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Brookhaven National Laboratory
Instrumentation Division

R&D Programs
Facilities
Staff

BROOKHAVEN
NATIONAL LABORATORY

BROOKHAVEN SCIENCE ASSOCIATES

INSTRUMENTATION DIVISION

R&D PROGRAMS

FACILITIES

STAFF

May 2001

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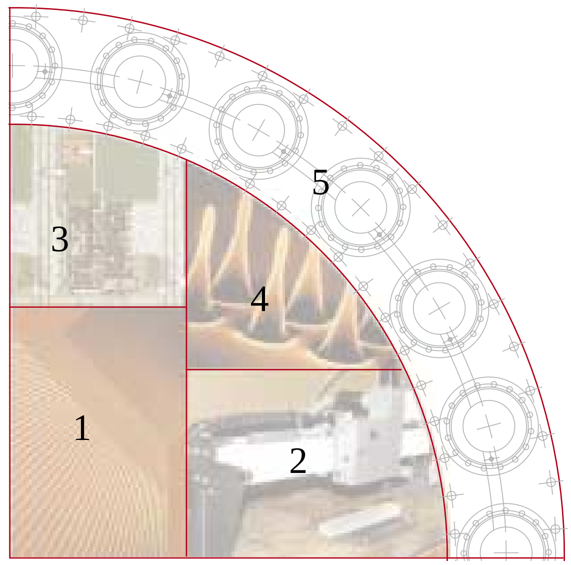
On the Cover:

1. Partially depleted 2-sided silicon strip detector, used for determining position of beam in the ATF. Signals from each of the 2 µm pitch strips are multiplexed via fan-out at lower right to an AMPLEX chip.
2. 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.
3. Monolithic CMOS shaping amplifier. Micron, and now deep sub-micron, CMOS technology allow engineers to package many channels of electronics into a single chip, reducing cost and power consumption on very large scale detector systems.
4. Silicon columns with submicron tip radii are produced by reactive ion etching, and may be used as field emitting devices in high brightness electron sources for new generation of accelerators at the ATF.
5. Mechanical drawing of 120° thermal neutron spectrometer for use in spallation source experiments. This state-of-the art detector uses ultra-pure gases and advanced low noise electronics to yield unsurpassed high rate, high resolution operation.



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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:	25 Scientific/Professional; 19 Technical; 4 Administrative	
Research Areas:	Detectors, signal processing, optics, microfabrication	
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:	35,000 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 & characterization of ultra-short photon & 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
25 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.
S. Qian	Design and development of high-precision optical metrology instrumentation.
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.
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.

[1] Physics Department

[2] Linear Accelerator Laboratory, Orsay, France

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.

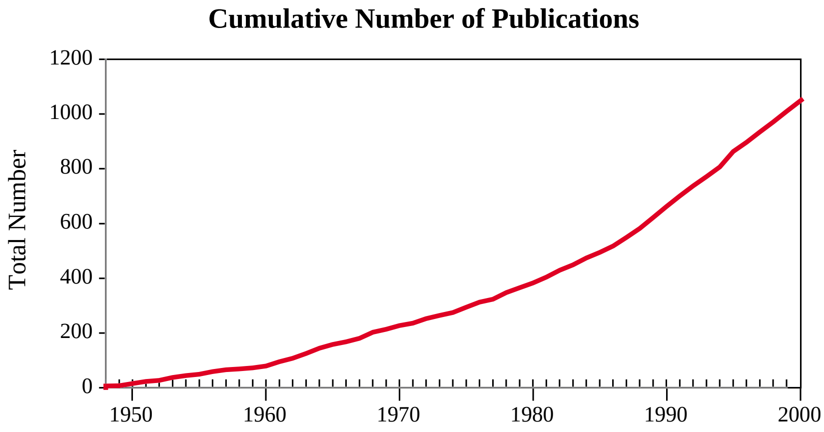
Printed Circuit Board Design and Layout	
Supervisor	A. Kandasamy
Technical Advisor	J.A. Mead
Technical Staff	K.A. Ackley, R.E. Machnowski, R.J. Ryan, K.J. Wolniewicz
Printed Circuit Board Fabrication	
Supervisor	J.A. Mead
Lead Technician	R.J. Angona
Technical Staff	P.D. Borello
Electronics Technical 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
Machine Shop	
Supervisor	R.H. Beuttenmuller
Technical Staff	W.R. King, R.R. Ryder
Semiconductor Detector Fabrication	
Supervisor	Z. Li
Lead Technician	R.H. Beuttenmuller
Technical Staff	D.C. Elliott
Administrative Support	
Supervisor	C. Williams
Staff	B. Gaer, D. Grabowski, J. McGowan, M. Riddick

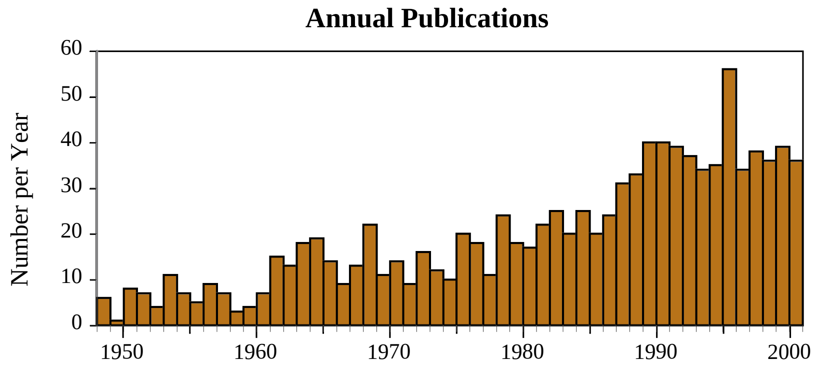
COLLABORATIONS

Project	Collaborators
Semiconductor Detectors	
Semiconductor Position Sensitive Detectors	Milan Poly; CERN
Multi-element and Silicon Drift Detectors	Wayne State
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
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 at the RHIC and NSLS	Biology; Chemistry; Physics; NSLS
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
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
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

Z. Li
W. Chen
P. Rehak
R. Beuttenmuller

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.

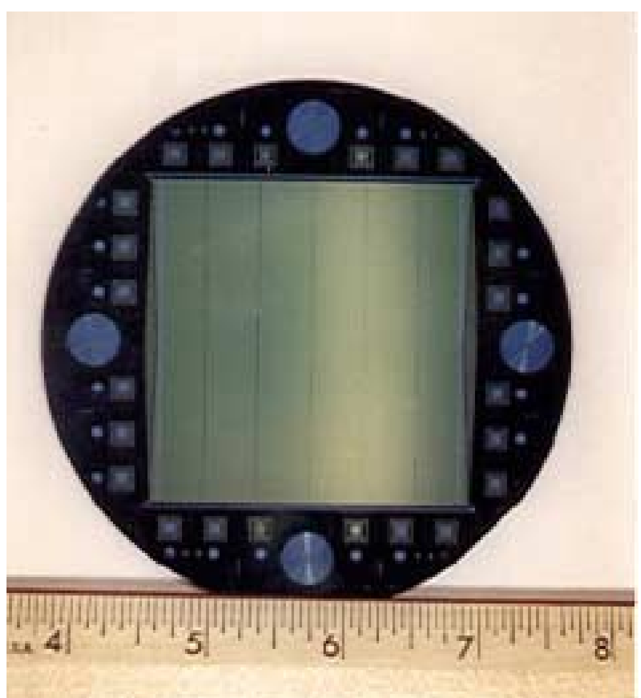
Simulation and development of novel Si detectors with non-conventional electrode arrangement for better position sensing (possible sub-micron resolution) and improved radiation hardness to displacement radiation sources such as neutron, proton, and pions, are currently underway at BNL.

Contact: Z. Li, (631) 344-7604, zhengl@bnl.gov

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 energy physics experiments at BNL and other sites (e.g. CERN) around the world. Its state-of-the-art design and processing facility for RPD is

▼*Silicon drift detector for STAR*



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

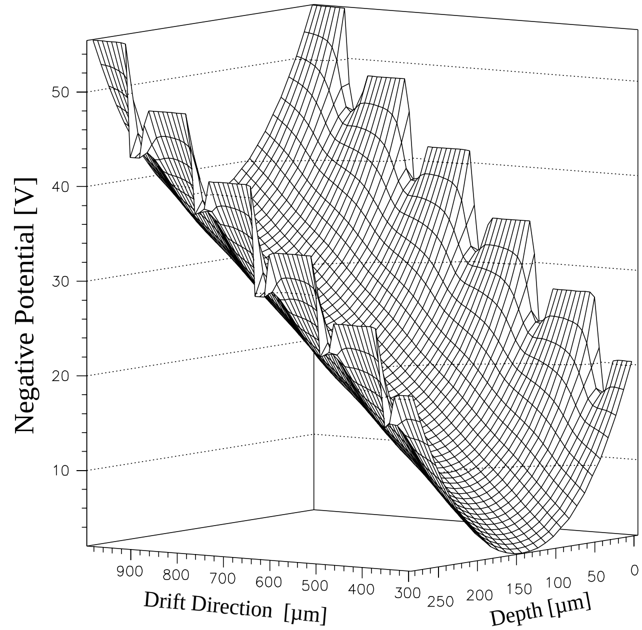
Simulation Tools

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, double-side photolithography mask aligner, 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.



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

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

- Standard probe station for I-V, C-V tests on test diodes
- Probe-card testing facility for STAR drift detectors
- 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 such as at the LHC. Deep Level Transient Spectroscopy (DLTS), Thermally Stimulated Current (TSC) measurements, and Transient Current Technique (TCT)

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

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).

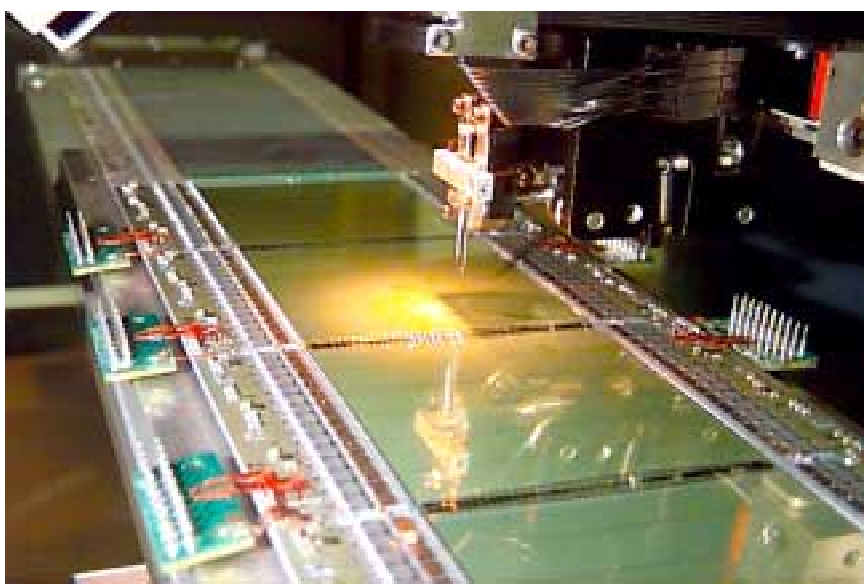
The defect analysis system (DLTS, TSC, and TCT), including optical defect filling techniques, has been first developed here at BNL and is now in routine use in analyzing irradiated samples. The "reverse anneal" effect was correlated with a deep acceptor at E_C-0.42 eV, which is usually attributed to 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.

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, and RD39 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);



▸ *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.*

- 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

Semiconductor Detector Fabrication Status, continued

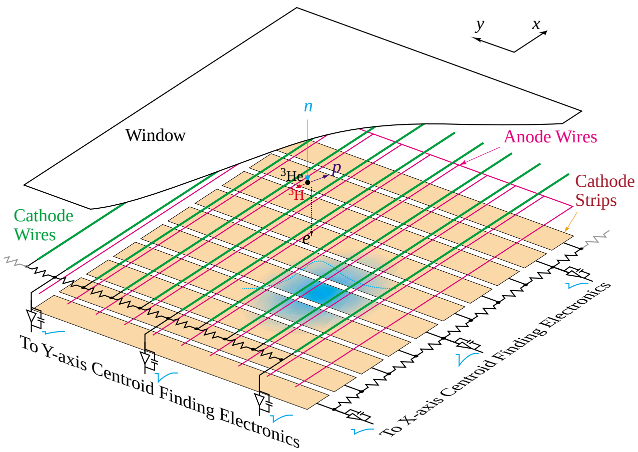
Detector	Application	Results/Status
50 micron pitch strip detectors	Muon Beam Finder (CERN)	In use for two years in M2 test beam (V. Polychronakos)
2 and 8 micron pitch strip detectors	Accel. Test Facility, BNL	Production used PdSi method Z. Li et al., IEEE TNS NS38 (1991)
50 micron pitch strip detectors	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 On-going
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 Just started
Cryogenic Si detectors Improved radiation hardness	CERN RD39	T. Niinikoski, CERN On-going

Gas Detectors

G. C. Smith
P. Rehak
N. A. Schaknowski
B. Yu
E. F. Von Achen

The gas detector group carries out fundamental studies on the physics of gas-based radiation detectors, and has resources for producing limited 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.

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. Outside BNL, we develop a range of advanced neutron detectors for experiments at national user facilities such as LANSCE at Los Alamos, HFIR at Argonne, the research reactor at NIST, and for future experiments at 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.



▲ *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 array, which typically contain hundreds of wires with diameters < 50 μm.*

Facilities

Some important resources within the group are:

- X-ray production and calibration equipment
- Thermal neutron source
- Collection 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
- Comprehensive array of nuclear instrumentation modules
- Bench stations for system testing

▶ *A mask depicting the new Brookhaven logo was etched in copper-clad kapton. The picture shows an X-ray transmission image of the mask, recorded with a two-dimensional wire chamber that is under development as an advanced neutron detector. The image, about 180mm wide, illustrates the excellent position resolution and linearity achievable with these devices.*

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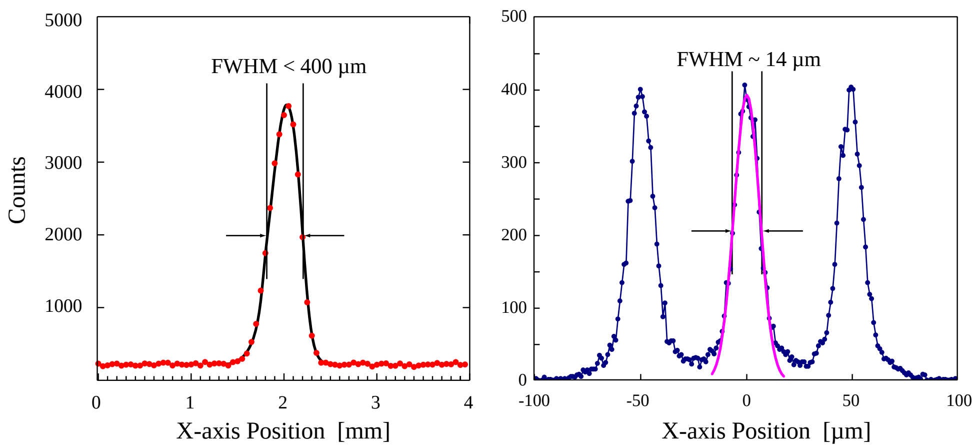
▶ *Left: a 400µm FWHM position resolution was achieved using the 5×5cm² thermal neutron detector.*
Right: a 14µm FWHM position resolution was obtained in a test chamber with a xenon mixture at 10 atm. of pressure. These measurements represent the best position resolution ever recorded by gas-based detectors.



X-ray Detectors for Synchrotron and Plasma Studies

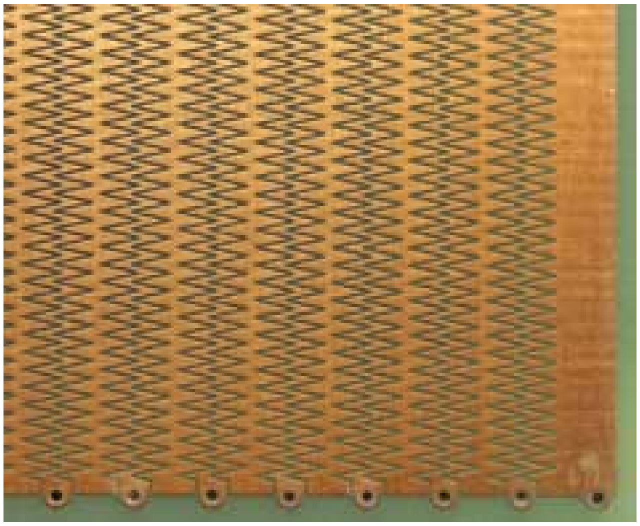
The primary motivation for X-ray detectors comes from the wide-range of experimental studies at the NSLS. Our instruments have been used in structural biology, polymer investigations, and scattering experiments in physics and chemistry. The table indicates the large number of detector systems that are 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 redirect 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.

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 important for a range of studies where signal levels are very weak.



◀ *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.*

▲ *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.*

The group also designs and develops position-sensitive devices for other applications. A current example is an annular detector with 1° angular resolution and multichannel readout for backscattering studies. Operating in ionization mode, this advanced design takes advantage of the Division's microelectronics techniques.

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.

Additional Applications

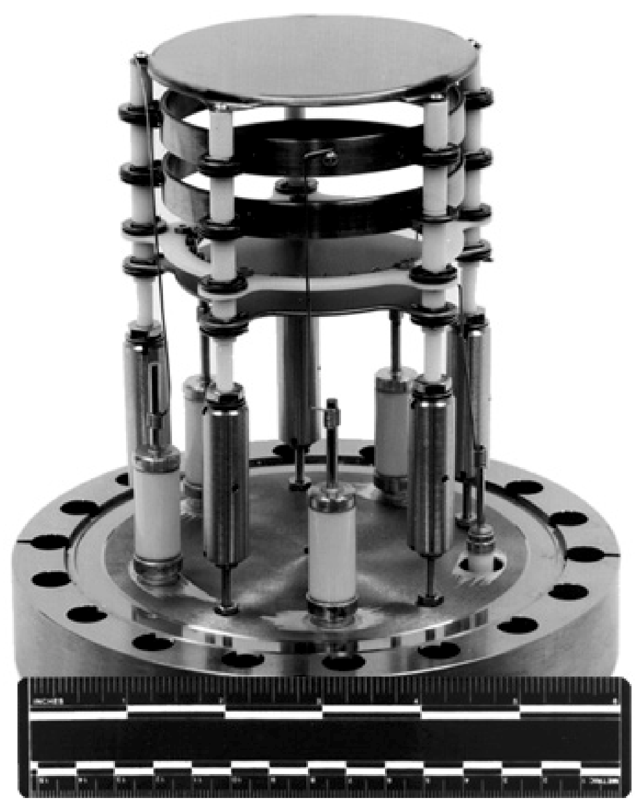
The major additional fields for gas-based detectors are in HEP/NP experiments and in non-proliferation and safeguards techniques involving gamma-rays and neutrons. Some key examples of these activities are:

- *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
- *High resolution gamma-ray and neutron detectors*
  In collaboration with BNL's department of non-proliferation and national security, 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. Neutron detectors have been developed for coded aperture techniques to locate clandestine sources of neutrons.
- *TPC and Micro-pattern detectors for RHIC*
  New instruments using recent advances in technology and gas physics are being studied for proposed upgrades of RHIC experiments

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.

▼ *Internal elements of a high-pressure Xenon ionization chamber for detecting gamma rays in an arms control and safeguards application.*



The emergence of micropattern detectors in the 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 some of the nation's most advanced gas-based detector systems.

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▸ *A snap shot of the new 120° thermal neutron detector being assembled. Shown here are the 8 curved wire segments mounted on a stainless steel flange, and the aluminum presure vessel being lowered down to complete the high pressure enclosure.*

Gas Detectors Constructed for Specific Facilities

	Application	Detector	Resolution	Counting Rate	Pressure
X-ray Synchrotron Applications	Instrument & Diagnostic Development NSLS, U4	Soft X-ray Fluorescence	N/A	$> 10^5$ ph s^{-1}	3000 Pa
X-ray Synchrotron Applications	X-ray Microscopy NSLS, X1A	Soft X-ray, Multi-anode, High Rate	N/A	$> 10^6$ ph s^{-1}	3000 Pa
X-ray Synchrotron Applications	Powder Diffraction NSLS, X7A NSLS, X27	1D Planar Delay Line 1D Curved Blade (45° coverage)	10cm×1cm $\Delta l/l=1/1000$	5×10^5 ph s^{-1}	1-4 atm
X-ray Synchrotron Applications	Time-resolved and Static Diffraction NSLS, X12B	2D Planar Delay Line 1D 100 Wire High Rate	10cm×2cm 10cm×10cm $\Delta l/l=1/1000$	5×10^5 ph s^{-1}	1 atm
X-ray Synchrotron Applications	Inelastic X-ray Scattering NSLS, X21 NSLS, X25	1D Planar Delay Line 2D Planar Delay Line	10cm×1cm 10cm×2cm $\Delta l/l=1/1000$	5×10^5 ph s^{-1}	1-4 atm
X-ray Synchrotron Applications	Studies at Liquid Vapor Interfaces NSLS, X22	1D Planar Delay Line	10cm×1cm $\Delta l/l=1/1000$	5×10^5 ph s^{-1}	4 atm
X-ray Synchrotron Applications	EXAFS SPEAR, Stanford and ALS, LBNL	2D Planar Delay Line	10cm×2cm $\Delta l/l=1/1000$	5×10^5 ph s^{-1}	1 atm
X-ray Synchrotron Applications	X-ray Scattering APS, Argonne	1D Planar Delay Line 2D Planar Delay Line	10cm×1cm 20cm×20cm $\Delta l/l=1/1000$	5×10^5 ph s^{-1}	1-4 atm
X-ray Synchrotron Applications	Plasma Studies NSTX, Princeton University	1D Planar Delay Line	18cm×10cm (×3) $\Delta l/l=1/1000$	2×10^5 ph s^{-1}	1 atm
Neutron Applications	Macromolecular Crystallography	2D Planar (×3)	20cm×20cm 256×256 array	5×10^4 n s^{-1}	9.5 atm
Neutron Applications	Membrane Spectrometer	2D Planar	20cm×20cm 256×256 array	5×10^4 n s^{-1}	9.5 atm
Neutron Applications	Materials Chemistry Spectrometer	2D Planar	5cm×5cm 512×512 array	5×10^4 n s^{-1}	14.6 atm
Neutron Applications	Chemical Crystallography	2D Planar (×3)	20cm×20cm 256×256 array	5×10^4 n s^{-1}	9.5 atm
Neutron Applications	Small Angle Scattering	2D Planar	50cm×50cm 256×256 array	5×10^4 n s^{-1}	5.5 atm
Neutron Applications	Protein & Membrane Crystallography LANSCE #14, Los Alamos	2D Curved (120° coverage)	1.5m×20cm 2048×256 array	$> 10^6$ n s^{-1}	9.5 atm
Neutron Applications	Spin Echo Spectrometer NIST	2D Planar	20cm×20cm 256×256 array	5×10^4 n s^{-1}	9.5 atm
Neutron Applications	Crystal Backscattering Spectrometer ISIS, Rutherford, and SNS	1D Truncated Cone (operates in ionization mode)	1°	10^5 n s^{-1}	8 atm
Neutron Applications	Instrument Development SNS	2D Planar	20cm×20cm 256×256 array	5×10^4 n s^{-1}	9.5 atm
Neutron Applications	In-house R&D	2D Planar	20cm×20cm 256×256 array	5×10^4 n s^{-1}	9.5 atm

Cryogenic Detectors

V. Radeka
D. S. Makowiecki
P. Rehak
S. Rescia

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 region

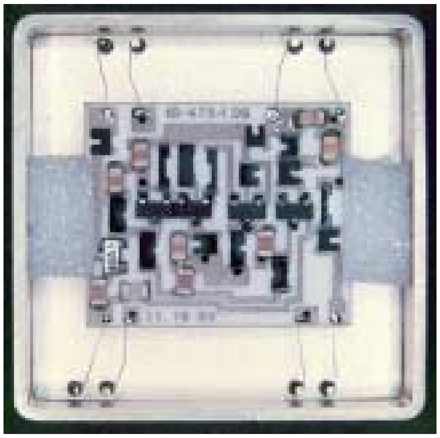
Fast Noble Liquid Ionization Calorimetry

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 -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, $5.6\sqrt{E}$, 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 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 Activity

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 develop-

◀*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*



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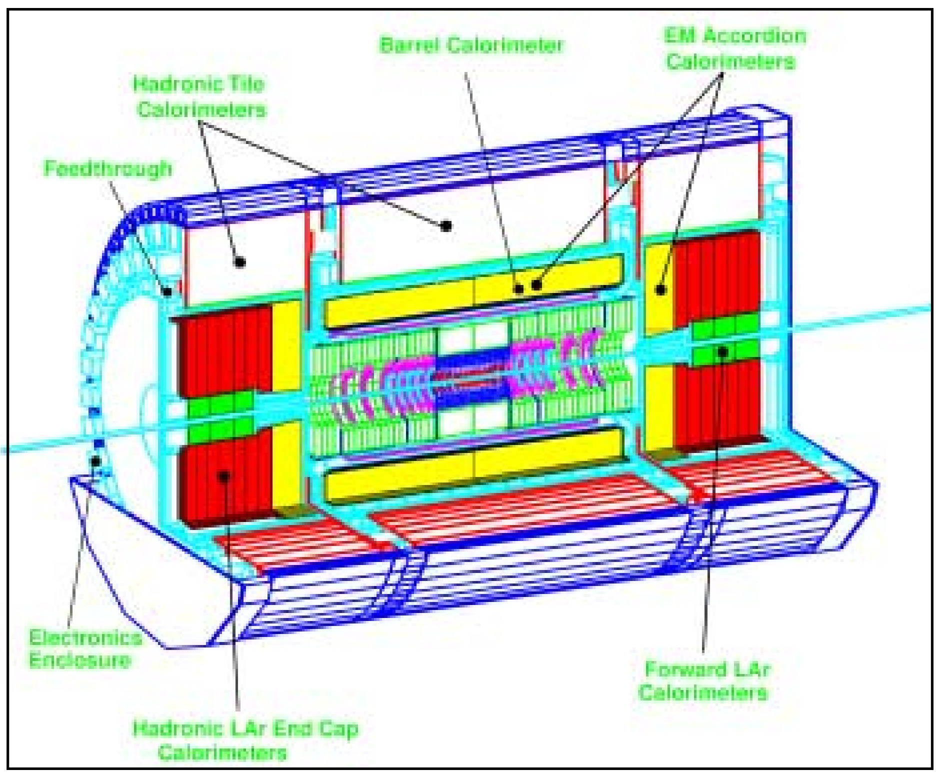
ment: optimization of detector design, electrode design, cold-to-warm feedthroughs, calibration system, and readout electronics. R&D work on the components for which BNL is responsible has been completed. The ATLAS barrel detector requires 5 different types of summing boards and 14 different types of motherboards with cryogenic high precision resistors (tolerance < 0.1% at 90 K). Since low level signals need 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 not to create electromagnetic interference. 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 provide 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. Activity is in full swing for the manufacturing and testing of the large quantities needed for the detector: 64 feedthroughs, 32 crates, several thousands summing boards and readout boards and 50,000 hybrids (200,000 channels) are needed. 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.

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 use of such a transformer allows formation of the tower connection of four cells inside the cryogenic vessel, thus reducing the number of cables penetrating the cryostat.



▸*Cross section of the proposed ATLAS detector calorimeter. The full cryostat of the Barrel Calorimeter 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 between. Each half barrel consists 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 to the electronics enclosures housing the FEBs and auxiliary electronics (trigger builder, calibration, monitoring, slow control, etc.)*

Facilities and Capabilities

The art of cryogenic detectors involves know-how 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 non-standard materials) and the machine shop. Readout electronics are designed and built in the Division's Hybrid and Microelectronics Lab. Radiation tests are carried out at the division g-ray irradiation facility. 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 2m), 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.

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 mobility 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 mm, 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 mm for a cell of transverse dimension of 1-2 mm is possible. Position measurements in both directions are done within about 1 ms, which is compatible with the expected bunch crossing time of 2 ms in the planned m+ m- 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.

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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.

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. Relying on a thorough understanding of the user's experiment, we provide compact, low noise packaging of ASICs together with commercial parts on a PCB or hybrid circuit for a complete signal processing solution. Specific abilities include:

- Full custom, transistor-level design, mask layout including extraction and verification of critical analog blocks;
- Accurate SPICE simulation including component noise characterization and modeling done in-house;
- Access to state-of-the-art semiconductor processing including submicron CMOS, BiCMOS, and high-speed bipolar, incorporating precision passive components for analog design;
- Digital standard cell libraries and compatible synthesis tools;
- In-house PCB and hybrid shops for high-density packaging and rapid prototyping;
- Cost estimation (ASIC and PCB);
- Fully equipped test laboratories for device characterization through system level testing.

Facilities

- **Full suite of ASIC design tools including:**

  Design capture:
  - Innoveda e-Products
  - Cadence Orcad Capture
  - Tanner Tools S-Edit

  Circuit simulation:
  - Avant HSPICE
  - Cadence PSPICE

  Full custom layout:
  - MAGIC
  - Cadence Journeyman
  - Tanner Tools L-EDIT

  Layout extraction and verification:
  - MAGIC
  - Tanner Tools LVS

  PCB and hybrid layout and analysis:
  - PADS PowerPCB
  - AUTOCAD
  - Hyperlynx

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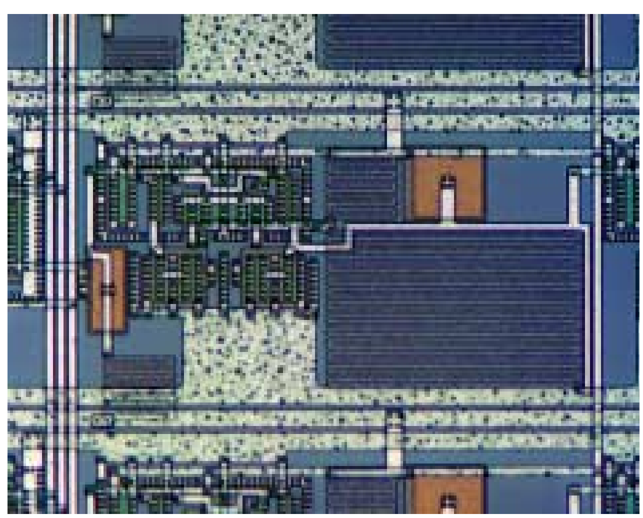
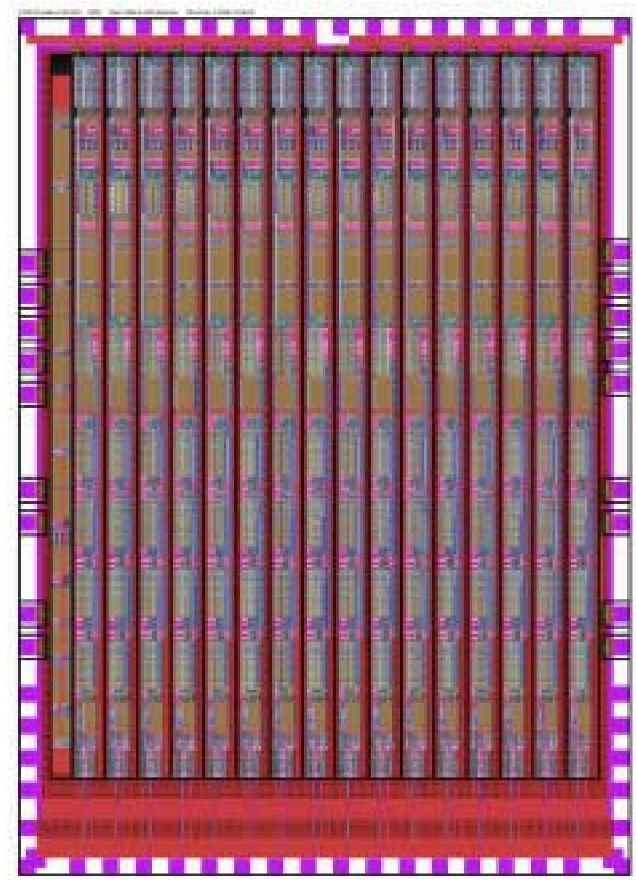
▼Monolithic CMOS shaping amplifier, approximate size 100 μm × 200 μm, showing layout of passive components. The resistor is a serpentine of polysilicon, resistivity 22Ω per square, line width 2 μm. Capacitor (pink square) at top of serpentine is formed by sandwiching a SiO_2 layer between two polysilicon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





▶ *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)

- **Foundry arrangements with:**

  Agilent Tech. (MOSIS):
  0.5 µm CMOS

  TSMC (MOSIS):
  0.35, 0.25 and 0.18µm CMOS

  Peregrine (MOSIS):
  0.5 µm CMOS SOS

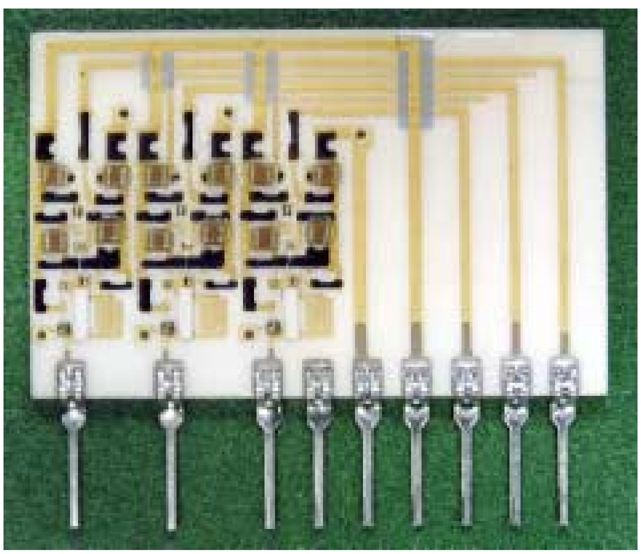
  Maxim:
  bipolar

  AMS (Europractice):
  1.2 and 0.8 µm CMOS and BiCMOS

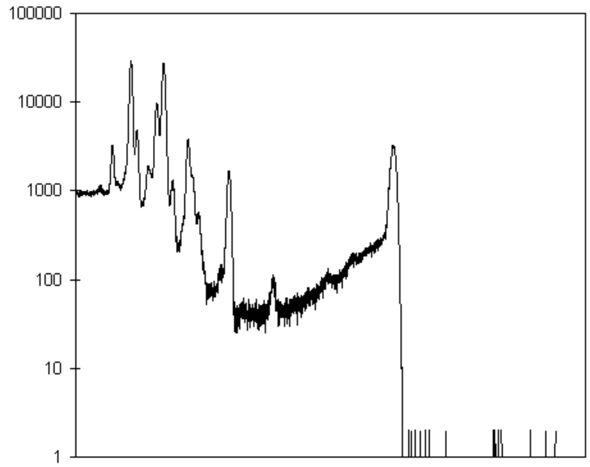
  Temic:
  0.8 µm radiation-hardened SOI CMOS and BiCMOS (DMILL)

  IBM
  0.35 and 0.25µm CMOS and 0.5µm SiGe.

- **Two test laboratories:** full suite of test equipment including analytical prober, semiconductor device characterization with noise measurement, time- and frequency-domain test equipment up to 5 GHz.
- **PCB fabrication facility**: recently upgraded, can produce up to 24 layer boards on a variety of substrates with a minimum line width down to 1 mil; line spacing down to 2 mils, holes down to 4 mils, full surface-mount assembly capability.
- **Hybrid circuit prototyping:** alumina, beryllia, or fiberglass substrates, automatic and manual wire bonders, encapsulation, inspection, test, and rework.
- **Access** to other Division laboratories, including analytical electron microscopy, vacuum deposition laboratory, and solid state irradiation facility (20 kCi ^{60}Co source.)



◀ *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).*



▲^{241}Am spectrum measured with CMOS preamplifier and silicon drift detector. The equivalent input noise charge at -70ºC is 13 rms. electrons, the best noise ever measured in a MOS-based charge-sensitive amplifier.*

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**. Co-integration of high-resolution analog functions with digital VLSI; design and layout techniques to minimize coupling of fast logic signals into sensitive analog nodes; high-performance analog circuits in submicron technologies with low supply voltages.

• **Array and pixel detector readout.** Imaging and tracking applications where the sensor array is either integrated with, or closely coupled to the electronics front-end.

• **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.

• **Wireless RF communications**. Miniaturized spread-spectrum radio operating in the 2.5 GHz ISM band.

Projects

High Energy and Nuclear Physics

Front-end electronics for PHENIX and STAR experiments at RHIC and for ATLAS at the LHC. We produced more than 50,000 channels of FEE ASICs and boards for PHENIX and more than 100,000 channels of ASICs and hybrids for STAR. We will deliver more than 50,000 channels of FEE for ATLAS, and we will participate in detector upgrades and new experiments at the Brookhaven accelerator complex.

X- and Gamma-Ray Detection and Imaging

A CMOS charge sensitive amplifier coupled to a silicon drift detector (both designed at BNL) recently achieved the best energy resolution for X-rays of any MOS-based amplifier. We are now adopting this concept for use with other solid state detectors. In collaboration with eV Products (Saxonburg, PA) we have developed a series of multichannel ASIC front-ends for CdZnTe detectors. These will be used in medical imaging, industrial inspection, and security/surveillance, where they can take the place of bulkier and heavier scintillator-based detectors. These ASICs are now offered commercially by eV Products.

For high-resolution, high-throughput experiments at synchrotron sources, we are exploring circuits optimized to work with multi-element pad detectors cooled to -20ºC. Passive and active pixel array detectors based on silicon, amorphous selenium, liquid xenon, and scintillator-coupled photodiodes are also being investigated for imaging applications. In parallel with the detector development, we are studying monolithic approaches to the control and readout.

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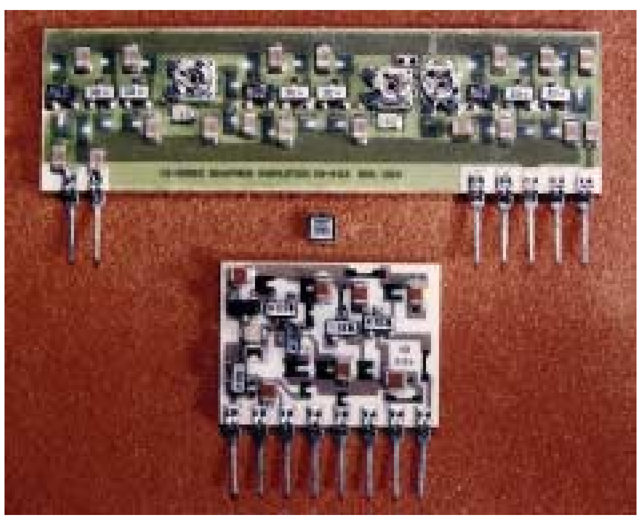
▼*Miniaturization achieved by monolithic circuit is shown in this picture. At bottom is a single preamplifier in hybrid technology, while at top is a fast shaping amplifier in the same technology. The small monolithic circuit in the center contains eight preamplifier/shaper channels, with virtually the same noise and linearity characteristics as the hybrid components. About a 2000:1 area savings is realized.*



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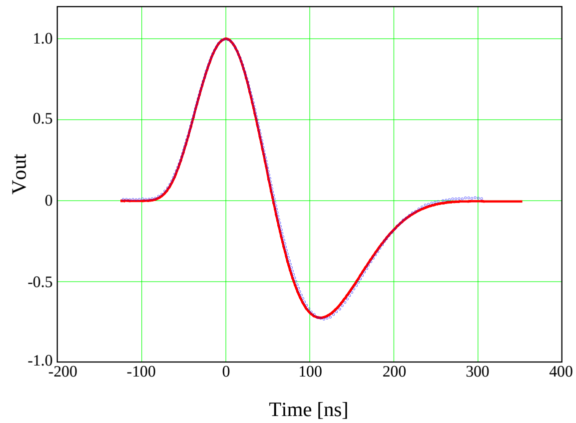
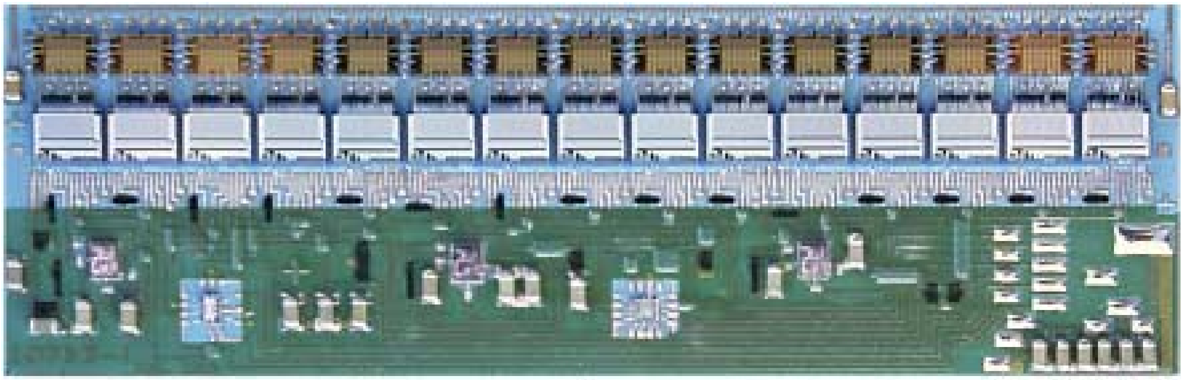


▲*Output waveform from a CMOS 0.5µm 16-channel preamp-shaper for ATLAS Cathode Strip Chamber (input capacitance in the 20 - 100 pF range). Blue points: simulation. Red line: measurement (baseline removed). The shaping is a 7th order semigaussian bipolar complex with ≈ 70 ns peaking time; the gain is ≈ 4 mV/fC with ≈ 30 mW dissipated power per channel.*

▼ *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	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	CRADA eV Products	Preamplifier / shaper / driver	CMOS 1.2 µm	G. De Geronimo
IC44	CRADA Symbol	Direct-conversion receiver	CMOS 0.5 µm	H. Vu, T. Vu, A. Kandasamy
IC45	CRADA eV Products	Preamplifier / shaper / driver, unipolar	CMOS 0.5 µm	G. De Geronimo
IC46	CRADA eV Products	Preamplifier / shaper / driver, blr	CMOS 0.5 µm	G. De Geronimo
IC47	CRADA Symbol	LNA	CMOS 0.5 µm	D. Zhao
IC48	CRADA eV Products	Preamplifier / shaper / driver, bipolar	CMOS 0.5 µm	G. De Geronimo
IC49	CRADA eV Products	Multichannel preamplifier / shaper / driver	CMOS 0.5 µm	G. De Geronimo
IC50/64/70	ATLAS CSC	16-channel preamplifier / shaper	CMOS 0.5 µm	P. O'Connor, A. Kandasamy
IC47/51/57	CRADA Symbol	LNA & mixer	TSMC 0.35µm	D. Zhao
IC51/52	R & D	Test structures	HP 0.5µm and TSMC 0.35µm	P. O'Connor, A. Kandasamy
IC54/60/63/69	CRADA eV Products	16-channel programmable preamplifier/shaper	HP 0.5µm	G. De Geronimo
IC55	CRADA eV Products	Slow 16-channel preamplifier/shaper	HP 0.5µm	G. De Geronimo
IC56/59/65	CRADA eV Products	Fast 4-channel preamplifier/shaper	HP 0.5µm	G. De Geronimo
IC58	R & D	Bandgap reference	HP 0.5µm	A. Kandasamy, G. De Geronimo
IC61	CRADA Symbol	Transceiver	TSMC 0.35µm	D. Zhao
IC62/67	CRADA eV Products	Fast 4-channel preamplifier/shaper bipolar	HP 0.5µm	G. De Geronimo
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

Printed Circuit Board Design, Fabrication and Assembly

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K.A. Ackley
R.E. Machnowski
R.J. Ryan
K. Wolniewicz

J.A. Mead
R.J. Angona
P.D. Borello
F.C. Densing
D.A. Pinelli
J. Triolo

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

- PADS PowerLogic - Schematic entry
- Viewlogic ViewDraw - Schematic entry
- PADS 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.

▶ *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.*

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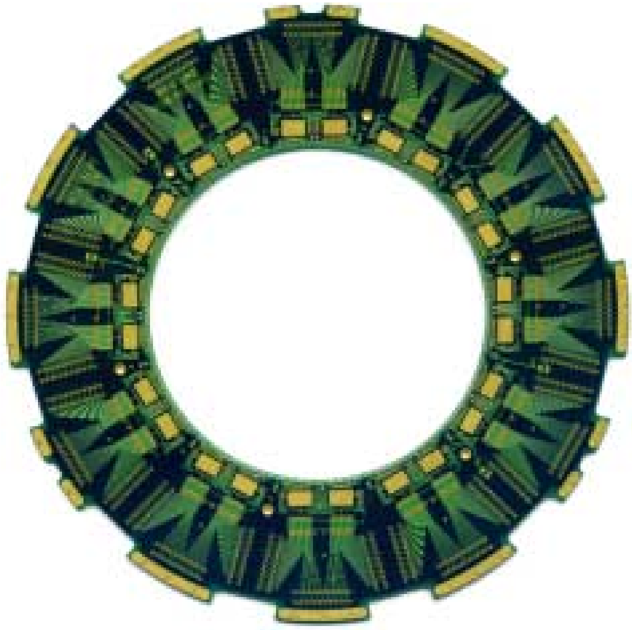

▲*Seen above is a circular circuit board made for the silicon vertex telescope at the NA45 experiment at CERN. The board houses 24 monolithic circuits that amplifies the signals from the silicon detector mounted in the center of the board.*

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, Teflon, 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 experiments for Brookhaven experiments and collaborations. Some of the experiments 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.

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- Numerically controlled drilling machine capable of hole sizes down to 4±1 mils; programmable Z-axis; drill rate of 200 hits/minute.
- 36” wide Western Magnum Laminator.
- Optibeam and OLEC AP-300 exposure units capable of transferring ultra-fine width and pitch traces to the material using its highly collimated light source.
- Developer and Etcher with 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.
- Automated screening machine.
- CVS/SERA analytical equipment for accurate chemical process control.
- Tsunami board cleaner.

▼*Automatic Optical Inspection (AOI) system in operation for detecting faults in circuit board layers.*

▲ *Assembled multilayer printed circuit board is being inspected after the components have been soldered to the board using the surface mount reflow oven.*

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.

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.

Data Acquisition and Control Systems

S. Rankowitz
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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 the major scientific research programs at the Laboratory and throughout the world. The Instrumentation Division has provided detector and computer control systems for a wide range of DOE-sponsored programs, such as at the Cosmotron and the AGS 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 for Molecular Structures for Life Sciences. The Division has played a pioneering role in many other smaller research programs, from pioneering 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 present.

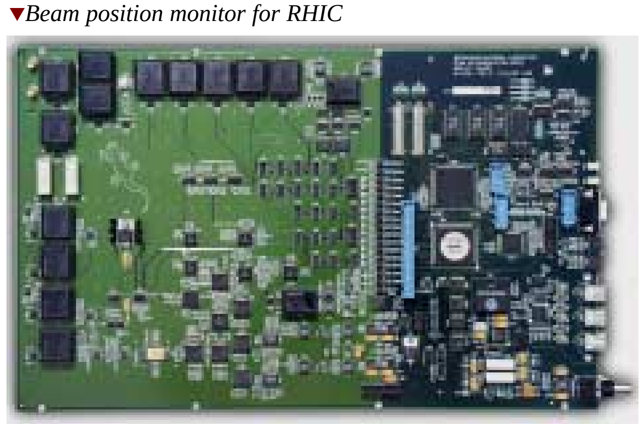
In the late 1950s, real time computer installations in instrumentation and laboratory automation became feasible for the first time. In the nuclear instrumentation field, the interest was mainly associated with multiparameter, multichannel data acquisition and analysis. Developments in the computer industry quickly transformed the issue of how to use computers to what was the most appropriate computer system architecture for the particular laboratory environment. Various approaches were proposed for multi-user systems. Dedicated architectures supposedly could be used independently of other people's plans, experiments and laboratories. However, the high cost of peripherals and large memories made such systems prohibitively expensive. The higher level languages in operating systems were geared towards more general configurations rather than dedicated applications. Consequently, early support developed for general purpose multi-user centralized architectures, where all resources were pooled within one structure with the idea of gaining economy and performance by sharing, with some loss of independence flexibility.

In 1965, the Instrumentation Division pioneered the development of a multiple spectrometer control system (MSCS) to simultaneously operate, control and monitor one x-ray spectrometer and 8 neutron spectrometers at the new Brookhaven HFBR. This system provided both time-shared multi-experiment control and real-time data reduction. The spectrometers were used by independent research groups and, consequently, had to be individually controllable. The typical spectrometer had 5 motor-driven axes, 2 detectors, limit and error switches, incremental axis angle encoders, beam intensity monitor counters, ovens, dewars, etc., which all needed to be monitored. All control stations were identical and interchangeable, and provided the direct interactions familiar to users of manual controllers. These stations could be operated under local or computer control (Scientific Data Systems SDS 920), where the computer was centrally available to the individual experimenters. All semi- and fully-automatic operations were handled from the computer console. Data recording and display for all the experiments were centered in this room.

A centralized computer control was selected for the HFBR system because any individual spectrometer controller had to include a general computational facility. The complexity of the experiments planned for the new Reactor required that settings for a measurement may be based on the results of a previous measurement. If individual controllers were to be used, they would have to be small, economical, general-purpose digital computers. Memory size and peripherals requirements would vary with the complexity of the control computations. The most economical approach for the system was to centralize all the computational power and timeshare its use among the individual spectrometers.

In the early 1970s, smaller and more powerful computers, introduced by Digital Equipment Corp. (PDP-11), made possible the development of a Multi-User Real Time Computer Network with functional distribution system architecture. A computer network for real-time data acquisition, monitoring, and control of a series of experiments at the Brookhaven HFBR was developed and placed in routine op-

▼Beam position monitor for RHIC



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eration to replace the centrally controlled multiple spectrometer control system. The nine spectrometers, and several additional experiment connections, were controlled by the new Reactor Experiment Control Facility (RECF).

The PDP-11 computer was unique at the time as a result of its UNIBUS structure, i.e., a well documented, published backplane signal and timing specification. It was in widespread use, enabling industrial companies and users to provide compatible modules, components, subassemblies, and interfaces. It became the most universal *de facto* standard available to all. Many of the components for spectrometer control and monitoring were built as printed circuit cards to be plugged directly into the UNIBUS backplane for interfacing directly to the processor. Third party vendors competed to provide new semiconductor memories to replace the prevailing magnetic core memory technology of that period.

In the late 1970s, an important system component was added to the multiprocessor node UNIBUS architecture: a random access memory resource where large, common data arrays of up to several million words and common control parameters were stored and could be accessed by several functional processor nodes. It provided the basis of several large scale and some smaller systems, most important of which were (1) a system for monitoring and managing animal inhalation chambers and restricted access rooms for experimental data acquisition and data analysis at the new Inhalation Toxicology Research Facility, and (2) a data acquisition and control system for a spectrometer with a 20 x 20 cm position-sensitive detector used in neutron scattering experiments at the Brookhaven HFBR.

In the late 1970s to early 1980s, continuing rapid decreases in the cost per function of microprocessors and functional large scale integration circuits included a new set of microprocessor products by Digital Equipment Corp., e.g., the LSI-11 microprocessor, based on a Q-BUS backplane and consequent 3rd party compatible hardware and software products. The instruction set and many of the structural features were compatible with the earlier PDP-11 minicomputers. Node components were interconnected via the Q-BUS (node BUS). A node consisted of one LSI-11 processor, one serial diagnostic channel for independent testing of the node, a random access memory and a terminator module with support hardware, such as time out circuits, real time clock, time-of-day clock, node start-up program and node identification in read-only memory. Up to 8 functionally-compatible nodes could form a cluster. Each node in the cluster was connected via an access port to a common random access memory resource of 67 million bytes.

A long distance inter-cluster communication link was designed with one node in each cluster, dedicated to operate the communication protocol with a program stored in read-only memory. The functional independence in this system allowed coupling of functionally incompatible or unrelated clusters.

In the early 1980s, the RECF at the HFBR was replaced with such a system at all the active spectrometers. For Molecular Structure Biology x-ray and neutron spectrometers, an

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

advanced time-resolving data collection system was implemented and placed in routine operation. Data from multiple high resolution position sensitive area detectors, with a maximum cumulative rate of 300,000 events per second, were collected. The events were sorted, in real time, into many time slice arrays. A programmable timing control unit provided a wide choice of time sequences and time-slice array sizes.

In 1987, the Instrumentation Division DAQ group adopted the new VME standard and designed and built the first VMEbus system based on the Motorola 68020 microprocessor, a Time-Sliced Data Acquisition System for Area Position Sensitive Detectors with secondary DMA capability to other CPUs, such as a Digital Equipment Corp. Microvax. Time slicing data acquisition systems were built in the early 1990s and are now in use at the NSLS and HFBR, at small angle spectrometer stations, as well as at the neutron protein crystallography station. The modular nature of the system is such that the hardware and the primary software for these different applications are nearly identical, while the secondary data-processing software is specifically tailored to the particular application.

After 1993, the Data Acquisition and Control Systems Group was almost entirely devoted to activities related to RHIC and one of its major experiments, PHENIX (Pioneering High Energy Nuclear Ion Experiment). The importance of RHIC to the Nuclear Physics program and to the Laboratory as a whole required an intensely focussed effort in areas where the Laboratory has direct responsibility, such as data acquisition for the RHIC beam instrumentation system, certain subsystems of PHENIX, e.g., the Time Expansion Chamber (TEC) tracking system front-end electronics; timing system; ARCNET control and monitoring communications network; and programmable pulse generator for experiment system testing. The implementation of these complex, dense, high speed systems required the development an introduction of new industry standards and technologies for field programmable gate array (FPGA) circuitry, digital signal processor (DSP), and fast optical and copper serial communications. Development of advanced fabrication and assembly methods for controlled impedance multilayer printed circuit boards us-

▲ *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.*

ing surface mounted components was essential for the success of all these systems.

Recently, the most prominent activity has been the readout electronics for the 120 degree neutron detector to be installed at LANSCE, which 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 daughtercard modules which include 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 under 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.

Also related to this activity is the development of a general purpose histogramming unit, which can support up to 8 independent detectors simultaneously. Each histogramming channel provides 8 megabits of high speed SRAM and can handle histogramming rates up to 20 million events per second. At the heart of the system is a StrongARM microprocessor which directs the readout of accumulated histograms to a PC via a USB port. Also included is a six inch 320×200 ¼ VGA LCD which provides a real time digital "twinkle box" display for any of the input data streams. With a versatile front end daughtercard design, this histogramming unit can easily adapt from the data format of the 120 degree neutron detector to any other data stream that requires histogramming, including the older 20cm×20cm detector readout electronics.

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PHENIX

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"Time Expansion Chamber Front End Electronics," RealTime99 Conference, Santa Fe, 14-18 June 1999.

"ArcNet Control Network," RealTime99 Conference, Santa Fe, 14-18 June 1999.

▼ *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.*

MICROFABRICATION/NANOFABRICATION

J. B. Warren
D. C. Elliott

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. The versatility of MEMS fabrication methods has generated increasing interest in the capabilities of the Instrumentation Division in this area. A number of applications involving integrated sensors and specialized microstructures for use in BNL's multi-user facilities, such as the NSLS, RHIC, and the ATF, are already under active development. The goal of the Microfabrication Laboratory is to respond to the specific needs of the BNL scientific community by fabricating microstructural components required for experimental apparatus, and to interact with local industries and academic institutions in joint ventures that enhance the MEMS manufacturing knowledge base.

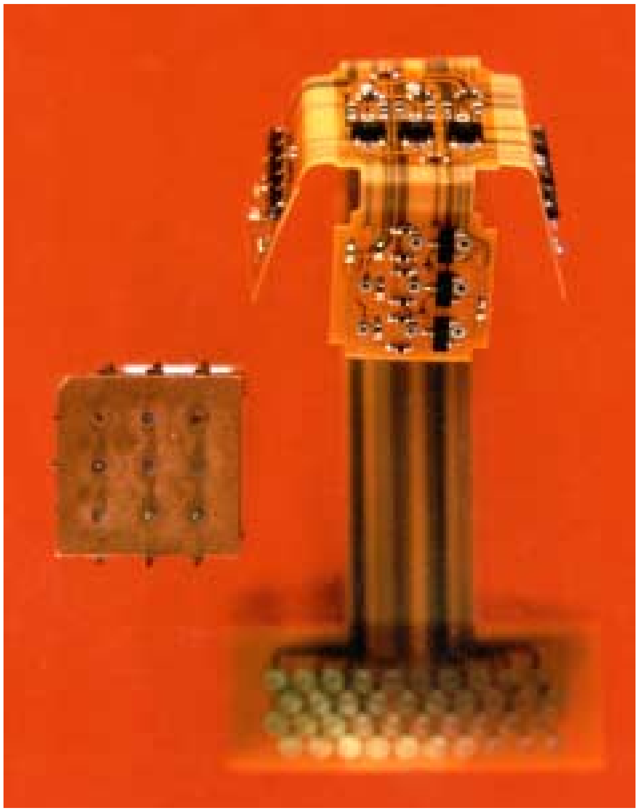
Facilities

The Microfabrication Laboratory is fully equipped with the hardware and software necessary for complete microfabrication design, processing, and characterization. Visiting investigators are encouraged to actively participate in the design process by learning the fundamental microfabrication 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 Plasmalab reactive ion etching and plasma-enhanced chemical vapor deposition chambers. Completed microstructures can be examined with a high resolution AMRAY 1845 scanning electron microscope equipped with a field emission gun, and a Princeton Gamma Tech image and X-ray analysis system.

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. Ongoing 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



▶ *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.*

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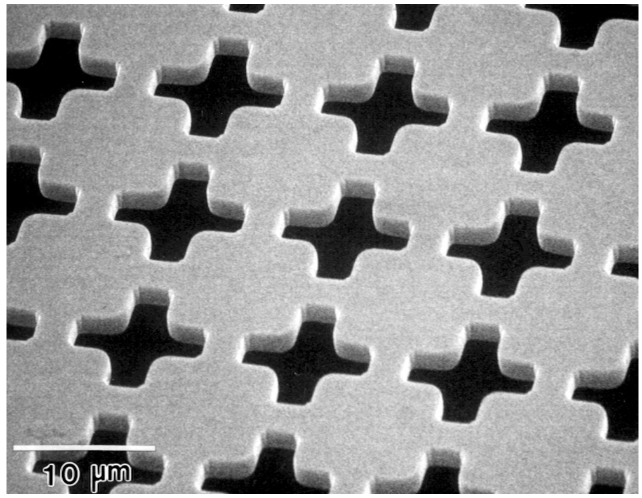


▲ *Freestanding thin metal membrane Infrared filters for interferometry in the 10-20 µm range*

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 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.

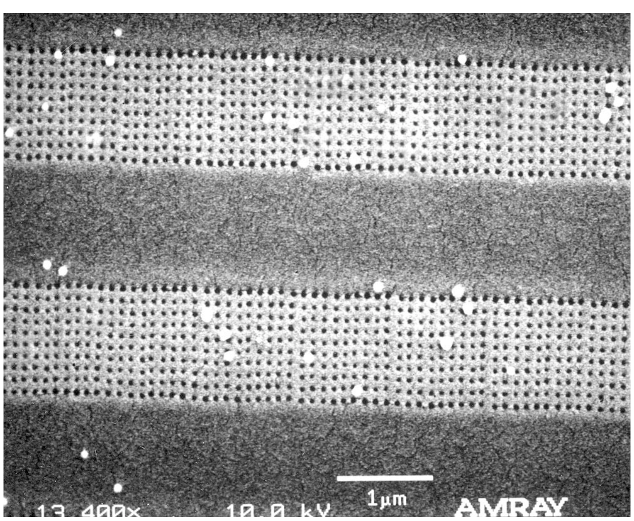
High aspect ratio lithography is also being used to pattern a freestanding membrane used as a deposition mask for electron beam evaporation. Here, coded openings, with a dimension of 2 to 3 µm are patterned in an array of high aspect ratio resist and then placed in close contact with a nickel foil in 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.

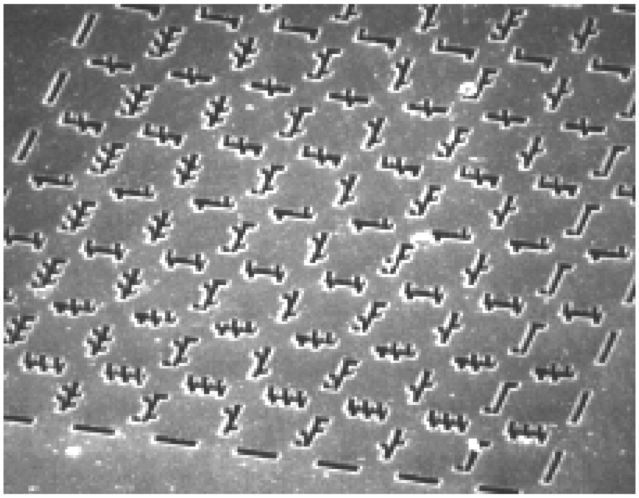
Other applications require freestanding metal membranes. For this case, the metal is electroplated around high aspect ratio resist. After electroplating, the resist is dissolved and a frame is bonded to the electroplated metal film. Patterned films measuring several square inches in extent have been 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.

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

Recently, an NPGS electron beam controller was interfaced with the AMRAY 1845 scanning electron microscope. This capability enables electron-beam sensitive photoresist, such as polymethyl methacrylate, to be patterned with a resolution equivalent to that obtained with dedicated electron beam pattern generators. The micrograph to the left shows an array of 30 nm diameter dots fabricated by this instrument. Plans are now underway to use this new capability to fabricate nanoelectrodes for charge transfer studies that are an essential component of the BNL Nanotechnology Initiative.

▼ *30 Nanometer Dot Arrays in PMMA Exposed with NPGS/ AMRAY 1845*





▲ *High Aspect Ratio Deposition Mask*

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)

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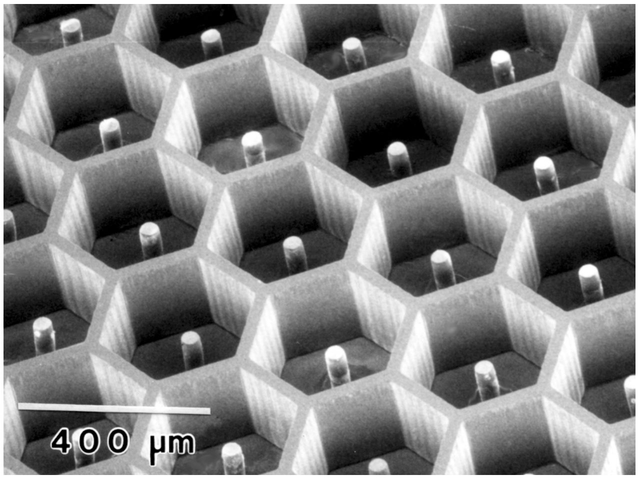
K. D. Moeller et al., "Cross Shaped Bandpass Filters for the Near- and Mid-Infrared Regions," *Applied Optics*, 35, No. 31, 1 Nov. 1996, p. 6210-6215.

▼ *High speed x-ray detector array for synchrotron applications*



Optical Metrology

P. Z. Takacs
S. Qian

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 continue to provide expertise in solving optical design and testing problems for the entire Laboratory. Major projects in which we have been involved are as follows:

- Upgrading the performance of the original Long Trace Profiler (LTP I) in the OML with new hardware and software.
- Assisting Ocean Optics, Inc., in the development of commercial versions of the LTP for various applica-

Pictured with the R&D 100 Award-winning LTP II are the major collaborators (clockwise from left): Steve Irick, LBL, Eugene Church and Peter Takacs, BNL, and Manfred Grindel, President of Continental Optical. Not available for this photo is Shinan Qian.

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tions. Ocean Optics is licensed by BNL to commercialize LTP technology.

- Collaborating in a research project with the Materials Fabrication Laboratory at RIKEN in Tokyo to install an LTP optical head on a precision grinding machine for rapid production of aspheric optics.
- Investigating the nature of damage to mirrors caused by long-term exposure to synchrotron x-rays.
- Developing models for predicting the performance of x-ray optics based on measurements of surface figure and finish parameters. This work is being done through a long-standing collaboration with Dr. E.L. Church, who has extensive expertise in signal processing theory.
- Developing standard artifacts and test methods for calibrating surface profiling instruments.

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. The core of the program was funded through internal overhead funds, with additional funding through an FWP which was initiated in FY'85 through the Materials Science Division of Basic Energy Sciences at DoE.

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 E.L. Church, 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

◄*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.*

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.

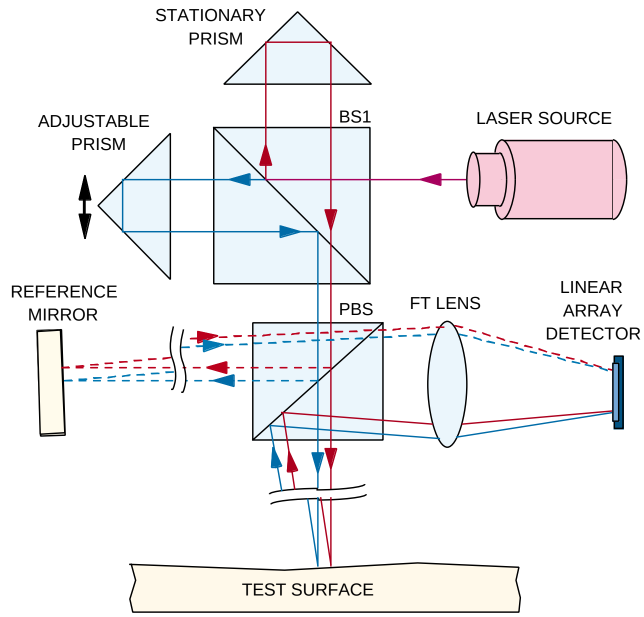
As a service to the SR community, we provided measurements for manufacturers who did not have the capability to measure surface roughness to the level of precision and accuracy required by SR applications. Based on our efforts at providing feedback to the manufacturers, the quality of optical surfaces 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.

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 about 14 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 experience in spectrophotometric instrument design and manufacture. OOI plans to redsesign the LTP mechanical system and add its own detector technology to improve the optical head.

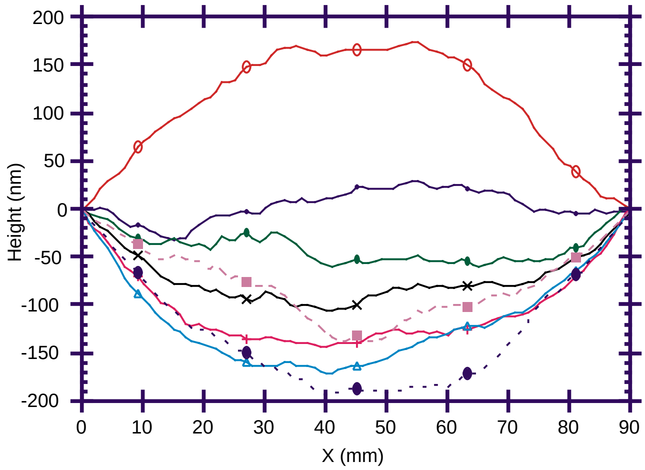


▲*Schematic diagram of the LTP optical system. Slope of the test surface is measured by scanning the optical head across the surface. Reference mirror removes all motion-induced error signals, allowing for extremely high precision and accuracy in long radius of curvature measurements.*

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 sur-



▲ *ISLTP measurements made at an APS beamline on a side-cooled Si mirror, showing changes in surface curvature as a function of exposure time to the SR beam. Initial transient deflection is convex; steady-state concave departure from nominal occurs after about 30 minutes of exposure. This steady-state condition was not predicted by finite element calculations*

faces 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 for continued LTP development through CRADA and SBIR programs

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Lasers and Electro-Optics

T. Srinivasan-Rao
T. Tsang
Q. Zhao
M. Montemagno
J. Walsh

The Laser Laboratory in the Instrumentation Division is actively involved in the develop ment 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 pulseare 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.

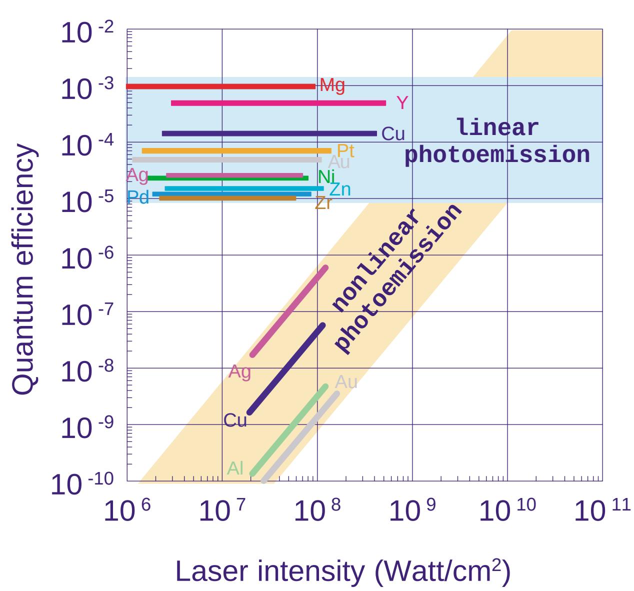
The photocathode materials that have been used so far could be broadly categorized into two types, namely cesiated semiconductors or simple metals. The cesiated semiconductors typically have a very large quantum yield and hence require a simpler laser system to drive it. This advantage is offset by the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

The research at the Instrumentation Division has focused on various methods to improve the quantum yield of metal photocathodes. A wide variety of techniques such as in situ surface ablation, energy transfer via surface phonons or multi photon process, optical field enhancement, surface field enhancement, and Schottky effect have been tested and shown to improve the quantum yield. More than a dozen metals have been tested for their photoelectric properties as well as laser induced damage properties.

Behavior of these metals under RF fields has been investigated in an ongoing experimental program at the Accelerator Test Facility in collaboration with scientists from NSLS. Recent experiments with bulk Mg, ion sputtered Mg and bulk Cu indicate that current densities of 40 kA/mm^2 could be obtained without damaging the metal surface. This is the highest current density reported so far from macroscopic metal electron emitters. We have also established a preparation technique for reliable cathode performance.

Currently, our laboratory is the only facility where metal photocathode research is being done for this application. These results are used extensively world wide in choosing the cathode materials. A number of academic and commercial institutions such as UCLA, CERN, Argonne National laboratory, MIT, Grumman-Northrup have been using metal cathodes based on this research.

▼*Experimentally measured quantum efficiencies of various metal photocathodes in the linear and the nonlinear photoemission regimes. It is expected that the nonlinear process will be more advantageous at high intensities before laser damage is initiated.*



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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.

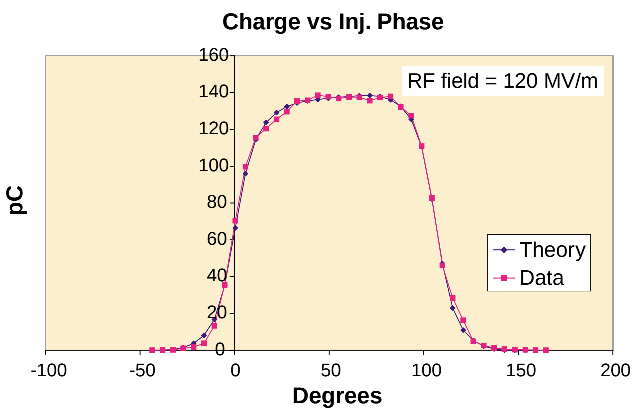
RF injectors

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 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.

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



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.

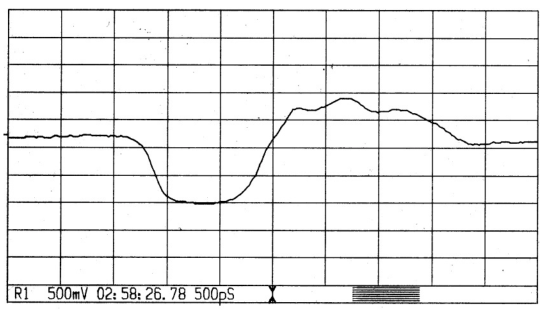
Another technique to minimize the emittance growth due to varying field is to use a pulsed electric field at the cathode. For this scheme to be successful, the pulse duration of the high voltage must be significantly longer than both the emission time and transport time of the electrons in the nonrelativistic 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.

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 can be supported by carefully prepared electrodes for duration of 1-5 ns without breakdown.

To satisfy these requirements, a high voltage pulser with pulse duration of ~ 1 ns, rise and fall times of ~150 ps and amplitude of ~ 1 MV has been constructed. With such a pulser, field gradients of 1.6 GV/m has been supported using copper cathode and stainless steel anode without significant dark current. Electron beams of superior quality can be obtained by irradiating the cathode simultaneously with a short pulse laser.

Computer simulations for 1 nC charge and 10 ps duration from 0.25 mm radius spot indicate that, with such fields, the transverse emittance of the electron beam could be an order of magnitude smaller than that currently available. This improves the brightness of the beam by two orders of magnitude. By optimizing the electrode

▲ *The GV/m pulsed electron gun at the Instrumentation Division*



▲ *Voltage trace at the cathode of the pulsed electron gun. Maximum voltage is 920 kV, duration ~700 ps, with rise and fall times ~100 ps after deconvolution.*

geometry, even higher currents can be generated with similar emittances. Such an optimization is currently underway. Experiments are in progress to produce 1 nC bunch with 100 fs duration and characterize the beam. Such an electron source will be highly desirable for both high-energy electron colliders and short wavelength Free Electron Lasers. This electron source is capable of producing beams with unprecedented brightness (>10^{16}A/m^2rad^2). 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 as an electron source.

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

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.

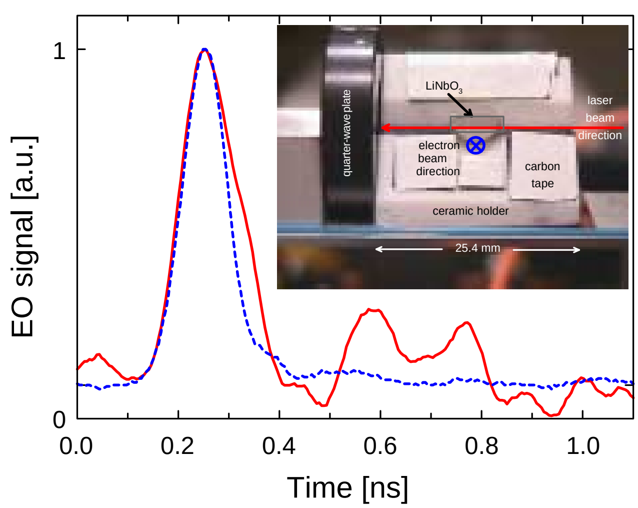
Electro-Optics in Particle Detectors

One of the developments at the instrumentation division is to apply the state-of-the-art laser technologies to high energy physics particle detectors. Present particle detectors are exclusively electronics, from detector signal identification to signal processing. With the growth of the physical size of modern detectors and the added complexity of various monitor and control channels, the number of necessary signal channels exiting a detector is almost unmanageable. Furthermore, cross talks and EM interference between channels often compound the difficulty of signal processing. We explore the possibility of detecting energetic particle by optical means and the transfer of the signals using novel optical techniques.

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 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, the risetime of the electron beam induced signal has been measured to be less than 70 ps, limited by the bandwidth of



▲ *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.*

the detection electronics. The EO signal due to ionization caused by the electrons traversing the EO crystal was also observed. It has a distinctively long decay time constant and signal polarity opposite to that due to the field induced by the electron beam. The success of the experiment suggested the EO technique may be ideal for the measurement of bunch length of femtosecond, relativistic, high energy, charged, particle beams. Experiments are in progress to measure the electron induced EO signal to the picosecond resolution. If successful, this idea could lead to the development of particle detectors with temporal resolutions possibly below picoseconds and spatial resolutions of a few microns which would be highly useful in both hadron and lepton colliders.

Transfer of detector signal

As a first approach, by replacing bulky copper signal cables with light-weighed fiber-optics components, one would drastically reduce the mass-volume of particle detectors. We explore an optoelectronic analog system using arrays of novel vertical-cavity surface-emitting lasers (Vcsel) for the transfer of particle detector signals.

Vcsel has a planar structure that is relatively simple to fabricate and mass-produce. Unlike edge-emitting laser diodes, where various steps of post optical processing are needed to form the cavity mirrors, a set of Bragg reflecting cavity mirror can easily be deposited on the Vcsel's planar structure, leading to strong optical confinement and lower lasing threshold to below 1 mA. Such sub-mA thresholds can be driven directly by most front-end electronics and contributes little thermal budget to the detector. The large GHz bandwidth of Vcsel is more than adequate for the highest ~100 MHz collision rate planned today. Furthermore, the planar nature of the Vcsel array structure simplifies the prefabrication alignment and facilitates the coupling to a ribbon fiber to yield multichannel of high optical throughput in a small mass-volume optical data link.

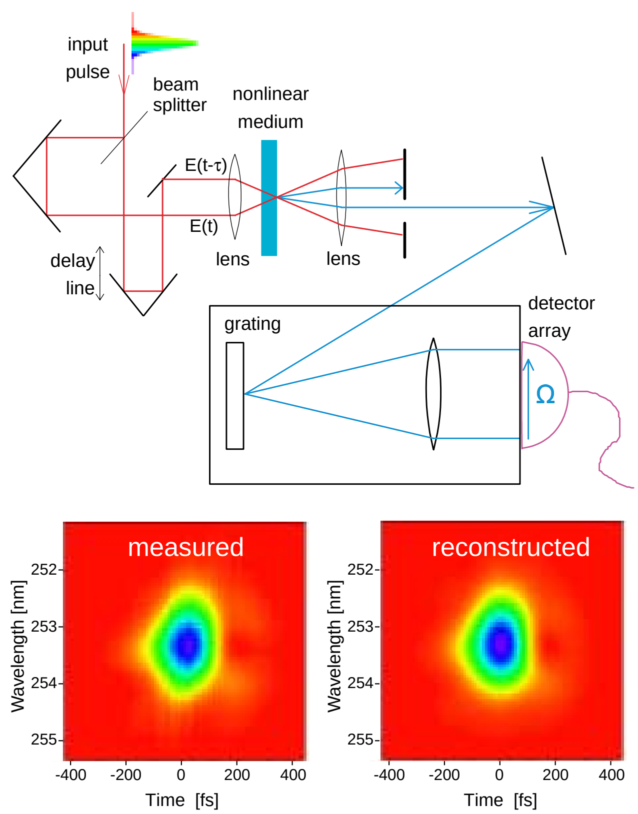
In collaboration with Center de Physique Des Particles de Marseille (CPPM) and Sandia in New Mexico, a 64-channel demonstration version of an optical analog link, at 850 nm wavelength using GaAlAs-GaAs multiquantum well structures, for transfer of particle detector signal is in progress. It is centered on the novel fabrication technique: selectively oxidized Vcsel developed at Sandia, where the in-situ oxide formation around the gain medium has improved many aspects of the lasing characteristics. The Vcsels have approximately 1 mA threshold and emitting 3 mW of optical power at the maximum operating DC current of 10 mA.

At our laser application laboratory, we investigate several lasing characteristics of the Vcsels including the linearity, spatial profile, polarization effects, spectral analysis, and the relative-intensity noise, all affecting the performance of an optical data link. One undesirable intrinsic characteristic of Vcsel is its undefined output polarization due to its azimuthal symmetric birefringence, resulting in large polarization switching noise. We investigate a method to tailor the birefringence of a Vcsel using a high-peak-power femtosecond laser. By locally altering the birefringence of a Vcsel, one can possibly tailor the desired polarization output and suppress the polarization switching noise allowing vcsels (of any wavelengths) to be used in analog applications.

Ultrashort-Laser-Pulse Measurement Techniques

THG-Frog

With the advance of solid state ultrashort lasers, sub10-fs laser oscillators are now widely available for many applications. Characterization of these ultrashort laser pulses and other ultrafast optical events traditionally rely on the novel frequency-resolved optical gating technique



▶ *Surface THG optical system. A pulse from a self-mode-locked Ti:sapphire laser is divided by a beam splitter. After one replica of the pulse is delayed with respected to the other, a 20x microscope objective is used to focus the two colinearly propagating beams on to the back surface of a 160-micron thick piece of cover glass. Two autocorrelated THG beams each carry a fraction of a nanowatt signal power sufficient for the required spectral measurements. One of the THG beams is recollimated and sent to a spectrometer equipped with a linear diode array for spectral recording. Spectrograms at various time delays, with 10-fs intervals, are collected and converted into a 256×256 pixel FROG trace. A set of measured and reconstructed FROG trace containing spectral cubic phase distortion is shown.*

via optical second harmonic generation on some nonlinear crystals. However, the intrinsic time symmetry of the second-order process limited its interpretation producing a time-reversal ambiguity.

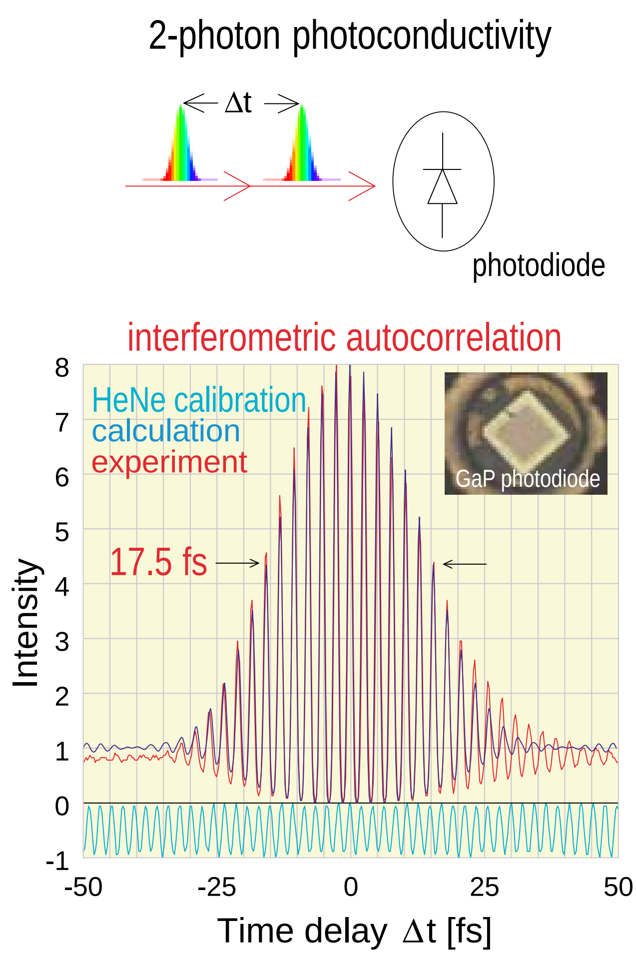
In collaboration with Sandia at Livermore, a novel, ultrashort optical pulse measurement technique has been developed that combines the surface third-harmonic generation (THG) and the frequency-resolved optical gating (FROG) technique to yield measurements of ultrashort optical pulses. The full time-dependent intensity and phase of an arbitrary low-power ultrashort optical pulse (events) can now be measured experimentally and characterized theoretically without a time-reversal ambiguity. THG is dipole-allowed, occurring in all materials with or without a crystal structure. It was demonstrated in our laboratory that such nonlinear THG process is much enhanced at an interface and is insensitive to phase-matching or excitation wavelengths. Therefore it can potentially be used to characterize ultrashort optical pulses of various wavelengths down to the vacuum ultraviolet. Because the enhanced THG occurs within an optical wavelength on the surface where material dispersion is absent, it is well suited for ultrashort optical pulse measurements, particularly for laser oscillators emitting pulses below the 10 femtosecond regime and/or at wavelengths where no nonlinear crystal is available for second-harmonic generation.

Using the enhanced THG technique developed at BNL, various institutes have mapped biological tissues and plant leaves leafs that are otherwise invisible under a typical microscope. These developments marked the possible use of surface THG as a characterization tool and an alternative method for imaging.

Compact Autocorrelator

Recently, autocorrelation measurement technique of ultrashort laser pulse has been simplified employing two-photon photoconductivity in a semiconductor. Using a GaAsP photodiode that has a bandgap of 2.5 eV, the pulse duration of a mode-locked 17-fs Ti:sapphire laser (1.55 eV) has been measured. The 2-photon photoconductivity has several key advantages over the conventional approach of using SHG for autocorrelation measurements. First, the intrinsic time response of the nonlinear process is measured to be shorter than any laser pulses available. Second, no polarization dependence or phase-matching conditions are needed. Third, distortion due to group-velocity dispersion is minimized because the interaction length is limited to an optical wavelength. Lastly, the design simplicity and the signal superiority resulted in an extremely compact measuring device.

However, like any other high-order autocorrelation technique, the phase of an optical pulse is not precisely measured in a 2-photon photoconductivity interferometric autocorrelation. Therefore, a full time-dependent, intensity and phase measurement technique that combines 2-photon photoconductivity and FROG is being developed. Such a technique would simplify the experimental arrangement yet provide sub-femtosecond resolution with detail phase information.



▲ *Interferometric autocorrelation of a 17.5 femtosecond pulse train measured on a simple GaP photodiode. Experimental arrangement is identical to a conventional SHG autocorrelation but without a phase-matching requirement and the need of a photomultiplier tube.*

Fixed Targetry Studies Using Laser Shadow Photography Technique

An issue for pion production in solid or liquid targets for the neutrino factories and the muon collider sources is the instantaneously deposited energy by the proton beam on the target. This energy will lead to rapid temperature rises, stress, and vaporization of the target. In the AGS E951 experiment, the viability of the targetry and the capture of a 24 GeV proton pulse are studied. A targetry diagnostic tool using laser shadow photography technique is used to image the event in high speed. 16 intense laser pulses are fired onto the target. The decay and the transient response of the targetry are captured in nanosecond duration at the rate of 1 million frames per second. This study provides benchmark values and allows the investigators to identify critical issues and limiting factors towards a muon collider.

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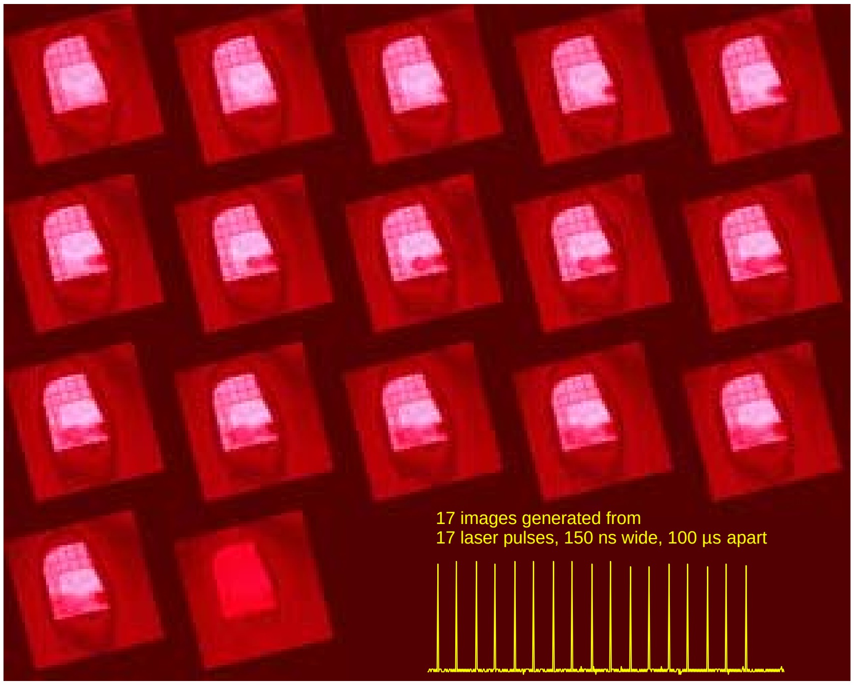


▸ *17 images of a target captured in 1 µs duration per image. The exposture time for each image is 150 ns. It is back illuminated by a laser pulse train shown in the inset.*

VACUUM DEPOSITION AND MATERIALS PROCESSING

R. P. Di Nardo

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.

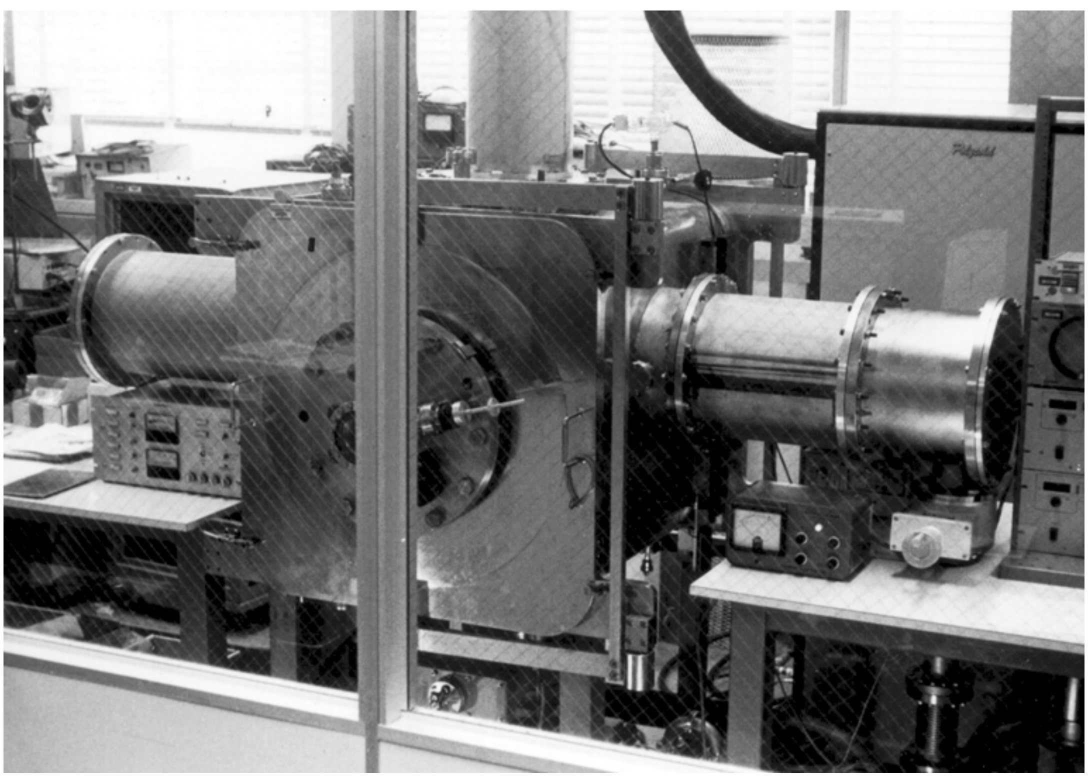
The Vacuum Deposition and Materials Processing Lab is listed in the Directory of Federal Laboratory Resources, U.S. Department of Commerce.

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.

▼ *Special coating chamber built for producing multilayer coatings for x-ray and neutron mirrors. It can handle substrates up to one meter in length. The cylindrical structures protruding from each side contain the translation mechanisms to move the substrates across the target sources.*



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SOLID STATE GAMMA-RAY IRRADIATION FACILITY

J.A. Kierstead

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 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.

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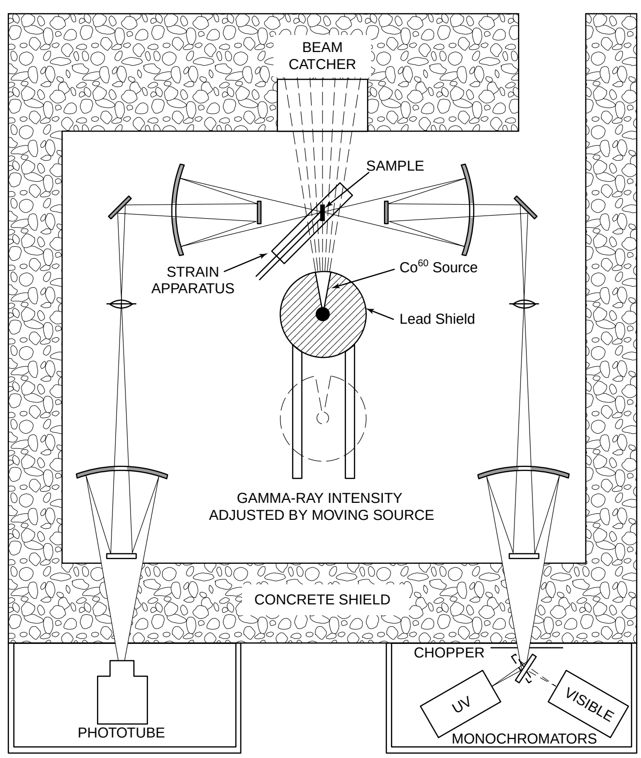
Studies completed with this equipment have unequivocally demonstrated that the radiation damage levels in almost all nonmetals is higher during irradiation than after irradiation; in some materials appreciably higher. Thus, to reliably evaluate the extent of radiation damage in a transparent material 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.

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



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

G.T. Walczyk
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.*

Contact: G.T. Walczyk, (631) 344-6069, gwalczyk@bnl.gov.

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-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

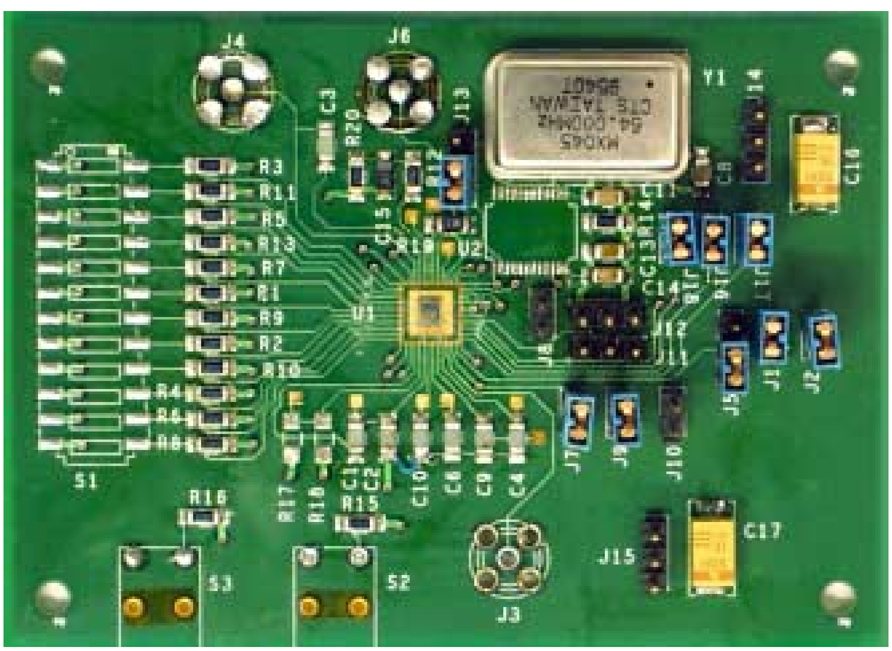
Award Date: May, 1997

Principal Investigator: P. O'Connor

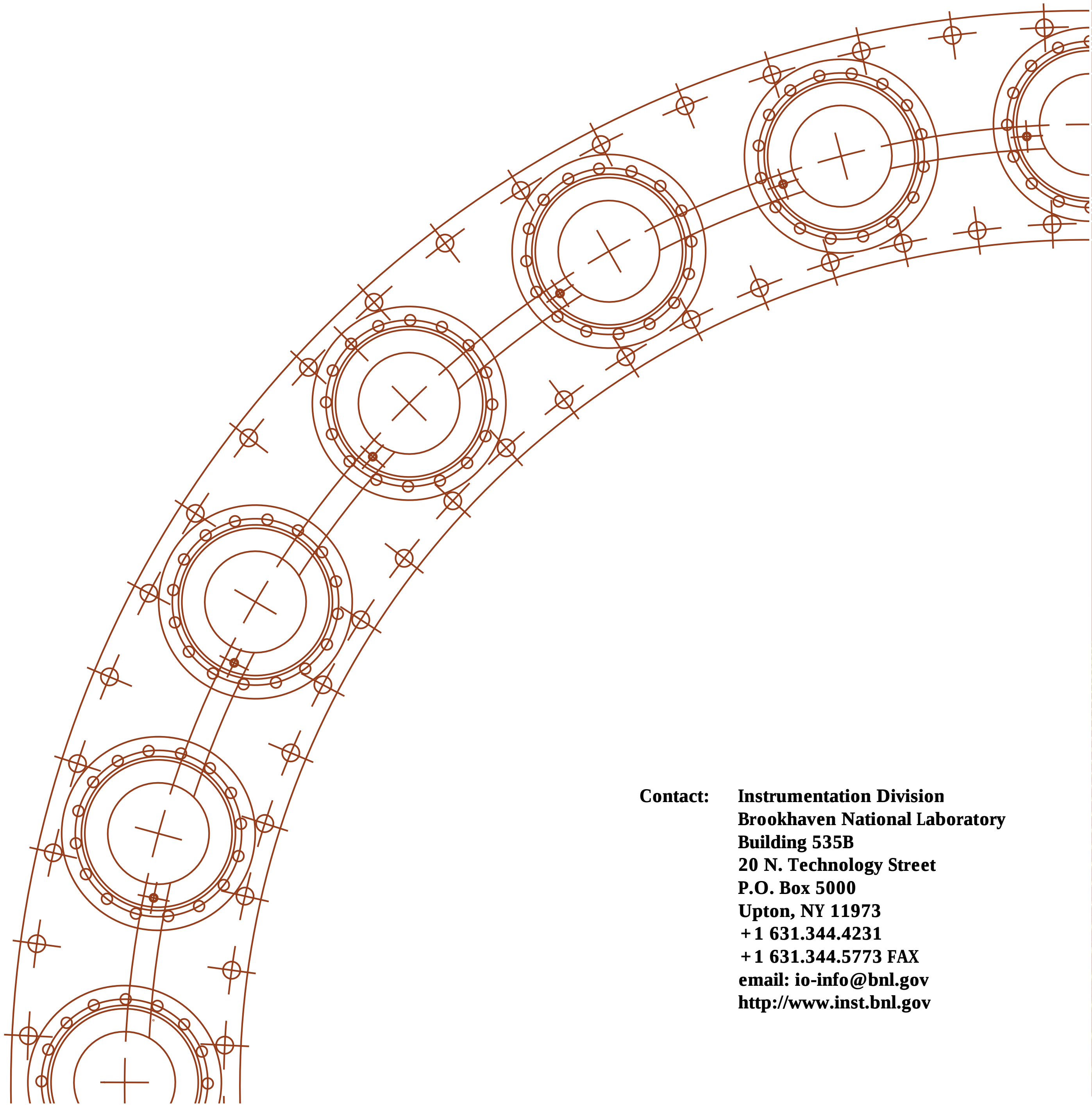
Title: **Microcircuits and Sensors for Portable Low-Power Data Collection and Transmission**

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.



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