Detector R&D:
Programs and Facilities for Future Projects

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Mumbai, January 13-14, 2011

Project X Physics Program

- **Rare decay experiments: muon-to-electron conversion, nuclear and neutron electron dipole moments, ultra-rare kaon decays**
  - A continuous wave (CW), very high power, superconducting 3 GeV Linac has also many other uses: Standard Model tests with nuclei (ISOL targets), possible energy and transmutation applications, cold neutrons
- **Long baseline neutrino oscillation experiments**
  - CW Linac coupled to an 8 GeV pulsed Linac (and to the Recycler and Main Injector) gives the most intense beams of neutrinos at high energy (LBNE) and low energy running simultaneously with the neutrino program
- **Platform for evolution to a Neutrino Factory and Muon Collider**
  - Links the Intensity frontier and the Energy frontier with a Lepton Collider
- **Associated experiments in this laboratory environment**

Outline

- In Search of a Radical Solution
- Experimental Challenges
- Types and Levels of Future Detector Development
- Current Projects and Opportunities
- Facilities
- Conclusions

In Search of the Radical Solution

- In the current issue, January 2011, of the magazine Scientific American there is an interview with a famous Indian scientist :

  “In Search of the Radical Solution”

- The sentiment in that interview applies, I believe, equally well to detector development in our field.

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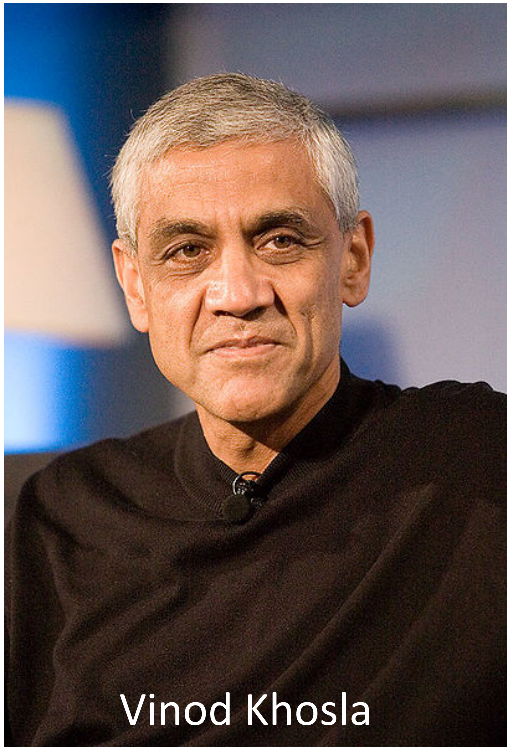
- "The greatest payoffs will come from fundamentally reinventing mainstream technologies"



-- Vinod Khosla

co-founder SUN microsystems

venture capitalist

http://www.scientificamerican.com/article.cfm?id=in-search-of-the-radical-solution
http://ScientificAmerican.com/jan2011/khosla

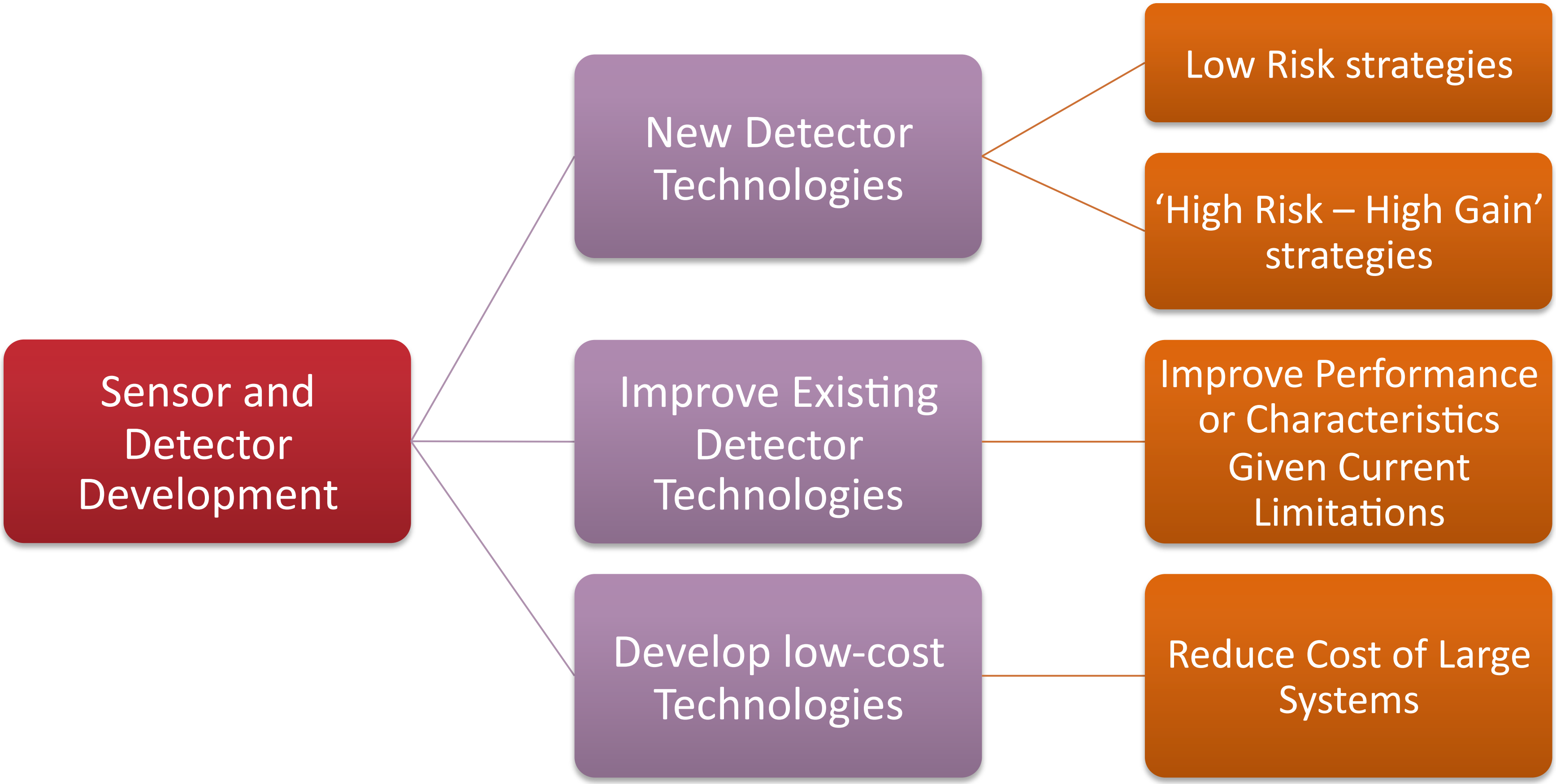
Experimental Challenges

- The next generation of detectors are extremely challenging

n^{th} generation experiment	Physics	Precision physics
Channel count technology scope/use physical size	Complexity	Increased lead time for detector development
Increased cost	Cost	Projects often out of reach of individual groups
Projects have longer and longer lifetimes	Continuance	Less opportunity for ongoing projects to get to R&D stage and vice versa

- Often, a scaling of existing technologies is difficult to justify

Types of Detector R&D

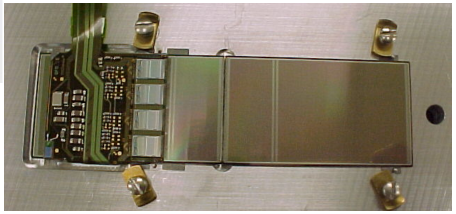


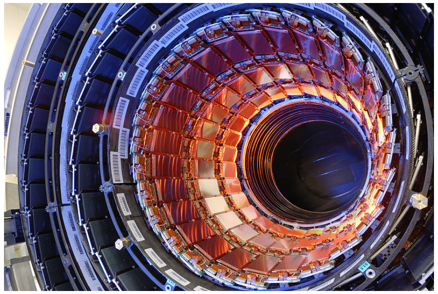
- All development efforts are of course driven by the science
- What is needed is a return to the fundamentals to develop the "radical solution"

Levels of Detector R&D

- R&D on basic technologies:
  - Investigate the feasibility of a new technology
  - Test of a concept
- R&D on technology development:
  - Building and testing of small scale, real devices
- R&D on detector development:
  - Incorporating the technology in a real engineered detector design

Si sensor
→ module
→ tracker





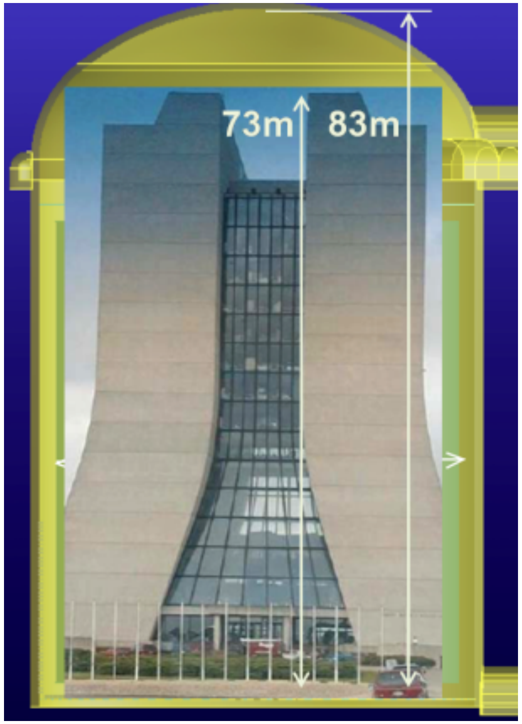
- Experiments and Detectors are of ever-increasing complexity
- Significant increase in reach and sensitivity of current detectors required
- Limits of scaling of existing technologies
- To reach our goals, this set of conditions leads to:
  - Combination of different areas of expertise: materials science, solid state physics, …
  - Understanding of the fundamentals: "Back to Basics"
  - Industrial partners

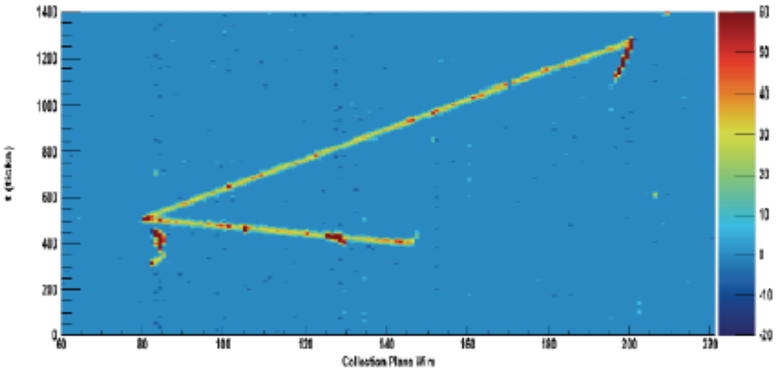
Current Projects and Opportunities

- Large Liquid Argon Time Projection Chambers
- Large Area Picosecond Photo Detectos
- Calorimetry
- Vertically Integrated, tiered Silicon Detectors
- Data Communication

Liquid Argon Detectors

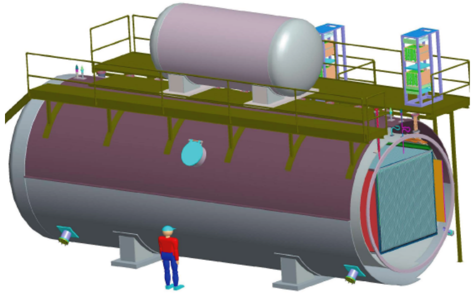
- R&D aimed at Large Detectors for long baseline neutrino physics:
  - Argon purity (without evacuation)
  - Large volume TPC design
  - Cold Electronics (in LAr)
  - DAQ reconstruction, analysis, simulation
- Can the technology be scaled and what is the scaling law?
- LAr TPC prototype at Fermilab: Argoneut
  - 175 liter active volume (550 liter vessel)
  - 480 channels of signal
  - ‘Imaging’ neutrino detector !





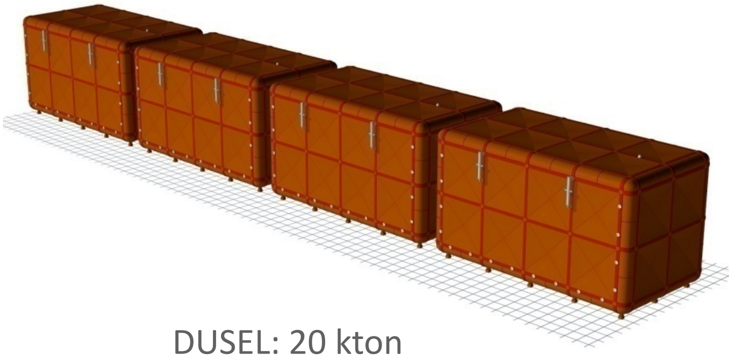
Liquid Argon Purity Demonstration

- Phase I:
  Demonstrate that the required electron lifetimes can be achieved without evacuation in a 20 ton Liquid Argon tank
  - Will also monitor the temperature gradients, concentrations of water, O_2, and N_2
- Phase II:
  Demonstrate that the purity can be maintained while placing TPC materials in the volume
- Phase III – IV – V: moving to larger scale



MicroBoone: 170 ton

→



DUSEL: 20 kton

LAr R&D Station

- A stand-alone R&D station for LAr purity monitoring established at Fermilab and operated as a user facility

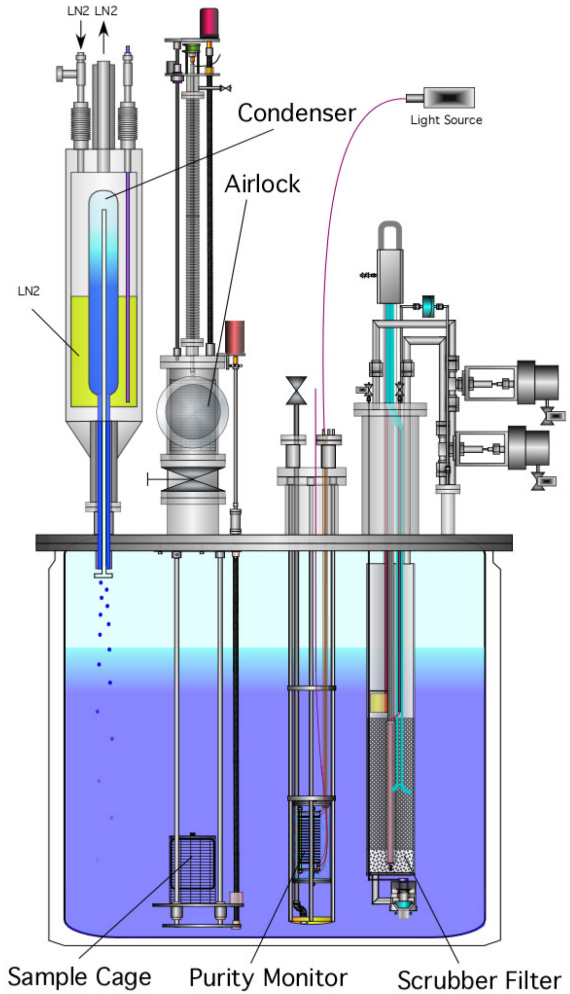
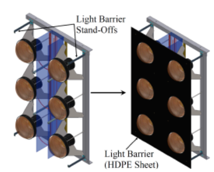
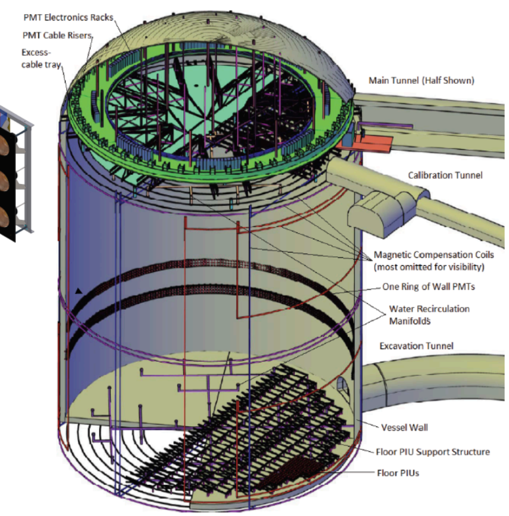


Photo Multiplier Tubes

- "Old" Technology
  - Used for decades
  - Robust, generally low noise
  - Simple biasing
- Time resolution ~2-3 nsec
- Spatial resolution limited by tube radius
- Total coverage offered is typically less than 40%
- Typical photocathode efficiency ~25%
- Few vendors

- Can this technology address the challenges of the next generation of H_2O Čerenkov experiments?





Proposed DUSEL Čerenkov detector

Large Area Picosecond Photo Detectors (LAPPD)

- Project with four primary goals:
  1. Large-Area Low-Cost Photo-detectors with good correlated time and space resolution (target 10 $/sq-in incremental area cost)
  2. Large-Area TOF particle/photon detectors with pico-second time resolution
     - < 1psec at 100 photo-electrons
  3. Understanding photo-cathodes so that we can reliably make high QE cathodes with tailored spectral response, and develop new materials and geometries
     - QE > 50%?, public formula
  4. Produce commercializable modules within 3 years
     - transfer technology to industry

The Development of Large-Area Fast Photo-detectors

April 15, 2009

John Anderson, Karen Byrum, Gary Drake, Edward May, Alexander Paramonov, Mayly Sanchez, Robert Stanek, Hendrik Weerts, Matthew Wetstein[1], Zikri Yusof
High Energy Physics Division
Argonne National Laboratory, Argonne, Illinois 60439

Bernhard Adams, Klaus Attenkofer
Advanced Photon Source Division
Argonne National Laboratory, Argonne, Illinois 60439

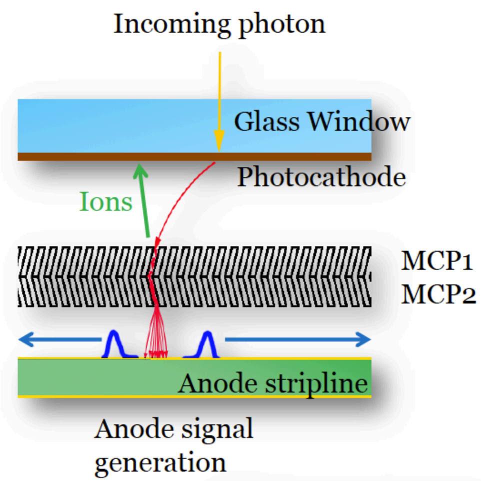
Zeke Insepov
Mathematics and Computer Sciences Division
Argonne National Laboratory, Argonne, Illinois 60439

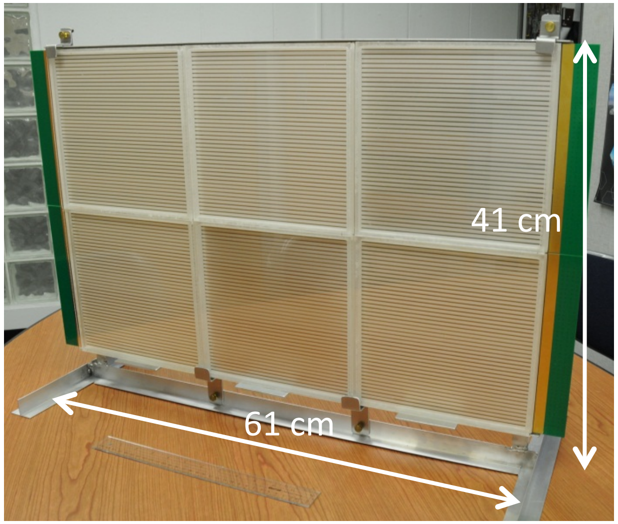
- Unique collaboration:
  - 3 National Laboratories
  - 6 Divisions at Argonne
  - 3 Universities
  - 3 Commercial Companies

http://psec.uchicago.edu/

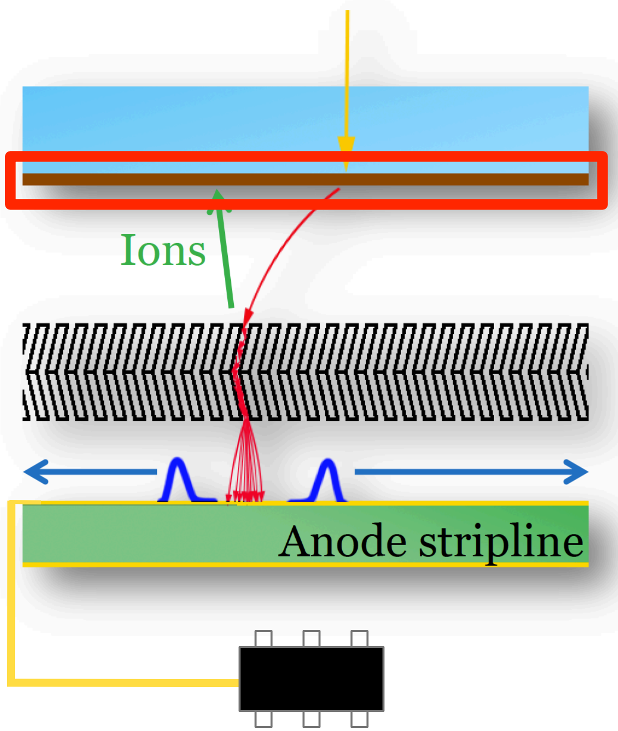
LAPPD: Approach

- Base on Existing Technology: Micro Channel Plate (MCP) photo-multiplier
  - Picosecond-level time resolution
  - Micron-level spatial resolution
  - Excellent photon-counting capabilities
  - Expensive
- New Aspect: Fully Integrated Approach
  - Exploit advances in material science and electronics to produce large-area MCP-PMTs:
    - Preserve time and space resolutions of conventional micro-channel plate detectors
    - At low enough cost per unit area



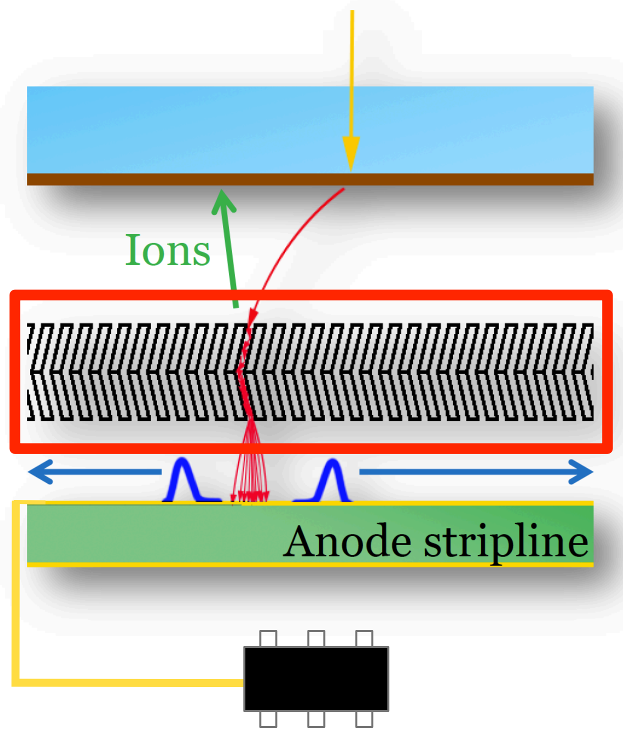


LAPPD Deconstructed



1. Photo-Cathode (PC)
   - Conversion of photons to electrons
   - Engineer III-V materials to develop robust high QE photo-cathodes
2. Micro-Channel Plates
   - Amplification of signal: two plates with tiny pores, held at high potential difference. Use Atomic Layer Deposition for emissive material on inert substrates to create avalanche
3. Transmission line, high speed readout
   - Anodes is a 50Ω scalable strip line silk-screen printing on glass ground plane (Borofloat 33)
4. Hermetic Packaging
   - Maintain vacuum and provide support. No internal connections; no penetrations
5. Electronics
   - Readout at both ends with fast custom CMOS SCA chip with 10GHz waveform digitization

LAPPD Deconstructed



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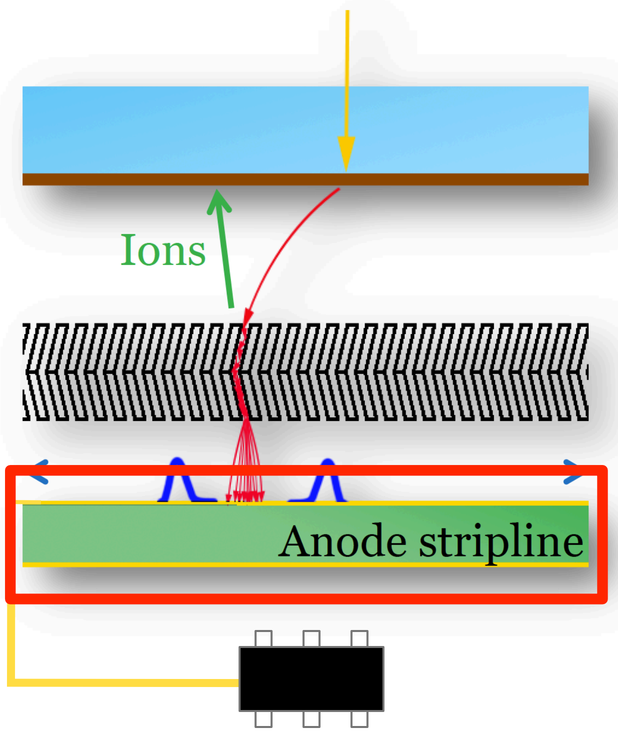

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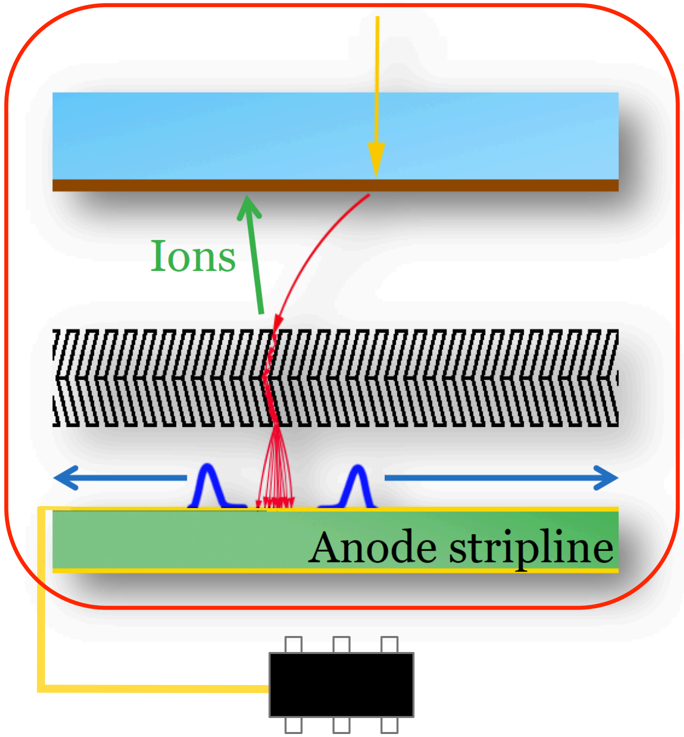

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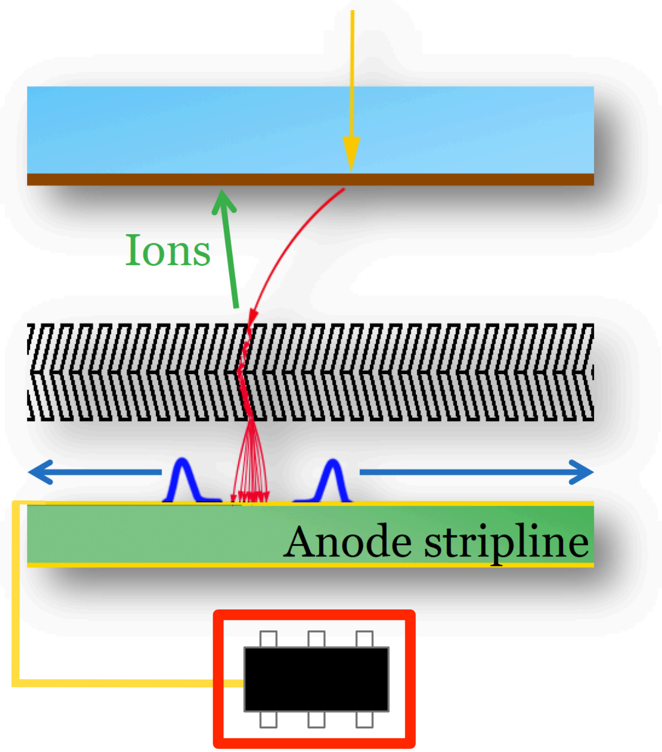

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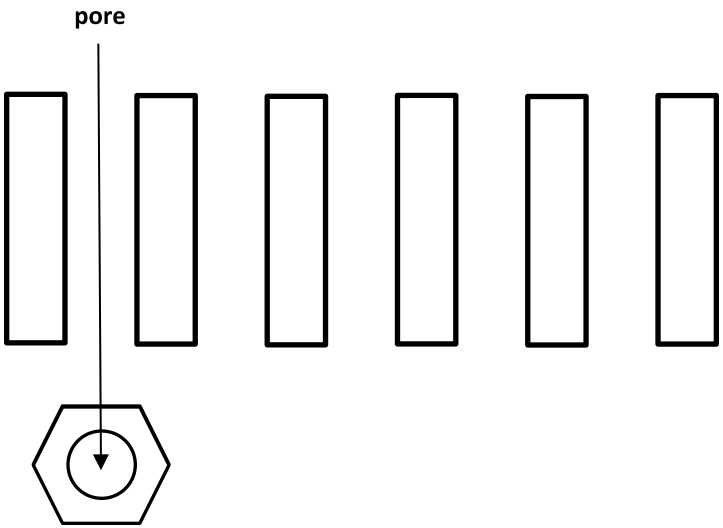
4. Hermetic Packaging
   - Maintain vacuum and provide support. No internal connections; no penetrations
5. Electronics
   - Readout at both ends with fast custom CMOS SCA chip with 18 GHz waveform digitization; optimized design yields pico-second timing resolution

MCP Fabrication with ALD

- Start with glass capillary array (borosilicate), pulled to appropriate pore size

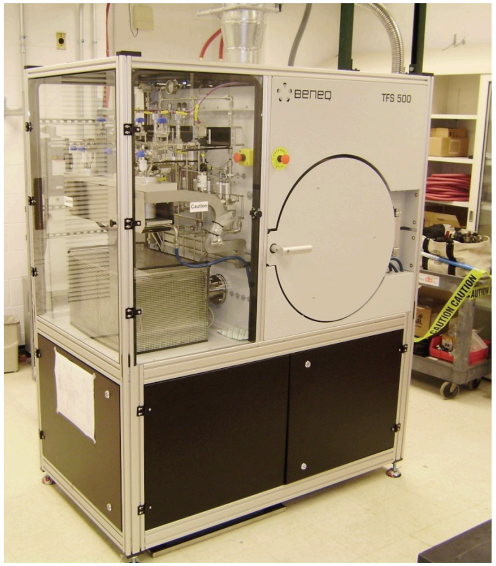
20 μm pores

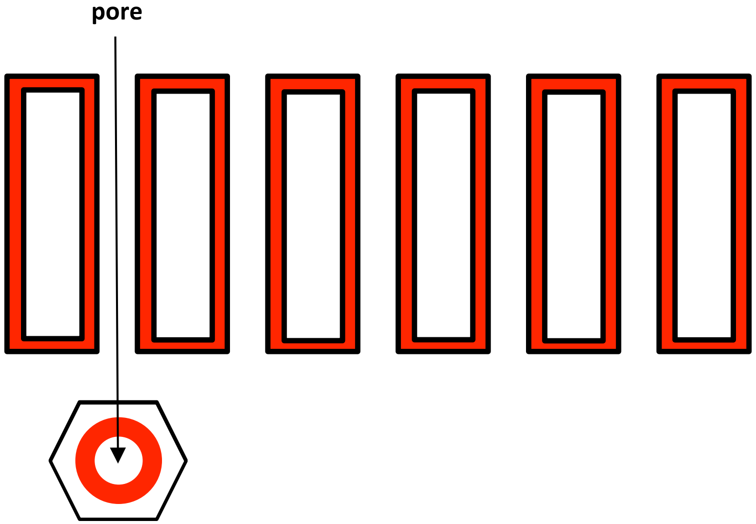


- Obtained MCP arrays with 33mm diameter, pore size 5 μm
- Goal is L/D = 40, D = 5 μm, 8"x8"

MCP Fabrication with ALD

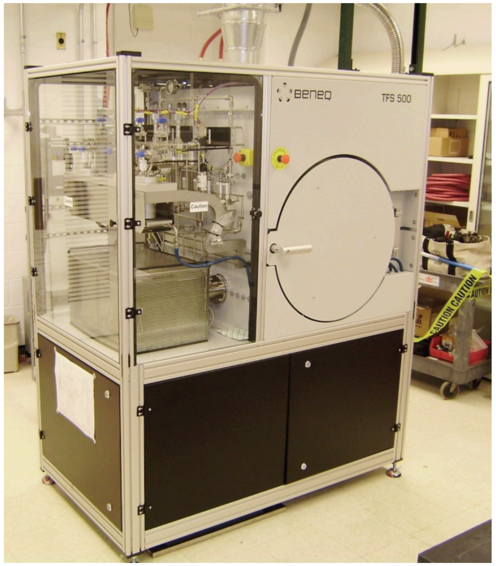
- Apply resistive coating, 17nm, using Atomic Layer Deposition, in Beneq reactor

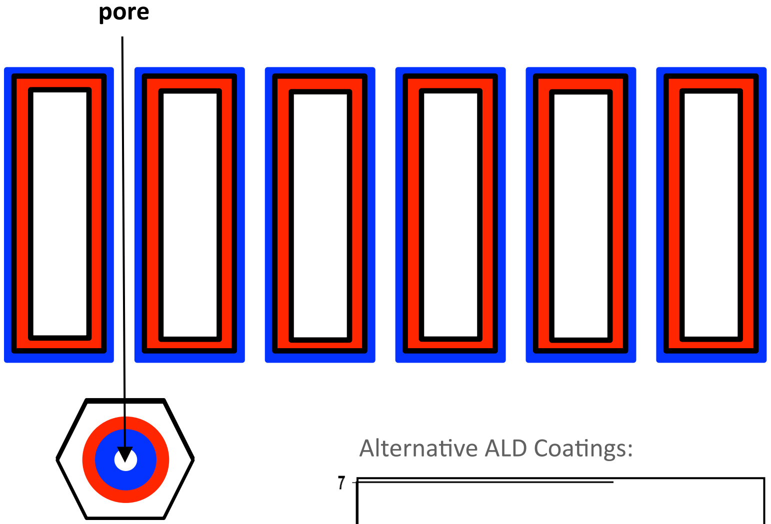




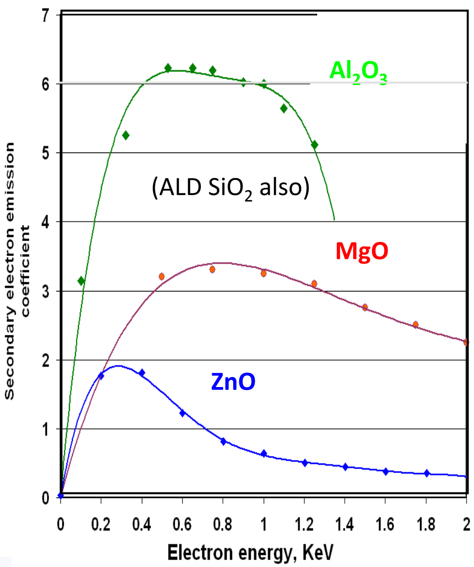
MCP Fabrication with ALD

- Apply emissive Al_2O_3 layer, using using Trimethyl Aluminum $Al(CH_3)_3$ and ALD





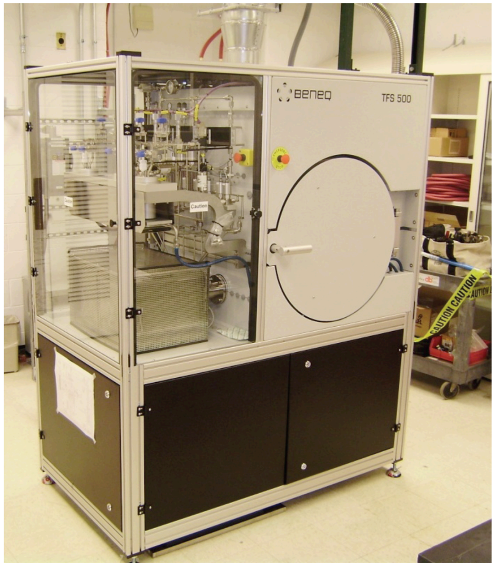
Alternative ALD Coatings:

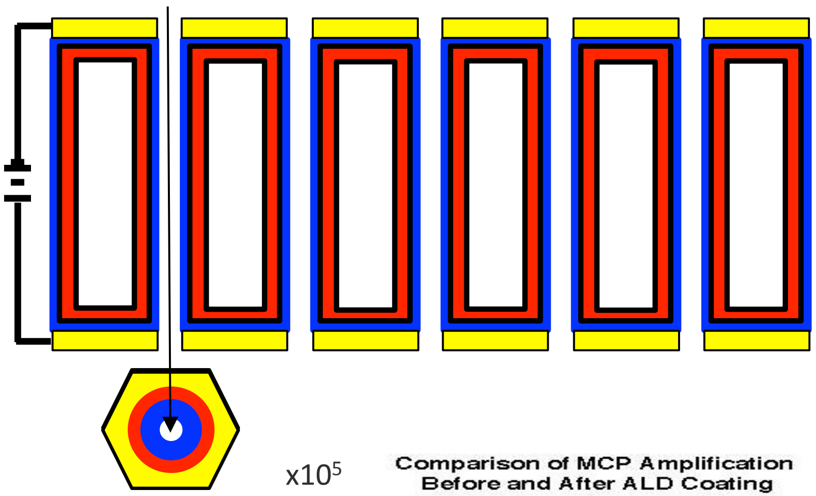


- Wide parameter space studied
  - Relative composition of materials
  - Temperature for ALD
  - Different materials and thicknesses
- Figure shows secondary electron emission coefficient as function of electron energy (keV)

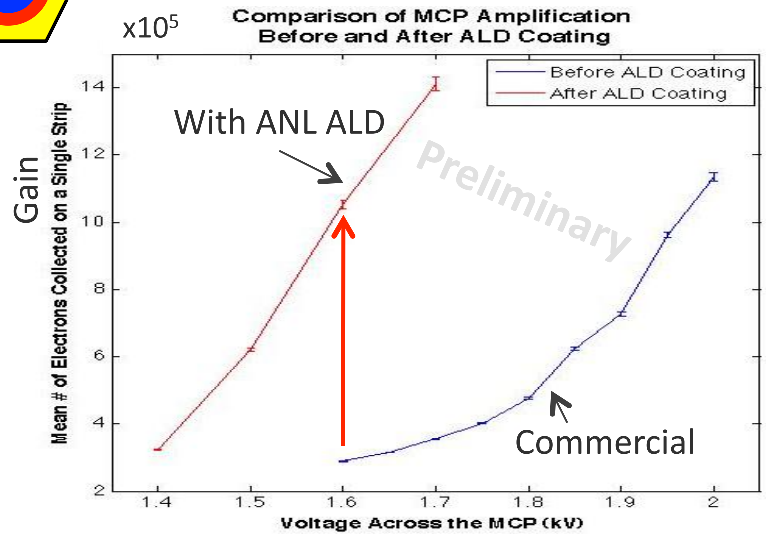
MCP Fabrication with ALD

- Apply conductive coating for HV, using thermal evaporation or sputtering



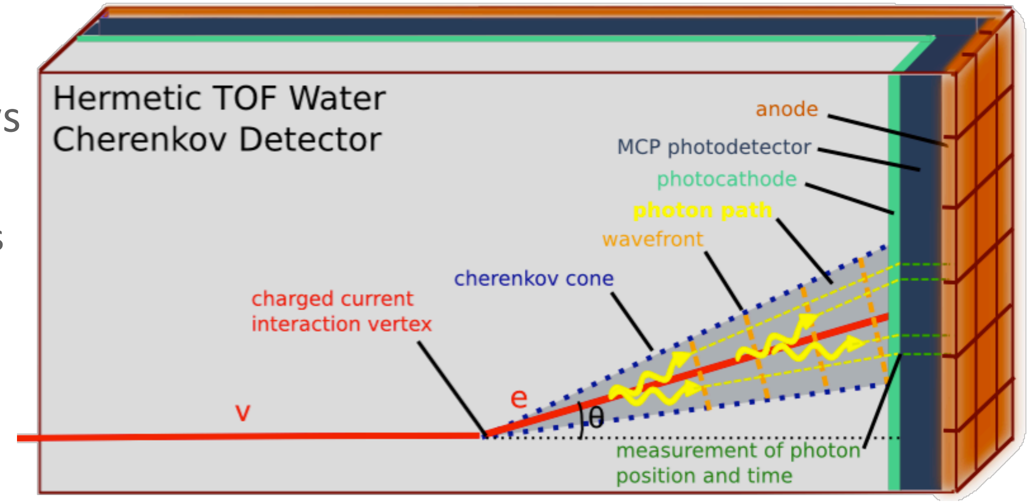


- First time applying new technology, a factor >5 improvement obtained in gain of ALD treated MCPs compared to commercial MCPs; area will be substantially increased

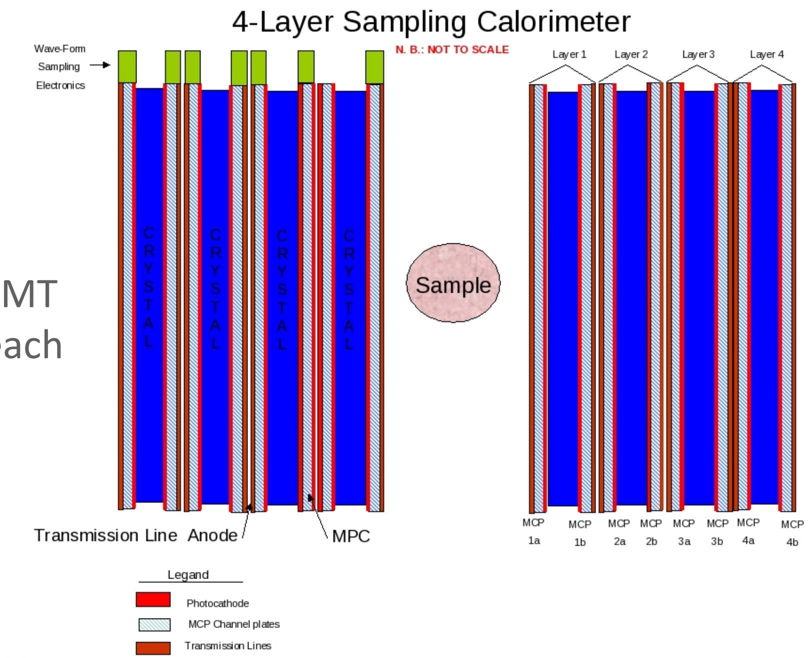


Applications

- Large area H_2O Čerenkov detectors
- Pico-second timing resolution allows for π^0/e rejection
  - 100 ps time resolution corresponds to about 1 cm space resolution
  - Vertex separation many cm



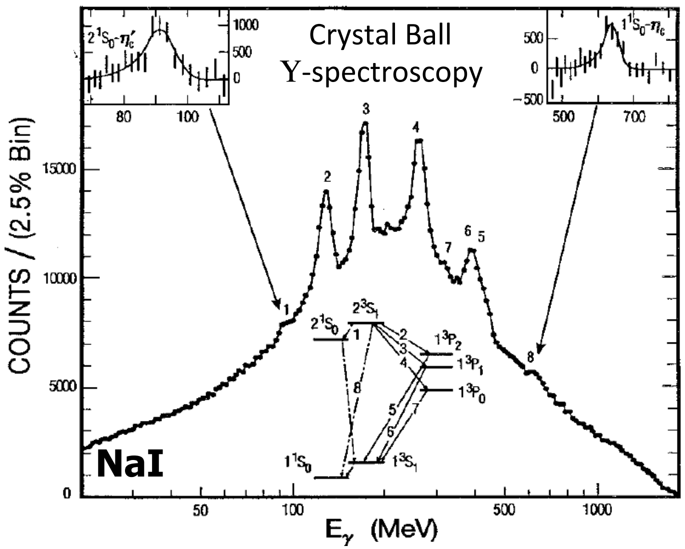
- Medical Imaging (PET)
- The better the timing resolution, the more accurate the image of depth of interaction
- Example:
  - Alternating radiator and planar MCP-PMT with 30-50 psec timing resolution on each side

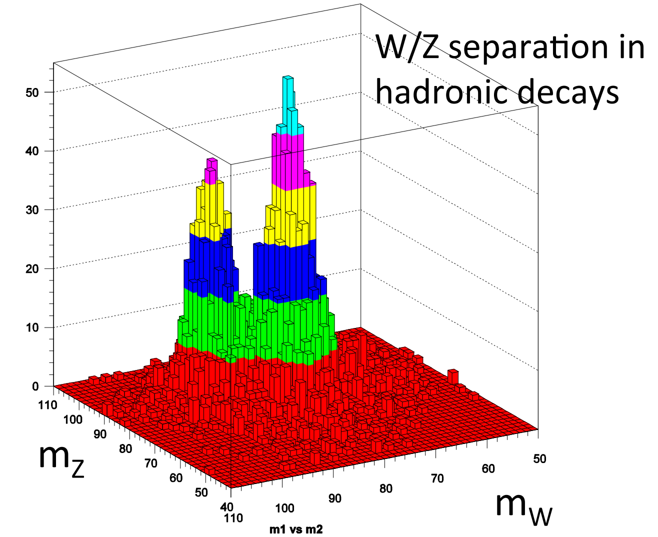


- Collider environment
  - Reconstruction of real 4-momenta

Calorimetry

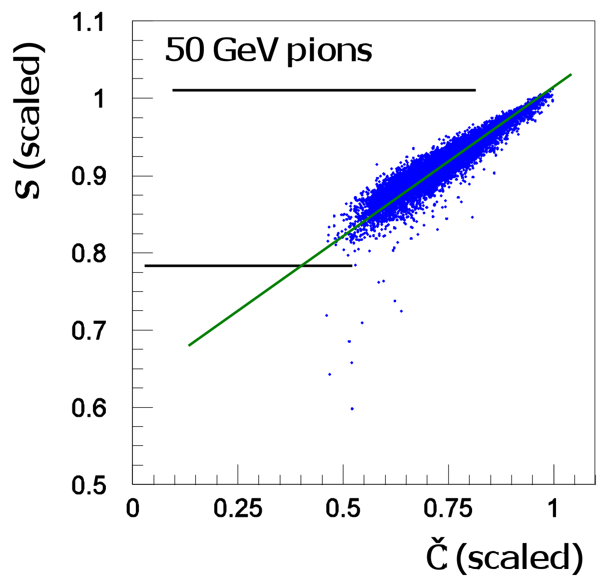
- Total absorption calorimetry, based on crystals, proven to be highly successful for electromagnetic calorimeters.
  - $\sigma(E)/E < 1\ \%$
- Can this be extended to hadron calorimeters?
  - To date, best hadronic jet energy resolution $\sigma(E)/E = 50\% / \sqrt{E}$
  - Is $\sigma(E)/E$ of 20-25% / $\sqrt{E}$ achievable?
  - This resolution would enable discrimination of W and Z boson decays into hadronic jets;
- Two approaches to reaching substantially improved hadronic energy resolution
  - Total Absorption Dual Readout Calorimetry
  - Digital Imaging Calorimetry

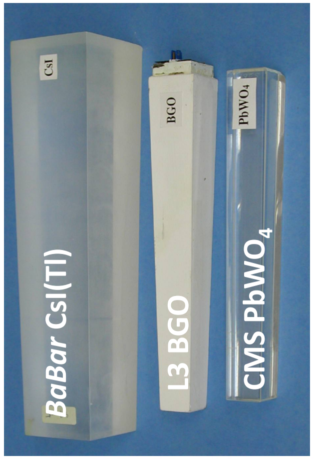


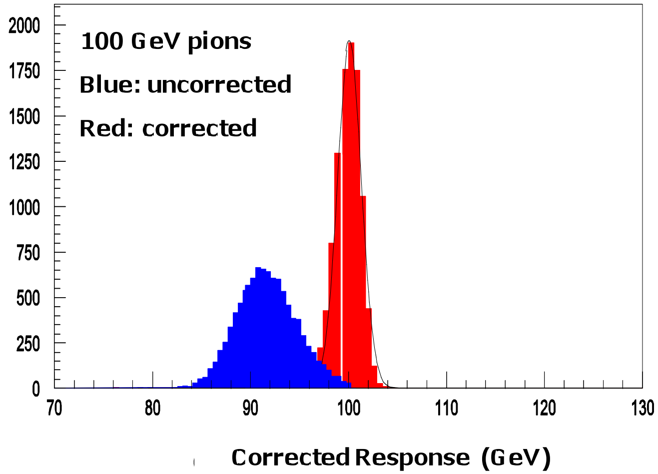


Total Absorption Dual Readout Calorimetry

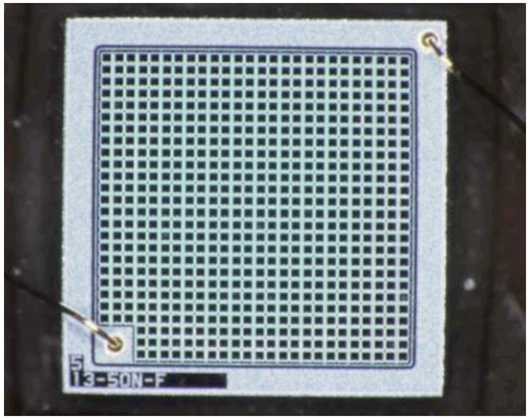
- Dual-readout calorimetry: measure every shower twice
  - Scintillation light: from all charged particles
  - Čherenkov light: β=1 particles, mainly EM
- Correct on a shower-by-shower basis using the correlation of the total observed ionization (S) and Čherenkov (Č) light
  - MC: Energy resolution (0.1-0.2)/√E (Gaussian)
  - MC: No constant term up to 200 GeV
- Development of crystals is key:
  - Density > 7 gr/cm^3
  - Scintillation and Čherenkov light separation



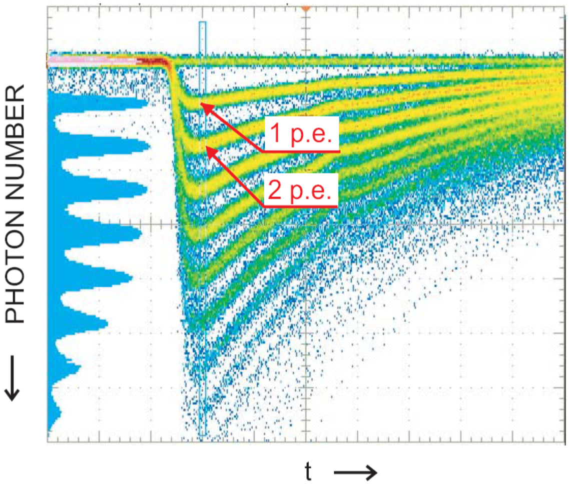




PPD or Silicon Photomultiplier

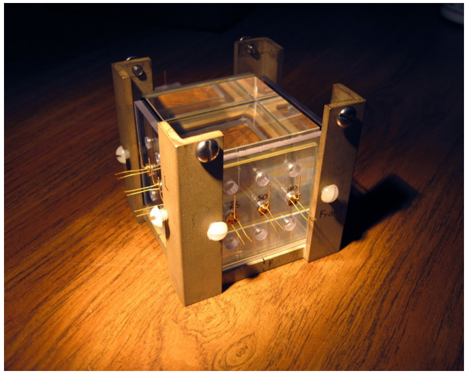


- This type of hadron calorimetry is enabled because of the availability of the PPD: Pixelized Photon Detector
  - Avalanche photodiode operating in Geiger-mode
  - Array of pixels connected to a single output
  - Digital device read out in analog way
  - Signal = Sum of all cells fired
  - Devices compact, insensitive to B-field
    low bias voltage



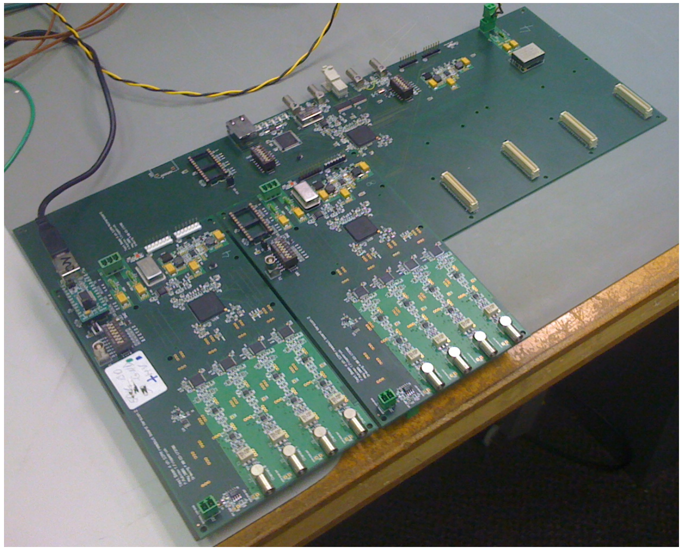
- Developed general facility for characterization of PPDs
  - Dark and photo response

- Mount on crystals and readout both types of light, in the lab and in the beam test

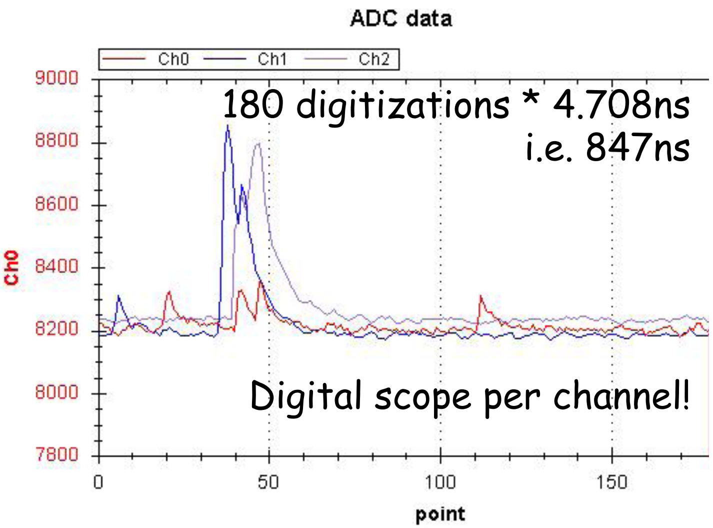


PPD Readout

- Developed TB4 (test beam 4-channel) readout
  - 12bit ADC (large dynamic range)
  - 212 MSPS (4.7ns)
  - ~100MHz bandwidth
  - Bipolar signals
  - USB setup, readout Ethernet
  - On-board bias generation
  - Allows for online signal processing

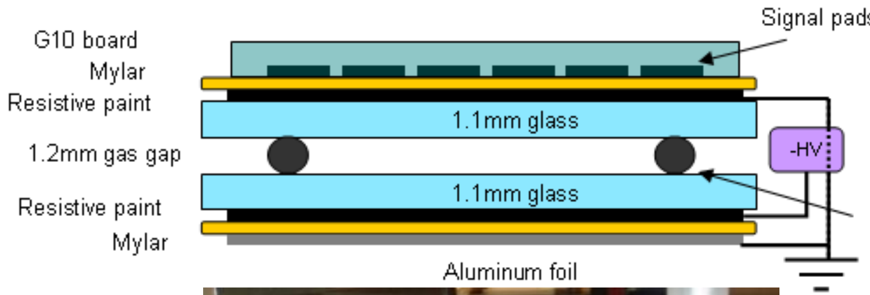


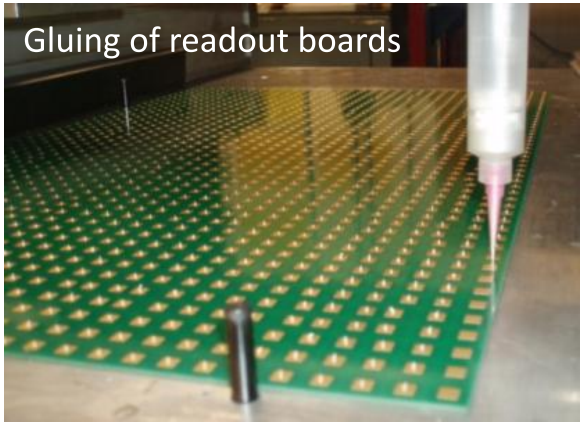
- Developing plans for dedicated ASIC for PPD readout

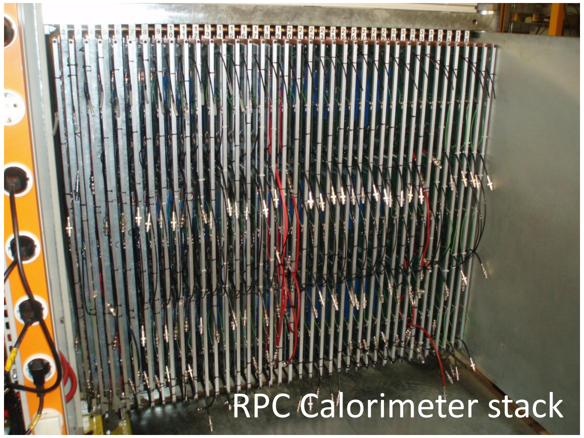


Digital Imaging Calorimeter

- Very fine-grained calorimeter based on glass Resistive Plate Chamber (RPC) technology
- Built 1 m^3 sandwich calorimeter
  - Absorber – 20 mm thick steel plates
  - Active element – Resistive Plate Chamber
    150 RPCs built (90cmx30cm)
- Configuration
  - Longitudinally – 40 layers individually readout
  - Laterally – 1x1 cm^2 pads
  - Depth ~ 4λ
- Readout
  - Fermilab designed 128 channel DCAL asic
  - Total of ~350,000 readout channels
  - Resolution Is 1 bit / pad
- Tested in Fermilab testbeam
  - Excellent performance
- Broad use of RPCs as particle detector



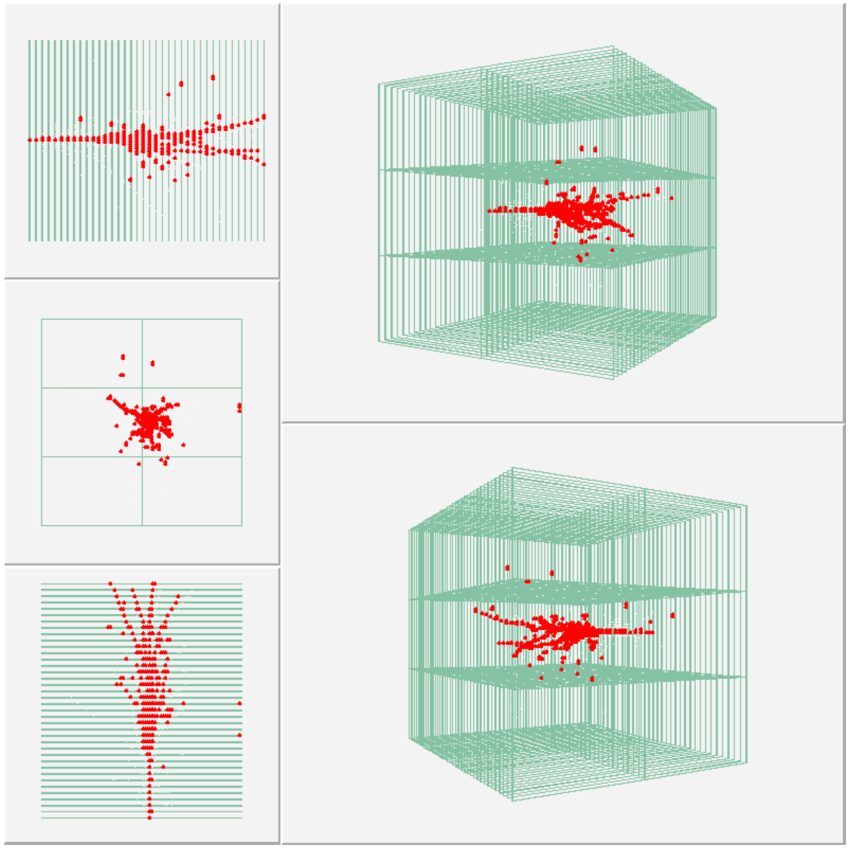




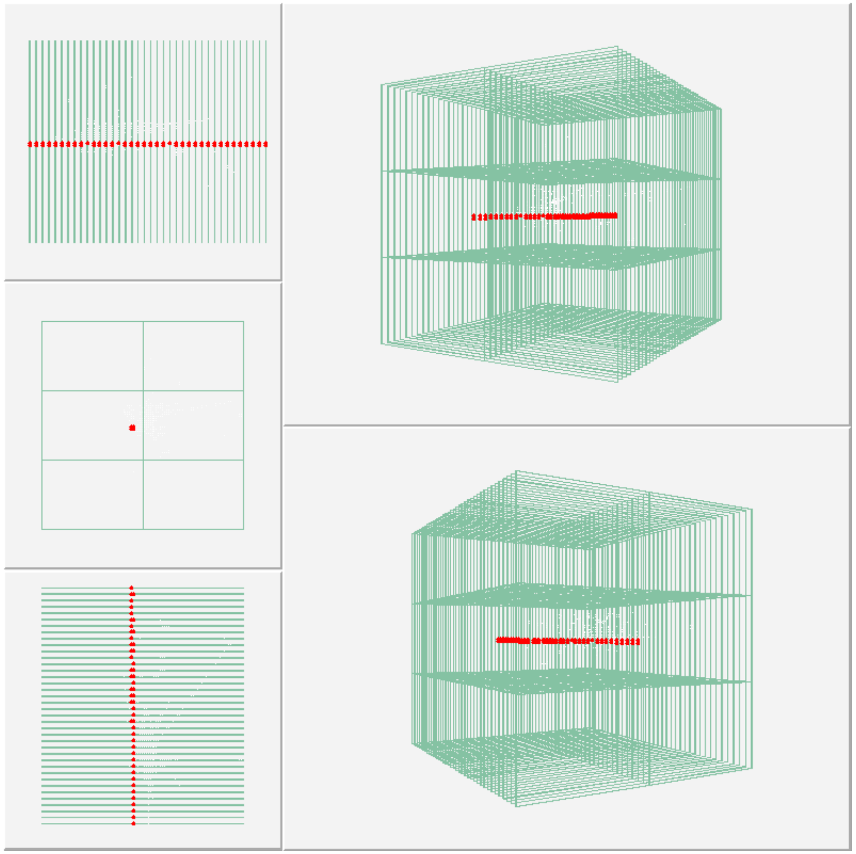
Testbeam Results

- Results from a 32 GeV Pion run in Fermilab Testbeam

Pion shower



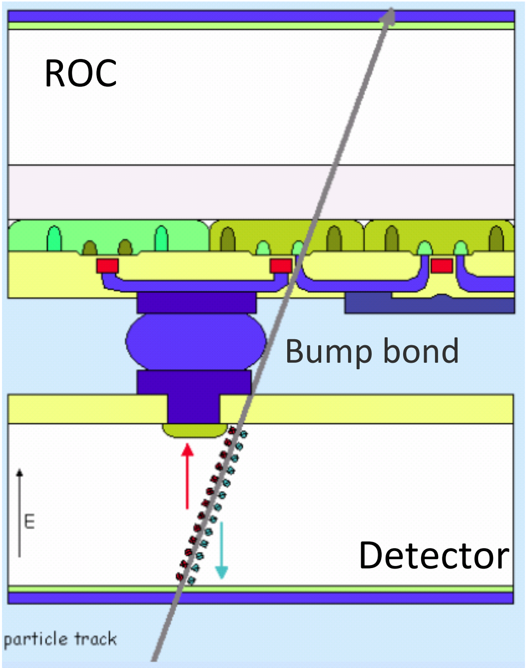
Single muon … no noise



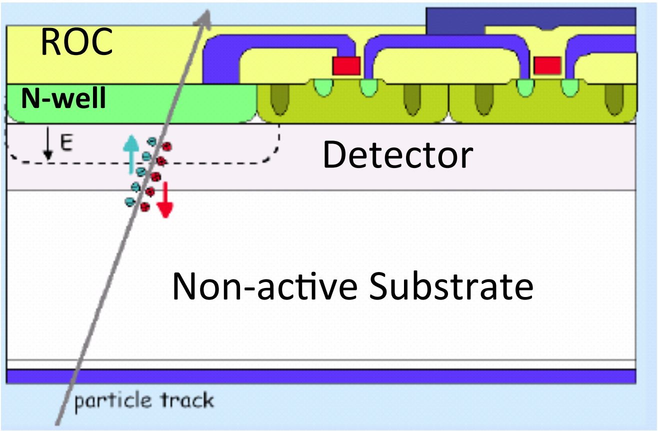
Silicon Detectors

- The physics reach of many experiments is greatly enhanced through the use of silicon detectors, often precision tracking and vertex detectors
- These detectors are highly demanding in terms of material budget, power, readout channels, …
- To address these issues, Monolithic Active Pixel Sensors (MAPS) are being studied
- These detector integrate detector and front-end readout electronics on the same substrate
  - Signals generated in the epitaxial layer
  - Few microns thick, small signals
  - Charge collection through diffusion
  - Device not depleted, relatively long collection time
- But, industry is pursuing other venue for memory logic, FPGA speed, …

“Conventional” Pixel Detector

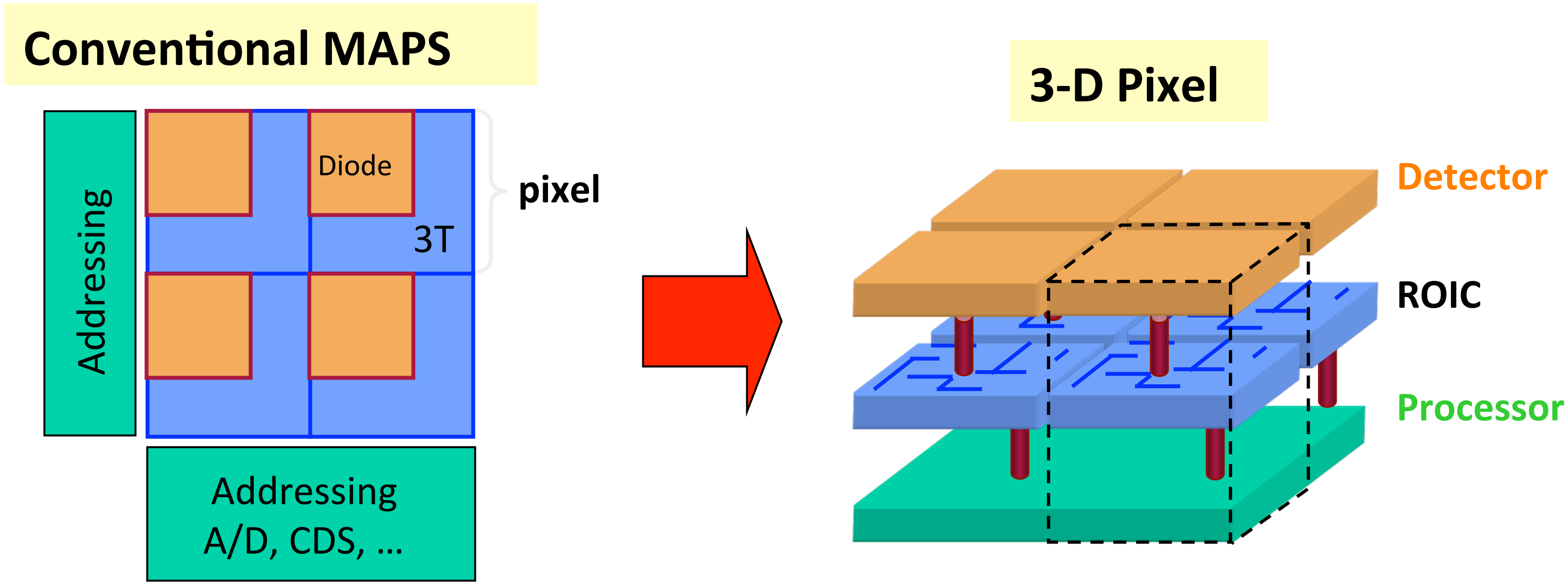


MAPS



Vertical Integration in Silicon - 3D

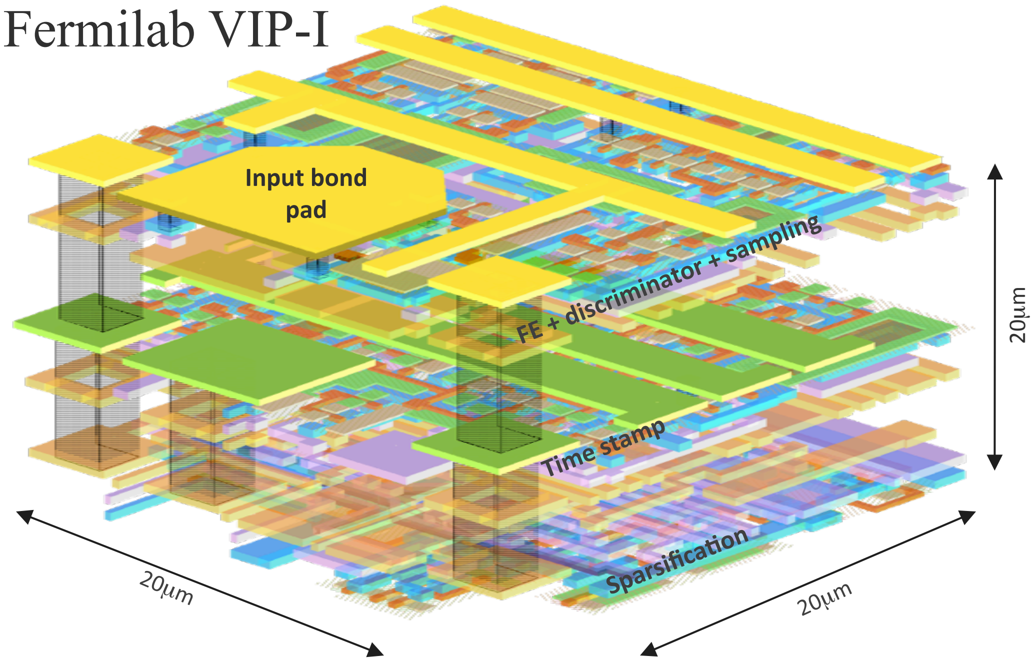
- Vertical integration of thinned and bonded silicon tiers with vertical interconnects between the IC layers
- Technology driven by industry; offers potential for transformational new detectors



3D Demonstrator Chip

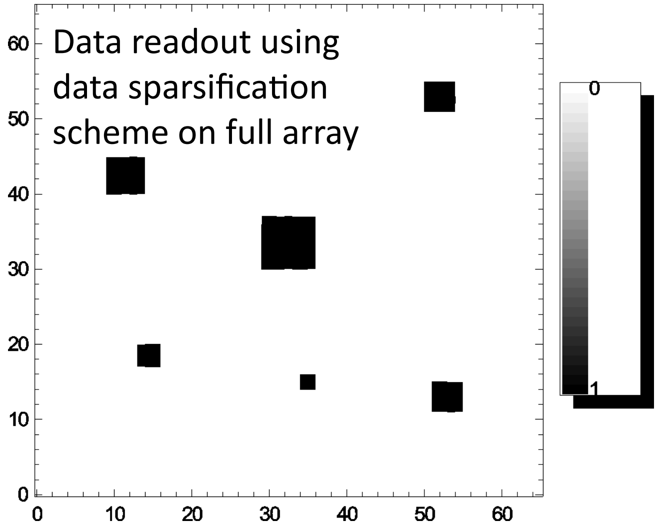
- Fermilab started to actively pursue the 3D technology in early 2006 in collaboration with MIT-LL
  - MIT-LL offered three-tier multi-project wafer (MWP) runs
- Designed Vertical Integrated Pixel (VIP) Chip for ILC detector readout

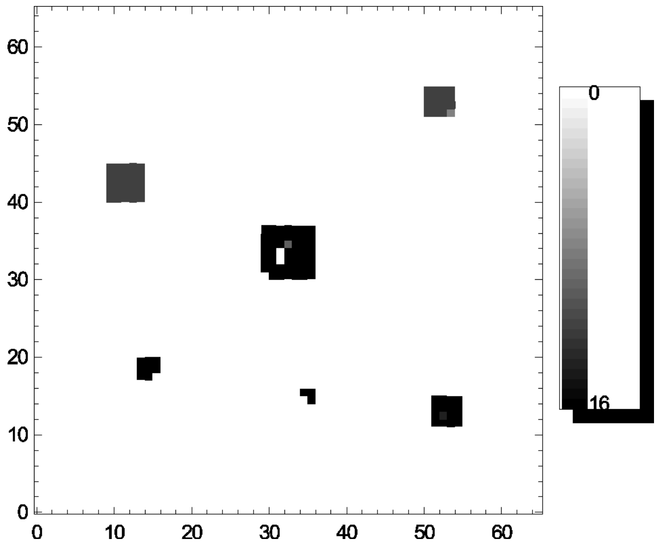
Fermilab VIP-I



- VIP-I Design
  - 3D design in three-tier, via last, 0.18 mm SOI process
  - 64 x 64 pixel array, 20x20 mm2 pixels, scalable to 1M pixels
  - Data sparsification, 5-bit digital and analog time stamp, high speed token passing
  - Analog output
  - No integrated sensor

Test Results of VIP Demonstrator Chip



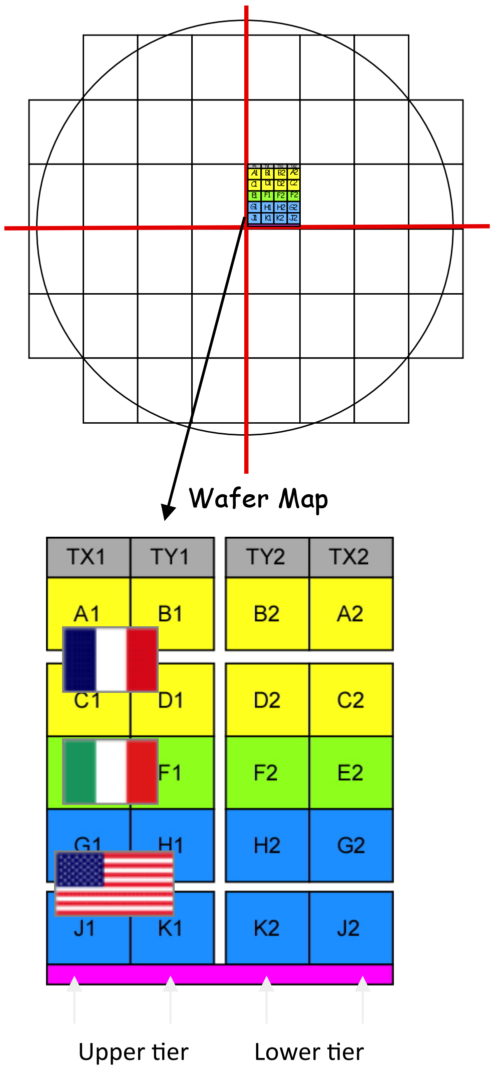


Preselected Injection (top) and Readout (bottom) pattern of pixels reported as hit using data sparsification

- VIP-1 chips tested in 2008; chip works !
- Major breakthrough in the development of advanced ASICs and integrated detector systems
  - An improved version of VIP-1 has been submitted to MIT-LL

- 3D technology driven by industry
- Started an initiative with leading local company (Tezzaron) to develop 3D technology
- Advantages:
  - Existing rules for vias and bonding
  - One stop shopping for wafer fabrication, via formation, thinning, bonding
  - Process is available to all customers
  - Lower cost

Fermilab 3D Multi-Project Run



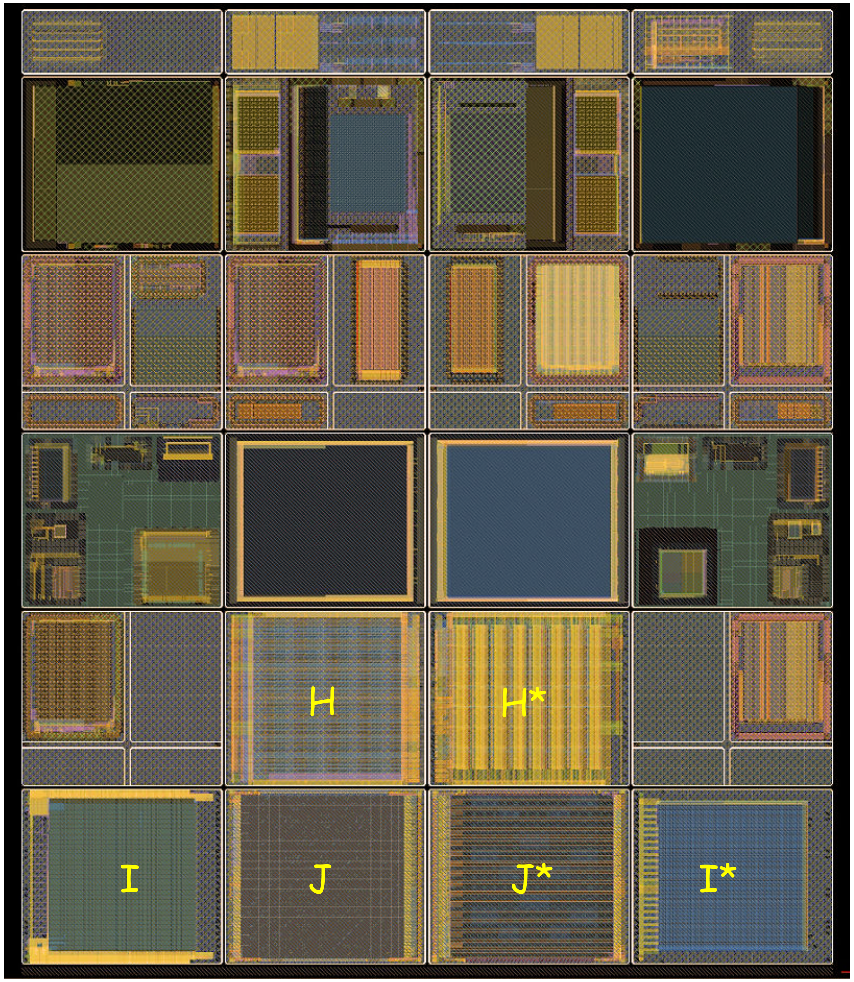
Reticle Layout

- Fermilab formed a 3D collaboration and hosted a 3D multi project run with Tezzaron
  - Two layers of electronics fabricated in the Chartered 130 nm process, useful reticle size is 16x24 mm
  - Wafers will be bonded face to face
  - Submission closed September 2009
- 17 Participating institutions in the MPW run
  - Fermilab host
  - 14 European institutions
  - Two US institutions (LBNL, BNL)
- Application for b-factory, ILC, CMS, ATLAS, imaging, …
  - Application is completely free to user!
- Frame divided into 12 sub-reticules for consortium members; more than 25 two-tier designs

Multi Project Wafer: Full Frame Layout

Test chips:
TX, TY
2.0 x 6.3 mm

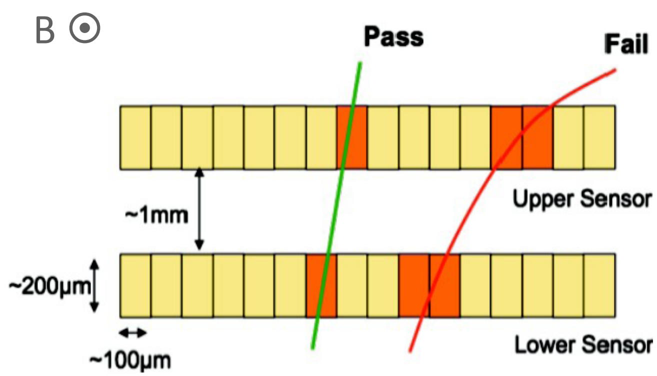
Subreticules:
A, B, C, D,
E, F, G, H, I, J
5.5 x 6.3 mm

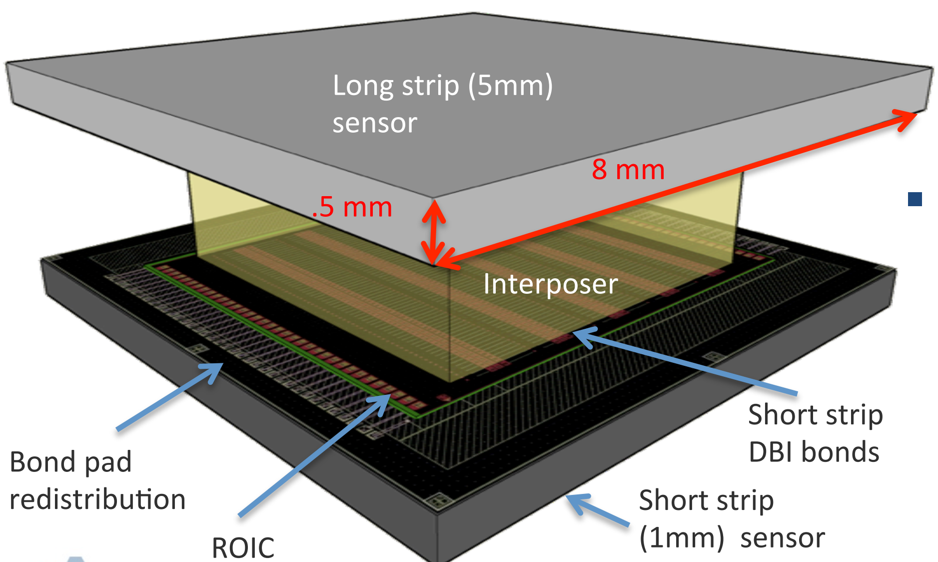


Top tiers — Bottom Tiers

Notice Symmetry about vertical center line

Application: Momentum Trigger

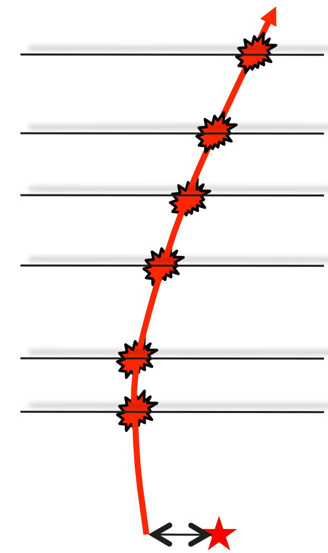




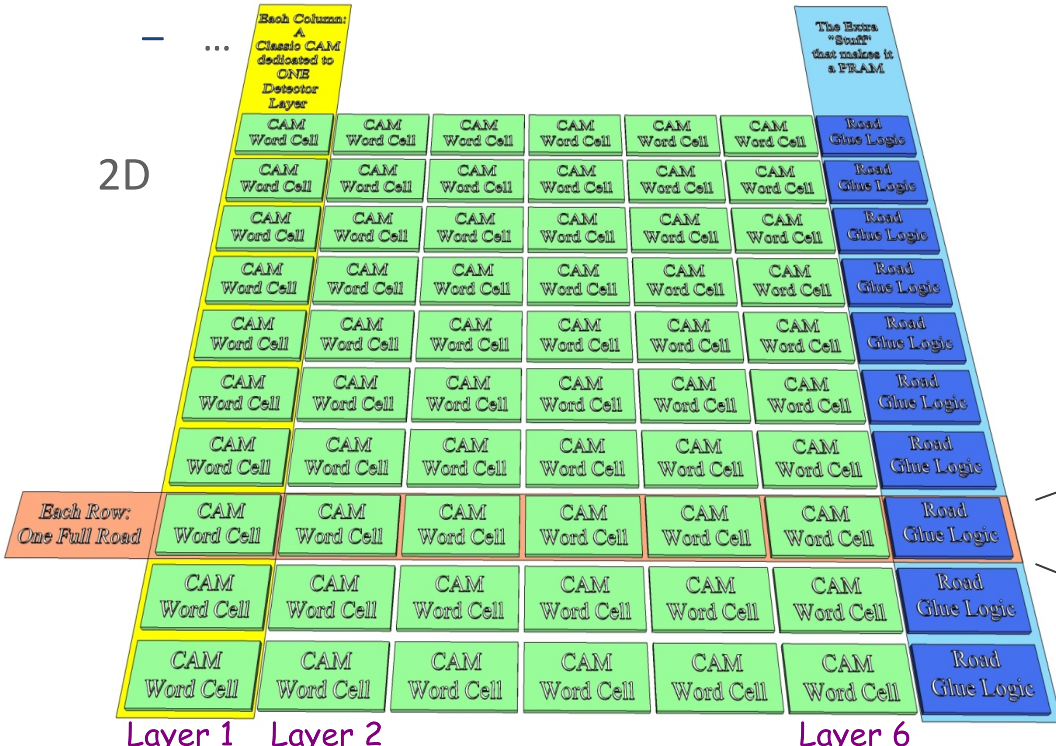
- In a collider experiment, only select high momentum tracks: track-trigger at the first trigger level for sLHC
  - Momentum filter using a pair of Si sensors separated by ~1mm
- Data flow is vertical !
  - Hits from two sensors correlated
  - Need Through Silicon Vias (TSVs) to transfer data from one sensor to the next
- Chip design:
  - The top tier looks for hits from long strips to provide phi information
  - The bottom tier looks for coincidence between phi and shorter z strips connected to bottom tier through interposer

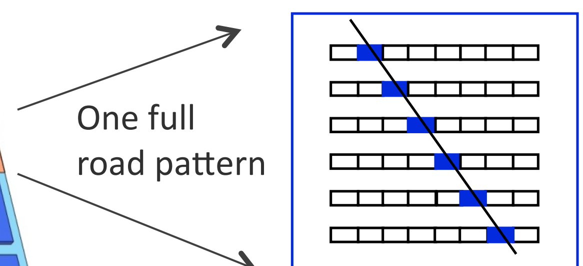
Application: Pattern Recognition

- To perform real-time pattern recognition, for example to identify displaced vertices, use Content Addressable Memory (CAM) cells
- The number of patterns that can be stored is limited
  - Memory available
  - Technology used (130 nm)
  - Size of stored content
  - …



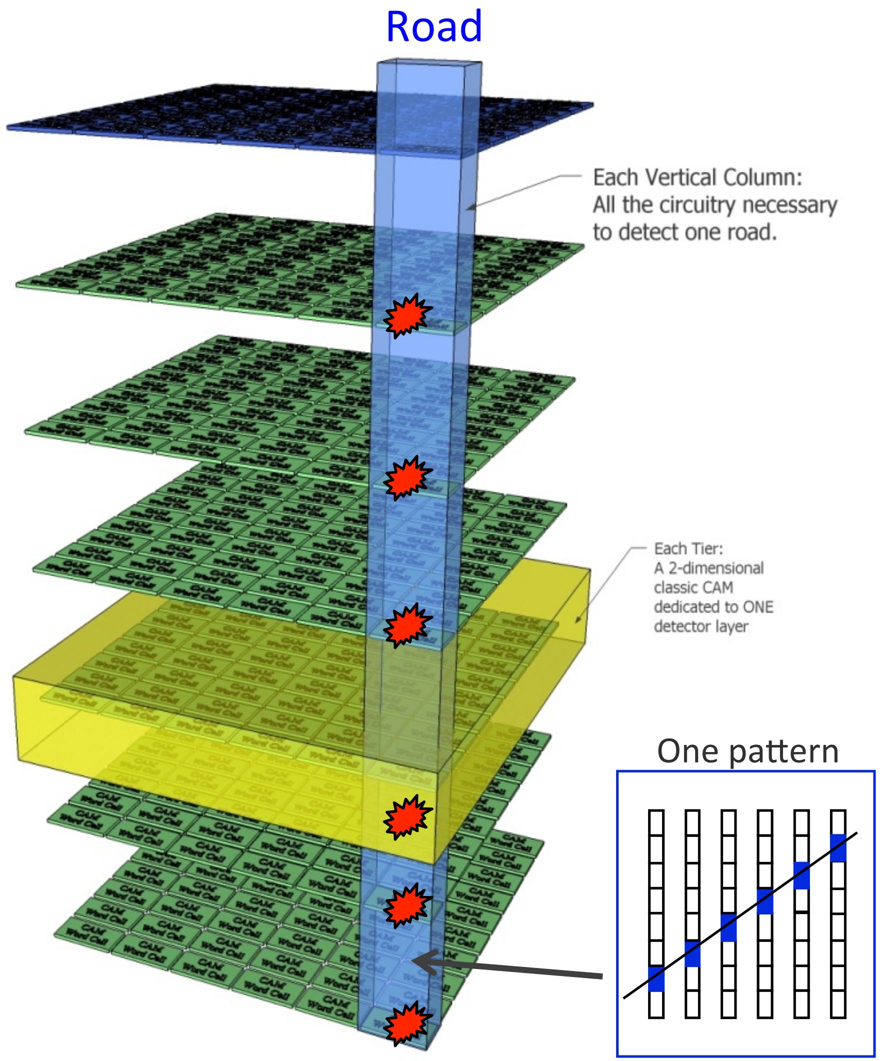
2D





Application: Pattern Recognition in 3D

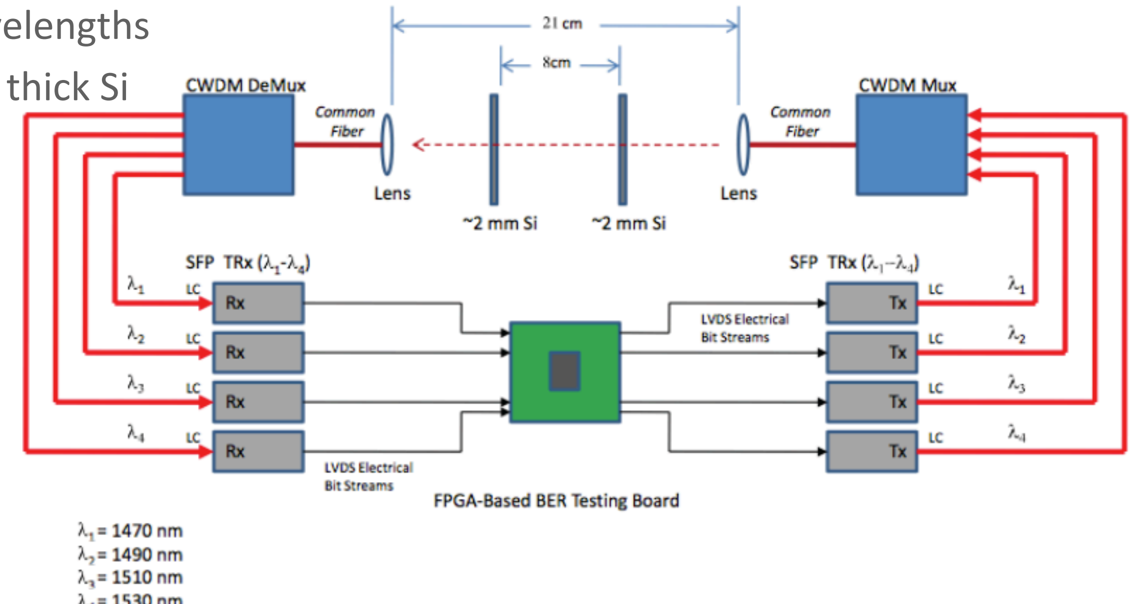
- Use 3D silicon technology to store each layer in a silicon tier



- Large number of patterns can be stored (~200k)
- Large number of Through Silicon Vias (TSV) needed
  - Currently can reliably achieve 160k TSV/mm^2
  - Via size is ~2μm
  - Contact yield is 99.9999%
- Note: vertical stacking in space domain; time domain may be equally possible
- Possibilities may ultimately be limited by our own imagination

Data Communication

- Next generation of detectors characterized by very large volumes and very large data size. Power is an issue, cables are impractical and constitute a lot of mass
- Explore optical / wireless data transmission
- Silicon is mostly transparent to infrared light
  - Test with four different wavelengths
  - Signal sent through 2*2mm thick Si
  - Bit Error Rate < 10^{-14}



- Can modulate the laser beam by the signal itself (GeSi-modulators), combined with MEMS technology to steer the beams
- Could allow for ultra-low energy consumption (50 fJ/bit, or 50 µW at 1Gb/s), with GHz bandwidth

Existing Effort

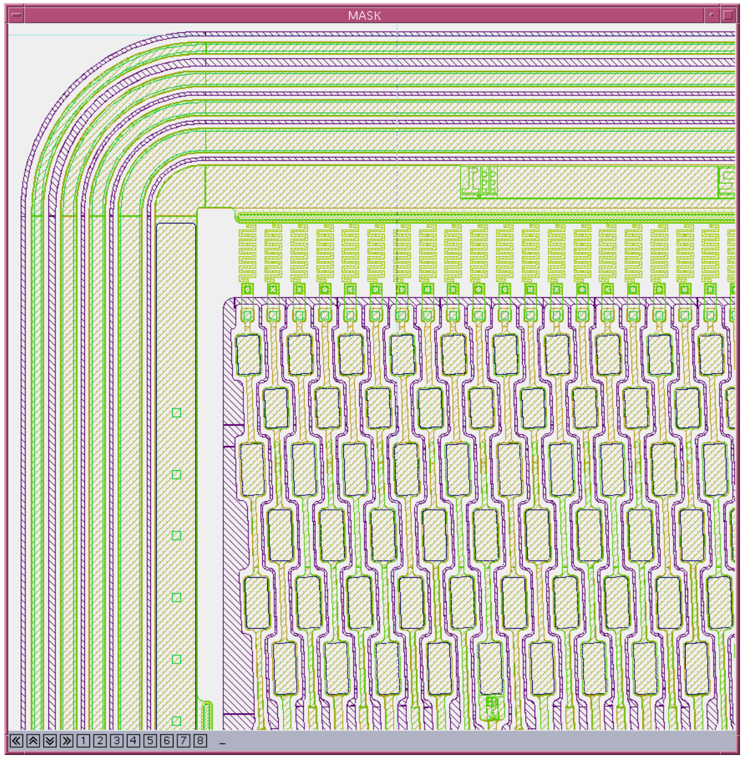
- Fermilab and Delhi University are working with Bharat Electronics (BEL) in Bangalore on the development of double-sided silicon detectors
  - Fermilab provided blank Si wafers
  - Delhi University did simulation and mask design

भारत इलेक्ट्रॉनिक्स
BHARAT ELECTRONICS

Quality, Technology and Innovation

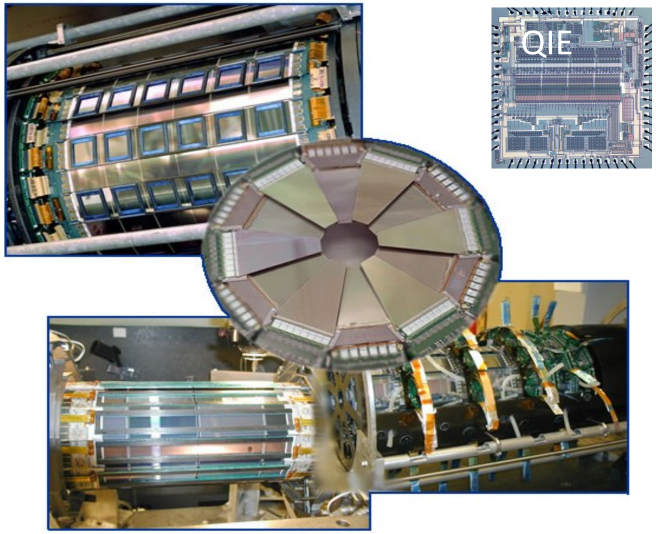
- First single-sided wafers for testing will be available in March

- After characterization of single-sided wafers, will develop double-sided design following the Dzero double-sided detector design



Facilities: Fermilab

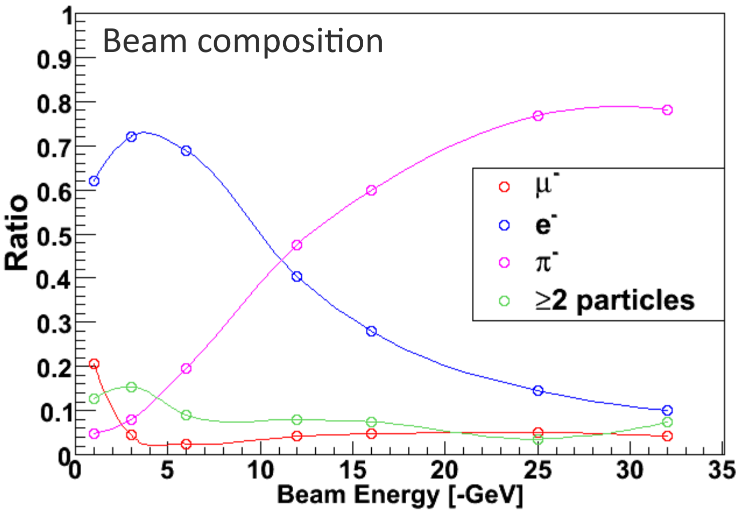
- Excellent electrical and mechanical engineering
  - Strong ASIC engineering group
    - Example ASICS: SVX, FSSR, TRIP, QIE, DCAL
- Unique facilities with trained technical staff
  - Silicon Detector Center
    - Built silicon detectors for CDF, Dzero, CMS, BTeV, Phenix
    - 7000 square feet of clean room
    - Wirebonding facilities
  - Scintillator extrusion
  - Thin film deposition
  - LAr cryogenics
  - Chamber stringing
  - CNC routing
  - Metrology on small and large scales

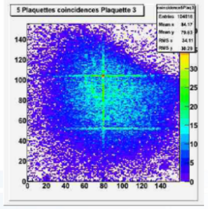


Facilities: Testbeam

- Fermilab Test Beam Facility (FTBF) with three operating modes open to all users
  - Proton mode: 120 GeV
  - Pion Mode: 8-66 GeV (secondary beam)
  - Low Energy mode: 500 MeV – 8 GeV (tertiary beam)
- Beam structure
  - One 4s spill every 1-2 minutes
  - Beam rate 100k per spill at 16 GeV
- Beamline Instrumentation
  - Cherenkov counters, Time-of-flight
  - Silicon pixel tracking stations, …
- Facility use in 2010:
  - 224 physicists from 72 institutions from 16 countries carried out 13 experiments

- Test beam experiments are generally one of the best learning experiences for physicists

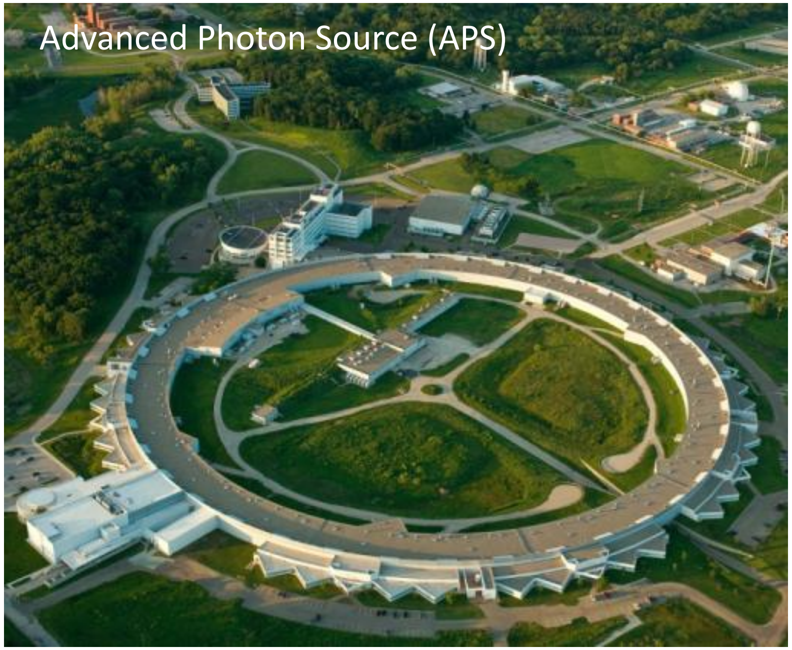




Beam profile monitored with Si pixel detector hybrid readout

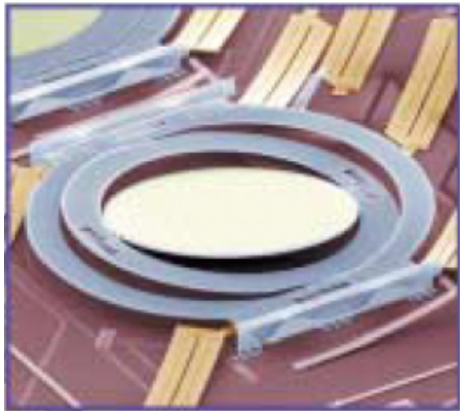
Facilities: Argonne

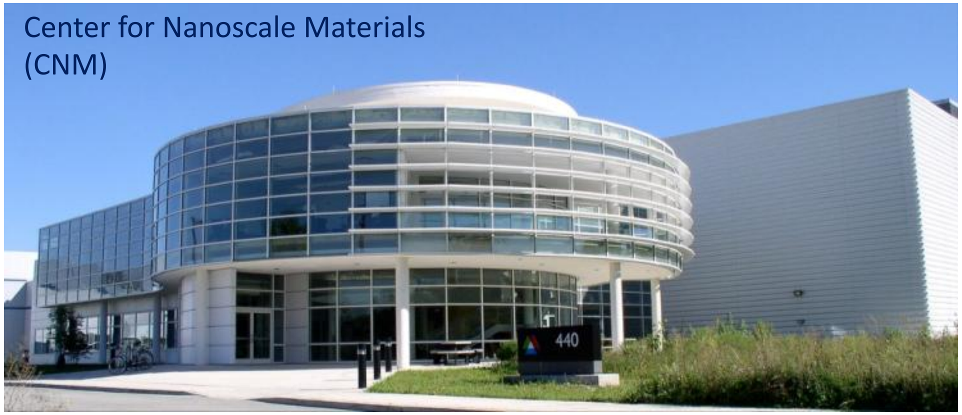
- Advanced Photon Source (APS)
  - 35 sectors, 3-100 keV photons
- Center for Nanoscale Materials (CNM)
  - Nano-scale lithography
  - Etching
  - …
- Both user facilities are freely available to the whole scientific community
- Material Science Division
  - Engineering of materials



Advanced Photon Source (APS)

CNM MEMS mirror for optical communication





Center for Nanoscale Materials (CNM)

Concluding Remarks

- We are “In Search of Radical Solutions” to enable better experimental science

- We believe these solutions can only be found through partnerships:
  - Partnerships with other disciplines to bring modern, new technologies to bear on the development for future detectors and sensors
    - Materials Sciences: Materials by Design (Atomic Layer Deposition, Thin film development, …)
    - Semiconductor Technologies
    - Nano-materials
  - Partnerships with other institutions
  - Partnerships with industry

- These solutions require going back to the basics of the underlying physics

- Argonne and Fermilab have initiated a program that is a first step to enable the search to find radical, transformational solutions

- We welcome new partners!

Backup Slides

Pore Activation via Atomic Layer Deposition (ALD)

Example:

- OH on surface provide reaction sites
- Trimethyl aluminum reacts liberating methane, forms Al_2O_3 layer. Leaves methyl group inhibiting further reaction on surface
- Exposure to H_2O removes methyl group. Leaves OH sites for next reaction