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Detectors For Science Working Group Report

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All Scientist Retreat

4 May 2017

Introduction

- Two pre-retreat meetings (~50 & ~10 participants)
- Contributions and discussions from
 - Intensity WG
 - Energy WG
 - Cosmic WG
 - Precision WG
 - Facilities, AD, TD
- Future needs for detector development mostly only vaguely known at this moment
- BUT: likely needs for capabilities/expertise/facilities can be defined

Neutrinos

- **Midterm:** three main experimental areas are:
 - NOvA: currently taking data, not much R&D
 - DUNE: data taking to start in ~2026, need to build 4 FD modules, and a ND
 - SBN: data taking to start in ~2018
- **Longterm:** very strong DUNE component; beyond that we need physics input from above experiments
 - Neutrino factory for precision measurements?
 - Go to lower energies for super nova neutrino studies?
 - Precision measurements of unitarity in neutrinos?
- **LAr detector development** (for 2nd, 3rd, 4th DUNE FD, ND, and also SBN):
 - Novel photon detection systems including VUV and NIR light collection, adding TPB coated foils, adding dopants to the argon, ARAPUCA light trap; more connections with electronics group needed
 - HV feed throughs
 - Improving ionization readout techniques (testing electronics, gain within the liquid, dual phase tests)
 - Additional LArIAT needs: pixel readout, gain in liquid
 - Magnetizing the LAr volume
- LAr TPC may not be optimal in very intense beam, **potential option for gaseous argon TPC** for ND
- **DAQ challenges:** very high data volume
- **Longterm detector R&D needs:**
 - Magnetizing LArTPC for DUNE
 - Identify charged-current tau neutrino interactions: very far away, very big, very good position resolution -- > emulsion blocks? other technologies?
 - Neutrinoless double-beta decay: very low effort at Fermilab right now; should we invest?

Energy Frontier

- **Nearterm: HL-LHC, detector technologies well defined**
 - Challenges are high PU, high radiation environment, large data throughput and strong data reduction needs
 - At Fermilab:
 - Outer Tracker upgrade: module assembly (complex double layer, pixels & strips, input to track trigger), mechanics and cooling, radhard optical links
 - Track Trigger: R&D, AM-based, one of three options in CMS
 - Pixels: sensor (small pixels, edgeless) and ASIC R&D (in RD53 with ATLAS)
 - HGCal: silicon-based high granularity forward calorimeter (sensor design, FE electronics, cooling, cassette assembly)
 - Had calo: radhard scintillator and photodetection R&D
 - Fast Timing layer: LGAD Si sensors, ps-timing electronics, R&D and construction
- **Longterm:**
 - Lepton collider: $e+e-$, Higgs factory (250-500 GeV) , muon collider?
 - Central tracker: high momentum resolution, excellent secondary vertex reco
 - Calorimetry: very high energy resolution
 - Muon system: hermetic, small punch through, high momentum resolution
 - Occupancy and radiation: relatively low interaction rate, no issues with triggering; challenging forward region due to radiation of electrons
 - Hadron collider: pp, next energy frontier (14-100 TeV)
 - Central tracker needs to preserve momentum resolution for $\sim 10x$ higher momentum tracks compared to LHC
 - Calorimetry: no major issues?
 - Muon system: muons are showering and become "electron-like" due to larger g factor, momentum resolution challenge
 - Occupancy and radiation doses not much worse than at HL-LHC
- **Some detector R&D needs and wishes:**
 - ASICs and sensors: few-nm architecture, 3D-silicon, CMOS technology, monolithic sensors, 8" wafers, in-house bump bonding and wafer processing and dicing
 - Other semiconductor materials, i.e. diamonds, GaAs, graphene, ... ?
 - New materials for support structures and cables, i.e. carbon nano tubes, graphene, ?
 - New scintillators and fiber materials
 - On-site testbeam facility crucial, on-site irradiation facility would be fantastic

Cosmic Frontier

- **Nearterm future:**
 - LZ: DM, noble liquids, start data taking in 2019
 - superCDMS: DM, sub-K, start data taking in 2020
 - ADMX: DM, sub-K, running now until beyond 2020
 - extension of ADMX: DM, sub-K, 2 LDRDs ongoing
 - pico-500: DM, very small FNAL role?
 - SENSEI: DM, Si detectors, LDRD now, could grow in coming year
 - NEXUS: DM, sub-K, detector calibration/testing facility for DM ideas (NuMI tunnel)
 - DESI: DE, Si detectors, start data taking ~2019
 - SPT-3G: CMB, sub-K, running now, some upgrades planned
- **Longterm future:** depends on outcome of G2 (for DM)
 - several tons bubble chamber: DM, investigate different targets
 - several kg single electron threshold experiments: DM, Si detectors or sub-K
 - directional detection ideas (gas detectors, graphene): DM
 - quantum detectors: DM, sub-K
 - high density - low resolution spectroscopy: DE, MKIDs (LDRD), sub-K, prisms
 - high resolution - low density spectroscopy: DE, billion object apparatus, superDESI, Si detectors, high density fiber positioning
 - 21cm survey: DE, ?
 - CMB-S4: CMB, sub-K
- **Sub-K expertise is becoming more important;** there is a need for a more efficient sub-K detector facility (maybe inside IERC?); in addition to NEXUS (low background underground sub-K cleanroom). Potential impact on intensity/energy frontiers?
- In addition to large integration lab space there is a **need for smaller testing lab space**
- Keep a **healthy diversity** to be ready for **future, small R&D**. Have done a lot of this in the past and it has paid off, e.g. PICO, DarkSide, DAMIC.

Precision Experiments

- **Future ideas:**

- g-2: negative muon run
- Mu2e-II: with PIP-II and different target
- REDTOP: eta factory
- Proton EDM
- TEDSE: Transfigured Electron Double Slit Experiment
- DM search using lepton beams

- **Mu2e-II detector R&D:**

- ultra low mass, high rate tracker ($\sim 0.1\%$ resolution on 100MeV/c tracks, peak rates 1MHz/cm²)
- ultra thin straw tracker (~ 8 micron thick): challenges concerning ageing, sag under tension, leak rate, etc.
- solid state photo sensors for BaF₂ calorimeter with ~ 20 krad dose expected
- SiPM for cosmic ray veto expected to be limited by neutron dose, aim to sustain $>10^{11}$ n/cm² (1MeV neutron equivalent)
- Development of >100 kW production target
- high throughput triggerless DAQ

Capabilities - I

Micro Detector Assembly and Packaging

- Currently based at SiDet; has been a critical piece of FNAL's involvement in the Tevatron experiments, CMS, DECam, DESI, SPT-3G and has also enabled a large effort on detector R&D for the HEP community.
- Keep up-to-date with the current technology for semiconductor and superconductor detector assembly.
- Allows FNAL to take leading roles in the fabrication of the next generation of detectors. This includes metrology, micro-bonding, bump bonding, dicing, wafer level processing and probing.

Capabilities - II

Sensor design/simulation expertise

- FNAL has currently a very limited involvement in sensor design (~ 1.5) for HEP experiments.
- We have extensive expertise in characterization, calibration, testing, packaging and integration of these sensors in HEP experiments.
- With the new nanofabrication facilities available in the Chicago area (U.of.C) and ANL, we have an opportunity to get more involvement in the design stage for semiconductor and superconductor detectors, but need to train people.

Capabilities - III

Sub-Kelvin Lab

- CPAD has identified the need for the development of infrastructure for **high-volume testing and fabrication of large cryogenic detector arrays** for use in future CMB instruments, X-ray instruments, neutrino detectors and dark matter detectors.
- The report calls for investment in critical infrastructure for cryogenic testing and micro-fabrication facilities.
- FNAL could develop a "**Sub-Kelvin Detector Fabrication and Testing Facility**", in a similar way that in the 90's it developed the successful SiDet facility for Silicon detectors.
- We are **now leading the assembly** of the detectors for the largest CMB instrument, and we have participation in several sub-K technologies that would shape the field in the future.
 - Currently involved in CMB array detectors, TES sensors for DM, development of single microwave photon detectors, microwave kinetic inductance detectors (MKIDs), readout systems for superconducting frequency multiplexed detectors, and cryogenic cavities for axion searches.
- Today we **have attracted external collaborators** to participate in these research efforts at FNAL and have been able to contribute significantly thanks to our engineering and technical teams. The next step would be to solidify our leadership in the field, by establishing a state of the art sub-Kelvin lab.

Capabilities - IV

ASIC group

- Our ASIC group has crucial contributions to many different experiments and research frontiers. We traditionally collaborate with US and international colleagues, helping to push the technological boundaries.
- In particular we have expertise in radiation tolerant and cryogenic ASIC designs.
- Through collaboration on BES projects, the group brings additional external (to HEP) funds to the lab.
- Recommend even broader involvement with other lab experiments, e.g. intensity/precision frontiers.

Capabilities - V

Liquid Argon R&D facility

- At PAB we currently operate two cryostat test stands close to 100% capacity. This is a crucial users facility for lab and university people.
- The cryostats are especially geared towards small scale, standalone measurements.
- A third cryostat will be added this or next year. A fourth one is foreseen for the medium term future.
- In addition, the operation of a cryostat at the FTBF adds another crucial component to our LAr R&D capabilities. It is geared for larger scale and longer running measurements, taking full advantage of the on-site test beam. The plan is to maintain this facility for the longer term by refurbishing it with a LAr recycling system to make it more economic.

Capabilities - VI

FTBF

- Strong need for this facility. Explore upgrade/expansion; add lower energy capabilities.

Irradiation facility

- Strong wish from the lab detector community to establish and maintain such a facility at MTA. Recommend to set up taskforce to establish use cases, specific needs, and to plan a way forward to make this happen.

PREP

- Useful facility in need of modernization. Support from DAQ and maybe ASIC groups needed.

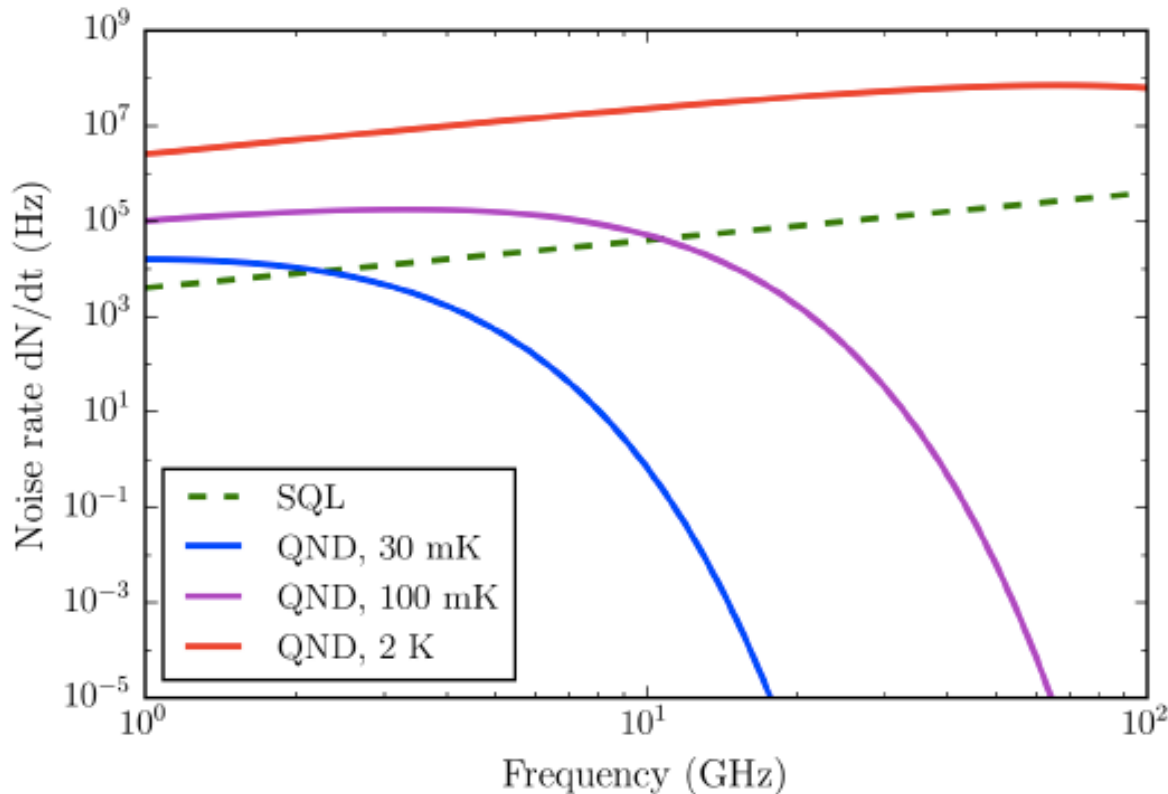
Thin film, special materials, scintillator extrusion facilities:

- All in need of additional expertise.

Detector Development Initiatives - I

Quantum detector initiative

- Search for axion Dark Matter
- Develop Qubit cavities to beat noise limited amplifiers above O(10GHz)
- Quantum non-demolition detector based on 3D superconducting qubit
- Single photon detectors around O(100GHz)
- With artificial atoms implemented using quantum dots



Detector Development Initiatives - II

Fast timing semiconductors (Astrophysics/Collider):

- The development of fast timing detectors has received a big push from the HL-LHC community.
 - A thin LYSO + SiPM layer in the barrel, LGAD layer in the endcap: ~ 30 psec. MIP timing up to $|\eta| < 3.0$
- At the same time, this type of technology has been identified as the next big step in astronomical instruments (fast camera for intensity interferometry).
- Recommend to explore interesting synergy.

Detector Development Initiatives - III

New Materials and detector technologies

- Graphene
 - carbon nanotubes
 - quantum dots
 - Nano wire bolometers
- We are not doing any of these yet, perhaps we should get more involved in the development of detectors with the next generation materials.

	R&D / CAPABILITY	microdetector assembly	sensor design/ simulations	sub-K lab	ASIC development	LAR test facility	Test Beam	Thin film/Special Materials/ Scintillator extrusion
Neutrinos	Lower Energy Detector for Supernovae					●		
	Improved Photon Detection Systems					●		
	R&D in HV Feedthrough					●		
	Improved charge readout				●	●	●	
	magnetization of LAr volume					●	●	
Energy	rad hard photodetector and scintillator	●					●	●
	smaller edgeless pixel sensors	●	●		●		●	
	new materials for Si det support structure	●					●	●
Cosmic	low threshold detectors (super, semiconductors, and	●	●	●		●		
	low energy nuclear recoil calibration					●	●	
	high density fiber positioner	●						
	superconductor detectors for VNIR		●	●				
	quantum detectors			●				
Precision	low mass, high-rate tracker	●					●	
	high-rate/dose photon sensors	●					●	

Summary

- Expand and maintain detector development capabilities at the lab
- Strengthen and rejuvenate expertise in various areas
- Need to collaborate as much as possible across the lab, projects, frontiers, divisions

BACKUP

(Unsorted) goals

- Broadcast better funding opportunities, facilities and technical expertise inside the lab, and also to other labs and universities for better collaboration.
- Detector developers need to have strong input for IERC design phase (~now). List of needed facilities at IERC and elsewhere at the lab:
 - Clean rooms (class?, size?, underground)
 - Cryogenic facilities (CO2 plants, ADRs, Dil Fridges, ?)
 - Cryogenic teststands at PAB (and in testbeam?)
 - Wirebonders, in-house bump bonding?
 - Precision metrology
 - Special materials, thin films, scintillator extrusion, more need for Chemists, Material Scientists?
 - Testbeam facility crucial
 - Irradiation facility (at MTA) would be very desirable
 - X-ray irradiation facility
 - PREP needs modernization of electronics and DAQ (network enabled, plug-and-play)
 - Better communication with AD and TD about instrumentation, facilities and technical expertise

(Unsorted) goals continued

- ASICs and sensors: few-nm architecture, 3D-silicon, CMOS technology, monolithic sensors, 8" wafers, in-house bump bonding and wafer processing and dicing
- Other semiconductor materials, i.e. diamond, GaAs?
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(Unsorted) goals continued

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(Unsorted) goals continued

- Collaboration with industry?
- How do we get the 3M back from the SBN?
- Need to make sure ASIC group is being kept alive (and expanded) with continuous projects from different frontiers. The same for DAQ and electronics needs.
- Can the ASIC group help with modernizing PREP?
- Would we need a new facility for COLDATA ASIC testing?
- Would be good to collaborate with Bern group on pixelated readout of LArTPC.
- ECA awards would be great to get recent ASIC PhDs to start working on new ideas.

(Unsorted) goals continued

- How do we solve the age problem of the detector expert community? Need to attract and educate young people for continuity and bright new ideas. E.g. Thin Film facility is critical.
- Strengthen further our unique skillset of capabilities of packaging, smallest and largest scales, including ASICs, plus full system integration including DAQ.