FERMILAB
DETECTOR R&D
STRATEGY

PREPARED BY THE FERMILAB DETECTOR ADVISORY GROUP

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1. *Executive Summary*

The Fermilab Detector Research & Development (R&D) Program is focused on exploiting Fermilab's world-leading capabilities to carry out cutting-edge activities that lay the foundations for achieving the highest priorities of the field of high energy physics (HEP), as codified by the most recent P5 report [1]. In addition, technology development needs and directions as identified by the Coordinating Panel for Advanced Detectors (CPAD) of the APS Division of Particles and Fields (DPF) [2] are taken into account; an updated CPAD report [3] summarizes the latest guidelines collected from the HEP community. In the recent Detector Basic Research Needs (BRN) activity organized by the DOE, four Grand Challenges were identified, each supported by a set of Priority Research Directions: *Advancing HEP detectors to new regimes of sensitivity, Using integration to enable scalability for HEP sensors, Building next-generation HEP detectors with novel materials and advanced techniques, Mastering the challenges of extreme environments and data rates in HEP experiments.* Each of these Grand Challenges has a set of Priority Research Directions linked to them. The final BRN report is expected to be published soon.

To address the Grand Challenges, Fermilab has identified two strategic focus areas in which it has world-leading capability: *Picosecond Timing* and *Noble-element Neutrino Detectors*. We are initiating a new annual call for proposals, with a small pilot program in FY20, in order to stimulate breakthrough ideas and attract new Fermilab PIs in these areas. With a high degree of collaboration with other institutions, Fermilab has met many of the R&D challenges set by the ambitious suite of planned particle physics experiments. For the next few years, the highest priority will be placed on R&D topics that will crystallize during the recently started Snowmass process. Strong emphasis will be put on fruitful collaboration with university partners and other national laboratories.

The program is funded through a KA25 Budget and Reporting (B&R) code that is subdivided into four thrusts (see Table 1 below): *Sensors/Detectors and Front-End Electronics (FEE), Detector Systems, Trigger/Data Acquisition Systems (DAQ),* and *Core*. Most detector R&D activities follow a multi-year strategic plan that is reviewed and updated annually. Detector R&D Lab Goals and Lab Objectives have been added to Fermilab's strategic planning database and are listed in Appendix A. Each goal has a set of objectives assigned to it, which are enabled by Fermilab's scientific and technical capabilities. A small fraction of the annual budget is reserved for low-cost, emerging tactical opportunities that have been identified by the Fermilab Detector Advisory Group (DAG) as high-priority needs. Execution of the R&D plan is managed by Fermilab's Detector R&D Coordinator, in close coordination with the DOE Office of High Energy Physics Program Manager for Detector R&D. Some examples of recent publications based on this R&D are given in [4].

In order to maintain and advance its cutting-edge detector technology capabilities, *the lab needs to modernize and upgrade its facilities and maintain or even expand its excellent technical workforce in critical areas*. The high-level plan is:

- Modernize and upgrade detector test facilities, including creating high-intensity test beam and irradiation facilities at PIP-II.
- Maintain and if possible expand the excellent technical workforce and place more emphasis on attracting postdocs and scientists interested in instrumentation.

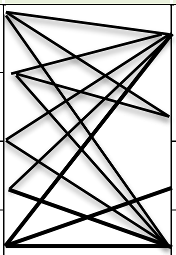
- Create R&D consortia centered around picosecond timing and noble element neutrino detectors in collaboration with other laboratories, universities, and industry, in order to facilitate a coherent R&D program in these areas.
- Prudently seek opportunities to transfer detector technology outside HEP as a way to keep strong detector development expertise, and updated facilities.

2. Program Overview

The Detector Advisory Group (DAG) [5] carries out strategic and tactical planning for Detector R&D and helps define short- and long-term R&D projects. The DAG meets regularly and advises laboratory leadership on detector R&D budgets and issues as well as on priorities among different R&D efforts. The group comprises the Detector R&D Coordinator, who chairs the Group, plus laboratory staff and two external advisors. The DAG membership includes scientists and engineers with expertise covering the entire range of detector technologies at the laboratory. Fermilab users and employees are encouraged to propose new R&D projects that are evaluated by the DAG. The laboratory routinely collaborates with other laboratories and university groups, as well as international and industry partners, on a variety of R&D projects. For example, in the area of CCD R&D we have collaborated extensively over the past years with LBNL as well as with industry. For superconducting detectors, we have established a strong collaboration between Fermilab, Argonne and the University of Chicago. Much of the R&D in these areas has been supported by KA25 funding.

The strategic planning and prioritization process for Detector R&D has been built upon input from DAG members and from the leadership of the three primary laboratory divisions involved in detector R&D (Particle Physics Division, Neutrino Division, Scientific Computing Division) via their representative members in the DAG, as well as from the Fermilab Chief Research Officer (CRO). Each member of the DAG is tasked annually with soliciting and collecting R&D topics within their area of expertise. Resource needs are established and aligned with DOE and laboratory budget guidance by consensual prioritization within the DAG, taking into account the P5 Science Drivers, BRN Grand Challenges and CPAD identified priorities. The DAG prioritizes the R&D activities, taking into account the technical and scientific expertise at the laboratory and additional expertise available through collaboration with universities and other national laboratories. Detector R&D program funding is subdivided among the three divisions involved in the R&D. The program is funded through a KA25 Budget and Reporting (B&R) code that is subdivided into **four thrusts: Sensors/Detectors and Front-End Electronics (FEE), Trigger/Data Acquisition Systems (DAQ), Detector Systems,** and **Core**. The mapping between P5 Science Drivers and R&D Thrusts is illustrated in Table 1.

Table 1: Mapping of KA25 Detector R&D Thrusts onto P5 Science Drivers and Physics Frontiers at Fermilab.

PHYSICS		**THRUST**
Higgs Physics		Sensors/Detectors & Frontend Electronics
New Physics		
Dark Matter		Trigger/DAQ
Dark Energy		Detector Systems
Neutrino Mass		Core

We have made a number of improvements to the Detector R&D program in response to the comments and recommendations received from the 2016 Comparative Review of the KA25 Detector R&D program at the National Laboratories. We have added several external experts to the Detector Advisory Group. We have integrated the Detector R&D B&R into the lab's annual strategic planning effort. We have moved all directed R&D for the HL-LHC CMS Upgrades onto programmatic support, enabling us to reorganize the remaining R&D portfolio into fewer, prioritized activities, resulting in a better-focused program overall. Higher priority is now being put into two main R&D areas (picosecond timing and neutrino detection) as well as blue sky R&D. Other R&D will be scaled down after consideration of the availability of alternative funding, collaborative opportunities and other related developments. As an example, the scintillator R&D effort, which had been criticized during the review, has now been redirected onto our two high priority areas of picosecond timing and neutrino detection. From an accounting point of view, these four larger R&D directions (*picosecond timing, neutrino detection, blue sky, other R&D*) will have individual R&D activities spanning across the four thrusts listed in Table 1.

In the recent Detector BRN activity organized by the DOE, four Grand Challenges were identified, each supported by a set of Priority Research Directions. To address these Grand Challenges, **Fermilab has identified two strategic areas: Picosecond Timing and Noble-element Neutrino Detectors.** Over the next five years (FY21-FY25) we plan to increase R&D in these two strategic areas from currently 21.5% each of the total program to 30% each. We will also increase support for "blue sky" R&D from 3% to 8% of the total portfolio in order to develop promising ideas that we expect will grow out of the Snowmass and P5 process. To enable this redirection, other collider detector R&D, astrophysics detector R&D, and some other smaller efforts will be relatively scaled back from their current cumulative 54% to 32% of the total. Further details of this plan are given in Table 2, which shows planned evolution in FTEs over this five-year period for the different R&D activity areas under four different budget scenarios spanning the range from optimistic to pessimistic. In all scenarios, the relative percentages of the different areas evolve as described above. In the optimistic budget scenario, effort in the two strategic areas grows:
picosecond timing goes up to 160%, neutrino detection 160%, and blue sky 300%, while all other R&D activity goes down by 68%. However, in the cases of flat or declining budgets, the picosecond timing and neutrino detection efforts

can only be maintained at the current levels, the blue sky effort increases only modestly, and all other R&D activity would be severaly cut, jeopardizing several important areas where the laboratory has unique capabilities, such as astro particle detector R&D and non-timing related collider detector R&D.

We are initiating a new annual call for proposals, with a small pilot program in FY20, in order to stimulate breakthrough ideas and attract new PIs into the program. The call specifically addresses ideas for picosecond timing and noble-element neutrino detector technologies as well as blue sky research. Proposals of one page for FY20 will be due on April 30 to the Detector Advisory Group and will be evaluated by its members. Successful proposals will include new ideas for R&D directions not currently being carried out in the above-mentioned strategic areas. Proposals that have the potential to lead to a larger R&D effort with subsequent funding from other sources, such as Lab Directed Research and Development (LDRD), Early Career Awards (ECA), etc., will be given priority. We expect that such an open call will lead to new ideas by new PIs that will enrich our program.

Table 2: Strategic evolution of technical workforce over the next five years split by R&D priority. Under consideration are four different funding scenarios.

	FTE/YEAR	FY20	FY21	FY22	FY23	FY24	FY25
Flat FTE (inflation compensation) + additional 3% growth/year	Picosecond	2.20	2.45	2.70	2.97	3.25	3.54
	Neutrinos	2.16	2.40	2.65	2.92	3.19	3.48
	Blue Sky	0.30	0.41	0.53	0.65	0.79	0.93
	Other	5.46	5.17	4.85	4.50	4.12	3.74
	TOTAL	10.12	10.43	10.72	11.04	11.34	11.68
Flat FTE (inflation compensation) +	Picosecond	2.20	2.38	2.54	2.72	2.88	3.06
	Neutrinos	2.16	2.33	2.50	2.67	2.83	3.00
	Blue Sky	0.30	0.40	0.50	0.60	0.70	0.80

no additional growth	Other	5.46	5.02	4.57	4.11	3.66	3.22
	TOTAL	10.12	10.13	10.11	10.10	10.08	10.08
Flat Budget (no inflation compensation)	Picosecond	2.20	2.30	2.37	2.46	2.52	2.59
	Neutrinos	2.16	2.25	2.33	2.41	2.48	2.54
	Blue Sky	0.30	0.39	0.47	0.54	0.61	0.68
	Other	5.46	4.85	4.27	3.72	3.20	2.73
	TOTAL	10.12	9.79	9.44	9.13	8.81	8.53
No inflation compensation and additional -3% loss/year	Picosecond	2.20	2.22	2.23	2.24	2.22	2.21
	Neutrinos	2.16	2.18	2.19	2.19	2.18	2.17
	Blue Sky	0.30	0.37	0.44	0.49	0.54	0.58
	Other	5.46	4.70	4.01	3.38	2.82	2.33
	TOTAL	10.12	9.48	8.87	8.30	7.77	7.29

3. *Detector Facilities and Workforce*

Fermilab's world class Detector R&D Facilities are a vital and integral part of Fermilab's mission. These facilities are used for detector research and development, testing, prototyping and construction, and also to support experiment operations. Using the same experts and equipment for all of these purposes is significantly more efficient than spreading these high-tech functions to many locations which would require duplication of training and facilities. Fermilab's detector R&D facilities provide an open and welcoming place for students and researchers from all over the world to develop and test new ideas. The national lab environment also provides a very fertile field for cross-pollination of detector technology to many areas of research. In May 2016, Fermilab's Detector Test Facilities were reviewed as part of the DOE Fermilab Facilities Operations Review. In the final report, the committee concluded that "*The detector and test beam facilities at Fermilab are key assets to the lab and US HEP now and in the future*" and that "*all aspects of detector operations and the detector test facilities are well aligned with the US program as outlined by P5. … The detector test-facilities have a long list of improvements and additional capabilities (both equipment and specially trained personnel) that would make them more effective if additional funding were available.*"

Fermilab's detector facilities are a crucial cornerstone in the R&D program. While some of them are world-class, others are nearing the end of their lifetime and need to be completely overhauled or replaced with more modern facilities. Here is the list of the existing Fermilab's detector facilities:

- The most broadly used facility is SiDet, the Silicon Detector Facility. This is the main location for detector development and assembly for the collider experiments and for astrophysics applications, as well as for Mu2e and some work for others. SiDet's capabilities include sensor packaging such as micro-bonding, probe stations for sensor testing, OPGs and CMMs for precision metrology, clean room space for micro- and macro-assembly and testing, a CO_2 plant, and much more. SiDet has been built for the Tevatron silicon detectors and has since seen many generations of collider and astrophysics experiments being conceived and assembled and enabled many table-top experiments and R&D breakthroughs. With an imminent move of some of its facilities to the Integrated Engineering Research Center (IERC, under construction), it is important to update and expand most of its equipment.

- As the leading neutrino physics laboratory in the country, Fermilab is also conducting many R&D efforts in the area of noble-element detector technologies, such as photodetection, HV instabilities, LAr distribution and purification, which mostly take place in the various cryostats of different sizes mainly at the Noble Liquid Detector Facility. Several cryostats, different in volume and aspect-ratio, are connected to a centralized liquid argon delivery system capable of guaranteeing contamination at 0.2 ppb O_2 equivalent level, 3 orders of magnitude better than what is commercially available. The infrastructure includes a suite of gas analyzers and discrete purity monitors, which can detect oxygen concentrations at the sub-ppb level, water concentrations at the ppb level and nitrogen concentrations at the sub-ppm level, as well as automatic controls. This rich and articulated infrastructure needs regular maintenance and could also profit from upgrades especially in the liquid argon filling and purification lines as well as in the control systems, so as to maximize the uptime for the users.
- Our photodetection work takes advantage of the Thin Film and the Scintillator facilities, where we have the capabilities to coat photodetectors, such as the ARAPUCA or LAPPDs, and to extrude large area scintillators or mold high-granularity scintillators.
- Another vital component of detector development at Fermilab is its ASIC group, whose activities are enabled by a steady support with licenses, modern equipment such as chip testing robots, as well as warm and cryogenic test stands.
- Of particular importance for the collider detector community, and increasingly so for neutrino experiments, is the availability of the Fermilab Test Beam Facility (FTBF). For astrophysics and also neutrino physics it would be beneficial to add a neutron beamline. In addition, Fermilab is in the process of establishing an Irradiation Test Area (ITA), which will be crucial for the HL-LHC detector upgrade program, but also for generic R&D for future collider detectors. In addition to the proton irradiation some material studies can be performed with electron irradiation at the IARC. It should be explored to what extent the IOTA facility could also be used for detector development. For the longer-term future, creating high-intensity test beam and irradiation facilities at PIP-II is very important and is under consideration.
- Other laboratory facilities include the rapid prototyping and special materials fabrication lab and large assembly space.

With the new construction of the Integrated Engineering Research Center several of these facilities will be combined under one roof and housed in a modern building with modern equipment. Having all engineering and technical expertise in close proximity to the scientists will be beneficial to the detector R&D and assembly program at the lab. Despite good availability of resources, one weak spot that has emerged over the last two years is the need for maintaining, if not strengthening, the expertise of Fermilab personnel by reinforcing hiring of young scientists and technical staff interested in development of detectors for HEP science. We need to give young people opportunities and encourage them to participate in hardware development. For example, the lab could establish a rule that all postdocs should spend at least 30% of their time on a hardware project.

Fermilab has been leading detector R&D for particle physics and astrophysics at DOE. **The competitive advantage of FNAL in this field comes from the expertise in the integration of novel sensor technology into scientific instrumentation.** The model that has worked until now to develop this expertise, and to maintain the associated facilities, is based on *having large HEP projects that carry most of the financial load*. This model has been extremely successful in the past. However, over the past decade *new standards for funding projects and accounting for efforts are challenging this model*, leading to a depletion of technical expertise, where in many areas we are down to the last person. This is clear at SiDet, the prime detector development facility at Fermilab, for which no significant investment has been done after the major production effort of the large collider experiments. This is also reflected in the depleted technical staff at these facilities.

One way to change this would be to change in paradigm by *prudently seeking the opportunities to transfer detector technology outside HEP*, as a way to keep strong detector development expertise, and updated facilities. With this added source of funding for instrumentation we could afford to hire more technical personnel and acquire more state-of-the-art equipment, which would in turn benefit our R&D efforts. The fields that could benefit from the current expertise in detectors at Fermilab include: imagers for astronomy beyond cosmology (planet search for example), medical instrumentation (in particular exploring the use of superconducting sensor technology as well as picosecond time resolution detectors for medical applications), space instrumentation for radiation detectors in small satellites (CubeSat and others), neutron imaging for thermal neutrons and ultra-cold neutrons, nuclear physics detectors, detectors for x-ray light sources, quantum metrology (such as quantum realization of the ampere), gravitational waves. To prudently seek these opportunities we need to invest, for example we could: include these transfer opportunities as part of the LDRD program, have some scientific effort available to work on these topics, make technical effort (temporarily not committed to a project) available for these activities, organize workshops with relevant communities, establish clear paths for partnership with commercial partners, seek collaborators at universities in other fields and give them access to lab expertise and facilities.

4. Strategic Detector R&D Areas

4.a Picosecond timing

One of the enabling technologies for the HL-LHC and beyond will be detectors with time resolution of the order of picoseconds. We refer to “4D Tracking” to mean a tracking detector with a time resolution of the same order as its spatial resolution divided by the speed of light. So, 100 µm spatial resolution would translate to 330 fs time resolution. Although we are still far from reaching that figure, this is a worthwhile goal to pursue since it would mean a total paradigm shift in event reconstruction technology. It would allow, for example 3D vertexing of photons and the identification of the species of the great majority of particles produced in a future collider environment. Applications in the area of large liquid argon detectors for neutrino physics are also being studied. The precise determination of the time of the interaction through the detection of Cherenkov light, combined with <100 ps re-bunching of the proton beam, would enable the shaping of the energy spectrum of the incoming neutrino beam and help in reducing systematic errors.

Fermilab's current effort in picosecond timing R&D centers around a collaboration with several other institutions in the areas of Low Gain Avalanche Diodes (LGADs), High Voltage Complementary Metal Oxide Semiconductor (HV-CMOS) and Large Area Picosecond Photon Detectors (LAPPDs). With the group of Maria Spiropulu at Caltech we are collaborating on the characterization of LGAD sensors for future collider detectors, for which we are heavily utilizing a specifically designed source test stand at SiDet as well as the FTBF and soon the ITA. Early on we started collaborating with the group of Hartmut Sadrozinsky at UC Santa Cruz on LGAD characterization when the technology first was proposed as a candidate for the HL-LHC upgrades. This collaboration has persisted over the years and now also includes a group at BNL, which is specializing in the design and fabrication of these devices for future applications. Over the years we have benefited from this collaboration through common sensor and readout electronics design, common sensor fabrication submissions with various vendors and joined test beam campaigns. Currently, we are involved in a Phase 1 SBIR with Cactus Materials, exploring the development of radiation hard AC-coupled, epitaxial LGADs with thin buried layers using wafer bonding. This effort is in collaboration with BNL and building on a method that is the subject of a UC Santa Cruz patent.

With the addition of LGAD devices to the standard silicon telescope at the FTBF, we were involved in a R&D project with a Polish group and Caltech [5] on the development of a single photon counting hybrid pixel detector capable of fast timing. With the group of Henry Frisch at the University of Chicago, we are also developing a picosecond timing system at the Fermilab test beam facility (FTBF) based on LAPPDs. The group at UChicago is heavily involved in the design, characterization and commercialization of LAPPDs in collaboration with Incom [6]. The ANNIE experiment at Fermilab also provides a test bed for LAPPD modules, electronics and data analysis.

One common problem with all these fast timing technologies comes when scaling up from a single sensor to a large-scale particle detector, namely the precision distribution of the clock over large distances with the apparently inevitable drifts and jitter. To attack this problem, the Fermilab test beam system has now been expanded with "White Rabbit" hardware. This is a commercial system developed by CERN [7] and designed to synchronize with sub-nanosecond precision distant systems located many kilometers apart.

Other institutions in the US and abroad are also actively pursuing generic R&D for future applications of picosecond devices (e.g. UC Santa Barbara, Princeton, UVA, University of Minnesota). We plan to get in touch with all these institutions and seek ways to collaborate, create synergy and avoid duplication especially in the area of common system-level R&D. Companies like INCOM will also be involved following our mission of developing new technologies for science that support U.S. industrial competitiveness. All this could end up in the formation of a consortium of labs, universities and industries with the goal of the development of precision detectors for picosecond timing in a 5-10 year program centered at Fermilab.

4.b Noble-element neutrino detectors

Fermilab leads several areas of ongoing R&D related to noble element detectors, in support of the current and future short- and long-baseline neutrino programs (SBN and DUNE), as well as future noble element-based dark matter experiments. The main thrust of ongoing noble-elements R&D at Fermilab is to extend the reach of current technology, but explorations of new detection techniques and signal enhancement are also underway. The sensitivity of future neutrino and dark matter detectors can be improved by reducing energy thresholds, which will require improvements in both photon detection and in ionization signal collection. In parallel, research into improving the reliability of HV will be important for future large detectors, where cost can be reduced by achieving longer drift distances. Longer drift distances necessitate tighter controls on purity of the noble liquid or gas, for which R&D is needed to improve cryogenic purification systems.

The Noble Liquid Detector Test Facility (commonly called PAB), has been developed over the past several years into a user facility at which groups from universities and other laboratories can develop and test their novel devices in one of the available cryogenic test stands. There are currently five liquid argon (LAr) cryostats at PAB, with extensive purification system infrastructure to supply them. A large number of non-FNAL groups already make use of the equipment and the engineering and scientific R&D expertise available at this facility, and we expect demand to grow over the coming years. The leading areas of R&D in these existing test stands, motivated by the needs discussed above, are:

- **Noble element light properties and light collection**: Ongoing R&D includes development and testing of different types of light collection systems for LAr scintillation (wavelength-shifting bars, ARAPUCAs, near-infrared light) and other ideas for wavelength shifting (e.g., Xe-doping). R&D done at PAB has been in collaboration with colleagues from UC Santa Barbara, Colorado State University, Tufts, Syracuse University, UT Arlington, Indiana University, and University of Campinas, Brazil. Continued and expanded collaboration with these groups and others is expected in the next 5-10 years, as systems are developed for DUNE and other experiments.
- **High voltage development**: The Fermilab group members at PAB are leading experts in high-voltage breakdown in liquid argon, and in the design and construction of HV feedthroughs. They have led an extensive campaign of HV breakdown measurements at this facility, and they continue to serve as an invaluable resource for others involved in R&D in the same area. Another area of active R&D related to HV (and also to enhanced signal collection) is the study of avalanche amplification of ionization electrons in the liquid phase of argon, similar to gas gain. This work is currently supported by the Fermilab's Laboratory-Directed R&D (LDRD) program. If controlled avalanche amplification in LAr is achieved, additional R&D will be needed to harness this new technique. Collaboration with other groups that have interest and expertise in HV is expected, including UCLA, CERN, U. Bern, and Yale.
- **Advances in cryogenics and cryogenic purification systems**: FNAL engineers have designed and operated a number of cryogenic systems for LAr experiments, which has built up a large pool of expertise. Expansion of the facility to include a dedicated cryogenics and purification test stand will enable the R&D that will further grow this expertise. The U. Wisconsin-Madison group (led by a former FNAL scientist) also has interest in cryogenic systems, and will likely partner with the Fermilab engineering group to continue this avenue of R&D.

Fermilab also participates in several other areas of noble-element detector R&D, such as signal collection, noble element detector calibration techniques, and LArTPC magnetization, all in collaboration with other national laboratory and university groups. The development of large-area, high granularity, high efficiency signal collection technologies (e.g., ASICs for liquid and gas noble element detectors) is critical for the upcoming DUNE program. The laboratory, in particular its ASIC group, has relevant expertise to advance the development of these signal collection solutions. There is an ongoing effort with groups that have complementary expertise at universities and other national laboratories (e.g., UT Arlington, U. Pennsylvania, Michigan State U., BNL, and LBNL) to advance the technology, and to validate it using a dedicated test stand at PAB. In order to fully exploit the potential of noble element detectors, the ability to characterize and precisely calibrate the propagation of charge and light over large sensitive volumes is also needed. Development of promising techniques such as hydrogen-doping to increase neutron detection efficiency are underway. This has been demonstrated in an initial test with liquid xenon at PAB, but it has not yet been attempted in LAr. Fermilab plans to continue collaboration with the UC Santa Barbara group to further advance this work. Groups at Northwestern, U. Michigan, and LANL are other potential partners for future development of calibration techniques. Finally, magnetization of multi-ton-scale noble element detectors would enable additional physics opportunities in these detectors by boosting particle ID performance. However, some non-trivial challenges need to be addressed that will require further development of large-scale high-temperature superconductors. Fermilab has expertise and interest in this area and foresees future partnership with experts from other institutions such as CERN.

Charged particle test beam facilities are also an ongoing important need for neutrino detector development. The MCenter beamline at the Fermilab Test Beam Facility has two experimental areas, both with capability to deliver beams of particles at low energy (~200-1,000 MeV/c) for calibration and detector response characterization. This facility hosted LArIAT in the past and is currently hosting the NOvA test beam detector. A test of a high-pressure gaseous argon TPC is planned in the timescale of the next 1-2 years, in collaboration with Royal Holloway University of London and Imperial College London. Future tests of pixel-based liquid argon TPCs may also be of interest in the next 5 years, in collaboration with UT Arlington, LBNL, and U. Bern.

4.c Blue Sky

We are supporting some generic R&D that we consider blue sky. It typically is of a high risk nature in the sense that a successful outcome is very uncertain. If successful, this R&D would lead to a breakthrough in that could revolutionize certain areas of HEP instrumentation. One current example of this blue sky R&D is our investigation of a semi-conductor scintillator with embedded quantum dots for fast light detection. This could be a candidate novel material for ultra-lightweight trackers or photodetectors for calorimeters at future colliders. Currently, blue sky R&D is minimally supported with 0.3 FTE. Given that we are currently in a position where we need breakthroughs in technology to enable the next generation experiments at the cosmic and energy frontier, and in light of presumably new ideas that will crystallize throughout the Snowmass process, we would like to grow this area by about a factor of three over the next five years.

5. Other Detector R&D Technology Elements

In addition to the strategic areas mentioned above, we are continuing a suite of other R&D efforts. The plan calls for an overall reduction in the following areas. Which area will be reduced by how much has not yet been decided. The DAG will give input on how these decisions will be made. The outcome of the Detector R&D BRN and the upcoming Snowmass process should also be taken into account when deciding the relative priorities between these areas.

5.b Silicon trackers

Over the past 30 years, Fermilab has been at the core of multiple generations of silicon-based tracking detectors going from a few square centimeters in area to hundreds of square meters. In that time the laboratory has built up equipment as well as an enormous depth of expertise in sensor technology and the associated mechanical and electronic design. At the core of the Fermilab expertise are the technicians and engineers who have many years of experience designing and building precise, low mass, thermally efficient assemblies. Use of these resources by astrophysics projects both enabled the projects and helped sustain the resources during the periods between large projects such as the Tevatron, LHC and their upgrades. Given the increasing periods between large projects the laboratory must be proactive in leveraging its expertise to continue and extend our collaboration in projects where expertise in silicon-based tracking is needed. Examples range from work on a future U.S.-based electron-ion collider, via large area muon tomography planes for national security to future international hadron or lepton collider detectors.

There are many locations within the DOE complex and University laboratories for silicon processing. Our goal is to collaborate with them on new technologies, while concentrating Fermilab infrastructure on sensor design and system packaging and test. *The focal point of the R&D will be on ultra-fast silicon and pattern recognition within the sensor.*

5.c Scintillators

Plastic and liquid scintillators have been used in HEP for over 50 years. The advent of wavelength-shifting fiber (WLS) readout along with high-performance solid-state photodetectors produced a renewed interest and opened new applications in HEP. Although they have been supplanted with other technologies for various applications, their use is still widespread and in recent years new applications have arisen, particularly in neutrino physics where large-scale water-based scintillator detectors and highly segmented plastic scintillator detectors are under study.

Fermilab has a long history in plastic scintillator technology, having invented extruded plastic scintillator. Many experiments world-wide have been supported through the scintillator extrusion facility at the lab. R&D in this area has waned in recent years while the emphasis has been placed on production. New opportunities now present themselves in that both CMS and DUNE are proposing scintillator detectors (HGCal/ECAL upgrade for CMS and the 3DST for DUNE). In these cases, the technology is injection molding, but many of the underlying detector issues are the same as for extruded plastic scintillator. *This technology will continue to support the Lab's scientific mission well into the next decade. The R&D in this area will continue to focus on radiation hardness, wavelength shifting materials, and light yield.*

5.d Calorimetry

Calorimeters used to be the subsystems of high energy physics experiments dedicated to the measurements of total energy of photons and electrons (EM calorimeters) and hadrons and jets (hadron calorimeters) with the energy resolution being the primary figure of merit. Advances in photonics and electronics and demands of emerging large highly granular detectors have changed the situation drastically.

In current and future generations of experiments performed at higher and higher luminosities and beam intensities the calorimeters are expected, in addition to the energy measurement, to provide precise timing information necessary for pile-up rejection and particle identification. They also contribute to the track reconstruction and participate in the sophisticated trigger algorithms. Survival and longevity of the detectors in high radiation fields becomes the critical requirement in high intensity environments. In neutrino experiments, the improvements of calorimetric performance of large liquid argon detectors becomes an important element of the optimization of the physics potential of the next generation experiments.

R&D in the calorimetric techniques is par-excellence a cross-disciplinary activity including combination of many different areas: large scale integration electronics (impacting the granularity and segmentation of the detectors), material science (development of new sensors, like LGADs, new organic and inorganic scintillators, quantum dots, etc.), photodetectors (including light collection and transmission, spectrum-enhanced or spectrum-optimized), large scale system integration (clock distribution at the picosecond level), sophisticated analysis algorithms (including the use of Artificial Intelligence). A significant contribution to the development of novel approaches to calorimetry (like Dual-Gate Calorimetry, optimization of time-resolved calorimetry) was enabled by the dedicated effort to improve the performance of the GEANT-based shower development codes. A unique role of Fermilab in the development and testing of new calorimetric techniques is related to the existence of the Fermilab Test Beam Facility. It plays a critical role enabling the tests of the individual components as well as the system level performance of the proposed detectors [8-9]. *The R&D in this area will continue to focus many of the requirements listed above.*

5.e Photodetectors

Photodetectors, which convert visible and near-visible photons (near-IR, UV) into an electrical signal, and the associated front-end electronics, play an important role in high energy physics experiments.

The fundamental conversion process relies on the photoelectric effect in photocathode-based sensors or on a photon-induced creation of a free carrier in a conduction band in semiconductor devices. Recently, there has been considerable progress on a novel class of photosensors employing superconducting nano-structures but the cryogenic requirements make their use in large experiments very challenging.

Photodetectors are used in a wide range of HEP experiments, including collider experiments, intensity frontier experiments and neutrino experiments. Their main use has been in calorimetric applications, thus the sensitivity and the energy resolution are of primary importance, but recent developments now emphasize other aspects, such as energy resolution, spectral characteristics and radiopurity. Future neutrino experiments critically depend on the development of cost-effective, very-large-area photodetectors. Photodetectors are needed in room-temperature applications, such as for water Cherenkov detectors and in applications where reliable operation at noble liquid temperatures (such as for the photodetectors in DUNE’s LAr detectors) are also needed. In addition, enhanced sensitivity in the deep UV region would be a significant advantage. Novel photodetection concepts, like the ARAPUCA, are examples of the implementation of newly available advanced photosensors for future generations of neutrino experiments. The development of fast photodetectors and fast front-end electronics may lead to development of new classes of experimental techniques exploiting Time-of-Flight of Cherenkov signals.

The focal points of our R&D will continue to be in the collaboration with vendors through testing and characterization, as well as development of new classes of photodetectors, such as cryogenically compatible SiPMs, and the collaboration with other labs and universities on development of new photodetection systems, such as LAPPDs.

5.f CCDs

Charge-Coupled Devices developed by the DOE are playing a key role in cosmic survey science (DES and DESI) over the past decade. The enabling technology has been the thick fully depleted CCDs designed at the micro-systems lab at LBNL. The skipper-CCD technology demonstrated at Fermilab in 2017 is making scientific CCD experiments possible in the single-photon regime. This is already having a huge impact in low mass dark matter searches, and the community is currently planning large detector arrays with this technology. It is expected that this technology will play a significant role in neutrinos and also future cosmic surveys. There is an ongoing effort to demonstrate skipper-CCDs as a new tool for quantum information science applications.

Fermilab has played an unequivocal leadership role in the characterization of the sensors, and also in the integration of these sensors into scientific experiments (sensor packaging, focal plane integration, detector integration). These scientific instruments based on CCD sensors have been produced within a collaboration of three partners. LBNL, for sensor design. FNAL, for sensor characterization and integration into instruments. DALSA foundry for sensor fabrication. DALSA is no longer interested in this partnership. In order to maintain FNAL leadership role in the development of experiments with low noise CCD sensors for astrophysics, we need to find a new partner for the development of thick, fully depleted low noise CCDs and skipper-CCDs. *Over the next few years, several avenues will be pursued for establishing this partnership including commercial CCD foundries, nanofabrication facilities and national labs, and even moving the skipper-CCD fabrication into CMOS.*

5.g KIDs

Kinetic Inductance Detectors (KIDs) and the Microwave version (MKIDs) are superconducting resonators with the ability of sensing energy deposition by taking advantage of their large kinetic inductance. When energy is absorbed by the resonator, the kinetic inductance changes producing a shift in the resonator frequency proportional to the amount of absorbed energy. The resonator is capacitively coupled to a superconducting transmission line and read out by supplying an RF signal and measuring the change in resonator frequency. Hundreds and even thousands of KID pixels can be connected in parallel on a single RF line.

KIDs provide the unique opportunity for multiplexing large numbers of superconductor detectors with simple readout electronics. Fermilab is actively involved in several efforts with MKIDs including the development of these sensors for Axion search, direct dark matter detector, optical and near-IR astronomy and also the next generation of CMB instruments. Fermilab is among the world leaders for the development of readout electronics for these sensors and has deployed these electronics in several astronomical instruments and laboratory test stands.

Fermilab is poised to take a leadership role in the deployment of KIDs for several astronomical experiments. Fermilab has the advantage of existing and planned cryogenic facilities, expertise in readout electronics, access to fabrication facilities at the U. Chicago and ANL, and local expertise in superconducting detectors.

5.h TES

Transition edge sensors are small superconducting films with precisely tuned transition temperatures, which, when kept in the middle of their superconducting transition, act as highly sensitive power to current amplifiers. For thin films with very small heat capacity, the TES allows for a qualitatively simple sensor design with unparalleled sensitivity to small power changes.

At Fermilab, we use TESs to sense phonons, or lattice vibrations, in cryogenic crystals in order to detect energy deposits down to eV energy scales. We have recently demonstrated 3-eV resolution in a 1-gram Si detector. By applying a moderate bias voltage across the detector, we have also demonstrated that we can convert charge energy to phonon energy and use the TES to measure electron-hole pairs at a resolution of less than 0.01 electrons. These detectors are thus both eV-scale calorimeters and cryogenic photon detectors.

For future applications, we are scaling these detectors to larger masses, and working on continuing to push TES volume down to produce Si detectors with 1-10 g masses and sub-eV resolutions. Theses detectors will be used for dark matter searches at NEXUS, an underground low-background facility for rare event searches. We are also exploring porting this TES technology to new targets (diamond and SiC) to expand our reach into different searches for new physics and broaden the application of this technology to other areas of HEP. Finally, we are exploring alternate materials for our TES sensors, such as AlMn, and new architectures for our phonon focusing films to improve efficiency and further reduce our energy thresholds.

5.i SNSPD

Superconducting Nanowire Single Photon detectors (SNSPDs) are sensors for infrared and visible photons with the ability of detecting single photons with a very high time resolution ~10 ps. Because of their unique advantage of providing single-photon detection in the IR with impressive time resolution, the sensors have been selected as the technology of choice for several quantum science and quantum communication applications.

Fermilab is currently involved in the development of a quantum network demonstration using these sensors. At the same time the ASIC group at Fermilab is involved in the development of low temperature readout electronics for these devices using LDRD and QIS funding. There is interest at Fermilab for using these sensors for astronomical instruments because their time resolution capabilities would allow to measure quantum correlations in the arrival time of photons, which would give access to intensity interferometry measurements in the optical and near IR bands. We are developing a new partnership with MIT-LL for the development of instrumentation based on this sensor technology.

5.j High speed data links

Fermilab is partnering with Freedom Photonics, UCSB, and LBNL to investigate the promise of silicon photonics-based approaches to radiation-hard, low-power, integrated optoelectronics including the use of wavelength division multiplexing techniques. *This approach is to meet the needs of next-generation collider experiments which are expected to require higher aggregate data throughput in radiation environments exceeding those of the HL-LHC. These same partners have recently expanded the area of interest to include optical components for use in cryogenic environments (with SMU).*

5k Smart electronics

Fermilab has developed FPGA-based readout systems for superconducting detector R&D. These systems are being further developed using RFSoC FPGAs from Xilinx. Frequency multiplexed readout to support MKIDs detectors have also been developed in collaboration with the University of Chicago and UCSB. Work is underway to develop Bayesian optimal filters for noise reduction in firmware for the Skipper CCD and to research cold electronics for these detectors. Fermilab is also developing FPGA-based modules to upgrade the capabilities typically made available to researchers through the Physics Research Equipment Pool (PREP). These modules are in use at the FTBF and have also been made available off-site to a growing number of interested customers. These systems are configured and operated using the Off-The-Shelf DAQ (OTSDAQ) framework. Recently, an effort has been initiated to explore the development of an FPGA board capable of operating at low levels of power dissipation in a cryogenic environment. This work is being pursued in collaboration with LBNL. Firmware development is targeted as a core competency for Fermilab. We are heavily involved in real-time machine learning, which often requires FPGA firmware development alongside high-level synthesis tools. *Fermilab plays a leading role in the hls4ml project which is a growing collaboration creating open source tools for implementing machine learning algorithms in register-transfer-level languages. We plan to perform R&D in the direction of on-detector machine learning applications for data reduction in FPGAs which will become more and more critical. Close development together with relevant ASICs will also be of importance for certain applications.*

5.l ASICs

The Fermilab ASIC Development Group develops fully custom integrated circuits for use in HEP experiments. While applications are wide-ranging, a particular research direction has been the development of readout electronics for fine-grained, highly pixelated detectors that host local readout electronics. These detectors are often associated with detectors that measure particle trajectories or "tracks" through a detector volume. As pixels decrease in size, the density of readout electronics increases, posing challenges in the routing of signal inputs and readout outputs, power distribution, power density, radiation tolerance mitigation, digital noise pickup, etc. In addition, the trend has been toward increasing the dynamic range, requiring more bits per event. In applications for the energy frontier, the event rates are prodigious. This combination of requirements results in the need for local processing or "triggering" to reduce the amount of data to be read out. This high-level of sophistication in front-end custom integrated circuits is the HEP analogy to the "system on chip" (SoC) concept being implemented currently in consumer and commercial ICs. The “mixed signal” nature of the chips, incorporating both low-level analog and high-speed digital circuits make this an especially challenging design area.

One of the strategies in the next generation of tracking detectors will be implemented with 3-Dimensional (3D) technology, incorporating a high-level of integration and signal processing capability. 3D technology has the potential to provide a qualitative leap in sensor/readout integration. Highly integrated detectors with small pixels and sophisticated processing can enable 5D sensing (time, x, y, z, angle) in a single layer by utilizing the full information available in the transient current pulse.

Other developments in emerging technologies include the move to smaller feature sizes technologies, and the incorporation of digital circuit synthesis. Current chip developments are primarily using 65 nm CMOS. The move to 22 nm and below is foreseen. This will require significant development of new libraries, especially for the analog circuitry. Digital circuit synthesis is already being used in current designs, using the Verliog hardware description language. The use of Universal Verification Methodology (UVM) is also in use but will become more important as the level of sophistication and complexity increase.

5.m Summary

The current Detector R&D portfolio is well aligned with the technical expertise and the science priorities at the lab. The R&D plans for the next five years build on past and current work and are designed to enable the next stage in scientific breakthroughs. While the focus in neutrino detection is more short term, concerned with the technologies for DUNE, in the longer term, successful R&D for astrophysics and collider detector technologies will define which suite of next generation experiments will be realized. As has also been identified by the recent BRN, co-design of sensors, electronics and system level aspects from beginning to end are of utmost importance. Individual detector technologies are increasingly covering more than one measurement principle. The concept of distinct sub-detectors, especially in collider experiments, but also in neutrino and cosmic experiments, will be replaced by highly integrated multi-purpose detectors, such as 5D trackers (spatial, temporal, directional), 6D calorimeters (spatial, temporal, directional, energy), or LAr TPCs with integrated dual readout electronics (charge, light). The overarching guidance to Fermilab’s Detector R&D plan is stemming from these considerations.

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Appendix A: Detector R&D Lab Goals and Objectives

Lab Goals:

GL-ID Lab Goal Summary	GL-01810 Develop detectors suitable for future lepton or proton colliders Future collider experiments need aforemost highly-granular, pico-second level fast detectors. In the case of lepton machines, the granularity and negligible material budget are the most stringent criteria, while for proton colliders precision timing and radiation hardness are the most crucial.
GL-ID Lab Goal Summary	GL-01820 Develop detectors suitable for upcoming neutrino experiments The focus here is to develop advanced nobel element detectors, with specific focus on TPCs. The main part of the R&D is going into efficient light collection and readout, charge amplification, pixelated readout, LAr doping and purification, as well as high voltage behavior.
GL-ID Lab Goal Summary	GL-01830 Develop detectors suitable for next generation precision experiments at Fermilab The main aspect here is R&D for a potential Mu2e-II upgrade, specifically for its ultra-lightweight tracker, but also for future flavor experiments.

GL-ID	GL-01840
Lab Goal	Develop detectors suitable for future astroparticle physics experiments
Summary	There are several lines of R&D planned here: detectors for low-mass Dark Matter detection, detectors for the study of CMB and Inflation, and detectors for future, large-scale spectroscopic surveys.

Lab Objectives:

Parent Lab Goal	**GL-01810: Develop detectors suitable for future lepton or proton colliders**
OB-ID	OB-06140
Lab Objective	Perform silicon sensor R&D for future generation silicon strip and pixel trackers for collider experiments
Summary	Perform R&D into new geometries, processing methods, materials, packaging and integration for silicon strip and pixel sensors for future collider experiments. This will include the move to larger wafer sizes, smaller pixel sizes, new doping methods, and other new concepts that will improve spacial precision, material, timing, radiation tolerance and other performances of the sensors. This is a longterm effort to advance silicon sensors for future generation trackers, keeping in mind the requirements that need to be matched for sufficient physics performance, including pixel size, time resolution, material and power budgets. This is a longterm effort to advance silicon sensors for future generation trackers, keeping in mind the requirements that need to be matched for sufficient physics performance, including pixel size, time resolution, material and power budgets.
OB-ID	OB-06150
Lab Objective	Perform generic ASIC R&D for collider detectors
Summary	In order to be able to collaborate with other institutions on ASIC designs in the future, it is important to invest in the tools and the training of our ASIC engineers in deep-deca nanometer technologies. We also need to perform generic R&D in the direction of both room temperature and cryo ASICs, and develop new methods to make the ASICs used for collider detectors more radiation tolerant, so that they will be performant at a future proton collider. R&D needs to be carried out to improve and industrialize 3D-integration, as well as the utilization of commercial CMOS processes.
OB-ID	OB-06160
Lab Objective	Perform generic scintillator R&D
Summary	Develop new processing methods of plastic scintillator, such as injection molding and 3D printing, including exploration of new geometries. Perform R&D in the

	direction of radiation hardness through doping and processing methods. Investigate the use of liquid scintillators for calorimeters at future colliders.
OB-ID	OB-06170
Lab Objective	Perform generic R&D for calorimetry
Summary	Develop new technologies for radiation-hard, high-granularity calorimeters. This involves R&D of photo-detection, geometries, dual readout calorimetry, radiation hardness, integrated pico-second large systems and materials such as silicon or scintillators (plastic or liquid).
OB-ID	OB-06180
Lab Objective	Perform generic R&D of high-speed readout links
Summary	Develop radiation-hard, low mass (or no mass = wireless) high-speed readout links, either optical or otherwise, that fulfill the needs of future collider detectors.
OB-ID	OB-06190
Lab Objective	Perform generic R&D for picosecond-level large systems
Summary	Develop the necessary technologies for large area, picosecond-level systems. Specifically, distributed large-area precision clocks and jitter issues need to be solved.
OB-ID	OB-06200
Lab Objective	Perform generic R&D into new materials
Summary	Develop new materials for sensors and support structures to meet the challenges for low mass and radiation tolerance of future collider experiments.

Parent Lab Goal	**GL-01820: Develop detectors suitable for upcoming neutrino experiments**
OB-ID Lab Objective Summary	OB-06210 Perform generic R&D into efficient light collection and readout Develop more efficient collection and readout of scintillation light in noble element TPCs. This includes doping, wavelength shifting, and more efficient photo detectors with larger area coverage.
OB-ID Lab Objective Summary	OB-06220 Perform generic R&D of electron amplification in noble elements Develop new methods to increase the charge before readout inside liquid or gaseous noble element TPCs for increased charge signal readout efficiency.
OB-ID Lab Objective Summary	OB-06230 Perform generic R&D to magnetize TPC volumes Develop methods to homogeneously magnetize large volumes of noble element TPCs for improved particle identification and separation.
OB-ID Lab Objective Summary	OB-06240 Perform generic R&D to improve HV stability in large TPC. Develop improved methods to stabilize the high voltage behaviour inside large volume noblee element TPCs.
OB-ID Lab Objective Summary	OB-06250 Perform generic R&D of LAr purification systems Develop more cost-effective and efficient methods of LAr purification for future large-scale LAr TPC experiments.
OB-ID Lab Objective Summary	OB-06260 Perform generic R&D of ASICs for cryogenic temperatures Develop ASIC components for cryogenic environments, such as LAr TPCs.

OB-ID	OB-06270
Lab Objective	Perform generic R&D for readout electronics for large TPCs
Summary	Develop new methods such as multiplexing and pixelated readout for future large volume TPCs.

Parent Lab Goal	**GL-01830: Develop detectors suitable for next generation precision experiments at Fermilab**
OB-ID Lab Objective Summary	OB-06280 Perform generic R&D of new materials Develop new materials and processing methods that will enable an ultra-lightweight tracking detector for a potential Mu2e-II upgrade. Ideas involve trackers made of ultra-thin straw tubes (3-7um), graphene, or quantum-dot solid state scintillators.
OB-ID Lab Objective Summary	OB-06290 Perform generic R&D of radiation-hard electronics components Develop radiation-hard electronics components, including DCDC converters that are usually not found off-the-shelf, but that do not quite have the harsh radiation tolerance requirements of collider detectors.

Parent Lab Goal	**GL-01840: Develop detectors suitable for future astroparticle physics experiments**
OB-ID Lab Objective Summary	OB-06300 Perform generic R&D of scientific CCDs Develop advanced scientific CCDs, including Skipper CCDs and their readout. Develop a commercially available scientific CCD, which could be the standard CCD or a CCD-in-CMOS technology. Develop the corresponding packaging and integration for large systems of CCDs.
OB-ID Lab Objective Summary	OB-06310 Perform generic R&D of superconducting detectors Develop new processing methods, new materials, new designs of superconducting detectors, such as (M)KIDs, TESs, SNSPDs. Develop their readout electronics and large-scale packaging and integration.
OB-ID Lab Objective Summary	OB-06320 Perform generic R&D of high-density fiber positioners Develop high-density fiber positioner systems for future surveys
OB-ID Lab Objective Summary	OB-06330 Perform generic R&D of photon-collectors for axion searches Develop new methods to efficiently collect photons from wide-band axion interactions.