Coordinating Panel for Advanced Detectors

RDC R&D Priorities

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Contacts: Jonathan Asaadi (CPAD vice-Chair), Jinlong Zhang (CPAD Chair)

Introduction

These generic detector R&D priorities were developed based on the key challenges identified by the 2021 Snowmass Instrumentation Frontier report [1], which concurred and broadened the Priority Research Directions in the 2019 DOE HEP Detector R&D Basic Research Needs (BRN) report [2]. The list was presented initially at CPAD Workshop 2024, synthesized for the Instrumentation Community Input to the European Strategy for Particle Physics (ESPP) 2026 Update [3].

US R&D Collaborations (RDCs) were established with generic R&D focus, and are organized along specific technology directions or common challenges, and aim to define and follow roadmaps to achieve specific R&D goals, as described in the 2023 P5 Report [4]. The RDC coordinators have been continuously articulating the R&D priorities by working with the community. Each priority item is described in this document as a work package (WP) with brief definition and concise dictionary text. A complete version of this document will be made available to the instrumentation community with a citable reference.

The proposals are encouraged to cite this document and highlight the scope consistency with the individual priorities. Collaboration letters will be prepared as needed.

RDC1: Noble Element Detectors

- **RDC1-WP1: Enhance and combine existing readout modalities**
  New ideas in charge detection (e.g. pixels, extreme low threshold detection, charge gain, ion detection); new ideas in light detection (e.g. new technologies, geometries, materials, wavelength shifting).
- **RDC1-WP2: New modalities for signal detection**
  Going beyond the current paradigm 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/enhanced architectures at the front-end, artificial intelligence/machine learning inside the detector).
- **RDC1-WP3: Challenges in scaling technologies**
  Scaling of purification, radiopurity, doping, high voltage, and other target challenges (e.g. large-scale purification, removing radioactive contaminants).

RDC2: Photodetectors

- **RDC2-WP1: Innovative photosensors**
  Investigation of new photodetector materials, architectures, and sensor designs to tackle unique experimental requirements. Novel photodetector development can range from the investigation of new sensing techniques, photoconductors, alloys and dopants, charge transport layers, the structural design of the sensor, and multi-sensor/application designs.
- **RDC2-WP2: Photosensor & instrumentation development**
  Novel implementations, modifications, and design of established photosensors to enhance experimental capabilities. Improving systems, either by the addition of auxiliary components or by creative modifications and implementations of these photodetectors, offers a path towards enhancing the experimental capabilities of existing systems.
- **RDC2-WP3: Large-area photodetector systems**
  Development of large-area systems for large experiments by utilizing scalable and/or large-area photodetectors. Innovative solutions in large-area photodetector systems, including but not limited to, R&D on scalability of light readout, dedicated technological advancements aimed to enable applications in future detectors, addressing key challenges such as noise hit rates, radio-pure materials, power dissipation, and large-bandwidth signal transmission.

RDC3: Solid State Tracking

- **RDC3-WP1: Developing and adapting non-silicon and novel configuration tracking sensors**
  Using new materials and configurations of material in order to address current issues for tracking detectors (large scale, lower cost, higher radiation tolerance, lower radiation length, improved timing and spatial resolution amongst others). This may include (but is not limited to) SiC, GaN, Ge, Ga2O3, thin films, GaAs/InGaAs quantum dots, trenched and 3D silicon and diamond devices.
- **RDC3-WP2: Developing scalable, low mass tracking systems**
  Providing integrated tracking systems with much lower radiation length in order to enable future experiment. This can be addressed with advanced integration of readout with sensor technologies at the industrial scale through packaging (wafer-to-wafer, adhesives, 3D integration) and monolithic processing (both MAPS and post-processing) techniques.
- **RDC3-WP3: Extending the performance reach of sensors toward fluences of 10^{18} neq/cm^2, timing of 1 ps, and characteristic dimensions of 5 microns**
  Taking the next leap in performance beyond the current state of the art which will enable the next class of future experiments.
- **RDC3-WP4: Developing advanced models of existing and new technologies**
  Enabling more targeted prototyping by developing predictive models of performance in planned experimental conditions. This can include architectures with features such as deep well charge collection, active gain, or 3D implants which as of now are not available currently.

RDC4: Readout and ASICs

- **RDC4-WP1: Cryogenic integrated circuits**
  Design integrated circuits for cryogenic applications at different temperature ranges: mK-4K range: biasing and amplification, sensor readout multiplexing for TES, MKID, SNSPD, SQUIDs, CMOS control; 77-165K range: pixelated ASICs for charge readout, readout of photon detectors with single photon resolution and sub-ns timing.
- **RDC4-WP2: High-speed data links**
  Development of high rate (>50 Gbps), bi-directional communication detector interface link technologies. Technologies include photonic data links that are cryogenic and radiation-hard.
- **RDC4-WP3: Shared access to technologies, IP exchange & training**
  Promote collaborative frameworks for shared access to advanced technologies and intellectual property (IP) exchange among research groups at Universities and National Laboratories. Provide training opportunities through short courses, workshops, and conferences in electronics for HEP including system design, powering, readout electronics architectures and ASIC design implementations.

RDC5: Trigger and DAQ

- **RDC5-WP1: Fast AI and neuromorphic computing on real-time hardware**
  Deployment of artificial intelligence / machine learning (AI/ML) algorithms and neuromorphic processing for trigger-level decision making, using real-time-capable hardware accelerators.
- **RDC5-WP2: Wireless control and readout**
  Wireless technologies enabling detector-to-DAQ communication for command and data transmission, reducing cable complexity and enhancing flexibility.
- **RDC5-WP3: Integrating modern computing architecture and emerging technologies**
  Use of heterogeneous hardware such as GPUs, embedded FPGAs, and chip-based systems in TDAQ to reduce decision latency and increase compute power, and utilization of new computing architectures by deploying appropriate workflows.
- **RDC5-WP4: Self-running DAQ system**
  Autonomous data acquisition systems capable of self-configuration, real-time fault mitigation, monitoring and performance optimization.

RDC6: Gaseous Detectors

- **RDC6-WP1: Advancing gaseous detector readout to the fundamental sensitivity limit**
  This includes efforts towards single-electron counting, negative ion drift (NID), ps timing, and ASIC readout.
- **RDC6-WP2: Developing new gas amplification structures for challenging environments**
  Such environments include gases w/o quencher, NID gases, high charge densities, and very high or low gas pressures.
- **RDC6-WP3: Achieving cost-effective scaling of gaseous detectors to large sensitive volumes and/or large readout areas**
  This includes efforts such as data reduction and multiplexing via AI/ML on the frontend, new materials and mechanical structures, strip readout, and modularization schemes.
- **RDC6-WP4: Achieving improved particle identification in gaseous detectors**
  Modalities include precision timing, cluster counting, and dE/dx.
- **RDC6-WP5: Establishing production facilities in the United States**
  This includes efforts to fabricate MPGD amplification and readout devices.
- **RDC6-WP6: Reducing the environmental impact of gaseous detectors**
  This includes development and adoption of alternative gas mixtures and gas recycling schemes.

RDC7: Low-background Detectors

- **RDC7-WP1: Ultra-pure materials**
  The development of ultra-pure materials for low-background detector construction. This includes both the production and/or growth of ultra-radiopure materials and surface treatment of those materials during and after production.
- **RDC7-WP2: Noble fluid purification**
  The purification of noble element fluids, for example by distillation or chromatography, to meet the requirements of multi-tonne-scale experiments.
- **RDC7-WP3: Radioassay capabilities**
  The advancement of novel radioassay facilities and techniques to characterize the ultra-radiopure materials needed for the next generation of experiments.
- **RDC7-WP4: Material activation controls**
  Strategies for the removal of problematic long-lived activation isotopes in solid-state detector materials, such as tritium.
- **RDC7-WP5: Radon mitigation**
  Strategies for the mitigation of radon and/or the removal of embedded radon progeny from plate-out on surfaces.
- **RDC7-WP6: Low-energy calibration**
  The advancement of new calibration techniques capable of calibrating sub-eV energy deposits in detectors.
- **RDC7-WP7: Low-background supporting technologies**
  The development of radiopure supporting technologies, such as cabling, packaging, and electronics, to enable the operation and control of low-background detectors.
- **RDC7-WP8: Theory at and below the eV energy scale**
  The parallel advancement of the theoretical phenomenology of materials, and specifically the relatively unexplored sub-eV energy regime that has traditionally been below the range of interest for particle physics but is considered “high-energy” in condensed matter.

RDC8: Quantum and Superconducting Sensors

- **RDC8-WP1: Pairbreaking, photon & phonon sensors**
  This subcategory includes, but is not limited to, devices such as Transition Edge Sensors (TESs), Microwave Kinetic Inductance Detectors (MKIDs), Metallic Magnetic Calorimeters (MMCs), Superconducting Nanowire Single-Photon Detectors (SNSPDs), Quantum Capacitance Detectors (QCDs), and Superconducting Qubits that can significantly surpass present limits in one or more of the following metrics: (1) energy threshold for single-excitation sensing, spectral resolution, or noise performance (2) detection efficiency at the lowest energy thresholds (3) dark count rate, including low-energy backgrounds (4) active area, response time, pileup rate and channel count.
- **RDC8-WP2: Coherent wave sensors**
  This subcategory includes, but is not limited to, devices such as Josephson Parametric Amplifier, Traveling Wave Parametric Amplifier, Kinetic Inductance Parametric Amplifier , squeezed state receivers, microwave to optical transducers, superconducting radio frequency cavities, superconducting resonator circuits, radio frequency quantum upconverters, mechanical tuning of cavities that aim to advance coherent wave sensors and measurement techniques to surpass the Standard Quantum Limit (SQL) sensitivity.
- **RDC8-WP3: AMO clocks, interferometry, NMR, optomechanical sensors**
  This subcategory includes, but is not limited to, techniques and devices such as Atomic, Molecular, and Optical (AMO) clocks, interferometry, Nuclear Magnetic Resonance (NMR), optomechanical sensors: neutral atoms, trapped ions, magnetometers, spin precession, optomechanical devices, optical-radio frequency-magnetic levitation, cantilevers etc. entangled probes to beat the SQL with optical readout etc.
- **RDC-WP4: Theory, simulation & material developments**
  This subcategory includes, but is not limited to, advancing theoretical modeling, and simulation of sensors and materials which are crucial aspects of developing high-performance quantum and superconducting sensors.

RDC9: Calorimetry

- **RDC9-WP1: Broad R&D on new materials**
  The calorimeters of the future will require materials with properties optimized for energy, spatial, or time resolution, sometimes requiring optimization of a combination of these properties. The development of materials optimized for specific applications can exploit the progress of material science.
- **RDC9-WP2: Broad R&D on calorimetry with ps timing**
  This initiative involves not only the study of ultrafast materials, but also photosensors and signal processors capable of delivering the desired performance.
- **RDC9-WP3: Large-scale system challenge**
  The large-scale/small-feature-size detectors of the future include several challenges to maintain the performance at the single detector unit: large data rates to be processed in a fast and efficient manner, low mass interconnections and support, power distribution, and heat management.
- **RDC9-WP4: Scalable calorimetry optimized for large volumes and low cost**
  Some applications, for example, future neutrino experiments, require large volumes of sensing material. The development of basic building blocks based on inexpensive materials that can be produced in large quantities provides a path to systematically improvable systems.

RDC10: Detector Mechanics

- **RDC10-WP1: Detector cooling**
  Evaporative and liquid cooling for both low and warm temperatures; gas/air cooling solutions for future detectors; connection technologies for cooling circuits. Liquid but pipe-less cooling solutions as a broader topic.
- **RDC10-WP2: Low-mass mechanics and thermal management**
  Novel approaches for low mass mechanics to design and manufacture advanced mechanical tracker support structures and thermal management for the next generation of detectors, particularly tracker systems, which includes characterisation of material properties; novel hypothetical active sensing materials for tracking detectors.
- **RDC10-WP3: System Design, Integration, and Qualification tools**
  Aspects of system design and integration for the vertex region of future particle physics experiments; the connection of engineering design tools with physics simulation software.

RDC11: Fast Timing

- **RDC11-WP1: Development of integrated timing systems**
  Achieving timing performance with system design including detectors, photosensors, and front-end electronics. While new sensor architectures (e.g., with higher sampling rate ADCs, finer TDCs) can push boundaries, achieving ultra-high timing precision requires detailed system design and implementation, taking into account thermal noise at the sensor and front-end, clock jitter and wander, and careful selection of detectors and photodetectors.
- **RDC11-WP2: Pushing the boundaries of fast-timing sensors**
  Investigating the characteristics, improving the performance, and developing new materials for sensors including silicon based devices like LGADs, vacuum photosensors like LAPPDs and HRPPDs, and gaseous detectors such as micro-RWELLS.

Cross-RDCs Topics

- **cRDCs-WP1: Intelligence in the front-end electronics**
  Integration of artificial intelligence / machine learning (AI/ML) algorithms for on-chip triggering and/or data-reduction capabilities. Technologies include smart pixel technology, embedded Field Programmable Gate Arrays (eFPGA), anomaly detection systems, and unconventional computing methods. [RDC1, RDC3, RDC4, RDC5, RDC6, RDC9]
- **cRDCs-WP2: Timing distribution with picosecond synchronization**
  Precision timing protocols and distribution systems enabling sub-picosecond synchronization over large-scale detector networks for TDAQ applications (1 ps over 1 km). [RDC3, RDC4, RDC5, RDC6, RDC9, RDC11]
- **cRDCs-WP3: Monolithic Active Pixel Sensors**
  Novel Monolithic Active Pixel Sensors (MAPS) with a focus on improving timing (few ns and below) and spatial resolution (sub-10um). This includes exploring novel materials and technologies (CMOS and beyond) and novel readout approaches. [RDC3, RDC4, RDC9]
- **cRDCs-WP4: Pixelated detectors for 4D tracking**
  Development of readout ASIC for precise 4D tracking at future colliders, with sub-100um pixel pitch and sub-50 ps timing resolution. Developments include: fast analog front-ends, Time-to-Digital Converters (TDC), timing synchronization strategies, hybridization and 3D integration strategies. [RDC3, RDC4, RDC11]
- **cRDCs-WP5: Readout electronics for sub-10ps timing detectors**
  Developing advanced readout electronics specifically designed for sub-10ps timing detectors, to be used in calorimetry applications with sensors like SiPM, LAPPDs, LGADs, *etc.*. Technologies include high-speed analog/mixed-signal readout ASICs that can accurately measure and perform on-chip processing, the development of digital SiPMs. [RDC4, RDC6, RDC9, RDC11]

References

1. *Report of the Instrumentation Frontier Working Group for Snowmass 2021*, arXiv (2021)
2. *DOE Basic Research Needs Study on High Energy Physics Detector Research and Development,* DOE HEP Detector R&D 2019 BRN report, August 2020
3. *Strengthening the Instrumentation Programme*, US Instrumentation Community Input to the European Strategy for Particle Physics 2026 Update, 2025
4. *Pathways to Innovation and Discoveries*, Report of the 2023 Particle Physics Project Prioritization Panel, 2023