FERMILAB-CONF-24-0539-PPD

Implementation of the HEP Instrumentation R&D Roadmap in the USA

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Abstract

In recent years, the High Energy Physics (HEP) community in the USA has evaluated the technological needs in detector instrumentation for future HEP experiments. Specific needs have been identified and an R&D program to reach them has been defined. This article will briefly summarize the planning process and will highlight the main findings and the road map to carry out the plan as defined by the community.

Keywords: Detectors, Instrumentation, HEP, USA, Planning

1. Overview of the Planning Process

In 2019 the DOE organized a Basic Research Needs workshop for HEP Detector R&D. At that workshop we examined connections between physics drivers and detector requirements, considering all the physics drivers. The work was organized both around the 2014 P5 physics drivers as well as eight different detector technology areas. We then identified connections between cutting-edge technologies and big ideas to support the physics reach. For each technology area we formulated a list of priority research directions, each with several thrusts and research plans attached. Special care was taken to identify synergies between different experimental options, such as detectors for different future colliders, or between noble element detectors for neutrino and dark matter physics. The full report can be found in [1].

In 2021 and 2022 the HEP community-driven planning exercise of Snowmass took place. One of the ten working groups, the so-called frontiers, was geared to discuss detector technologies and R&D needs for future experiments in collider physics, neutrino physics, intensity physics and at the cosmic frontier. This Instrumentation Frontier was organized in different topical groups along detector technologies, as well as cross cutting themes. The process concluded with a report [2]. The main recommendations of the Instrumentation Frontier group can be summarized as follows:

IF-1 Advance performance limits of existing technologies and develop new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.

IF-2 Develop and maintain the critical and diverse technical workforce and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation, at laboratories and universities.

IF-3 Double the US Detector R&D budget over the next five years and modify existing funding models to enable R&D consortia along critical key technologies for the planned long term science projects sustaining the support for such collaboration for the needed duration and scale.

IF-4 Expand and sustain support for blue-sky R&D, small-scale R&D, and seed funding. Establish a separate agency review process for such pathfinder R&D, independently from other research reviews.

IF-5 Develop and maintain critical facilities, centers and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines and industry.

The rest of this article will explain the implementation of the R&D consortia as recommended in IF-3 above.

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This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

2. Coordinating Panel for Advanced Detectors - CPAD

CPAD, the Coordinating Panel for Advanced Detectors is a panel of the APS/DPF (American Physical Society, Division of Particles and Fields). CPAD seeks to promote, coordinate and assist in the research and development of instrumentation and detectors for HEP experiments. Their main activities lie in the organization of annual instrumentation workshops, hosting vibrant exchange for people working detector R&D, brainstorming on new technologies and applications and allow for essential networking opportunities especially for early career colleagues. CPAD is also interfacing with industry partners and scientists and engineers in other disciplines, such as nuclear physics, quantum information science, chemistry and others. They promote the recognition and nurturing of careers in detector instrumentation through the annual DPF Instrumentation Awards and the GIRA (Graduates in Instrumentation Awards). As a new topic, following the 2022 Snowmass report, CPAD is now organizing the newly formed RDCs (R&D Collaborations).

3. Detector R&D Collaborations - RDCs

The R&D Collaborations, RDCs, are newly formed groups under the stewardship of CPAD, born out of the Snowmass recommendations. The principle idea is to create a network of US Detector R&D Collaborations while coordinating between different RDs and exchanging with the ECFA DRDs. The collaborations were created covering major technology areas in line with the 2019 Basic Research Needs workshop as described in 1. The goal of the RDCs is to bring together the community in a more persistent way than the annual CPAD workshops alone, to coordinate R&D efforts and to forge collaborations. The RDCs aim to create a robust R&D program towards the technologies needed to enable discoveries in future HEP detectors and to foster innovation in instrumentation. They allow for more streamlines and synergistic collaboration between university teams and laboratories to share expertise, tools and facilities, and avoid duplication of effort in light of limited funds. The RDCs have the potential to uncover new materials and methods for HEP detectors through interdisciplinary and synergistic research. They facilitate easy communication and connections between participants in US-based R&D efforts, CERN DRDs and other relevant partners.

CPAD has founded 11 RDCs, which are listed in Table 1.

Each RDC has formulated a preliminary list of priority research thrusts as follows.

RDC 1	Noble Element Detectors
RDC 2	Photodetectors
RDC 3	Solid State Tracking
RDC 4	Readout and ASICs
RDC 5	Trigger and DAQ
RDC 6	Gaseous Detectors
RDC 7	Low-Background Detectors
RDC 8	Quantum and Superconducting Detectors
RDC 9	Calorimetry
RDC 10	Detector Mechanics
RDC 11	Fast Timing

Table 1: The eleven RDCs formed by CPAD

3.1. *RDC 1: Noble Element Detectors*

- Enhance and combine existing readout modalities: explore new ideas in charge detection, e.g. pixels, extreme low threshold detection, charge gain, ion detection; explore new ideas in light detection, e.g. new technologies, geometries, materials, wavelength shifters.
- New modalities for signal detection:going beyond the current paradigm of just collecting electrons and photons, e.g. meta-stable fluids, micron-scale tracking, combined multimodal sensors; enhancement in the electronics and readout of the detectors, e.g. photonic readout solutions, new and enhanced architectures at the front-end, AI/ML inside the detector.
- Challenges inscaling technologies: scaling of purification, radiopurity, doping, high voltage, and other target challenges, e.g. large-scale purification, removing radioactive contaminants at multi-ton scale.

3.2. *RDC 2: Photodetectors*

- Innovative photosensors: achieve technological breakthroughs for new science reach, e.g. Superconducting Nanowire Single Photon Detectors, VUV sensitive detectors for low-light detection.
- Photosensor development to enhance experimental capabilities, e.g. improving single photon detection, timing or radiation hardness: SiPM, MicroChannel Plate PMT, CCD, Accessories such as filters, lenses, wavelength shifters, waveguides, fibers, and optics.
- Large Area Photodetection Systems: photo collectors and integrated readout for photo sensors.
- Scalability of light readout: moving to a hundred times larger detectors in the future. Challenges include noise hit rates, radiopure materials, power dissipation and large bandwidth signal transmissions.

3.3. *RDC 3: Solid State Tracking*

- Adapting non-silicon and novel-configuration sensors with improved costs, area, radiation tolerance and performance
- Develop scalable, low-mass detector systems, e.g. MAPS-based tracking (Monolithic Active Pixel Sensors)
- R&D on trackers for lepton colliders, which have similar requirements for timing and spatial resolution
- R&D on trackers for hardon colliders, which need to withstand extreme radiation and provide fine timing and spatial resolution
- Advances in detector physics modeling and device simulation

3.4. *RDC 4: Readout and ASICs*

- Circuits and architectures for 4D tracking and calorimetry: picosecond timing circuits, monolithic readouts, models and techniques for extreme radiation

- Big data management: energy efficient architectures and circuits, on-chip computing, on-chip AI/ML, fast interconnections and I/Os, advanced integration

- Cryogenics and deep cryogenics: 4K circuits and architectures for QIS, circuits and architectures for noble liquid detectors, cryogenic models and libraries

- Methodologies, tools and workforce development: design for verification methodologies, CAD tools and foundries with joint access, shared libraries and access model, domain knowledge transfer and training

3.5. *RDC 5: Trigger and DAQ*

- Intelligent data reduction and processing: real-time or low-latency data reduction and feature extraction, fast artificial intelligence and neuromorphic computing on real-time hardware

- Link technology development: high-bandwidth, radiation hard, low-power optical link above 50 Gbps, wireless readout

- Integrating modern comuting architecture and emerging technologies

- Self-running DAQ systems

- Timing distribution with pico-second synchronization over long distances

3.6. *RDC 6: Gaseous Detectors*

- Advance gas TPC readout to performance limits, enabling new experiments: maximize sensitivity by achieving 3D single electron counting, minimize background by developing radio-pure MPGDs, develop matching, highly scalable front-end electronics and readout systems, develop on-detector AI/ML and trigger-driven, highly multiplexes readouts

- Advance MPGDs for high-background environments: develop cylindrical and exotic-shape tracking layers, develop pico-second timing layers, improve radiation hardness, rate capability, robustness against sparking and aging

- Establish MPGD development, prototyping and production facility in the US

3.7. *RDC 7: Low-Background Detectors*

- CCDs for rare event searches: CCD R&D specific to low-backgrounds, lowering energy sensitivity, and minimizing dark rates. Moving to Ge CCDs, further development of skipper CCD infrastructure, utilizing novel substrates in industrial fabrication

- Monolithic charge readout: R&D to lower thresholds and backgrounds for point-contact and contact-free charge readout schemes for monolithic crystals

- Superconducting phonon sensing: R&D specific to phonon sensing for low-background detectors targeting dark matter and neutrino scattering

- Radiopurity R&D: research to produce readout electronics and support infrastructure that are radiopure and consistent with needs of low-background experiments

- Novel materials for rare event searches: develop new targets compatible with low-background searches at sub-eV scales for low-background experiments

3.8. *RDC 8: Quantum and Superconducting Sensors*

- Perform R&D into pairbreaking sensors, as well as photon and phonon sensors

- Develop coherent wave sensors

- Develop AMO, clocks, interferometry, NMR and optomechanical sensors

- Invest in the advancement of theory, simulation and novel material developments

3.9. *RDC 9: Calorimetry*

- Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements

- Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments

- Develop ultra-fast media to improve background rejection in calorimeters and particle identification detectors

3.10. *RDC 10: Detector Mechanics*

- Light-weight composite materials for detector support: dual use by providing structural support while also being thermally or electically conductive

- Develop detector mechanics while accommodating cooling, alignment, shock and vibrations, system integration aspects, radiation environments, thermal expansion

- Failure management: maintainability, services, maximum duty cycle

- Experimental magnet developments

3.11. RDC 11: Fast Timing

- Pico-second timing: for muon colliders (10ps) and for hadron colliders (1ps) while maintaining 10μm of spatial resolution or better; for neutrino experiments (¡100ps) with sub-cm spatial resolution
- Develop new materials to reach pico-second timing: expand from silicon
- Leveraging fast photodetection in cryogenic detectors
- High precision GPS-based synchronization and time stamping over long distances for neutrino applications
- Fabrication techniques to reduce costs of large area detectors
- Integration with readout electronics, such as fast MAPS, low capacitance hybrids, and development of photosensor electronics

4. Particle Physics Project Prioritization Panel - P5

Following the Snowmass community planning process, the Particle Physics Project Prioritization Panel, P5, went to work. It took the Snowmass report and many other inputs and formulated a 10-year strategic plan with a 20-year vision for HEP. While the RDCs can be organized as a grassroots effort, the rest of the Instrumentation Frontier recommendations require enhanced budgets for detector R&D. The vision of the HEP community now needs the support from the funding agencies. The last P5 report from 2013 received broad community support and was crucial to growing the HEP budget in the US. In the 2023 P5 Report ([3]) the following detector-related recommendations to the funding agencies can be found: "The particle physics community has identified the need for stronger coordination between the different groups carrying out detector R&D in the US. We strongly support the R&D Collaborations (RDCs) that are being established and will be stewarded by CPAD, the Coordinating Panel for Advanced Detectors, overseen by the APS/DPF. The RDCs are organized along specific technology directions or common challenges, and aim to define and follow roadmaps to achieve specific R&D goals. This coordination will help to achieve a more coherent detector instrumentation program in the US, and will help to avoid duplication while addressing common challenges. International collaboration is also crucial, especially in cases where we want to have technological leadership roles. Involvement in the newly established Detector R&D Groups at CERN is encouraged, as are contributions to the design and planning for the next generation of international or global projects."

Additionally, several of the more targeted Area Recommendations are addressing some of the recommendations made in the Snowmass Instrumentation Frontier report:

- **Area Recommendation 6:** Increase the budget for generic Detector R&D by at least $20 million per year in 2023 dollars. This should be supplemented by additional funds for the collider R&D program.
- **Area Recommendation 7:** The detector R&D program should continue to leverage national initiatives such as QIS, microelectronics, and AI/ML.

5. Summary and Outlook

A multi-year strategic planning process for HEP in the US has concluded recently. Several key recommendations for Detector Instrumentation have been identified. Among them is the formation of R&D Collaborations aligned with different technology areas. This has now begun in form of the recently formed CPAD RDCs. Several of the RDCs are in the process of identifying specific R&D programs, collaborators, institutions and resource needs and are preparing funding proposals to be submitted to the Comparative University DOE Funding Opportunity Announcement in September 2024. Once the funding agencies had sufficient time to address the recommendations in the P5 report, we will hopefully see new and increased ways of funding these efforts, which will benefit the field at large.

References

[1] B. Fleming, I. Shipsey, M. Demarteau, J. Fast, S. Golwala, Y.-K. Kim, A. Seiden, J. Hirschauer, G. Sciolla, O. Palamara, K. Scholberg, J. Cooley, D. McKinsey, C. Chang, B. Flaugher, S. Demers, M. Pepe-Altarelli, F. Lanni, R. Rusack, R. Guenette, J. Monroe, L. Winslow, P. Krizan, A. Geraci, K. Irwin, G. Carini, M. Newcomer, M. Artuso, C. Haber, D. Acosta, T. Bose, M. Begel, M. Narain, D. Dwyer, A. Connolly, A. Sonnenschein, R. Henning, K. Dawson, L. Newburgh, M. Reece, N. Serra, N. Akchurin, S. Eno, P. Rumerio, R. Zhu, J. Raaf, A. Pocar, J. Asaadi, H. Lippincott, G. Giovanetti, A. Lita, F. Sefkow, G. Campbell, A. Sushkov, R. Walsworth, A. Grassellino, A. Dragone, M. Garcia-Sciveres, T. Shaw, J. Thom-Levy, A. Tricoli, P. Merkel, W. Ketchum, J. Zhang, P. O'Connor, G. Karagiorgi, C. Ashton, L. Chaterjee, P. Lee, D. Hornback, H. Marsiske, M. Shinn, K. Byrum, G. Crawford, E. Lessner, D. Nevels, G. Rai, K. Turner, R. Ruchti, Basic Research Needs for High Energy Physics Detector Research & Development: Report of the Office of Science Workshop on Basic Research Needs for HEP Detector Research and Development: December 11-14, 2019 (2019). URL: https://www.osti.gov/biblio/1659761. doi:10.2172/1659761.

[2] P. Barbeau, P. Merkel, J. Zhang, et al., Report of the instrumentation frontier working group for snowmass 2021, arXiv:2209.14111[hep-ex] (2022) 53. URL: https://arxiv.org/abs/2209.14111. doi:10.48550/arXiv.2209.14111.

[3] Exploring the Quantum Universe - Pathways to Innovation and Discovery in Particle Physics. Report of the 2023 Particle Physics Project Prioritization Panel (2023) 180. URL: https://www.usparticlephysics.org/2023-p5-report/.