Instrumentation Division Report

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Presentation to the DOE HEP Program Review

APRIL 22-23, 2004

Outline

- **Core Technologies and Facilities**
- **Key Accomplishments and R&D for future HEP Program**

Instrumentation Division

Mission:

"To develop state-of-the-art instrumentation required for experimental research programs at BNL.
To provide limited production quantities of such instrumentation for BNL-related experiments."

Core technologies:

- **Semiconductor detectors** (pixel-, drift-, photo sensors);
- **Gas and noble liquid detectors**;
- **Microelectronics** (low noise analog/digital);
- **Lasers and Optics** (ultra-short photon & electron bunches, photocathodes, optical metrology);
- **Micro/nano Fabrication** (sensors, microstructures, e-beam lithography).

Staff:

44 Total (lost 3 in Oct. 2003)
24 Scientists & Professionals
21 Technical & Administrative

Publications in FY 02/03

All Programs: 43

Core Competencies and Program Areas Served

		Nuclear Physics	H. E. Physics	Accelerator Dev.	Chemistry	Material Science	Biology & Medicine	EENS	Industry Collab.
Semiconductor, Gas & Liquid Detectors	X-ray, gamma-ray Detectors (1D, 2D)					✓	✓	✓	
	High Resolution Neutron Detectors				✓		✓	✓	
	Silicon (strip-, pad-, drift-) Detectors	✓	✓	✓	✓	✓	✓	✓	✓
	Cryogenic Detectors	✓	✓						
	Gas Detectors for High Particle Rates and Multiplicities (Cathode Pad/Strip Chambers)	✓	✓	✓	✓	✓	✓		
Micro-electronics	Monolithic and Hybrid Low Noise Amplifiers	✓	✓	✓	✓	✓	✓	✓	✓
	Data Acquisition Electronics	✓	✓		✓	✓	✓	✓	✓
	Fast Noble Liquid Calorimetry Readout	✓	✓						
Lasers, Optics & Microfabrication	Optics Metrology		✓		✓	✓	✓	✓	✓
	Laser and Optics in New Accelerator Concepts: Photocathodes, Fast Pulsed Photocathodes	✓	✓	✓		✓	✓	✓	✓
	Electro-optics and Ultrashort Laser-pulse Techniques (ps — fs → as)	✓	✓	✓		✓			✓
	Micro/nano Fabrication			✓		✓	✓	✓	✓
	Total Effort in FY2003 [%]	35	25		40				

Program 04-08

In support of vital BNL programs:

- RHIC Detector Upgrades (silicon and TPC)
- e-cooler; e-RHIC:
  - *High Current Photocathodes*
- ATLAS Dets., and LHC upgrade
- Si-detectors for Polarimeters
- Si-detectors & microelectronics:
  - *-EXAFS at high photon rates*
  - *-X-ray Microscopy*
  - *-Protein crystallography*
  - *-TEAM*
- LSST
- New small animal PETs, MRI
- Neutron detectors for SNS
- Detectors and Microelectronics for Homeland Security Program

State-of-the-art core technology:

- Fine-grained Si and gas detectors
- Low noise microelectronics from submicron to nanoscale
- Femtosecond, photon and particle beam generation & diagnostics
- Nano-fabrication: pattern generation; deposition/ablation; characterization

Exploration:

- CMOS as direct conversion detectors
- Megapixel matrix on kohm cm Si
- Neutrino (“bubble”) detector
- Femtosecond ~100 eV source

HEP Activities

Projects/Experiments:

- ***LHC**, with Physics Dept.*
  - **ATLAS liquid argon calorimeter**: responsible for ***signal integrity, coherent noise, Faraday cage design from the electrodes → feedthroughs → readout crates;***
  - **ATLAS Cathode Strip Chambers and low noise electronics for muon detection**;
- KOPIO, MECO at AGS: Si-drift photo diode for calorimeter; calorimeter and tracker electronics;

R&D for Future Facilities (LHC Lum. upgrade, LC) and programs:

- ***Si-detector technology*** (the only facility for U.S. HEP program):
  - ***single-sided 2-d strip detectors; radiation hardness techniques***
- ***Microelectronics***, low noise,submicron-to-nanoscale;
- ***Picosec/femtosec beam diagnostics*** for future accelerators.
- ***LSST***
- ***Neutrino Detectors***, new concepts;

Silicon Detector Research

Si Detector Development and Processing at Instrumentation Div.

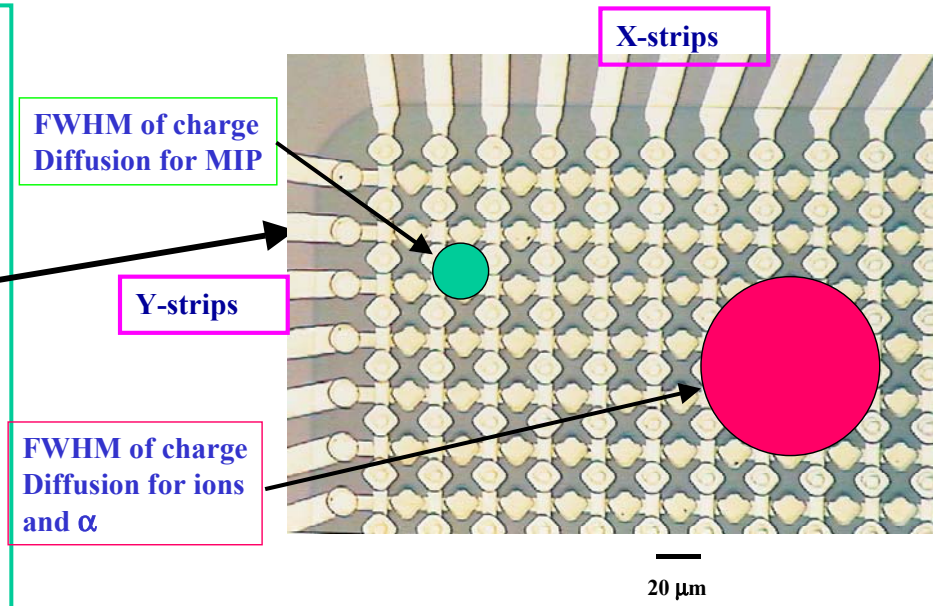
- **Novel Stripixel detectors**

  2d position sensing, 1-sided processing

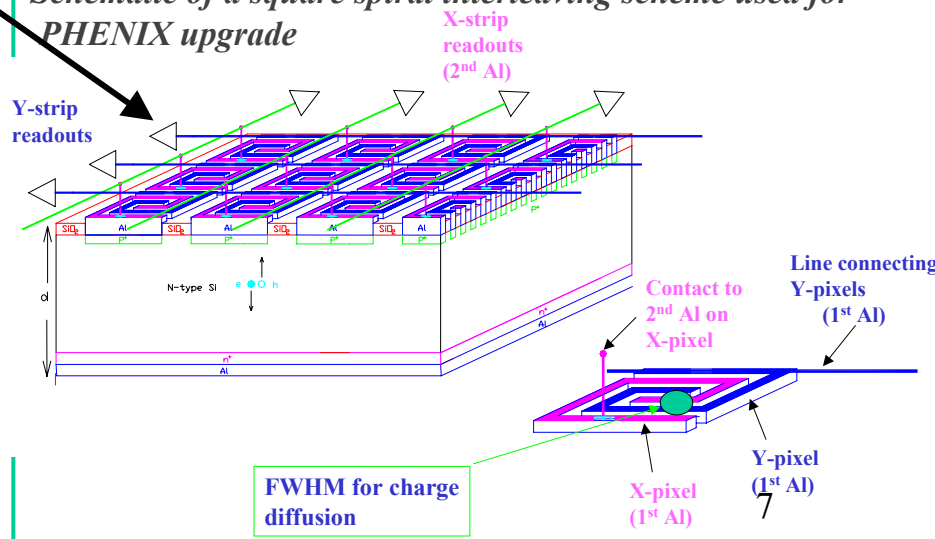
  - Heavy ion detector with submicron 2d position resolution (cell damage studies)
  - PHENIX Upgrade (25 μm position resolution in x and y obtained)
  - US-ATLAS Upgrade (radiation hard ~ ~ 2×10^{15} n/cm^2)

- **Strip detectors**
  - CERN NA60 (segmented, multi-pitch)
  - RHIC PP2PP (large Roman pot)
  - AGS/RHIC Polarimeter (wide strips)
- **Pixel/pad detectors**
  - NSLS: multi-element X-ray detectors
- **Active matrix pixel sensors**
- **Edgeless detectors**
- **Radiation hard/tolerant Si detectors**

  Low resistivity; oxygenated; cryogenic; CZ; Semi-3d; etc.



Schematic of a square spiral interleaving scheme used for PHENIX upgrade



Alternating stripixel detectors (ASD)

Individual pixels are alternately connected by X and Y readout lines (strips)

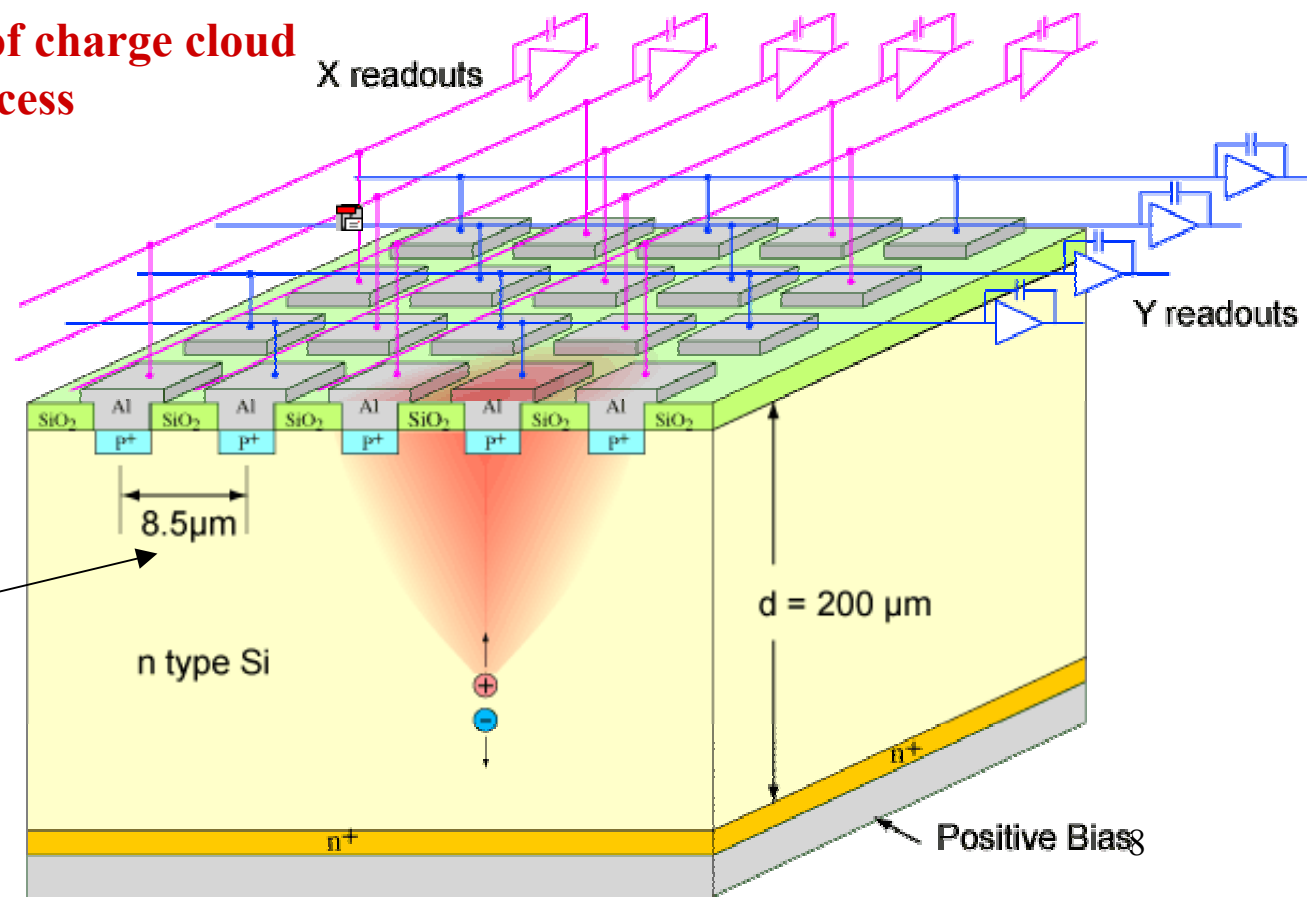
- **Two dimensional position sensitivity is achieved by charge sharing between X and Y pixels**
- **The pixel pitch must not be larger than the size of charge cloud caused by diffusion process**

Interpolating readout:

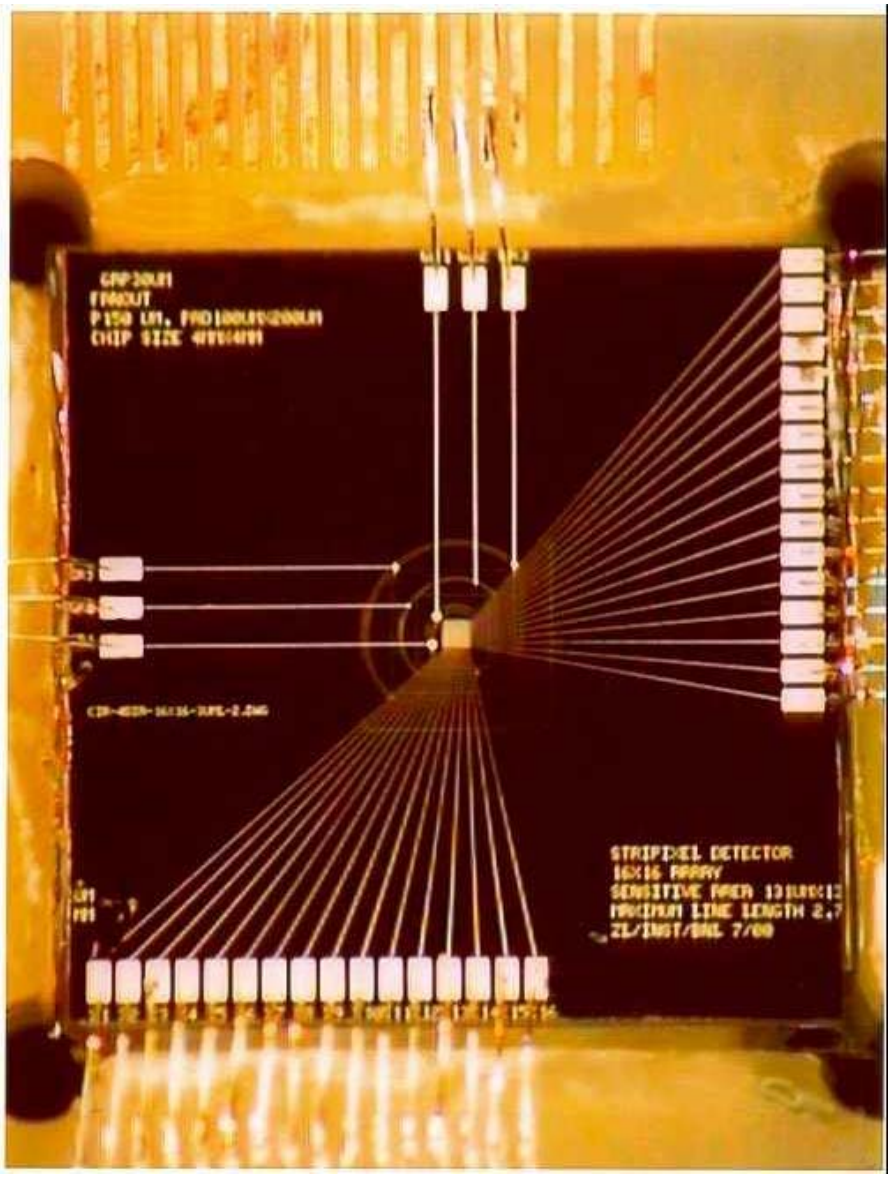
$$\frac{\sigma_x}{w} \approx \frac{2}{S/N}$$

Pixel pitch

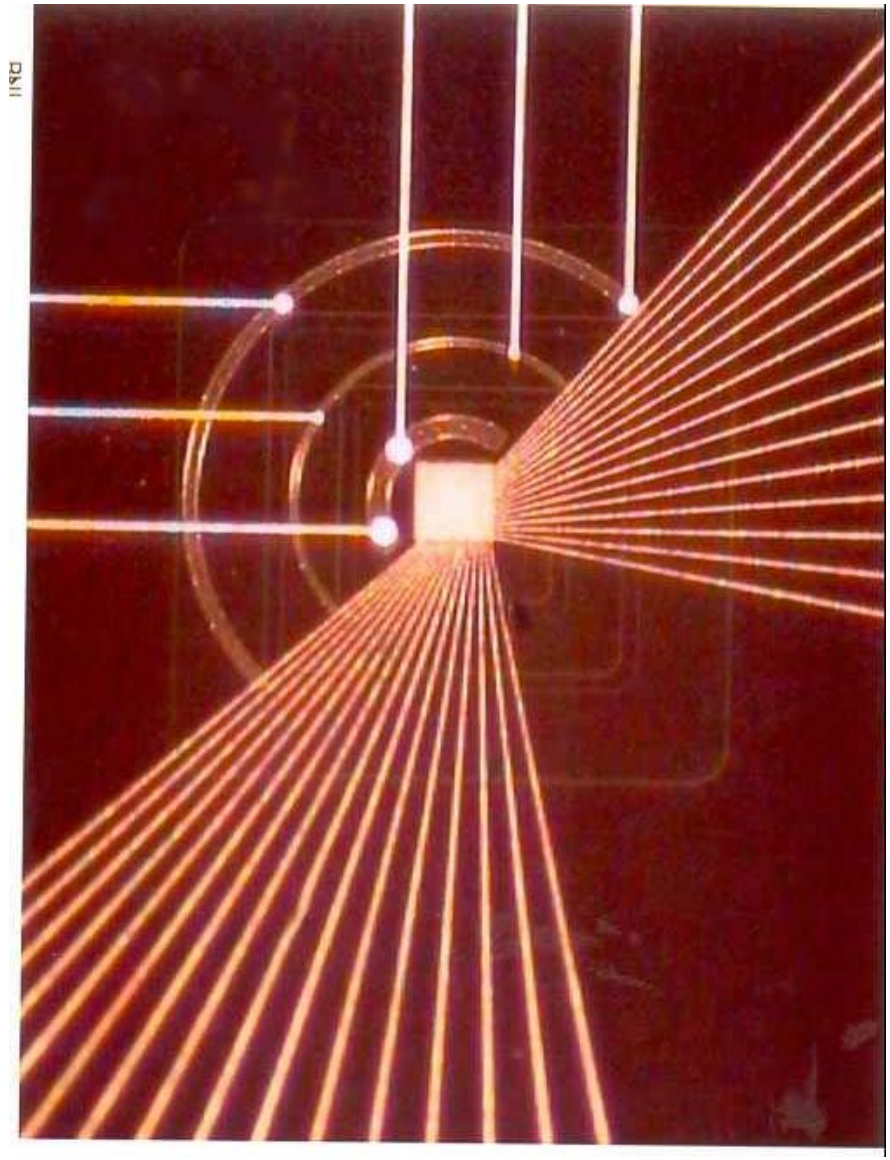
Interpolation factor w/σ_x~10-100



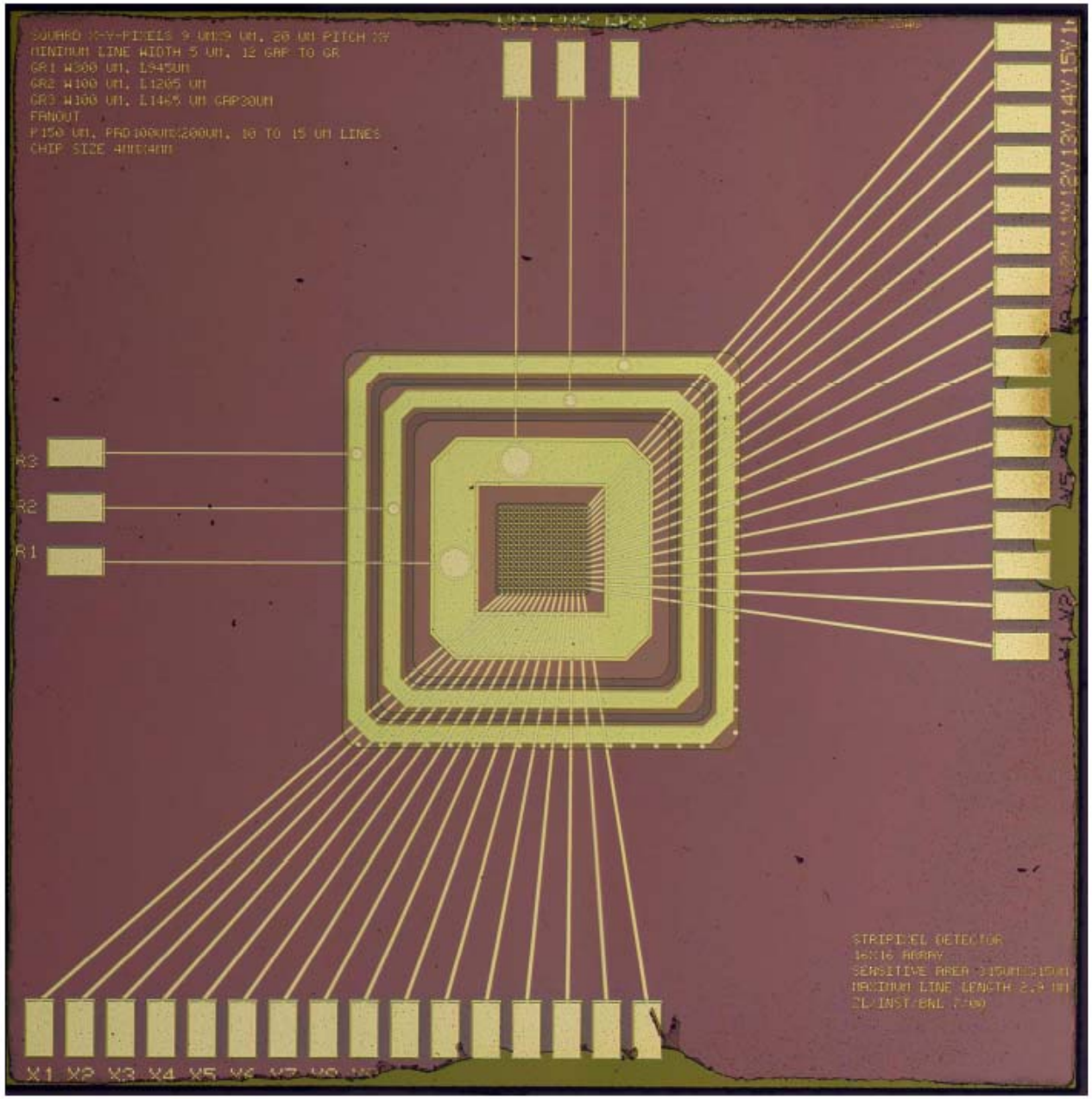
Detector ("Stripixel") Prototype with Connections Fanout



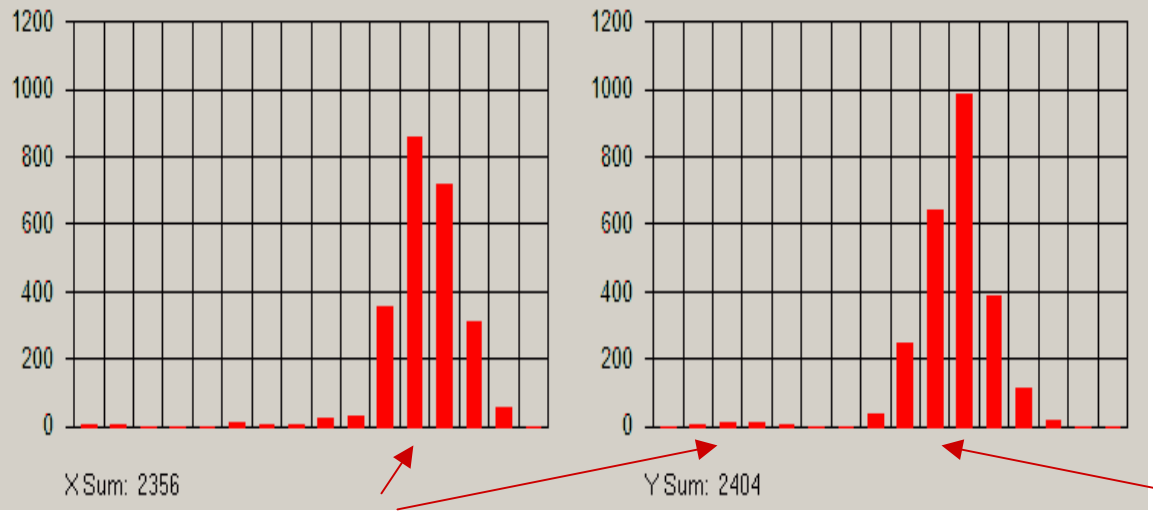
Chip size: 4x4 mm



4 x 4 mm detector chip with with 20 µm readout pitch



Micron Resolution Detector Tests

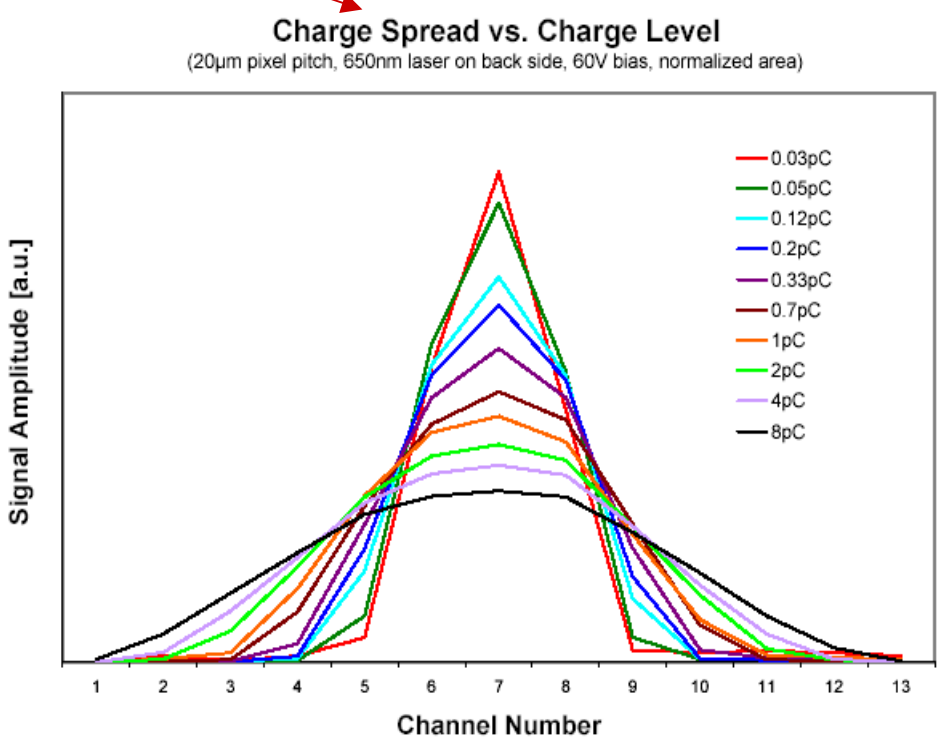


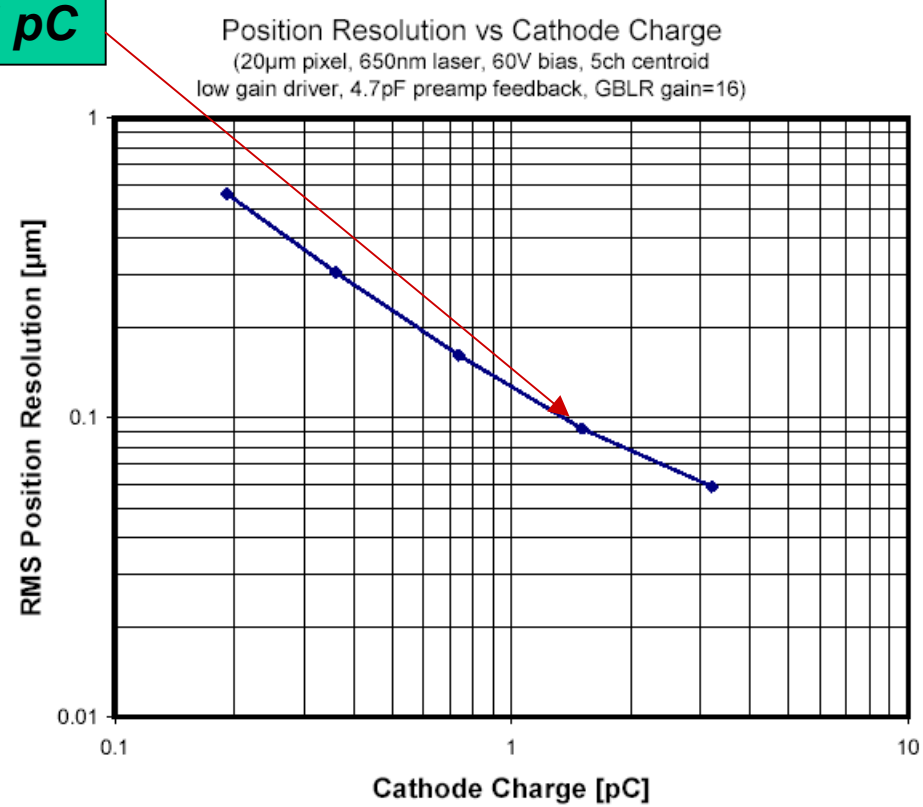
Iron ions 1GeV/nucleon: total charge in 200 μm Si ≈ 2.6 pC

1 bin ≡ 20 μm

Single ion charge samples in x,y

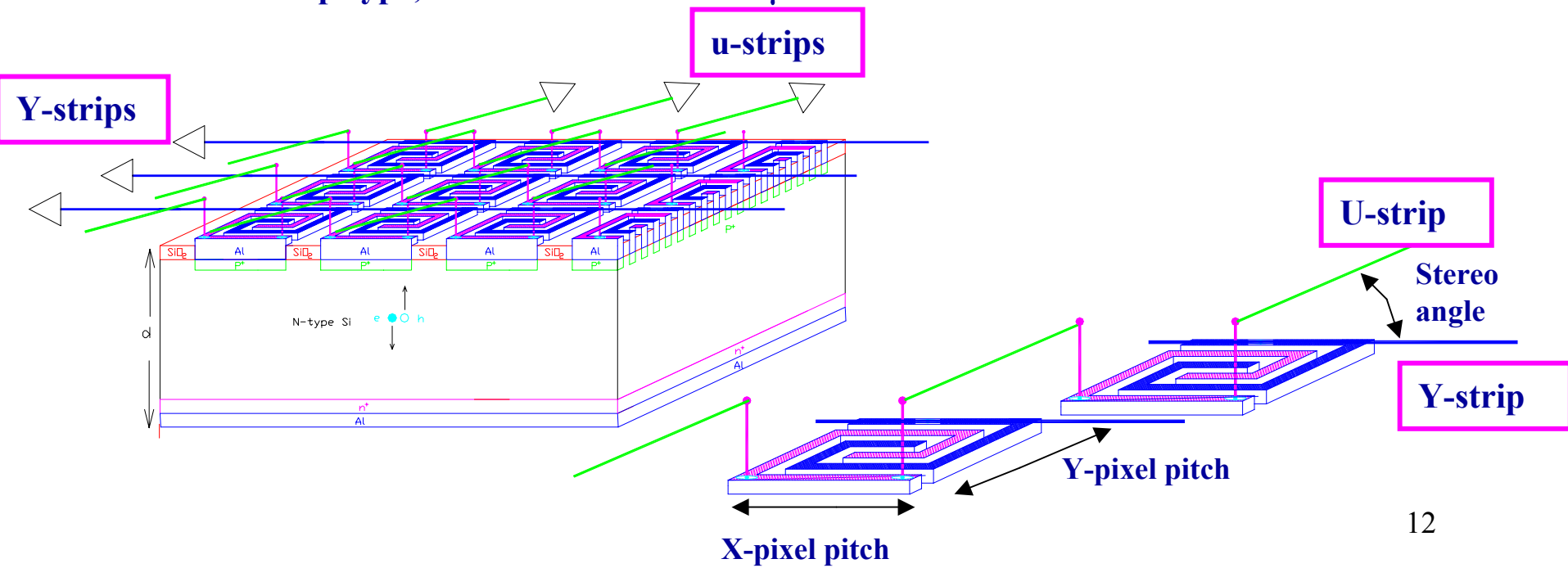
Laser tests: → **$\sigma_{x,y}$~0.1μm at ~1.4 pC**





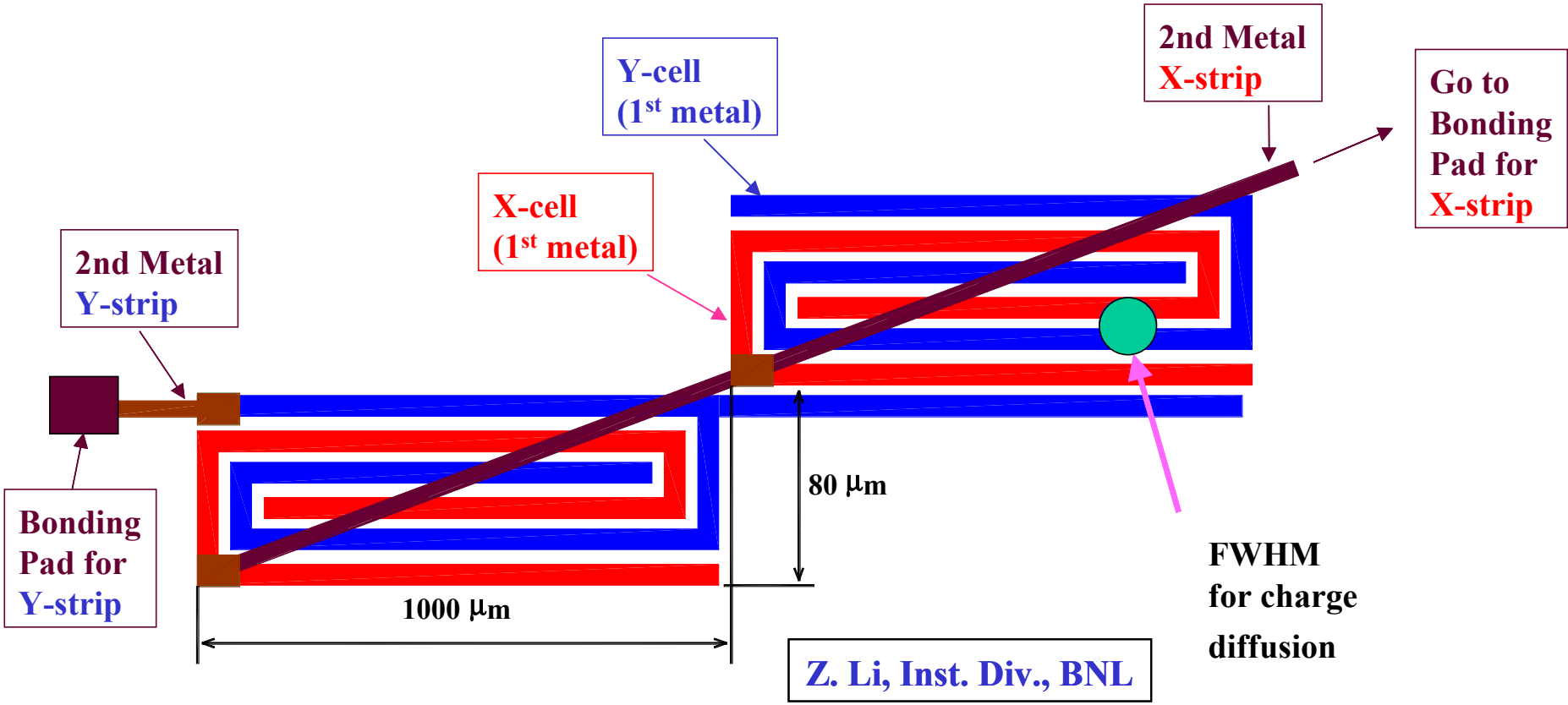
Schematics of Novel Interleaved Stripixel Si Detectors for PHENIX Upgrade and US ATLAS Upgrade

- **PHENIX Upgrade**
  - Pixel pitch: 1 mm (X) and 80 μm (Y)
  - Strip pitch: 80 μm (u) and 80 μm (Y)
  - Stereo angle between u and Y strips: 4.6 º
  - FZ n-type, detector thickness 400 to 500 μm
  - **US-ATLAS Upgrade**
    - Pixel pitch: 620 μm (X) and 50 μm (Y)
    - Strip pitch: 50 μm (u) and 50 μm (Y)
    - Stereo angle between u and Y strips: 4.6 º
    - MCZ p-type, detector thickness 200 μm



Schematic of the Prototype Stripixel Detector

PHENIX Upgrade



Pixel pitch: 1000 μm in X, and 80 μm in Y

Pixel arrays: 30x384

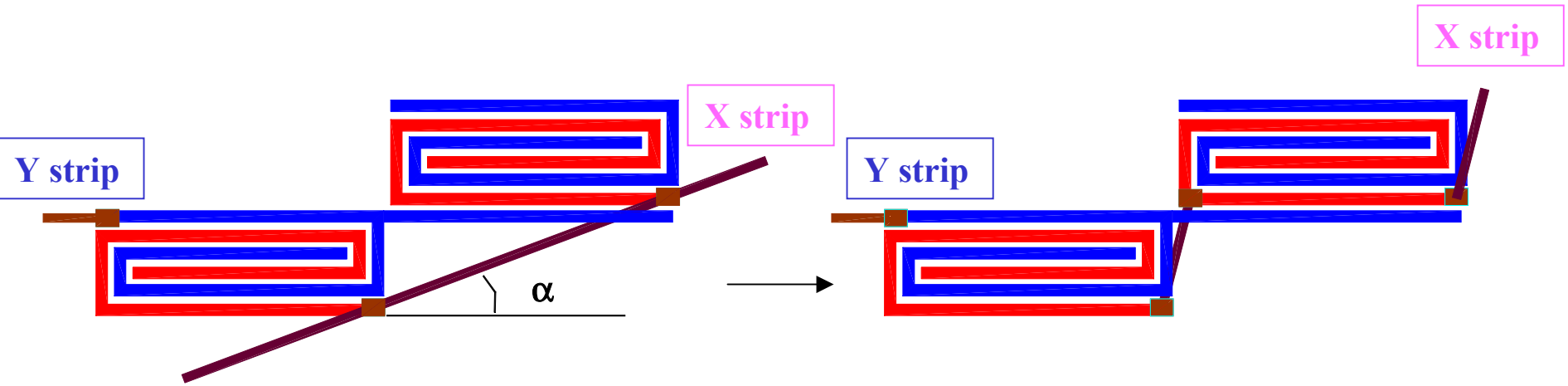
4.6° stereo angle between X and Y strips

σ_y = ~25 μm

Connection schemes for ISD:

The same stereo angle α

Shorter X strip line (by a factor of sin α) ------ good for small α

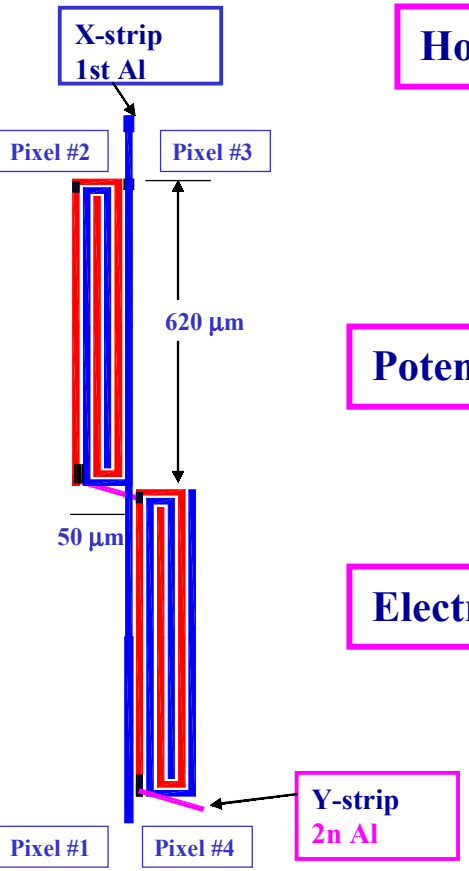


"*Pixel*" = interleaved cell

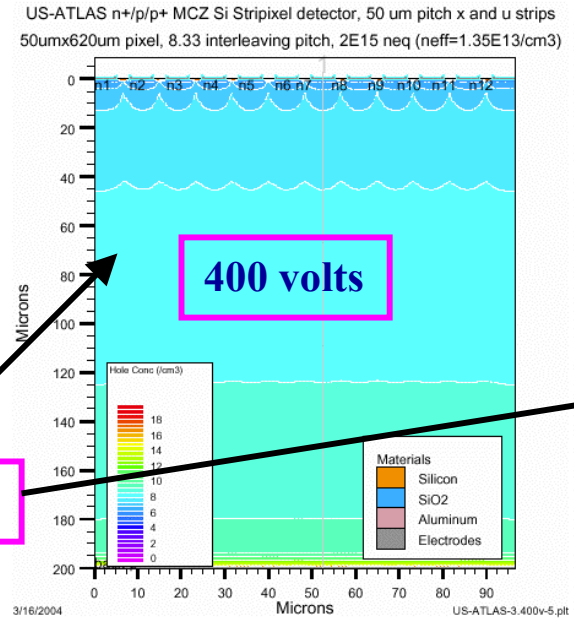
"*Strip*" = a string of interleaved cells

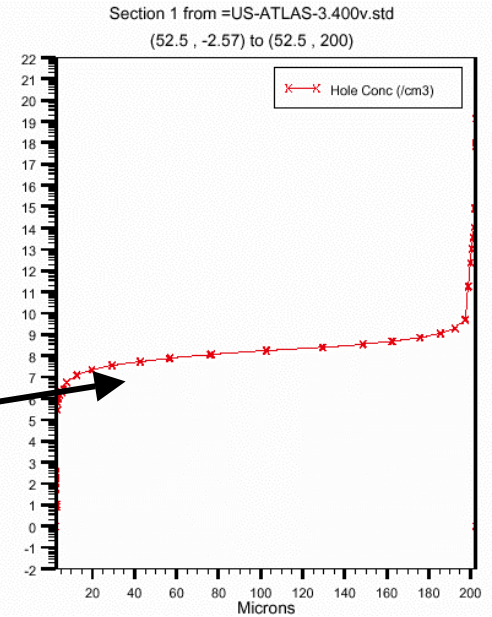
US ATLAS Upgrade

Electric simulation on the Novel n on p and n on n 2d-sensitive Si Stripixel detectors on MCZ wafers For US-ATLAS Upgrade After $2x10^{15}$ n_{eq}/cm^2 radiation



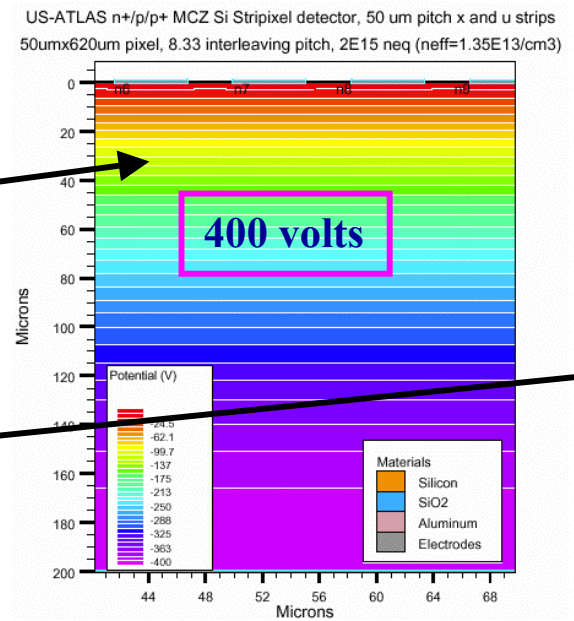
Hole concentration

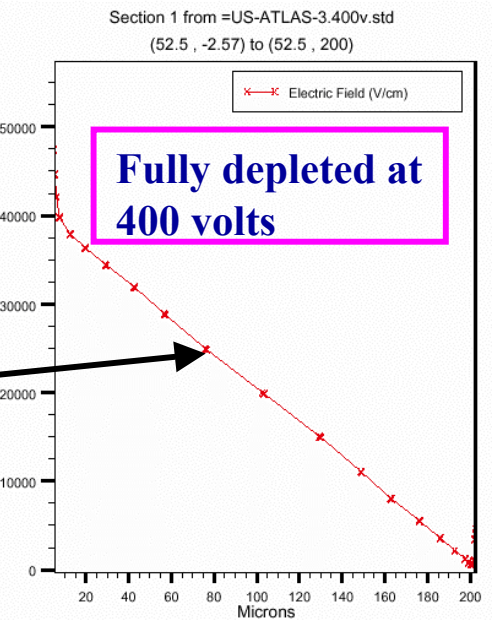




Potential profile

Electric field





Gas and liquid detector research

Time Projection Chamber (TPC) for Laser Electron Gamma Source

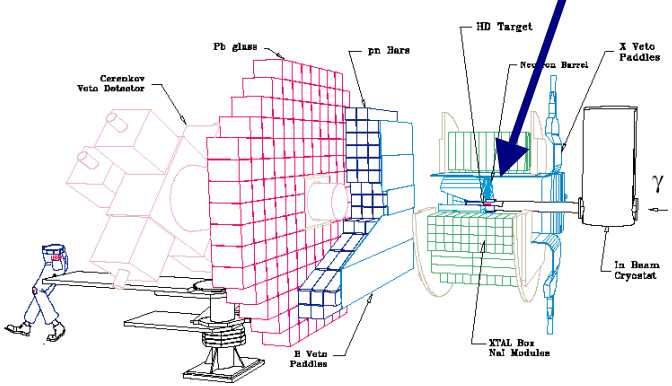
TPC Can

double-GEM planes

35cm

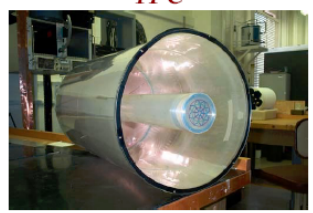
50cm

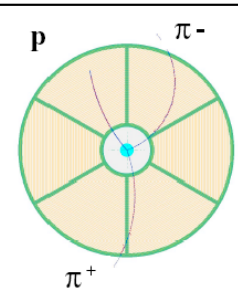
HV mesh plane and UV window for laser calibration



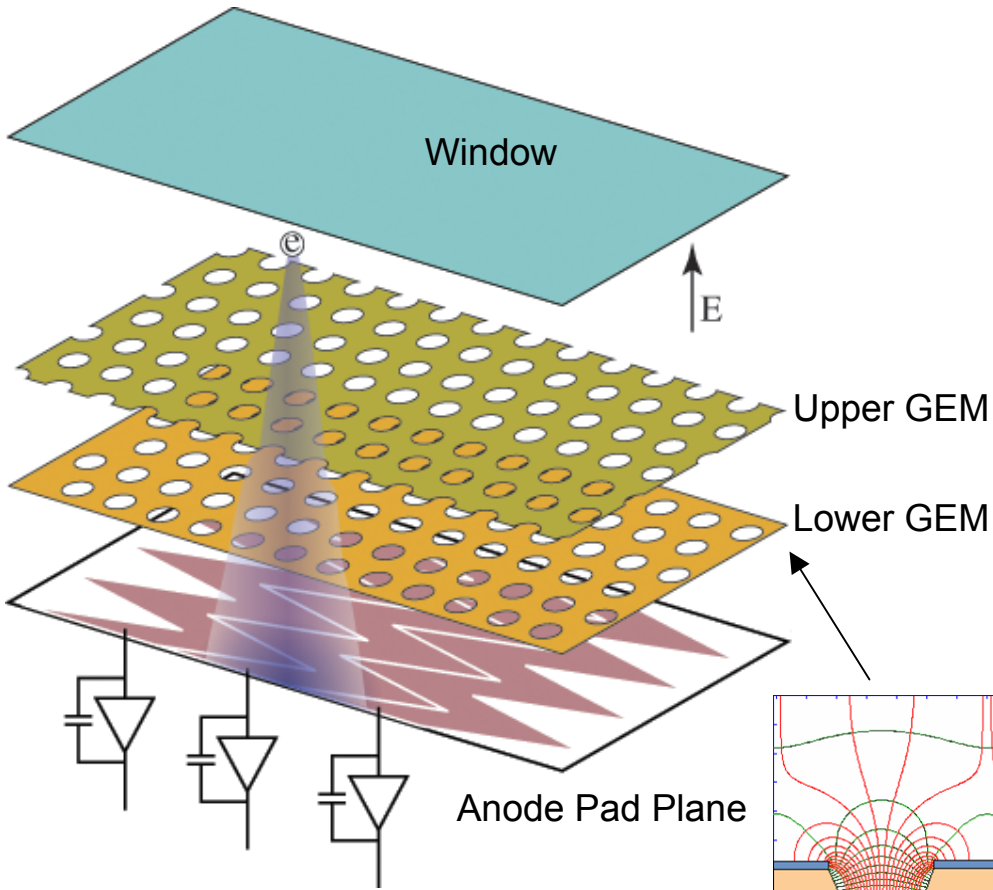
Spin ASYmmetry Array (SASY)

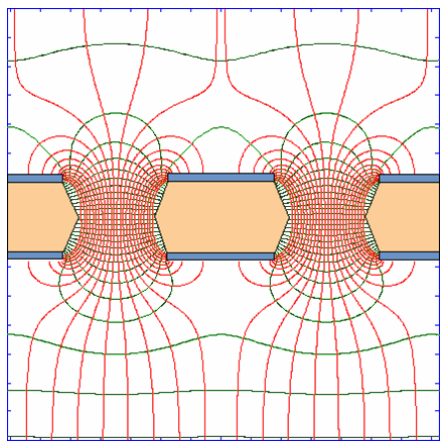
anode pad plane
~ 8000 pads
(front-end electronics in the back)



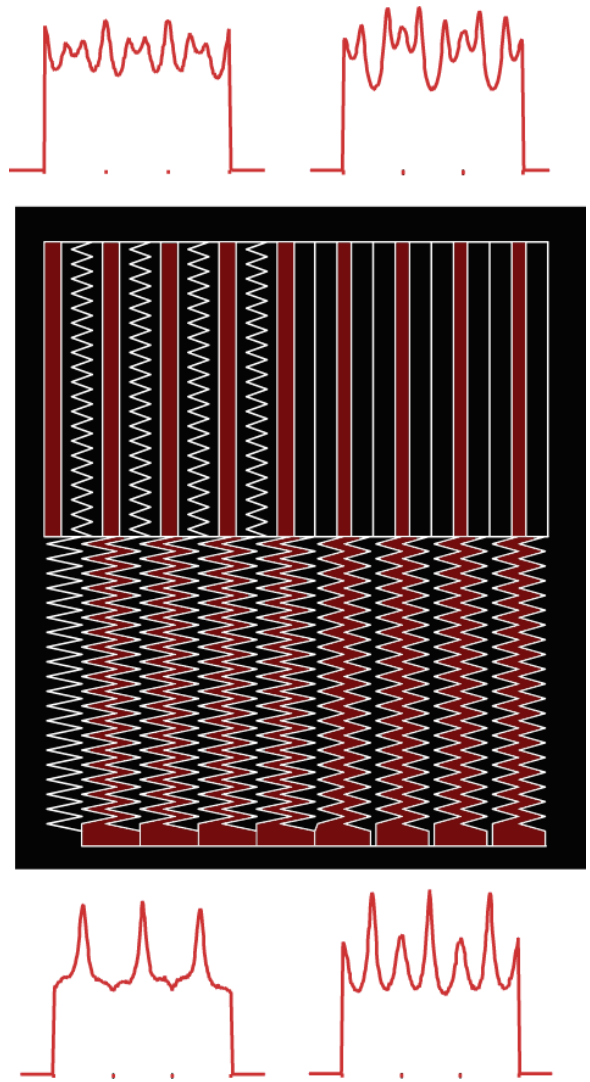


Interpolating Pad Readout for GEM (Gas Electron Multiplier)

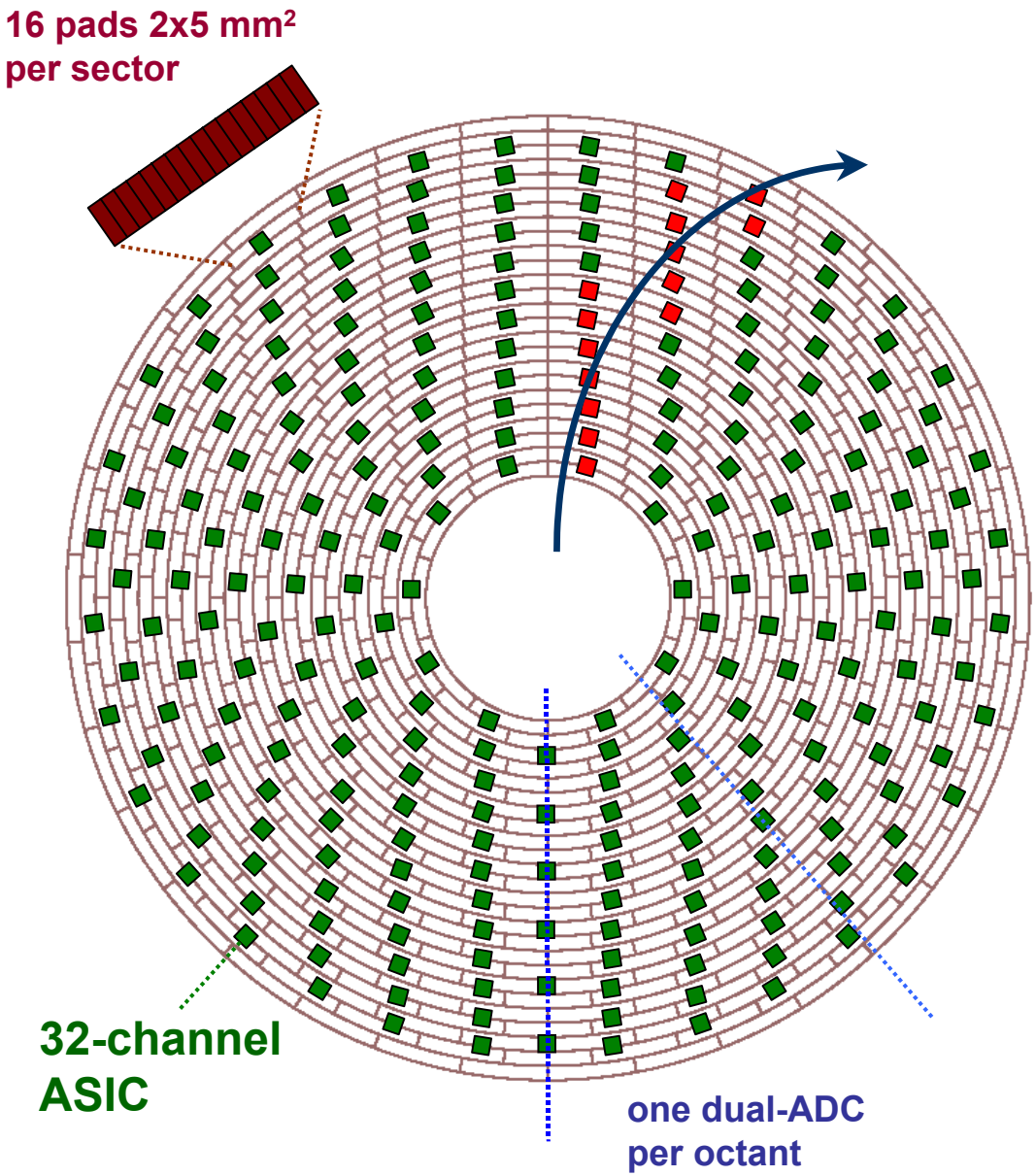




<100μm rms position resolution with 2mm pad pitch



Readout Electronics



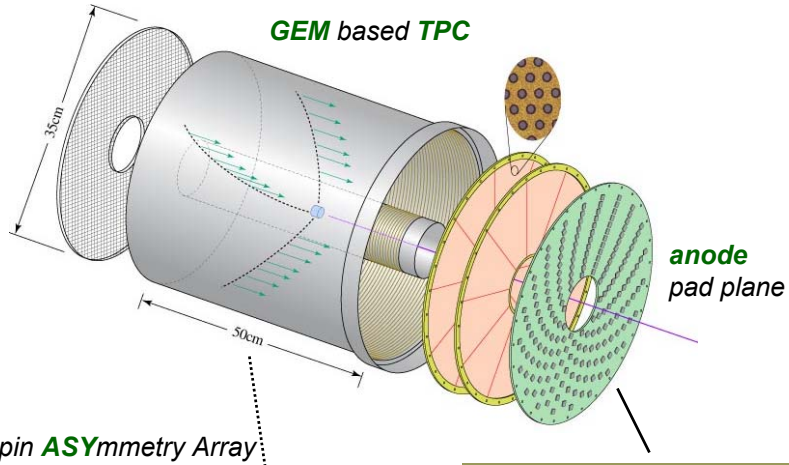
Tracking Measurement

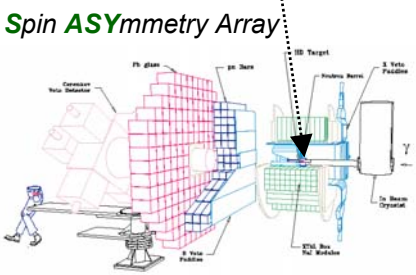
- Energy - triggered pad (xy)
- Energy - neighbor pads (xy)
- Timing (z)

Specifications

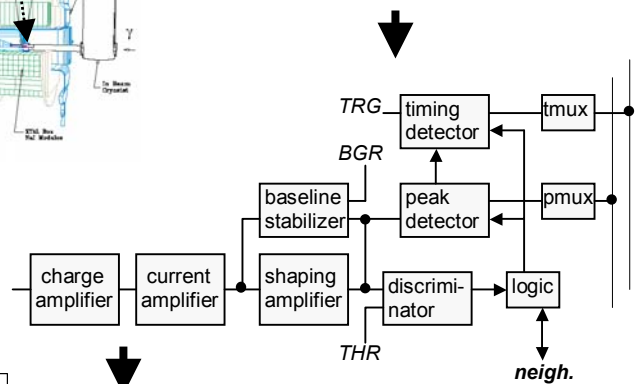
- ENC < 500 e^- rms
- Timing < 20ns
- Preamplifier/shaper/BLH
- Peak-detector
- Timing-detector (TAC)
- On-chip buffers
- Neighbor channel/chip enable
- Adjustable gain ≈ 17-32 mV/fC
- Channel masking
- Calibration
- Token/flag readout

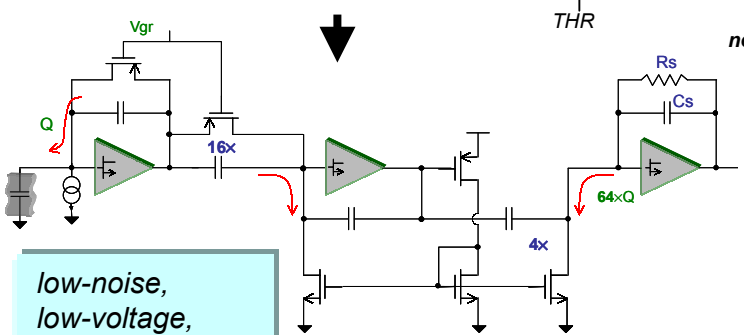
Application Specific Integrated Circuit for LEGS Time Projection Chamber



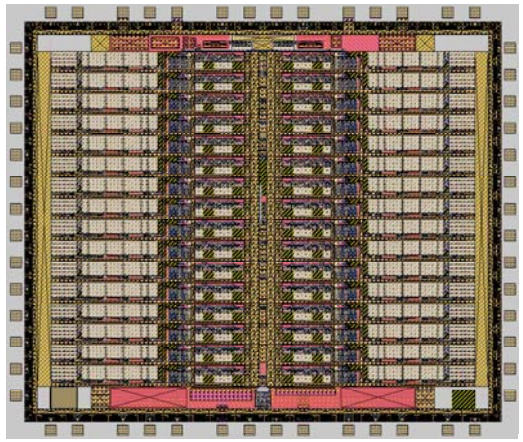


8000 front-end channels



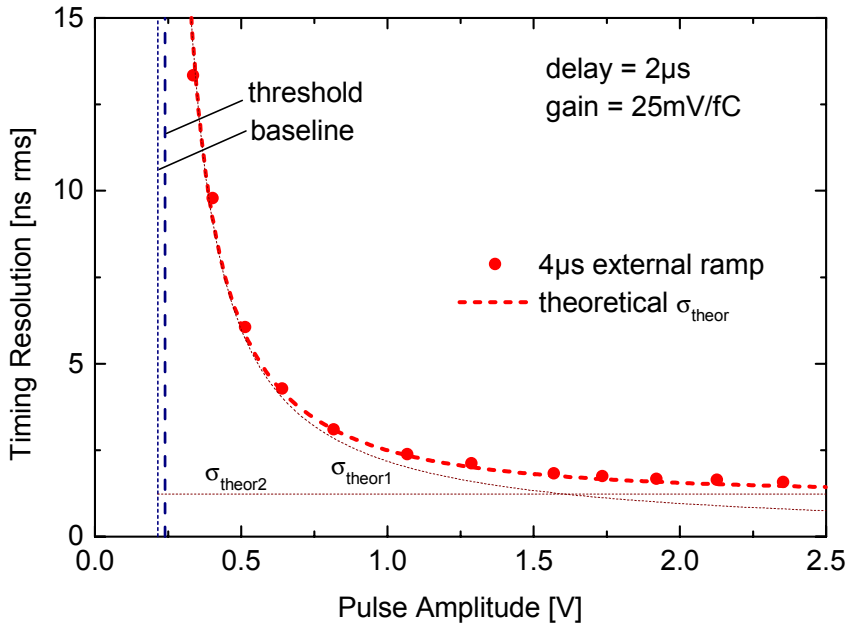


low-noise, low-voltage, continuous reset



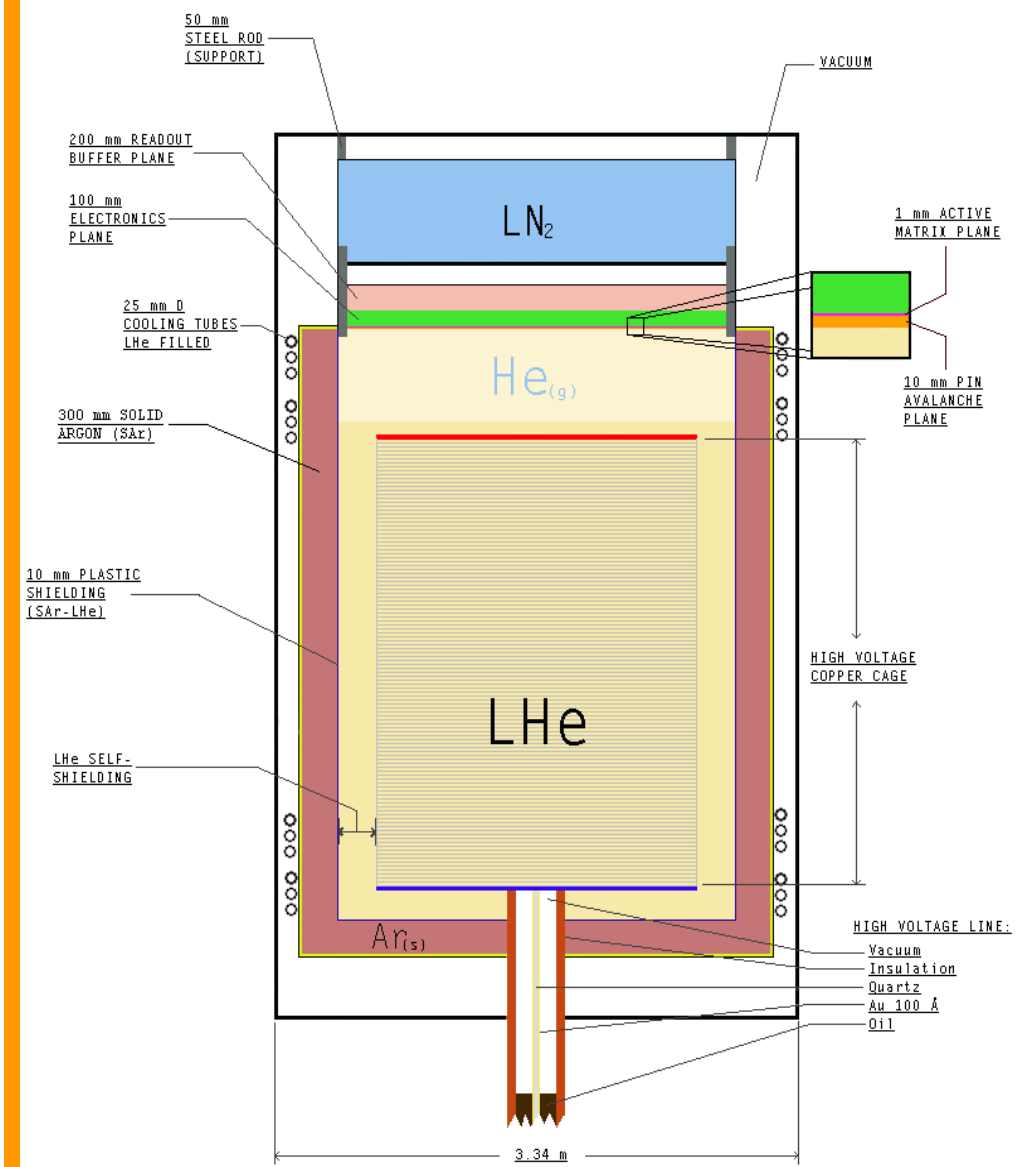
0.25μm CMOS, 3.6x3.1mm²

- 32-channel ASIC
- 1.2mW / channel
- peak/timing detection
- 250e- energy resolution
- 2ns timing resolution
- neighbor logic
- peak/timing detection
- sparsified readout



G. De Geronimo, J. Fried, B. Yu – C. Thorn (LEGS/BNL)

Neutrino detector based on tracking in liquid He



Applications:

Low Energy Solar pp Reaction Neutrinos, E < 423 keV

Astrophysical Neutrinos

Geophysical Neutrinos

Reactor Neutrinos and their Magnetic Moment

High Energy Clean Neutrino Events

Identification of Heavy Flavors in Neutrino Interactions

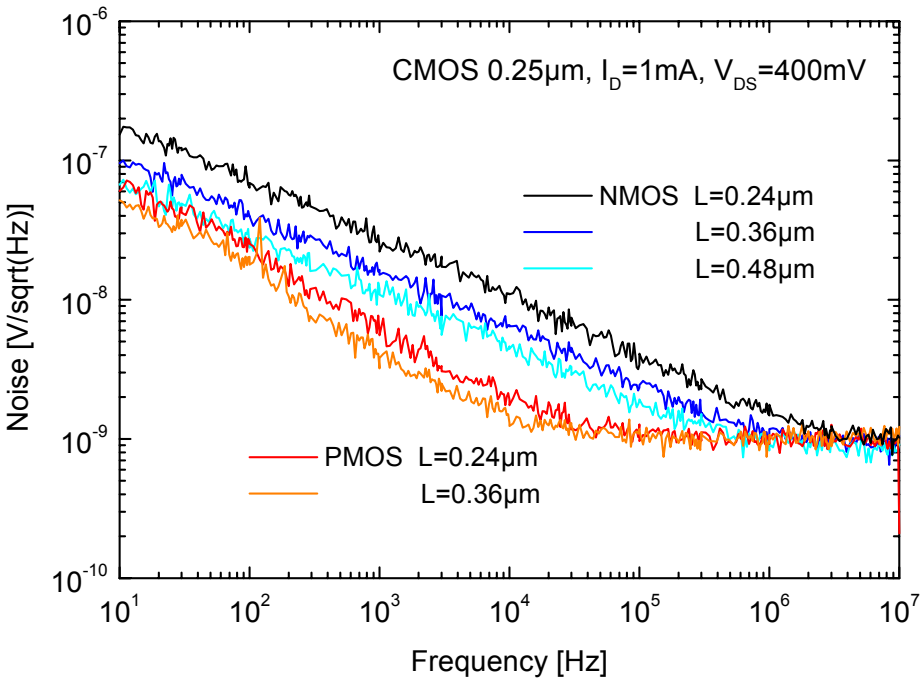
New Particle Search (SUSY – type)

R&D:
readout electronics (CMOS) at low temperatures; electron amplification;

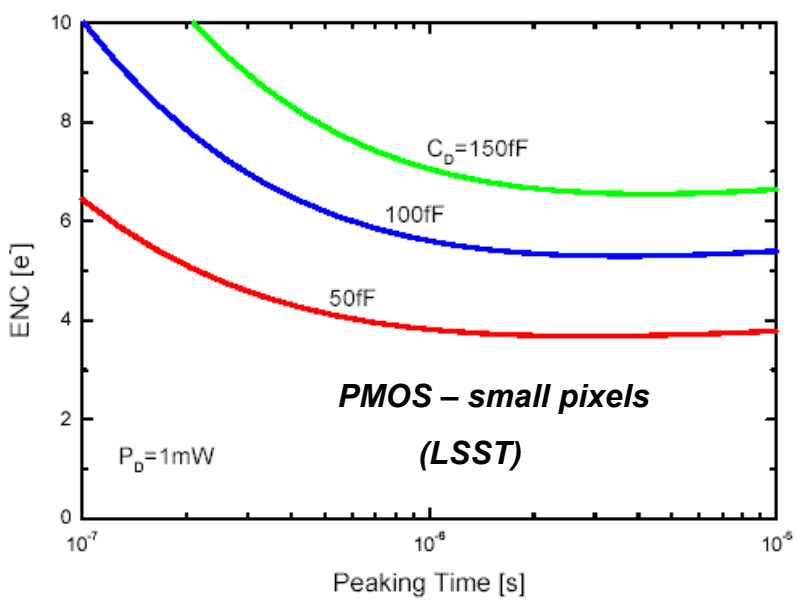
…….

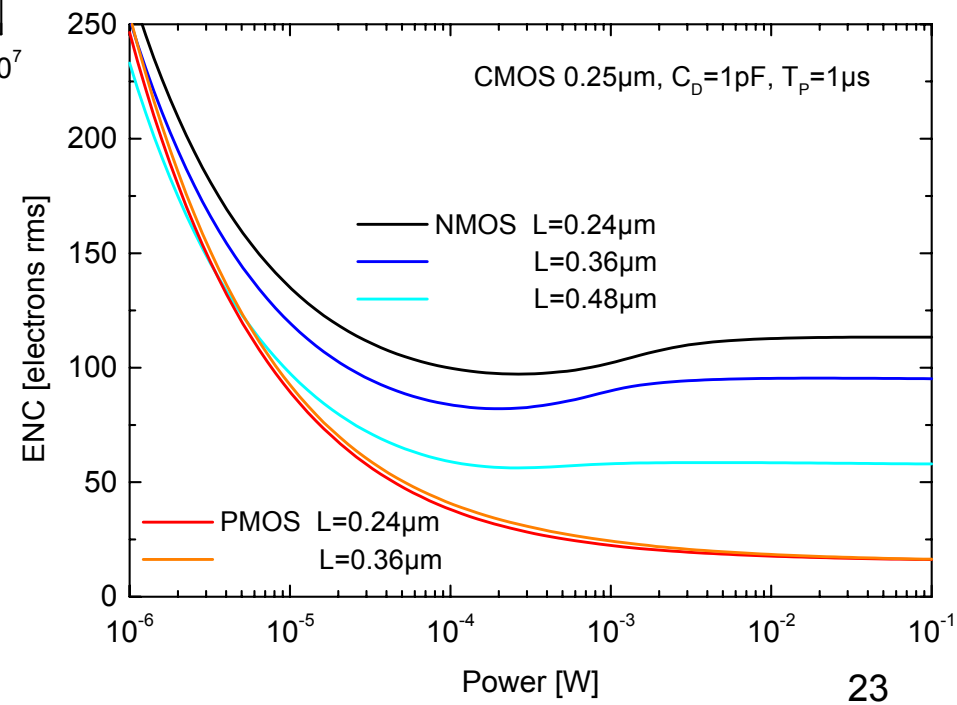
Microelectronics

Characterization of CMOS Technologies for Low-noise Low-power Front-ends

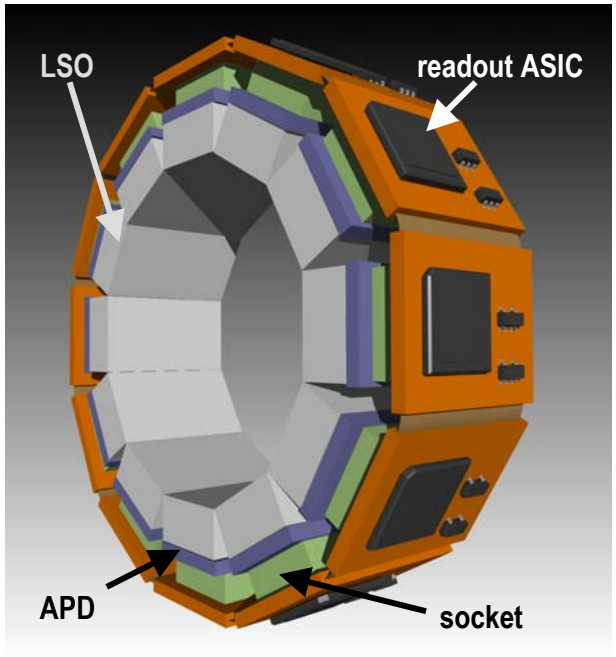


- n- vs p-channel
- channel length: L

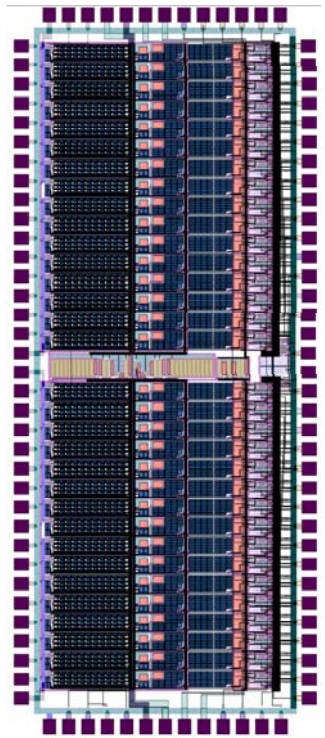




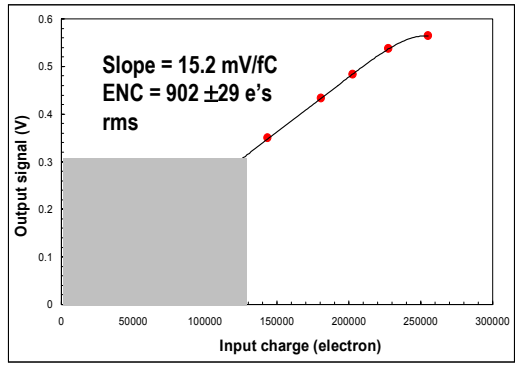
Electronics for a mobile, miniature animal PET tomograph



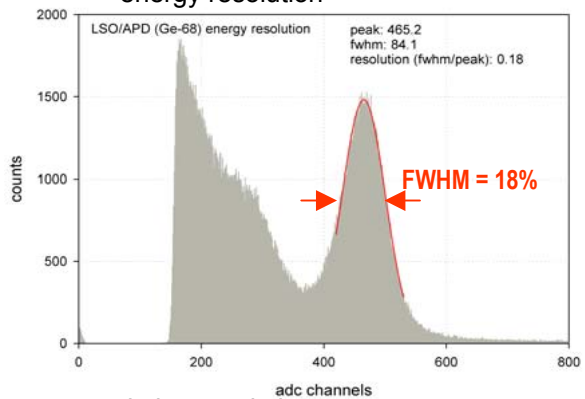
- 0.18 μm CMOS
- 1.5 mW/channel
- 32 channel ASIC
- Preamplifier + shaper + timing discriminator
- address encoding
- serialized output



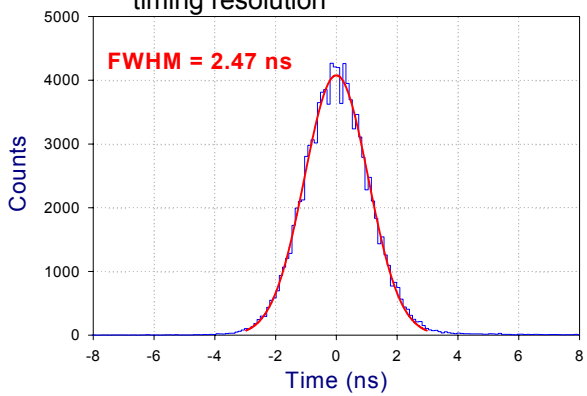
linearity



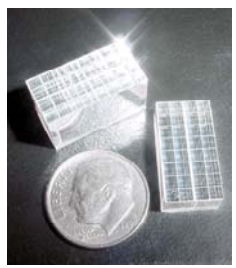
energy resolution



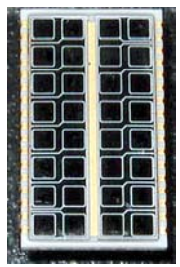
timing resolution



Mockup of the portable ring on the head of a rat



LSO scintillator

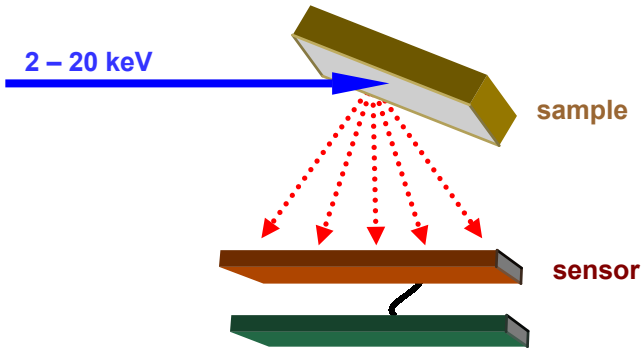


APD array

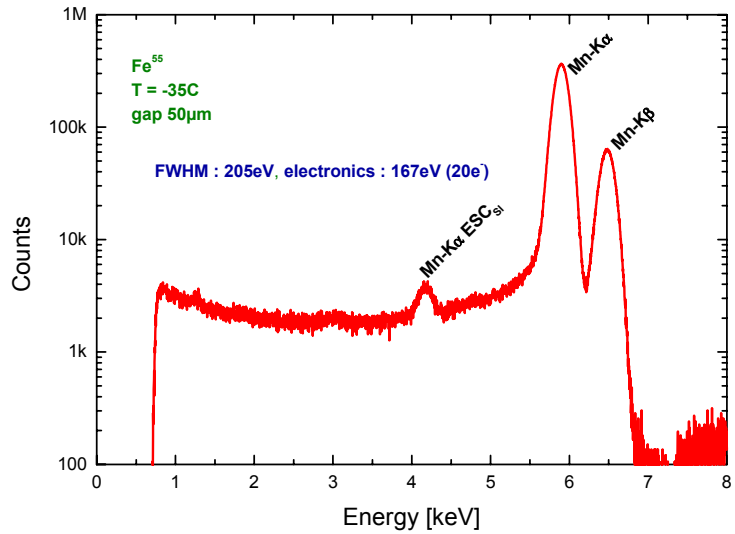
ASIC preamplifier with CFD vs. BaF_2/PMT

Application Specific Integrated Circuit for NSLS Experiments

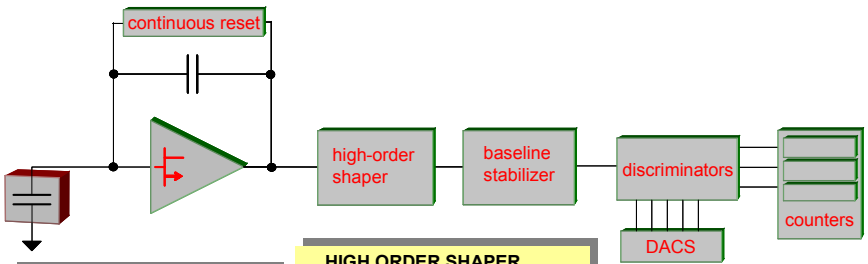
Fluorescence EXAFS Spectroscopy



front-end electronics



- 32-channel ASIC
- 8mW / channel
- 180,000 MOSFETs
- FWHM 170eV
- serial interface



INPUT p-MOSFET
- optimized for operating region
- NIM A480, p.713

CONTINUOUS RESET
- feedback MOSFET
- self adaptive sub-pA - nA
- low noise < 3.5e- rms @ 1µs
- highly linear < 0.2% FS
- US patent 5,793,254
- NIM A421, p.322
- TNS 47, p.1458

≈ 3 mW

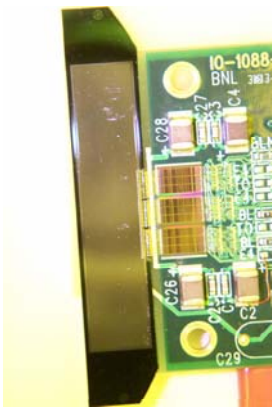
HIGH ORDER SHAPER
- amplifier with passive feedback
- 5th order complex semigaussian
- 2.6x better resolution vs 2nd order
- TNS 47, p.1857

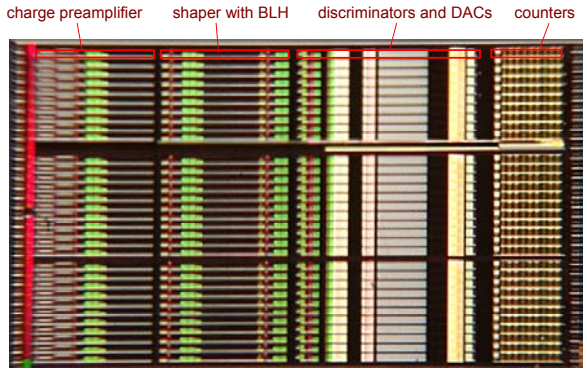
BASELINE STABILIZER (BLH)
- low-frequency feedback, BGR
- slew-rate limited follower
- DC and high-rate stabilization
- dispersion < 3mV rms
- stability <2mV rms @ rt×tp<0.1
- TNS 47, p.818

≈ 5 mW

DISCRIMINATORS
- five comparators
- 1 threshold + 2 windows
- four 6-bit DACs (1.6mV step)
- dispersion (adj) < 2.5e- rms

COUNTERS
- three (one per discriminator)
- 24-bit each

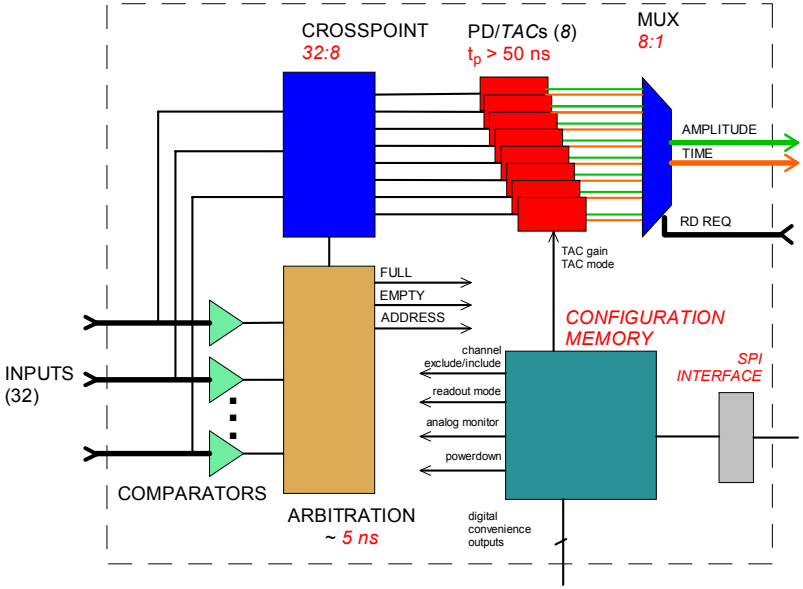




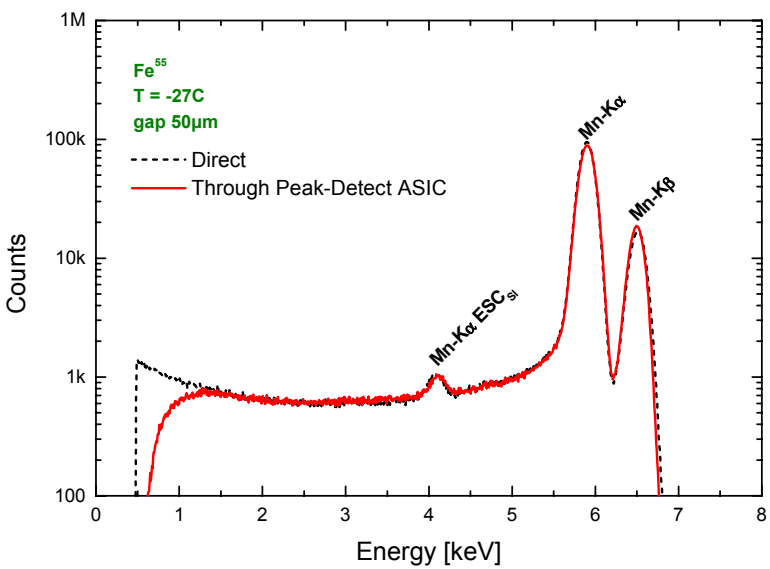
0.35µm CMOS, 3.6x6.3mm²

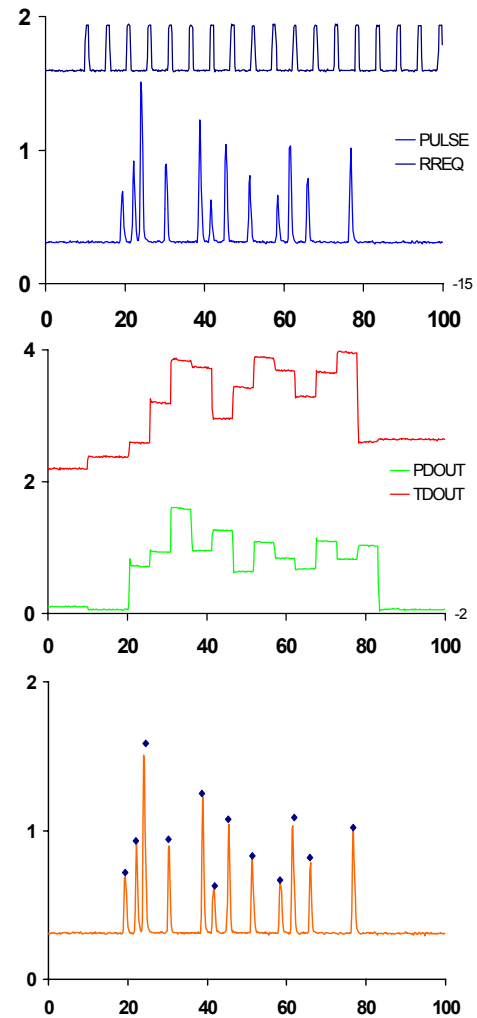
G. De Geronimo, P. O'Connor – P. Siddons (NSLS/BNL)

Amplitude/Time Measurement ASIC with Derandomization



- high-accuracy two-phase peak detector
- < 2mW / channel





ADC request

sensor

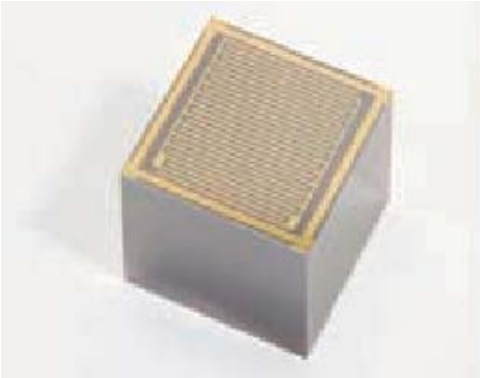
time output

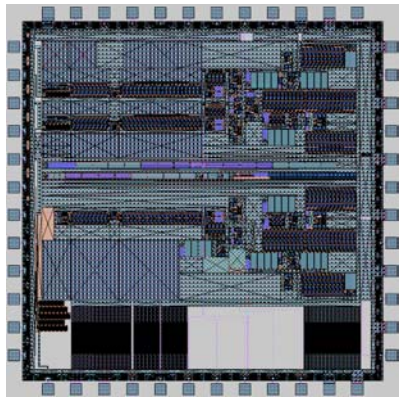
amplitude output

reconstructed signal

G. De Geronimo, A. Kandasamy, P. O'Connor – eV Products (PA)

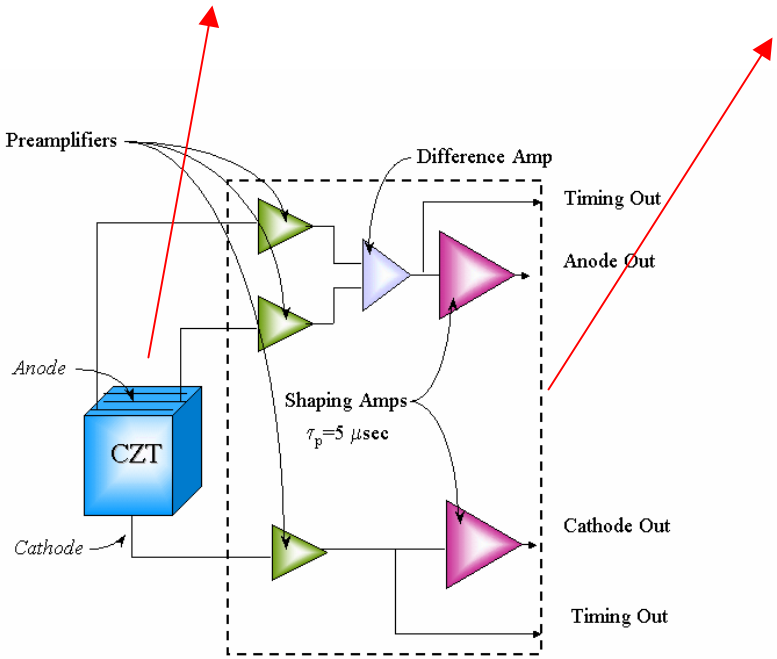
Application Specific Integrated Circuit for Coplanar Grid CdZnTe Detector

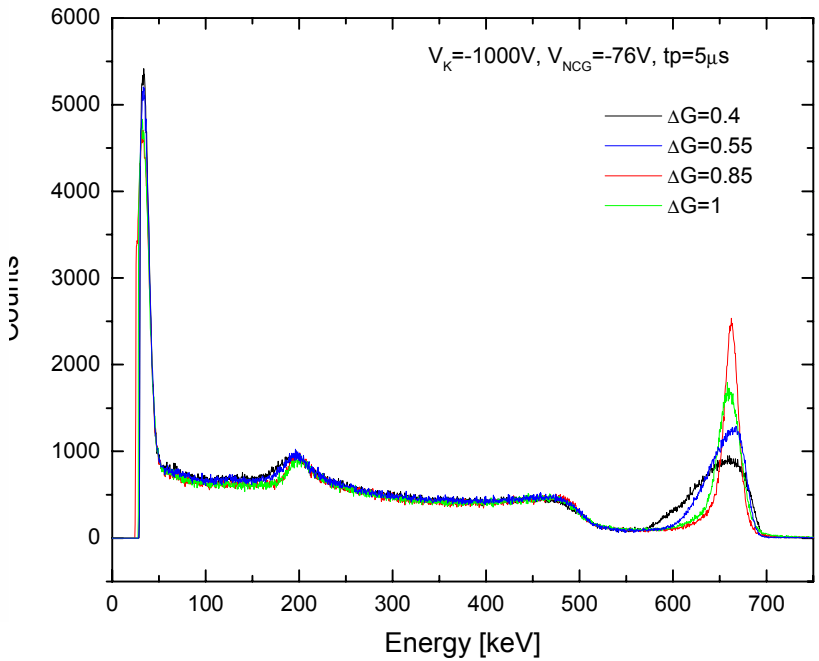




0.25μm CMOS, 3.1x3.1mm²

- 2 anode channels
- difference amplifier
- cathode channel
- high-order filter
- timing





G. De Geronimo, P. O'Connor – W. S, Murray (LANL)

LSST

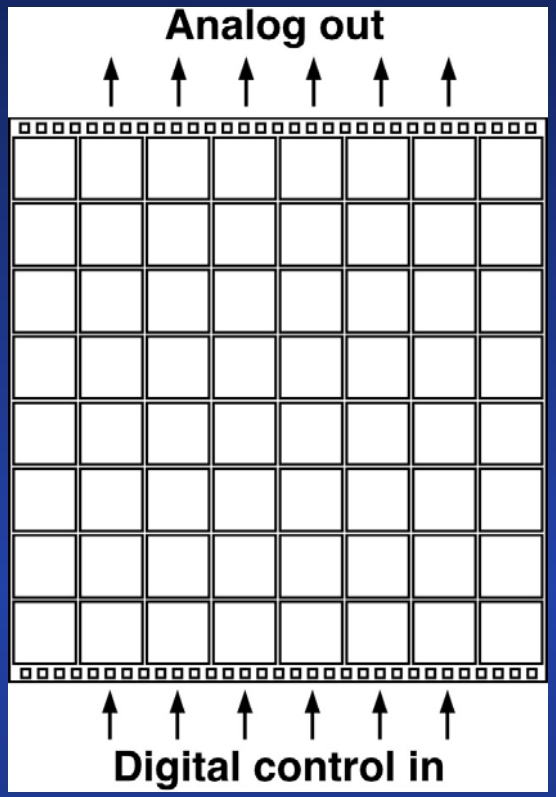
LSST Detector Challenge

- The focal plane array will have about ***an order of magnitude larger number of pixels*** (~2.8 gigapixels) than the largest arrays realized so far or being built.

- The effective pixel readout speed will have to be about ***two orders of magnitude higher*** than in previous telescopes in order to achieve a readout time for the telescope of ~ 2 seconds.

- The silicon detectors will have an ***active region ~100-250 μm thick*** to provide sufficiently high quantum efficiency at ~1000 nm, and they will have to be fully depleted so that the signal charge is collected with minimum diffusion as needed to achieve a narrow ***point spread function, <10μm***.

Highly Segmented CCDs for LSST: *An Example*



- High performance "scientific" CCDs have 1 to 4 signal ports, resulting in readout times of tens of seconds for larger CCDs.
- Assume a 2k x 2k=4 Mpixels CCD divided into 8 x 8 segments with 8 signal ports. With a clock rate of 4 μs/pixel (250 kHz), to achieve <5 rms e noise, it takes 2s to read out.

-The charge integrated in pixels in each CCD is read out by an 8-channel ASIC.

-An LSST focal plane array with ~700 CCDs+ASICS would be read out in parallel via 5600 signal channels. After digitization the data will be transferred from the camera at a much higher rate via a small number of data links.

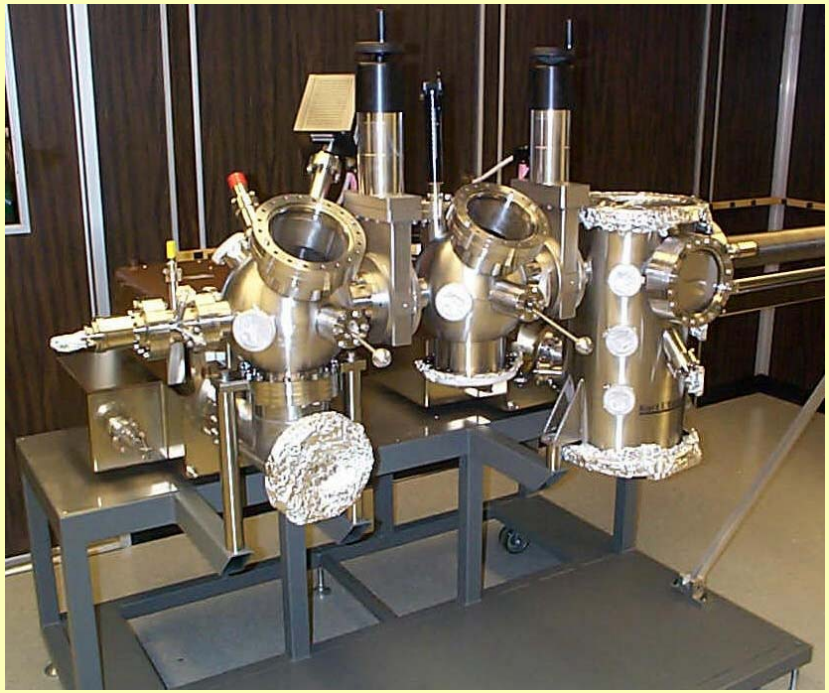
-By segmentation and the use of ASICs a short overall readout time is achieved, while charge signals are processed at a low CCD clock rate.

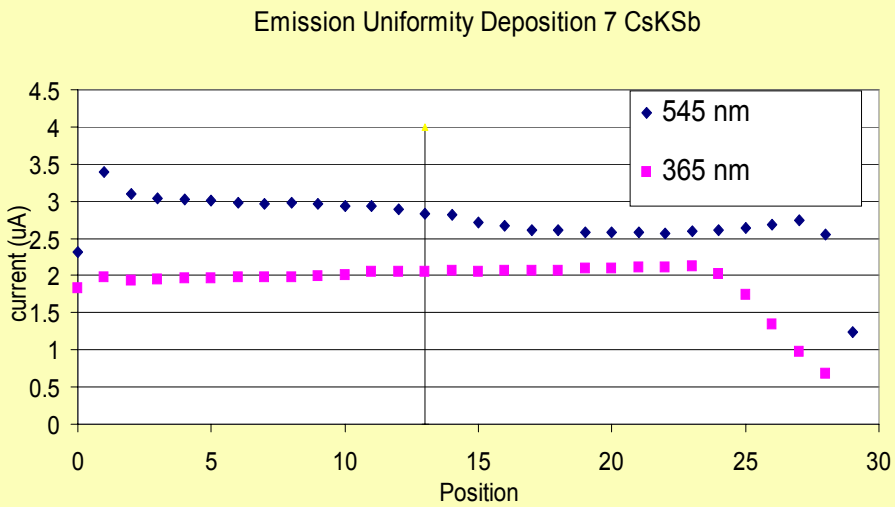
-Segmentation confines the effect of defects in the CCD and of blooming.

Lasers and Optics

Multialkali Photocathode Development (CAD, IO)

A multialkali cathode deposition and testing system





Goals:

- Electron beam parameters: charge 10 nC, PRF 10 MHz, average current 100 mA
- Quantum efficiency: few % for Visible photons
- Lifetime: >8 hrs at a vacuum of 1×10^{-9} Torr

Results so far:

QE up to 3% at 545 nm

Life time > weeks at low 10^{-9} Torr

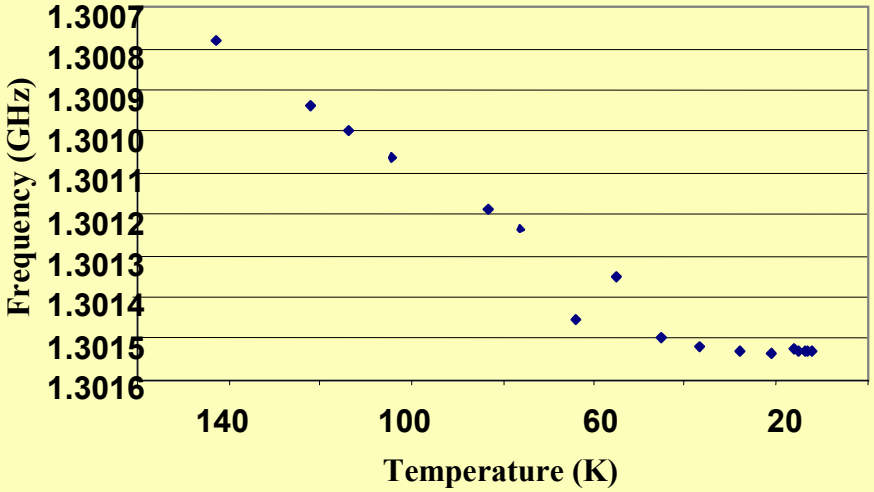
Increased QE at 365 nm

Uniform emission at 545 and 365 nm

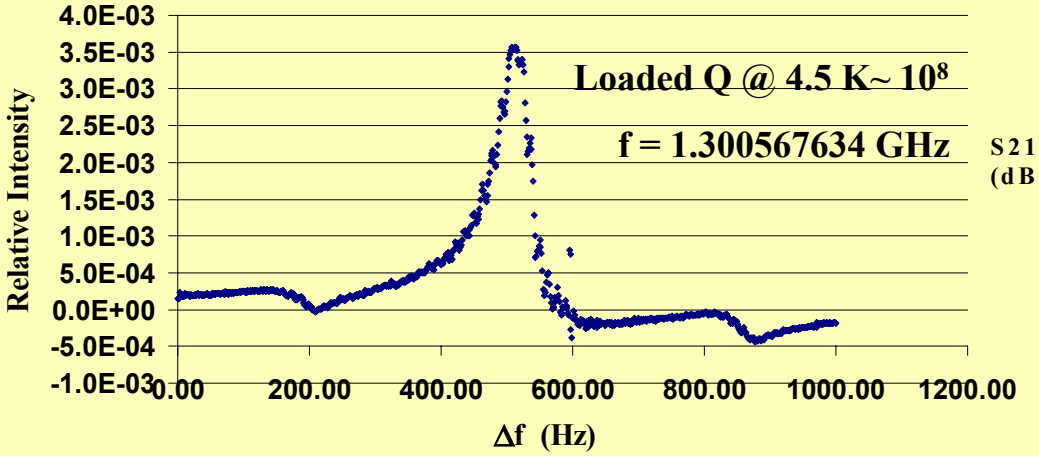
Current density comparable to RHIC II ***(e-cooling)*** requirement, few days of life time

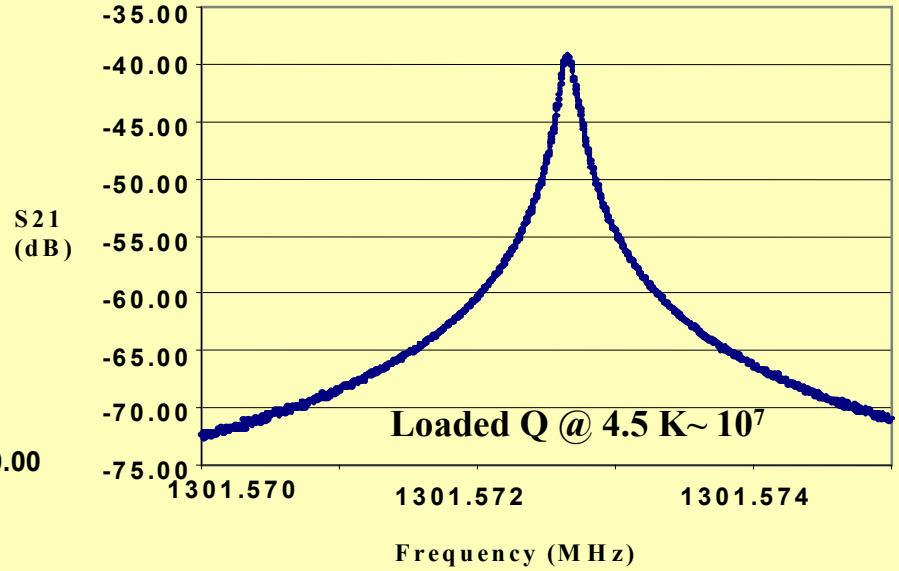
All Nb Superconducting Photoinjector (CAD, IO, AES)

Cavity Performance Before BCP

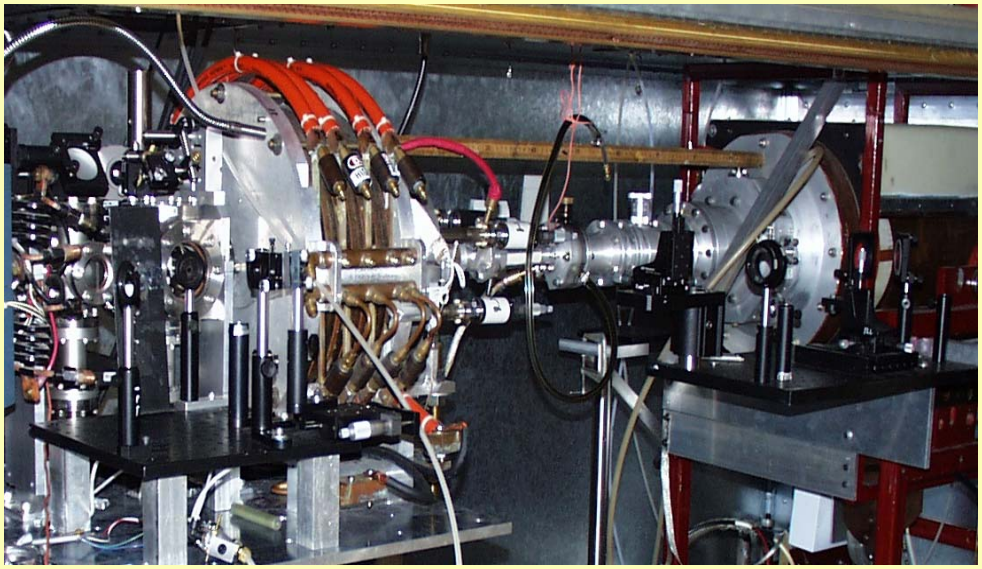


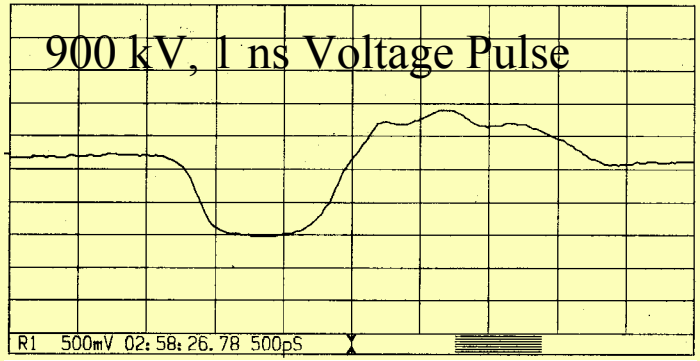
Nb Cavity Frequency After BCP

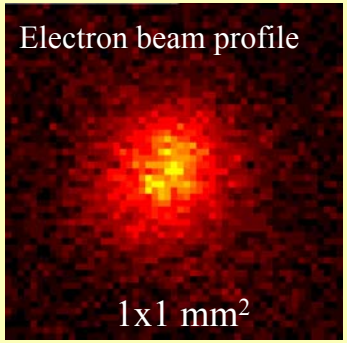




Pulsed Power Injector



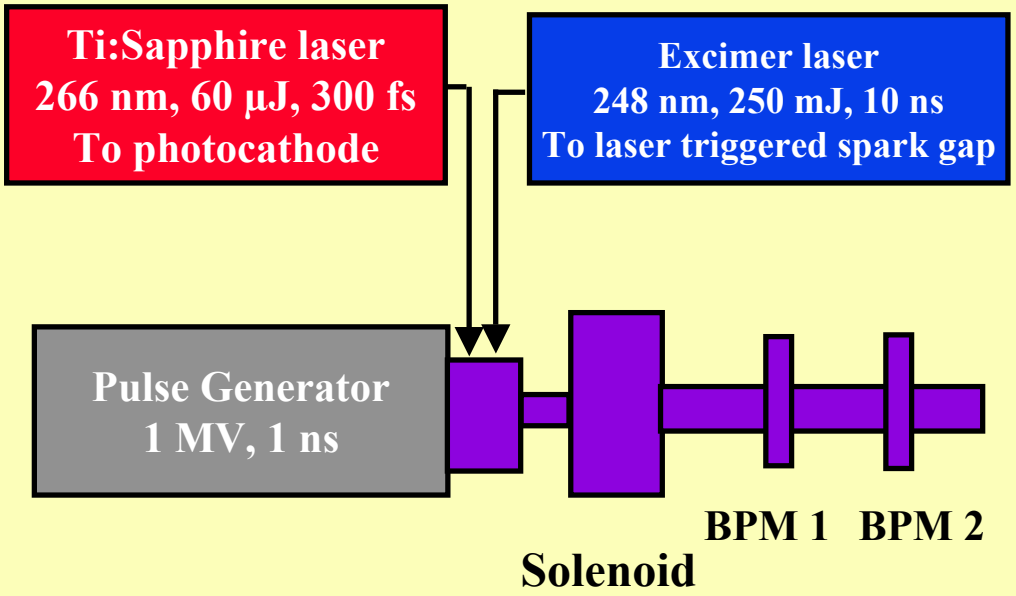




Spot size ~65 µm rms

Charge ~0.4 pC

emittance ~0.7 mm mrad



System Capabilities

Voltage range: 150 - 900 kV, 1 ns FWHM

Cathode laser: 60 µJ, 300 fs FWHM, 266nm

System timing jitter: <1 ns

Accelerating gradient: >1 GV/m

Maximum current density: >100 kA/cm^2

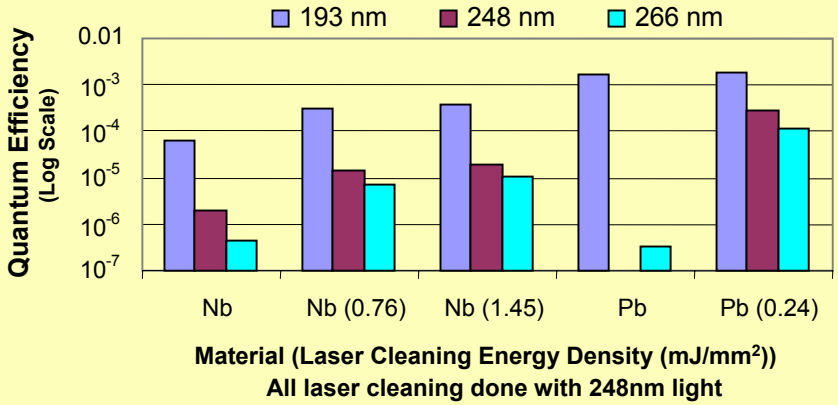
Maximum charge: >60 pC from 300 fs laser

New direction in laser applications

Superconducting Lead Photoinjector Development

To improve the Quantum Efficiency of superconducting photoinjectors. This research may lead to an injector capable of meeting the high average current requirements of tomorrow's LINAC-based Light Sources (up to 1nC bunch charge, 1 mA average current, 1 MHz rep. rate).
Preliminary Measurements:

Lead has Four to Ten times higher QE than Niobium



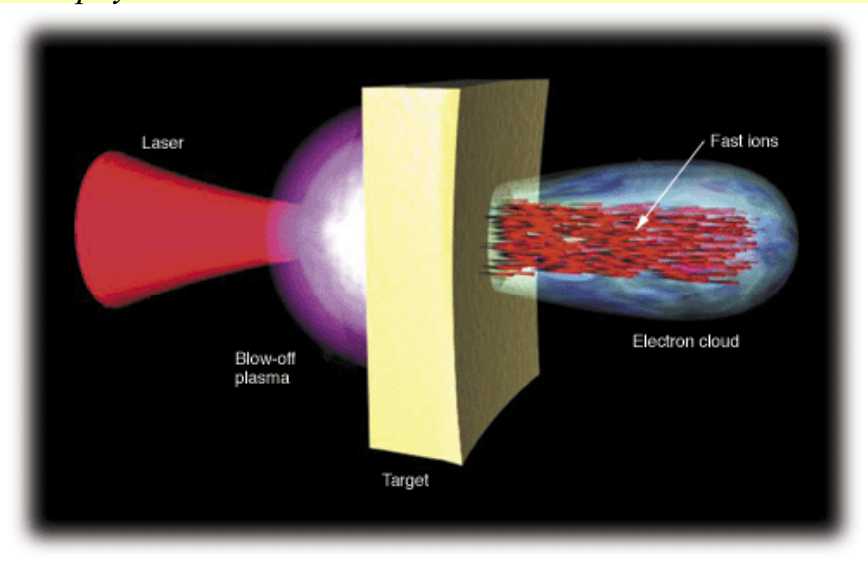
What we propose:

Develop techniques to deposit lead on the cathode region of a niobium superconducting injector. Optimize laser parameters to maximize charge extraction without quenching.

LDRD submitted 2004

Electron and X-ray Production by Ultra-intense Laser Interaction with Material

To develop a laser-based source capable of efficiently producing multiple types of radiation. Multi-TW laser sources have the potential to provide spatially coherent, femtosecond particle (electron, proton positron, ion) and X-ray beams, revolutionizing fields such as radiography and astrophysics.



Livermore Petawatt Facility

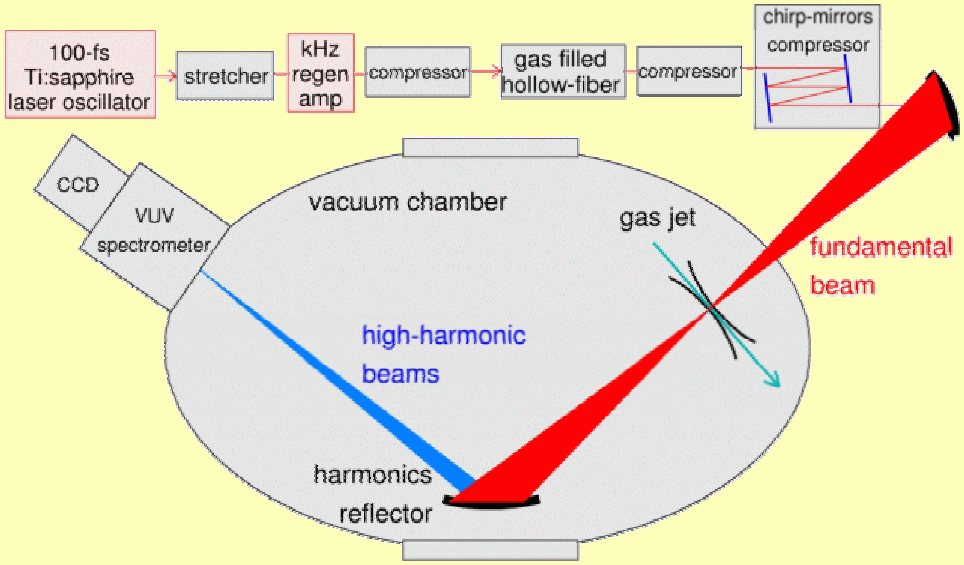
What we propose:

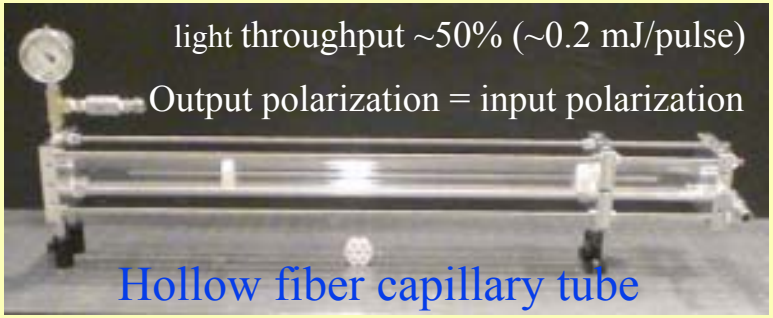
Optimize target and laser pulse parameters to produce characteristic (K-α) X-rays and energetic electrons. Provide a diverse particle source useful for radiography and detector calibration.

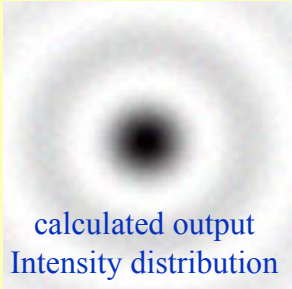
LDRD submitted 2004

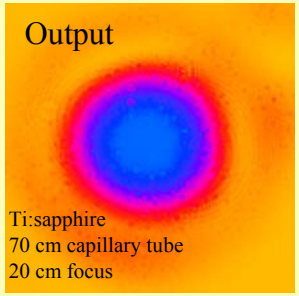
Generation of Coherent, Femtosecond, High Brightness VUV and X-Ray Beams Using High Order Harmonic Conversion

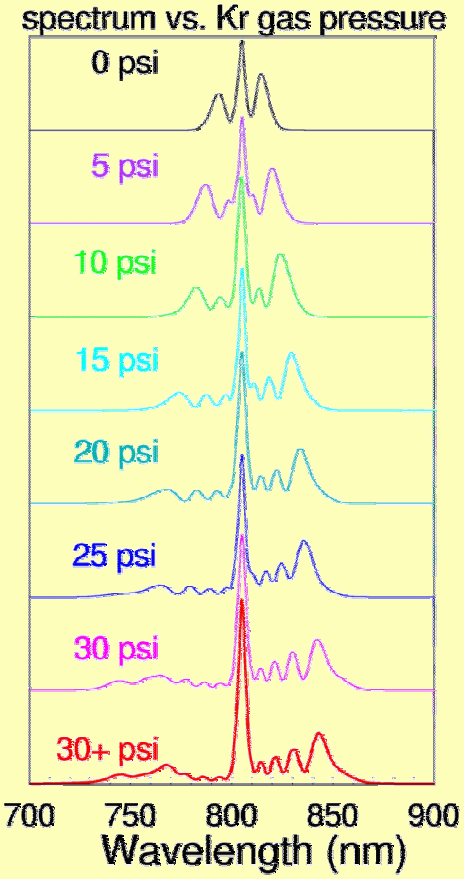
2002 LDRD



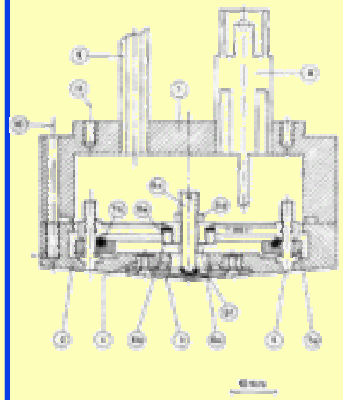


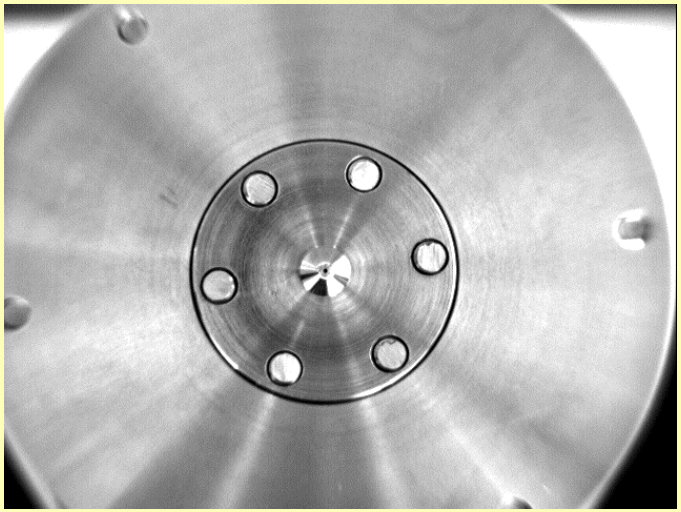






high repetition rate gas jet





gas jet operation at ambient

New direction in laser applications

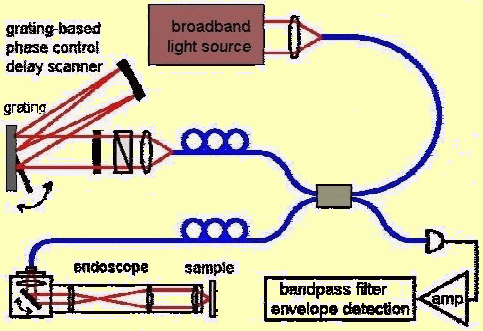
LDRDs submitted 2004

Optical coherent tomographic (OCT) imaging of biological tissues

To develop a noninvasive medical diagnostic tool using non-ionization radiation sources. The program benefits the Life and Physical Science programs to be established at BNL

What we know:

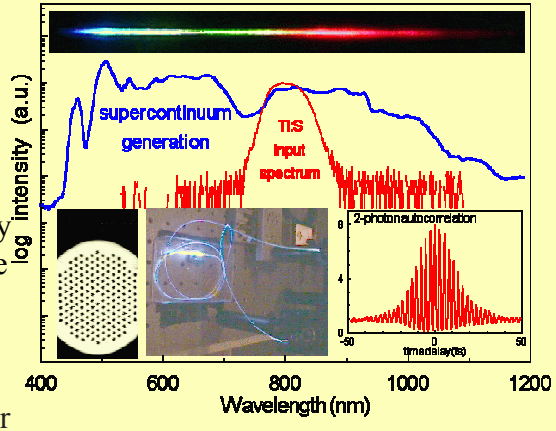
OCT is a non-contact interferometric technique that measures the reflected or back-scattered light from within the subsurface biological tissue. The image resolution improves with larger laser bandwidth



typical OCT setup

What we propose:

OCT imaging using supercontinuum light source → highest image resolution. Combine a fluorescence-guided method to substantially enhance the efficiency and the sensitivity for rapid medical diagnosis. The new technique has the potential for the detection of early-stage cancer can be much improved.



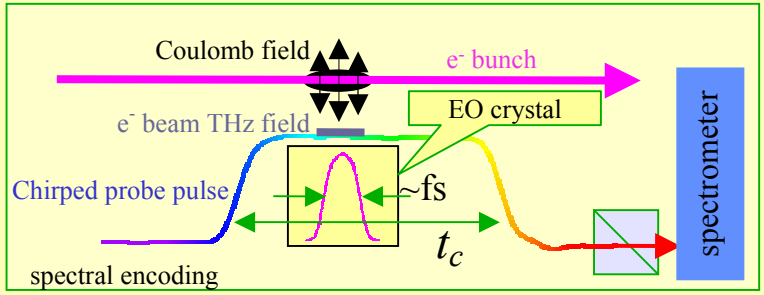
Cupercontinuum light source at BNL

Characterization of femtosecond electron bunch: cross-correlation technique

The electron bunch lengths continue to drop below the sub-100-femtosecond regime in various accelerator facilties including the SDL and the ATF at BNL, optical pulses of equal duration or shorter are needed to characterize the femtosecond electron bunch

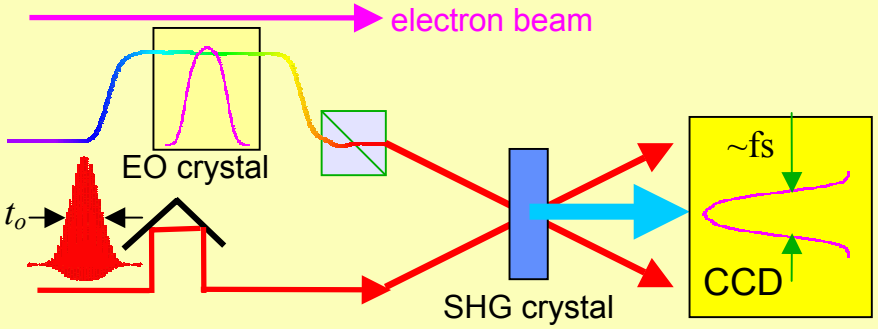
What we know:

Spectral encoding technique has an intrinsic time resolution limitation that is always longer than the duration of the unchirped optical pulse



What we propose:

Spectral encoding & cross correlation technique to remove the intrinsic time resolution limitation completely → measurement of electron bunch length to below100-femtosecond for the first time.



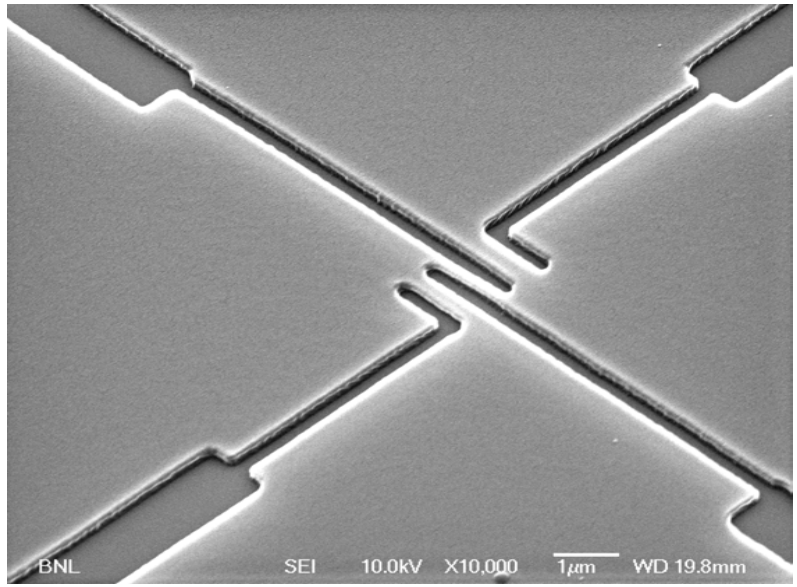
Optical System Design

- M. Diwan, Physics
  - Lens for Cerenkov imager for neutrino detector project
    - Low resolution, underwater, broad wavelength band
    - Large angular acceptance range

ZEMAX optical design code
OptiCAD optical system analysis code

Micro/nano Fabrication

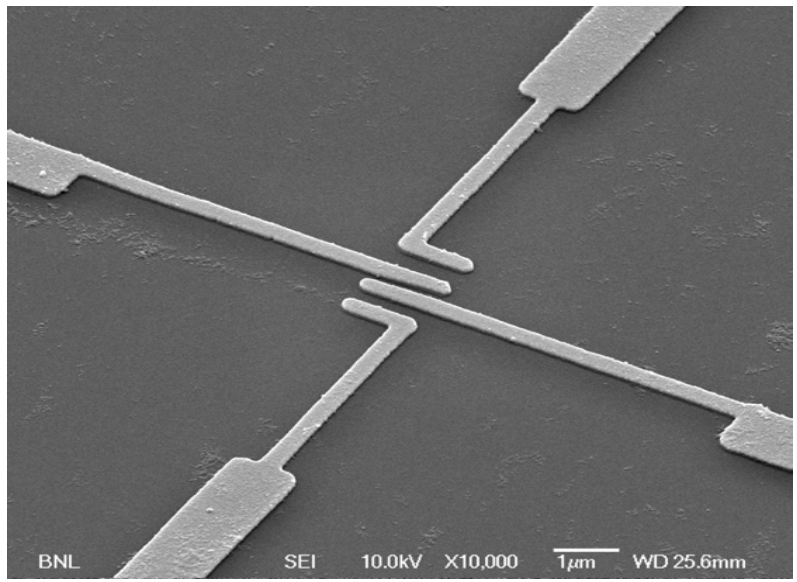
*



PMMA after nanopatterning in JSM-6500F

Since installation in July 2003, Instrumentation's high resolution scanning electron microscope, the JEOL JSM-6500F serves a dual role: electron beam lithography at the nanoscale and high resolution imaging.

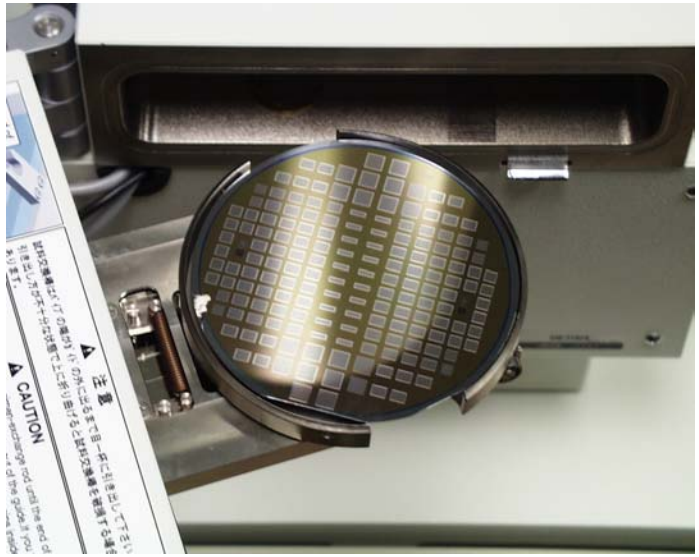
Of particular importance is a Schottky field emission gun that can produce a probe current of up to 100 nA. Probe currents of this magnitude permit pattern writing speeds several hundred times greater than those found with analytical SEM's.



Gold electrode array after resist "lift-off" fabrication step.

*Gold electrode array prepared for studies of IR emission from carbon nanotubes by J. Misewich, S. Wong, A. Stein & J. Warren

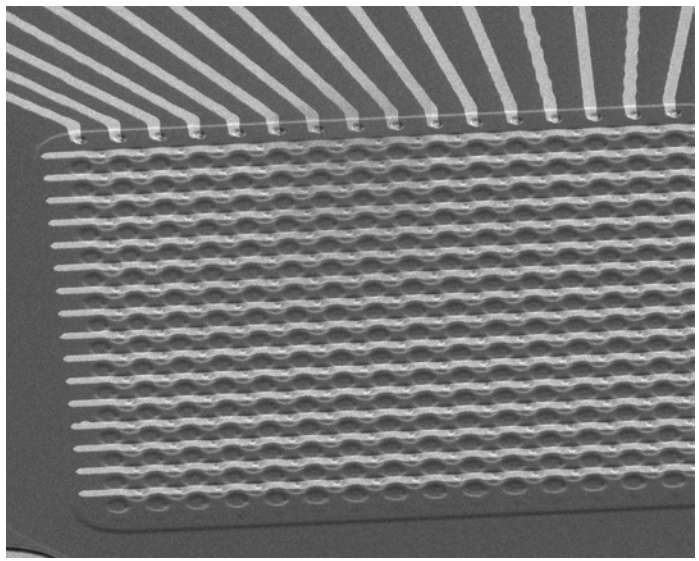
J. Warren



4” wafer prior to insertion into chamber

The JSM – 6500F high resolution imaging capabilities are shown with a micrograph of a Strippixel detector fabricated for NASA used in ion beam damage studies.

Wafers up to 6” in diameter can be inserted in the chamber and the entire wafer area can be examined at nanoscale resolution.



Micrograph of Strippixel array fabricated by Z. Li and D. Elliott in the Semiconductor Detector Facility

J. Warren

Collaborations outside BNL

Non-DOE Federal Agency

- **National Space Biomedical Research Institute (NSBRI), "Micron Resolution Detector", V. Radeka, Z. Li.**

Other National Labs

- **Los Alamos National Laboratory, "Application Specific Integrated Circuit (ASIC) for Coplanar Grid (CPG) CdZnTe", PI: P. O'Connor**
- **ANL, Neutron Detector, PI: G. Smith**
- **SNS/ORNL, Neutron Detectors, PI: G. Smith**
- **NIST, Neutron Detectors, PI: G. Smith**

CRADAs

- **Advanced Energy Systems, PI: T. Srinivasan-Rao**
- **Symbol, Integrated Imaging ASIC, PI: P. O'Connor**
- **eV Products, Readout ASICs for CZT Detectors, PI: P. O'Connor**

SBIR subcontract

- **Photon Imaging, Readout ASICs for gamma camera, PI: G. De Geronimo**

Work for Others

- **Frequency Electronics Inc., Radiation Effects Testing, J. Kierstead**
- **Advanced Energy Concepts, Si Detector Technology, Z. Li**

Grants for Projects from Diverse Sources

Non-Federal Agency

- **National Space Biomedical Research Institute (NSBRI), "Micron Resolution Detector", V. Radeka, Z. Li.**

Other Labs

- **Los Alamos National Laboratory, "Application Specific Integrated Circuit (ASIC) for Coplanar Grid (CPG) CdZnTe", PI: P. O'Connor**
- **ANL, Neutron Detector, PI: G. Smith**
- **SNS/ORNL, Neutron Detectors, PI: G. Smith**
- **NIST, Neutron Detectors, PI: G. Smith**

DOE/OBER

- **Biophysical Instrumentation Research, KP1101010, PI: G. Smith**
- **Medical Applications Instrumentation (PET), KP1401030, P. O'Connor, J.F. Pratte**

CRADAs

- **Advanced Energy Systems, PI: T. Srinivasan-Rao**
- **Symbol, ASICS, PI: P. O'Connor**
- **eV Products, ASICS, PI: P. O'Connor**

Work for Others

- **Frequency Electronics Inc., Radiation Effects Testing, J. Kierstead**
- **Advanced Energy Concepts, Si Detector Technology, Z. Li**

Mission *vs* Funding

- Grants from diverse sources are clearly beneficial as they broaden the scope of work and make available the Division's expertise to other institutions. They should be pursued to ***augment*** the base Instrumentation program supported by G&A, and ***they must not detract*** from supporting BNL research program and core technologies.

- Benefit of Instr. Div. to BNL ("and the community at large"):

  Provide technology base and expertise, and serve as ***a resource for important programs and initiatives***, such as ***RHIC experiments, electron cooling, ATLAS/LHC upgrades, LSST, Linear Collider, as well as for NSLS, detectors at SNS, nanotechnology, and medical imaging***.