Strategic Plan for Detector R&D at Fermilab

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Detector R&D Organization at Fermilab

- **Detector Advisory Group**: ~15 experts of different detector technologies across the lab, including 2 external advisors, led by P.M.

- Detector R&D website

- Meet bi-weekly to **prioritize** ongoing R&D efforts, new proposals, coordination issues, budget, strategic and tactical investments

- Most R&D projects fall under a multi-year plan with annual updates. **Prioritization through:**
  - Review annual achievement reports, publications, awards
  - Review annual funding requests for ongoing R&D
  - Review presentations for new R&D initiatives
  - Solicit occasional strategic and tactical guidance from senior lab management

Detector R&D Organization at Fermilab

- Broad, successful program with long lists of publications, theses, follow-up funding (e.g. LDRD, ECA, private foundations, programmatic)

- KA25 often serves as seed for larger efforts, e.g:
  - Juan Estrada's CCDs for DM → DAMIC, CONNIE experiments, DM New Initiative
  - Javier Tiffenberg's Skipper CCDs → LDRD, ECA, Heising-Simons Foundation
  - Artur Apresyan's LGADs → LDRD, ECA, HL-LHC CMS

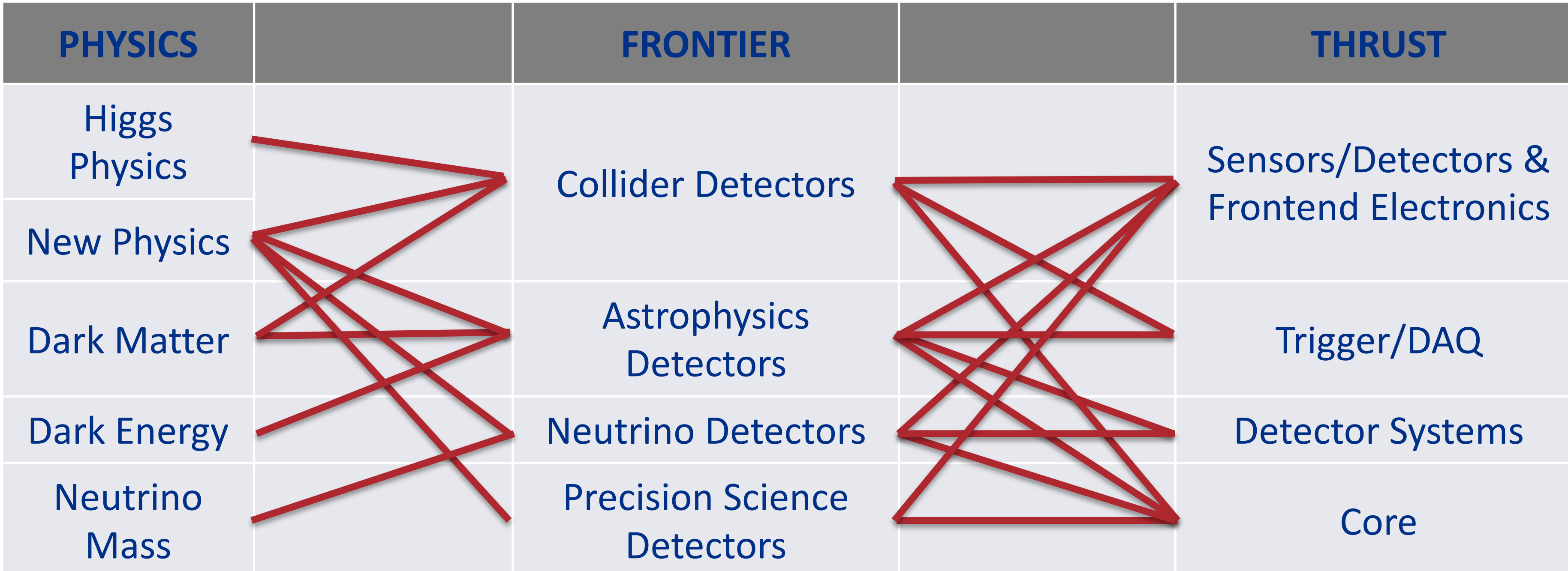
- Organize Research Techniques Seminar series (web page)

- Last Comparative DOE Review: February 2016, favorable (report)

- Very positive 2019 PAC report:

  "… Due to its leading role in US particle physics, the R&D effort at Fermilab is essential in ensuring the future success of the particle physics program across all the frontiers and the Committee congratulates the tremendous success of the program. …"

Detector R&D Thrusts, guided by P5 and CPAD Grand Challenges



We are positioning ourselves to influence and execute next Snowmass / P5 process

- Fermilab is organizing strategic lab planning process for 2026 and beyond, also for detectors

Budget Overview

- Overall annual KA25 budget for Detector R&D: ~$4M
  - Average annual budget per project ~$75k
  - Only technical labor supported, no scientists; total ~10 FTE

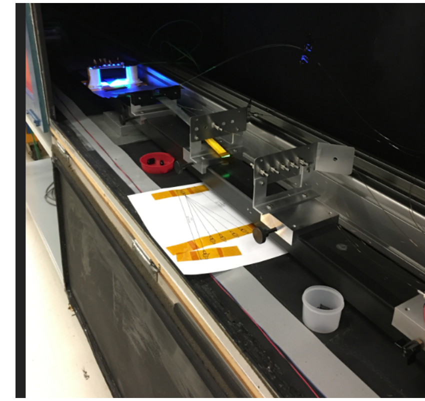
- Sensors/Detectors & Frontend Electronics (48%):
  - Silicon sensors, ASICs, 3D-interconnects, scintillators, wavelength shifters, CCDs, MKIDs, warm and cold readout electronics, precision timing
- Trigger/DAQ (22%):
  - Low-noise, low-threshold readout systems, warm and cryogenic, RFSoC for superconducting detectors, test beam DAQ, highspeed links
- Detector Systems (23%):
  - Photo detectors for LAr TPCs, HV studies in LAr, LAr doping with Xe, pixelated TPC readout in test beam, LXe TPC for Dark Matter searches
- Core (8%):
  - Tactical initiatives, Research Techniques Seminar, travel

Integration into HEP Detector R&D Community

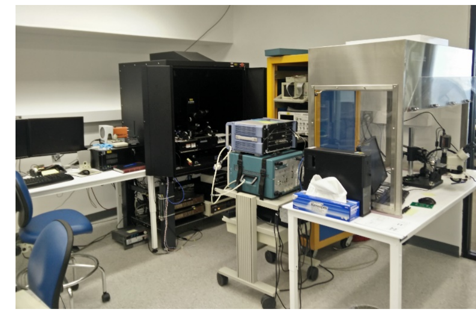
- The Fermilab Detector Advisory Group includes
  - senior experts in their fields, who serve the broader HEP community as workshop/session organizers, matter experts on panels, reviewers (SBIR, NIM, PDG, US-Israel funding, etc.)
  - two external advisors from UTA and ANL
  - Several active members of CPAD (the Coordinating Panel for Advanced Detectors of the APS/DPG), shaping future directions of HEP instrumentation nationwide
  - Active participation in upcoming BRN for Detectors
  - P.M. is a newly recruited member of the ICFA Instrumentation Panel
  - contact points with CERN Detector R&D community
    - e.g. will give a talk on *Detector R&D at Fermilab and in the US* at the next CERN Detector R&D Day in October

- Advertising at Fermilab's annual Users Meeting: 2017, 2018

Detector Facilities and Infrastructure



- Common Detector Test Facility Systems
  - Silicon Detector Facility
  - Precision Metrology
  - Scintillation Detector Development Facility
  - Thin Film Facility
  - Noble Liquid Detector Development (PAB)
  - Rapid Prototyping and Special Materials



- ASIC Development Facility
- Fermilab Test Beam Facility (FTBF)
  – Future: Irradiation Test Area (ITA)

Promote and benefit from partnership with universities and other national laboratories. Previous construction projects at Fermilab either created or contributed to these facilities enabling subsequent Projects and research efforts to capitalize on these investments. Current projects and laboratory operations co-fund these facilities.

Facility Modernization

- New Integrated Engineering and Research Center (IERC):
  - New clean rooms
  - Concentrate technical and engineering expertise under one roof

- Campus Modernization Plan:
  - Proposing relocation of village labs, modernization of some existing labs, and some new large assembly lab space

- Succession planning: expertise in several areas down to last person

- Test beam facility under constant maintenance/modernization strain
- Irradiation Test Area (ITA):
  - New proton irradiation facility at Fermilab
  - Cleanup of test area completed
  - Received construction funds in September, thank you!
  - Should be up and running at the end of February 2020

Collider Detector R&D

Collider Detector Challenges

- **Electron colliders** (e.g. ILC, CLIC, FCC-ee)
  - High-granularity trackers (x20 finer and x10/x100 lighter than HL-LHC CMS barrel/endcap)
  - High-granularity calorimeters (x200 finer than HL-LHC CMS

- **Hadron colliders** (e.g. HE-LHC, FCC-hh)
  - High granularity trackers and calorimeters (x5 HL-LHC pileup)
  - Radiation hard sensors and frontend electronics (x30 HL-LHC fluence)
  - Electronics, trigger systems and high-speed links (x4 HL-LHC particle rates)

- **Muon collider**
  - Huge background from muon decays from beam; requirements similar to electron machine detectors, but even smaller pixel sizes (20μm) and fast sensors (50ps) needed everywhere

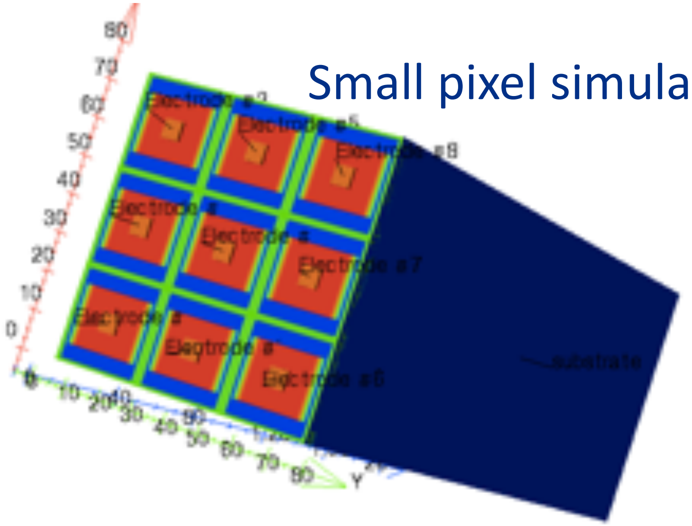
Silicon R&D

Multi-tier 3D integrated systems of readout electronics and small (<25 micron pixels)

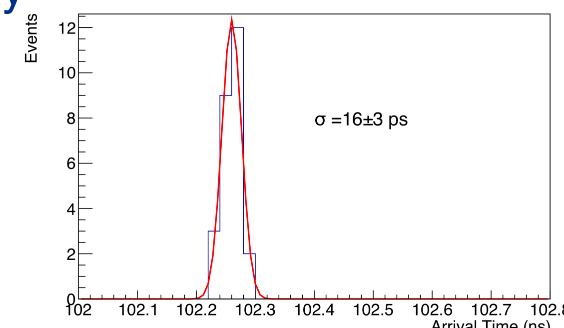
- Can integrate ps timing, pattern recognition, and momentum reconstruction on a single detector with a sensor, analog, and digital tier
- Use full current pulse information in a highly integrated detector+readout. Digital tier combines pixel information and provides signal-to-background discrimination
- Builds on our pioneering work on 3D

Development Plan

- Years 1-2 – Develop 3D technology (with MIT-LL), simulate full analog system
- Year 3 – build two-tier prototypes
- Year 4 – Develop digital tier
- Year 5 – build demonstration chip

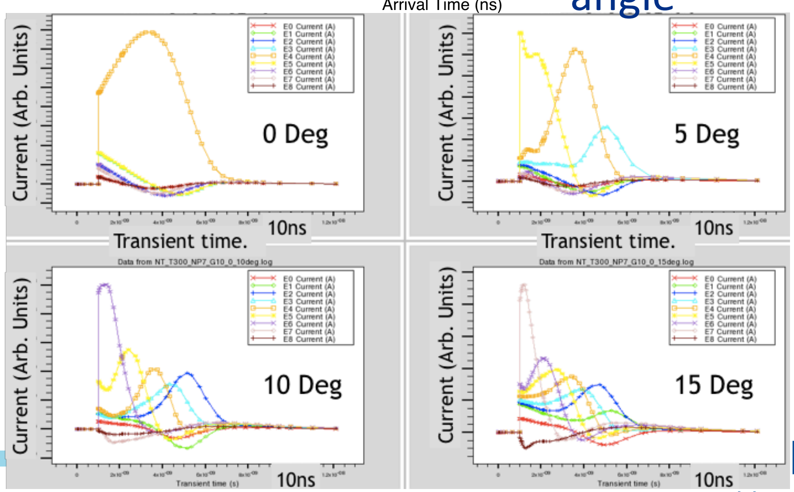


Small pixel simulation



Timing resolution

Pulse shape vs angle



Link with Lab Capabilities

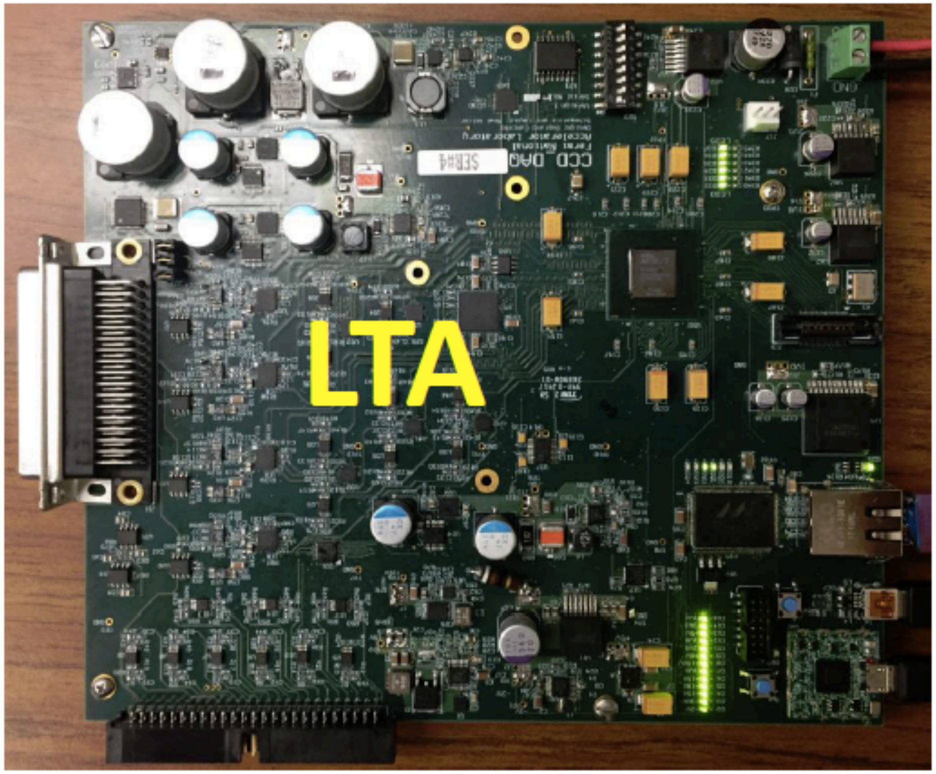
Collider Detectors	Key Detector Challenges	FNAL Lab Capabilities
Tracking	High-granularity tracker with ultra-low mass, timing stamp, radiation-hard sensors and frontend electronics	Silicon sensor and ASIC R&D: CMOS, hybrid pixels, very small pixels, ultra-fast silicon, radiation-hard designs, pico-second system design, alternative materials, silicon module packaging, assembly and integration, mechanical support structures, cooling
Calorimetry	High-granularity calorimeter with timing stamp; dual readout	Silicon sensor and ASIC design, packaging, cooling, radiation-hard crystal and plastic scintillators, extrusion and injection molding, high-light-yield photodetection, new materials R&D
Trigger and DAQ	trigger and readout links for high particle rates	low-mass high-speed optical and electrical links, silicon photonics, trigger electronics including machine learning in FPGAs

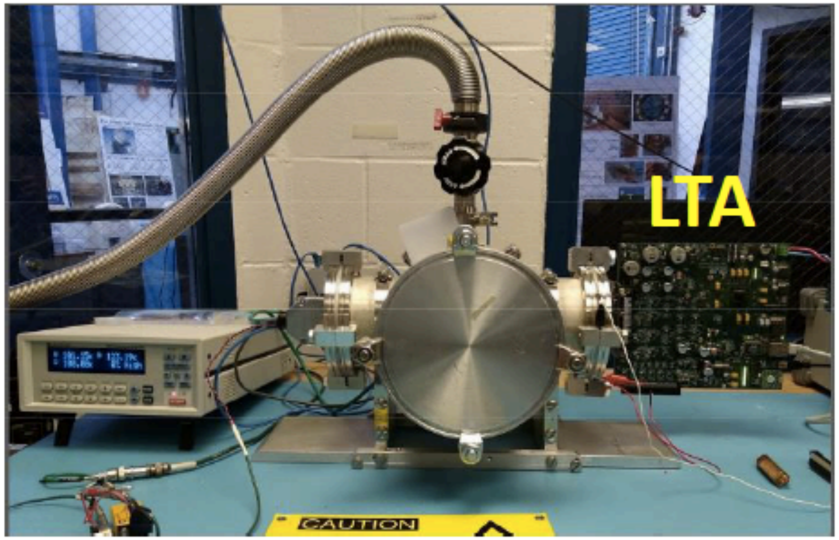
Astrophysics Detector R&D

Astrophysics Detector Challenges

- **CMB** (e.g. CMB-S4 and beyond)
  - Number of detectors in receiver scale by more than order of magnitude
  - Improve receivers and packaging
  - New sensors
- **Dark Matter** (e.g. axions, sub-GeV DM)
  - Photon collection and detection in magnetic field
  - Lower threshold sensors and readout
- **Cosmic Surveys** (e.g. Stage V Dark Energy spectroscopic survey)
  - More channels than DESI, higher signal-to-noise needed
  - New sensors with lower noise, going further into the IR
  - Higher density fiber positioners

Readout Electronics:
Low Threshold Architecture (LTA) for Skipper CCD Readout





- Single sample 1.3 e-1 noise achieved (lowest for any CCD readout system at Fermilab)
- LTA has replaced all previous CCD readout systems at SiDet
- It has been officially adopted for all current and new experiments using skipper CCDs
- New version LTA-QSM being fabricated

Link with Lab Capabilities

Astro Physics Detectors	Key Detector Challenges	FNAL Lab Capabilities
CMB Receiver	Number of detectors in receiver needs to scale by more than an order of magnitude; multiplexing; packaging	Detector packaging, wirebonding, multiplexed readout electronics; cryostat integration
Sensors	Cryogenic, superconducting, lower-threshold sensors: TES, KID, SNSPD, bolometers; CCD-in-CMOS; Ge-CCD	Sensor design, packaging, readout electronics, testing
Readout electronics	Low-noise, low-threshold, cryogenic	Electronics and cryo engineering
Fiber positioner	More channels than DESI, higher efficiency and signal-to-noise needed; higher density fibers	Mechanical and electrical engineering; simulations

Neutrino Detector R&D

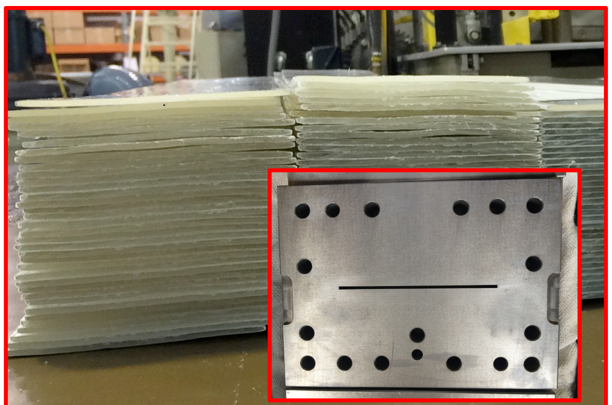
Neutrino Detector Challenges

- **DUNE**
  - Near Detector challenges: measure hadrons in decay pipe, pileup of n interactions, charge separation and momentum measurement require high B-field
  - Far Detector (4^{th} module): increased photon detection coverage and scintillation light collection efficiency, high-speed data links to allow for continuous readout
- ν_τ **oscillation** experiment:
  - Tracker with 10s of microns resolution and automated readout
  - Large mass, totally active volume
- **Low energy neutrino** interaction (e.g. coherent scattering)
  - Need to detect nuclear recoils in liquid noble TPC through ionization charge (x100 better signal-to-noise)

Photo Detection R&D

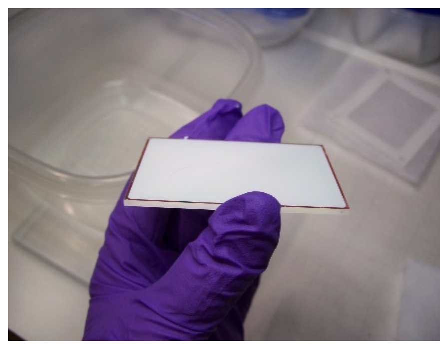
- Photo detection in LAr: big ongoing area of R&D; very low efficiencies at LAr scintillation wavelenegth
- Various technologies still being investigated
- Leveraging Fermilab's extrusion and thin film capabilities

Use UV-transmitting acrylic pellets to test extrusion into plates as replacement for wavelength shifting plates currently used in ProtoDUNE.

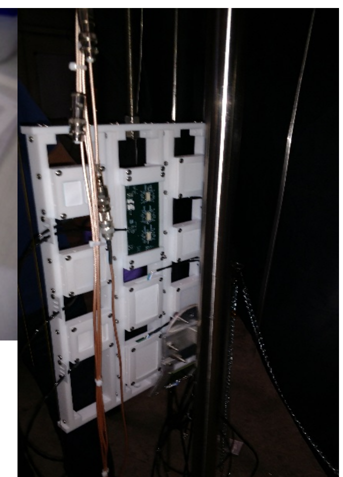


Wavelength shifting plates

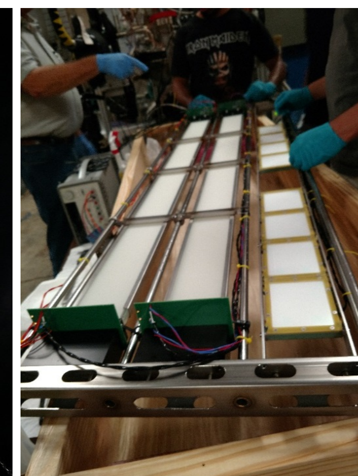
Arapuca: R&D on WLS vacuum coatings and cleaning/baking procedures on dichroic filters. This has led to other WLS coating requests for DUNE R&D-on SIPM arrays, on specialty liquid argon PMTs, on resistive acrylics.



WLS coated dichroic filter



Array of coated dichroic filters at Tallbo



CERN test of dipped acrylic bars and dichroic filters (all made at FNAL)

Link with Lab Capabilities

Neutrino Detectors	Key Detector Challenges	FNAL Lab Capabilities
Photo Detection	Increased coverage, wavelength shifting in LAr, light trapping, LAr doping, cryogenic photodetectors and readout	Cryogenic test stands at PAB, testbeam, extensive LAr TPC and photo detection expertise
Magnetized LAr TPC	Large, homogeneous magnetic field inside medium-sized TPC	TPC expertise at PAB and test beam (LArIAT); availability of test beam for measurements of charge separation and momentum in magnetized TPC
High-pressure gaseous Ar TPC	Gas properties, front-end readout development, full detector design	Pressurized gas TPC test stand at PAB, expertise in TPC and photon detectors, expertise in high-voltage feedthroughs
High Voltage	Suppression of sparking on interior surfaces	Ongoing R&D at PAB test stand, fundamental process simulations
Transition Radiation Detector	x-ray detectors, rad-hard magnets	ASIC group x-ray detection expertise, TD magnet group expertise
Tracker for tau neutrino oscillation experiment	Micron level position resolution; large, totally active mass	Synergy between neutrino and collider detector experts possible

Precision Science Detector R&D

Detector Challenges: Mu2e-II, DarkQuest, REDTOP, etc.

Radiation-hard electronics

Medium high radiation levels; component qualification needed

Fast radiation-hard calorimeter

Including photon sensors

Ultra-low mass tracker

R&D of new materials, e.g. graphene

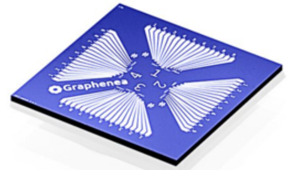
High-efficiency cosmic ray veto system

neutron fluence issue on SiPM/scintillator

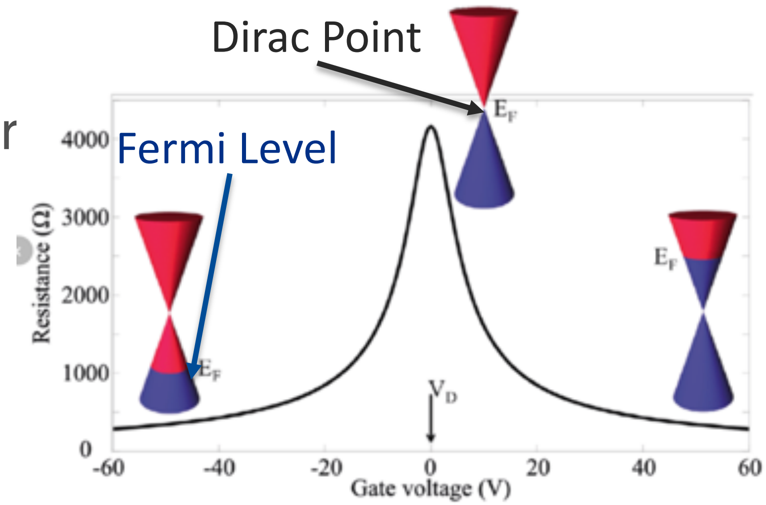
High power, radiation-hard POL delivery

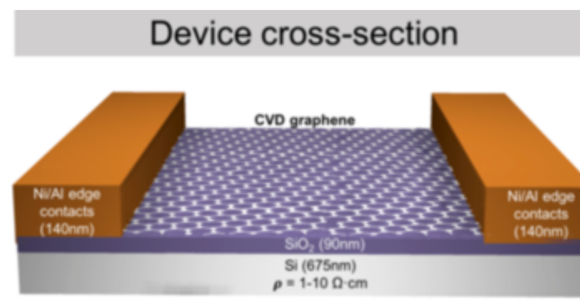
Radiation- and B-field-hard DC/DC converters

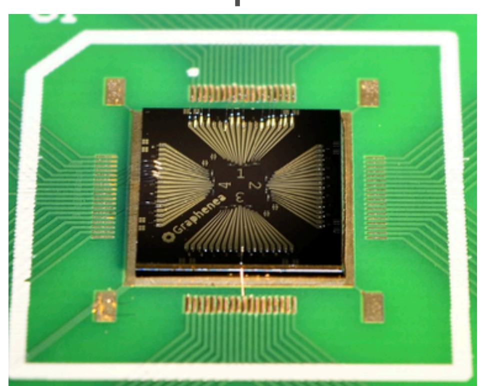
Graphene R&D

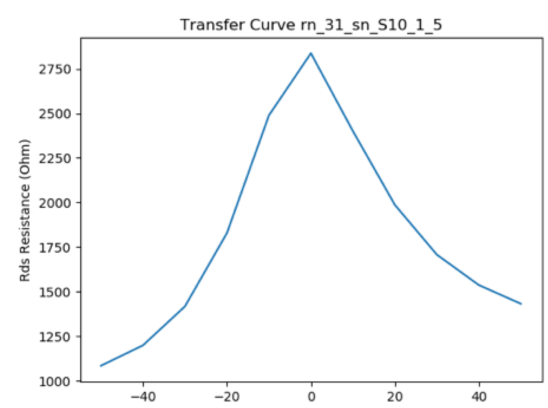


- Graphene can be used as semiconductor or insulator
- Variable conductance depending on applied gate voltage
- Company (Graphenea) provides test structures, open to custom designs
- Air-tight packaging essential, atmospheric contaminations shift Dirac point
- Wire bonding challenging on very thin substrates
- Next: bench measurements with photons









Link to Lab Capabilities

Precision Experiment Detectors	Key Detector Challenges	FNAL Lab Capabilities
Rad-hard electronics	Qualification of off-the-shelf components for radiation hardness; if nothing available, development of rad-hard electronics	Rad-hardness expertise from collider community, ASIC and readout electronics and links
Calorimetry	Fast, rad-hard calorimeter and photo detectors: <10% energy resolution, 500ps timing, rad-hard up to 1MRad and 10^{13} n_{eq} MeV/cm^2	Rad-hard plastic scintillators, SiPMs, packaging; semiconductor quantum dot scintillators
Tracker	Ultra-low-mass with <10% X_0, <100ps TOF tracking for particle identification	Silicon tracker development and packaging; new materials, e.g. graphene
Cosmic Ray Veto	Very high veto efficiency (>99.99%); neutron fluency in SiPM-scintillator packages	Scintillator extrusion, scintillator doping, injection molding, tile/strip+SiPM packaging
DC-DC converters	Performance in radiation and magnetic field environments	ASIC and electronics engineering group; operational experience
Pico-second electronics	System-level issues: clock stability, jitter, noise	ASIC and electronics engineering; synergy with efforts for future collider detectors

FY20 FWP Walk-up (base budget: $3.9M)

- 1. **Exploration of deep deca-nanometer ASIC technologies ($190k):**
  - e.g 28nm CMOS for future applications at room and cryogenic temperatures through fabrication of a tiny ASIC test structure with transistors and to perform measurements at room temperature, 80K and 4K
  - allows Fermilab ASIC engineers to stay current with state-of-the-art technologies, and positions us well for future projects

  → Addresses Collider (rad-hard, high-granularity tracker and calorimeter) and Neutrino Detector Challenges (pixelated cryogenic readout)
- 2. **High-granularity readout of Noble Liquid detectors ($420k):**
  - collaborate on R&D following a new idea regarding high granularity readout of a TPC
  - Develop front-end circuits for cold operation
  - might require 3D structures and the goal would be to achieve a 5 mm pitch.

  → Addresses Neutrino Detector Challenge (pixelated cryogenic readout)
- 3. **Injection molded scintillators ($96k):**
  - develop a different processing technology for plastic scintillator
  - Fermilab developed extruded plastic scintillator almost 20 years ago. Injection-molding plastic scintillator is the logical next step which is now more relevant since it presents an attractive solution for future collider detectors.

  → Addresses Collider Detector Challenge (high-granularity, rad-hard calorimeters)

Summary

Fermilab has a broad and deep Detector R&D program driven by what the HEP community needs

Vibrant combination of facilities, technical personnel and instrumentation scientists as well as long culture of Detector R&D allows for very productive collaboration between divisions and with other laboratories and universities

KA25 R&D often seeds larger efforts with additional funding sources. With increased funding this could have an even bigger impact.

Fermilab Detector R&D Program crucial for upcoming Snowmass process and beyond

BACKUP

R&D Needs – Collider Detectors: Trackers

Ongoing R&D:

- CMOS silicon sensor R&D: Can provide very precise spatial and timing resolution, a low material budget as well as high radiation tolerance while maintaining a reasonable production and cost effort. CMOS Monolithic Active Pixel Sensors (MAPS) combine the sensing part and the readout circuitry in one layer. With this, the production effort, costs and material budget can be significantly reduced.

  CMOS R&D w/i ASIC group (w/ BES)

- Hybrid pixel detector R&D: For very high radiation environment, e.g. 3D sensors, active edge planar sensors, spatial and time information, e.g. deep trench electrodes: need specialized ASICs (deep-deca nanometer technologies) and need to solve interconnection issues (DBI, TSV).

  Interconnects (VIPRAM, MIT-LL); RD53 work: SEU studies

  Wishlist: deep-deca nanometer

- Ultra-small pixel R&D: Very small pixel size (25mm) on thick (200mm) sensors can deliver track angle within single sensor and fast timing information; needs fast, smart 3D integrated electronic.

  R&D on very small pixel size (20/25μm) silicon

- Ultra-fast silicon R&D: Need R&D to increase fill factor and radiation hardness of gain layer.

  Epitaxial LGADs
  Radiation testing

- Picosecond-level system design R&D: Readout ASICs, clock distribution, electronics jitter, module design, cooling.

  picosecond system R&D

- Alternative semiconductor material R&D: e.g. graphene for large-scale, ultra-low mass tracking systems.

  Graphene (LDRD)

R&D Needs – Collider Detectors: rest

Ongoing R&D:

- Large-area silicon arrays for calorimetry: packaging, cooling, large fill factors, radiation hardness, readout speed — CMS HGCal
- Crystal R&D for calorimetry: radiation hardness, segmentation, light yield, photo detection — ~
- Plastic scintillator R&D for calorimetry: radiation hardness through doping (3D printed, injection molded, co-extruded); explore new materials such as polysiloxanes. — Longterm leader for HEP
- Semiconductor scintillator R&D: e.g. quantum dots for fast light read out, low mass, radiation hardness — Quantum dot R&D w/ SUNY Albany
- SiPMs on scintillator tiles or strips: coating, wrapping, automated assembly — CMS HGCal
- Segmented gas amplification structures: e.g. MicroMegas — -
- High-granularity Noble Liquid calorimeter R&D: (e.g. LAr) for radiation hardness — -
- High-speed readout links — Silicon Photonics (potential for SBIR)

R&D Needs – Astrophysics Detectors

Ongoing R&D:

- CMB sensor packaging and characterization
  - New sensors
  - Multiplexing readout

MKIDs for optical and IR; warm electronics

- Readout electronics for superconducting detectors

Cold electronics for TES for CMB

CCD DAQ

RFSoC for superconducting detectors

- Single photon detectors, e.g. TES, KIDs, SNSPDs (below IR)

MKIDs for optical and IR

- Low-noise semiconductor detectors (CCD-in CMOS, Skipper CCD, Ge-CCD)

Technical labor for SENSEI 100g demonstrator

Wishlist: CCD-in-CMOS R&D (applied for LDRD)

- Cryogenic bolometers
- Photon concentrators for axions

Wishlist: Wideband Axion-to-Photon Converter (applied for LDRD)

- Multi-fiber positioner for future surveys

High-density fiber positioner (applied for LDRD)

R&D Needs: Neutrino Detectors

Ongoing R&D:

- LAr Scintillation: increasing photon yield to enable low energy event detection—especially for very large LAr Detectors with increasingly long drift regions.
  - Arapuca etc.
  - Xe doping
  - Wavelength shifting
- High Voltage Stability studies: pushing power supply capabilities and potential HV instabilities around the cathode
  - HV studies & spark protection
- High-pressure GAr TPC: for near detector
  - (Jen Raaf ECA)
- Electron multiplication in LAr: either in LAr itself, or in the electronics to allow for very low energy event detection with large detectors
  - (Angela Fava LDRD)
- Magnetized LAr detectors: LAr-temperature superconductors to place magnet in the LAr.
  - LArIAT setup at testbeam
- Transition Radiation Detector: x-ray detectors and rad-hard magnets
  - ASICs w/ BES; FNAL APS-TD
- Pixel Electronics: pixelated TPC readout for near and far detector (4th module)
  - Support of collab. at testbeam
  - Wishlist: if addl. funding
- Tracker: large mass, fully active, with 10s of micron resolution and automatic readout for ν_τ oscillation experiment
  - –

R&D Needs – Mu2e-II, DarkQuest, LDMX, Redtop

Ongoing R&D:

- Radiation-hard electronics
  - Medium high radiation levels; component qualification needed
- Fast radiation-hard calorimeter
  - <10% energy resolution and 500ps timing
  - ~1MRad and 10^{13} n_{eq}MeV/cm^2
  - Including photo sensors
- Ultra-low mass tracker
  - <0.1% X_0 with <100ps TOF tracking for PID
  - R&D of new materials, e.g. graphene
- High-efficiency cosmic ray veto system
  - >99.99% efficiency, neutron fluence issue on SiPM/scintillator
- High power, radiation-hard POL delivery
  - Radiation- and B-field-hard DC/DC converters

Semiconductor scintillator w/ QuantumDots

(8μm-wall straws – applied for LDRD)

Graphene/GFETs (LDRD)

Rad-hard DC/DC converters