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

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Topics

Strategic Planning Process in the US

Recommendations for Detector Instrumentation

Coordinating Panel for Advanced Detectors

R&D Collaborations

BRN for Detectors in 2019:

Basic Research Needs for HEP Detector R&D (DOE-driven exercise)

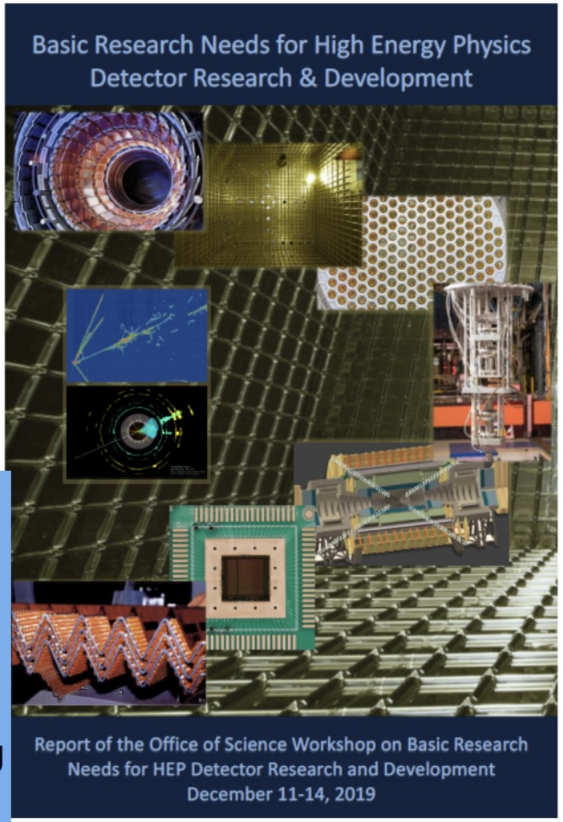
- Methodology:
  - examine connections between physics drivers and detector requirements, considering ALL the physics drivers

Physics Panels → Physics Objectives / Measurements → Technical Requirements → Priority Research Directions } Work organized around 2014 P5 Physics Drivers

  - Connect with current cutting-edge technologies and identify big ideas to support physics reach

Technology Panels → Priority Research Directions → Thrusts → Research Plans

1. Calorimetry
2. Noble elements
3. Photodetectors
4. Quantum sensors
5. Readout and ASICs
6. Solid State and Tracking
7. Trigger and DAQ
8. Cross-Cutting Research

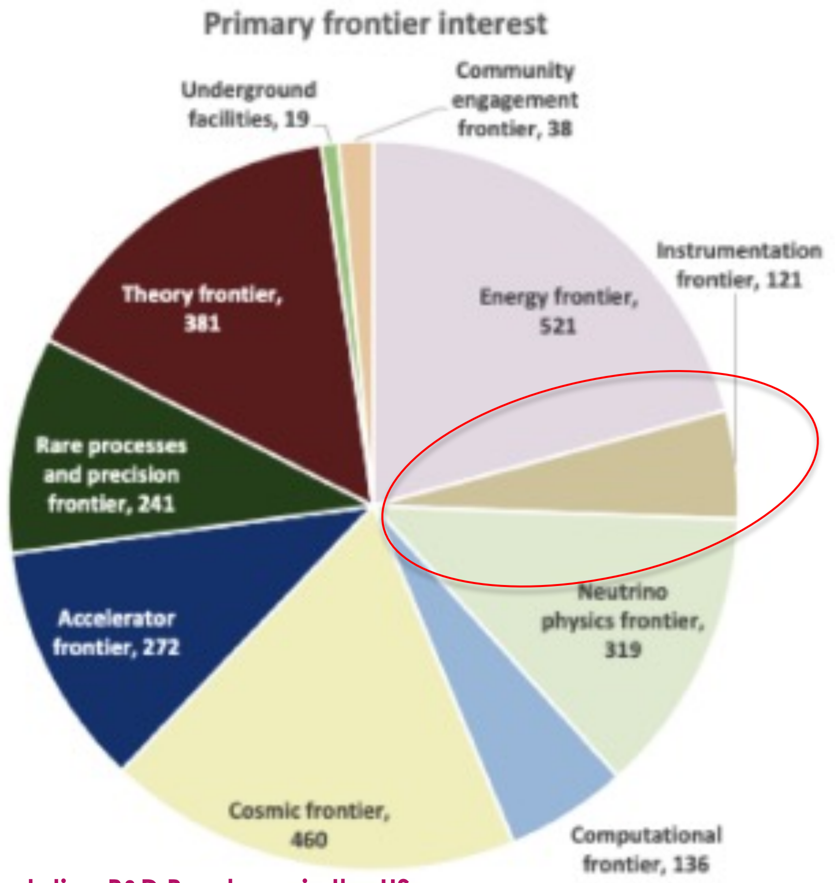


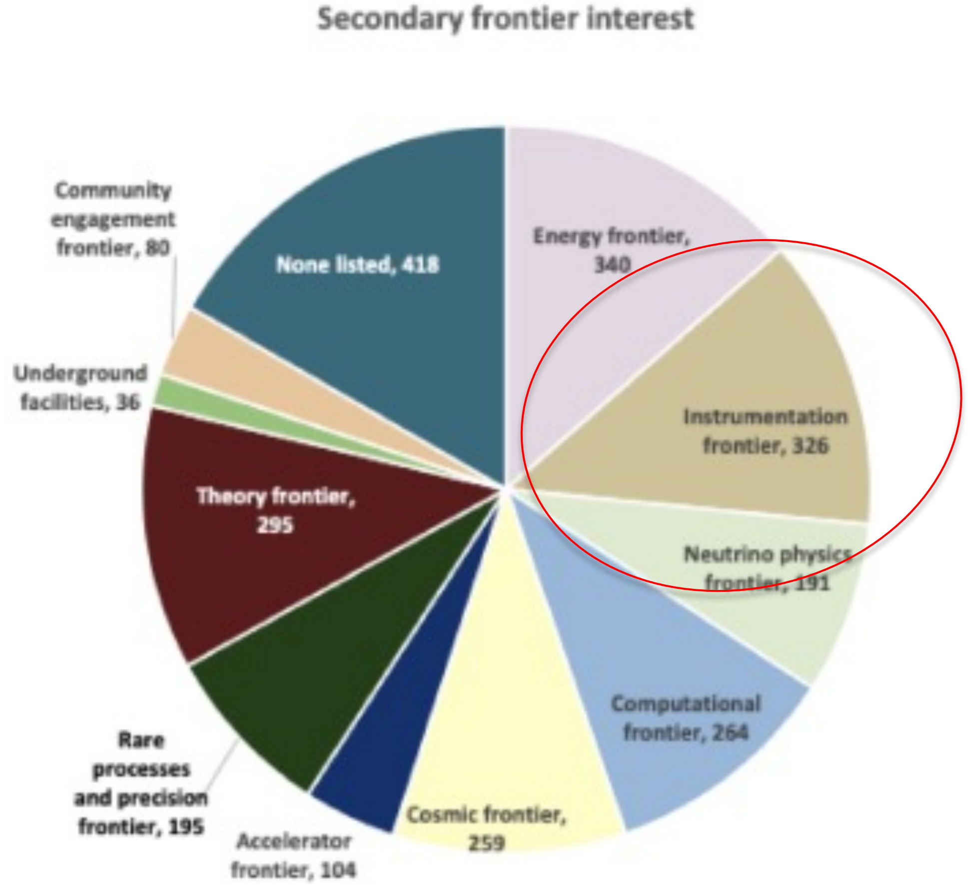
Snowmass 2021-2022:
HEP community-driven planning

- Organized in 10 Frontiers (physics, technology, community)
- **Instrumentation Frontier** is geared to discuss detector technologies and R&D needs for future experiments in collider physics, neutrino physics, intensity physics and at the cosmic frontier, paying close attention to synergies between the different Topical Groups, and with other Frontiers and research areas outside HEP

1.5-year long process culminated in a 2-week meeting in July 2022 in Seattle

From the 2021 Snowmass community workshop survey





Organization

IF conveners:
Phil Barbeau (Duke), Petra Merkel (FNAL), Jinlong Zhang (ANL)

Topical Group	Co-Conveners			
Quantum Sensors	Thomas Cecil (ANL)	Kent Irwin (SLAC)	Reina Maruyama (Yale)	Matt Pyle (Berkeley)
Photon Detectors	Chris Rogan (KU)	Juan Estrada (FNAL)	Carlos Escobar (FNAL)	
Solid State Detectors and Tracking	Tony Affolder (UCSC)	Artur Apresyan (FNAL)	Steve Worm (DESY/Humboldt)	
Trigger and DAQ	Darin Acosta (Rice)	Wes Ketchum (FNAL)	Stephanie Majewski (Oregon)	
Micro Pattern Gas Detectors	Bern Surrow (Temple)	Maxim Titov (Saclay)	Sven Vahsen (Hawaii)	
Calorimetry	Andy White (UTA)	Minfang Yeh (BNL)	Rachel Yohay (FSU)	
Electronics/ASICs	Gabriella Carini (BNL)	Mitch Newcomer (Penn)	John Parsons (Columbia)	
Noble Elements	Eric Dahl (Northwestern/FNAL)	Roxanne Guenette (Harvard)	Jen Raaf (FNAL)	
Cross Cutting and System Integration	Jim Fast (JLab)	Maurice Garcia-Sciveres (LBNL)	Ian Shipsey (Oxford)	
Radio Detection	Amy Connolly (OSU)		Albrecht Karle (Wisconsin)	

Snowmass IF Recommendations

- From the 2021 Snowmass Report: key recommendations from the Instrumentation Frontier:

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 collaborations 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.

Collaborations, Partnerships, Facilities

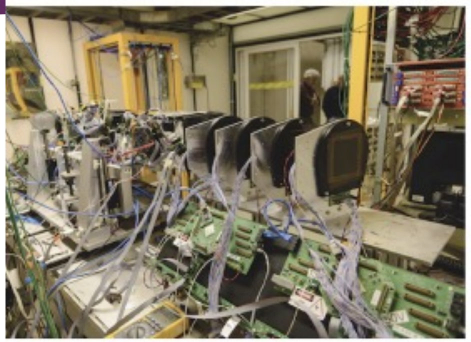
Technology Access

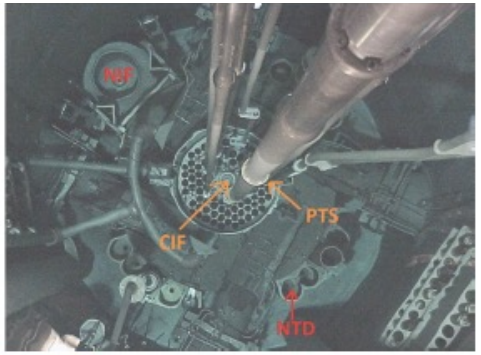
ASICs

- **Ensure institutional retention of >3 decades of collider detector instrumentation design and development experience:**
  - System design → moving towards co-design/co-simulation
  - Hierarchical approach to design and simulation of high-channel detector sub-systems
  - Integrated sensors and readout on single/multiple parallel substrates (e.g. MAPS)
  - Engage designers in building radiation tolerant ASIC blocks for future Systems-on-a-Chip (SoC) → to maintain state of art readiness (front-end readout, local memory, on-chip supply conversion DC-DC and LDOs)
- Maintain HEP-specific ASIC web resources for tutorials, examples, references (rad-tolerant/cryo)
- **Future designs will require broad, multi-institutional access to:**
  - Advanced technology nodes for ASIC fabrication
  - CAD design and design management tools and training
  - Hierarchical system simulation tools

Need to maintain & enhance our facilities

- Test Beams
  - Hadrons at FNAL, LANL, CERN, KEK
  - Electroncs at SLAC, DESY, Mainz, JLab
- Calibration Facilities
  - Low energy beams, especially neutrons
- Irradiation Facilities
  - BNL, FNAL, PNNL, Sandia
- Dedicated detector development labs, e.g.
  - SiDet and NLTF at FNAL
  - MSL at LBNL
- Ultra-low-background radiochemical analysis and mass-spectrometry
  - PNNL (ICPMS), ANL (AMS)
- Microelectronics, sensor and imager design
  - BNL, FNAL. LBNL, SLAC, Sandia
  - Penn, Northwestern, SMU, Stony Brook University, Washington University, UIC, UIUC, Purdue, UW, Columbia, Stanford, etc.

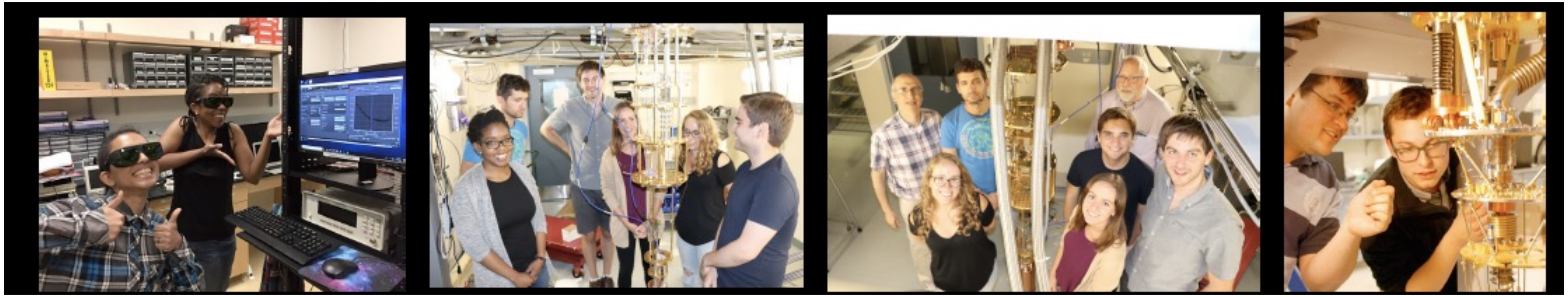




Lithography Etching Film Deposition CCD Wafer

Training the Instrumentation Workforce

- Fundamental to the success of HEP
  - Exciting physics + instrumentation = opportunity to attract and train students from diverse backgrounds
- Build on current success:
  - Dissertation awards, fellowships, traineeship awards
  - Student and postdoc placement and retention
  - Investment for University, National Lab and Industry workforce



Detector R&D Consortia

- CERN RD Collaboration Model
  - Topical collaborations around specific technology developments
  - Originated in 1990 with RD-1, now at RD-53
  - ECFA Detector Roadmap (2021)recommended creation of new ones in Calorimetry, Photo Sensors & PID, Liquid Detectors and Quantum Sensing. These RD Collaborations are proposed to be global in extent. **The US HEP community should engage broadly and early to help shape these new RD collaborations**

- NNSA Office of Defense Nuclear Nonproliferation (NA-20) Consortia
  - Topical collaborations around specific thrust areas in nonproliferation
  - Based out of Universities
  - Laboratories participate via existing funding streams from NA-22 and benefit from students and pipeline for career scientists in the field
  - **Strong focus on workforce development**

CPAD
Coordinating Panel for Advanced Detectors

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 high energy physics experiments
- Originated from 2012 Snowmass process (Instrumentation Frontier)
- Over last few years developed bylaws that regulate CPAD leadership: 2-year rotating terms for Chairs and Executive Committee members, nominations from the community

Main activities:

- **Annual workshops** hosting vibrant exchange for people working on detector R&D, brainstorming on new technologies and applications; essential networking opportunities for early career colleagues
  e.g. organized **Quantum Sensing for HEP** workshop in 2017, kicking off a whole new field in US
- Interfacing with **industry partners**
- Interfacing with **other disciplines**, e.g. Nuclear Physics, QIS, Material Science, Chemistry, etc.
- **Recognition and nurturing of careers** in detector instrumentation: annual DPF Instrumentation Awards and GIRA Awards (Graduates in Instrumentation Research Award)
- **NEW: RDCs = R&D Collaborations**

CPAD RDCs: webpage

RDCs:
R&D Collaborations under the auspices of CPAD

- Newly formed groups under the stewardship of CPAD
- Born out of Snowmass recommendation
- Create a **network** of US Detector R&D Collaborations
  - coordination between different RDCs and exchange with ECFA DRDs
- These Collaborations were created **covering major technology areas** in line with the 2019 BRN. The goal 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

- Goals:
  - Create a robust R&D program towards the technologies needed to enable discoveries in future HEP detectors and foster innovation in instrumentation
  - Allow for more streamlined and synergistic collaboration between university teams and laboratories to share expertise, tools and facilities, and avoid duplication in light of limited funds
  - Potential to uncover new materials and methods for HEP/collider dets.
  - Facilitate easy communication and connections between participants in US R&D Collaborations and CERN DRDs and other relevant partners
- First step: organize R&D Collaborations (RDCs) along specific key technologies in line with BRN
  - identify initial lead people and liaisons with European DRDs
  - organize workshops to define key R&D directions that connect different communities

Principal Ideas behind the RDCs

Detector R&D in many different technology areas is essential to realize many of the future planned experimental efforts spanning all of the frontiers in High Energy / Nuclear Physics

Much of the efforts needed require **collaboration** and **coordination** in order to realize the technologies required

- **Collaboration**: The required expertise/resources/new ideas often live within multiple people, institutions, labs and only by bringing these pieces together can we hope to realize the technological challenges
- **Coordination**: We live in a resource limited funding environment and so we need efforts to be coherent, minimize duplication, and to build off of progress happening elsewhere (both in other technologies and in other places)

What will the RDCs do?

Long term goal:

- **Provide a collaboration** which can link together facilities, expertise, people, and experience to tackle technology challenges across HEP/NP
- **Facilitate new funding mechanisms** for R&D related to a specific technology area which will take place as part of the collaborations' activities
- Work with the CPAD executive committee, ECFA DRDs, and the broader R&D community to foster a collaborative, supportive, and coordinated environment for new ideas, blue sky efforts, and **non-project specific R&D**

What is the envisioned structure

- **Each RDC has 2-3 coordinators who work with CPAD executive committee and the community to define the R&D goals**
  - These need to align with the BRN and Snowmass efforts
  - These should be sufficiently generic to allow for new or unforeseen ideas
- **The RDC coordinators will work with the community to put together “work packages” which bring together a collaboration to tackle some idea / technology**
  - These can be university- or lab-led
  - Should have associated timelines and milestones
- **These work packages can then be turned into proposals for funding**
  - In the short-term future, these may be responses to the comparative review funding announcements or reallocation of lab-based (KA25) funds
  - In the long term, this hopefully becomes a new funding mechanism with dedicated FOA and a new funding stream

➔ planning to submit a few coordinated funding proposals for next round of competitive DOE funding opportunity in September 2024

R&D Collaborations

RDC	Topic	Coordinators
1	Noble Element Detectors	Jonathan Asaadi, Carmen Carmona
2	Photodetectors	Shiva Abbaszadeh, Flavio Cavanna
3	Solid State Tracking	Sally Seidel, Tony Affolder
4	Readout and ASICs	Angelo Dragone, Mitch Newcomer
5	Trigger and DAQ	Jinlong Zhang, Zeynep Demiragli
6	Gaseous Detectors	Prakhar Garg, Sven Vahsen
7	Low-Background Detectors (incl. CCDs)	Noah Kurinsky, Guillermo Fernandez-Moroni, Daniel Baxter
8	Quantum and superconducting Detectors	Aritoki Suzuki, Rakshya Khatiwada
9	Calorimetry	Marina Artuso, Minfang Yeh
10	Detector Mechanics	Andy Jung, Eric Anderssen
11	Fast Timing	Gabriele Giacomini, Matt Wetstein

These groups are now identifying R&D topics, goals and roadmaps!

2023 CPAD Workshop at SLAC - November 7-10

RDC Kick-off

279 participants (record due to RDCs?!) - including 33 remote and 54 students

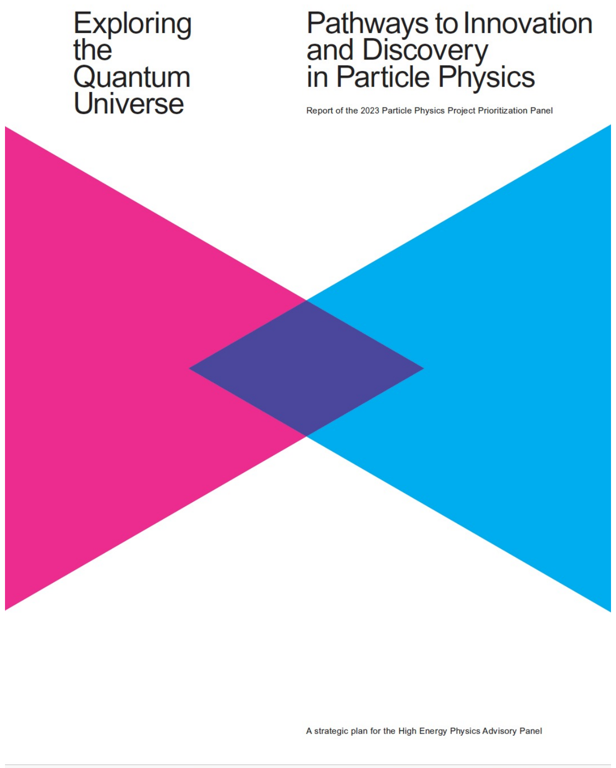
33 parallel sessions with 191 presentation

20 plenary presentations

29 posters

P5: Particle Physics Project Prioritization Panel

- RDCs can be organized as grassroots effort, but everything else needs enhanced budgets for detector instrumentation
- The vision of the HEP community now needs support from the funding agencies
- The 2023 P5 Report took Snowmass report and many other inputs and formulated a 10-year strategic plan with a 20-year vision for HEP.
  - Last P5 report from 2013 received broad community support and was crucial to growing HEP budget in the US



from the P5 report:

Detector R&D Recommendations

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. Targeted future collider detector R&D in particular, such as for Higgs factories or a muon collider, is covered in Section 6.5.

from the P5 report:

Detector R&D Recommendations

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.

Intra-Collider Synergies

take advantage of synergies until Higgs Factory decision is taken globally

- **Effort to coordinate** R&D needs for Higgs factories (linear and circular), as well as more specific coordination within FCC-ee,, ILC and MuC communities
- **Current/near-future:**
  - Si-based Calorimetry: Calice & CMS HGCal
  - Scintillator-tile-based calorimetry: CMS HGCal & EIC
  - LGADs: HL LHC ATLAS & HL LHC CMS & EIC
- **Future:**
  - MAPS: will be ubiquitous; low mass, high granularity, can include fast timing: HL LHC & EIC, FCC-ee, ILC, MuC
  - Standard silicon tracking
  - Calorimetry: PF and Dual Readout, different materials and technologies: many commonalities among different colliders
  - Gaseous detectors: applications in tracking, calorimetry, muon detection
  - Radiation hardness: FCC-hh & MuC
  - Many other synergies: ASICs, readout electronics, TDAQ, on-detector AI/ML

Summary

- Decadal strategic planning for HEP in the US concluded recently
  - BRN for Detectors, Snowmass, P5
- CPAD is in the process of enabling enhanced collaboration in detector instrumentation → RDCs
  - planning on strong ties with other regions
- Use the P5 report to increase funding for generic and directed Detector R&D

BACKUP

BRN: identifies Priority Research Directions

e.g. for silicon tracking:

PRD	Thrust	Synergies
Develop high spatial resolution pixel detectors with precise per-pixel time resolution to resolve individual interactions in high-collision-density environments	1. small pixel size ≈10µm 2. timing O(1-10ps) 3. Extreme radiation ($10^{18} n_{eq}/cm^2$)	Lepton colliders, LHCb Upgrade 2 Hadron colliders
Adapt new materials and fabrication/integration techniques for particle tracking	1. Adapting new materials and novel configuration sensors with new industrial partnerships 2. Develop readout electronics matched to new sensor characteristics, including new processing such as 3D integration	Lepton and hadron colliders Charged lepton flavor violation
Realize scalable, irreducible mass trackers	1. Highly integrated monolithic active sensors 2. Scaling of low mass detector systems 3. System for special applications (space/dark matter/rare processes)	Lepton and hadron collider, heavy flavor experiments at hadron machines, dark matter, charged lepton flavor violation

SNOWMASS Findings: Detectors for Collider Experiments

Tracking

Push 4D resolution, low mass and radiation hardness:

- Development of sensor technologies
  - Achieve 4D-capability from timing sensors with fine segmentation and able to cope with high occupancies and radiation tolerance
  - Large area sensors with improved uniformity, e.g. traditional sensors, LGADs, and wafer-scale MAPS
  - Sensors that deliver tracklet 4-vectors instead of hit data
  - Major advances in ASIC development and approaches: bandwidth optimization, low noise, small area and low power dissipation
  - New materials for sensor and electronics: unified design of full systems
- Advanced packaging and edge-computing paradigms
  - Vertical integration of multi-tier processing electronics and sensors, optimization of detector thickness
  - Industry partnerships and adoption of new technologies
- Radiation hard technologies and more effective cooling
- Cohesive set of simulation tools

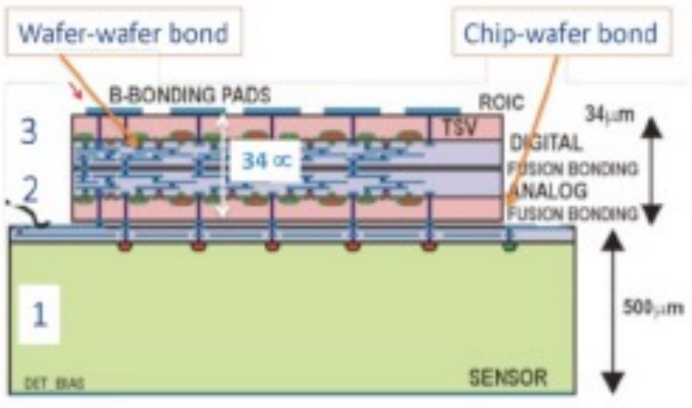
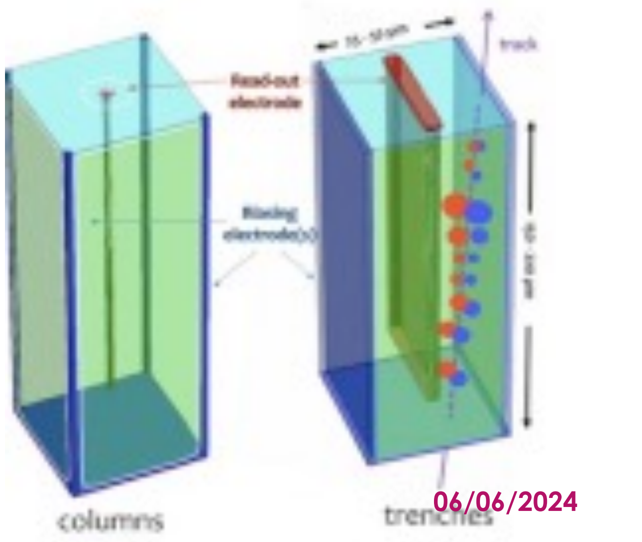
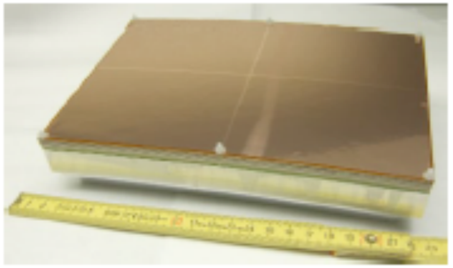


Figure 1: Example of 3D integration of sensor and readout chip.

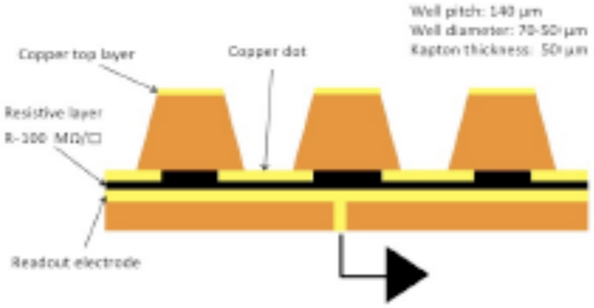


Tracking with Micro Pattern Gas Detectors

- MPGDs have major roles in TPCs and large area muon detection systems. Essential features – large area, low material budget
- TPCs – ILD/ILC, potential Belle II wire chamber replacement, for a detector at CEPC
  - MPGD readout: GEM, GridPix, ...
  - Synergy with Si ASIC development – wafer post-processing, gas amplification on top of pixelized r/o chip
- Muon detection systems
  - Precise muon tracking, trigger and tagger for collider detectors
  - Instrument large areas, high efficiency, in high-background, high-radiation environment
- Challenges:
  - Discharge protection (e.g. micro R-well), miniaturization of readout elements
  - FCC-hh very forward endcap regions
  - Multi-TeV Muon Collider: Fast Timing MPGD, use timing to mitigate beam-induced background



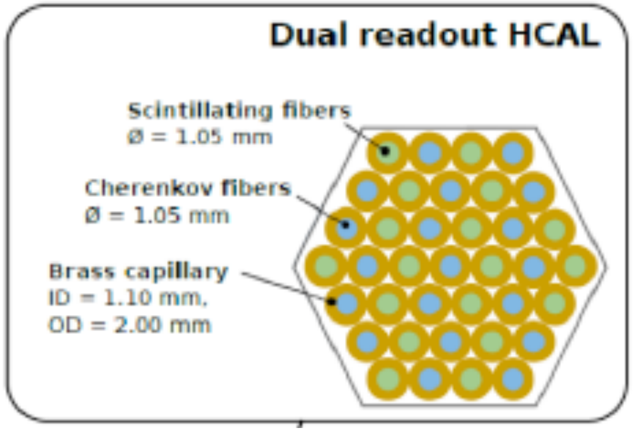
Triple-GEM r/o module for LCTPC

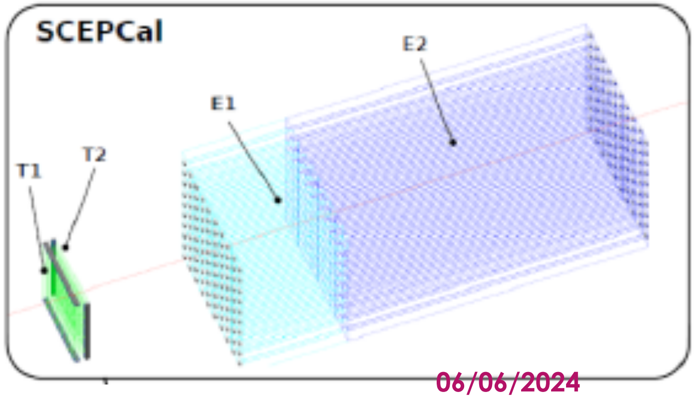


Micro R-well

Calorimetry

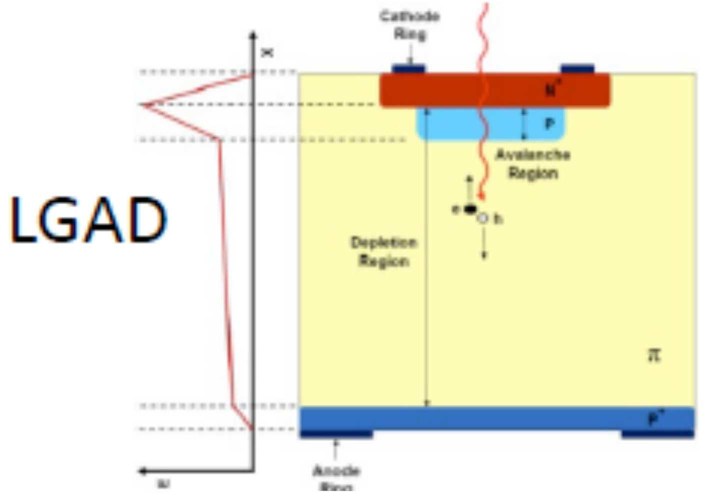
- **Two major approaches: particle flow (PF) and dual readout (DR)**
- Recent addition of fast timing information
- Development of new, radiation-hard active materials
- Challenges remain:
  - Mechanics, integration, costing of a realistic spaghetti calorimeter
  - Red-sensitive SiPMs and novel optical materials to boost the Cherenkov signal/noise in homogeneous crystal setups
  - Scaling to 10-100M channels at reasonable cost
  - Thermal and power management of front-end ASICs
  - Compact design (minimizing gaps between sampling layers)

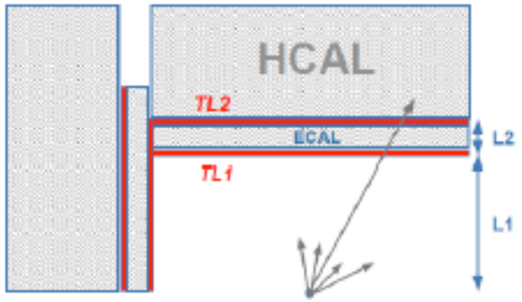




Picosecond Timing

- Timing layers
  - Low-gain Avalanche Detectors (LGADs): ~30ps time and 1mm spatial resolution
  - Ultra-fast silicon monolithic sensors with integrated readout (CMOS): 10-20ps
  - Micro-channel plate (MCP) detectors for single ionizing particles: ~few ps
  - 2-stage Micromegas + Cherenkov radiator equipped with photocathode: <100ps
  - LYSO crystals + SiPM: few 10s ps
  - Deep-diffused avalanche photodiodes: ~40ps
  - Coherent microwave Cherenkov detectors: ~0.3 – 3ps
- Volume timing:
  - Silicon tiles, e.g. LGADs: few 10s ps
  - Plastic scintillator tiles or strips with SiPM readout: sub-ns - few 10s ps
  - Multi-gap RPCs: sub-100ps
  - Highly-granular crystal-based detectors, using a highly-segmented readout
- **R&D needed on electronics to support timing resolution satisfying the constraints on power consumption associated with highly-integrated systems with extreme channel counts**





Individual CPAD RDC Status and Plans

RDC1: Noble Element Detectors

Jonathan Asaadi
Carmen Carmona

- **Areas of R&D Priorities:** In the broadest sense, these are rearticulations of the BRN 2019 report and Snowmass 2022 reports
  - **Topic Area #1:** 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 **(Overlap with RDC2)**
      - e.g. new technologies, geometries, materials, WLS,
  - **Topic Area #2:** 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 **(Overlap with RDC 4,5)**
      - e.g. Photonic readout solutions, new/enhanced architectures at the front-end, AI/ML inside the detector
  - **Topic Area #3:** Challenges in scaling technologies
    - Scaling of purification, radiopurity, doping, high voltage, and other target challenges
      - e.g. Large scale purification, removing radioactive contaminants @ > ton scale
- We fully endorse the other identified challenges in the BRN and Snowmass reports, but have opted to focus on these topic areas as a place to start

RDC2: Photodetectors

Shiva Abbaszadeh
Flavio Cavanna

- Areas of R&D Priorities

- **Innovative photosensor** (Blue skies research) technological breakthroughs for new science.
  - SNSPD: Superconductive Nanowires Single Ph Detector.
  - VUV sensitive detectors for low-light detection
- **Photosensor (& Instrumentation) development** to enhance experimental capabilities (eg improving Single Photon detection, timing, radiation hardness, ..).
  - SiPM - main stream in photosensors development (Radiation tolerance, Spectral sensitivity, correlated noise, … ultimately Digital SiPM).
  - MicroChannel Plate (MCP) PMT (—>LPPD) *[RDC#11 - Fast Timing]*
  - CCDs: Ge CCD or Skipper CCDs [*RDC#5 - Low-Background Detectors (incl. CCDs)]*
  - “Accessories”: Filters, Lenses, Wavelength shifters, Waveguides, Fibres, PoF, SoF, Optics.
- **Large Area PDSystems** (PhotoCollectors and integrated readout for photo-sensors) project specific R&D

- R&D on scalability of light readout for current and future neutrino/DM experiments *[RDC#1 - Noble Element Detectors and RDC#10 - Detector Mechanics]*. Increase of photo-coverage to improve energy resolution and lower threshold. Dedicated developments should achieve applications in future detectors - ten to a hundred times larger, compared to the present (OptCoverage —> 10, 100 and ultimately 1000 m2). Noise hit rates, radiopure materials, power dissipation, large bandwidth signal transmission (readout channels and data volumes

RDC3: Solid State Tracking

Tony Affolder
Sally Seidel

- Areas of R&D Priorities
  - Topic Area #1: Adapting non-silicon and novel-configuration sensors
    - Improved costs, area, radiation tolerance, performance
  - Topic Area #2: Scalable, low-mass detector systems
    - MAPs based tracking,
  - Topic Area #3: Trackers for Lepton Colliders
    - Similar requirements for timing and spatial resolution
  - Topic Area #4: Trackers for Hadronic Colliders
    - Extreme radiation with fine timing and spatial resolution
  - Topic Area #5: Advanced modeling

PRD	Thrust
PRD 18: Develop high spatial resolution pixel detectors with precise per-pixel time resolution to resolve individual interactions in high-collision-density environments	Thrust 1: Lepton colliders, requiring timing on the order of 10 ps; pixel pitch on the order of 10 microns Thrust 2: Hadron colliders, requiring timing resolution down to 1 ps to achieve HL-LHC-like pileup, in a high radiation environment (up to fluences in the order of $10^{18} n_{eq}/cm^2$)
PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking	Thrust 1: Adapting non-silicon and novel-configuration sensors (diamond, large-bandgap semiconductors, thin film materials, nanotechnology, 3D sensors, new emerging materials) with new industrial partnerships Thrust 2: Development of readout electronics matched to new sensor characteristics, including new processing such as 3D-integration
PRD 20: Realize scalable, irreducible-mass trackers	Thrust 1: Highly integrated monolithic, active sensors Thrust 2: Scaling of low-mass detector system Thrust 3: Systems for special applications: space-based tracking detectors, and dedicated searches for rare processes and dark matter

RDC4: Readout and ASICs

Angelo Dragone
Mitch Newcomer

- Areas of R&D Priorities (preliminary and non-exhaustive)
  - Topic Area #1: Circuits and Architectures for 4D Tracking and Calorimetry
    - Picosecond Timing Circuits
    - Monolithic Readouts
    - Models and Techniques for extreme radiation
  - Topic Area #2: Big Data Management
    - Energy efficient architectures and circuits
    - On-Chip Computing
    - On-Chip AI/ML
    - Fast Interconnections and I/Os
    - Advanced Integration (3D, Photonics, Wireless)
  - Topic Area #3: Cryogenic and Deep Cryogenics
    - 4K Circuits and Architectures for QIS
    - Circuits and Architectures for Noble Liquid Detectors
    - Cryogenic Models and Libraries
  - Topic Area #4: Methodologies, Tools, and Workforce Development
    - Design for Verification methodologies
    - CAD Tools and Foundries shared joint access
    - Shared libraries and access model
    - Domain knowledge transfer and training

RDC5: Trigger and DAQ

Zeynep Demiragli
Jinlong Zhang

- Areas of R&D Priorities
  - Intelligent data reduction and processing (with RDC4 ?)
    - Real-time / low-latency data reduction and feature extraction
    - Fast artificial intelligence and neuromorphic computing on real-time hardware
  - Link technology (with RDC4 ?)
    - High-bandwidth, rad-hard, low-power optical link (>50Gbps)
    - Wireless readout
  - Integrating modern computing architecture and emerging technologies
  - Self-running DAQ system
  - Timing distribution with picosecond synchronization (1ps over 1 km) (with RDC4 ?)

RDC6: Gaseous Detectors

Prakhar Garg
Sven Vahsen

- Areas of R&D Priorities
  (based on Snowmass report, highly preliminary, biased, and non-exhaustive)
  - **Topic Area #1:** Advance gas TPC readout to performance limits, enabling new experiments
    (DM, neutrinos, existing and future lepton colliders, EIC)
    - Maximize sensitivity by achieving 3d single electron counting (incl. via negative ion drift)
    - 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 multiplexed readouts
  - **Topic Area #2:** Advance MPGDs for high-background environments
    (Nuclear physics and future hadron colliders)
    - Develop cylindrical and exotic-shape tracking layers
    - Develop pico-second timing layers
    - Improve radiation hardness, rate capability, robustness against sparking and aging
- **Topic Area #3**: Establish MPGD development/prototyping(/production) facility in the US

RDC7: Low-Background Detectors

Daniel Baxter
Guillermo Fernandez-Moroni Noah Kurinsky

- Areas of R&D Priorities
  - **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 fabs.
  - **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; includes TES, KIDs, Qubit-based Sensors, MMCs, and other novel techniques
  - **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**: New targets compatible with low-background searches at sub-eV scales for low-background experiments

RDC8: Quantum and Superconducting Sensors

Rakshya Khatiwada
Aritoki Suzuki

- Areas of R&D
  - Pairbreaking, Photon & Phonon Sensors
  - Coherent Wave Sensors
  - AMO, clocks, interferometry, NMR, Optomechanical Sensors
  - Theory, Simulation & Novel Material
- Upcoming RDC8 meeting soon to go over work package document

RDC9: Calorimetry

Marina Artuso
Minfang Yeh

- Areas of R&D Priorities (Still under devlopment with the community)
  - From the BRN report three main broad R&D areas
  - Topic Area #1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements
  - Topic Area #2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments
  - Topic Area #3: Develop ultrafast media to improve background rejection in calorimeters and particle identification detectors

RDC10: Detector Mechanics

Eric Anderssen
Andreas Jung

- Aims at detectors for future colliders
  - FCC-ee, muon Colliders, and more
- Areas of R&D Priorities
  - Light-weight composite materials for detector support (radiation-hard, highly thermally conductive)
    - Dual-use, e.g. electronically or/& thermally conductive, etc. while providing structural support
    - Rails to support detectors
    - Mechanical & thermal finite element analysis for manufacturing or during operation (FEAs)
  - Detector cooling aspects (Pipe materials, connections, fittings)
  - System integration aspects, beampipe bakeout, beampipe interfaces
  - Alignment, shock & vibrations in-situ or transport or magnet discharge, etc.
  - Radiation aspects: epoxy, mechanics materials, access
  - Thermal expansion differences, issues due to humidity / outgassing
  - Failure management: Maintainability, services, maximum duty cycle

  - Magnet developments

RDC11: Fast Timing

Gabriele Giacomini
Matt Wetstein

- Topic Area #1: Picosecond timing
  - ~10ps for muon colliders, ~1ps for hadron colliders,while keeping ~10um of spatial resolution (or less)
  - <100 ps (single photoelectron) for neutrino experiments with sub-cm resolution
- Topic Area #2: new materials to reach ps timing
  - Expand from silicon (LGAD, 3D)
- Topic Area #3 Leveraging fast photodetection in cryogenic detectors
- Topic Area #4 High precise GPS-based synchronization and time stamping over long distances for neutrino applications
- Topic Area #5 Fabrication techniques to reduce costs (LAPPDs)
- Topic Area #6 integration with read-out electronics (fast MAPS, low capacitance hybrids, …), photosensor electronics