Report of the FNAL Internal Detector R&D Review

5 November 2014

This committee comprised of external reviewers was charged (Appendix 1) with reviewing the broad program of KA25-funded detector R&D at FNAL. The committee heard presentations describing the R&D activities in overview, the facilities at the lab, and how funding is allotted to the projects. A pair of committee members as listed below, with their affiliation shown in parentheses, attended each of 5 parallel sessions which described in detail the projects in:

- Cosmic frontier detectors: Jeter Hall (PNNL); Dan Akerib (SLAC)
- Silicon tracking : Paul Grannis (Stony Brook); Alex Grillo (UCSC)
- DAQ & Trigger: Mark Oreglia (chair, U.Chicago); Henrik von der Lippe (LBNL)
- Calorimeter & Photodetector: Jose Repond (ANL); Chris Tully (Princeton)
- Liquid Argon: Hanguo Wang (UCLA): Bo Yu (BNL)

The committee is impressed with the high quality of detector R&D conducted by FNAL and physicists and engineers from other national laboratories and universities. Major developments in detector development for both near- and far-term experiments have been made possible by unique expertise at FNAL and several very important facilities that are unique and world-class:

- FNAL Test Beam Facility (FTBF)
- Silicon Detector Facility (SiDet)
- Scintillation Detector Facility (ScDet)
- Application Specific Integrated Circuit Facility (ASIC)
- Precision Metrology Facility (PMet)
- Vapor Deposition Facility (VDep)
- Rapid Prototyping and Special Materials Facility (Proto)
- Adiabatic Demagnetization Refrigerator (ADR)
- Liquid Argon Material Test Stand and Associated Facilities in PAB

Appendices 2-6 describe findings by the committee for each of the program areas. The remainder of this section will describe the comments and recommendations for the program as a whole.

Comments:

The detector R&D program is broad and continues to nurture creative ideas that advance the experimental programs in the directions of the Energy, Intensity, and Cosmic Frontiers. At the same time, the range of programs and management of same is sufficiently well focused to maximize the benefits of the high value facilities supported by the KA25 program at FNAL with strong university collaborations.

The R&D program appears to conform to Recommendations 27 and 28 of the P5 report insofar as there is a large amount of university involvement and an emphasis on R&D to enable near-term experiments. The committee did not have sufficient time and information to assess how well P5 Recommendation 27 is being addressed, but our general impression is that much more than 50% of the program addresses near-term/high priority projects. It was rather nebulous as to how major decisions are made about KA25 funding distribution to various projects, but we did get the impression that lab management, the R&D committee and project managers provide reasonable oversight of the R&D program. Ultimately it is the job of the program managers to oversee efficacy of their projects and adherence to P5 recommendations.

The Detector Advisory Group provides biweekly review and advice on the content of the program. The DAG consists primarily of the R&D area managers and Fermilab line managers, with only one external member. While the decision on priorities and funding levels for projects should remain with the Fermilab managers and those persons should participate in the DAG discussions, some degree of independent evaluation would be desirable.

The R&D program has been effective in outcomes and cost. The committee wishes to highlight several breakthrough achievements:

- Successful development of 3D Si photon pixel detectors
- Development of 3D Associative Memory trigger processors
- Advances in LAr purification and development of low-cost/large scale cryostats
- Innovative new techniques in calorimetry

The committee wishes to emphasize the importance of the FNAL facilities, specifically the FTBF. This is a unique facility in the Americas and essential for development and testing of detectors, both old and new. Accessibility to this and other FNAL facilities is of utmost importance to the US HEP program.

Recommendations

University involvement and KA25 funding

- The role of the project managers should be better defined to facilitate more coherence with the university component.
- Project managers should hold 5-10% funding in reserve for external participation (already a practice by some of the managers, and we applaud that).

Balance of Near-term to Generic R&D Funding

- The Laboratory should periodically review the budget in detail to assess concurrence with P5 Recommendation 27.

Use of Facilities

- Test Beam committee should include significant university/external representation; the current first-come, first-served policy will not ensure the most effective use of the facility as it becomes more popular.

- Expansion of the FTBF to include irradiation facilities is encouraged, but care should be taken to avoid duplication of other US facilities.

Detector Advisory Group

- The DAG should include more members external to the Fermilab managers drawn from universities and other Laboratories, perhaps meeting on a monthly cycle.

Appendix 1:

Charge for the Fermilab Detector R&D External Review

In preparation for the next triennial review of the DOE Office of High Energy Physics (OHEP) general detector R&D portfolio, anticipated for the summer of 2015, the Fermilab directorate requests a review of the associated Fermilab detector R&D program. Since the last triennial review, U.S. detector R&D researchers have developed a common vision for detector R&D manifest in the Snowmass Instrumentation Frontier report, and the broader U.S. particle physics community has strongly endorsed the Prioritization Panel for Particle Physics Projects (P5) report which contains the following two recommendations regarding detector R&D:

> **Recommendation 27**: "Focus resources toward directed instrumentation R&D in the near-term for high-priority projects. As the technical challenges of current high-priority projects are met, restore to the extent possible a balanced mix of short-term and long-term R&D."
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> **Recommendation 28:** "Strengthen university-national laboratory partnerships in instrumentation R&D through investment in instrumentation at universities. Encourage graduate programs with a focus on instrumentation education at HEP supported universities and laboratories, and fully exploit the unique capabilities and facilities offered at each."

We request that you assess the quality and impact of Fermilab detector R&D efforts conducted in the last several years and to assess the merit, feasibility and alignment of proposed activities with the Snowmass vision and P5 recommendations for the U.S. detector R&D program. In particular we request that you:

1. Evaluate the impact and promise of the group's research efforts in detector R&D:
   a. The quality and impact of the Detector R&D by the group in the past three years.
   b. The scientific significance, merit, and feasibility of the proposed future program and the competence and promise of the group for carrying it out.
   c. The adequacy of resources for carrying out the proposed research, and cost-effectiveness of the research investment;
   d. How well do the group's proposed activities align with the Snowmass vision and P5 recommendations?

2. Assess how effectively the detector R&D effort has exploited and leveraged existing facilities at Fermilab and the importance of these facilities to the future proposed program of work. Evaluate whether additional facilities are needed.

3. Evaluate Fermilab's status and plans for collaborative efforts with universities, other national labs, and industry, in the general areas of detector R&D and technology transfer. Has Fermilab been effective in maintaining and seeking out additional partners for collaborative research?

Fermilab will provide relevant information in advance of the review which addresses these items and facilitates reviewer evaluations. Upon the completion of the review, we request that the review committee submit a letter summarizing their findings and evaluations.

Appendix 2: Cosmic Frontier Detectors

Findings:

The Fermilab research and development in Cosmic Frontier detectors has a distinguished record of developing advanced detectors that go on to be funded projects. The groups developing Cosmic Frontier detectors rely heavily on the SiDet facility and have been making the case to extend the capability of this facility to millikelvin temperature detectors.

Detector R&D over the past several years within the cosmic frontier group at Fermilab has been very effective in helping to launch science projects that gain program funding outside of KA25. One impressive example is the use of the DECam CCD development as a technology basis for the DAMIC dark matter search. A second example was the directed development of stable bubble chambers for the COUPP dark matter search.

The current main emphasis of the program is the development of MKID detectors and associated readout systems, and is well-connected with university collaborators. It is clearly long-range R&D and not yet tied to a specific project. However, this is not a negative assessment — indeed, this work was flagged by the P5 report as a needed technology development to follow-up dark energy measurements expected from LSST. The funding level for this activity is modest in the context of the overall KA25 program at FNAL, and so on its own doesn't represent a significant tilt away from P5 Recommendation 27.

Comments:

MKIDs

The CCD group has a history of expertise, and Fermilab's efforts have transformed the field of astronomy with the projects SDSS, DECam, and now DESI. This group should be commended for reaching into the University community to advance some of the highest technology, long-term detector technologies, MKIDs. The MKID technology has significant, long-term R&D before it can be adopted for large projects, but the investment in the Fermilab detector R&D portfolio is modest. Fermilab is encouraged to invest the appropriate scientific research into further developing the scientific case. Recent work has shown significant promise for future dark energy follow-up projects and this scientific case should be advanced and promoted as the detector technology advances.

The CCD/MKID group has heavily leveraged the SiDet facility through the years and is contributing to extending the capabilities to low temperature detectors, which have the possibility of radically transforming detector paradigms in general. This capability has already resulted in other users, for CMB and dark matter projects.

P5 did note the promise of the technology in their report noting, "proposals to develop novel Microwave Kinetic Inductance Detectors would allow the billions of galaxies found by LSST to be used for wider field/lower resolution RSD."

CMB

There was a small investment in CMB efforts in the past three years. This effort has transitioned to a significant LDRD project. A recently hired, junior scientist is leading the nascent effort. The scientific and technical expertise of the junior scientist seemed very high. The ambition in this thrust seemed low given the scale of investments being made. It was stated that the effort would culminate in a 2-3 FTE project role in the CMB-G4 project. This does not seem like a significant return on the large investment Fermilab is making in this research and development.

The focus on CMB is well aligned with the P5 report, as P5 recommended investing in future CMB technologies and named CMB-G4 as a priority project. This thrust at Fermilab has moved from the detector R&D portfolio to the LDRD portfolio. Any future investments by the detector R&D fund should be aimed at securing a large leadership role in the CMB-G4 project.

The lines between LDRD, SPT-G3, and detector R&D were not clear. Those lines should be clear given the laws that forbid supplementing approved projects with LDRD. It seemed that the LDRD was focused on developing facilities and expertise for CMB-G4, which is an appropriate use of LDRD.

SiDet Facility

Cosmic detector R&D at Fermilab heavily leverages the SiDet facility, and engages in extending the facility for advanced detector development. The millikelvin capability at Fermilab is already fully subscribed and the CMB needs include a new ^{3}He refrigerator. This extension of the already unique capability of the SiDet facility should be commended and continued. Fermilab should consider further investments in SiDet to distinguish the low temperature detector testing capabilities.

In addition to the MKID program, the group operates an Adiabatic Demagnetization Refrigerator as a user facility. The ADR supports the MKID R&D as well as work on Superconducting Tunnel Junctions for for a possible neutrino decay experiment and for technical development support of the SuperCDMS program to measure thermal properties of test structures. While the ADR facility appears modest for a national lab (many university groups operate such refrigerators), the implementation as a user facility is unique and well-supported, and the proximity to the MKID work at FNAL appears to be an essential aspect of that overall program. Finally, there is CMB R&D effort that is mostly funded through an LDRD grant, and leverages some of the facilities supported by KA25.

Collaborations

The cosmic detector R&D includes significant collaborations with University groups, both in importing and exporting technology. The CCD efforts have resulted in dark matter searches with the University of Michigan, the University of Chicago, and SNOLAB. The CMB effort is a collaboration with the University of Chicago and Argonne National Laboratory. The committee was not presented with any evidence of collaboration with, or technology transfer to, private industry in the area of cosmic detectors.

Program Size

The size of the investment in cosmic detectors in the detector R&D portfolio is small and shrinking. Fermilab should ensure that its investments are large enough to ensure appropriate impact and eventual returns. If the cosmic detector investment is too small, then Fermilab will have a difficult time distinguishing itself in this research.

Recommendations:

- Investigate transforming the ADR capability at SiDet into a cryogenic detector facility that distinguishes it from the scale of work that could be done at universities.

- The MKID R&D should be pursued on its current track as a modest long-range component of the overall R&D program at Fermilab. The detector R&D should be complemented by scientific research to continue strengthening the case and the community for a future dark energy camera based on MKID technology.

Appendix 3: Silicon tracking

Findings

1. After many years of sometimes frustrating work, the 3-D silicon technology pioneered at Fermilab has now produced a working chip, the VIPIC. This chip has been successfully operated in an accelerator environment and has produced physics results with notably low noise performance. The VIPIC chip is designed for use in X-ray photon imaging at light sources, and has been funded with comparable budgets from the Fermilab KA25 budget and funds from DOE/BES.

2. KA25 funding for the VIP chip program aimed at ILC vertex detectors has ramped down.

3. Each of the silicon projects reviewed seems to have both project-directed and generic components. The early phases of more generic R&D have led to more project oriented applications as is appropriate for the KA25 program. In particular, the work conducted as a part of the RD53 program seems to be more project oriented.

4. The 3-D silicon R&D has successfully brought a variety of vendors into collaboration. The VIPIC chip has been a productive collaboration of several Laboratories and universities.

5. Conceptual design has started for 3-D implementations of a large area forward silicon readout calorimeter (HGC) for CMS.

6. Work has begun on conceptual design of the FCP pixel chip for inner layers of the CMS vertex detector, and radiation dose response of target transistors has been carried out at Sandia Lab in the context of the RD53 consortium.

7. Good use has been made of university students, particularly for testing prototype chips.

Comments

1. The committee congratulates the silicon tracking group for its success in fabricating the VIPIC chip. This important milestone should encourage further work to develop more applications. We foresee many potential applications for HEP and more broadly in science. It will take more work to demonstrate that this technology can be competitive in cost with alternative technologies especially considering component yields and assembly labor costs. The development of the VIPIC-Large camera for BES should help define these parameters.

2. The movement toward project-directed R&D for silicon tracking is well aligned with the recommendation of the 2014 P5 panel.

3. Testing of the VIP chip should continue in collaboration with other Lab and university partners, followed by beam tests at Fermilab, so as to enable a ramp up on this project, should decisions to proceed with ILC be made.

4. The productive collaborations forged with other Laboratories, universities and vendors in the ASIC and sensor development has been a very promising development that should be continued in future projects.

5. The technical specifications for HGC are challenging and the design choices have not been made by CMS as yet. Moving forward on this project should occur in a measured way so as to accommodate the CMS plans, and should take into account the technical evaluation of the succeeding stages of the project. Working with Tezzaron to be a viable U.S. sensor manufacturer could have many positive advantages for the field but is very speculative given the past history of U.S. companies finding this market not to meet their acceptable profit levels. Fermilab support for this venture, especially with funds, should be watched closely to minimize exposure.

6. The engagement of university groups and provision of projects for students should be further encouraged and nurtured. Potential projects for Fermilab KA25 funding should be examined to see if they can be a good match for university groups to undertake, and if so, spun off to such groups.

7. The FCP pixel project is still not well defined within CMS and the roles of Fermilab and other collaborators are not yet well defined. A step-wise program taking into account the various CMS activities should be undertaken.

Appendix 4: DAQ & Trigger

The review committee heard talks on: the 3D Associative Memory trigger chip program, modification of commercial devices for high speed optical communications, DAQ for IR photon detectors used in CMB experiments, and development of generic rad-hard sensors. The 3D AM trigger chip is a stellar example of a revolutionary device conceived during collaboration with a university and carried to fruition at FNAL.

Findings:

The FNAL TDAQ groups are pursuing a vigorous program of R&D on significant problems relevant to current experiments and with several projects likely to have a long-term influence on technology, such as high-speed/high-bandwidth optical communication, radiation-hard sensors and electronics, and fast trigger processing electronics. Advances in these areas have been made possible by engineering and physics expertise at FNAL in collaboration with university engineering and physics groups. Indeed, the TDAQ group is to be commended for not only working closely with university partners, but also for using a fraction of the KA25 funding to bring students to FNAL where they receive mentoring while working on these projects. The new DAQ facilities for sensor characterization (CAPTAN) potentially enables in-house and outside users easy access to experimentation in sensor design. However, it remains to be seen if this one-size-fits-all DAQ system will be cost effective and useful to the majority of users.
Combination of near term and long term science needs are driving the requirements for the trigger and DAQ systems. HL-LHC is the dominant driver.

Recommendations:

- Continue working closely with university engineering groups in the development of new enabling technologies. There may also be more opportunities to work with private industry.
- Consider reviewing the utilization and cost/benefit of the CAPTAN system.
- Continue to use near and long term science as drivers of technology and system requirements.

Appendix 5: Calorimeter & Photodetector

Findings:

- The calorimeter/photodetector effort relies on and makes excellent use of several Fermilab facilities: FE-electronics (ASIC) design, scintillator chemistry lab, scintillator extrusion lab, thin film lab, optics lab. These are first class facilities, which also serve a wider community.
- The facilities perform a dual role by providing a service to the community (and Fermilab), but also by furthering the knowledge in their respective fields and by improving their technical capabilities.
- Significant progress was achieved in the development of dual readout calorimetry, where an approach based on total absorption calorimetry based on glass and fibers is being pursued. Recent prototypes now show sufficient light collection for both the scintillator and the Cerenkov components.
- Total absorption dual readout calorimetry based on crystals, which had been developed in the past years, was not mentioned and seems to have been abandoned.
- Fast timing studies explore a number of new devices with a high potential to make a cost-effective, high technology break-through for large area systems, such as SiPMs, MPCs, etc.
- Involvement in the HGCAL upgrade of CMS is being planned and will be ramped up following a positive down select in February 2015.

Comments:

- The above mentioned facilities are in part unique to North America and provide invaluable help in the development of new detector technologies.
- The proposed plan to increase involvement in the Phase II upgrade of the CMS endcap calorimeter appears reasonable and offers a number of areas where Fermilab can make a significant contribution.
- The HGCAL upgrade faces a number of difficult technical challenges. The feasibility of the project has not yet been demonstrated.
- A proof of principle for the dual readout approach to the measurement of hadron energies has not yet been given. The single particle resolutions presented so far (by other groups) have not been impressive.

Recommendations:

- The project-driven support of calorimeter/timing/ASIC development aimed at the HL-LHC Phase II upgrade is encouraged.

- We recommend that the dual readout project shift its emphasis from exploring techniques to improve the light yield to a full conceptual design that could be a proof of the dual readout principle per se. We believe that the investment in the construction of a full-scale hadron calorimeter prototype would be within the scope of KA25 if there is a corresponding positive decision on a potential future project.
- More directed development towards a fast timing prototype that meets the needs and constraints of the CMS Phase II endcap calorimeter region is encouraged.
- We encourage facility leaders to make a more concerted effort to understand what complementary capabilities exist at other national labs and at universities
- We applaud the proposal to reserve 10% of the budget for use in collaborative projects with Universities and recommend that the program leader reach out to university group leaders and actively encourage involvement with Fermilab, especially through student and postdoc involvement on-site.

Appendix 6: Liquid Argon

Major developments in the last two decades have shown that liquid noble gases as target materials are well suited for particle detection. Liquid argon is a readily available material that can be used in very large detectors such as the multi-kiloton LBNF. The ICARUS collaboration demonstrated what was possible with the liquid argon technology. Fermilab recognized the technology and took leads on the systematic study of the technology aiming to small (dark matter) and large-scale (neutrino physics) applications.

<u>Findings:</u>

1. The LAPD (Liquid Argon Purity Demonstrator) together with the Long Bo TPC successfully demonstrated >3 ms electron lifetime (<30 ppt O_2 equivalent) in a non-evacuated cryostat with a 2.5 m drift distance. The in-house experience in construction of multi-ton liquid argon cryogenic and purification systems laid the foundation of the current LBNE liquid argon detector design concept.
2. Underground argon production achieved collection of the 152 kg of underground argon needed for The DarkSide 50 experiment, with the possibility of use for other interest groups such as National Security and Climate Studies. Underground argon processing systems are working properly at Fermilab. Fermilab is the only argon-39 depleted argon source in the world. Further tests are needed to validate the usability of the underground argon for DarkSide, using the SCENE detector.
3. Material Test Stand is a fully developed multi-purpose system to systemically study material properties related to argon purity and provides clean argon for other tests with controlled environments, such as HV, light detection and readout electronic studies.
4. SCENE, a project for measurement of the effect of the electric field on light collection and ionization production by recoil argon nuclei (important for dark matter searches using noble liquids) has achieved breakthrough understanding of fundamental properties of argon response to recoil nuclei.
5. HV studies are critical to any TPC system. Fermilab has constructed HV feed-throughs and developed systematic measurements to study argon breakdown and uncovered the correlation between the liquid argon purity and high voltage instability. This finding has alerted the LAr community to be far more cautious and rethink the HV system design for current and future LAr TPCs.
6. Fermilab collected an invaluable set of data from ArgoNeuT (250 kg LAr TPC in NuMI beam) and plan to expand with LArIAT in order to fully understand particle ID with particles from a well understood beam.
7. Fermilab maintained very close relationship with University and other national lab partners to fully utilize the existing facilities. The works in the tall-Bo cryostat have resulted in numerous publications in the studies of light production, transmission and detection in liquid argon, as well as many innovative photon detector concepts and designs applicable to LBNF and LAr1ND.
8. An invaluable team of technicians and engineers has been assembled with experience and expertise in cryogenics.

9. Fermilab has organized annual LArTPC R&D workshops as well as timely topical workshops such as LIDINE on light detection and “high voltage in liquid noble gases” at Fermilab.

Comments:

The LAPD results are major milestones for the LBNF project. It enabled the project to design a very large cryostat without the need of evacuation in order to remove oxygen and other contaminants. It demonstrated a large-scale clean argon production capability.

The understanding of the HV properties of LAr is crucial to the design of the near term high priority projects such as LAr1ND and LBNF TPCs. The high voltage cryostat (HVC), coupled with the pure argon system at Fermilab, has the unique capability of studying HV breakdown under controlled LAr purity. This is also an area to attract university participation.

Full understanding of the sources of impurities affecting electron lifetime in liquid argon is key to the success of LBNF projects. The material test stand is critical to validate all materials to be used in the LBNF projects.

The SCENE project could not have achieved the timely result without the support of Fermilab experts and the full use of the Fermilab facilities’ capabilities. This project has also trained many young students from participating universities.

The Argon distillation system has expanded dramatically from a simple distillation column to a full production line capable of processing raw gas mixture from an underground source to pure “argon-39 free” argon.

The Detector R&D done by the Fermilab groups are of very high quality and already had major impact on both LBNF and dark matter search projects. The proposed LAr1-ND and LArIAT projects are important to the LBNF project, with the current group competent enough to carry out the work, based on their past achievements.

The achievements so far are impressive and resources are limited, so continued cooperation and coordination with all labs and university groups interested in these subjects are needed to avoid duplication. The track record has shown that the proposed R&D efforts, such as future HV studies at PAB, argon purification, light detection studies, materials tests and SCENE studies, could be done effectively.

The activities and proposed work align well with the Snowmass vision and specifically the P5 recommendations 27 and 28.

The liquid argon R&D effort of the Fermilab team has effectively collaborated with many universities and national labs such as University of Chicago, Princeton, Naples, Notre

Dame, Temple, UCLA, BNL, Indiana University, M.I.T., Michigan State University, PNNL, Yale, and groups in the LArIAT collaboration.

Recommendations:

- The LArSoft effort is an integral part of the LArTPC R&D program, and as such, it should also be supported by the detector R&D program fund.

- The High Voltage R&D program should be expanded from the current scope to include further generic studies as well as project specific tests. It should be supplemented by detector R&D, as well as direct project funds to advance its progress.

- The current engineering and technician team should be maintained if expansion is impossible. Note that the achievements so far could not have been done without the effective engineering team.