Instrumentation Technologies Enabling Current and Future Science

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Instrumentation Division, BNL

August 24, 2012

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Outline

- Instrumentation's core technologies and BNL programs
- Solid-state Detectors – Si, diamond
- Liquid-based detectors – liquid argon (LAr)
- Gas-based Detectors – ^{3}He
- Detectors for Medical Applications
- Laser/Photo Cathode Studies
- Wrap-up

ASICs in all applications

Instrumentation Division

Core Competencies ↔ Program Areas Roadmap

BROOKHAVEN NATIONAL LABORATORY

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

R&D Facilities

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

Staff (41)

Scientific:	16
Professional:	11
Technical:	10
Administrative:	4

Publications

Annual: ~50
Cumulative: 1370

Patents : 18

Stripixel & ASIC for Diffraction Studies in Synchrotron Detectors

Instrumentation's Core Competencies

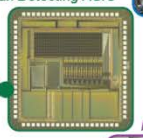
- Semiconductor Detectors
  - Si : X- & gamma ray detectors
  - Si : charged particle detectors
  - Si : CCDs
  - Ge: X- & gamma ray detectors
- Gas & Noble Liquid Detectors
  - Micropattern Gas Detectors
  - Noble Liquid TPCs
  - Noble Liquid Calorimetry
- Electronics
  - Low Noise ASICs
  - Radhard Electronics
  - Digital Signal Processing
  - SQUID Based Amplifiers
  - Special Printed Circuits
- Lasers & Optics
  - Ultra-short Photon & Electron Sources and Measurements
  - Photocathodes
  - Optics & Optical Metrology
- Micro/Nano Technology
  - Sensors & Microstructures
  - Micro/Nano Fabrication

BNL Science Area or Directorate

- Nuclear & High Energy Physics
  - RHIC & ATLAS Detector Upgrades & Other HENP Experiments
  - Neutrino & Special Detectors
  - LSST & Astrophysics
- Accelerator Development
  - Photocathodes for e-cooling & e-RHIC
  - Polarimetry at RHIC
  - Beam Diagnostics
- BES &PS
  - X-ray Detectors for Light Sources
  - Optical Metrology for Light Sources
  - CFN Technology Support
  - Detectors for Electron Microscopy
  - Ultra-fast Techniques
- Life Sciences
  - PET/MRI Imaging Techniques
  - MRI at 9T
  - Detectors for e-microscopy
  - Biomedical Detectors
- GARS
  - Neutron, X- & gamma ray Detectors for Homeland Security
  - Aerosol Characterization
- Other Labs.
  - X-ray Detectors (LCLS, NRL, NASA, DHS, DOD)
  - Electronics & ASICs (LCLS, SNS, NRL, NASA, DHS, DOD)
  - Neutron Detectors (SNS, LANCE)
- Industrial Partnerships
  - ASICs for Radiation Detectors
  - Optical & e-beam Metrology
  - RF Communications

Hi-res. Si x-ray Detector

120° Neutron Detector



Peak Detecting ASIC

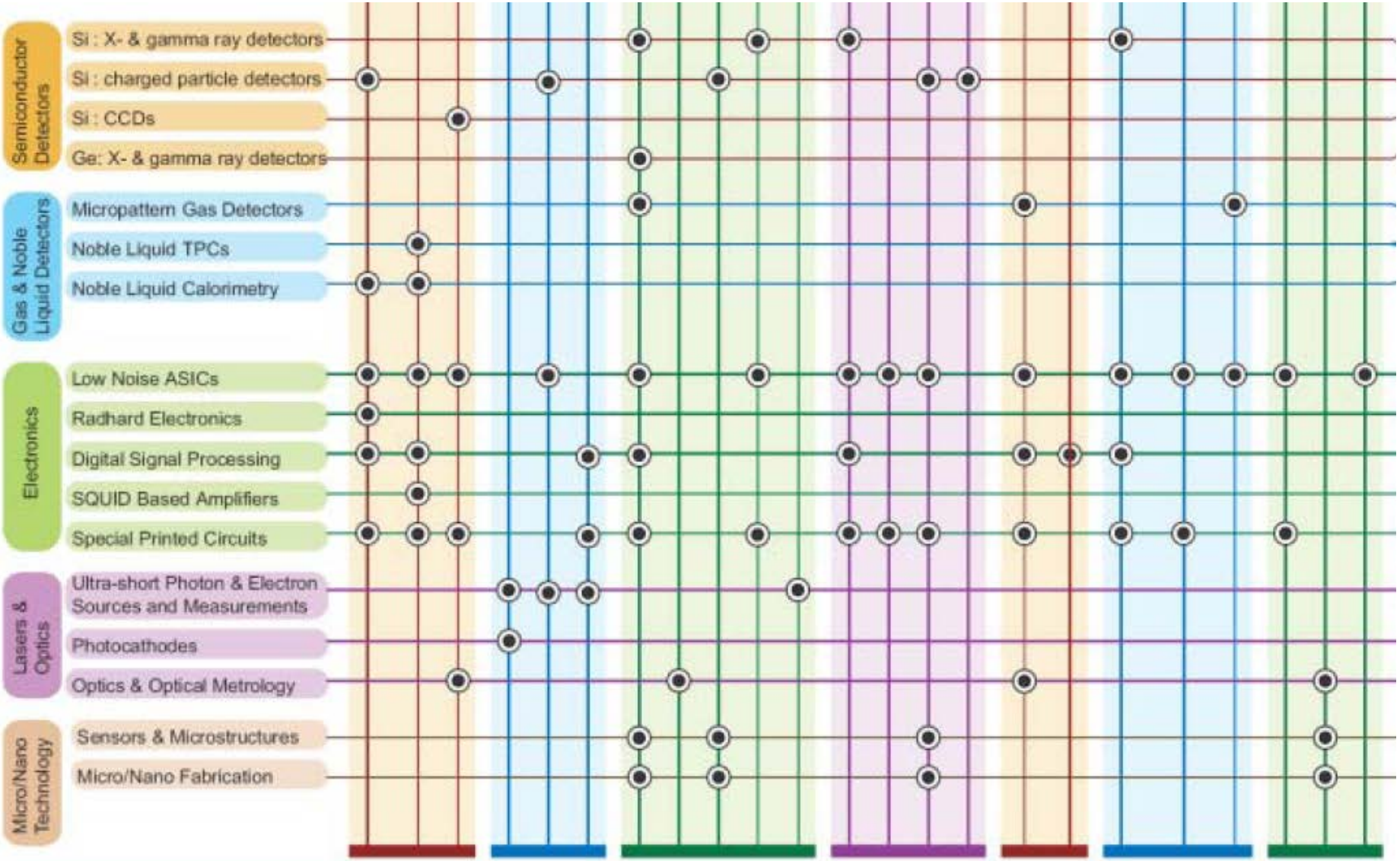
Photocathode R&D

Lighthouse-style Fresnel lenses

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

http://www.inst.bnl.gov

Core Competencies in IO

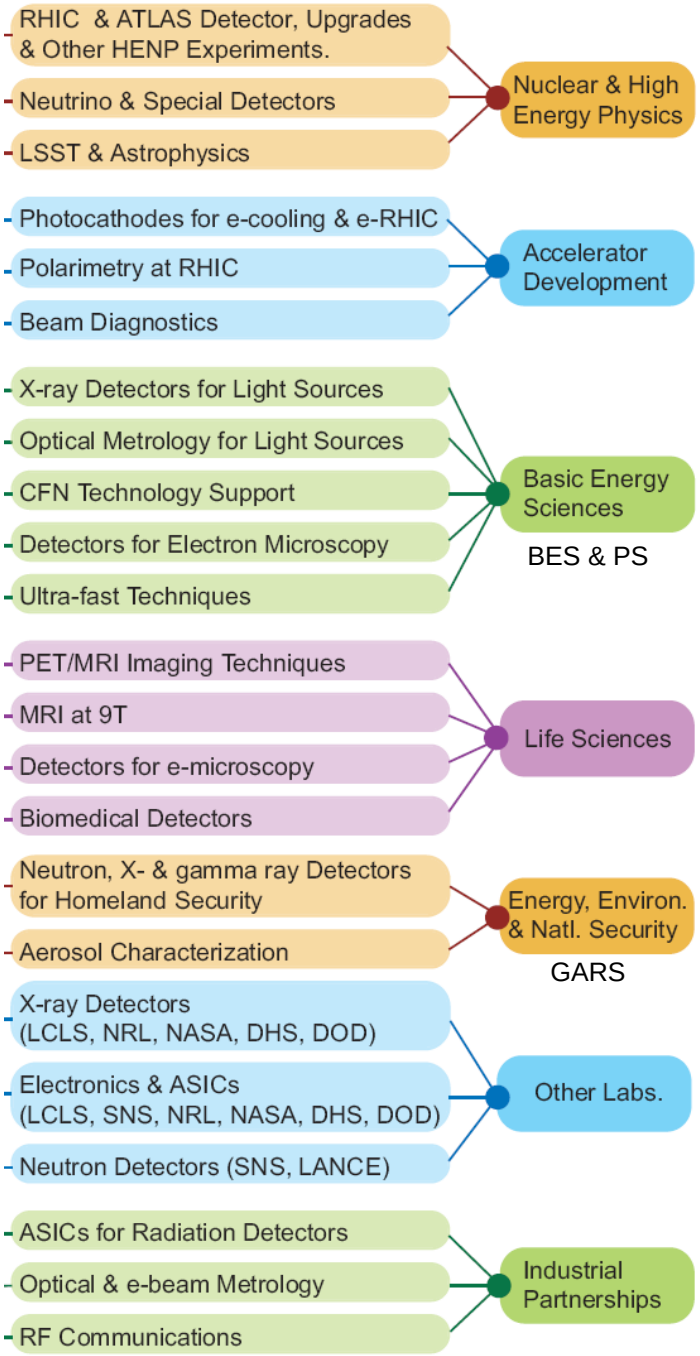


Future Research Areas: Nano-electronics, Si - Detectors Integrated with Microelectronics.

Instrumentation contributions to BNL science and activity areas

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

Our goal: to make the Lab scientists and science programs more competitive by development of enabling technologies



Summary of w_i for Key Detection Media

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

Material	w_i (eV)	Application
Superconducting Tunnel Junction (STJ) Semiconductor Microcalorimeter	~2.5. 10^{-3}	X-ray, eV resolution
Ge	2.9	γ-ray
Si	3.6	Tracking; X-ray
CdTe & CZT	5.2	γ-ray
Diamond	~13	High temp detectors, Flux Measurement
Xe	22	γ-ray, X-ray
Kr	24	γ-ray, X-ray
Ar	26	GeV, TeV calorimetry
^{3}He	40	Neutron
Se	~ 50	X-ray radiography
NaI (+PM)	200	SPECT
LSO (+APD)	~ 100	PET
$PbWSO_4$	~ 2×10^5	TeV calorimetry

Solid-State Detectors

Solid State Detectors for Synchrotron Radiation

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

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

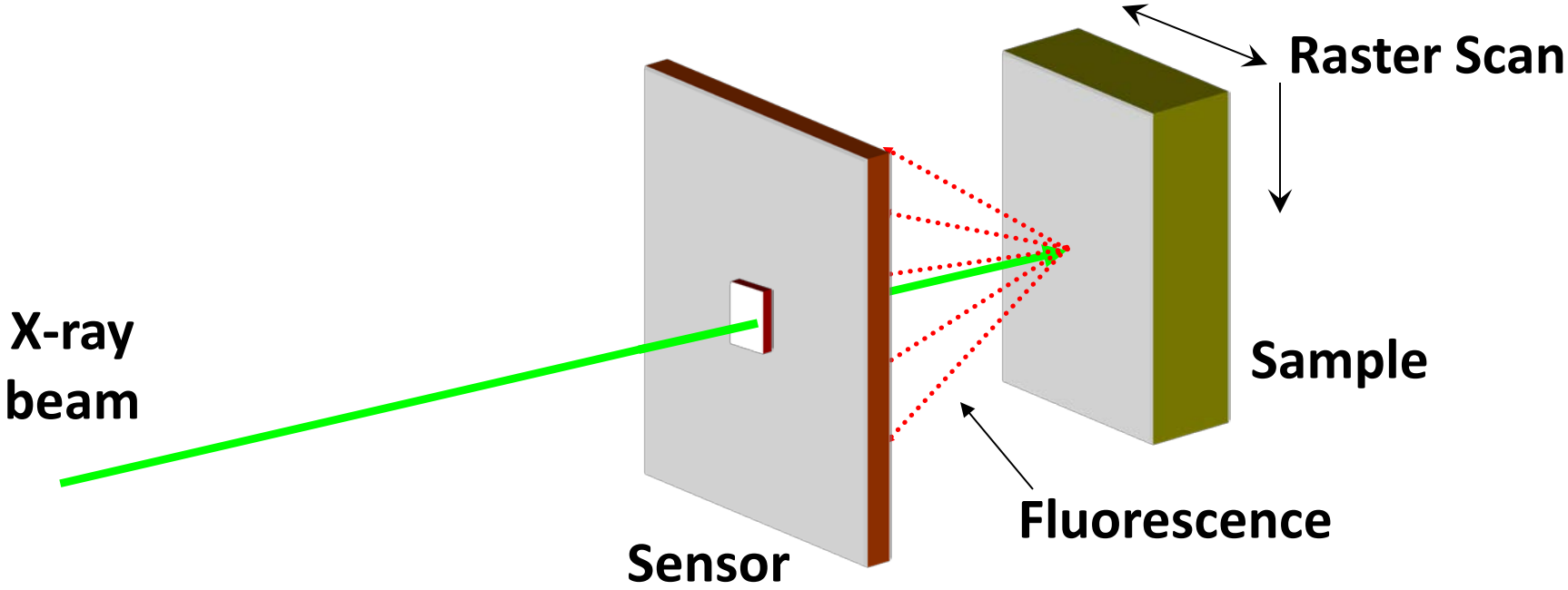
Other key areas:

- Small and Large Angle Scattering
- X-ray Protein Crystallography
- Biological and Biomedical Imaging

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

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

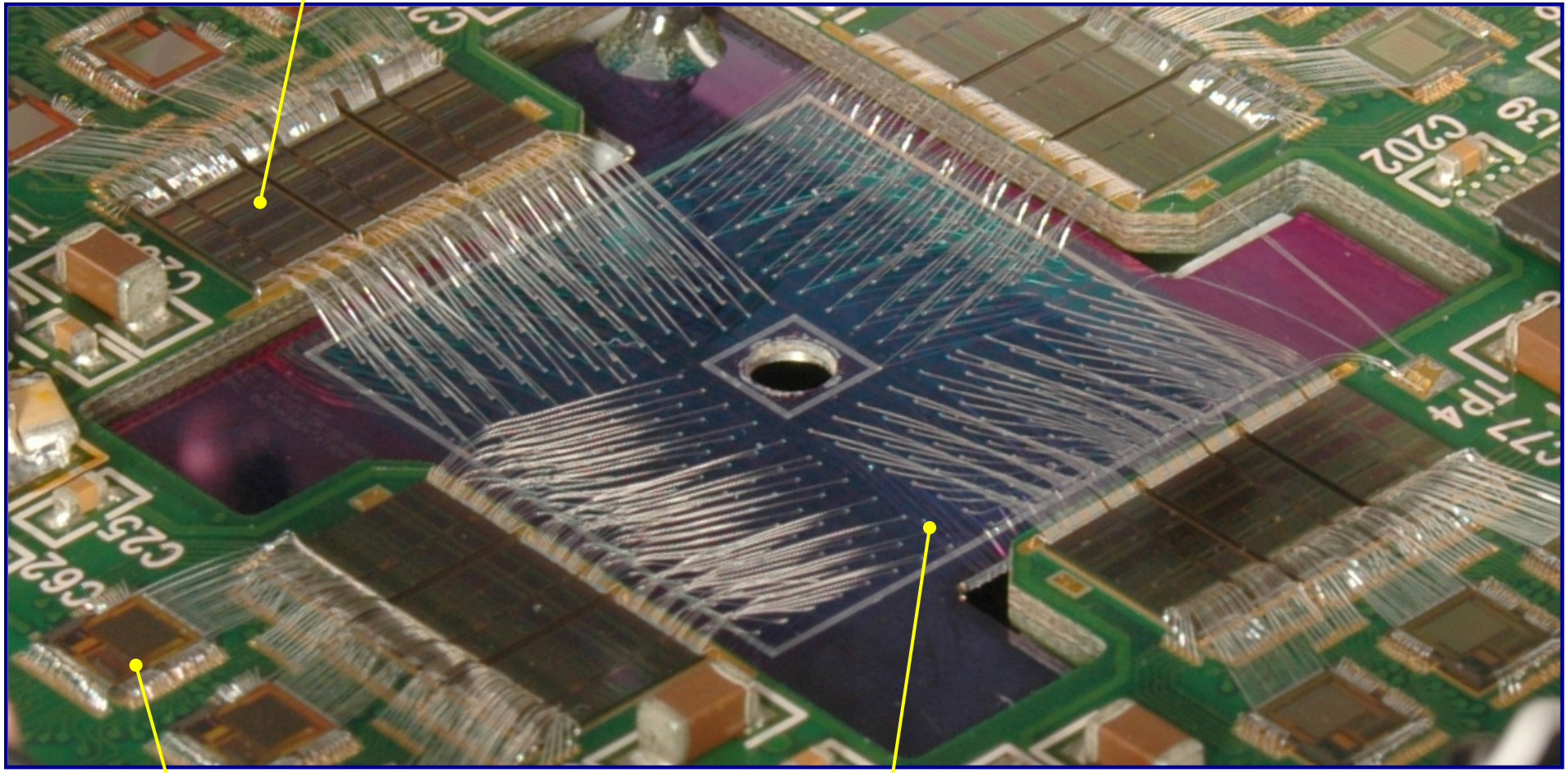
Backscattering Geometry for Fluorescence Microprobe – Maia Detector



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

Maia Detector – Microprobe for Elemental Mapping

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

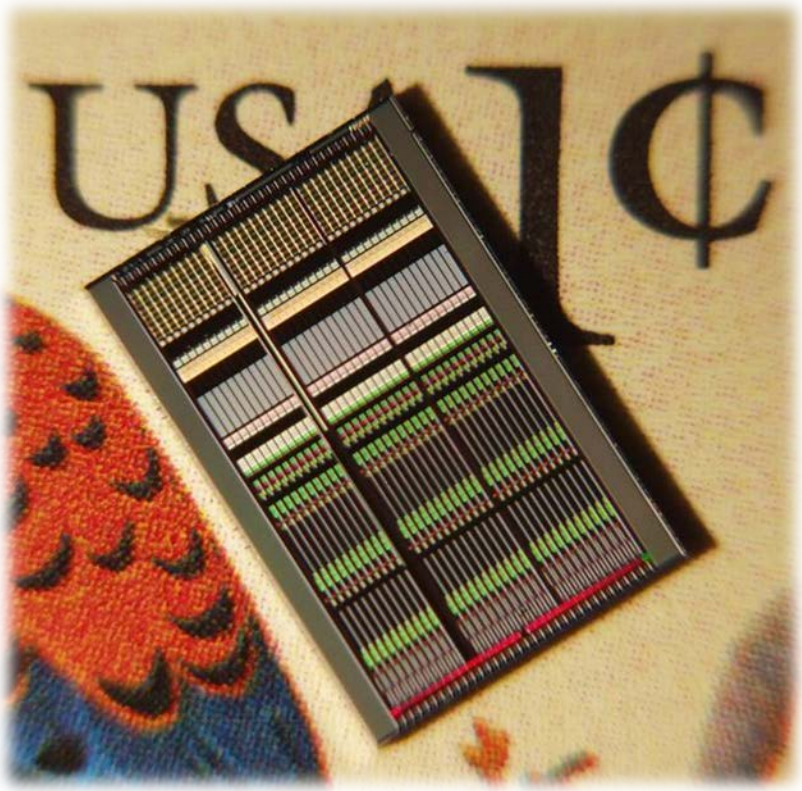


SCEPTER ***chip developed for industry, adopted by NSLS***

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

Hermes chip:

ASIC (Application Specific Integrated Circuit)



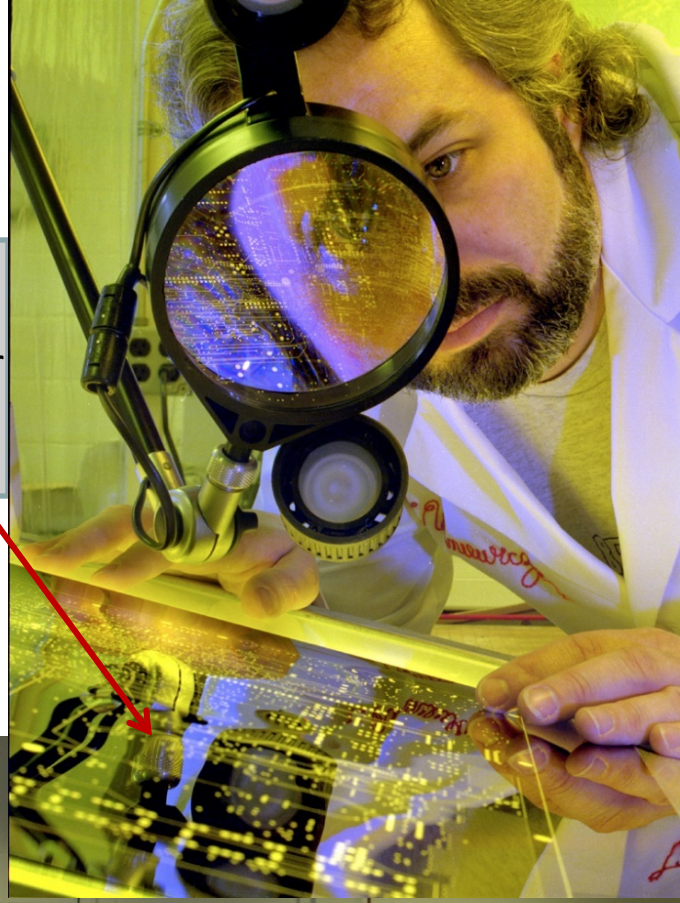
32-channel ASIC, BNL IO

Size: 3.7 x 6.3 mm²

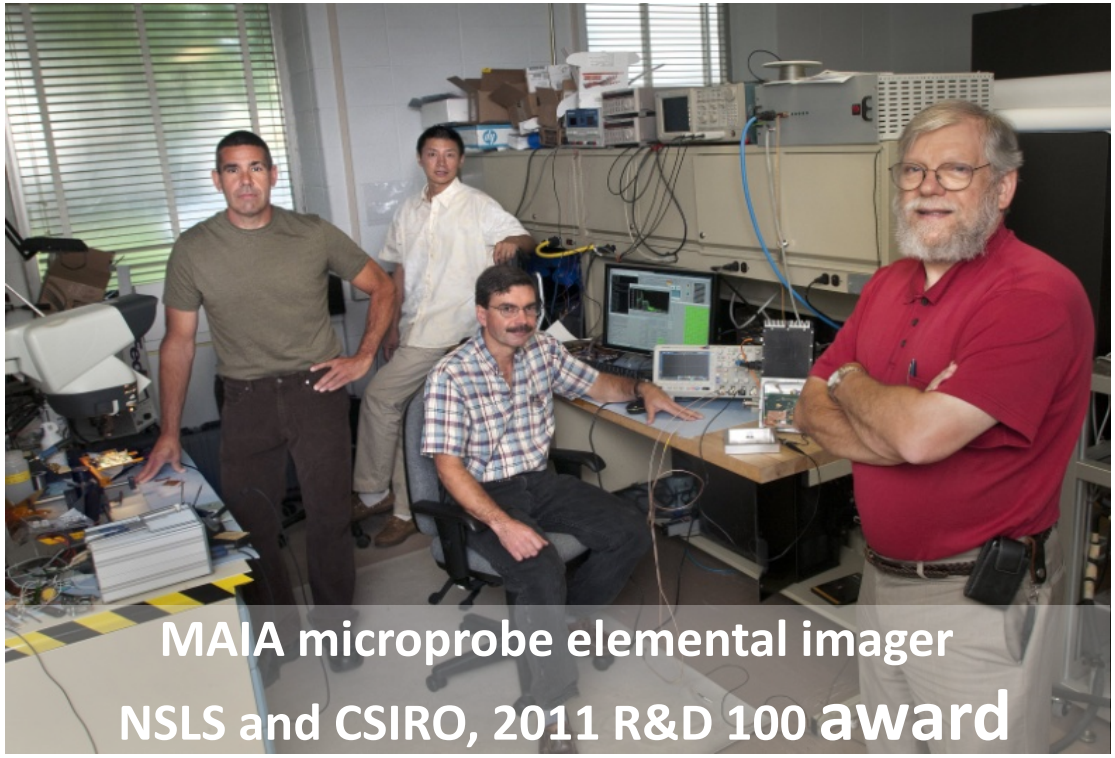
- **amplifier**
- **filter**
- **discriminator**
- **counter**
- **8 mW/channel**

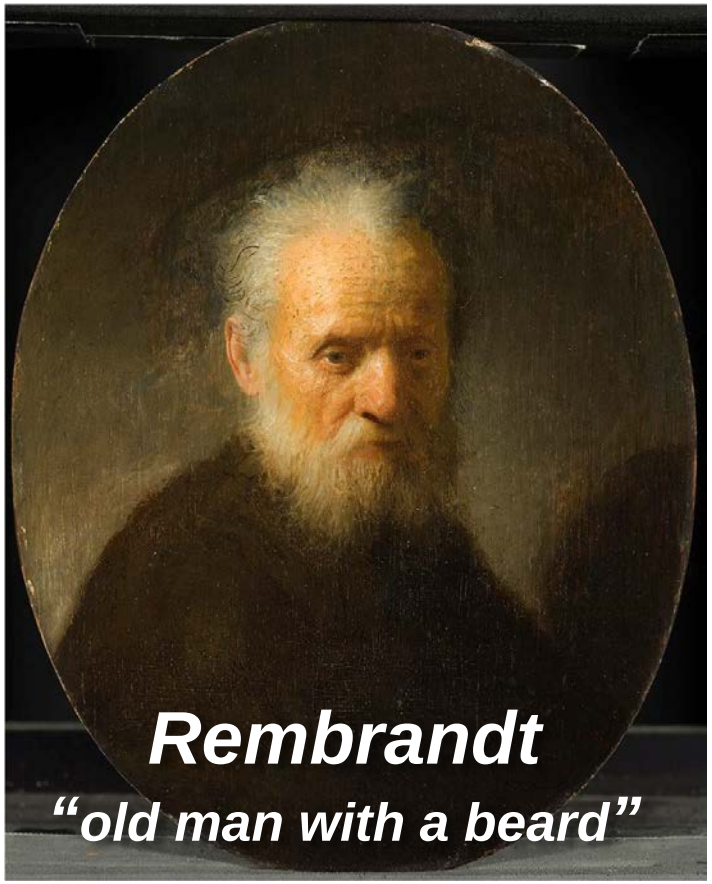
ASICs make possible multi-channel detectors such as Maia

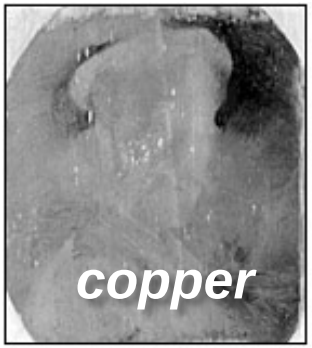
Computer aided design of multi-layer circuit boards



Microprobe for Elemental Mapping

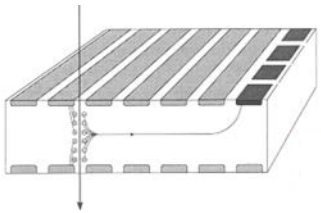




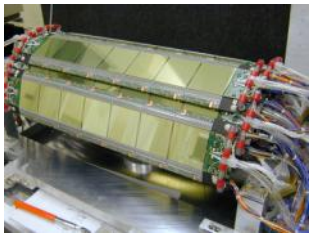


Silicon Drift Detector (SDD)

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



- *Invented in 1983 by Emilio Gatti and Pavel Rehak – thought by many at the time to be technically unachievable*
- *Novel principle: charge carriers drift in a long, narrow channel in the plane of the wafer (solid state equivalent of gas drift chamber) – device provides excellent timing and low capacitance*
- *Solved long-term problem of accurate position/energy measurements with reduced number of readout channels count*
- *Successful concept and development has led to other novel devices, e.g., deep depletion CCDs (flown on XMM mission).*



STAR Silicon Vertex Tracker

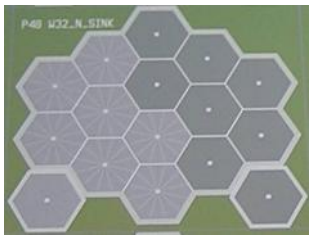
Major impacts in Office of Science research interests:

SDDs now used in commercial EMs

- *Used in both fundamental and applied research, for particle tracking and X-ray spectroscopy*
- *Position-sensing element in high energy and heavy ion experiments:*

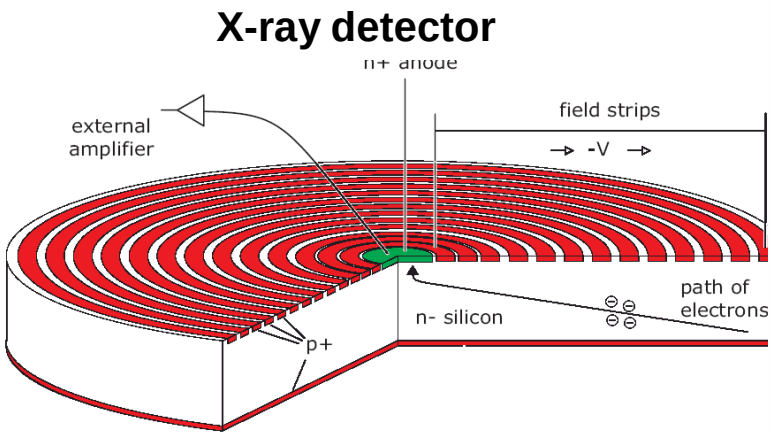
  CERES experiment at CERN; ALICE experiment at CERN

  STAR experiment at RHIC (Silicon Vertex Tracker)
- *SDD arrays used in high rate, high resolution fluorescence in synchrotron science*
- *Growth of SDDs as high res^{n} x-ray detectors in commercial electron microscopes*
- *Space science applications – low power, large angular coverage*

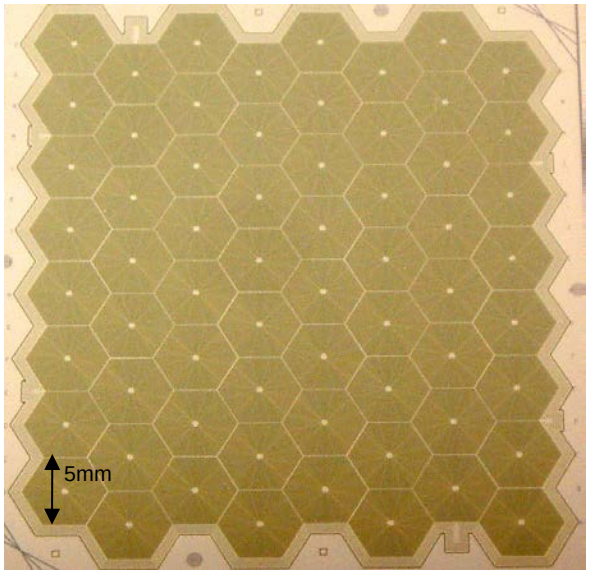


SDD array for NASA

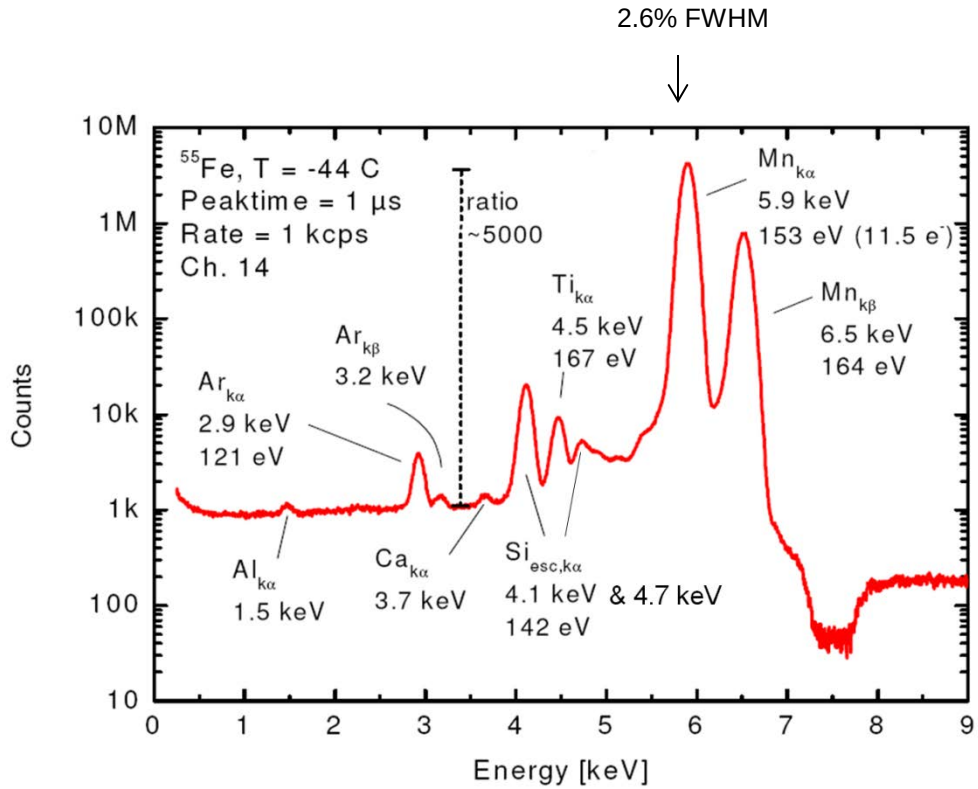
Silicon Drift Detector (SDD) for X-rays



Schematic of cylindrical version of SDD



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

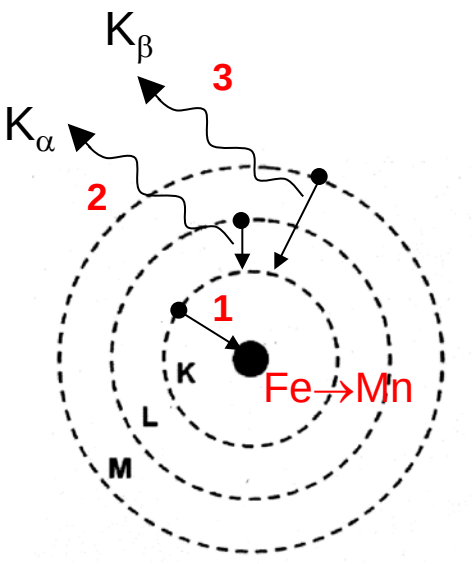


Example of excellent spectroscopic resolution of SDD, from irradiation with ^{55}Fe. Typically 120-160eV FWHM @5.9keV

^{55}Fe isotope – 6 keV X-rays

For Mn: K shell binding energy = 6.54 keV
L shell binding energy = 0.64 keV
M shell binding energy = 0.05keV

1. K electron captured by Fe (Z=26) nucleus – becoming a Mn (Z=25) nucleus
2. L electron fills K hole, fluorescence occurs, **K_α = 5.90 keV**
3. M electron fills K hole, fluorescence occurs, **K_β = 6.49 keV** (~12% prob. of #2)



Typical ^{55}Fe source

Energy Resolution for X-rays

$$\Delta E / E = 2.35\ (\sigma_P / P) = 2.35\ [(\sigma_N / N)^2 + (\sigma_e / N)^2 + \text{others}\ ]^{1/2}$$

where $(\sigma_P / P)^2$ is relative variance on the signal amplitude

N is the number of electrons created by the x-ray

σ_e is the rms electronic noise

Fano factor limit at 6keV ~ 1.8%

No. of electrons created is given by:

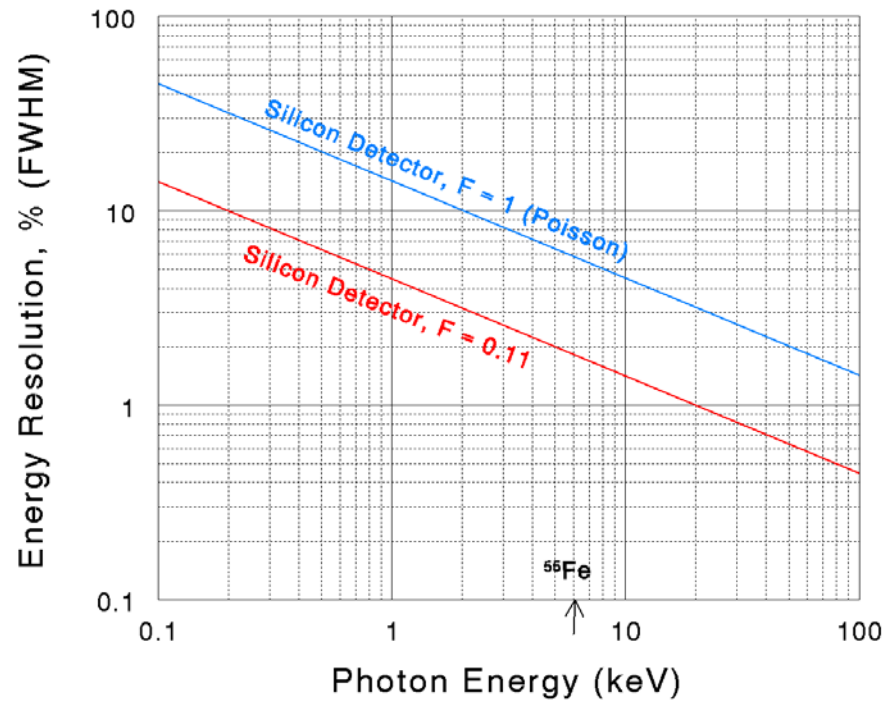
$N = E / w$

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

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

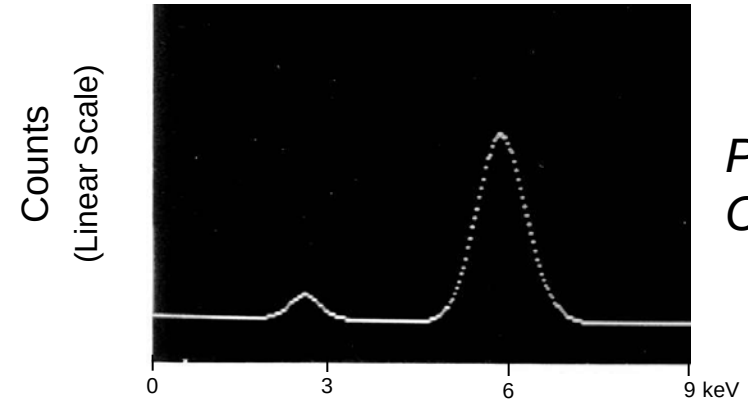
$\sigma_N^2 = FN$

where F is the Fano Factor

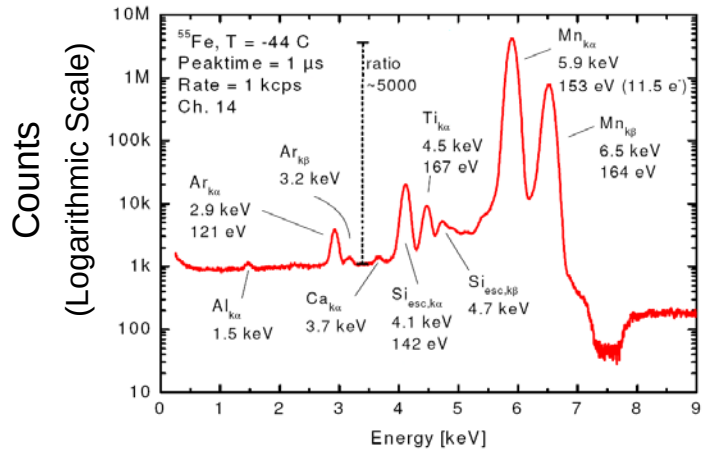


^{55}Fe Energy Spectra Comparison

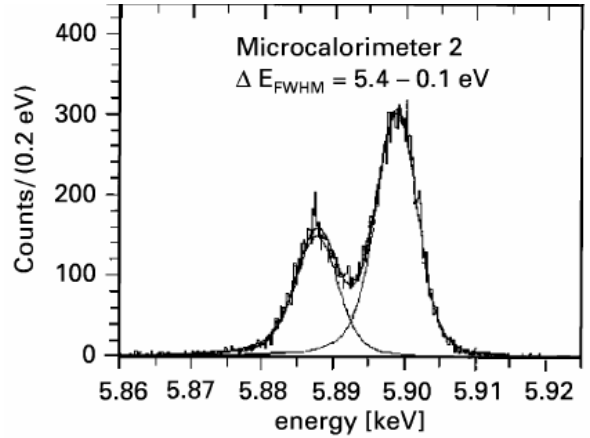
Anode Signal Amplitude →



Proportional Counter



Silicon Drift Detector



Microcalorimeter

Spiro et al, NIM A461 (2001) 304-310

Diamond Detectors for Synchrotron Radiation

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

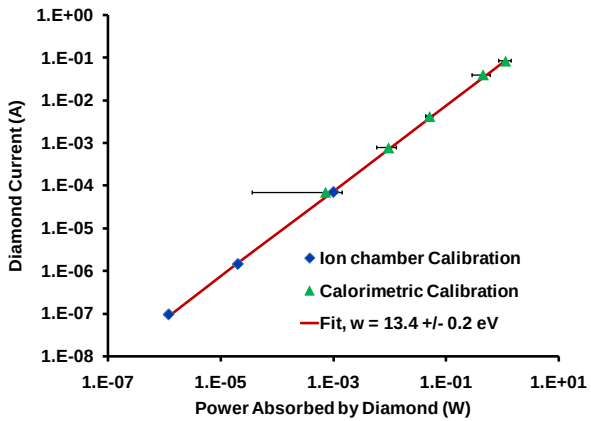
- Why Diamond?
  - High **thermal** conductivity and low coeff^{t} of thermal exp^{n} : can tolerate heat
  - High **transmission** for manageable thicknesses; vacuum-compatible, compact
  - Wide band **gap**: can operate in the light at room temp. with no noise penalty
  - High **speed** capability (compared to a gas-filled ion chamber)

    electrons and holes have saturation $v_d \sim 0.2\ \mu m\ ps^{-1}$

Diamond Detectors for Synchrotron Radiation

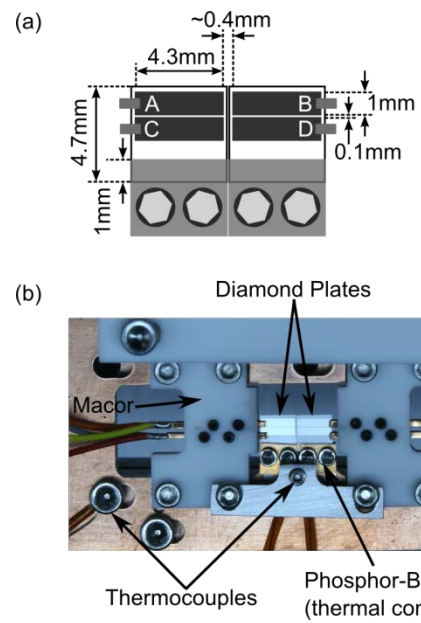
Calibrated X-ray flux monitors

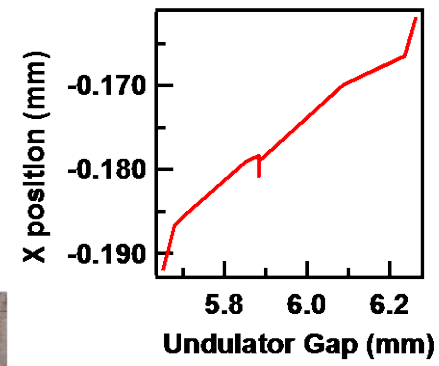
- Linear over 12 orders of magnitude



Diamond Beam Position Monitors

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

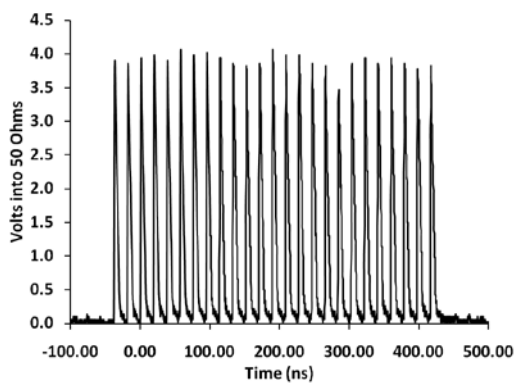




Custom 4-channel current amplifier (not shown) - GDG

Fast Timing

- Resolving time structure of storage ring current



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

$$d_x = G_x \cdot \frac{(A+C)-(B+D)}{A+B+C+D}$$

$$d_y = G_y \cdot \frac{(A+B)-(C+D)}{A+B+C+D}$$

Liquid-based Detectors

Liquid Argon (LAr) Time Projection Chamber (TPC) for a Booster Neutrino Experiment (MicroBooNE)

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

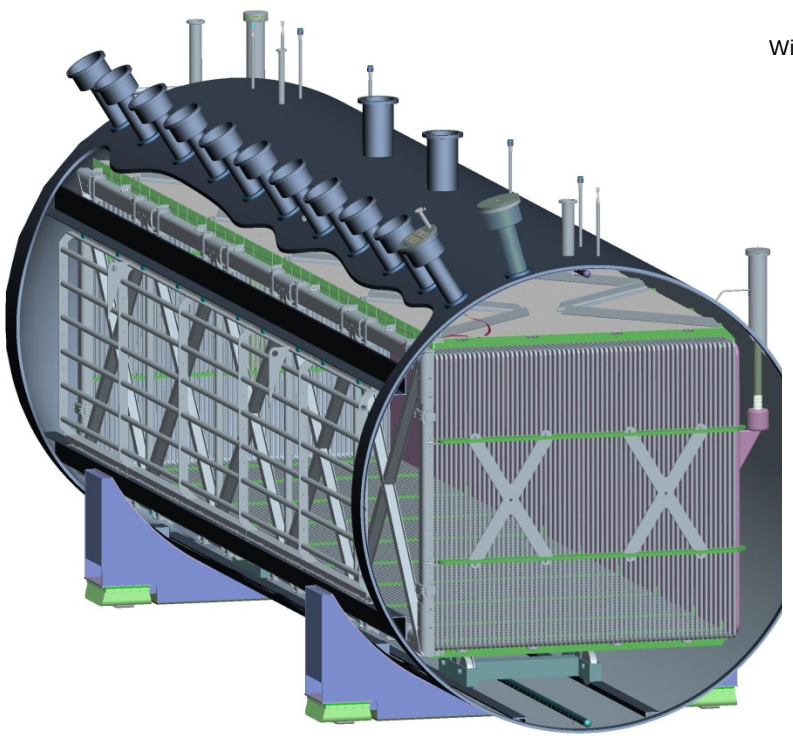
- The experiment will measure low energy neutrino cross sections and investigate the low energy excess events observed by the MiniBooNE experiment.
- The detector serves as the necessary next step in a phased program towards the construction of massive kiloton scale LArTPC detectors.
- Detector R&D: LAr TPC for larger scale detectors (DUSEL)
- Builds on our expertise with cold electronics/ASICs

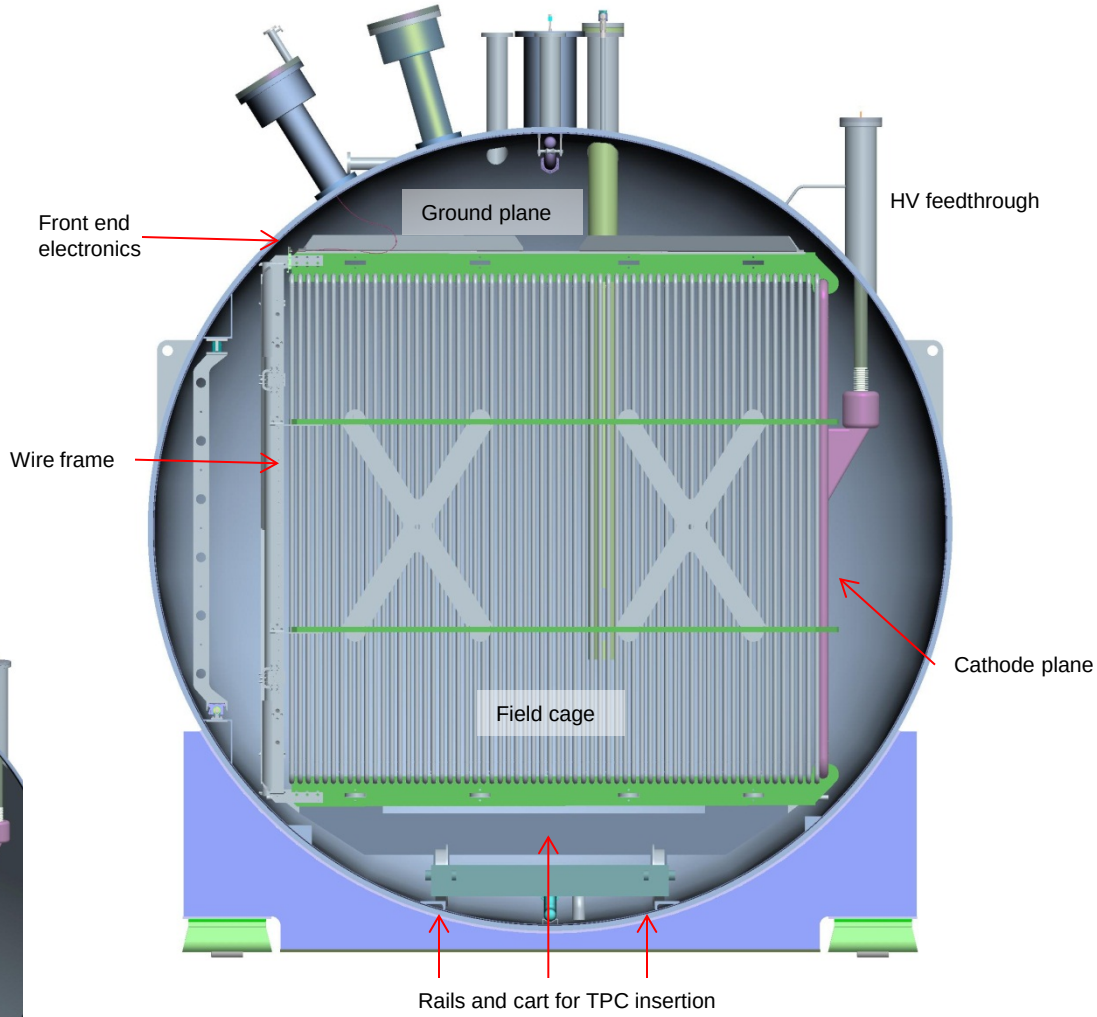
Main Components in the MicroBooNE TPC

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

Number of Wires:
- Y: 3456
- U, V: 2400 each
- Total: 8256

Weight: ~ 5 tons
~ 100 tons LAr active volume



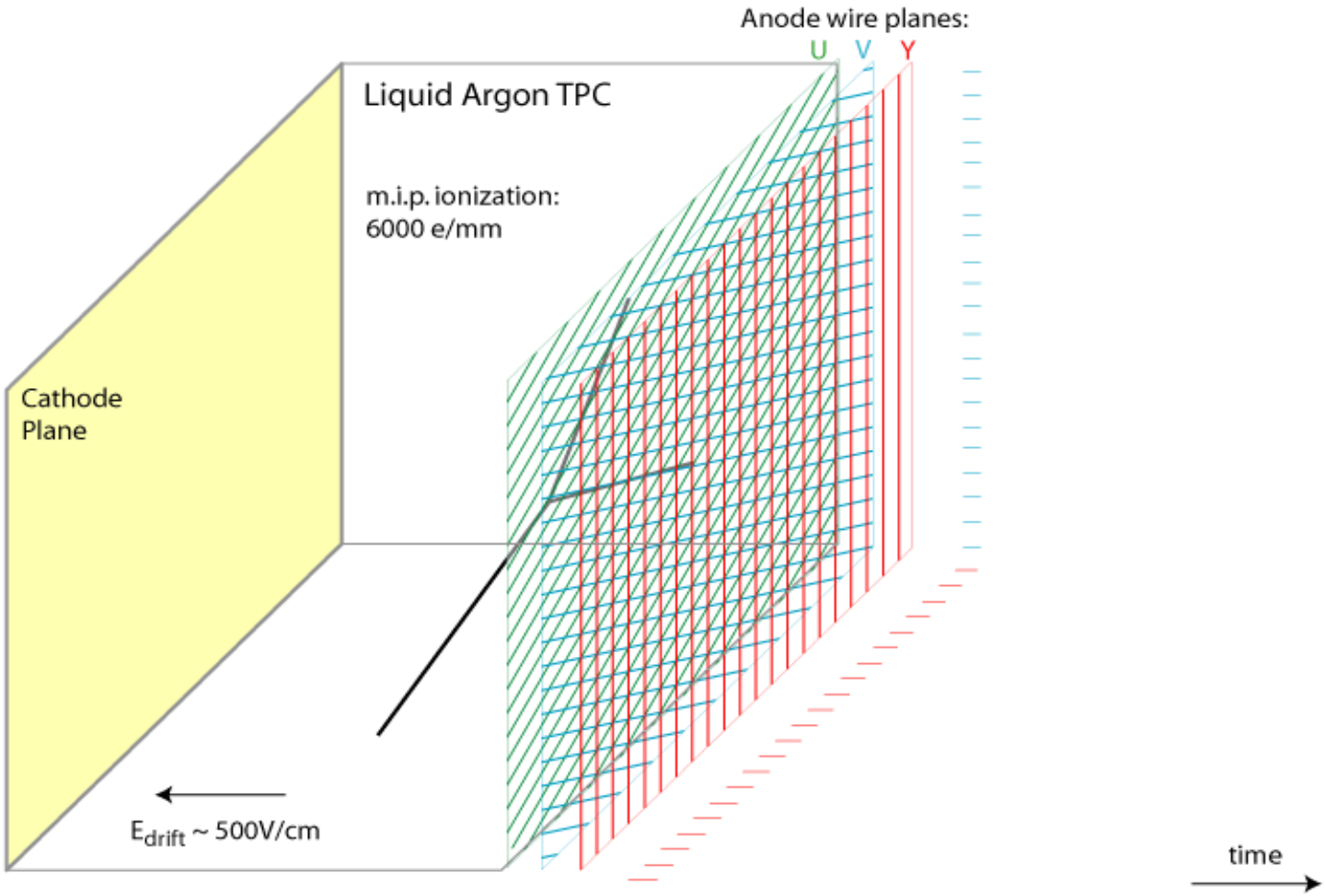


Large Volume LAr TPC

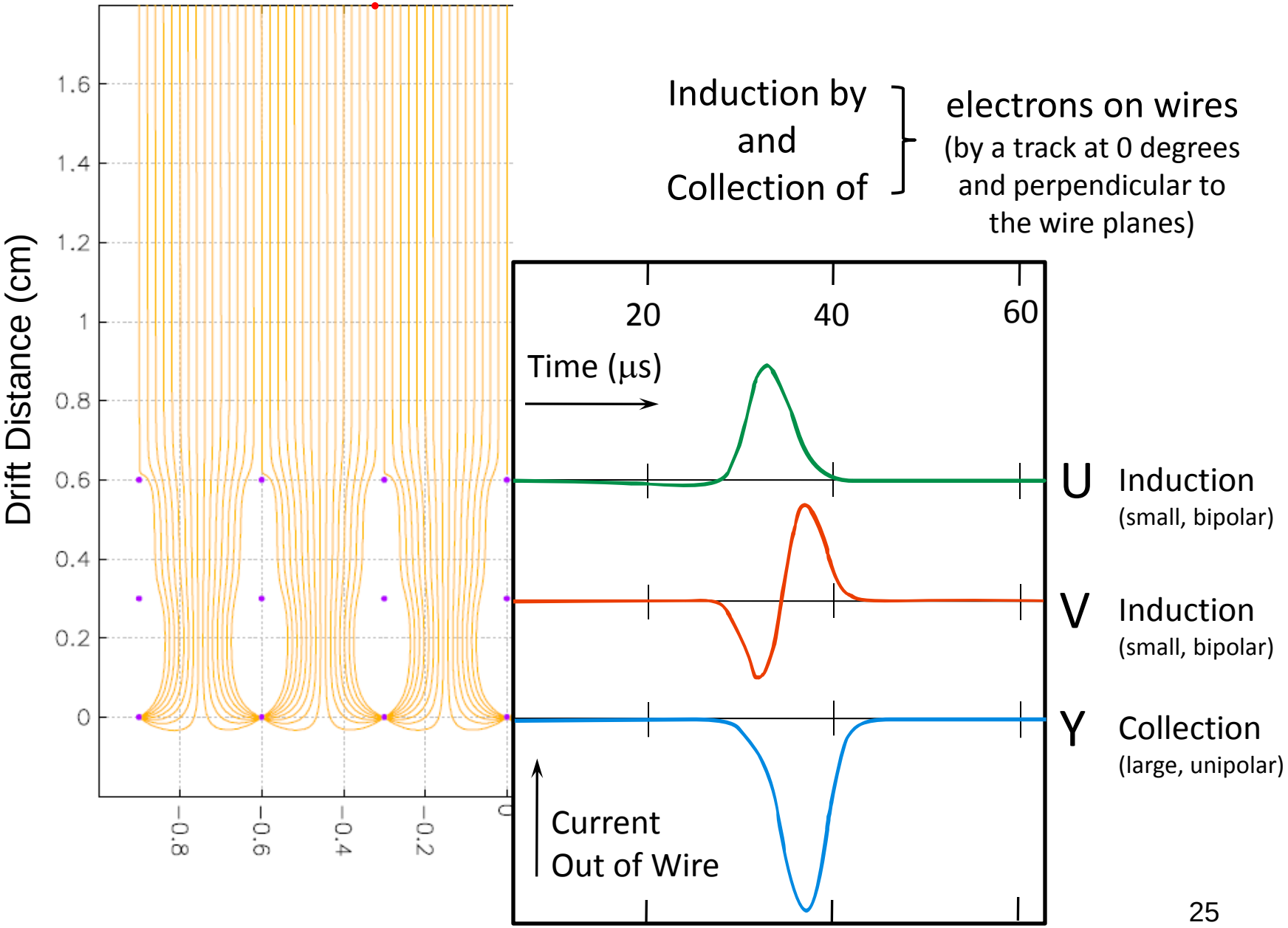
- Full 3D event reconstruction, sub-mm position resolution
- dE/dx for particle ID, e/γ separation >90%
- Low energy threshold particle energies →1 - 2 MeV
- Scalable to multi-kiloton size

if

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



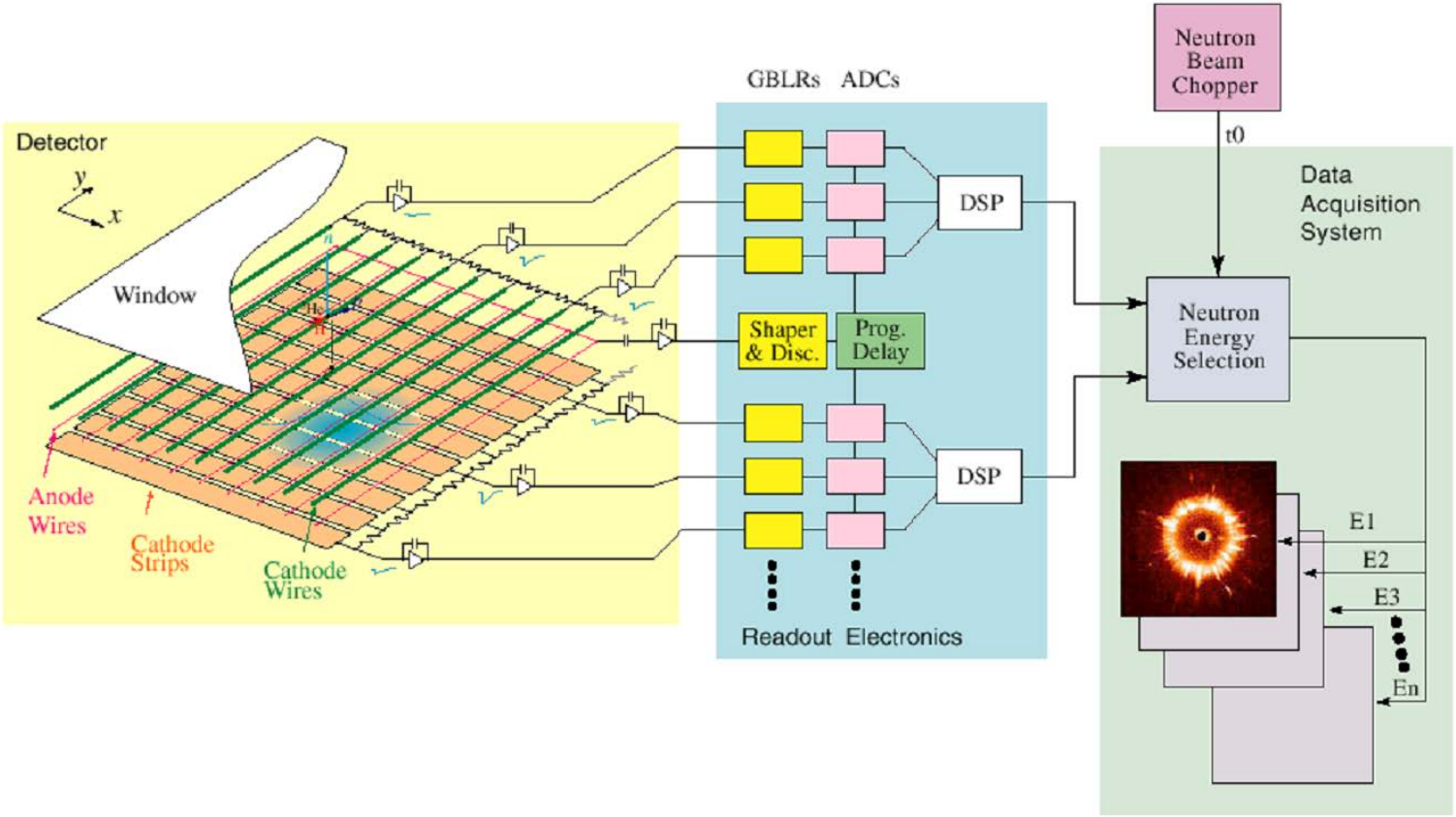
LAr TPC - Charge Signal Formation



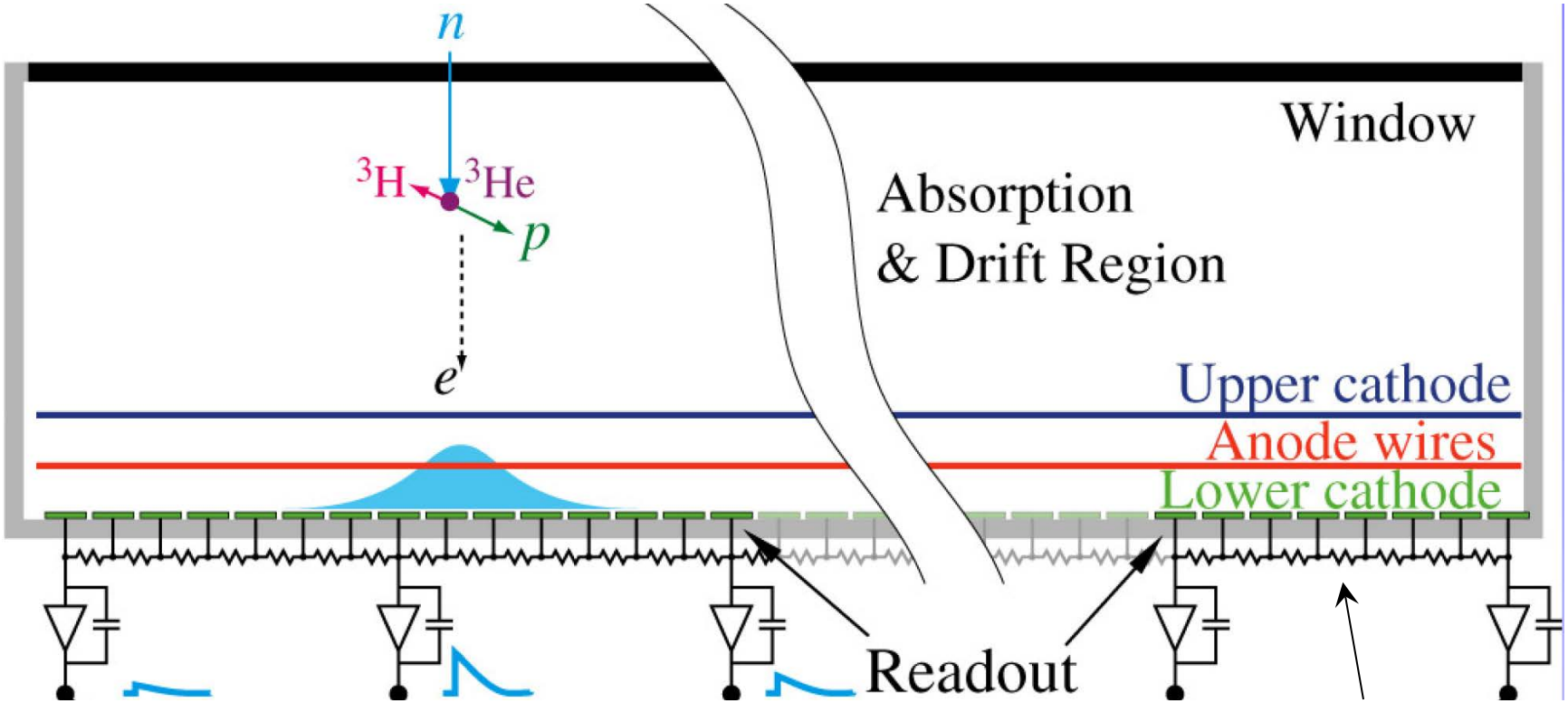
Gas-based Detectors

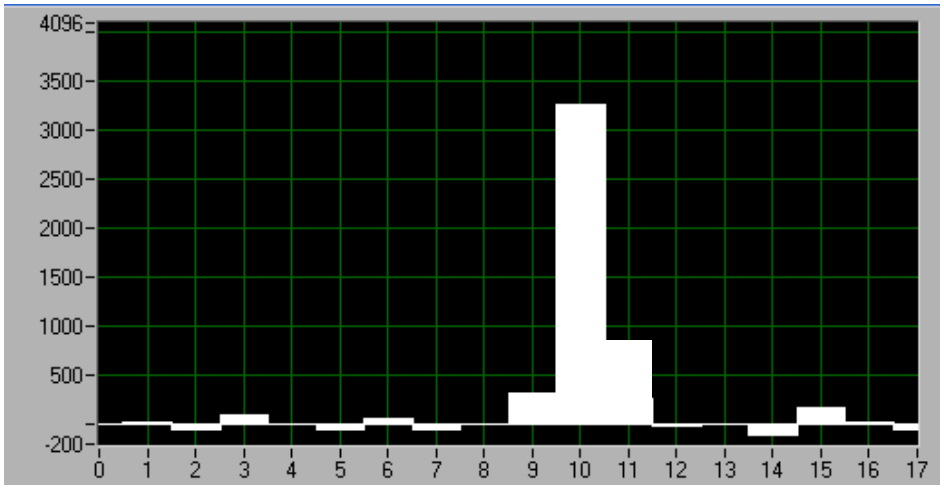
Multi-Node Centroid Readout

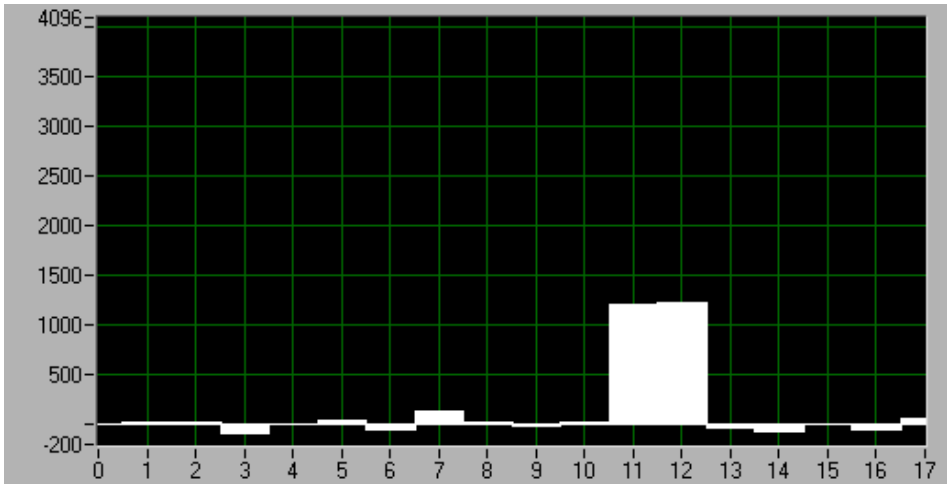
Block diagram for multi-wire neutron detector and data acquisition at a spallation source



Multi-node Charge Division: node samples vs position







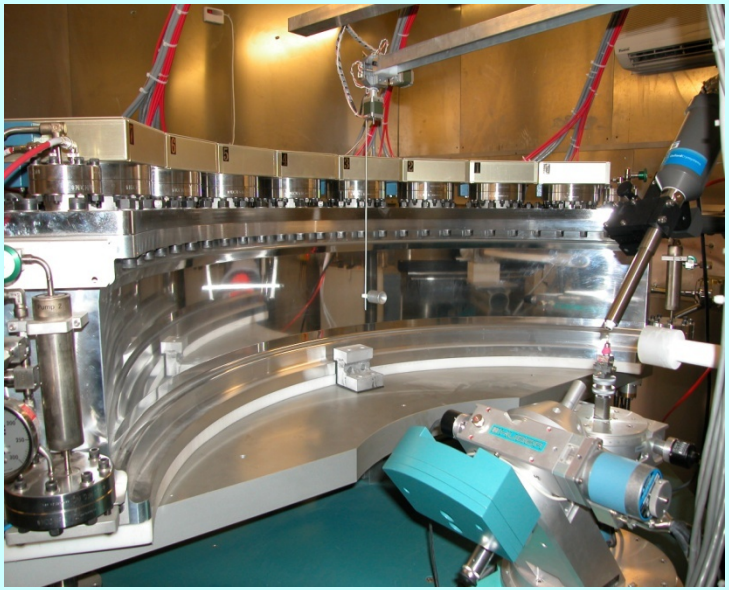
Thermal Neutron Detectors Based on ^3He:

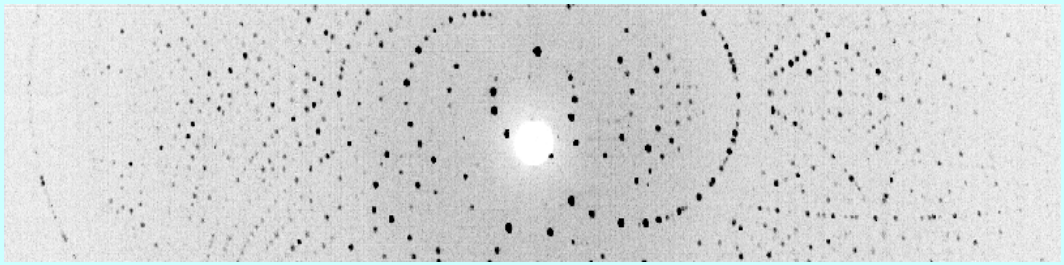
120º curved detector (~ ¼ million resolution elements)

LANSCE, Los Alamos National Laboratory

Installation: January 2002

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



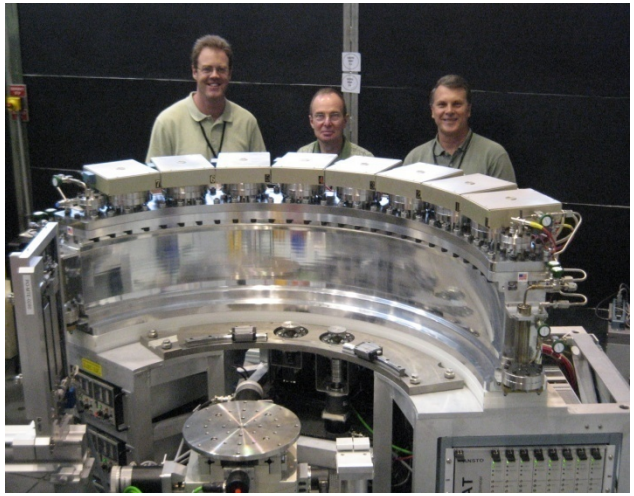


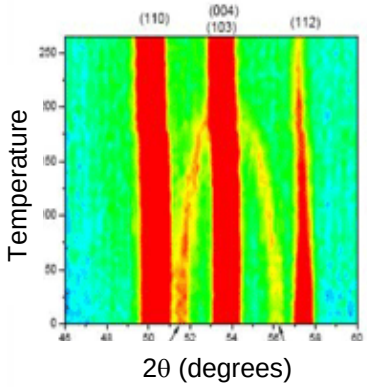
Typical diffraction spectrum from protein crystal – detector's novel internal electrode design results in continuous coverage over the 1.5m × 20cm area

ANSTO, Australia

Installation: January 2007

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





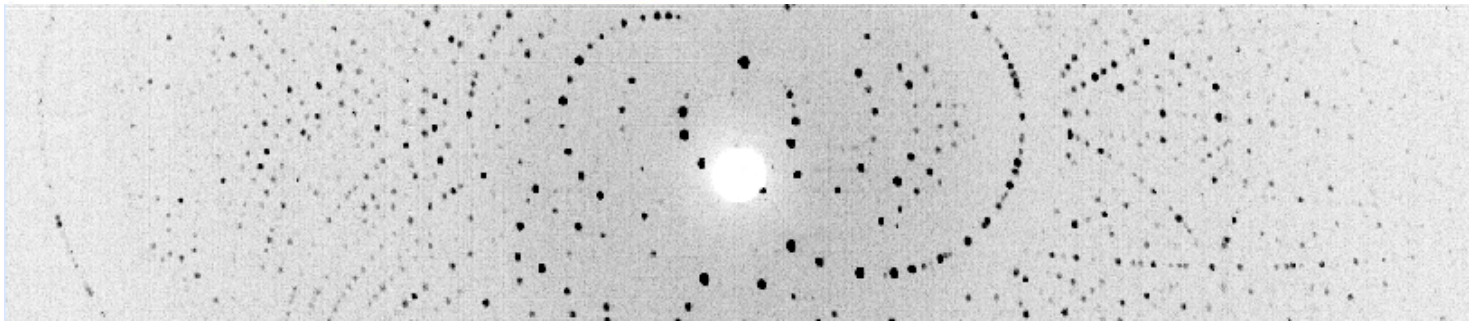
First user of HIPD – magnetic powder diffraction of Pr, Lu, Mn,Ge alloy, showing structural change as a function of temperature

Journal Covers from Research at LANSCE's PCS

About the 120° detector:

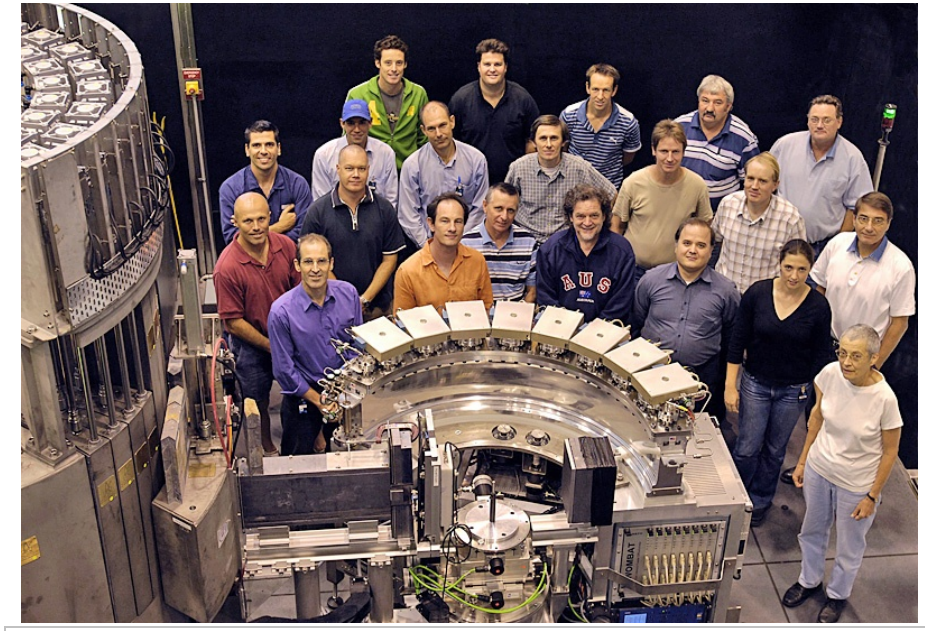
- **Uninterrupted operation since installation in 2002**
- Position res^n ~ 1·2 mm (FWHM)
- Global rate ~ 500kcps
- Sensitive area: 150cm× 20cm
- Radius of curvature: 70cm
- Picture elements: 2× 10^6
- Resolution elements: 250 k
- Low Gas Gain ~ 50
- Absolute position stability (~ 50μm)
- Long term elec. stability (10yrs +)

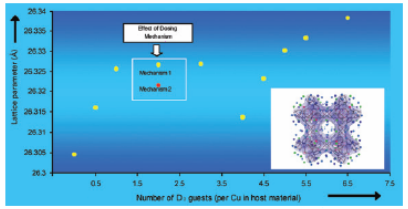
Typical diffraction spectrum from detector system



Wombat Instrument at ANSTO's Opal Reactor

(HIPD: High Intensity Powder Diffractometer)



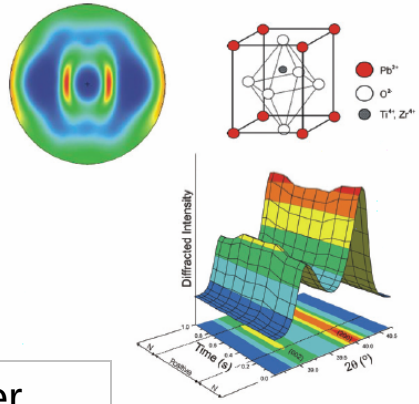


Range of new materials which can be studied.

Case Study 1: *In situ* chemical physics

Recently, a new class of porous materials has been developed in which the structure (and properties) can be changed through the absorption of other molecules, called 'guests'.

The way in which a change is applied can also affect structure. Recent research on a porous framework material indicates a structural change dependant on the rate of guest sorption. Wombat will be able to uncover the mechanisms for such perturbations in structure.



Phase transition in PZN-8.5PT

Case Study 2: Piezoelectric materials

Ceramic lead zirconate titanate (PZT) is a very popular material for electromechanical transducer applications due to its large piezoelectric response and low cost. Devices such as ultrasound generators, hydrophones, high-voltage generators, impact sensors, and micro-positioning systems are just a few which take advantage of the exceptional properties of PZT. There are a whole range of piezoelectric materials based on the PZT structure, with the potential for applications to be explored.

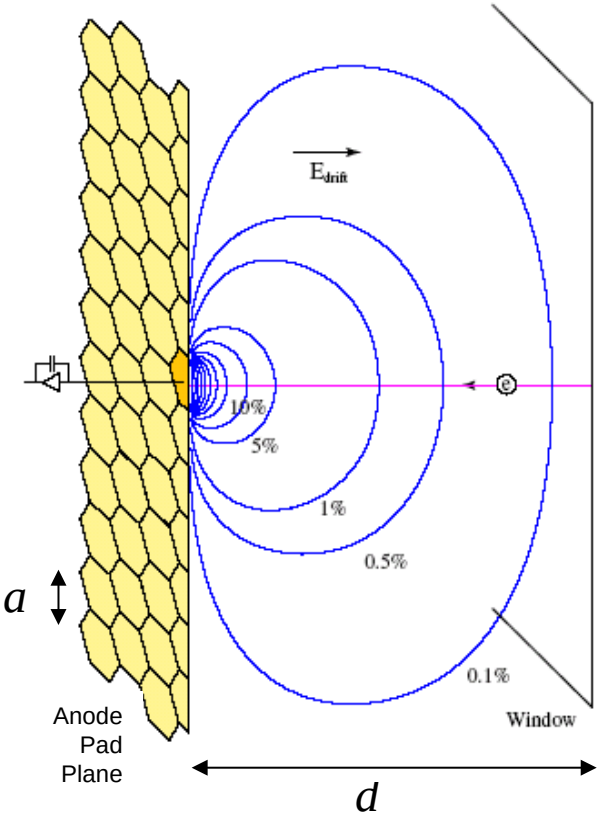
Wombat will be used to perform rapid stroboscopic measurements to determine how these materials change structure with the application of an electric field, combined with longer duration measurements to study fatiguing effects over time which can lead to device failure.

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

- 120° detector installed in 2007
- **Has operated very stably, without interruption, for these last 5 years**
- **Prolific publication output**

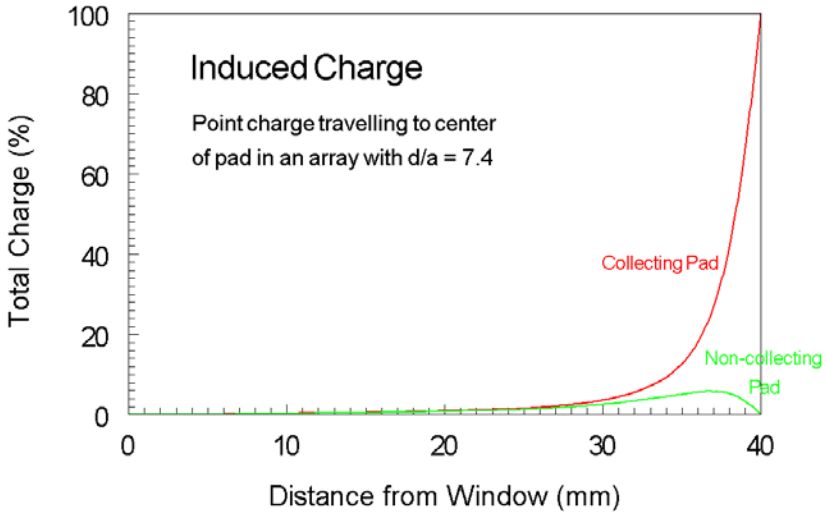
Two-Dimensional, Pixel Detector for Neutrons

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



Weighting potentials for a single pad in a parallel plate geometry

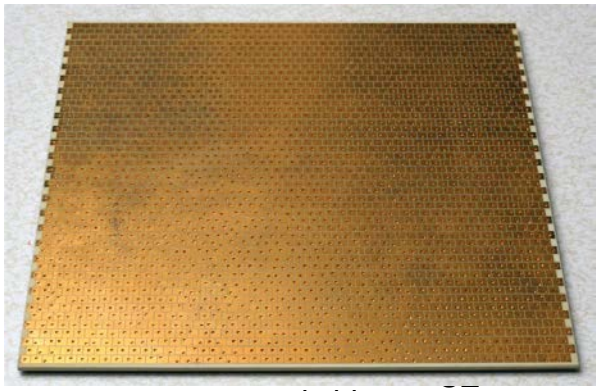
Neutrons



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

64 channel
2mW ch^{-1}

ASIC side
(Application Specific Integrated Circuit)

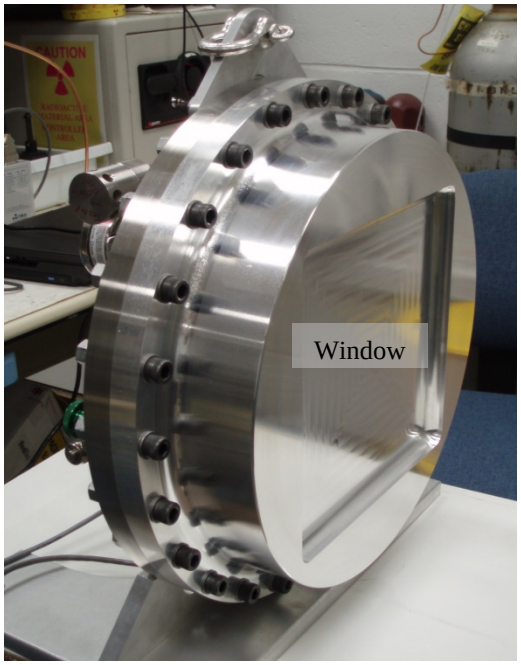


Pad side

Thermal Neutron Response, Pixel Detector

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

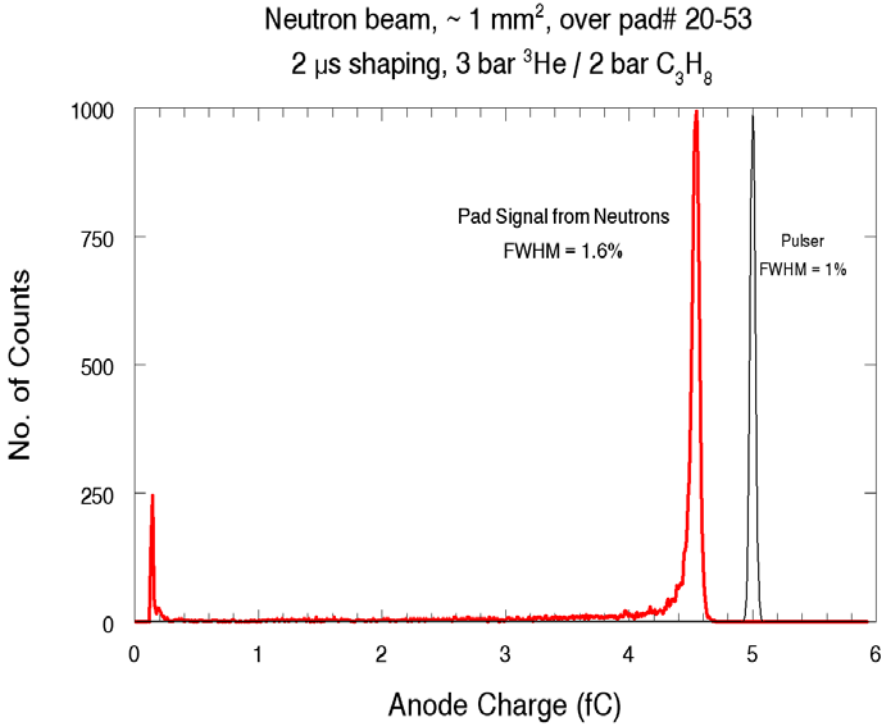
(~25- 30k electrons, or ~ 5 fC)

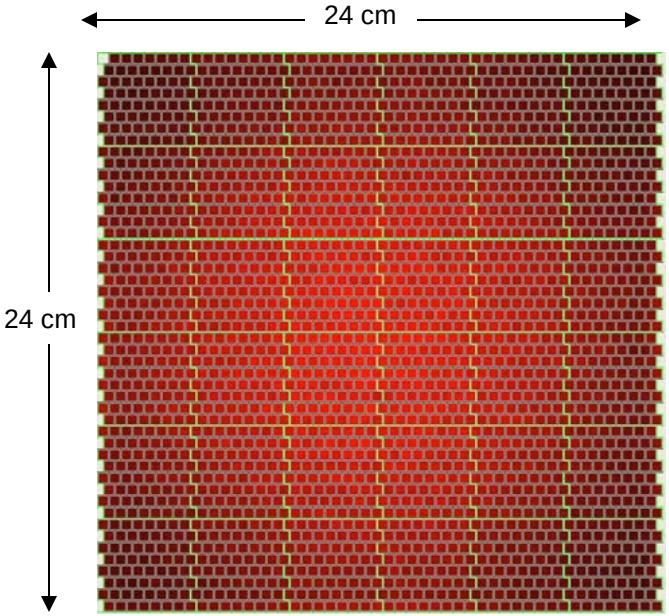


Completely assembled detector

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

Pulse height response from one pad





Intensity response illumination with p source of neutron: Boundaries in grec… represent pads read out by one 64 channel ASIC - there are 36 ASICs in total, 2304 pads.

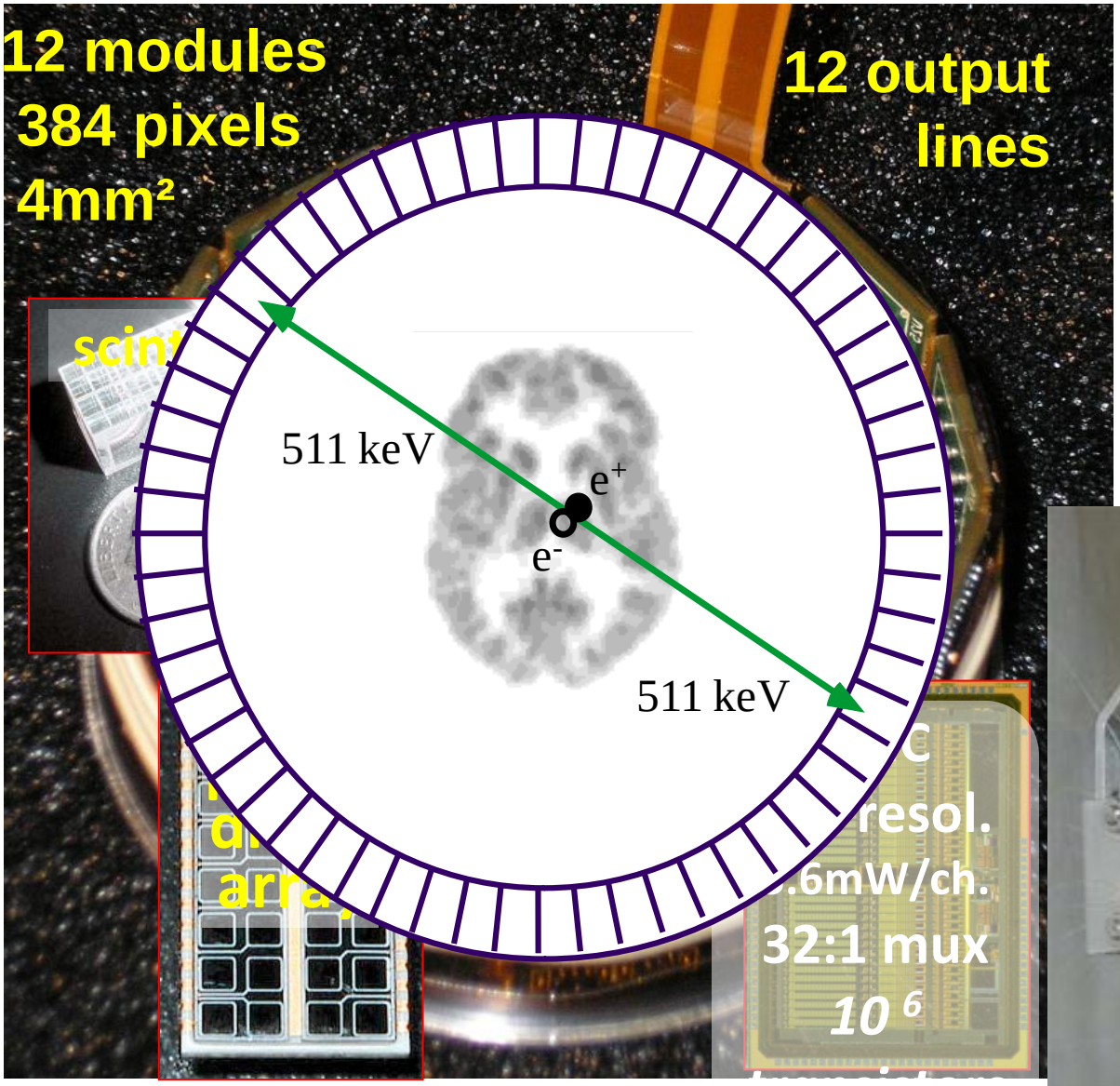
Presently preparing a contract with ANSTO for a 1m × 1m detector based on this pad technology for SANS. Value ~ $1.8M (Work for Others)

Instrumentation Radiation Detector Development

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

Detectors for Medical Applications

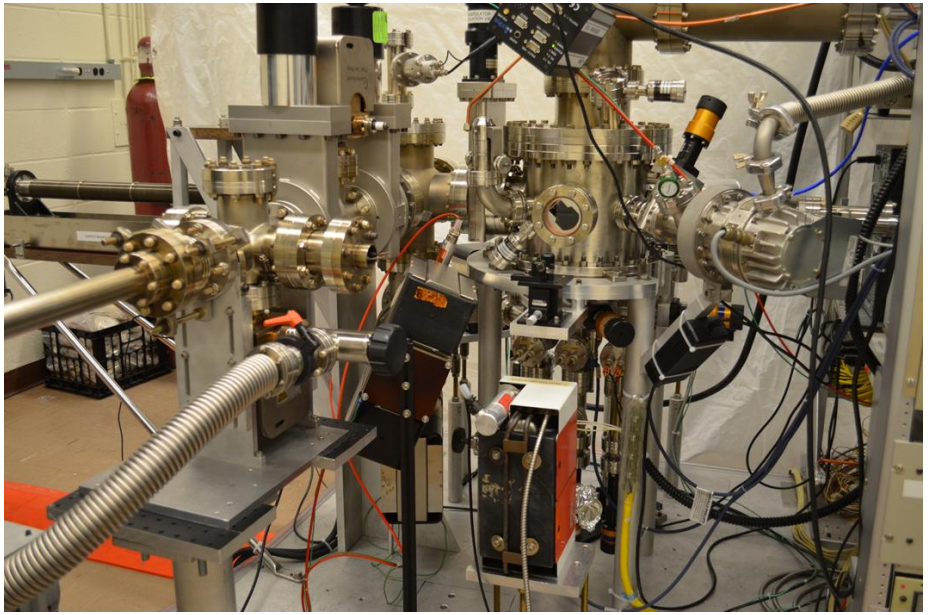
Small Animal PET (RatCAP) and MRI (at 9T)



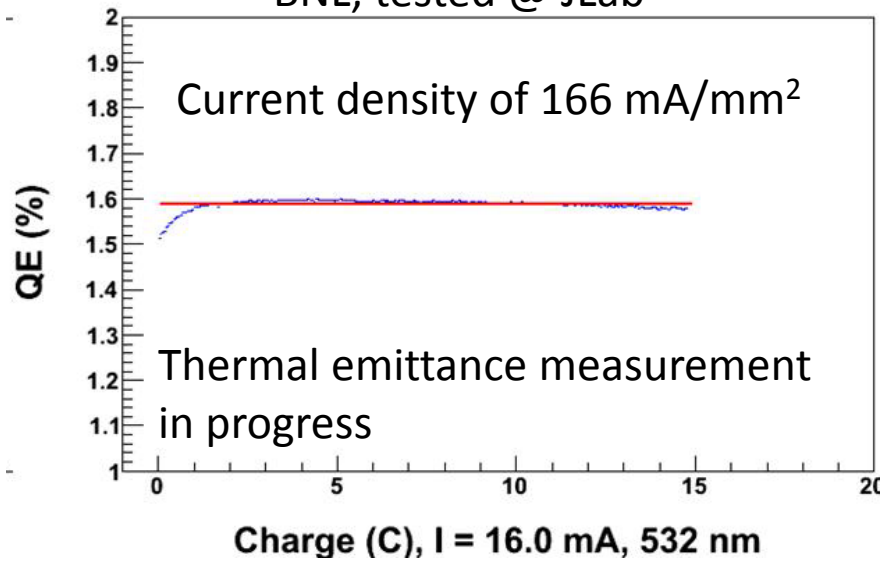
Laser/photocathode Studies

Need for *high QE-long life-low thermal emittance* cathode for ERL, FEL applications recognized in ~2001. Research started soon after …

Cathode Fabrication for ERL:

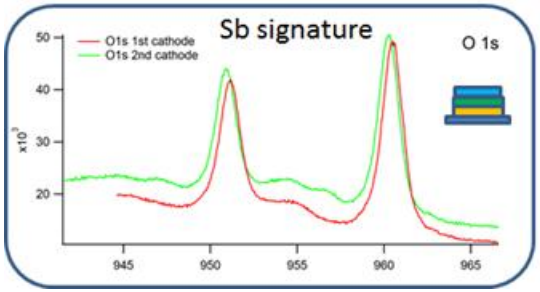


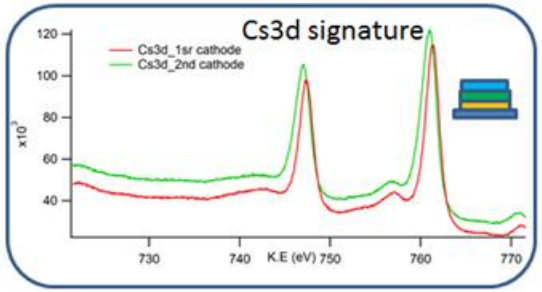
Recent Result with Cathode Fabricated @ BNL, tested @ JLab

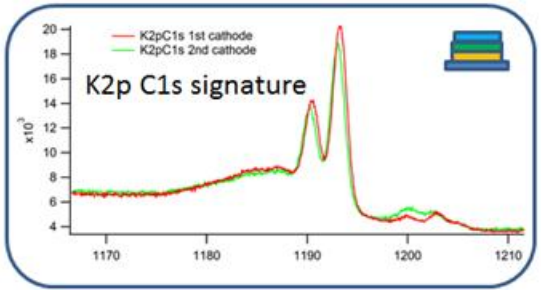


Unique project to understand basic science of the evolution of cathode fabrication at NSLS, CFN, IO

Cathode evolution measured with XPS in CFN







Wrap-up

Current and Future R&D and Projects

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

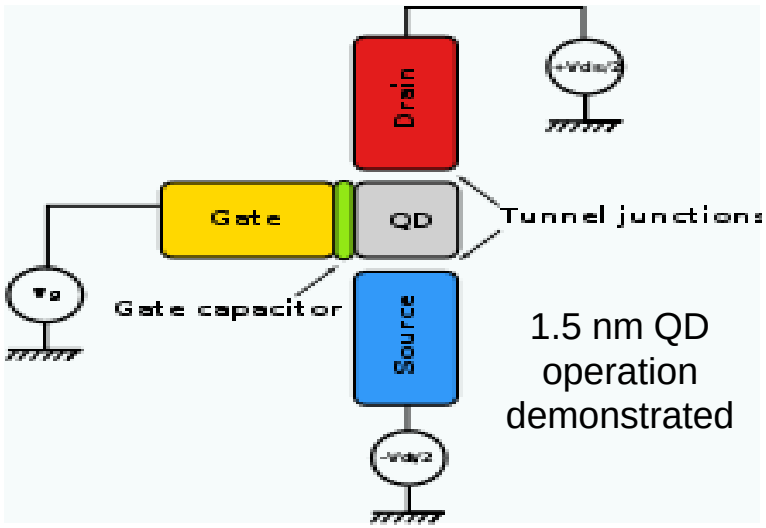
Looking far ahead, ?? years

Two dominant research activities on “exotic” transistors, that promise higher speed and higher circuit density

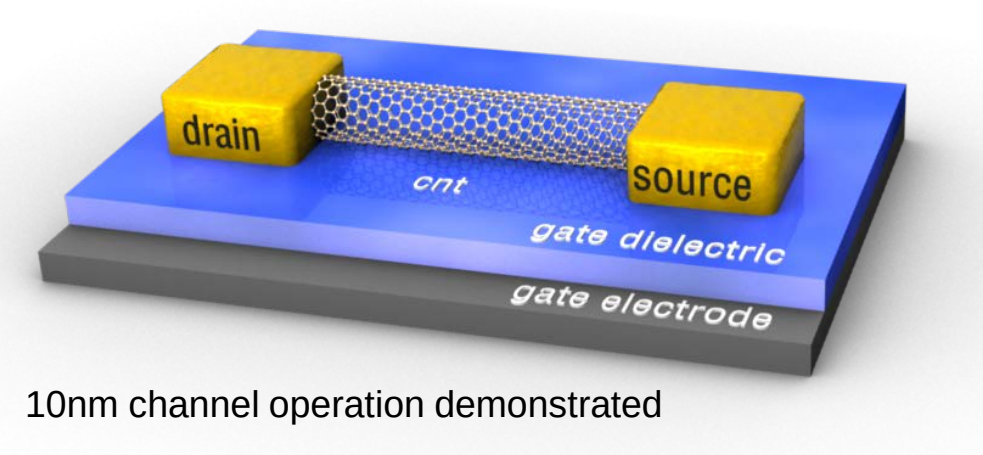
1. Single electron transistor:

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

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



1.5 nm QD operation demonstrated



10nm channel operation demonstrated

2. Carbon Nanotube Transistor:

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

Uniformity and reproducibility have not yet reached levels required by microelectronics

Acknowledgements to the excellent team we have in the Division, and to our collaborators

Back-up

Examples of "Return on Investment"

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

- *Liquid Argon Calorimetry (1973)*
  Has become a high resolution calorimetry technique for HEP. Used in many experiments at CERN, DESY, SLAC. This development significantly increased BNL role in LHC/ATLAS, and will lead to a role in future neutrino detectors.
- *Low Noise Techniques (1975)*
  Fundamental studies for optimized front-end electronics; circuit techniques now utilized in all ASICs for detectors; numerous ASICs for most science areas.
- *Optical Metrology (1983)*
  Critical, non-contact, measurement techniques for precision aspheric optics for NSLS
- *Silicon Drift Detectors (1983)*
  Seen as one of most dramatic developments in Si detectors; immense impact in X-ray science, HEP/ NP
- *Interpolating Cathode Strip Chambers, CSCs (1984)*
  Developed for multi-wire x-ray detectors, resulted in increased BNL role in PHENIX and ATLAS
- *Micro/Nanofabrication (1990)*
  MEMS and EM development, expertise used in clean room design for CFN
- *Photocathodes (1990)*
  The highest current electron sources for accelerator research and FELs
- *Microelectronics (1990-2010) – a critical enabling technology for many programs*
  Examples of detectors not possible without ASICs: Si dets. for NSLS, LEGS TPC, RatCAP, new neutron dets., CZT detectors, Proxiscan, LAr neutrino detectors, …
- *Beam Diagnostics (2006-):*
  Novel beam profile measurements for RHIC and other accelerator facilities

Ingredients for success: Collaboration with lead scientists

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

Examples of successful collaborations:

- *Development of RatCAP*

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

  Physics Dept: Francesco Lanni, David Lissauer, Vinnie Polychronakos + 11 Instr. staff
- *Advanced X-ray detection techniques*

  NSLS Dept: Peter Siddons + 11 Instr.
- *Optical metrology of grazing incidence mirrors*

  NSLS Dept: Beamline scientists + 2 Instr.
- *X-ray detectors for soft x-ray microscopy*

  NSLS Dept / SBU/ANL: Chris Jacobsen + 9 Instr.
- *Position-sensitive thermal neutron detectors for homeland security*

  NNS Dept: Peter Vanier + about 6 Instr. personnel + microelectronics
- *LSST focal plane sensors:*

  Physics Dept: Morgan May (Sam Aronson) + 7 Instr.
- *DOE's OBER: neutron detectors for protein crystallography*

  LANL: Benno Schoenborn, Paul Langan + 9 Instr.
- *DOE's BES: neutron detectors for SNS*

  ORNL/SNS: 6 Instr.
- *LBNE/μBoone Lar neutrino detectors*

  Physics Dept, Columbia, Yale, FNAL + 5 Instr.

Some more examples:

SDL/ATF: Ilan Ben-Zvi. Beam Diagnostics, RHIC: Dejan Trbojevic. CRADAs: Symbol, eV Products. Photo-injectors: DESY/JLAB