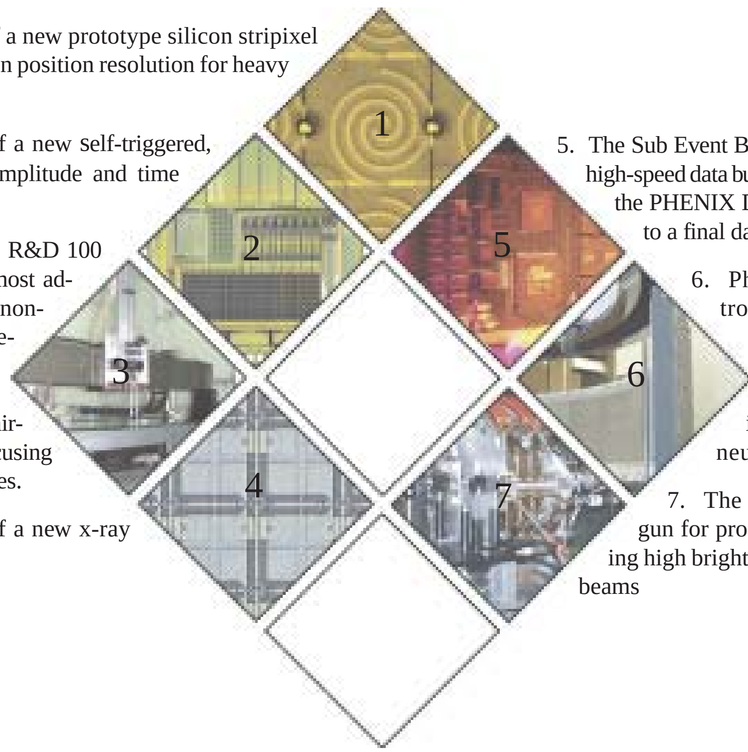
On the Cover:

1. Microphotograph of a new prototype silicon stripixel detector with sub-micron position resolution for heavy ion detections

2. Microphotograph of a new self-triggered, self-sparsifying peak amplitude and time measurement ASIC.

3. Long Trace Profiler, R&D 100 award winner and the most advanced instrument for non-contact optical measurement of the surface figure and surface roughness on large aspheric mirrors, used for X-ray focusing in synchrotron beam lines.

4. Microphotograph of a new x-ray active pixel sensor.



5. The Sub Event Buffer PCI Card provides high-speed data buffering and transfer from the PHENIX Data Collection modules to a final data storage system

6. Photo of the 120° Neutron Detector during assembly. This detector represents the current state of the art in gaseous thermal neutron imagers.

7. The GV/m pulsed electron gun for producing and characterizing high brightness ultra short electron beams

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Brief Overview

Mission:	Develop state-of-the-art instrumentation for current and future Laboratory programs
Established:	1948
Division Head:	Veljko Radeka
Staff:	28 Scientific/Professional; 16 Technical; 4 Administrative
Research Areas:	Semiconductor detectors, gas and noble liquid detectors, micro-electronics, lasers and optics, micro/nano fabrication
Facilities:	Clean rooms for semiconductor processing (Class 100) and detector fabrication Laser and optics laboratories Hybrid and integrated circuit design and testing Microfabrication and electron microscopy laboratory Vacuum deposition laboratory Printed circuit fabrication Irradiation facility
Total Laboratory/ Office Space	36,000 sq. feet

Highlights of Accomplishments:

Fast transistorized electronics for physics experiments	1956
First video game	1958
Positron emission tomography (PET) detector	1960
Neutron detectors	1973
Liquid argon calorimeter	1973
Synchrotron radiation detectors	1982
Silicon drift detector	1983
Long Trace Profiler	1987
Monolithic low-noise circuits	1990
Nanostructures	1994
Deep sub-micron low-noise circuits	1999

Our Mission

To develop state-of-the-art instrumentation required for experimental research programs at BNL, and to maintain the expertise and facilities in specialized high technology areas essential for this work. Development of facilities is motivated by present BNL research programs and anticipated future directions of BNL research. The Division's research efforts also have a significant impact on programs throughout the world that rely on state-of-the-art radiation detectors and readout electronics.

Our staff scientists are encouraged to:

- Become involved in challenging problems in collaborations with other scientists.
- Offer unique expertise in solving problems.
- Develop new devices and instruments when not commercially available.

Scientists from other BNL Departments are encouraged to bring problems and ideas directly to the Division staff members with the appropriate expertise. Division staff is encouraged to become involved with research problems in other Departments to advance the application of new ideas in instrumentation. The Division Head integrates these efforts when they evolve into larger projects, within available staff and budget resources, and defines the priorities and direction with concurrence of appropriate Laboratory program leaders. The Division Head also ensures that these efforts are accompanied by strict adherence to all ES&H regulatory mandates and policies of the Laboratory. The responsibility for safety and environmental protection is integrated with supervision of particular facilities and conduct of operations.

Historical Perspective

The Instrumentation Division was founded in 1948, shortly after the Laboratory began operations, for the purpose of supplying detectors and fast electronics for high energy and nuclear physics experiments. The founders of the Laboratory recognized that specialized skills and facilities would be needed to develop sophisticated detectors for the proposed experimental programs and established a dedicated facility for that purpose. With the development of increasingly complex detectors and electronic systems, this rationale is as true today as it was 50 years ago.

As the major User Facilities of the Laboratory were built, the Instrumentation Division developed detectors to study the particles and radiation that were produced. Gas, liquid, and semiconductor detectors for making precise measurements of position, time, and energy soon set the standard for the state-of-the-art and have been emulated worldwide. The front-end electronics forms an integral part of the detection system, and the Division devotes a high level of effort to co-developing optimal signal processing, using the latest technology, for each detector that is built.

During the late 1970's research in areas related to optics started in the Division. The need for accurate characterization of x-ray mirrors used in synchrotron radiation beam lines resulted in the establishment of the Optical Metrology laboratory. A Laser Laboratory was established to study problems related to the generation, acceleration, and detection of particles and for high speed data acquisition and transmission. A capability to fabricate micro-machined structures has also been added, which complements our optics and microelectronics efforts.

Complementing our scientific expertise is a unique dual mode of conducting research. As a participant in a major experiment, an Instrumentation team builds a specialized detector along with its associated signal-processing electronics to create a highly-effective, customized instrument. It has been through this mode of scientific collaboration that world-class experimental apparatus has been developed here.

At the same time, through our generic research mission, the Instrumentation Division is free to study new techniques that have no immediate application to any experimental program. In this way several groundbreaking developments have occurred. Examples are: the silicon drift detector, high-aspect ratio micromachining techniques, the video game, ultrashort laser pulse characterization, and ultralow-noise preamplifiers for low-capacitance detectors. More novel concepts, now in an embryonic stage of development within the Division, may one day serve as a foundation for entirely new classes of instruments.

Core Technologies

Research in the Instrumentation Division is concentrated in 5 core areas:

- **Semiconductor detectors**

  Pixel detectors
  Drift detectors
  Photo sensors

- **Gas and noble liquid detectors**

  X-ray and gamma ray detectors
  Thermal neutron detectors
  Calorimetry
  Neutrino Detection

- **Microelectronics**

  Low noise analog
  RF for remote sensors
  Data acquisition and control

- **Lasers and optics**

  Generation and characterization of ultra-short photon and electron bunches
  Optical metrology

- **Micro/nano fabrication**

  Sensors
  Detector microstructures
  Nanoscience test structures

Facilities

Facility	Special Capabilities
Gas Detector Laboratory	Clean rooms, fabrication and x-ray and particle test facilities
Semiconductor Detector Laboratory	Clean rooms, oxidation, mask alignment, wire bonding, detector characterization and testing, defect analysis system
Hybrid Circuits Laboratory	Low noise electronics prototype development
Monolithic Circuits Laboratory	Design, simulation, testing
Computer-aided Circuit Layout	Design of detector electrodes and multilayer circuit boards
Multilayer Printed Circuits	Fabrication of detector electrodes and multilayer circuit boards using FR4/ Polyimide/Teflon/glass and tetrafunctional materials
Optical Metrology Laboratory	Digital optical surface profiler, Long Trace Profiler
Laser Laboratory	Photoemission and fast switching studies; Ultrafast laser applications
Micro/nano Fabrication Laboratory	Fabrication of micro/nano structures, analytical electron microscopy
Vacuum Deposition Laboratory	Coatings and multilayers
Solid State Irradiation Facility	^{60}Co source. Radiation effects in insulators and semiconductor materials and devices

Scientific and Professional Staff

Areas of Interest and Expertise

V. Radeka, Division Head

28 Scientists and Professionals; 48 total including technical and administrative

W. Chen[1]	Designing and processing for position sensitive silicon detectors.
G. De Geronimo	Low noise monolithic integrated circuits.
R.P. Di Nardo	Electrical and optical coatings, detector fabrication, and specialized materials processing; training coordination & quality assurance.
J. Fried	Experiment control and data acquisition system design.
J.A. Harder	High speed electronics, monolithic circuits, analog and digital system design.
A.T. Hrisoho[2]	Visiting Senior Scientist: signal processing and noise in physical measurements; detectors and electronics.
S.S. Junnarkar	Signal processing electronics, high speed data acquisition.
A. Kandasamy	Monolithic circuits, CAD, testing; design automation.
J.A. Kierstead	Radiation effects in optical and semiconductor material and devices.
Z. Li	Fabrication methodology for position sensitive silicon detectors; physics of detector grade material; device physics and radiation hardness
D. Makowiecki	Detector grade material; device physics; radiation hardness.
J.A. Mead	Signal processing electronics and low background counting systems.
P. O'Connor	Monolithic circuits, signal processing electronics, semiconductor device physics.
J-F. Pratte	Low noise monolithic integrated circuits.
S. Qian	Design and development of high-precision optical metrology instrumentation.

[1] Physics Department

[2] Linear Accelerator Laboratory, Orsay, France

V. Radeka	Signal processing and noise in physical measurements; detectors and electronics.
S. Rankowitz	Systems, electronics, and design automation.
P. Rehak	Physics of particle and radiation detectors; semiconductor detectors.
S. Rescia	Signal processing and noise in physical measurements; detectors and electronics.
N.A. Schaknowski	Development of high resolution, gas-filled, radiation detectors and ultra-high vacuum systems.
J. Smedley	Generation and characterization of high brightness, ultra short electron bunches
G.C. Smith	Physics of and electronics for advanced ionization detectors; applications of such detectors to particle physics, solid state physics, and biology.
T. Srinivasan-Rao	Short pulse, high power, IR, visible and UV lasers, laser driven photocathodes for electron gun and switching applications, electro-optic sampling and generation of coherent short pulse XUV, x-ray radiation.
F.W. Stubblefield	Multiprocessor operating systems, high-speed data acquisition electronics and computer interfaces, medical electronics for flow microfluorometry.
P.Z. Takacs	Optical design and testing; figure and finish metrology of grazing incidence optical components; scattering of x-rays from smooth surfaces and its relation to surface topography.
T.Y.F. Tsang	Ultrafast laser spectroscopy; high-intensity laser-matter interaction; surface-enhanced spectroscopy; nonlinear optics; fiber optics; optical detectors for high energy physics.
J.B. Warren	Analytical electron microscopy, including SEM, EDX, microdiffraction, and computer simulation of crystal defect images, fabrication of microstructures.
B. Yu	Physics of and electronics for advanced ionization detectors; applications of such detectors to particle physics, solid state physics and biology.
Q. Zhao	Design and testing of S band RF injectors; electron beam diagnostics.

Technical Support Staff

Several technical support activities in the Instrumentation Division are essential to the Scientific and Professional areas in the Division and to many other programs and activities throughout the Laboratory.

Printed Circuit Board Design and Layout

Supervisor	A. Kandasamy
Technical Advisor	J.A. Mead
Technical Staff	K.A. Ackley, R.E. Machnowski, R.J. Ryan, K.J. Wolniewicz

Printed Circuit Board Fabrication

Supervisor	J.A. Mead
Lead Technician	R.J. Angona
Technical Staff	H. Hansen

Electronics Technical Support

Supervisor	J.A. Mead
Technical Staff	F.C. Densing, D.A. Pinelli, J. Triolo

Radio Communications and Audio Services

Supervisor	S. Rankowitz
Lead Technician	G.T. Walczyk
Technical Staff	R.L. Dumont

Laser and Electro-optics Technical Support

Supervisor	T. Srinivasan-Rao
Technical Staff	M. Montemagno, J. Walsh

Semiconductor Detector Fabrication

Supervisor	Z. Li
Lead Technician	R.H. Beuttenmuller
Technical Staff	D.C. Elliott

Gas Detector Technical Support

Supervisor	G.C. Smith
Technical Staff	E.F. Von Achen

Machine Shop

Supervisor	R.H. Beuttenmuller
Technical Staff	W.R. King, R.R. Ryder

Administrative Support

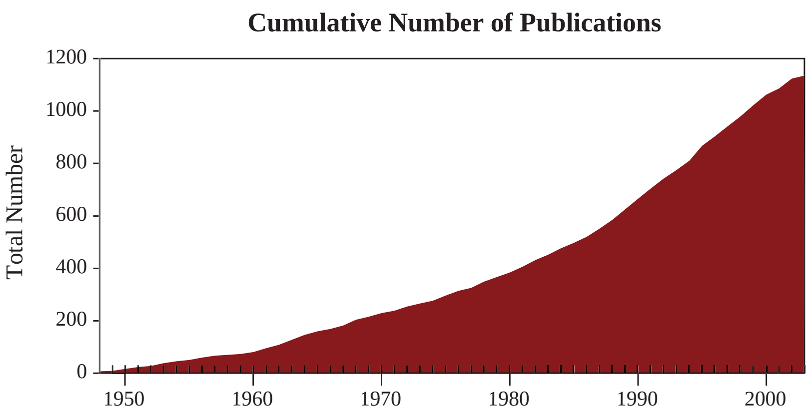
Supervisor	D. Grabowski
Staff	M.E. Brathwaite, B. Gaer, J. McGowan

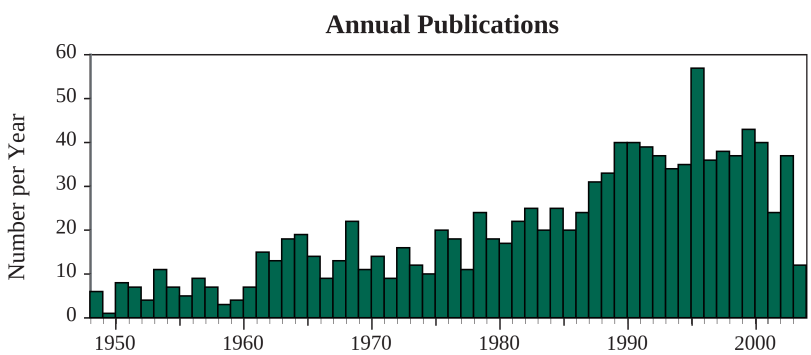
Collaborations

Project	Collaborators
Semiconductor Detectors	
Semiconductor Position Sensitive Detectors	Milan Poly; CERN
Multi-element and Silicon Drift Detectors	Wayne State; NSLS
Radiation Damage	CERN; Univ. Hamburg; Univ. Florence
Gas and Noble Liquid Detectors	
X-ray Detector 1D & 2D, <100µm FWHM resolution	Biology; NSLS; Physics
High Resolution (<400µm FWHM) Neutron Detectors	Chemistry; Biology; LANL; NIST; SNS
Interpolating Pad Chambers for High Particle Multiplicities	Physics; CERN
Fast Noble Liquid Calorimetry; High Resolution EM Calorimeter with Liquid Krypton or Argon	Physics + 9 inst.; CERN; Columbia Univ. (Nevis Labs.)
Microelectronics	
Hybrid and Monolithic Low Noise Amplifiers	Penn; Milan Poly; Pavia; Symbol Technologies
Front End Electronics for Various Detectors	LAL Orsay; Pavia; Penn; eV Products
Fast Noble Liquid Calorimetry Electronics Operated at Low Temperatures	Physics; LAL Orsay; CERN
Data Acquisition Systems for Particle and Position Sensitive Detectors	Biology; Chemistry; Physics; NSLS; SNS
Optics And Laser Technology	
Optics Metrology and Properties of Optical Surfaces	NSLS; APS; LBL; Ocean Optics, Inc.
Lasers, Photocathodes, Fast Switching	Physics; ATF; SLAC; CERN; Brookhaven Technology Group; TJNAF; Advanced Energy Systems
Electro-optics and Ultrashort-Laser-Pulse Measurement Techniques	AGS; Physics; CPPM; Sandia; Montana State Univ.; Univ. of Pittsburgh
Micro/nano Fabrication	
Micro/nano Structure Fabrication	New Jersey Institute of Technology; SUNY

Publications

Solutions to problems encountered in the development of state-of-the-art detectors and fast electronics often involve investigations into the fundamental physical processes behind these devices. Instrumentation Division policy has always been to encourage staff members to publish the results of these investigations and to actively participate in collaborations with other institutions. The unique expertise and scientific contributions of Division staff have been recognized in the national and





international scientific communities by numerous requests to participate in review panels and present invited talks at conferences and seminars throughout the world. The publication record of Instrumentation Division staff over the 5 decades of our existence is shown in the following charts. A milestone was reached early in 1999 when the total number of publications reached the 1000 mark.

The complete publication list for the Division can be found on its web site at the following world wide web address: http://www.inst.bnl.gov/publications/publist.html. Requests for individual publications can be made directly to the Division office or through the Research Library at Brookhaven National Laboratory.

Future R&D Directions

Instrumentation Division R&D efforts directly oriented toward future BNL facilities and programs

RHIC	New detector techniques for STAR and PHENIX; High average current electron source for e cooler and eRHIC.
LHC	ATLAS liquid argon calorimeter; low noise electronics for muon detectors
NSLS	Energy-resolving x-ray detectors for high count rates; Position-sensitive silicon and gas detectors for x-ray scattering
SNS	Neutron detectors with time-of-flight capability
CAP/ATF	High brightness electron sources
Muon Collider	Detector techniques for very high backgrounds
Medical Imaging	Special PET detectors
EENS Collaborations	Safeguards program — n, γ detectors; IAEA safeguards program; Remote detection Nano-particle analysis

Detector Development Programs

The program of the Division and the development of necessary facilities are motivated by present research programs and anticipated future directions of BNL programs. Thus a large part of our detector research and development is oriented toward the experimental programs at the AGS and RHIC, particularly with respect to future upgrades of the PHENIX and STAR experiments. With the needs of future hadron colliders in view, a program in detector development is being pursued in support of the BNL involvement in the ATLAS experiment at the LHC.

A significant part of the detector development program concerns x-ray and neutron scattering studies of molecular and crystal structures. Advanced synchrotron detectors are provided for the NSLS, and techniqies are studied for very high rate experiments at the APS (Argonne). A wide range of position sensitive neutron detectors are made in support of DOE programs at LANSCE (Los Alamos), IPNS (Argonne), SNS (Oak Ridge), as well as at NIST.

There are three major areas of detector development in the Division:

- **Semiconductor Detectors**
- **Gas Detectors**
- **Cryogenic Detectors**

Each type of detector is optimized for detection of a particular type of radiation. Development and construction of these detectors requires the specialized resources and facilities that are found in the various laboratories of the Division.

▼ The Instrumentation Division is a leader in the development of thermal neutron detectors. Shown here is a large, curved detector containing eight independent multiwire segments for protein crystallography studies at Los Alamos.

Semiconductor Detectors

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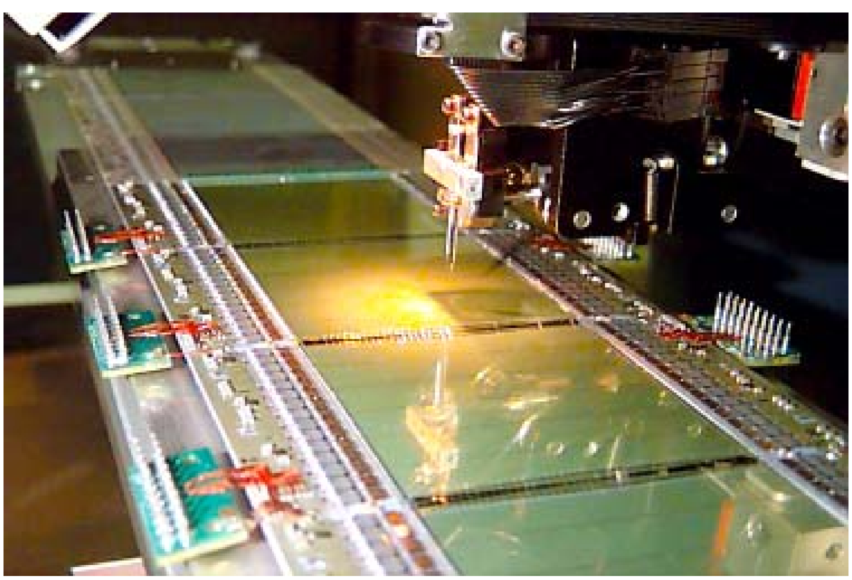
W. Chen
P. Rehak
R. Beuttenmuller
D. C. Elliott

Semiconductor charged particle detectors first became important to nuclear physics research in the early 1960s. Brookhaven's Instrumentation Division was one of the first groups to study, develop and produce these devices in the USA and continues as a leader in this area to this day. In 1964 lithium-drifted germanium detectors were introduced, and BNL promptly began to produce high quality gamma-ray spectrometers using these devices. These in-house produced devices allowed BNL nuclear physics to excel in the field of gamma ray spectroscopy. Development continued at BNL with these detectors as the material of choice changed from lithium-drifted to high purity germanium. Along with the production of high-resolution devices, BNL also made early and significant contributions to the understanding of radiation damage effects in germanium, starting in 1967 and continuing through 1979. In the early 1980s planar manufacturing technology was introduced to silicon detector fabrication, coinciding with interest from high energy physics in high precision, position-sensitive charged particle detectors. A cleanroom was established at BNL and IC fabrication methods were introduced, yielding detectors first for the CERN NA34 experiment in 1985. We have since designed and produced a wide variety of silicon detectors (pad, micro-strip, drift, and pixel detectors) with applications in HEP, X-ray spectroscopy, and nuclear physics at BNL, CERN, FNAL, LANL and other institutes. Studies on radiation effect in silicon have continued along with the detector development work, for which BNL remains one of the leading groups in the world.



Detector R&D

Semiconductor materials have been used for detecting radiation for almost as long as the transistor has been invented. About 15 years ago, three new kinds of semiconductor detectors were proposed:

- Drift detector
- Fully depleted charge couple device (CCD)
- Low capacitance drift photodiode and X-ray detector

The invention of these new detectors took place in the Instrumentation Division of BNL, where most of the analysis was done. The first detectors were produced at LBNL and at MPI Munich. Recently, several experiments at CERN and at BNL have used, or are presently using, silicon drift detectors to measure the position of fast charged particles passing through the detector. Experiments planned at RHIC and LHC are building large vertex detectors based on silicon drift detectors. These detectors are the direct result of development work done in this Division. The usefulness of these detectors has extended into other areas of science. Presently, silicon X-ray drift detectors are commercially available for microanalysis in electron microscopes. A fully depleted CCD is ready to be launched in 1999 as a main focal plane detector for the Multi-Mirror X-ray (MMR) satellite mission.

Simulation and development of novel Si detectors with non-conventional electrode arrangement for better position sensing (possible sub-micron resolution) and improved radiation hardness to displacement radiation sources such as neutron, proton, and pions, are currently underway at BNL.

Semiconductor Processing

The Instrumentation Division's Semiconductor Detector Development and Processing Lab (SDDPL) has been the main R&D center for development and production of prototype solid-state radiation and particle detectors (RPD) for various nuclear and high

◀ Silicon Vertex Tracker drift detector modules for the STAR Project are wire-bonded to each other (center) and to Hybrid Amplifiers (sides) on the Automatic Wire Bonder machine. The Bonder is capable of placing 2 bonds per second, but is normally operated at half that rate. Each module requires over 2,400 individual bonds to be made. All 216 modules will require about 531,000 total bonds, which will take almost 20 working days to complete.

energy physics experiments at BNL and other sites (e.g. CERN and FNAL) around the world. Its state-of-the-art design and processing facility for RPD is unique in the United States among university, industrial, and other national laboratory facilities, and is one of only a very few that exists elsewhere in the world. Our capabilities encompass the complete detector production process, which includes simulation of processing and device electrical behavior, detector and mask design, all the necessary detector processing steps (from oxidation to photolithography to metallization) except for ion implantation (performed by an outside service with a turnaround time of 2-3 days), and detector testing and characterization.

Facilities and Tools

Simulation Tools

The processing simulation tool allows one to go through the entire detector processing even before a single wafer is handled. This step provides understanding of the physics of detector processing, helping to identify and eliminate potential problems before the actual processing. Key features of the simulation tool include doping profiles of various ion implants.

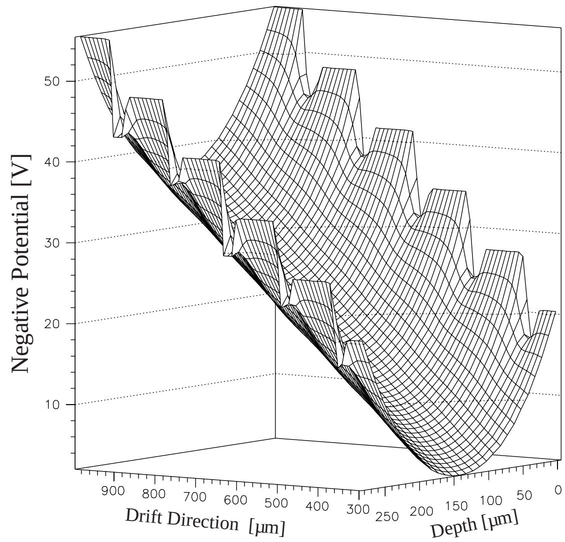
The device simulation tool allows one to check detector behavior under working biases before processing and testing. This step provides the understanding of detector physics under working conditions and prevents potential failures of detectors before they are processed. Key features of the simulation tool include profiles of electric potential, electric field, and carrier concentrations.

Fabrication Facilities

A new Class-100 cleanroom has been in use since June 1996. The 600 sq. ft. room includes fully-instrumented wet benches, hot deionized water, better ventilated photoresist spinner, larger gowning area with pass-through, megasonic cleaning, automatic photoresist coating track, new MA6 mask aligner with double-sided photolithography capability, two-target sputtering system, exterior furnace installation, and a large capacity nitrogen boil-off system. Conditions inside the room, with constant temperature and humidity, are monitored by a central control unit. Verification of Class-100, or better, operation has been achieved. Supporting systems include laser wafer cutter and automated wire bonder.

After fabrication, detectors are tested using our testing and analytical facilities:

- Standard probe station for I-V, C-V tests on test diodes



▲ A 3-D plot simulation of the electric potential distribution, in a silicon drift detector for STAR at RHIC

- Probe-card testing facility for STAR drift detectors
- Transient current/charge technique (TCT) with red and infrared lasers for charge collection measurements and detector internal electric field mapping.
- Defect analysis systems: I-DLTS, TSC, and TCT, with laser lights for carrier generation (mainly used for identification and analysis of processing-related defects and irradiation-induced defects).

Radiation Damage Effect Hardness Studies

Silicon radiation detectors continue to be applied to nuclear and high-energy physics experiments in both increasing complexity and quantity. Detector radiation hardness against displacement damage has become a major issue in the development of silicon tracking detectors for high-energy physics experiments at the LHC.

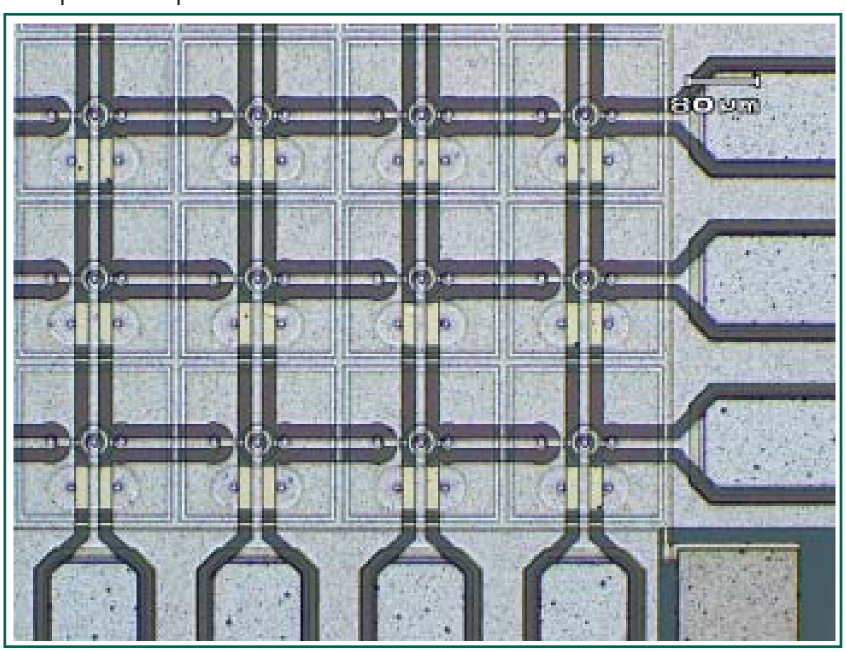
We have been studying the effects of fast neutron and ionizing particle radiation on the electrical properties of silicon radiation detectors, which are in widespread use as position sensitive detectors in high energy physics experiments. These damage effects will be especially important in high luminosity experiments

▼ Double-sided mask aligner station in the Class 100 cleanroom facility.

such as at the LHC. Deep Level Transient Spectroscopy (DLTS), Thermally Stimulated Current (TSC) measurements, and Transient Current Technique (TCT) reveal specific defect structures in the silicon lattice that cause increased thermally-generated current (dark current), space charge transformations (or "inversion"), and short and long term annealing effects. Interaction of defects with benign, endogenous impurities in the silicon material used in these detectors offer possible amelioration of the effects of bulk displacement defects and we are pursuing methods of enhancement of these impurities (e.g., O, Sn, C, N).

The defect analysis system (DLTS, TSC, and TCT), including optical defect filling techniques, has been first developed here at BNL and is now in routine use in analyzing irradiated samples. The "reverse anneal" effect was correlated with a deep acceptor at E_c-0.42 eV, which is usually attributed to the di-vacancy or di-vacancy related cluster defects. High carbon content material was found to exhibit annealing and radiation effect properties not very different from normal material upon neutron radiation. Positron annihilation studies have been applied to neutron-irradiated silicon for the first time and an indication of clusters (voids), which break up during anneal and supply vacancies, has been observed. Measurements on oxygenated silicon detectors using BNL's oxygen diffusion technology (developed in 1992) have shown improved rad-hardness to radiation of charged particles (protons, pions, etc.) of a factor of up to 3 from standard materials. The BNL developed High-Temperature-Long-Time (HTLT) silicon (oxygenated), and its variation with the controlled introduction of thermal donors (TD), the HTLT(TD) silicon, have been found almost totally radiation hard to gamma (electron) radiation, partially radiation hard (improved by a factor of 2 or more) to charged particles (protons, pions, etc.). In particular, the HTLT(TD) silicon detectors are the idea material for detectors operated in high charged particle environment (up to 10^{15} 1MeV neutron equivalent/cm^2). We are the first group to use low resistivity silicon materials for particle detectors with improved radiation hardness. Low resistivity silicon and oxygenated silicon are now the leading candidates of the actual material used for detector fabrication in LHC applications.

▼ Microphotograph of 12 pixels from a corner of an Active Matrix Detector. The horizontal lines distribute the controlling signals for the gates of switching transistors along each row of the matrix. The vertical lines carry charges accumulated in individual pixels to outside preamplifiers. Individual switching transistors are in centers of each pixel. The source of each transistor is the charge collecting electrode of a pixel, the gate is a ring connected to a horizontal controlling line and the drain is a small central disc connected to a vertical readout line. There are two layers of metal lines to accomplish the required connections.



Continued measurements of material-engineered samples will be made to establish electronic effects of specific structures (di-vacancy, clusters, etc.). Further studies will continue in defect/material engineering (gettering of the main defects by purposely- introduced impurities), structure engineering (different detector configurations for improved radiation tolerance), and operational engineering (low temperatures, charge pumping, etc.) to change the defect charge states that result in improved radiation hardness. We are a major contributor in CERN R&D collaboration (RD48, the ROSE collaboration, RD39 Collaboration, and RD50 collaboration) devoted specifically to the improvement of detector charge collection efficiency and development of radiation-hard silicon detectors for both ATLAS and CMS at the LHC and other experiments at CERN.

X-ray Active Matrix Pixel Sensor

A new detector concept, the *X-ray Active Matrix Pixel Sensor* (XAMPS), is being developed for protein crystallography. It is a silicon pixel array detector with matrix readout facilitated by integrated JFET switches. The XAMPS is conceptually similar to two other imaging devices: the CMOS active pixel sensor used for visible light imaging, and the active-matrix flat panel imager (AMFPI) which has applications in both visible light and X-ray imaging. The XAMPS detector was conceived from the start as a device to address the needs of protein crystallography. It combines attractive features of several technologies which originated in other fields (visible light imaging, high energy particle tracking). The main features of XAMPS are:

- like the CMOS active pixel sensor it uses integrated switch transistors and has fast readout;

- like the AMFPI it is sensitive to X-ray energies in the range of interest to crystallography, and can be made in large sizes;
- like the CCD it has nearly 100% fill factor and low noise (around 1 quantum equivalent);
- like the DEPFET it uses direct-converting high-resistivity silicon as a starting material and adds monolithically integrated JFETs for matrix readout;
- like the various pixel array detectors (PADs), with bump-bonded readout electronics, the XAMPS can resolve single photons and has dynamic range of more than 10^4.

Among all the detectors optimized for X-ray energies of interest to crystallography (typically12 keV), only the XAMPS combines 100% fill factor, single photon sensitivity, readout speed fast enough to accept the full intensity of third-generation light sources without mechanical shuttering, good combination of pixel size and overall area, monolithic assembly, and tolerance to radiation.

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Semiconductor Detector Fabrication Status

Detector	Application	Results/Status
400 element pad detector, ceramic overlay; three sets of charge-divided strips	NA 34 (CERN)	Used in exp. For three years Beuttenmuller et al., NIM A252 (1986) 471
512 element pad detectors, large and small interior holes	E814 (AGS, BNL)	Used for several years as multiplicity counter Giubelino, et al., NIM
192 element pad detectors square array	TRD test	Used at CERN for several years (V. Polychronakos)
192 element pad detectors circular array	NA 44 (CERN)	Used at CERN for several years (V. Polychronakos)
3" diameter cylindrical silicon drift detectors	NA 45 (CERN)	First drift detector application, Chen et al., IEEE TNS NS39, 619(1992), NIM A326 (1993)
STAR 6.3×6.3 cm^2 silicon drift detectors	SVT for STAR at RHIC	Prototype detectors for 216 detector SVT array Now installed in RHIC
50 micron pitch strip detectors	Muon Beam Finder (CERN)	In use for two years in M2 test beam (V. Polychronakos)
2 and 8 micron pitch strip detectors	Accel. Test Facility, BNL	Production used PdSi method Z. Li et al., IEEE TNS NS38 (1991)
50 micron pitch strip detectors	Current AGS	L. Remsberg, V. Polychronakos
PHOBOS test detectors	PHOBOS at RHIC	Polymide coating test, FOXFET structures Ryan, Busza, MIT
120 element array high-rate EXAFS detectors	NSLS X19	Successful tests with 16 elements Pullia et al., NIM, BNL-62142, 62735
16 element strip for diffraction	NSLS	Siddons (on-going)
Radiation effects test diode, gamma ray irradiation	BNL gamma source	Kraner et al., Italian Phys. Soc., Vol. 46, Baldini ed., Bologna (1994)
Radiation effects test diode, displacement damage effects	Fast neutrons	Z. Li et al., numerous publications
p-type pixel detectors ($n^+/p/p^+$) 48µm×192µm pixels, 120×8 array 96µm×96µm pixels, 16×60 array	Prototype for CMS at LHC	Lander, UC Davis Z. Li et al., NIM A435, 178(1999)
n-type pixel detectors ($n^+/n/p^+$) 125µm×125µm pixels, 24×32 array 250µm×62.5µm pixels, 12×64 array	Prototypes for CMS at LHC	Chien, Johns Hopkins Univ. Z. Li et al., NIM A409, 180(1998) W. Chen et al., IEEE TNS, Vol. 45, 348(1998)
n-type pixel detectors ($p^+/n/n^+$) 200µm×200µm pixels, 24×32 array n-type pixel detectors ($p^+/n/n^+$) 300µm×30µm pixels, 16×16 array	Fermilab BteV	Anderson, Kwan, Fermilab Z. Li et al., NIM A409, 180(1998) W. Chen et al., BNL-64979
100 µm pitch large-area strip detectors 37 cm^2 sensitive area, AC coupled with implanted biasing resistors	Prototype for PP2PP at RHIC Roman Pot	Guryn, Physics To be tested at Fermilab On-going
Drift detector array for high-rate EXAFS	NSLS X19	Siddons, NSLS, to be tested, on-going
2 mm pitch strip detectors for low energy carbon ion detection (PC CNI Polarimeter)	RIKEN/AGS/RHIC	On-going
n-type pixel detectors ($p^+/n/n^+$) 50µm×425µm pixels, 24×32 array	CERN NA60	C. Lourenco, CERN Prototype detectors developed

Semiconductor Detector Fabrication Status, continued		
Detector	**Application**	**Results/Status**
50 and 500 µm pitch large-area strip detectors Beamscope	CERN NA60	C. Lourenco, CERN On-going
Edgeless Si strip detector with zero dead space LHC Total cross section measurement	CERN RD39/TOTEM Roman Pot	T. Niinikoski, CERN On-going
Pad (large 3mm×3mm pixels) detectors Compton camera	LANL	Mohini and J. Sullivan, LANL On-going
Strip and pixel detectors with micron spatial resolution 8µm to 75µm pitches,8µm×8µm to 75µm×75µm pixels	NASA	Proposal of Fe ion beam study cell approved On-going
Cryogenic Si detectors Improved radiation hardness	CERN RD39	T. Niinikoski, CERN On-going
Segmented Si micro-strip detectors with various pitches and segmented strips.	CERN NA60	C. Lourenco, CERN Tested by proton beam at CERN
Si stripixel detectors for PHENIX Upgrade: 2d position sensitivity, 1-side processing; 384 X strips, 384 Y strips; 4.6° stereo angle; 80 µm x 1000 µm pixels, 30x384 array	BNL/RIKEN	H. Enyo, RIKEN Prototype detector beam tested On going
Polarimeter 2 Si strip detectors Double-sided large (mm) Si strip detectors with filed-plate as channel-stopper on N-side	AGS/Physics	Sandro Bravar, Physics Prototype in processing
Active Pixel Sensors for protein crystallography	INST/Medical	P. Rehak et al., IEEE TNS, 49, (2002) p1006
Multi-element Si sensor with readout ASIC for EXAFS spectroscopy	NSLS	P. Siddons, NSLS G. De Geronimo et al., Proc. PIXEL2002 International Workshop, Carmel, CA, 2002; SLAC Electronic Conference Archive, in press.

Gas Detectors

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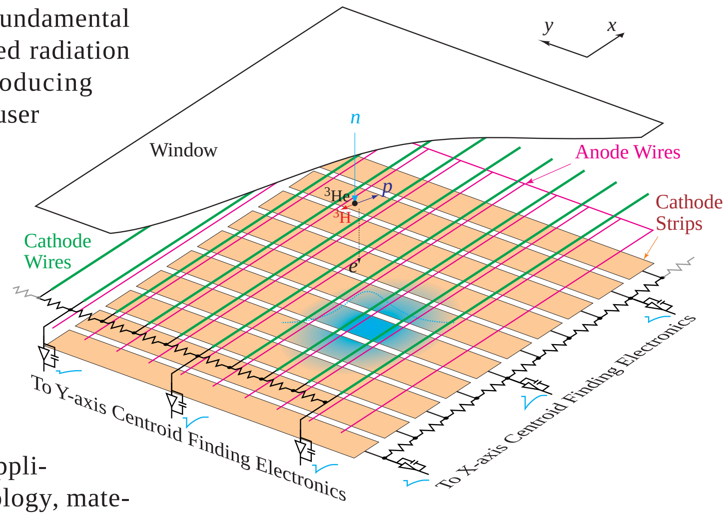
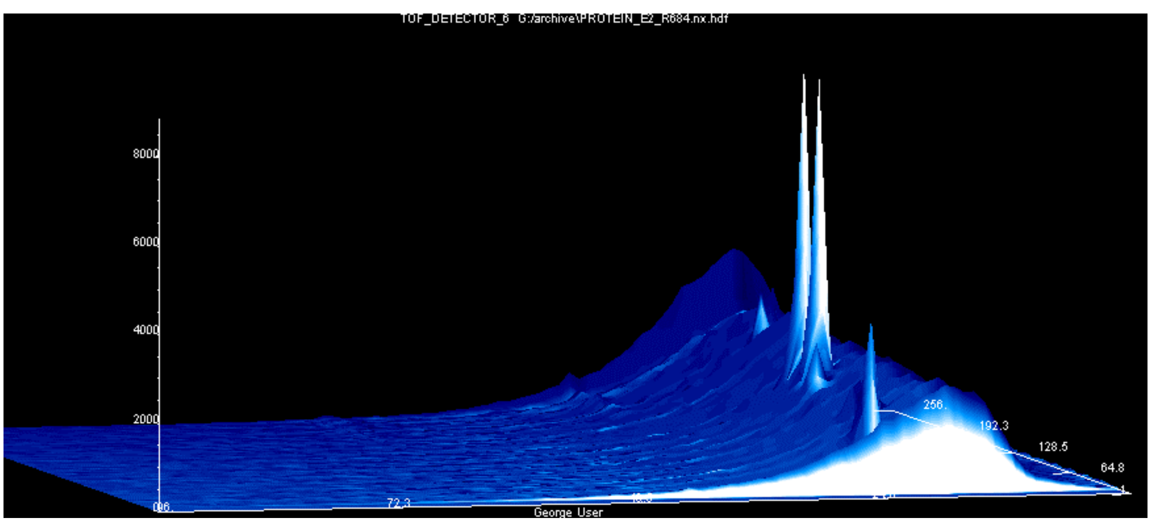
The gas detector group carries out fundamental studies on the physics of gas-based radiation detectors, and has resources for producing small numbers of detector systems for user facilities. Frequently involved with pioneering developments, the group initially made important contributions to high-energy physics detectors, such as the spark chamber in the 1960s, and the multi-wire proportional chamber in the 1970s. In the last two decades the group has continued to make significant improvements in gas detector performance and has also actively pursued their applications in additional fields such as biology, materials science and chemistry. The new century brings further innovative developments, with gas micro-pattern detectors providing potential enhancements to rate capability and position resolution, and easier, more reproducible fabrication methods.

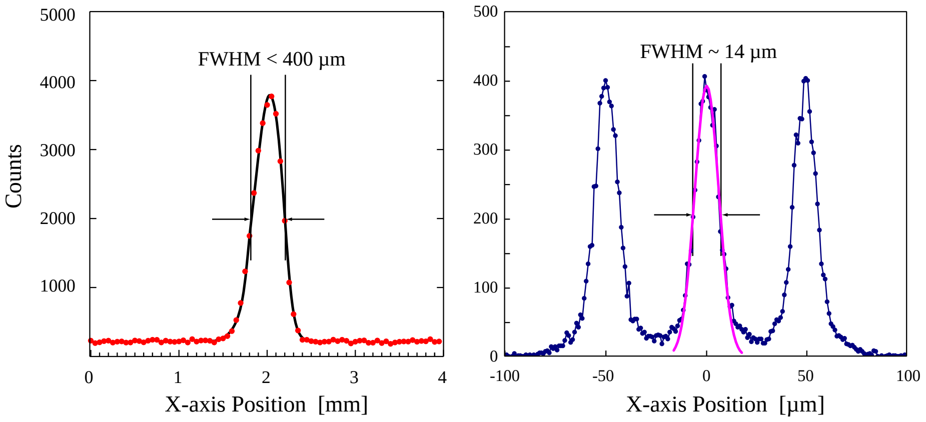


▲ Schematic diagram illustrating the principle of operation in all high performance imaging thermal neutron detectors developed at BNL. Special techniques are developed to fabricate these wire arrays, which typically contain hundreds of wires with diameters < 50 µm.

The research and development of the group plays a key role in BNL's mission, particularly toward providing new detection systems for the major user facilities. Purpose-designed radiation detectors, often one-of-a kind, are designed and fabricated for use in forefront experiments at user facilities such as the NSLS and AGS. We look for solutions to the unique problems encountered by colleagues working on RHIC experiments through studies with prototype systems. Beyond BNL, we develop a range of advanced neutron detectors for experiments at national user facilities such as LANSCE at Los Alamos, IPNS at Argonne, the research reactor at NIST, and for future experiments at the SNS. We develop forefront X-ray detector systems for other DOE synchrotron facilities and plasma physics laboratories, such as the APS at Argonne and Princeton's NSTX. We provide collaborative support for gas detector system design in CERN's LHC ATLAS experiment. Essential to this development of advanced detectors is a continual emphasis on studies of the fundamental characteristics of ionization and electron multiplication in gases.



◄ Time profile (right to left) of measured neutron intensity from coenzyme of vitamin B12, using the group's new detector at LANSCE's protein crystallography station. Time represents duration of one beam pulse (~ 30ms) from the spallation source, highest energy neutrons being recorded to the right, lowest energy neutrons to the left. Diffraction peaks sit on top of a scattered background of neutrons.



◀ Left: 400µm FWHM position resolution was achieved using the 5×5cm² thermal neutron detector.
Right: 14µm FWHM position resolution, for 8keV x-rays was obtained in a chamber with a xenon mixture at 10 atm. of pressure.
These measurements represent the best position resolution ever recorded by gas-based detectors.

Facilities

Some important resources within the group are:

- X-ray production and calibration equipment
- Thermal neutron source
- Range of α, β, and γ-ray isotopes
- Clean room and laminar flow benches
- Microscope and inspection facilities
- Wire winding and lithographic facilities
- Mechanical and electrical CAD tools for detectors
- Ultra clean noble gas delivery and purification systems
- UHV and RGA equipment
- Calibration, measurement and analysis equipment
- Extensive set of nuclear instrumentation modules
- Bench stations for system testing

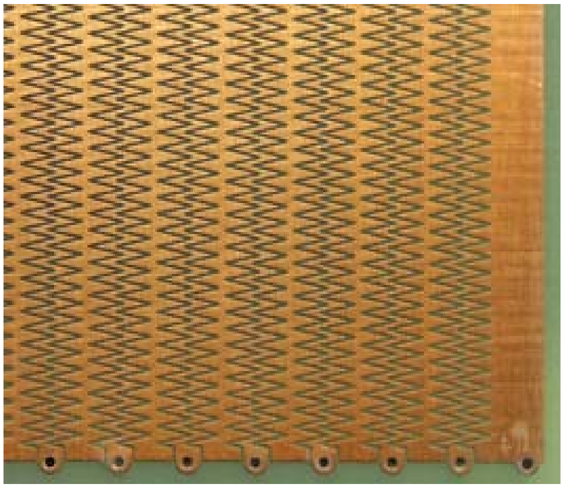
X-ray Detectors for Synchrotron and Plasma Studies

The primary motivation for X-ray detector development comes from the wide-range of experimental studies at the NSLS. Our instruments have been used in structural biology, polymer investigations, and scattering experiments in physics and chemistry. The table indicates the large number of detector systems that are presently in use on NSLS beam-lines. Emphasis is on detectors with excellent position resolution and linearity, uniform illumination response, high count-rate capability and long-term stability. For example, most of these characteristics are essential for muscle movement dynamics, a key study in structural biology.

The features required for synchrotron applications often push the envelope of detector operation to extremes and it is essential that a fundamental understanding of many basic phenomena in gas physics be known. For example, following a series of basic measurements on photoelectron path lengths in various gases, our group has developed techniques that yielded the best position resolution ever measured for X-rays in a gas-based detector. It is through these types of basic study that new instruments can be developed for state-of-the-art experiments. Our close interaction with users provides an understanding of their experimental requirements, permitting advanced systems that are not available commercially to be produced in a timely manner. Frequently, new concepts such as micro-pattern detectors are driven by the HEP/NP community, and we are well positioned to re-direct these techniques to the synchrotron environment.

Thermal Neutron Detectors

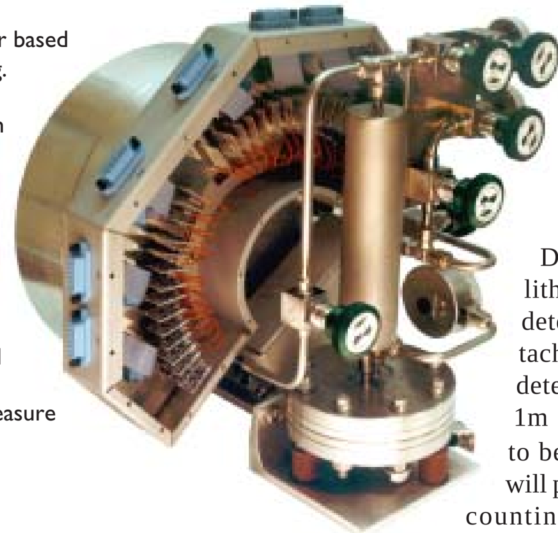
A wide range of high precision position sensitive thermal neutron detectors has been developed in support of the nation's neutron user facilities, particularly for beam lines dedicated to structural biology studies. Recent activity has been increasingly focused on applications at spallation sources.



◀ Section of a position-sensitive cathode, fabricated using printed circuit techniques. This recent example from the group illustrates a "zig-zag" electrode in which the interpolating property of the precisely defined strips permits accurate performance with fewer electronic channels than previous electrodes.

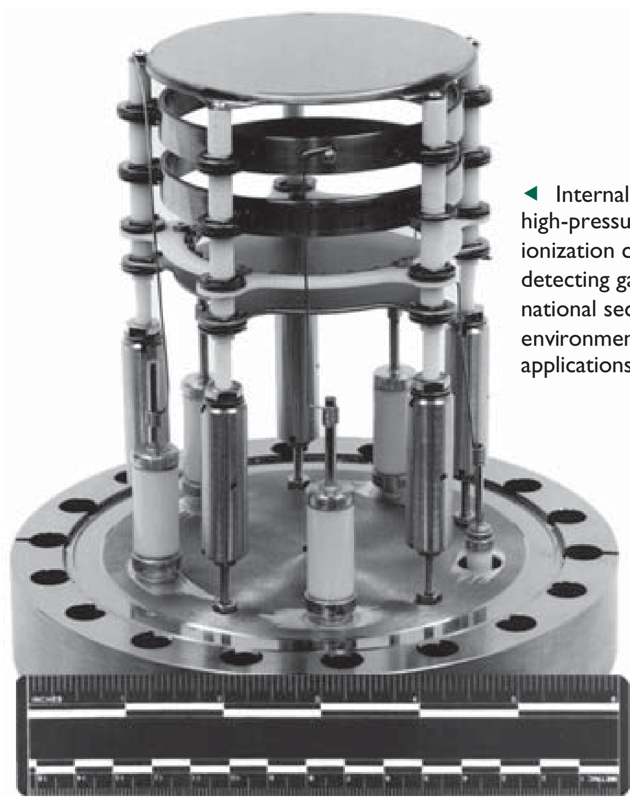
The element with the second largest cross-section for thermal neutron absorption is ^{3}He (after gadolinium). A combination of ^{3}He and propane provides an outstanding mixture for use in multiwire proportional chambers, resulting in one- and two-dimensional devices with excellent position resolution, high efficiency and counting rate capability, good timing resolution and low sensitivity to gamma-rays. In addition to these excellent characteristics, gas-based devices do not suffer from blooming effects found in scintillator detectors. Combined with the purpose-designed position readout, our gas based detectors have excellent absolute position stability, a characteristic that makes possible long exposure experiments. This is especially important for situations often encountered where weak diffraction peaks are present in an intense and uniform scattered background.

A variety of detector configurations have been implemented with sensitive areas ranging from 5cm×5cm to 50cm×50cm to 1500cm×20cm. The table illustrates the range of disciplines to which these detectors have been applied. These detectors possess position resolution unsurpassed by any gas detector group in the world, and they have demonstrated excellent reliability even when operating over a number of years.



▶ Thermal neutron detector based on ^{3}He and propane gas filling. This device has a position resolution of less than 400μm FWHM, the best ever recorded for neutrons by a gas detector. This class of detector utilizes resistive charge division to achieve high resolution performance. The open electronics at rear of the detector shows hybrid preamplifiers (see Microelectronics) used to measure the charge signal, and hence determine position.

A new program is underway to develop one and two-dimensional neutron detectors that operate in ionization mode. This capitalizes on both the large primary signal created via neutron conversion in ^{3}He, about 25,000 electrons, and the Division's expertise in monolithic circuits. Pad (or strip) detectors with preamplifiers attached to each pad will permit detectors with areas up to 1m × 1m and up to 40,000 channels to be fabricated. These devices will potentially have much greater counting rate capability (above $10^8 s^{-1}$) and virtually no degradation (ageing) with time, compared with present devices, and have been targeted as key elements for future SNS instruments.



◀ Internal elements of a high-pressure Xenon ionization chamber for detecting gamma rays in national security and environmental control applications.

Detectors for High Energy and Nuclear Physics

Three key examples of the group's activities in high energy and nuclear physics are:

- **Cathode strip chamber (CSC)**
  Originally developed in the group's synchrotron detector R&D, CSCs have been implemented as key elements in the ATLAS experiment of CERN's LHC.
- **Pad detectors**
  Multi-element pad detectors were first developed for fixed target heavy-ion experiments at the AGS. The concept was used in the design of subsystems for RHIC experiments
- **TPC and Micro-pattern detectors**
  New instruments using recent advances in technology and gas physics are being studied for

proposed upgrades of RHIC experiments. The encouraging results from research and development that have been performed with GEM (Gas Electon Multiplier) has led to its choice as the electron multiplication stage in a micro-TPC under development for two separate projects, one with RHIC and one with Physics/NSLS. These two instruments will also benefit from electron transport studies that have been performed with different gas mixtures.

Detectors for National Security

This is a particularly important field at this time. We collaborate actively with BNL's Department of Non-proliferation and National Security in developing specific gamma-ray and neutron detector systems. A low power, low maintenance instrument has been developed for field work to detect specific gamma-lines. The device is based on highly compressed xenon and yields energy resolution better than NaI by a factor of four. Neutron detectors have been developed using coded aperture techniques to locate clandestine sources of neutrons and for trials for locating land mines.

Basic Research and Development

Basic R&D in gas detector physics and electronics yields significant advances in performance. Techniques developed recently by our group to improve the performance of position-sensitive detectors include a method to reduce parallax broadening at large scattering angles, and a method that significantly reduces anode wire modulation. Fundamental studies made by our group have enabled us to develop gas-based detectors with position resolution unsurpassed by any other group for both X-rays and neutrons.

The emergence of micropattern detectors in the last few years has spawned a new generation of gas-based detectors fabricated by lithographic techniques. We are contributing to these exciting developments with the invention of the micro-pin array (MIPA) and with new studies on the gas electron multiplier (GEM).

Close ties exist between the gas detector and semiconductor detector groups. There is also collaboration with the Division's microelectronics laboratory, printed circuit design and fabrication laboratory, microfabrication and machine shop. The existence of these specialist capabilities "under one roof" provides a unique resource for developing the most advanced gas-based detector systems.

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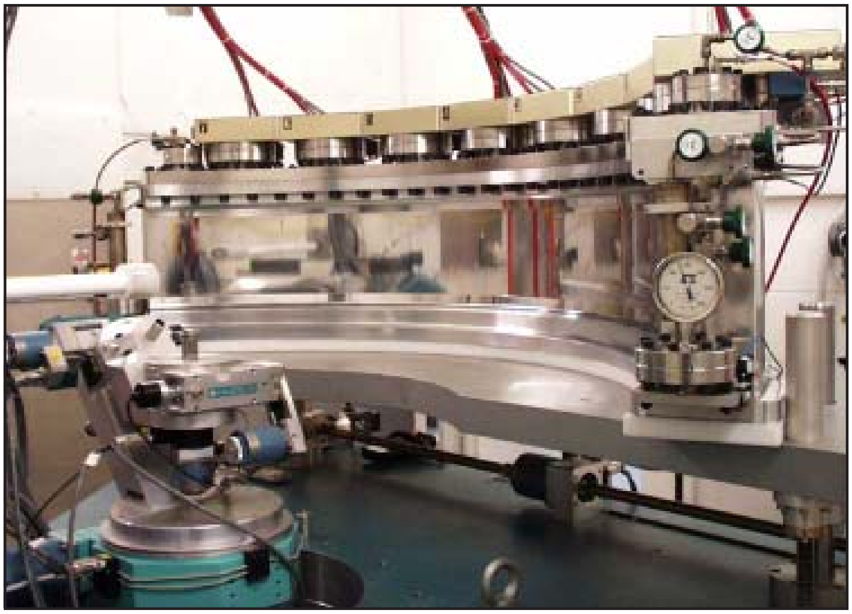

▲ Large area curved detector recently developed for protein crystallography. This picture shows the detector positioned on a goniometer, with protein sample position at the 70cm focal point to the left. This multi-segment detector has a continuously sensitive collecting area of 1.5m×20cm, and 1.3 mm resolution. It represents the state-of-the-art for combining, in one instrument, high accuracy, high count rate, large area coverage, and insensitivity to gamma-rays.

Gas Detectors Constructed for Specific Facilities

	Application	Detector	Resolution	Counting Rate	Pressure
X-ray Synchrotron Applications	Instrument & Diagnostic Development NSLS, U4	Soft X-ray, Parallel Plate	N/A	> 10^5 ph s^{-1}	3000 Pa
	X-ray Microscopy NSLS, X1A	Soft X-ray, Multi-anode	N/A	> 10^6 ph s^{-1}	3000 Pa
	Powder Diffraction NSLS, X7A NSLS, X27	1D Delay Line, 10cm×1cm 1D Curved Blade (45° coverage)	$\Delta l/l=10^{-3}$ $\Delta l/l=10^{-3}$	5×10^5 ph s^{-1} 10^6 ph s^{-1}	1-4 atm
	Time-resolved and Static Diffraction NSLS, X12B	2D Delay Line, 10cm×10cm 1D 100 Wire,10cm×2cm	$\Delta l/l=10^{-3}$ $\Delta l/l=10^{-2}$	5×10^5 ph s^{-1} 10^8 ph s^{-1}	1 atm
	Inelastic X-ray Scattering NSLS, X21 NSLS, X25	1D Delay Line, 10cm×1cm 2D Delay Line, 10cm×2cm	10cm×1cm 10cm×2cm $\Delta l/l=10^{-3}$	5×10^5 ph s^{-1}	1-4 atm
	Studies at Liquid Vapor Interfaces NSLS, X22	1D Delay Line, 10cm×1cm	$\Delta l/l=10^{-3}$	5×10^5 ph s^{-1}	4 atm
	EXAFS SPEAR, Stanford and ALS, LBNL	2D Delay Line, 10cm×2cm	$\Delta l/l=10^{-3}$	5×10^5 ph s^{-1}	1 atm
	X-ray Scattering APS, Argonne	1D Delay Line, 10cm×1cm	$\Delta l/l=10^{-3}$	5×10^5 ph s^{-1}	1-4 atm
	Plasma Studies NSTX, Princeton University	1D Delay Line, 18cm×10cm (×3)	$\Delta l/l=10^{-3}$	2×10^5 ph s^{-1}	1 atm
Neutron Applications	Macromolecular Crystallography	2D Charge Division (×3), 20cm×20cm	1.3mm, 512×512 array	5×10^4 n s^{-1}	9.5 atm
	Membrane Spectrometer	2D Charge Division, 20cm×20cm	1.3mm, 512×512 array	5×10^4 n s^{-1}	9.5 atm
	Materials Chemistry Spectrometer	2D Charge Division, 5cm×5cm	0.4mm 512×512 array	5×10^4 n s^{-1}	14.6 atm
	Chemical Crystallography	2D Charge Division (×3), 20cm×20cm	20cm×20cm 512×512 array	5×10^4 n s^{-1}	9.5 atm
	Small Angle Scattering	2D Charge Division, 50cm×50cm	2.5mm 512×512 array	5×10^4 n s^{-1}	5.5 atm
	Protein & Membrane Crystallography LANSCE #14, Los Alamos	2D Charge Division, (Curved 120° coverage)	1.3mm 2048×256 array	> 10^6 n s^{-1}	9.5 atm
	Spin Echo Spectrometer NIST	2D Charge Division, 40cm×20cm	1.3mm 512×256 array	5×10^4 n s^{-1}	9.5 atm
	Crystal Backscattering Spectrometer ISIS, Rutherford, and SNS	1D Truncated Cone, operateing in ionization mode	1°	10^5 n s^{-1}	8 atm
	Instrument Development SNS	2D Charge Division, 20cm×20cm	512×512 array	5×10^4 n s^{-1}	9.5 atm
	In-house R&D	2D Charge Division, 20cm×20cm	512×512 array	5×10^4 n s^{-1}	9.5 atm
	SNS Experiments (under design)	2D Pad, operating in ionization mode, 1m×1m	5mm, 512×512 array	10^8 – 10^9 n s^{-1}	4 atm

Cryogenic Detectors

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BNL is the birth place of the liquid argon calorimeter, pioneered by V. Radeka and W. J. Willis in 1973 and since then used in many high energy physics (HEP) experiments at BNL and throughout the world (E806, E807, L1, D0, NA48, etc.). The cryogenic detector group made important advances in the capabilities of these detectors and pioneered the fast calorimetry readout techniques that opened the door for its use in the next generation high luminosity hadronic colliders. The ATLAS experiment at CERN Large Hadron Collider (LHC) to begin operation in 2006 will use a liquid argon detector for the central and forward regions.

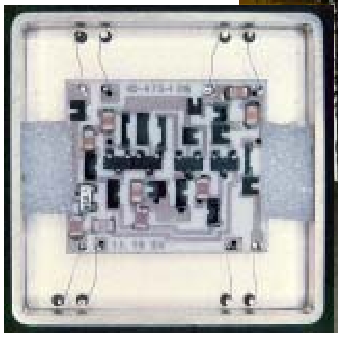
Fast Noble Liquid Ionization Calorimetry

The study of fast calorimeters began with the ELIOS-NA34 detector, built at BNL in the late 80s. To overcome the limitations of the long charge transfer time through the connection out of the cryogenic vessel, a cryogenic preamplifier was developed that was able to work at the liquid argon temperature of 90 K (-183°C). The result was a device about an order of magnitude faster than previous calorimeters, which was successfully operated at CERN over many years without any failures. In the 1990s liquid krypton detectors were developed for high resolution calorimetry for the proposed Superconducting Super Collider (SSC). To date, the best energy resolution for a sampling calorimeter, 5.6%/√E, with a negligible constant term, was measured on a test detector at CERN in 1994. An additional important characteristic of fast cryogenic calorimeters is their excellent timing resolution, 4.15 GeV ns/E for the 1994 LKr device. These results show how good readout design and signal processing can obtain a fast response from a detecting medium with response time slower than crystal or silicon. In the framework of the SSC activity, several types of cryogenic preamplifiers for high capacitance calorimeters were also developed, including a monolithic version built on a radiation hard JFET process developed *ad hoc* in collaboration with Interfet, Inc. for cryogenic applications. A discrete version, designed by the cryogenic group and engineered and built in Europe, equips the 13,000 channels of the NA48 liquid krypton calorimeter at CERN.

Current Activities

Barrel Lar Calorimeter for the ATLAS experiment at LHC

The current activity of the cryogenic detector group is mainly devoted to the liquid argon calorimeter for the ATLAS detector at the Large Hadron Collider (LHC) currently being built at CERN. This effort is in collaboration with many institutions (Nevis Labs., University of Arizona, University of Pittsburgh, Stony Brook University, and BNL's Physics Department). BNL involvement includes many aspects of the Barrel Calorimeter development: optimization of detector design, electrode design, cold-to-warm feedthroughs, calibration system, and readout electronics. R&D work on the components for which BNL is responsible has been completed and construction and testing is being carried out. The ATLAS barrel detector requires 5 different types of summing boards and 14 different types of motherboards with cryogenic high precision resistors (tolerance < 0.1% at 90 K). Since low level signals need

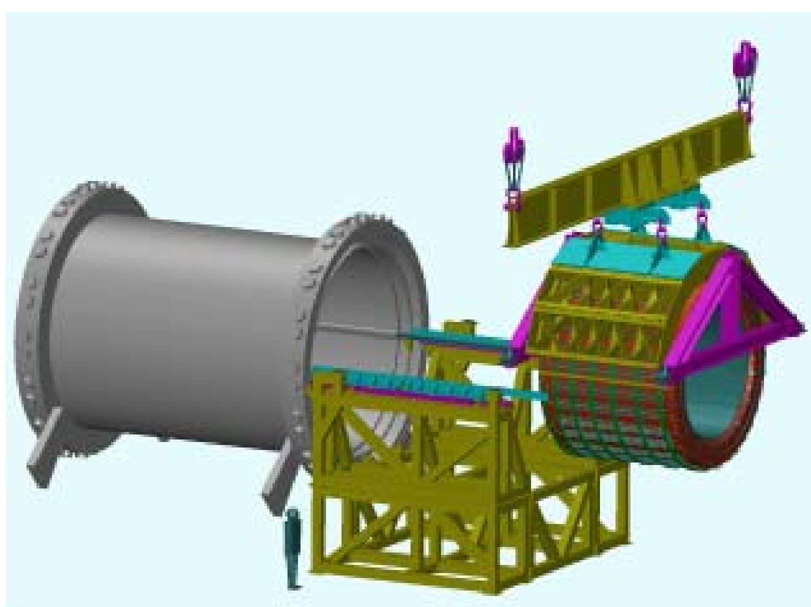


▶ The NA34 calorimeter before lowering into the cryogenic vessel, suspended from the vessel cover. The large white volumes are acrylic foam "fillers". On the right side is the front section, connected to preamplifiers outside the vessel by the low inductance flat cables (gold colored cables in the picture). To the right one can see the hadronic section and the cryogenic preamplifiers, shown enlarged in the photograph below.

to be transmitted from the electrodes to readout preamplifiers located at the feedthroughs, particular care has been taken in designing the shields and grounding of the readout in order to minimize electromagnetic interference (EMI). The low noise preamplifiers and all the data acquisition electronics are built as a single large, water-cooled printed circuit board (FEB: Front-End Board). The FEB enclosure, a specially engineered crate capable of being mounted in any orientation (it will have to be mounted all around the calorimeter), has been designed and prototyped, along with the cooling system and the Faraday cage shield to prevent electromagnetic interference (EMI) to the sensitive preamplifier input. BNL has participated in the CERN tests of the LAr prototype calorimeters aimed at testing the detector and the readout hardware and at assessing their performance. The design of a radiation and neutron resistant, high efficiency, low noise switching power supply to pro-vide the low voltage, high current supplies of all ATLAS calorimeters is being carried out. Radiation and neutron resistance tests as well as tests for single event burnout (SEB) due to high energy neutrons and protons are being performed at the BNL irradiation facility and at Harvard cyclotron. A custom designed power supply is being developed with a commercial company for this application. In the framework of the ATLAS activity, BNL has been a contributor in the design of the transmission line readout of fast calorimeters, which is being employed by ATLAS. A new type of quad hybrid low noise, low power, high dynamic range preamplifier has been designed for this purpose. The possible failure modes of the electronics have been studies to determine its reliability. A mean time between failure (MTBF) in excess of 1.7 million hours has been estimated, enough to guarantee less than 0.5% single channel failures per year over the 10 year expected life of the detector. Manufacturing and testing of the large quantities needed for the detector is being completed. All the 64 feedthroughs have been installed on the cryostat and several thousands summing boards and readout boards have been assembled in the modules. Over 50,000 hybrid front-end preamplifiers (200,000 channels) have been manuf actured and tested. Production is carried out at commercial facilities, but test and burn-in of critical components is performed in house. Fully computer-controlled automated test stations, which allow full traceability of each device under test have been set up for this purpose.

▼ Computer-generated rendering of the insertion of the ATLAS barrel calorimeter into the Lar cryostat. The cryostat will be 6.8m long, with an outer radius of 2.25m. Inside the liquid argon vessel the calorimeter consists of two half barrels, with a gap of few millimeters in between. Each half barrel consists of 16 modules, each made of 1024 lead-stainless steel converters with copper-polyimide multilayer readout boards in between. Connections are made at the front and back face of the calorimeters using motherboards, which also house the calibration resistive networks. Readout and calibration signals are routed through cold-to warm feedthroughs (the cilindrical objects on the cryostat rim) to the electronics enclosures housing the FEBs and auxiliary electronics (trigger builder, calibration, monitoring, slow control, etc1`).

◀ A completed module, ready to be tested in liquid argon.



In a collaboration with the University of Arizona, the cryogenic group has designed the connection of the ATLAS forward calorimeter to the front-end preamplifier via a wide bandwidth transmission line transformer designed for cryogenic operation in a magnetic field. The transformer coupling of the high capacitance tower to the readout preamplifier achieves a good signal to noise ratio without compromising the speed of response and at the same time reducing the number of feedthrough connections penetrating the cryostat.

Detection of Electron Nano-Bubbles in Liquid Helium for a Solar Neutrino Experiment

It is known that electron mobility in insulating, non polar liquids is surprisingly low. This is due to the formation of "electron bubbles": the electron is not free, but is at the center of a bubble with several nanometers radius. The fundamental reason underlying bubble formation arises from Pauli's exclusion principle: the potential well giving rise to the bound state of the electron exists because of the repulsion between the excess electron and the electrons belonging to the molecules that constitute the fluid.

Recently a group of physicists from Brookhaven and Columbia University began discussing the concept of a solar neutrino experiment. The experiment is based on the detection of electrons produced by ionization of a fast electron which gains the energy from scattering with a solar neutrino. The final scope of this effort should lead to the design and execution of an experiment to determine the incident direction of solar neutrinos down to an energy of about 150 keV.

A short analysis of the rates of interaction of solar neutrinos and volume of the detector shows that the detector should have about 10^{12} position elements ("voxels"). However, the rate of the interactions is very low. To achieve the effective granularity of 10^{12} voxels with about 10^5 channels the idea of a time projection chamber is pushed to the extreme thanks to the extremely low electron bubble mobility in liquid helium. The formation of a nano- bubble decreases the velocity of signal charges to 20 cm/s at the drift field of 1 kV/cm. Such a low drift velocity gives enough time to read-out the position in a plane perpendicular to the drift direction with a reduced number of read-out channels. The very low temperature of liquid helium decreases the diffusion of the electron bubbles so that, in spite of long drift times, the loss of position resolution due to diffusion is negligible. Different readout schemes, either optical or electronic (or a combination of both) are being investigated.

$\mu^+\mu^-$ Liquid Neon Tracker and Vertex Detector

Recently, there has been a considerable effort to assess the feasibility of a muon-muon collider. One of several problems is a large particle background, due to decaying muons, which arrive at the detector simultaneously with those particles of interest from the $\mu^+\mu^-$ interaction. The radiation dose near the intersection will be high enough to forbid silicon vertex detectors.

In this activity we are trying to design and to produce a background blind, radiation hard vertex detector and tracker for $\mu^+\mu^-$ collider experiments by using liquefied rare gases for both the vertex detector and for the inner tracker. The idea behind this detector takes full advantage of the small size of the collision region of a $\mu^+\mu^-$ collider. The region has radial dimensions of less than 1 µm, while its extent in the beam direction is of the order of 1 mm. In the energy range of physics interest, the momenta of charged particles are high enough to be only slightly bent in the solenoidal magnetic field. The tracks are therefore straight lines emerging from a known point. The elementary detection cells are long towers pointing to the interaction. A fast particle produced at the interaction point traverses the detection cell along its long dimension, depositing large amount of ionization charge. Background particles cross the cell along a much shorter trajectory, creating much less ionization. The first rejection of the background is thus based on a simple measurement of the ionization. The position resolution within each cell can be obtained from the drift time of ionizing electrons in one direction and from the sharing of the induced charge in the other direction. A preliminary analysis show that a resolution of about 10 µm for a cell of transverse dimension of 1-2 mm is possible. Position measurements in both directions are done within about 1 µs, which is compatible with the expected bunch crossing time of 2 µs in the planned $\mu^+\mu^-$ collider. The detection medium may be liquid argon or liquid neon. The liquid argon, though easier to work with due to less strict purity requirements, causes more multiple scattering due to its higher atomic mass and thus limits the momentum resolution. Liquid neon, thanks to its lower atomic mass, allows a more precise momentum resolution. However, in pure liquid neon electrons form bubbles as in liquid helium with a mobility about 5 orders of magnitude lower than free electrons. Dissolving a small amount of argon in neon should block the formation of nanobubbles around the electrons, thus preserving the high mobility required for this application.

Facilities and Capabilities

The art of cryogenic detectors involves knowhow from many different disciplines, ranging from vacuum techniques, materials science, contamination control, cryogenics to modeling of detectors components and readout electronics. The group has a proven track record of design, fabrication, installation and operation of noble liquid calorimeters at BNL and at outside facilities. We rely on a suite of techniques developed over the years to model detector parameters. We can measure and monitor liquid purity and properties in test cells. Readout electrodes are modeled as equivalent circuits either analytically or with the help of circuit simulation programs (HSPICE, PSPICE). Instrumentation Division electronic measurement instruments are invaluable to measure the characteristics and electrical properties of detector components as they are built, both to validate the design and for quality assurance. Prototyping and construction relies on the support of the Printed Circuit Board (PCB) Design facilities, PCB fabrication (often with nonstandard materials) and the machine shop. Readout electronics are designed and built in the Division's Hybrid and Microelectronics Lab. Ionizing radiation tests are carried out at the division γ-ray irradiation facility while neutron and high energy proton tests are performed at nearby facilities. Over the years we have developed a close link with many vendors of specialized services, ranging from large printed circuit board manufacturing (as long as 2 m), to precision silk screening over large areas, to multilayer flexible circuits and to components to be operated in cryogenic environment which allow us to reliably contract out fabrication work too large to be handled in-house.

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A great deal of information on the ATLAS experiment and the Lar calorimeter can be found on the experiment web page at the URL: http://www.usatlas.bnl.gov or http://atlas.web.cern.ch/Atlas.

Microelectronics

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From the outset, one of the Instrumentation Division's main roles has been to provide custom-designed electronics for a wide range of research programs. In particular, low-noise circuits for processing the signals from sensitive radiation detectors have been an area of focus for almost 50 years, and BNL has established a worldwide reputation as a leader in this field. More recently, we have been seeking to apply some of the sweeping developments in microelectronic technology to provide high performance electronic systems for experiments requiring either (1) extreme compactness, (2) very high quantity (>1000) of identical units, or (3) special electrical characteristics unavailable in conventional, commercial devices.

Starting in the 1990s, an increased emphasis has been placed on monolithic techniques. Despite the overwhelming advantages of silicon VLSI for digital circuits, it poses many constraints for low noise, high precision signal processing work. The Microelectronics Group conducts research on circuit design to provide solutions to these problems. The resulting techniques are then used to develop custom ASICs to support the experimental programs of BNL scientists.

Capabilities

The Microelectronics Group specializes in the design and prototyping of analog and digital circuits in CMOS, bipolar, and hybrid technologies, including their interfacing to detectors and data acquisition systems. The design approach centers on close collaboration with the experiment scientist, and with detector specialists in the Division. Five experienced ASIC designers in the group then develop custom monolithic circuits with state-of-the-art performance. Unique facilities in the BNL Microelectronics group include:

- transistor noise characterization laboratory;
- accurate CMOS preamplifier noise model for pre-simulation design;
- in-house printed circuit shop, silicon detector fabrication, automated wirebonding and encapsulation equipment;
- analytical electron microscopy;
- gamma irradiation facility for radiation effects testing.

In addition, the group makes use of commercial and academic CAD tools for 2D and 3D electrostatic modeling of detector and interconnect structures; design capture; analog circuit simulation; logic synthesis; and IC physical design. We access analog and mixed-signal CMOS/BiCMOS ASIC fabrication through multiproject wafer services. In 2002, our group fabricated its first circuits in 0.18 micron CMOS. There are two test laboratories with a full suite of test equipment including an analytical probe station, time- and frequency-domain characterization to 5 GHz, and several standard spectroscopy counting chains.

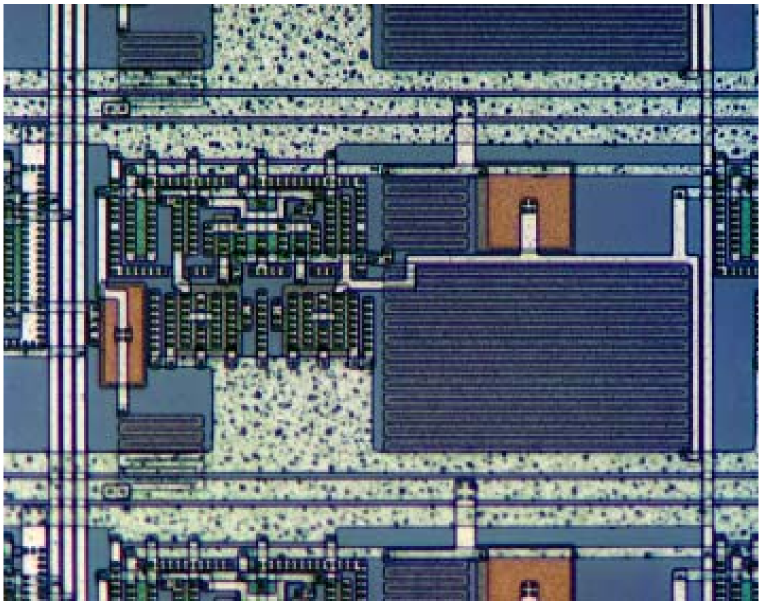
Current Research Areas

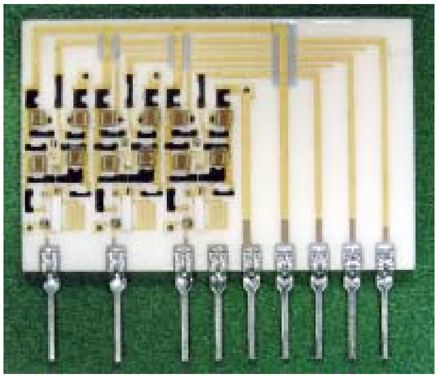
• **Low-noise charge sensitive amplifiers**. This is a broad area encompassing circuits for gas, liquid, and solid detectors; detector capacitances ranging from 10^{-14} to 10^{-8} F; and work on circuits which must operate in cryogenic or heavy radiation environments.

• **Precision signal-processing subcircuits**. Flash ADC, switched-capacitor waveform memory, calibration and timing circuits, high order filters, baseline restorers, peak detectors, derandomizers, multiplexers.

• **Mixed signal ASICs**. Implementation in the same ASIC of both digital and high precision analog functions operating at the same time; the fast logic signals can easily propagate to the sensitive nodes of

▼ Monolithic CMOS shaping amplifier, approximate size 100 µm × 200 µm, showing layout of passive components. The resistor is a serpentine of polysilicon, resistivity 22 Ω per square, line width 2 µm. Capacitor (pink square) at top of serpentine is formed by sandwiching a SiO_2 layer between two polysilicon plates.





◀ Triple preamplifier card, developed for use in a wide range of radiation detectors. Components are fabricated on a 0.025 inch thick alumina substrate. Special transistor packages, chip capacitors, and thick film resistors are used. Finished product is encapsulated in very high resistivity clear coating, primarily to inhibit moisture. (Winner of IR-100 award).

the analog sections through substrate, ground and supply; in order to minimize these effect, the use of specific design and layout techniques is investigated.

• **Device characterization**. Noise properties of FETs in various technologies; cryogenic and radiation effects; device and parasitic modeling for circuit simulation.

• **Hybrid microcircuit technology**. Pushing the state of the art in density and complexity by working with new materials and techniques.

• **CMOS sensors.** Novel devices that use the built-in junctions of CMOS IC technology to sense ionization produced by photons and charged particles.

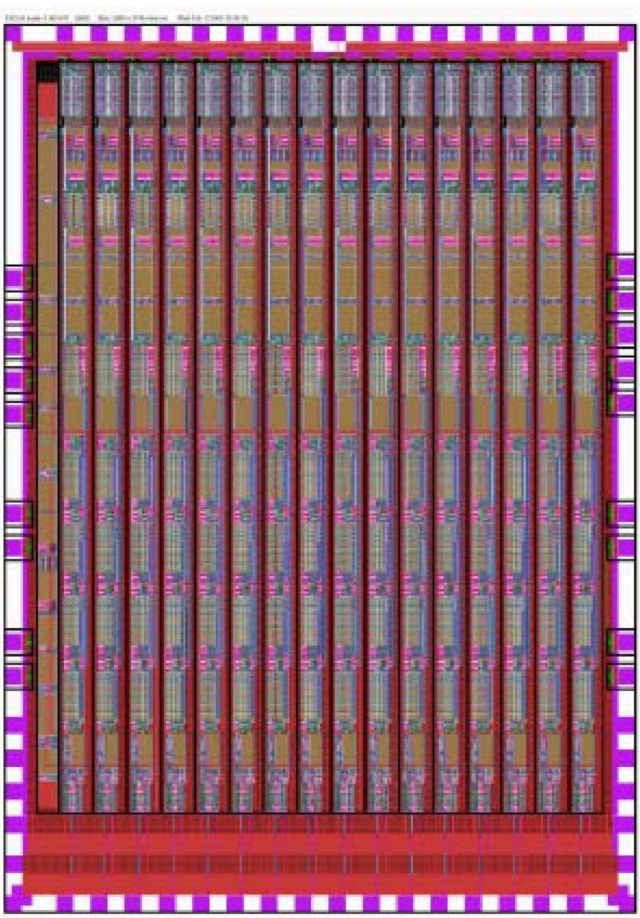
Recent Projects

Limits of Low Noise in CMOS Preamplifiers

A CMOS charge-sensitive preamplifier coupled to a silicon drift detector (both designed at BNL) recently achieved the best energy resolution (13 r.m.s. electrons) for X-rays of any MOS-based amplifier [1]. The result was obtained by careful optimization of the input MOSFET coupled to the ultra-low capacitance drift detector and by use of a novel feedback configuration for capacitor reset [9]. Studies of the effects of CMOS technology scaling on noise are underway to help predict the performance potential of new front end circuits [8].

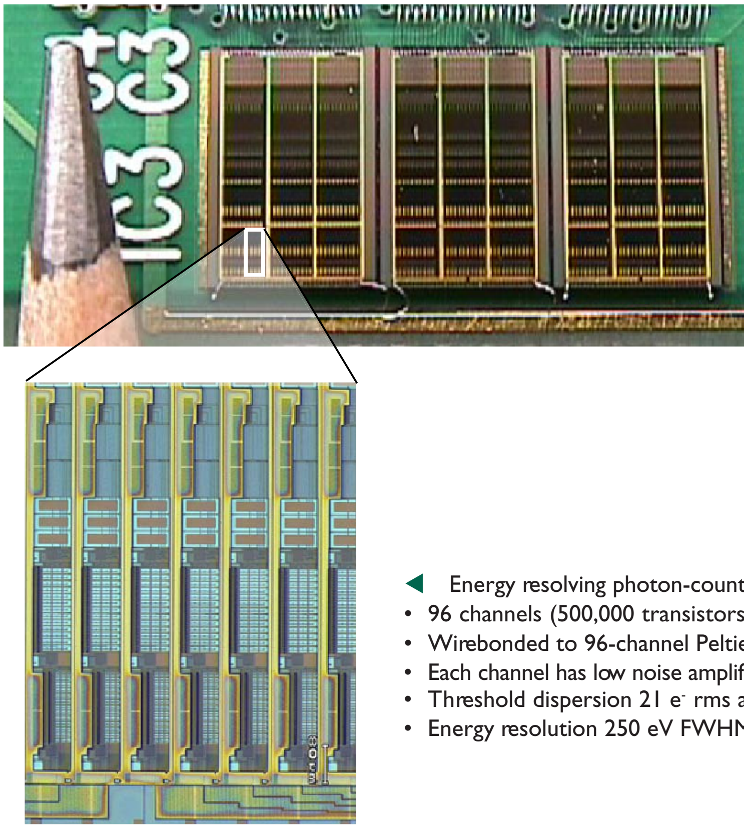
Particle and Nuclear Physics

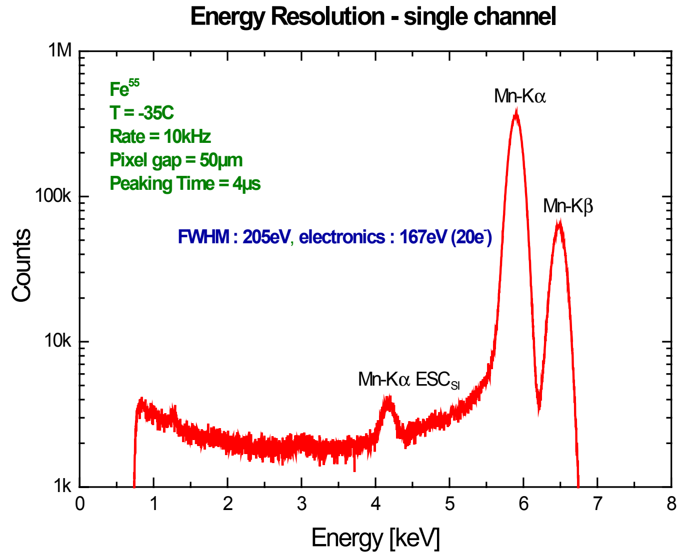
High energy physics research has historically been a heavy user of microelectronics, following the widespread adoption of complex detectors at colliding beam experiments. The Microelectronics



◀ CMOS 16-channel programmable Preamp Shaper monolithic circuit chip for eV Products. Actual size 3.7 mm × 5.1 mm. Some characteristics of the chip are listed below.

Size	5.1mm×3.7mm
Channels	16
Shaping	Unipolar 5th Order Complex Semigaussian
Gain	30, 50m, 100 and 200mV/fC
Peaking time	0.6µs, 1.2µs, 2.4µs, 4µs
ENC^2 (1.2µs, 200mV/fC)	$\approx 26^2+(27/pF)^2+55^2/\sqrt{nA}+0.17Q/q$
ENC Dispersion (σ)	≈ 10%
Power dissipated	≈ 18mW/ch
Integral Linearity Error	< 0.3% Full Range (12.5fC) at 200mV/fC
Cross Talk (bonded)	< 0.4% (< 0.1% non adjacent)
Baseline Adjustment	-100mV to +400mV
Detector Leakage Current	< 150nA, Self Adaptive
Gain vs C_{IN}	< 0.1% / pF
Baseline vs I_{DET}	< 300µV / nA
Gain vs I_{DET}	< 0.1% / nA
Baseline vs V_{dd}	< 30µV / mV
Gain vs V_{dd}	< 0.001% / mV
Baseline vs Temperature	≈ 75µV / °C
Gain vs Temperature	≈ -0.040% / °C (≈ -400 ppm / °C)
Peak. Time vs Temperature	≈ 0.0065% / °C (≈ 65 ppm / °C)
Max Baseline Shift vs Rate	< 8mV at Fixed Rate × Peaking Time ≈ 0.2
Max Gain Change vs Rate	< 0.1% at Fixed Rate × Peaking Time ≈ 0.2
Gain Dispersion (6σ)	≈ 0.32%
Calibration Cap. Disp. (6σ)	≈ 0.13% (nominal value 100fF)





◀ Energy resolving photon-counting ASIC for EXAFS detector

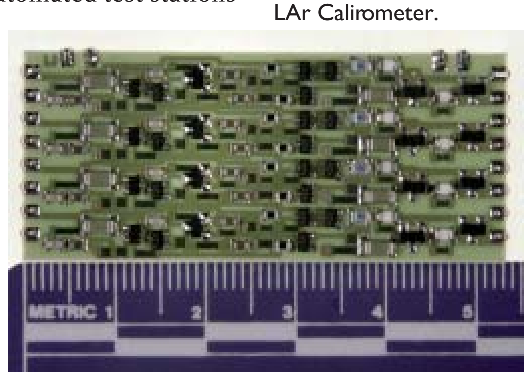
- 96 channels (500,000 transistors)
- Wirebonded to 96-channel Peltier-cooled Si pad detector, 1 x 1 mm^2 pads, 0.8 pF
- Each channel has low noise amplifier, threshold and two window discriminators, three 24-bit counters
- Threshold dispersion 21 e$^-$ rms after adjustment
- Energy resolution 250 eV FWHM (30 e$^-$ rms) at 10 kcounts/pad/s

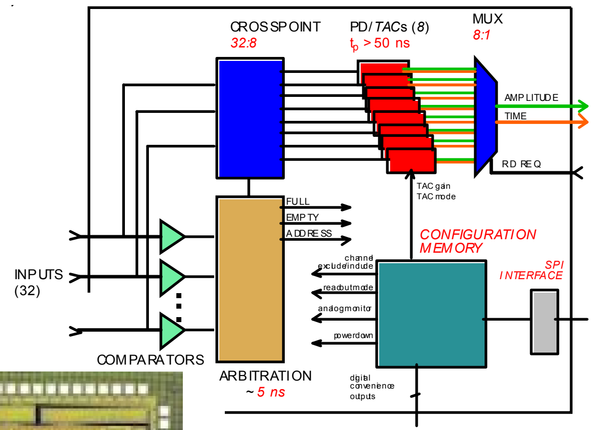
group designed and produced over 150,000 channels of front-end electronics for the PHENIX Time Expansion Chamber [2] and the STAR Silicon Vertex Tracker at BNL's own RHIC collider. For the ATLAS detector at the CERN LHC, we are developing about 250,000 channels of readout electronics for the Electromagnetic Calorimeter and precision Muon Spectrometer. These circuits must operate for over 10 years in an inaccessible, high radiation environment. As an example of a smaller project, the Laser-Electron Gamma Source at the NSLS is developing a new Time Projection Chamber which will be instrumented (8000 channels) with a custom front-end chip. We are also participating in electronics R&D for future experiments at the AGS (RSVP program), RHIC-II, Next Linear Collider, and muon storage rings.

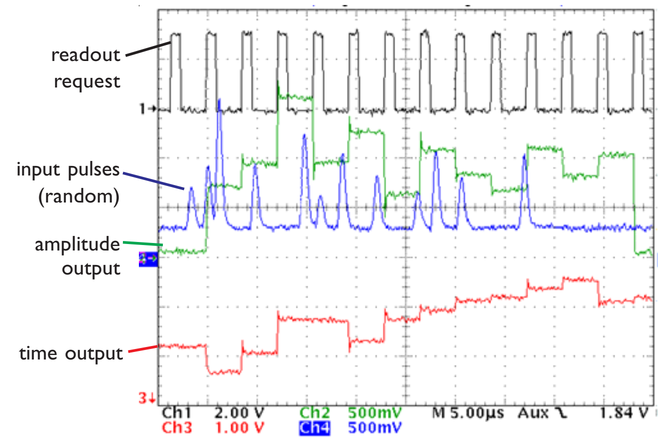
Besides requiring large numbers of circuits, each of these experiments also benefits from the best possible electronics noise performance. With high-sensitivity front ends better energy, position, and/or time resolution can be obtained. In many cases the low noise of the preamplifier allows the detector to run at lower gain which improves its stability and extends its lifetime.

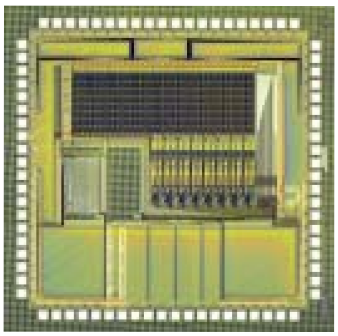
BNL has been a contributor in the design of the transmission line readout of fast calorimeters, which is being employed by ATLAS. In the LAr calorimeter a quad hybrid low noise, low power, and large dynamic range (linearity over 16 bits) preamplifier is used for this purpose. The hybrid exhibits exceptional radiation hardness with little change in performance up to a total integrated dose of 10^6 rad and a 10^{14} fluence of 1 MeV neutrons. The possible failure modes of the hybrid have been studied to determine the reliability. A mean time between failure (MTBF) in excess of 1.7 million hours has been estimated, enough to guarantee that less than 0.5% single channels fail per year over the 10 year expected life of the detector. The production is carried out by outside vendors, but test and burn-in of the hybrids is performed in house. The production is now completed with all quad hybrids having now been manufactured, burned-in and tested. All hybrids were screened to a gain of ±2%, a peaking time of ±1 ns, and to be low noise. The tests were performed using computer controlled automated test stations which measure 16 hybrids (64 channels) at a time, alert the operator to any failures and allow failed hybrids to be segregated. The total yield was about 30,000 hybrids (120,000 channels) with a failure rate of 0.3%. Each hybrid has a serial number allowing full traceability of the device.

▼ Photo of a quad, low noise, low power, large dynamic range pre-amplifers module for the LAr Calirometer.







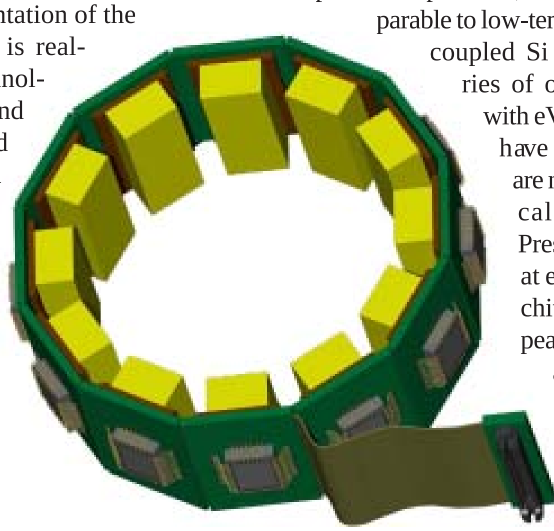


◀ Amplitude and time measurement ASIC. This chip captures the peak amplitude and time of pulses on 32 channels and stores the data in analog form until ready for readout. Signals from any channel are routed to one of eight available storage locations. Comparators and fast arbitration logic allows the circuit to work with pulses down to 30 ns width at rates up to several MHz. A novel two-phase offset-free peak detector achieves high absolute accuracy (0.2%), linearity (0.05%), and time resolution (5 ns) at a power consumption of only 2 mW/channel. The self-triggered, self-sparsifying operation will enable the development of readout systems with unprecedented efficiency and rate capability.

Medical Imaging

In collaboration with the Physics, Chemistry, and Medical Departments, the Instrumentation Division is working on the development of a miniature and portable Positron Emission Tomography (PET) Scanner. The *RatCAP*, Rat Conscious Animal PET, is intended to further research in neurobiology by studying the brain metabolism of an awake rat, with minimal restriction of motion. More precisely, the scanner will be used to study toxicological dependencies and pharmaceutical interactions. Projected completion of the first scanner is in late 2004. The mandate of the Instrumentation Division is to realize the electronics for the camera, the data acquisition system and the coincidence units. The size of the scanner (4 cm diameter), the high density of detectors (768 channels) and the low power budget (1W), require VLSI implementation of the front end electronics, which is realized in a CMOS 0.18 µm technology. The 32 channel front-end ASIC acquires the timing and position information of the 511 keV photons to 1 ns precision and encodes them into one output in order to minimize the number of interconnection with the data acquisition system, hence maximizing the camera's mobility. The data acquisition system, whose task is to encode the timing information of every channel with the detector address at a rate over 10^6 per second, will then send the information to the coincidence units for images reconstruction.

We have designed a series of ASICs for processing the signals from multiple element $Cd_xZn_{1-x}Te$ (CZT) detectors used in nuclear medicine, bone densitometry (DEXA method), mammography, dental radiography (intra-oral and panoramic), intraoperative cancer probes, and industrial applications. CZT detectors, when coupled with high performance ASIC electronics, offer compact size, low weight, room temperature operation, and energy resolution comparable to low-temperature Ge or scintillator-coupled Si detectors. Through a series of ongoing CRADA projects with eV Products, Inc., these chips have been commercialized and are now used in a range of clinical medical instruments. Present R&D efforts are aimed at efficient data acquisition architectures based on precision peak detectors, at lower power and higher levels of integration, and at applications of CZT to the detection of nuclear contraband. [3]



▶ Detector configuration for a head mounted positron emission tomograph (PET) for imaging the brain of an awake rat. The ring consists of 12 arrays of 2 x 2 x 10 mm^3 LSO scintillator crystals (shown in yellow) coupled to avalanche photodiode arrays (APD). A rigid-flex board houses the readout electronics, implemented as a mixed-signal ASIC in 0.18 micron CMOS. The ring (125 g) is attached to the head of a conscious animal to allow studies of brain function without the disruptive effects of anesthesia.

X- and Gamma-Ray Detection and Imaging

High-brightness synchrotron and neutron sources coming on line require new instrumentation to take advantage of the photon/neutron flux. One approach to deal with such high-rate probes is to subdivide the detector into a highly-segmented array of pixels with individual signal processing electronics. A recent example is the development of a silicon pad detector and energy-resolving photon-counting ASIC for a 384-channel X-ray fluorescence detector at the NSLS. This project required extremely low noise (< 300 eV FWHM, equivalent to 35 r.m.s. electrons) with high overall rate (10^7 photons/cm^2/s). A segmented Si detector was fabricated and coupled to an ASIC which incorporated in each channel a low noise preamp, high order shaper with programmable gain and filtering, baseline stabilizer, threshold and 2 window discriminators, four 6-bit DACs for fine threshold adjustment, three 24-bit counters, and serial readout. The 180,000-transistor chip showed an electronic noise of only 26 e^- with a Peltier-cooled detector (1 mm^2 pixel size). The low noise was achieved with simultaneously with a high rate of digital activity on-chip. [5-6]. Similar techniques will be applied to new detectors proposed for the NSLS and SNS.

CMOS sensors

We are actively investigating circuits with built-in sensors made from the native junctions in a standard CMOS process. Ionization charge released by photons or charged particles can be collected by the nwell-substrate junction and sent to signal-processing electronics. Applications in visible light imaging, X-ray detection, and charged particle tracking are proposed. While CMOS sensors have non-ideal characteristics, the benefits of monolithic integration can outweigh the drawbacks for many applications. The first design has been done in collaboration with a CRADA partner (Symbol Technologies) and is aimed at ultraminiature optical scanning devices.

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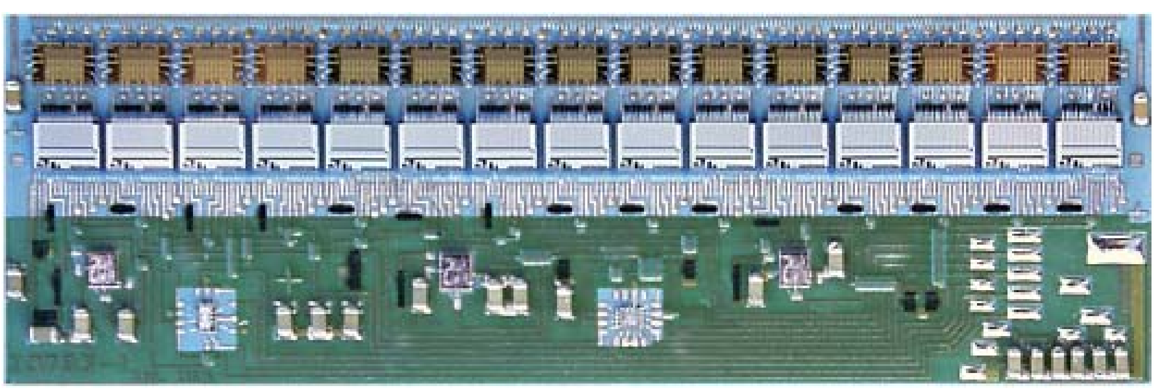

◀ 240-channel hybrid readout circuit for the STAR Silicon Vertex Detector at RHIC. This 6×2 cm^2 circuit contains 30 custom ICs which interface to the anodes of a silicon drift detector on 250 μm pitch. Preamplifiers, shaping amplifiers, and analog buffer memory are provided on this hybrid circuit.

ASICs Developed by the Microelectronics Group

Chip	Project	Function	Technology	Designers
IC31	PHENIX TEC	Preamplifier / shaper	CMOS 1.2 µm	P. O'Connor, A. Kandasamy
IC34/50/64/70/71	ATLAS CSC	Preamplifier / shaper / discriminator / track & hold	CMOS 1.2 µm	P. O'Connor, A. Kandasamy
IC35/37	STAR SVT	Preamplifier / shaper	CMOS 1.2 µm	P. O'Connor, S. Hart
M531A	STAR SVT	Preamplifier / shaper	Bipolar	D. Di Massimo
PHX-FADC	PHENIX TEC	Flash ADC	CMOS 1.2 µm	J. Harder
IC38/IC1-AMS	Xray/SDD	Preamplifier	CMOS 1.2 µm	G. Gramegna, P. O'Connor
IC40	Wireless	Frequency synthesizer/ transmitter	CMOS 0.5 µm	H. Vu, T. Vu, A. Kandasamy, W. Miller
IC43/45-49/54-56/59/60/62/63/65/67/69	CRADA eV Products	Amplifiers for CZT	CMOS 1.2, 0.5 µm	G. De Geronimo
IC44	CRADA Symbol	Direct-conversion receiver	CMOS 0.5 µm	H. Vu, T. Vu, A. Kandasamy
IC47/51/57	CRADA Symbol	LNA & mixer	TSMC 0.35 µm	D. Zhao
IC51/52	R & D	Test structures	HP 0.5µm and TSMC 0.35µm	P. O'Connor, A. Kandasamy
IC58	R & D	Bandgap reference	HP 0.5µm	A. Kandasamy, G. De Geronimo
IC61	CRADA Symbol	Transceiver	TSMC 0.35µm	D. Zhao
IC66	CRADA eV Products	32 channel comparator/ multiplexer	HP 0.5µm	G. De Geronimo, A. Kandasamy
IC68	R & D	Peak detector/ derandomizer	TSMC 0.35µm	G. De Geronimo, A. Kandasamy
IC72	NSLS	Photon-counting chip for EXAFS	TSMC 0.35µm	G. De Geronimo
IC73	ATLAS CSC	Digital multiplexer	HP 0.5µm	A. Kandasamy
IC74	R & D	Peak detector/derandomizer	TSMC 0.35µm	G. De Geronimo, P. O'Connor, S. Junnarkar
IC75	ATLAS CSC	Clock fanout	HP 0.5µm	S. Junnarkar
S1	CRADA Symbol	Linear array light sensor	TSMC 0.25µm	B. Carlson, M. Yan, G. De Geronimo
CMC1-2	PET RatCAP	Preamp/shaper for PET	TSMC 0.18µm	J.-F. Pratte

Printed Circuit Board Design, Fabrication and Assembly

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As the "brains" of sophisticated electronic devices used in experiments throughout the Laboratory, specialized circuit boards are required. These Printed Circuits Boards (PCBs) are exposed to such extreme environments as high radiation, humidity, and cryogenic temperatures in a wide variety of experiments. Circuit boards for these diverse applications are not readily available commercially. Our facility is capable of designing, fabricating and assembling unique PCBs for Instrumentation Division research activities and for other Laboratory programs and activities requiring such specialized circuit boards.

Recent expansion and upgrading of this facility with state-of-the-art equipment has made it an invaluable resource to the Division, for BNL's scientific community, and for our international collaborators.

The Division's PCB design, fabrication and assembly personnel possess the skills and expertise required for realizing many different types of boards. The fabrication facility can prepare multilayer circuit boards with drilled holes of unprecedented accuracy and, with the equipment available, conducting circuit lines in the boards can be made much thinner, and the spacing much closer, than those on commercially mass-produced boards.

Design

The PCB design group has personnel, software, and equipment geared towards fabricating and assembling the circuit boards.

Capabilities

- Schematic entry
- Place and Route.

  Manual place and route.
  Automatic place and route.
- Data translation for artwork generation.
- Generation of data for CNC drilling of boards.
- Photo-plotting (artwork) capabilities.

Software

- Mentor Graphics PowerLogic - Schematic entry
- Mentor Graphics ViewDraw - Schematic entry
- Mentor Graphics PowerPCB - Place and Route
- Cadence Specctra – Automatic place and route engine.
- AutoCAD – Computer Aided Drafting
- CAM 350 – Artwork generator and analysis.
- HyperLynx – Signal Integrity analysis

Equipment

- Cymbolic Sciences F9650 LASER Plotter.
- Optronics L2620 LASER Plotter.
- Kodamatic 66s Photo Processing Unit.

Fabrication

The printed circuit board fabrication group produces custom circuit boards from the engineer's initial design to the finished board, with the capability to produce features such as fine holes for via structures and components, ultra fine width and pitch conductive circuit traces. The facility also has the capability to fabricate boards using a wide range of materials like Kapton, Polyamide and other low loss materials, etc. The facility has an optical inspection station in its process line, which is used for inspecting individual layers for defects such as under or over etched traces, shorts, or opens in traces.

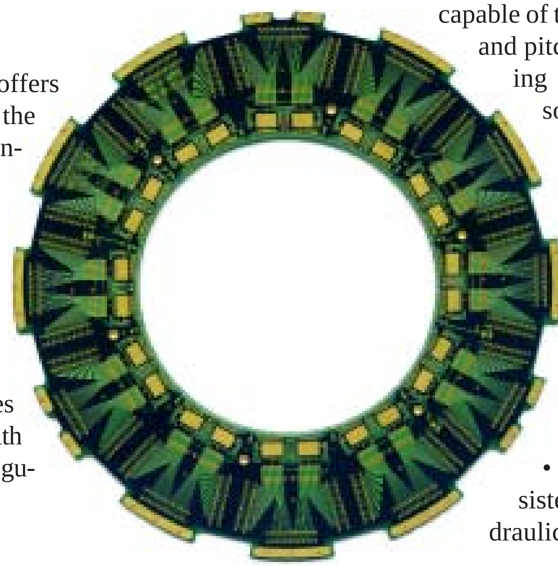
The facility has been and is actively involved in producing prototypes for various Brookhaven experiments and collaborations. Some of the experi-

▼ Photo-plotter in the darkroom being loaded with a 26"×20" photographic film for transferring the images from the workstations to the film using a low power laser beam.

ments for which the facility has provided its services are:

- RHIC experiments at Brookhaven
  - RHIC Beam instrumentation
  - PHENIX
  - STAR
- AGS facility at Brookhaven
- LHC experiments at CERN
  - ATLAS
  - NA45

The fabrication facility offers a wide range of services for the scientific community using environmentally safe techniques and equipment, complying with all local, state and federal regulations.



▶ A circular circuit board made for the silicon vertex telescope at the NA45 experiment at CERN. The board houses 24 monolithic circuits that amplifies the signals from the silicon detector mounted in the center.

Capabilities

- Multilayer printed circuit boards.
- Rigid-Flex boards.
- Optical inspection of individual layers.
- Computer controlled machinery (drilling, routing) for high precision and repeatability.
- Liquid Photo Imageable (LPI) solder mask and legend.

Equipment

- Dynamotion DM31– CNC drilling machine capable of hole sizes down to 3 mils within a ½ mil radius; programmable Z-axis; drill rate of 200 hits/minute.
- 36" wide Western Magnum Laminator with integrated IR cleaner.
- Optical Radiation and OLEC exposure units capable of transferring ultra-fine width and pitch traces to the material using its highly collimated light source.
- Developer and Etcher with frequency inverter pump speed control to vary spray pressure for various line weights; LPI solder mask and legends.
- Camtek 2V30 – Automatic optical inspection station.
- Accudyne – Vacuum-assisted computer-controlled hydraulic laminating press.
- Dynamotion/ATI CNC router.
- Precision oven with temperature range from ambient to 550°F, with fully programmable cycles for preparing the boards for assembly.
- Marseco Scrubber for surface preparation.
- CVS/SERA analytical equipment for accurate chemical process control
- Tsunami board cleaner

Assembly

The circuit board assembly group in Instrumentation is a cost-effective means of assembling specialized custom circuit boards or for performing any kind of rework on existing fixtures or off-the-shelf electronics. The personnel closely integrated into the web of the electronics group in Instrumentation are skilled in the art of assembling electronic components into the circuit boards fabricated either at the facility or elsewhere. The boards prepared by this group then make their way into an experiment or onto an engineer's test bench. The group utilizes a wide range of equipment for assembling large or very small components to silicon die as small as 2 mm × 2 mm with as many as 40 input/output pads in them.

◀ Ron and Howard inspect a sheet of core material to be laminated into a multi-layer printed circuit board.

Capabilities

- Through hole and surface mount component assembly (QFP's, BGA etc.).
- Wire bonding for monolithic components.
- Chip on board assembly.
- Custom test fixtures and panel assembly.

Equipment

- OK Industries SMT 8001 – Manual pick and place machine for surface mount component assembly.
- OK Industries KEM 410 –Infra-red reflow oven for soldering surface mount components.
- Novastar 2000A Convection reflow oven used for soldering large size circuit boards and BGA assemblies.
- Pace TF500 – Circuit board rework station.
- K&S 4123 – Manual aluminum wedge bonder.
- K&S 4526 – Manual aluminum wedge bonder.
- K&S 4124 – Manual gold ball bonder.
- Palomar 2470 – Automated wedge bonding machine with pattern recognition capabilities.
- Dage 4000 – Die and Ball shearing machine and wire pull tester.
- MARCH Plasmod – Plasma cleaner for die cleaning.
- Asymtek C700 – Automatic fluid dispensing system for die encapsulation for chip on board circuits.
- Vision Engineering – LYNX inspection station.
- DataPaq Reflow Tracker – Reflow oven temperature monitoring system.
- Asymtek C700 - Automatic fluid dispensing system for die encapsulation for chip on board circuits.
- PACE XR 2000 – X-Ray circuit board inspection station.
- PACE TF 2000 – BGA circuit board installation and re-work station.

▲ John is demonstrating the x-ray circuit board inspection stationa the BGA re-work station.

Data Acquisition and Control Systems

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Since the MERLIN computer was built in the 1950s to collect and analyze data in High Energy Physics experiments, the Instrumentation Division has been active in advancing the technology of data acquisition and experiment control for scientific research programs at BNL. The Instrumentation Division has provided detector and computer control systems for a wide range of DOE-sponsored programs, such as at the Cosmotron, AGS, and now RHIC, for High Energy and Nuclear Physics; at the High Flux Beam Reactor (HFBR) and the National Synchrotron Light Source (NSLS) for Basic Energy Sciences and Structural biology. The Division has played a pioneering role in many other smaller research programs, including Positron Emission Tomography (PET) data acquisition in the 1960s to the development of FASTRUN, a high performance computing device for molecular mechanics using a pipeline architecture with a power of 500 million floating point operations per second, used to calculate the forces and energy produced by pair-wise interactions of many objects in a system for a Life Sciences program in the 1980s.

The Instrumentation Division has produced 4 generations of neutron and x-ray spectrometer data acquisition systems for experiments at the HFBR from its inception in 1965 to the 1990s based on computer technology advances.

After 1993, the Data Acquisition and Control Systems Group was almost entirely devoted to activities related to RHIC Beam Instrumentation and one of its major experiments, PHENIX. The importance of RHIC to the Nuclear Physics program and to the Laboratory as a whole required an intensely focused effort in areas where the Laboratory had direct responsibility.

▼ Beam position monitor for RHIC

RHIC Beam Instrumentation

The Beam Position Monitor Electronics data acquisition section was the group's largest involvement for the RHIC machine. Over 700 planes of these electronics were installed and are currently in use in the RHIC facility. Each board includes two 16 bit digitizers, a fixed point digital signal processor (DSP) with SRAM and FLASH, an ALTERA in-system field programmable gate array, a beam synchronous timing interface, and an IEEE1394 Serial Bus (Firewire) for communications with the controls system. Two boards are packaged together in each module, but each board functions as a completely independent position channel. The control system communicates with the channels via shared memory in a VME/IEEE1394 interface board. Up to 12 channels are connected to each interface board via the IEEE1394 Serial Bus. Due to the large number of channels, the system was designed so that both DSP software and FPGA firmware can be reprogrammed remotely for easy feature updates and/or bug fixes. With the use of software running on the DSP, the channels can operate in different modes. During injection, a turn-by-turn record for each injected bunch is written to shared memory. For the rest of the collider cycle, the channels periodically send a turn-by-turn record for a particular bunch and simultaneously stream signal averaged position data at 10Hz. A recently developing project involves the upgrade of two beam position monitor electronics in each transverse plane and ring with high-capacity memory mezzanine cards. This upgrade will use the available PCI Mezzanine Slot (PMC) that exists in the existing design, and require only software changes on the DSP. This will provide these planes with the capability to digitize over 50 million consecutive turns of RHIC beam, or over 10 minutes of beam phase space evolution.

The PLL Tune Feedback System signal processing and data acquisition section was another involvement for the RHIC machine. The architecture consists of a Pentek VME Quad DSP board, VME NCO board, and a custom data acquisition module that includes a 3 MSPS digitizer, 672 pin BGA FPGA and programmable gain stages. The

▲ Generic ARCNET board used for intelligent general purpose control in the high magnetic field environment of PHENIX.

Pentek board includes four TI '6701 DSPs, providing over 4 GFLOPS of performance. The functions performed by the Pentek DSP include I/Q demodulation, phase and loop gain compensation during the frequency and relativistic slip factor swing of acceleration, IIR Filtering, and NCO control. This system has successfully demonstrated tune feedback with a phase-locked loop system in both rings; RHIC is only the second accelerator in the world to demonstrate a working tune feedback system.

PHENIX Infrastructure

The timing system for PHENIX provides three primary functions for all its detector subsystems. First, it is a mode bit scheduler, which outputs programmable eight bit mode commands on a clock-by-clock basis to the FEMs. Second, it provides data flow control with its readout enables to the FEMs, and monitors the number of level-1-accepts generated by the level1 system. Third, it provides low jitter distribution and generation of timing signals, namely the Beam Clock, Beam ClockX4 (generated on board via PLL), and LVL-1 Accept. The timing system consists of a single Master Timing Module and one (or more) Granule Timing Module for each detector subsystem (a total of about 25 Granule Timing Modules are currently in operation). It outputs all of its information on high-speed fiber links from its location in the counting house to the detector Front End electronics in the main detector hall.

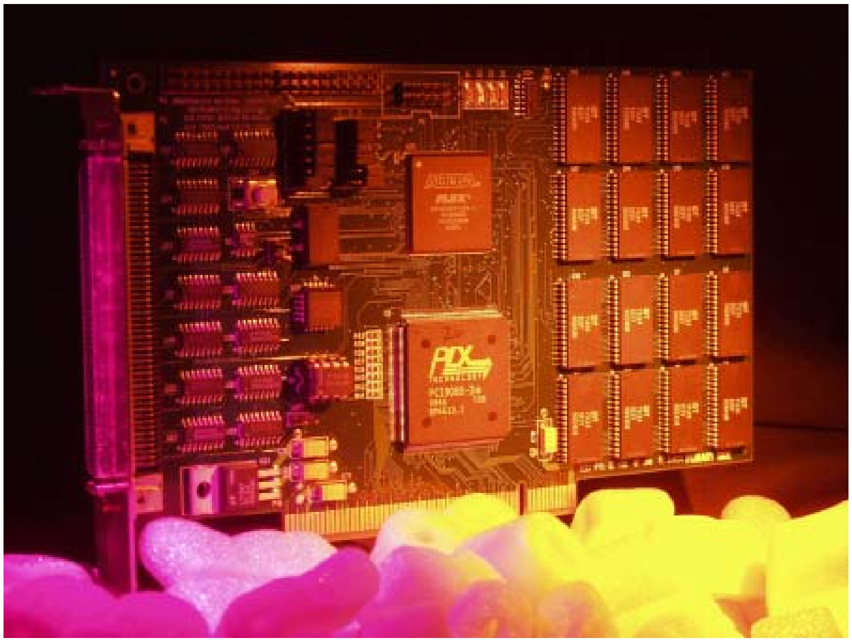
The Generic Arcnet Board provides PHENIX universal "slow" system monitoring and controls using the IEEE standard ARCNET "factory floor" protocol and 8051 style microprocessors.

The Sub Event Buffer provides high-speed data buffering and transfer from the PHENIX Data Collection modules to a final data storage system. The Sub Event Buffer designed as a PCI card with two 2MB memory banks is capable of up to 133MB/sec of data transfer using scatter gather DMA. With the Altera FPGA the Sub Event Buffer is programmed to maximize the throughput of the high-speed 32 bit LVDS interface used to communicate with the Data Collection Module.

PHENIX Detector Subsystems

The TEC Front End Electronics for PHENIX consists of a Preamp Shaper board, which is mounted on the chamber and the Front End Module (FEM). Four preamp shaper boards are connected to one Front End Module (FEM) via four cables. The FEMs are located in racks adjacent to the detector. Each Front End Module can handle 64 channels in parallel. The FEM uses pipeline architecture to keep up with high LVL-1 rates. When the FEM receives a LVL-1 Accept the signals from each chamber wire are sampled at 40 MHz. All 64 chamber wires are sampled in parallel. The digitized data is stored in a custom IC called the DMU. The DMU collects and stores 80 samples. The data is then read from the DMU and arranged in packets of 80 samples per channel. Header words consisting of detector ID, beam clock counter, LVL-1 counter, module address and parity are added to the packet. This data is then sent

▼ The Sub Event Buffer provides high-speed data buffering and transfer from the PHENIX Data Collection modules to a final data storage system.



◄ Digital centroid-finding module for the 120° thermal neutron detector for the spallation neutron source at LANL. Eight modules are needed for the entire detector. Onboard FPGA and DSP circuits decode the neutron position information in parallel, reaching a total counting rate of more than one million events per second.

serially over a 40 MHz fiber optic link to the PHENIX data collection system.

The MUON Tracking FPGA code was designed for the Muon Tracking digital control board built at Los Alamos National Laboratory. The FPGA code uses many complex algorithms used to readout and control the entire Muon Tracking system. The FPGA code has a unique solution of controlling the on board analog memory system allowing data to be stored and read simultaneously at high data rates. Similar detectors with long trigger delays and simultaneous read and write can utilize this technique. The FPGA code generates output data that follows the PHENIX DCM (Data Collection Module) standard while being able to store up to 20 samples worth of data at high rates.

New Projects

As the construction phase of RHIC and PHENIX has finished and successful operations started, the Data Acquisition and Control Systems Group has been supporting other important state of the art projects at BNL and other DOE Laboratories.

The readout electronics for the 120-degree neutron detector installed at LANSCE, provides a fast digital implementation of a centroid finding algorithm. The motherboard is built on an 8HP, 9U, VME64x form factor and provides for the readout of thirty-three cathode channels and three next neighbor channels for a single 20cm by 20cm neutron detector. The system is scalable to handle up to eight detectors simultaneously. The motherboard accepts three different daughter card modules, consisting of the digital centroid module, anode discriminator/shapers module, and gated base line restorer modules (1 per cathode channel). The digital centroid module provides a 2D x/y position result with up to ten-bit resolution in fewer than 4 microseconds. This computation is completed in less than the cathode channel shaping time and therefore doesn't contribute to any detector dead time. To achieve this speed a multistage pipeline was set up in a latest generation Altera FPGA. The functions performed in each stage of the pipeline are ADC channel readout, offset/gain correction, a maximum channel charge location search and a difference over sum computation. An onboard DSP provides routines for calibration, histogramming and various offline tasks. A separate transition module provides an interface to the either the LANSCE data acquisition system, or a PC via a high-speed digital link.

The Real-Time MRI motion compensation board for the MRI division will provide the corrections in the MRI magnetic fields and RF in real time to compensate for motion in small animals during scans. The board receives the translation and rotation vectors from the motion tracking

◄ Prototype Time Expansion Chamber Front End Modules (TEC FEM) for PHENIX. Two 64 channel modules are shown installed in a crate. Over 200 of these modules have been installed in PHENIX.

sensors along with the three analog gradient waveform signals and radiofrequency (RF) signals. The analog gradient waveforms will be digitized and then read into a Digital Signal Processor (DSP) along with the translation and rotation vectors where an algorithm determines the corrected gradient signals. These corrected gradient signals will then be transformed back to the analog domain using a digital-to-analog converter (DAC). The update rate for these corrections will be on the order of 10 µs.

The Active Matrix data acquisition system interfaces to a custom active matrix pixel sensor developed in Instrumentation, which will be used in the scanning transmission electron microscope (STEM) for the Biology Department. The electronics collects data from the 32×32 pixel sensor, using 32 high speed ADCs, subtracts baseline offsets, and then forwards the data to a PC's hard disk for off-line analysis.

The RAPTOR electronics is complete control system for the RAPTOR project for the Energy Sciences & Technology Department. The design's IO runs a standard industrial 24v interface. The controls system for RAPTOR is designed around an 8051 microcontroller with a custom keypad and display interface. An onboard ARCNET and serial interface allows RAPTOR to be remotely controlled. The RAPTOR electronics can control up to 14 industrial devices, monitor 8 control sensors, and read two analog sensors.

SPLAT II is a timing and control system for the Department of Environmental Sciences. It is a PCI card to allow ease of control through a PC software interface. The board contains large banks of on board memory, high speed LVDS interface, two ADCs and a large Altera FPGA. The PCI board interfaces to the external I/O board through high speed LVDS used to interface directly with the SPLAT II device.

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Micro/Nano Fabrication

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Microfabrication of commercial products and scientific instrumentation based on MEMS, or Micro Electro Mechanical Systems, is now a worldwide activity. Derived from the batch-processed methods of the integrated circuit industry, current MEMS products include inertial sensors for automotive airbags, inkjet printer heads for printers used in the personal computer market, and biomedical sensors for DNA hybridization analysis. More recently, the applicability of MEMS methods such as electron beam lithography for the fabrication nanoscale structures has been one of the prime drivers for the new Center for Functional Nanomaterials (CFN) at BNL. A number of applications involving nanomaterials at the CFN as well as microsensors at BNL's other multi-user facilities, the NSLS, RHIC, and the ATF, are under active development.

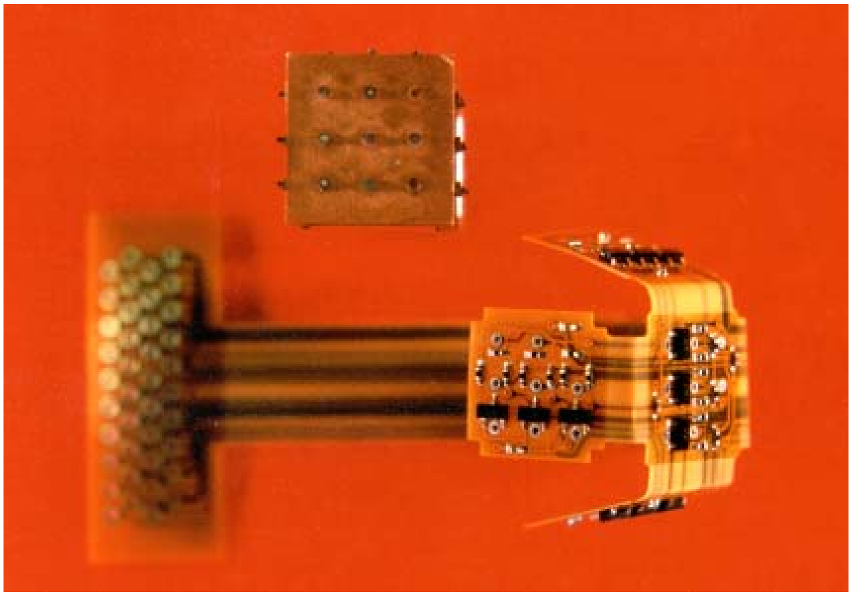
Facilities

The Microfabrication Laboratory is fully equipped with the hardware and software necessary for complete design, processing, and characterization of micro or nanoscale strtuctures. Visiting investigators are encouraged to actively participate in the design process by learning the fundamental fabrication processes, such as anisotropic etching, plasma etching, and high aspect ratio lithography, and by designing mask sets for the chosen method. Patterning steps take place in a Class-100 clean room equipped with resist spinners, developing tanks, and etching stations. A Karl Suss MJB-3 mask aligner, with both vacuum and hard contact modes, is used for UV exposure, and a Nikon optical microscope, equipped with a custom-designed quantitative metrology measurement capability, is used for analysis. An adjoining Class-1000 room contains oxidation furnaces for growing oxide layers on silicon wafers, a wet bench for anisotropic etching, and Plasmatechnology reactive ion etching and plasma-enhanced chemical vapor deposition chambers. A new state-of-the art field emission scanning electron microscope, a JEOL 6500, will be installed in June 2003. This unit has an electron beam lithography attachment that enables patterning with a 4 nm spot and currents of 1 nA.

Current Projects

The Microfabrication Laboratory was formed in 1989 to assist the newly formed Accelerator Test Facility in the fabrication of microstructure arrays used to study novel acceleration mechanisms with a laser linac. The expertise gained in this area has since been used to manufacture specialized microstructures for many investigators in both academia and industry. Current emphasis is on using electron beam lithography to assist in the CFN Jumpstart Program. Prior MEMS-related projects include infrared filter arrays for NASA, high resolution masks for e-beam deposition for Brandeis University, and industrial collaborations with Lockheed-Martin and Standard Microsystems to develop multi-axis accelerometers and improved versions of ink jet printer heads using high aspect ratio microfabrication

In the Lockheed-Martin CRADA, a variant of high aspect ratio microfabrication (commonly known as the LIGA process) has been used to form the critical component of a micro-accelerometer with three translation and three rotational sensing axes. The device works by levitating a cubical proof mass with permanent magnets mounted on each face of the cube. Microfabricated copper levitation coils oppose the field of each magnet and provide a restoration force that keeps the proof mass centered in the sensing enclosure. Levitation coil current levels are monitored to determine the actual acceleration

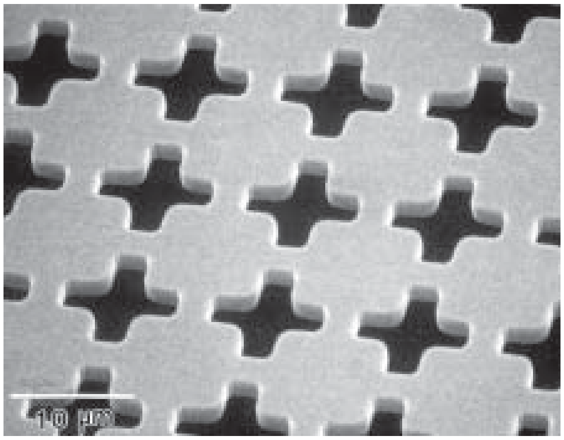


◄ CRADA with Lockheed Martin Tactical Defense Systems to develop a micro-accelerometer with 3 translation and 3 rotational measurement axes. The prototype uses high aspect ratio electroplated copper coils to levitate permanent magnets attached to a cubical proof mass.

component for each axis. With the multi-G accelerations commonly encountered in aerospace applications, high current levels in the coils lead to thermal dissipation restrictions that can only be circumvented by lower resistance coils. These low resistance coils can be fabricated in a given space only by increasing the aspect ratio of the coil cross-section, a procedure that can only be achieved by high aspect ratio microfabrication.

High aspect ratio lithography is also being used to pattern a freestanding membrane used as a deposition mask for electron beam evaporation. Here, coded openings, with a dimension of 2 to 3 µm are patterned in an array of high aspect ratio resist and then placed in close contact with a nickel foil in preparation for vacuum metallization. Since the foil is only a few thousand Angstroms thick, it cannot be patterned directly using normal methods. Chromium is deposited through the membrane openings to form a pattern on the foil that is irradiated with positrons and then reexamined with a high-resolution transmission microscope for crystal defects induced by the positron interactions. This technique is being developed by Prof. Karl Canter of Brandeis University and BNL's Physics Department, using positron sources located at BNL and LLNL.

Other applications require freestanding *metal* membranes. For this case, the metal is electroplated around high aspect ratio resist. After electroplating, the resist is dissolved and a frame is bonded to the electroplated metal film. Patterned films measuring several square inches in extent have been formed in this manner. As shown in the micrograph, freestanding nickel filter arrays fabricated in this manner have been used as infrared filters that selectively pass a narrow band of the infrared spectrum. Critical dimensions of the individual pattern holes are on the order of 2-3 µm. The bandpass spectrum depends critically on the hole pattern, pitch, and film thickness. Prof. Dieter Moeller of the New Jersey Institute of Technology and Dr. Jim Heaney of NASA's Goddard Space Flight Center have been involved in this effort.

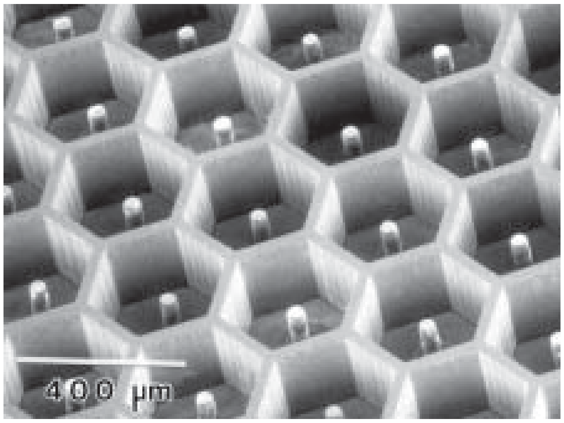


▲ Freestanding thin metal membrane Infrared filters for interferometry in the 10-20 µm range

High aspect ratio microfabrication with SU-8 photoresist is being used to fabricate two-dimensional position-sensitive detector arrays that have the potential to greatly increase the data collection rates of X-ray diffraction experiments at the NSLS and other synchrotrons. The SU-8 resist can be patterned with traditional UV lithography, yet display micostructural aspect ratios that heretofore were only achievable using X-ray lithography with a synchrotron. SU-8 is an epoxy-based resist and is sufficiently rugged to be integrated into the microstructure of the detector. The micrograph shows a detector array where both the anode and cathode are composed of vacuum-metallized SU-8. Anode and cathode portions of the array are formed by sequential patterning steps of both the anode and cathode portions of the array. The anode is composed of a cylinder 200 µm high and 50 µm in diameter that is enclosed by the hexagonal cathode that is 400 µm high.

An example of nanoscale fabrication has been the development of high aspect ratio electrode arrays that have been patterned by electron beam lithography. As shown in the micrograph, an electron-beam sensitive resist is patterned to form an array of electrodes with a nanoscale gap. By using directional vacuum evaporation, the top surface of the electrodes are coated with gold. Since no metal strikes the vertical sidewalls of the electrode during the deposition process, they remain insulating and the top surfaces of each electrode pair are electrically isolated from the substrate. Nanoscale objects such as SWCNT's, or single wall carbon nanotubes, are then deposited on the top electrode surface. SWCNT's

▼ High speed x-ray detector array for synchrotron applications

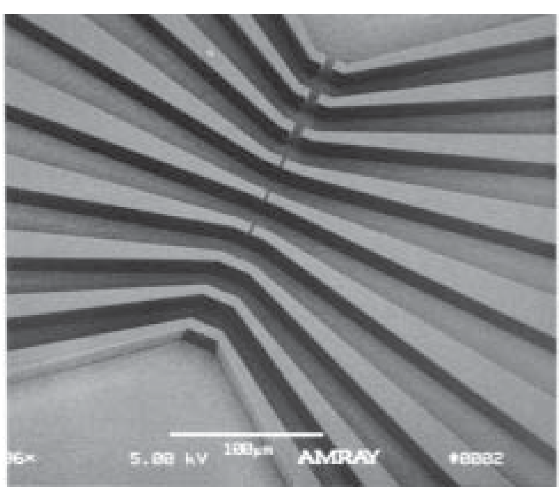


that are properly positioned over the nanoscale gap between each electrode pair can then be studied in conductivity experiments.

Significant Accomplishments

- Developed High Aspect Ratio Silicon Grating for Use in Laser Acceleration experiments at the Accelerator Test Facility (1989)
- Developed several methodologies for the Fabrication of Patterned Thin film Membranes for IR Spectrometers and Positron Re-emission Spectroscopy. (1992-1995)
- CRADA with Lockheed Martin Tactical Defense Systems of Archbald, PA for the Development of Multi-Axis Accelerometer using Advanced Microfabrication Methods (approved 1995)
- Developed Rapid Prototyping method for the in-house design and fabrication of microstructures (1996)
- CRADA with Standard Microsystems of Hauppauge, LI, NY for the Development of High Aspect Ratio Resist in Ink Jet Printer Head Fabrication (approved 1998)
- Developed method using multilayer metallized SU-8 resist to form position sensitive X-ray detector array for synchrotron X-ray diffraction applications (1998).
- Participated in the planning of the CFN and was awarded "Jumpstart" funding from DOE in 2002 to work with outside users in the development of functional nanomaterials.

▼ High Aspect Electrode Array Fabricated in Micro/Nano Fabrication Laboratory Using Electron Beam Lithography.



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Optical Metrology

Located within the Instrumentation Division, the Optical Metrology Laboratory (OML) at Brookhaven National Laboratory is actively involved in improving the quality of optical components used in synchrotron radiation (SR) beam lines throughout the world. Established in 1983, the OML has developed instrumentation and measurement techniques that are critical to the successful performance of high-precision aspheric optics, such as those found in beam lines at the National Synchrotron Light Source. The instrument technology that has been developed in the OML has been successfully transferred to industry under the auspices of a CRADA initiated in 1993.

Major Activities

- Provide metrology services to users and manufacturers of synchrotron optics.
- Provide feedback to manufacturers to enable process improvement.
- Develop and maintain the capability to measure surface roughness and figure error on large optics.
- Maintain specialized instrumentation and expertise for performing optical testing, installation, and alignment of synchrotron optics.
- Develop new test methods, techniques, and instrumentation.
- Maintain a stock of standard optical laboratory components and equipment available on loan to BNL staff and guest workers for experiment breadboarding.
- Provide guidance and expertise in the selection, specification, and fabrication of optical components.
- Study the properties of surface roughness and how it affects image quality in grazing- and normal-incidence x-ray optics.

Current Projects

The resources of the Optical Metrology Laboratory are available to the SR community for roughness and figure error testing of components to be used in beam line systems. Our specialized facilities and laboratory space are available to NSLS users and other laboratory groups for installation and alignment of components in monochromator systems and for breadboarding of special tests and experiments. We provide expertise in solving optical design and testing problems for the entire Laboratory. Most of our work involves developing applications for surface form error measurement with the Long Trace Profiler (LTP). Major projects and collaborations in which we have been involved are as follows:

- Developing a Vertical Scan LTP (VSLTP) with Continental Optical Corp. for measuring complete x-ray telescope mirrors and mandrels for a Phase II SBIR project sponsored by NASA Marshall Space Flight Center.
- Developing an In Situ Long Trace Profiler (ISLTP) instrument through a CRADA program with Continental Optical Corporation in collaboration with the Advanced Photon Source at Argonne National Laboratory.
- Working with Ocean Optics, Inc., in the development of compact versions of the LTP for various applications. Ocean Optics is licensed by BNL to commercialize LTP technology.
- Collaborating in a research project with the Materials Fabrication Laboratory at RIKEN in Tokyo

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▶ Current LTP installation in Optical Metrology Lab. A 1 meter long Si cylinder mirror is shown under test. The "open architecture" optics board allows for rapid prototyping and testing of various external and internal components.

to install an LTP optical head on a precision grinding machine for rapid production of aspherinc optics.

- Developing models for predicting the performance of x-ray optics based on measurements of surface figure and finish parameters.
- Investigating error sources in the LTP that limit the measurement accuracy at the 1 microradian level.

Rationale for a Metrology Laboratory

In the early part of the 1980s, during the construction phase of the first NSLS beam lines, it became apparent that conventional optical fabrication and testing techniques were inadequate to meet the needs of the synchrotron radiation community. Mirrors needed for grazing incidence beam lines were often shaped like segments of cylinders or toroids, or far off-axis conic sections: paraboloids and ellipsoids. These mirrors proved extremely difficult to manufacture, since they required unconventional grinding and polishing techniques, and no suitable metrology techniques existed for testing the quality of these surfaces.

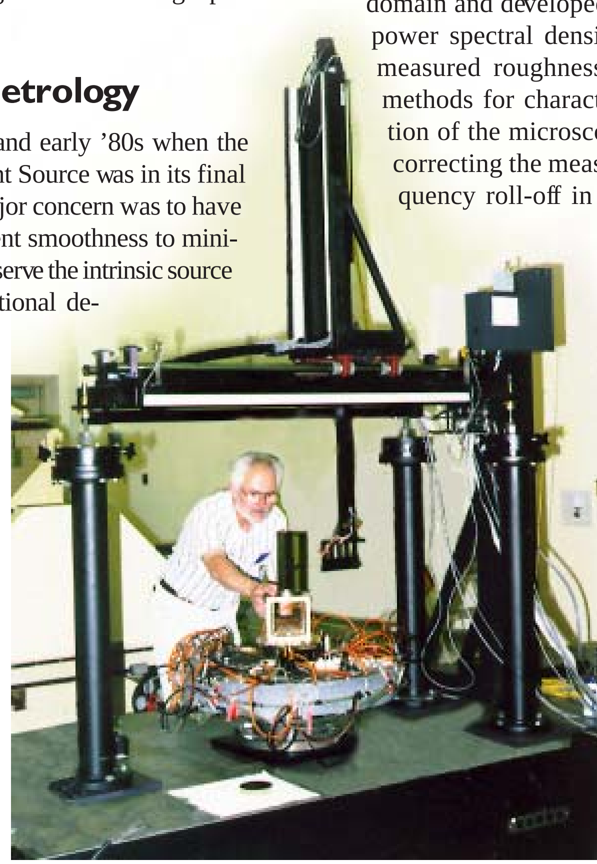
Recognizing the need to develop optical metrology instrumentation and techniques tailored specifically to grazing incidence optics, the Instrumentation Division established a program in 1983 to investigate surface roughness and figure errors in high performance optics.

Surface Finish Metrology

During the late '70s and early '80s when the National Synchrotron Light Source was in its final construction phase, the major concern was to have mirrors made with sufficient smoothness to minimize scattered light and preserve the intrinsic source brightness. The unconventional design of grazing incidence optical systems required the use of far off-axis aspheric mirrors — cylinders, toroids, ellipsoids and paraboloids — that were extremely difficult to manufacture and polish to a smooth finish. One of the primary reasons why it was so difficult to manufacture grazing incidence aspheres was the lack of suitable metrology instrumentation that could accommodate full-size meter-long optics. To insure that mirrors and optical systems would be able to meet the stringent requirements imposed by the synchrotron beam quality, the Optical Metrology Laboratory was established in 1983 in the Instrumentation Division.

Fortunately, at about this time, a commercial surface profiling instrument was developed that revolutionized surface roughness measurement technology. The micro phase-measuring interferometer (micro PMI) enabled quick and accurate measurement of surface roughness with sub-Ångstrom level accuracy on parts of any size or shape. We acquired a WYKO NCP-1000 Digital Optical Profiler and began providing manufacturers with feedback that allowed them to improve the quality of the surfaces provided to us. Since we were pushing micro PMI technology beyond the limits of its intended use, we established a research effort, in collaboration with Dr. E.L. Church, who has extensive expertise in surface roughness and scattered light theory, to understand the performance of the instrument and to validate the link between surface roughness measurements and the actual performance of a mirror in a SR beam line. This has been, and continues to be, a very fruitful collaboration.

Using signal processing techniques, we analyzed the instrument performance in the spatial frequency domain and developed software to compute the power spectral density (PSD) function of the measured roughness profiles. We developed methods for characterizing the transfer function of the microscope-based profiler and for correcting the measured profiles for high-frequency roll-off in the imaging system. Our efforts at understanding the performance of this new type of surface profiler eliminated the error sources that plagued the intercomparison of roughness measurements made with different techniques and permitted accurate prediction of scattered light intensities from x-ray mirrors. Our methodology for using the PSD function to describe surface roughness has been incorporated into an ISO standard and is in the process of being added to ASTM and ANSI standards.



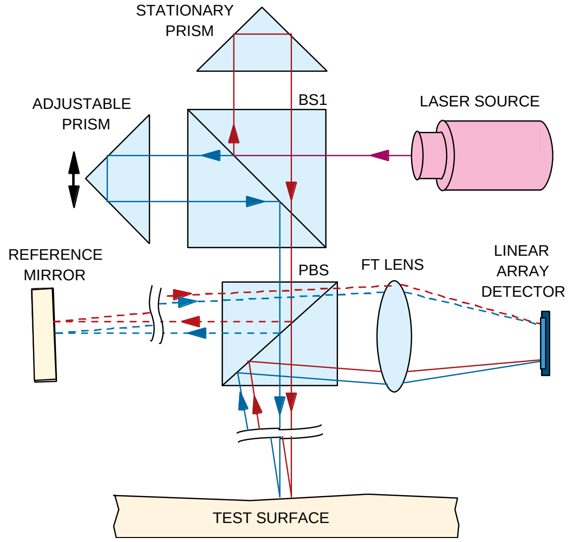
▶ Vertical Scan LTP (VSLTP) installed at NASA Marshall Space Flight Center for measurement of x-ray telescope optics in a vertical orintation. A small Wolter telescope mandrel is shown in position for testing.

As a service to the SR community, we provided measurements for manufacturers who did not have the capability to measure surface roughness to the level of precision and accuracy required by SR applications. We also have a special stand-alone AFM head that is used to measure the surface topography of full size optics at nanometer lateral scales. This instrument is particularly useful for UV and soft x-ray diffraction grating characterization. Based on our efforts at providing feedback to the manufacturers, the quality of optical surfaces delivered for use at the NSLS, and at other synchrotron facilities around the world, improved significantly. For this work we were recognized with a Federal Laboratory Consortium Award for Excellence in Technology Transfer in 1989.

Surface Figure Metrology

Despite our successful efforts to have low Ångstrom-level surface roughnesses made on aspheric optics, we quickly discovered that most of the conventionally-polished large cylindrical mirrors in use at the NSLS had large slope errors that broadened the image and seriously compromised the intrinsic source brightness of the machine. Figure measurement techniques for SR mirrors were extremely crude at this time. There were no commercial instruments capable of measuring grazing incidence aspheres with the required accuracy, so the final product was seldom within the desired range of specification for both surface roughness and figure error. After finding an effective solution to the surface finish measurement problem, we then turned our attention to the figure measurement problem.

Early in the 1980s, a surface profiling technique was developed by von Bieren at Rocketdyne Corp., which was called the pencil-beam interferometer, that was ideally suited for the measurement of long cylindrical aspheres. A development effort was started at BNL to apply this technique, and an instrument incorporating an improved version of the interferometer was developed, which we called the Long Trace Profiler (LTP). The LTP is optimized for measuring the figure and slope errors on meter-long aspheres that have a long radius of curvature in the axial direction. It can handle surfaces with a total slope change of 10 mrads with better than 1 μrad repeatability. Despite the limited angular acceptance range, the LTP can handle about 99% of all mirrors used in grazing incidence optical systems. As with the micro PMI, we provided feedback to manufacturers and have seen a steady improvement in the quality of SR mirrors, not only for the NSLS, but for all SR facilities for which the mirrors were destined.

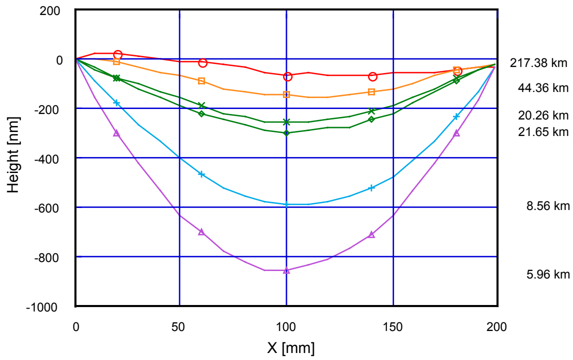


▲ Schematic diagram of the LTP optical system. Slope of the test surface is measured by scanning the optical head across the surface. Reference mirror removes all motion-induced error signals, allowing for extremely high precision and accuracy in long radius of curvature measurements.

Recognizing the usefulness of the LTP in the manufacture of SR optics, Continental Optical Corporation (COC) obtained a license from BNL to manufacture the LTP as a commercial product. Under the auspices of a CRADA established with BNL, an improved version of the instrument, the LTP II, was developed. At present, there are 16 LTPs in operation around the world. It has become the *de facto* standard for the measurement of SR mirrors. The license for manufacturing LTPs was transferred from COC to Ocean Optics, Inc. (OOI) in early 2000 after the COC business was sold to OOI. The CRADA with OOI continues today with the goal of developing new uses and applications for the LTP technology. OOI has extensive ex-

▶ Current implementation of the surface roughness profiler in the OML. Custom modifications allow it to measure Ångstrom-level roughness on full-sized SR mirrors quickly and easily.

▶ Measurements made with the LTP on a Si cylinder in a mirror bender in the face-down configuration. The initial unbent height profile has been subtracted from each curve. Surface height deflections of 50 nm over the 200 mm trace length are clearly visible. Repeatability between successive scans at the same radius is better than 25 nm. Radius of curvature for each profile is indicated in the margin.



perience in spectrophotometric instrument design and manufacture. OOI plans to redesign the LTP mechanical system and add its own detector technology to improve the optical head.

The LTP II received an R&D 100 Award in 1993 as one of the most significant instruments of the year. It also received a Photonics Circle of Excellence award in 1993 for innovation in optical instrumentation. Our efforts at recognizing the commercial potential of the LTP resulted in a Federal Laboratory Consortium Technology Transfer award in 1997.

Significant Accomplishments

- Developed the Long Trace Profiler (LTP) for measuring the surface figure of large aspheric x-ray optics with unprecedented precision and accuracy. This instrument is now the *de facto* standard for synchrotron mirror metrology throughout the world.
- Developed accurate quantitative methods for measuring surface roughness on precision optical surfaces with a micro phase-measuring interferometer instrument. Fully characterized the performance of the instrument through analysis of the system transfer function.
- Developed a surface roughness specification technique based on the PSD formulation and fractal theory. This technique is now incorporated into an ISO surface roughness specification.
- Developed quantitative formulation to link x-ray image quality to the surface PSD function.
- Developed a standard artifact for diagnostics and calibration of scanning probe microscopes, stylus profilers, and optical profiling instruments
- Successful technology transfer program with Continental Optical Corporation and Ocean Optics, Inc. for continued LTP development through CRADA and SBIR programs

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Lasers and Electro-Optics

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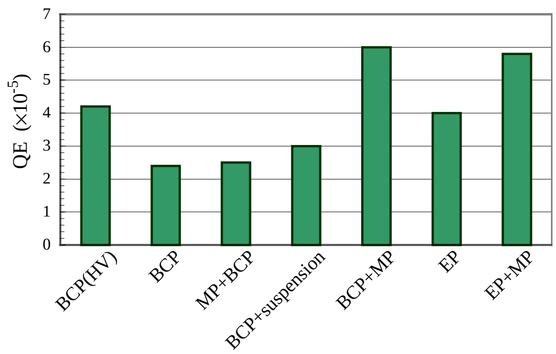
The Laser Laboratory in the Instrumentation Division is actively involved in the development of efficient, high quality photoelectron sources, optical version of particle detectors with high spatial and temporal resolution, and diagnostics for ultrafast laser pulses. Various pulsed and continue wave laser systems with optical pulse duration ranging from a few tens of femtosecond to a few microsecond, wavelengths range from ~1300 nm in the Infrared to 266 nm in the ultraviolet, and energies of nanoJoule to nearly a Joule per pulse are used in these research programs. In addition to these lasers, the laboratory also has two unique high voltage pulse generators capable of delivering 1 MV and 5 MV in <1 ns with rise and fall times of <150 ps. These pulse generators along with fast lasers are used to generate electron beams with unprecedented brightness. These fast lasers are used for detector applications as well as the development of diagnostic tools for ultrafast optical events.

Photocathode Research

In the past decade, RF injectors have been used as high brightness electron sources for free electron laser and accelerator research. The novel component in this injector is the photocathode, which is incorporated into the RF cavity and acts as the source of the electrons. The ease with which the electron bunch parameters such as the charge, the current, the current density, and the spatial and the temporal profile could be modified is a major advantage of these injectors. The complexity of the injector is determined primarily by the choice of the photocathode material and the laser system that drives the photocathode.

▲ Two ½ cell Nb cavities

The photocathode materials that have been used so far could be broadly categorized into two types, namely cesiated semiconductors or simple metals. The cesiated semiconductors typically have a very large quantum yield and hence require a simpler laser system to drive it. This advantage is offset by the delicate nature of the material. Its susceptibility to contamination reduces the lifetime to a few days and necessitates use of



▲ Results of several surface preparation techniques of superconducting Nb. Laser cleaning energy density is around 0.3 mJ/mm^2.

complex preparation techniques and vacuum levels exceeding 10^{-9} Torr. The metal cathode, on the other hand, is relatively insensitive to contamination and has a very long lifetime, but has low quantum yield.

In recent years, there has been increased interest in high average current photoinjectors, injectors that can provide electron bunches of ~ 100mA. Such high current applications impose stringent requirements on the photocathode high quantum yield as well as long lifetime. Our efforts have been focused on two approaches: improving the quantum yield of all niobium superconducting RF injectors where the superconducting Nb at the rear of the cavity will act as the photocathode and improving the lifetime of multialkali photocathodes.

Several surface preparation techniques of superconducting Nb has been tested and the results are shown in the first figure above. To test the performance of an all Nb superconducting injector, a ½ cell Nb cavity has been designed and fabricated. The cryostat and the RF system are being assembled. Currently efforts are underway for cryogenic testing of the cavity as well as the injector. This research and development is undertaken as a CRADA with Advanced Energy Systems.

In parallel, an ultra high vacuum deposition chamber has been designed and fabricated for depositing and testing multialkali cathodes. The system is undergoing vacuum tests and the first deposition is expected within a few months. Results from both these approaches are expected to lead to high brightness, high average current electron injectors for applications such as electron cooling of ion beams and Free Electron Lasers.

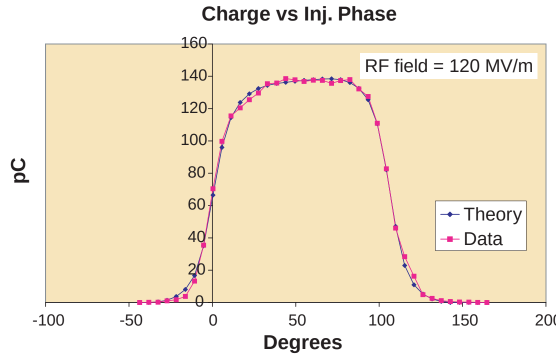
Generation of High Brightness Electron Beams

The future electron colliders require bunches of very high brightness electron beams to provide the high luminosity beams required these machines. The short wavelength Free Electron Lasers (FEL) also require electron beams with high current and emittance comparable to the wavelength. The research in the Instrumentation Division in the generation of such high brightness electron beams follow two parallel paths, RF injectors and pulsed power guns.

RF injectors

In a typical electron beam, if the transport at high energy is designed carefully, the emittance and the brightness of the electron beam is dominated by its momentum and energy distribution at the source, namely the cathode. The electron emission from the cathode is modified by the field seen by the electrons within the cathode. This field is a combination of the surface field due to the applied RF and the space charge field due to the electrons in the vicinity of the cathode. The velocity distribution of the

▼ Ultra high vacuum deposition chamber



▲ Model calculations accurately predict the extracted charge as a function of the phase between the RF field and the laser pulse.

emitted electrons and hence the transport of the electrons are also affected by this dynamic field.

An ongoing experimental program that investigates the electron emission and the properties of the electrons at the cathode in a RF injector is in place at the ATF. This is a collaborative effort between scientists from Instrumentation Division and the NSLS.

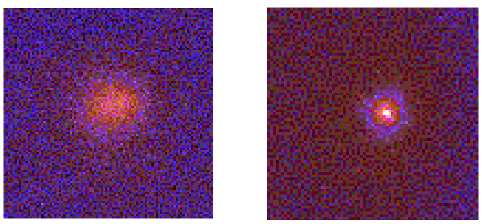
In the most recent experiments, the emitted charge was measured as a function of the RF phase at which the laser illuminated the cathode. A dynamic model that takes into account the variation of the field in the emission regime and its impact on both emission and transport of subsequent electrons is currently being developed. When completed, this model would be able to explain experimental data. In addition, it would also provide the temporal shape and momentum distribution of the electrons at the source, and can be used to optimize the laser parameters to reduce the longitudinal emittance.

With this dynamic model, the electrons can be characterized accurately for the first time at their source. These characteristics can be used as the input parameter for the beam transport, and optimal parameters for the laser beam can be determined. The emittance growth in the injector could be minimized with such a laser beam and the brightness of the electron beam could be improved significantly. From a practical point of view, this research has also led to the development of surface preparation technique for achieving highest quantum yield and reliable performance from the cathode.

Pulsed power gun

The inherent emittance and brightness of the electron beam from the RF injectors are limited by the temporal and spatial variation of the applied RF field at the cathode while the electrons are emitted and transported. The space charge forces experienced by the electrons in the vicinity of the cathode where the electrons are nonrelativistic also affect the brightness adversely. Nonlinear correction techniques that minimize these effects in RF injectors are being studied.

Another technique to minimize the emittance growth due to varying field is to use a pulsed electric field at the cathode. For this scheme to be successful, the pulse duration of the high voltage must be significantly longer than both the emission time and transport time of the electrons in the nonrelativistic regime and the electrode geometry should be optimized for minimum field variation over the emitting area. In addition, very large field should be established at the cathode to overcome the space charge effects.

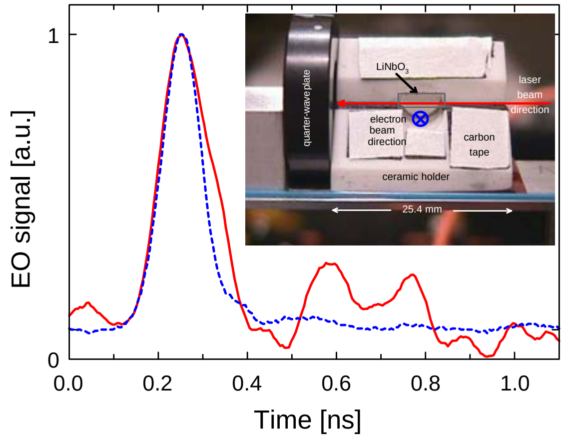


▲ Typical electron beam spot recorded at the first (left) and the second beam profile monitor. Their dimensions are 0.58mm and 0.2mm respectively (rms).

The highest field that could be maintained at the cathode is limited by the occurrence of electrical breakdown. It has been shown that field gradients exceeding 1 GV/m for duration of 1-5 ns can be supported without breakdown by using carefully prepared electrodes.

By adjusting the solenoid current, the electron beam can be focused on the second BPM. The spot sizes measured at both these BPMs are then used to calculate the emittance of the beam. Typical spots in the two BPMs are shown in the Figure. Electron beams were produced from 1 mm diameter spot, with 300 fs laser, up to 400 kV bias and up to 400 MV/m gradient. The smallest spots obtained at second BPM have a 1-σ width of 100 µm and a normalized emittance of 0.7 mm-mrad. Charges up to 60 pC had been extracted from the cathode, corresponding to a current of 200 A and current density of 30 kA/cm^2. Emittance could not be measured for this charge due to saturation of the BPM. Already, a number of institutions such as the Lawrence Livermore National Laboratory, the Source Development Laboratory in BNL have shown interest in using this device both as an electron source and as a test bed for high field measurements.

A CRADA has been established to use our device as a working model. A new pulse generator capable of delivering up to 5 MV on the cathode has been constructed and is being tested



▲ Solid line - the electro-optical signal detected by a 12 GHz photoreceiver on a 7 GHz oscilloscope. Dash line - instrument response. Inset is the close-up view of the experimental setup.

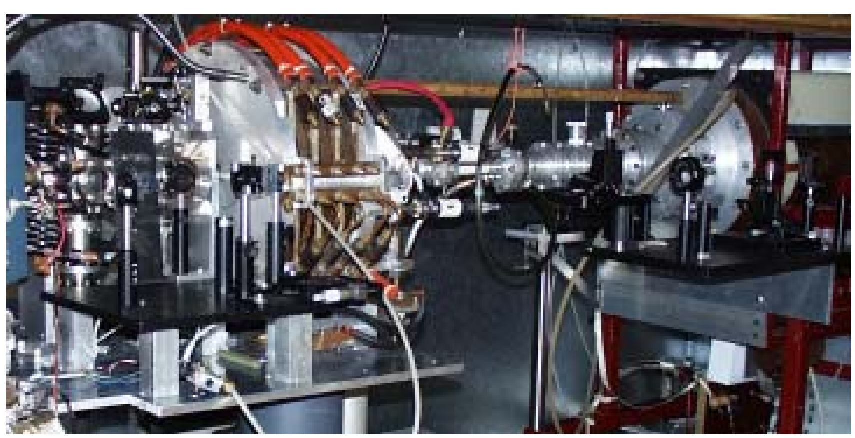
This project has also proved to be a sound learning ground for graduate students since it encompasses a wide range of topics such as the lasers, high voltage systems, electron optics and electron diagnostics and yet small enough for one person to be responsible for all these systems.

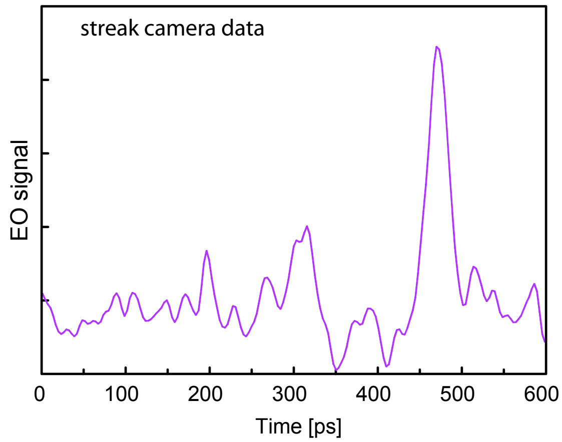
Electro-Optics in Particle Detectors

Ultrafast particle detector

It is well known that the response time of the polarizability of optical crystals is in the femtosecond regime. If the electric field produced by the relativistic charged particle can be probed by such crystals, the passage of these particles could be detected with unprecedented temporal resolution, limited only

▼ The GV/m pulsed electron gun and beam line for producing and characterizing high brightness ultra short electron beams





▲ The electro-optical signal measured by a streak camera with a 2 ps resolution,average of eight data traces.

by the bandwidth of the associated electronics. This scheme also has an added benefit of removing the detector from the vicinity of the interaction region, reducing the real space required near the beam line.

Experiments have been done using the electron beam at the ATF to examine the temporal shape of the electron beam field induced polarization. A short 10 ps duration, 50 MeV electron beam passes in the vicinity of a phase modulator and induces a large electric field in the modulator. The perturbed field induced by the electron beam is probed with a highly polarized optical beam propagating in the modulator. By measuring the change in the ellipticity of the optical beam during the passage of the electron beam.

In one version of the apparatus, the light field propagates at 45 degree to the principle axis of the crystal. The electron beam induced signal is measured to be less than 1 ns limited by the bandwidth of the photoreceiver.

In another version of the apparatus, a free space Mach Zehnder interferometer is employed to probe the electron induced phase change. The electro-optical signal is sent to a streak camera. Less than 40 ps fast optical transient is measured.

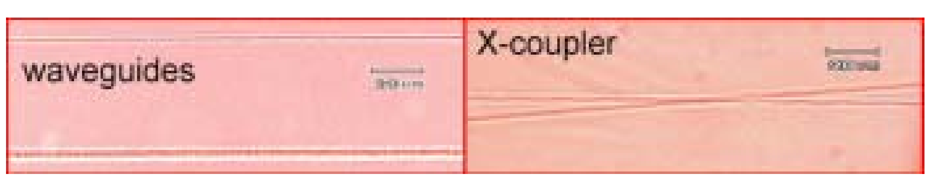
Several variations of the apparatus are planned to lower the temporal resolution to the femtosecond regime. Upon the success of these initial experiments, the project may be expanded to the construction of a real detector. If successful, this idea could lead to the development of particle detectors with temporal resolution in the femtoseconds and spatial resolution of a few microns which would be highly useful in both hadron and lepton colliders.

Ultrashort-Laser-Pulse Applications: Femtosecond laser micro-machining

Laser machining is a process that uses a focused optical light beam to selectively remove materials from a substrate to create a desired feature on or internal to the substrate materials. The process is non-contact yet it has high spatial confinement. Comparing to other mechanical machining techniques, laser machining exhibits low heat deposition to the working piece. The process generally relies on the linear optical absorption and plasma formation mechanisms. However, conventional laser machining, cw or pulsed, can not create micron-sized structures because linear optical absorption of the materials often lead to heat deposition, micro-cracks and small collateral damage to the surrounding is unavoidable.

Femtosecond laser micro-machining is a rapidly advancing area of ultrashort laser applications. It utilizes the ultrashort laser pulse properties to achieve an unprecedented degree of control in sculpting the desired microstructures internal to the materials without collateral damage to the surroundings. Using femtosecond rather than picosecond or nanosecond light pulses, laser energy is deposited into small volumes by multiphoton nonlinear optical absorption followed by avalanche ionization. Because the typical heat diffusion time is in the order of nanosecond to microsecond time scale whereas the electron-phonon coupling time of most materials are in the picosecond to nanosecond. Therefore when laser energy is deposited at a time scale much shorter than both the heat transport and the electron-phonon coupling, the light-matter interaction process is essentially frozen in time. The affected zone altered from solid to vapor phase and to plasma formation almost instantaneously. Unlike conventional laser machining, femtosecond laser machining reduces collateral damages to the surroundings. Because the machining process is not dependent on the linear absorption at the laser wavelength, one laser beam

▼ Waveguide and x-coupler created by scanning a fused silica substrate across a laser beam focused at 100 micron depth from the surface

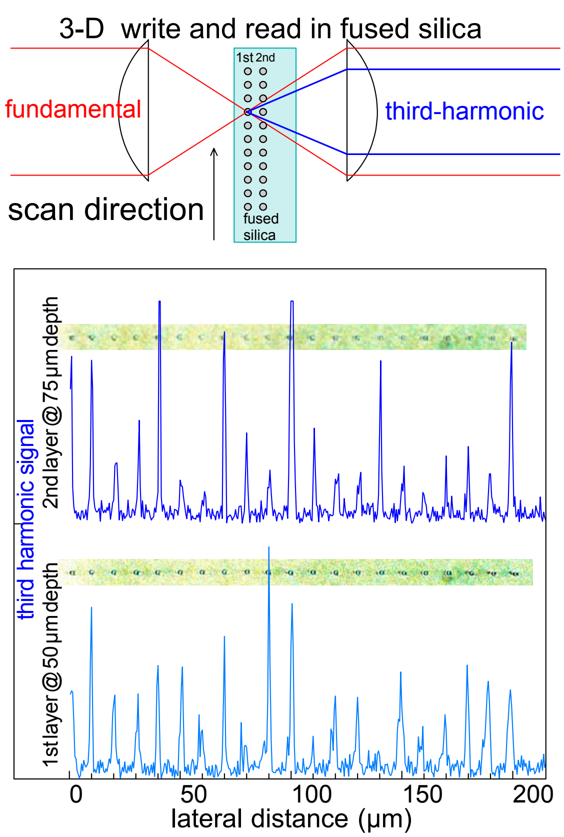


system can machine virtually any dielectric, metals, and mechanically hard materials.

By careful control of the laser intensity, one can produce only permanent refractive index modification on the work piece. Direct writing of optical waveguides in three-dimension becomes possible. More importantly, passive and active optical devices can potentially be fabricated directly in three-dimension using one laser system in one processing step.

Despite of the various potential applications of femtosecond laser micro-machining, the precise mechanism of the process is still under investigation. Various groups are studying practical issues such as reliability, stability, and lifetime of the fabricated devices. We have developed an online diagnostic technique for the micro-machining of various materials. It was found in one of our early studies that the third-order nonlinear susceptibility, which is dipole allowed on all materials, was efficiency enhanced by the non-uniformity of a medium either in the linear refractive index or in the nonlinear susceptibility. A surprisingly strong optical third-harmonic (THG) is generated in the forward direction only at the material interface. This THG is maximized when the interface is located at the beam waist of the light pulse. The onset of the THG signal with input laser energy can be use to establish the threshold for the creation of the micro-machined features on the sample. Furthermore, the same laser beam but at different intensity levels can be used to create and then probe the micro-machined structures at various depth in the substrate on the fly. Hence a novel 3-D optical read and write scheme is proposed and demonstrated.

Because of the nature of the nonlinear optical fabrication process, features size smaller than the diffraction limit can be created internal to the substrate at various depths. 3-dimensional submicron structures can be defined to produce miniature photonic components, read only memory chips, and hollow channel waveguides that may be of interest in the area of optical communication network, optical data memory, and biological optical chips.



▲ The laser beam first micro-machined at high intensity two rows of data separated vertically by 25 microns. Readout of the data is achieved by detecting the third-harmonic generated only at each individual data point (voxel) using the same laser beam but at a much lower intensity.

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Vacuum Deposition and Materials Processing

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The Vacuum Deposition and Materials Processing Laboratory provides special electrical, optical, mechanical, and magnetic thin film coatings for particle and x-ray detector systems fabricated within the Instrumentation Division, for researchers at BNL's other divisions and departments, accelerators (AGS, NSLS, RHIC, Dynamitron and Tandem Van de Graaff) and reactor, and for other outside educational and research institutions (i.e., the Materials Science Department at Stony Brook University.) The Laboratory also provides vacuum brazing, heat treatment, and materials consulting services to BNL's divisions and departments. Technical and instructional support is also provided to BNL's Science Education programs.

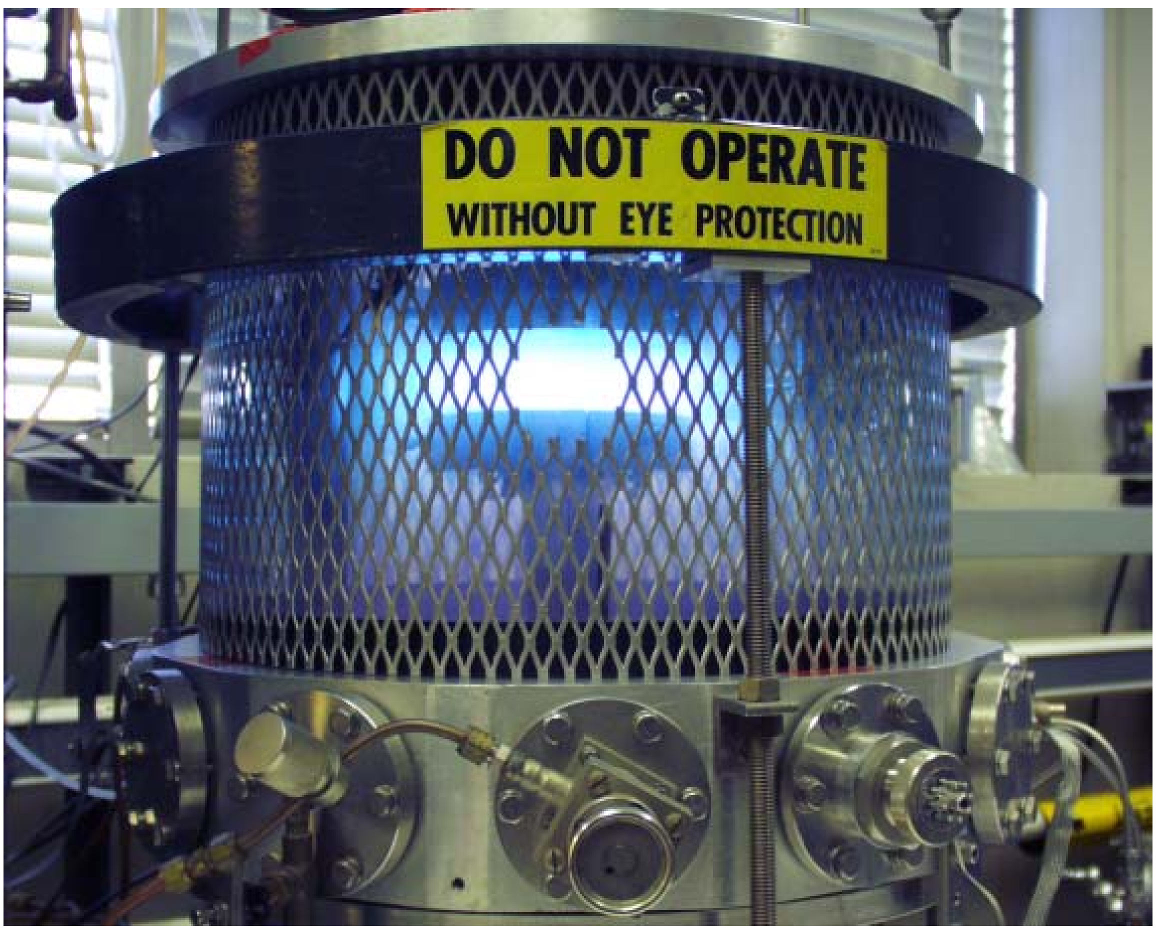
The Vacuum Deposition and Materials Processing Lab is listed in the Directory of Federal Laboratory Resources, U.S. Department of Commerce.

Facilities

The Vacuum Deposition and Materials Processing Laboratory, located in Building 535B, contains a parts preparation room (chemistry lab), a testing and measuring room, and a thin film deposition and vacuum furnace room. The available equipment includes:

- Resistance and electron-beam thermal evaporation, and rf and dc sputtering systems for thin film deposition
- Vacuum ovens for soldering, brazing and heat treating
- Systems for leak detection
- Systems for measuring the physical properties of materials.

▼ Rf and dc sputtering systems for thin film deposition



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Al and Cr coatings on Mylar window	P. Rehak, G.C. Smith and B. Yu, "A Method for Reduction of Parallax Broadening in Gas-based Position Sensitive Detectors, *IEEE Transactions on Nuclear Science*, 44 (3), June 1997
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Solid State Gamma-Ray Irradiation Facility

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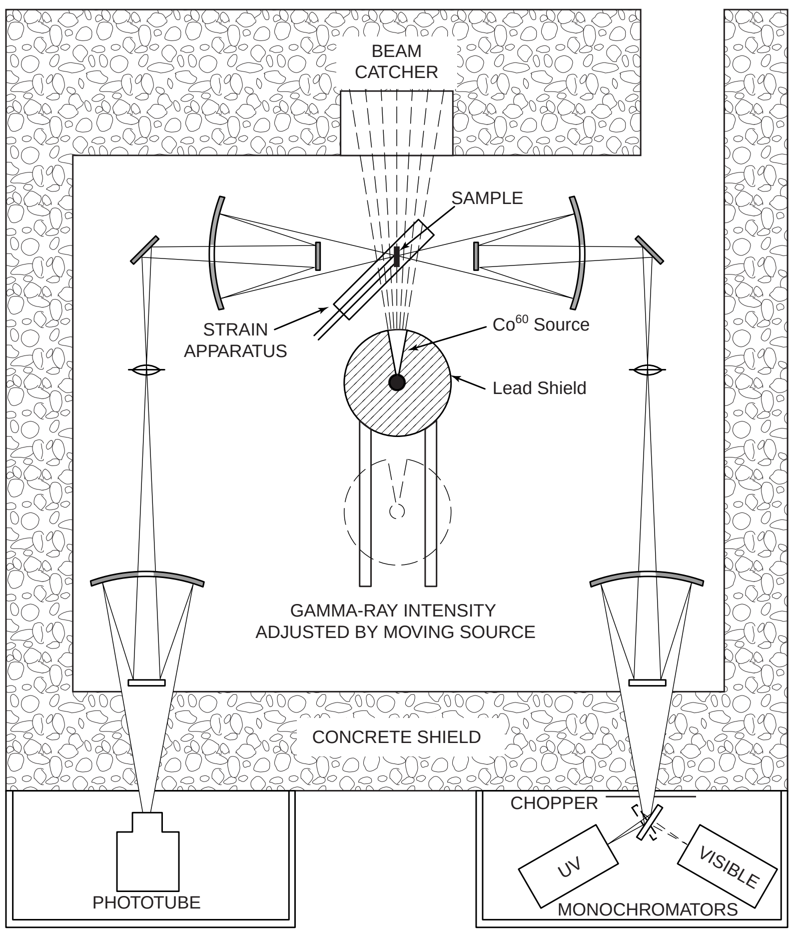
The Solid State Gamma-Ray Irradiation Facility (The Brickpile) was designed for basic radiation damage studies on transparent nonmetals. The "walk-in" irradiation chamber is roughly 14 × 14 feet and is surrounded by a concrete block shield sufficiently thick to permit people to work adjacent to the shield during irradiations. The existing Facility was completed in 1965. It was preceded by a prototype with a relatively low level source. In 1991 the ^{60}Co source in the Facility was upgraded to approximately 20,000 Curies. As of January, 1998 the conveniently obtained dose rates, on samples roughly 8 by 8 inches, range from approximately 10^4 to 2×10^5 rad/hour. This can be increased to about 10^6 rad/hr for small samples. By remotely moving the source and its shield the dose rate at a fixed sample position can be changed, even during an irradiation.

Facility

The principal scientific equipment contained in this Facility is a 13 meter long optical relay system that can be configured to operate in several different modes: as a spectrophotometer, as a system for measuring luminescence spectra and intensity, as a radiation damage source, etc. The figure shows the irradiation chamber and the equipment used to make measurements during irradiation.

As presently operated, spectral transmission or absorption measurements can be made at any wavelength between 219nm and 1000nm at temperatures between 4K and 900°C. Additional equipment can be installed in the Facility, e.g. a stress-strain machine to study the effects of strain applied during



▲ The experimental equipment for making simultaneous optical absorption, radioluminescence, and other measurements on samples during ^{60}Co gamma-ray irradiation.

irradiation. Also, to study luminescence, the phototube is replaced with a scanning spectrophotometer. All control functions and data recording are performed by a computer.

A typical radiation-induced color center formation study consists of a cycle of measurements made at selected wavelengths which is repeated at selected time intervals. Also, most studies are continued after the irradiation has been abruptly terminated to study the decay of the coloring, phosphorescence, and other properties of the radiation-induced defects.

With an upgrade of the spectrophotometer system, it will soon be possible to make simultaneous optical absorption and luminescence emission spectrum measurements on strongly emitting luminescent materials, such as crystals, plastic scintillators and other materials used in particle detectors, during irradiations ranging from the highest to lowest dose rates. Optical absorption measurements are currently restricted to non-luminescent or weakly luminescent materials during irradiation, or to strongly luminescent materials after irradiation.

Studies completed with this equipment have unequivocally demonstrated that the radiation damage levels in almost all nonmetals is higher during irradiation than after irradiation; in some materials appreciably higher. Thus, to reliably evaluate the extent of radiation damage in a transparent material to be used in a radiation field, it is essential to make measurements during irradiation. Usually measurements are made at room temperature, but measurements can be made at temperatures between liquid helium temperature and roughly 1000° C with installation of the appropriate thermal environmental chambers.

In addition to the spectral studies for which it was originally designed, this Gamma-Ray Irradiation Facility has been very useful in a large variety of radiation damage studies. It is particularly useful for making measurements during irradiation on items such as electronic circuit boards, optical lenses, prisms, biological samples, etc. Also, it has been used extensively to irradiate equipment too large to be irradiated in other radiation facilities. Recently the Facility has been used to induce polymer crosslinking (Stony Brook) and to predose crystal oscillators used in satellites (FEI).

The Solid State Gamma-ray Irradiation Facility has been used to measure the radiation-induced absorption, radioluminescence, thermoluminescence, and other properties of many materials. In the table below is a partial list of materials, particularly of scintillation crystals, that have been studied extensively at this Facility.

MATERIAL
BaF_2
CsI
$PbWO_4$
CeF_3
PbF_2
$YalO_3$
FeS_2
$PbCO_3$
Alkalai Halides

Radio Communications and Audio Services

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R.L. Dumont

The Radio Group in the Instrumentation Division does a number of essential behind-the-scenes activities that help make life and work at the Laboratory function smoothly and safely. The Radio Group is responsible for installation and maintenance of on-site, NTIA-licensed spectrum dependent communications systems and services. These include maintaining all of the two-way radio communication systems for the Security Group and Fire & Rescue, Plant Engineering Utilities and Buildings & Grounds, and also for large experimental facilities such as the AGS, RHIC, ATF, NSLS, and the Tandem Van de Graaff.

Perhaps the most recognized service provided by the Radio Group is the site-wide radio paging service. The Group currently maintains over 1,900 personal pagers. The group is also responsible for set up and maintenance of the Lab-wide emergency notification system, the Plectron system.

In addition to radio communications services, the Group also provides audio services for various Laboratory functions, such as meetings and conferences at Berkner Hall, employee training, health seminars, and special BERA programs. The group supervises the installation of and provides maintenance for numerous public address systems at various locations around the Laboratory, such as at the Medical Department, and the BNL Firehouse.

Another service provided by the Radio Group is maintenance of the local CATV system for Staff Services in the BNL apartment and dormitory housing areas. Staff are licensed in various radio communications areas and provide consulting services to the rest of the Laboratory.

▲ The Radio Communications and Audio Services Group is responsible for audio-visual services at many Laboratory functions. George Walczyk and Ray Dumont (front) are shown here at work at the AV console in Berkner Hall.

Technology Transfer Activities

The Instrumentation Division is actively involved in collaborations with industries interested in commercializing technologies that have been developed here as a result of our research and development activities. A number of Cooperative Research And Development Agreements (CRADAs) have been established to promote the technology transfer process over the past several years. The CRADAs that have been established cover a wide range of Division activities, highlighting the versatility of the Division staff and the diverse nature of its expertise. Recent CRADA activities are summarized in the following paragraphs.

CRADA BNL-C-02-04

Partner: Symbol Technologies

Award Date: Auguest 2002

Principal Investigator: P. O'Connor

Title: **CMOS Imaging Arrays with integrated Signal Processing**

Symbol Technologies pioneered the development of the laser barcode scanner and is today a leading producer of data capture devices used in industry. With the recent growth of handheld computing devices for the consumer market, many potential new applications for data capture engines are foreseen. However, the physical size and power consumption of the engine must match the small form factor of the portable platform. Neither the laser-scanned nor CCD-based imaging engines can meet these demanding miniaturization goals. The objective of this CRADA is to develop monolithic barcode imaging engines using deep submicron CMOS technology and advanced optical packaging.

Using the newly developed Active Pixel Sensor (APS) approach, we will integrate an array of photosensors and amplifiers with the complete analog and digital electronics chain on a single, commercially manufacturable chip. An optical-grade plastic will be used to package the integrated circuit, and the optical surfaces will be formed in this plastic package.

CRADA BNL-C-01-14

Partner: eV Products

Award Date: November, 2001

Principal Investigator: P. O'Connor

Title: **Precision Pulse Processing Circuits for Spectroscopic Imaging**

Imaging detectors require highly integrated electronics in order to process signals from detectors characterized by a large number of pixel sensors, typically 10^3 - 10^4. In addition, some applications demand good energy resolution of each detected photon. To address these needs, we propose to develop a mixed-signal ASIC implementing an innovative Peak Detector and Derandomizer circuit (PDD) to be integrated in commercial CMOS technology. The proposed PDD ASIC employs novel techniques to provide derandomization and spectroscopic accuracy for the most demanding applications.

Our industry partner eV Products develops instruments based on CZT pixel detectors for X-ray and gamma-ray imaging. The PDD ASIC will provide a dramatic reduction in complexity and cost of such instruments. and can be used to strongly enhance the rate performance. The PDD ASIC builds on previous collaborative work behveen eV and BNL on the development of low noise amplifier ASIC front-ends for CZT sensors. It will be implemented in an imaging detection system currently under development at eV Products. Finally, the PDD ASIC will be useful in High Energy Physics experiments and in life sciences research at DOE'S synchrotron light sources.

CRADA BNL-C-01-08

Partner: Advanced Energy Systems, Inc.

Principal Investigator: T. Srinivasan-Rao

Title: **Development of high duty factor, high brightness, all niobium, superconducting RF gun**

Electron beams with high-duty factor and brightness are required in a variety of applications including next generation free electron lasers and relativistic ion colliders. Use of existing technologies to achieve these beams is not viable. In the conventional DC guns, space charge effects limit the brightness of the electron beam that can be generated. The normal temperature RF guns, though excellent in providing high brightness beams at a low repetition rate, become inadequate due to the large losses, and the resulting high RF powers required for driving these devices at high repetition rate. A potential solution for generating such high duty factor and high brightness electron beams is to integrate the photocathode into the end wall of the superconducting RF cavity, similar to the situation in normal conducting RF guns. The inherent low loss of the superconducting cavity reduces the power requirements of the RF system significantly while preserving the excellent beam qualities inherent in an RF gun. The objective of this project is to design and fabricate such an RF gun, and test its capability to generate a high quality, high duty factor, electron beam.

We propose to use the niobium of the cavity end-wall itself as the cathode material to generate electrons. This ensures that no foreign material is introduced into the accelerator, thus obviating all the associated problems, eliminating the injector/accelerator interface with its potential for emittance growth, and greatly simplifying the overall injector design so that high reliability and efficiency can be anticipated.

CRADA BNL-C-01-05

Partner: Ocean Optics, Inc.

Award Date: February, 2001

Principal Investigator: P. Z. Takacs

Title: **MetrologyTools for Surface Profile Measurement**

A Small CRADA with Ocean Optics, Inc., was funded in 2001 to develop a next-generation Long Trace Profiler (LTP) using technology and expertise provided by Ocean Optics in the area of detector development and software and hardware engineering. Ocean Optics is a leader in the field of miniature spectrophotometric instrumentation and acquired the patent license for the LTP from Continental Optical Corportion in 2000. The present CRADA is focused on developing a miniaturzed version of the LTP that can be made more stable and more portable than the previous commercial version of the instrument.

CRADA BNL-C-00-15

Collaborators: BNL: NSLS, CAD, IO,

Industry: Advanced Energy Systems Inc

Title: **Development of high average current, high brightness, all niobium, superconducting RF injector**

Duration: 2001-2002

Objective:

- Construct an all niobium superconducting RF cavity
- Prepare the end wall of the cavity to improve photoelectric yield
- Irradiate the end wall of the cavity with continuous train of UV laser pulses to generate electron beams
- Optimize the cavity and laser parameters for minimum emittance and maximum brightness

This source will also act as a testing ground for NSLS PERL project and CAD RHIC Cooler project

CRADA BNL-C-99-12

Partner: Brookhaven Technology Group Inc. in collaboration with Battelle Pacific Northwest National Laboratory

Award date: March, 1999

Principal Investigator: Triveni Srinivasan-Rao,

Title: **Development of a high current, high gradient, laser excited, pulsed power electron gun**

Our expertise in developing high brightness electron sources and our unique capability to establish field gradients exceeding 1 GV/m on macroscopic surfaces have resulted in a CRADA with Brookhaven Technology Group, Inc. to design and build a novel pulsed power high brightness electron gun. Using the technology developed in the Laser Laboratory, subpicosecond electron bunches will be generated by optically irradiating a metal surface in the presence of ~ 1 GV/m field gradient. The electron beam produced will have brightness approaching 10^{16} A/m^2 rad^2, which is 2 orders of magnitude greater than the present level of 10^{14} A/m^2 rad^2, a parameter highly sought after for future linear colliders and short wavelength FELs.

This high current, fast pulsed, laser excited, electron gun is an enabling technology with applications that benefit research in linear colliders, Free Electron Lasers, cellular biology, molecular science, materials science, and the study of transient phenomena in the sub-nanosecond time frame. It will also be used to study properties of materials in the presence of high fields, such as dark current emission and high voltage breakdown characteristics, that will provide information critical to the development of high frequency accelerating structures. In addition, using bremsstrahlung radiation from these ultra short relativistic electrons, the gun is expected to be an efficient source of x-ray photons for imaging transient effects in biological samples, microlithography and micromachining. These excellent beam qualities will be augmented for the first time by the simplicity and compactness of the device resulting in an efficient, affordable product with superior performance and unique capabilities.

CRADA BNL-C-97-05

Partner: eV Products, Div. of II-VI, Inc.

Award Date: March, 1997

Principal Investigator: P. O'Connor

Title: **Development of Multi-Channel ASICs for CdZnTe Gamma Ray Detectors.**

A major contributor to the success of our Division in the development of high energy particle detectors has been the development of monolithic circuits that advance the state-of-the-art in circuit design. Recognizing our expertise in this area, eV Products, Inc. established a CRADA with us for the purpose of designing multichannel CMOS preamplifier and shaper ASICs with high leakage current handling capability to aid the commercialization of CdZnTe (CZT) gamma and x-ray detector arrays. The circuits provide compact, high performance readout for medical imaging products under development by eV Products, Inc. The present single and multichannel designs use novel circuit topologies to achieve low noise, low power, high DC stability, high dynamic range, baseline restoration and high drive capability.

CRADA BNL-C-97-03

Partner: Symbol Technologies

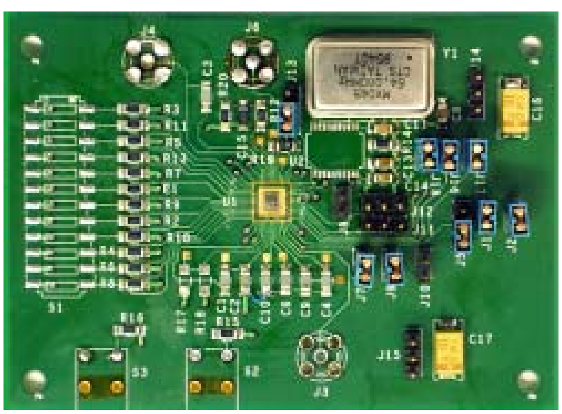
Award Date: May, 1997

Principal Investigator: P. O'Connor

Title: **Microcircuits and Sensors for Portable Low-Power Data Collection and Transmission**

Our expertise in developing new CMOS circuits has resulted in a CRADA with Symbol Technologies for the design, fabrication, and testing of two novel devices for wireless data collection and transmission: an optical photosensor array and a 2.4 GHz single-chip, frequency agile radio transceiver. A significant milestone in the "radio-on-a-chip" program was achieved with the demonstration of a fully-integrated CMOS transmitter. We replaced the transmitter section of an existing Symbol 915 MHz handheld, cable-less bar code scanner with our IC and achieved error-free performance over a range of 60 feet.

The next major circuit to be developed will be a direct-conversion AM receiver, using the same frequency synthesizer already demonstrated in the transmitter for the local oscillator. Both devices can be processed in a standard industrial CMOS integrated circuit process.



◄ Wireless transceiver prototype developed in the CRADA with Symbol Technologies. Integrated circuit, center, is fabricated in 0.5 micron CMOS and operates in the 2.4 GHz unlicensed radio band.

Event of the Year

Ray Davis Jr., a retired Brookhaven chemist, won the 2002 Nobel Prize in Physics. One key technique used in his solar neutrino experiment was developed at the Instrumentation Divisoin. Here is an extract from BNL's *Discover Brookhaven* (Vol. 1, No. 2) describing the contribution.

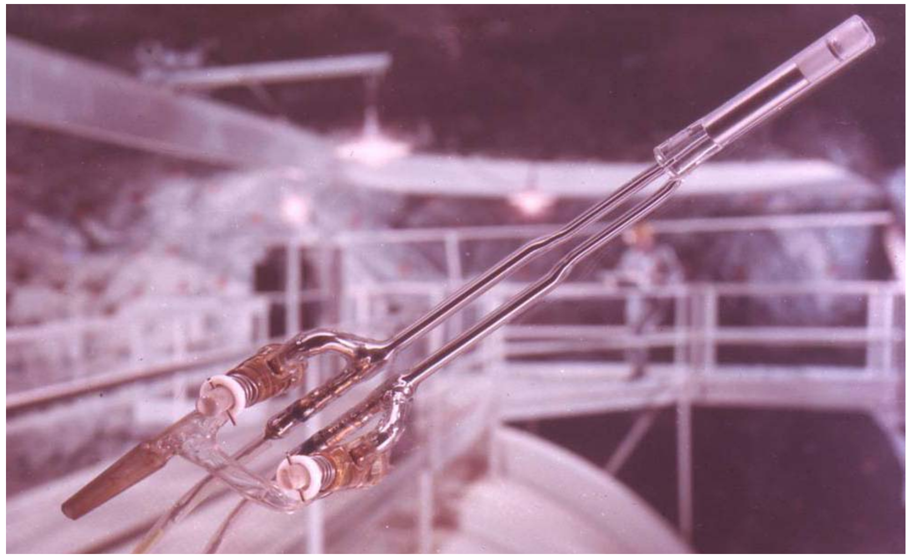
Instrumentation Research & Development at Brookhaven

To detect solar neutrinos directly in his Homestake Mine experiment, Ray Davis made use of a neutrino capture reaction, whereby, when an atom of chlorine-37 captures a neutrino, it becomes argon-37. In the subsequent decay of argon-37 back to chlorine-37, Auger electrons are emitted with a total energy of 2.8 kilo electron volts (keV), which Davis measured using a proportional counter.

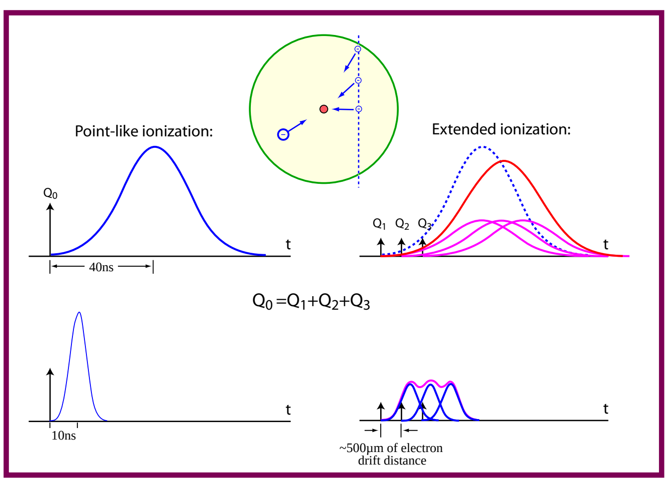
During the first three years of the now Nobel-prize winning experiment, a "single-parameter" technique was employed to detect the Auger electrons. While this technique did produce an upper limit for the neutrino capture rate, it could not distinguish between the point-like ionization produced by the Auger electrons and the extended ionization tracks of more energetic electrons arising from gamma-ray and other background events.

To solve this problem, Lee Rogers and Veljko Radeka of Brookhaven's Instrumentation Division employed a two-parameter technique that rejected between 85 and 98 percent of the background-radiation events. To apply this "pulse rise-time" method to Davis's experiment, the Instrumentation researchers developed low-noise amplification and signal processing on a nanosecond time scale.

The new detection system was introduced in 1970, and, after one year of its operation, the first clear signal of a solar neutrino was observed. As Ray Davis has commented, "The pulse rise-time system development gave the Homestake experiment new life," thanks to instrumentation research and development at Brookhaven Lab.



The very small number of argon-37 atoms created by solar neutrino capture are first extracted from the large tank (background) containing about 10^{31} chlorine atoms and then transferred into a proportional counter (foreground) with an active volume of approximately 0.5 cubic centimeters.



(Above) Emitted following the electron-capture decay of argon-37 to chlorine 37, the Auger electrons lose all of their energy (2.8 keV) over a very short distance in the counter gas and produce a point-like ionization. Background events, due mostly to gamma rays, produce much more energetic electrons, which result in extended ionization tracks. The charge due to ionization is amplified by an avalanche process near the center wire, which is an anode, and produces signals as illustrated in the figure. On the very short time scale of a few nanoseconds, there is a clear distinction in the signal waveforms between point-like and extended ionization, which provides the unique signature that distinguishes argon-37 decays from background radiation.

(Below) The electronic counting system developed to distinguish between argon-37 decays and background radiation shows the peak signal current ("Ampl. Diff. Pulse") as a function of energy deposited for each detected event. Red circles represent argon-37-like events, while white circles show the background-like events. The discrimination properties are shown by illuminating the counter using iron-55 x-rays for point-like ionization, and cobalt-60 gamma rays for extended ionization. The response for energies around 2.8 keV is shown in the inset.