Snowmass 2021

IF03: Solid State Detectors and Tracking White Paper Status

T. Affolder, A. Apresyan, S. Worm

on behalf of IF03 working group

July 19, 2022

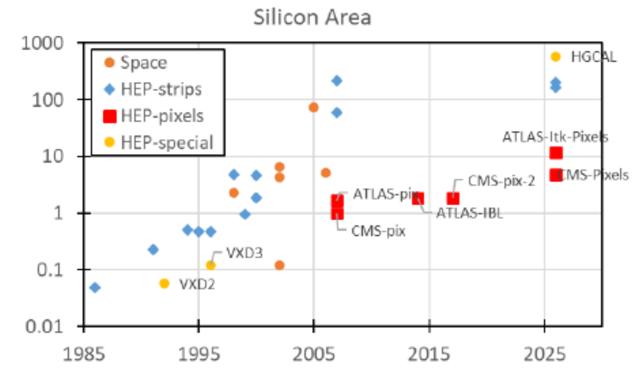
Fermilab DESY. UC SANTA CRUZ

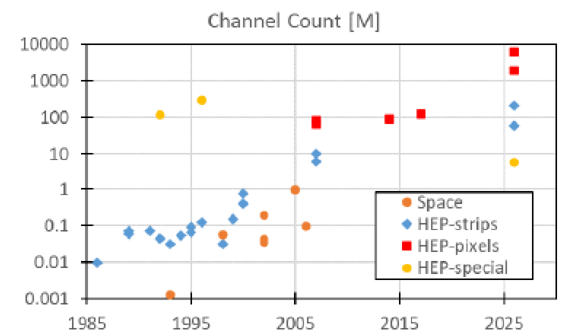
What is IF03?

- IF03 tracking: https://snowmass21.org/instrumentation/tracking
  - Past meetings/presentations available at: https://indico.fnal.gov/category/1183/
- This topical group aims to study detectors and technologies needed for charged particle tracking:
  - Technologies for colliders, fixed target, or precision measurement experiments
  - Ranging from silicon to diamond and other alternative materials.
  - Also non-solid-state trackers, e.g. for high-intensity experiments.
  - 3D integration, ultra-lightweight materials for mechanical support & cooling.
- Trackers should be discussed in the context of future experimental challenges
  - Identify technological challenges and technology opportunities with different future accelerators
  - Moreover "blue sky" R&D is important => opportunities for future transformative breakthroughs'

Experimental Needs

- A large number of future and proposed experiments require silicon trackers with ~0.1-1% X_0 per layers
  - Also non-solid-state trackers, e.g. for high-intensity experiments.
- Extremely challenging while simultaneously:
  - Increasing segmentation and radiation tolerance
  - Enabling long lived particles, dense jet tracking
  - Providing precision timing resolution in a tracking environment
  - Increasing system size
  - Improving replaceability/maintenance (robotic)
  - With finite budgets and schedules,….





From V. Fadeyev

Goals for Today's Meeting

- Summarize the outcomes of the process so far
  - 8 White papers based on 30+ LOI inputs plus additional sources
    - Dominant outcome/focus of this topical group since the Snowmass restart
- Developing the 2-4 'bullet-pointed' top-level messages or recommendations from IF03
  - These feed into the IF frontier and then global Snowmass recommendations
- Go over the circulated draft and discuss any improvements, additions, etc. we can make to better clarify the rich work in tracking in the US
  - Ensure it is capturing the full community
  - Links to draft of IF3 summary (https://snowmass21.org/_media/instrumentation/snowmassbook_if03_v1.pdf)
  - Links to community feedback to draft (https://docs.google.com/document/d/1vSz_xmtA1Swz4MjZPvQIebHAm5eDI92DFRvTUSoaSlc/edit?usp=sharing)

White papers in IF03

arXiv:2202.11828v1 [physics.ins-det] 23 Feb 2022

Novel Sensors for Particle Tracking: A Contribution to the Snowmass Community Planning Exercise of 2021

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ABSTRACT

Five contemporary technologies are discussed in the context of their potential roles in particle tracking for future high energy physics applications. These include sensors of the 3D configuration, in both diamond and silicon, submicron-dimension pixels, thin film detectors, and scintillating quantum dots in gallium arsenide. Drivers of the technologies include radiation hardness, excellent position, vertex, and timing resolution, simplified integration, and optimized power, cost, and material.

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arXiv:2203.07626v2 [physics.ins-det] 29 Mar 2022

Submitted to the Proceedings of the US Community Study
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Monolithic Active Pixel Sensors on CMOS technologies

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Nicole Apadula, Alberto Collu, Carl Grace, Leo Greiner, Yuan Mei, Ernst Sichtermann
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University of Oregon, Eugene
Marcel Demarteau
Oak Ridge National Laboratory
Whitney Armstrong, Manoj Jadhav, Sylvester Joosten, Jihee Kim, Jessica Metcalfe, Zein-Eddine Meziani, Chao Peng, Paul E. Reimer, Marshall Scott, Maria Żurek
Argonne National Laboratory
R. Caputo, C. Kierans, A. Steinhebel
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Contents

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15-March-2022

Fast Timing With Silicon Carbide Low Gain Avalanche Detectors

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Abstract

4H-Silicon Carbide, when considered as a material for the fabrication of Low Gain Avalanche Detectors for particle timing and position measurement, offers potential advantages over Silicon. We discuss an ongoing study of this material aimed at the fabrication and test of prototype fast timing sensors. This work is well aligned with technical directions identified in the recent Department of Energy study, "Basic Research Needs for High Energy Physics Detector Research and Development".

Introduction

In this contributed paper to the Snowmass proceedings we discuss ongoing work to study and develop Low Gain Avalanche Detectors (LGADs) using 4H Silicon Carbide (4H-SiC) rather than Silicon. This effort is very well aligned with all three of the Priority Research Directions (PRD's) identified for future tracking detectors in the recent DOE Basic Research Needs Study [1]. The PRD's are (PRD18) fast timing, (PRD19) new materials and processes, and (PRD20) low mass scalable tracking systems.

The work is being carried out as a collaboration between Physics Division staff at Lawrence Berkeley National Laboratory and large bandgap device and processing researchers at North Carolina State University (NCSU). NCSU, located in the Raleigh Durham Research Triangle Area, is a center for research and development on large bandgap devices, mainly for power applications. Many companies with expertise in large bandgap materials are located in this area as well.

Present upgrades to high energy and heavy ion collider detectors, and also proposed detectors at the new Electron Ion Collider, have embraced the importance of fast (~10 ps) timing on individual charged particles to enable 4D tracking, pileup rejection, and particle ID. The DOE BRN on Instrumentation states as a key goal "Develop high spatial resolution pixel detectors with high per-pixel time resolution to resolve individual interactions in high-collision-density environments". Much work on fast timing has centered on the Silicon LGAD concept [2]. This is an enhancement to the familiar position sensitive silicon detector (strips, pads, and pixels) which adds a moderate gain layer below the rectifying implant. However LGADs suffer from the same challenges as regular Silicon detectors as they are susceptible to bulk radiation damage and must, consequently, be operated a very low temperatures. This low temperature leads to bulky and complex cooling requirements.

The goal of this project is to explore the LGAD concept realized initially in Silicon Carbide (4H-SiC) rather than in Silicon. This material has already been studied and demonstrated as a radiation detector but in niche applications [3]. It has not found widespread application in large HEP or NP trackers, due, in part, to small signal and difficult fabrication. However, SiC detectors can, in principle, operate at very high temperatures,

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arXiv:2203.14347v1 [physics.ins-det] 27 Mar 2022

Transcendental Preprint
March 29, 2022

Light-weight and highly thermally conductive support structures for future tracking detectors

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ABSTRACT

Detector mechanics can play a significant role in a detector's performance, improvements typically require in-depth study of total mass, novel ways to reduce the total mass, as well as more integrated design concepts to save on material budgets and optimize performance. Particle detectors at future colliders rely on ever more precise charged particle tracking devices, which are supported by structures manufactured from composite materials. This article lays out engineering techniques able to solve challenges related to the design and manufacturing of future support structures. Examples of current efforts at Purdue University related to the high-luminosity upgrade of the CMS detector are provided to demonstrate the prospects of suggested approaches for detectors at new colliders: a future circular collider or a muon collider. Detectors at electron-positron machines have significantly smaller material budgets and require targeted concepts.

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Simulations of Silicon Radiation Detectors for High Energy Physics Experiments

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Abstract: Silicon radiation detectors are an integral component of current and planned collider experiments in high energy physics. Simulations of these detectors are essential for deciding operational configurations, for performing precise data analysis, and for developing future detectors. In this white paper, we briefly review the existing tools and discuss challenges for the future that will require research and development to be able to cope with the foreseen extreme radiation environments of the High Luminosity runs of the Large Hadron Collider and future hadron colliders like FCC-hh and SPPC.

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Strategies for Beam-Induced Background Reduction at Muon Colliders

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Abstract: This Snowmass study explores methods for the reduction of Beam-Induced Backgrounds (BIB) at a future muon collider. Studies are performed for a collision energy of 1.5 TeV, and a detector with a tungsten nozzle designed to block the majority of the BIB. In this context, detector strategies are explored to further reduce the BIB, with a focus on the innermost layers of the tracker where its density is highest. In addition, a conceptual design of a calorimeter built to reject BIB is presented.

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4-Dimensional Trackers

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March 29, 2022

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1 Introduction

Precision timing at the level of 10-30ps will be a game-changing capability for detectors at future collider experiments. For example, the ability to assign a time stamp with 30ps precision to particle tracks will allow to mitigate the impact of pileup at the High-Luminosity LHC (HL-LHC). With a time spread of the beam spot of approximately 180ps, a track time resolution of 30ps allows for a factor of 6 reduction in pileup.

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arXiv:2203.06093v3 [hep-ex] 5 Apr 2022

Integration and Packaging

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April 7, 2022

ABSTRACT

Vertically integrated (3D) combinations of sensors and electronics provide the ability to fabricate small, fine pitch pixels with very small total capacitance monolithically integrated with complex circuitry. The small capacitance enabled by the fine pixel pitch, low interconnect capacitance, and very short signal path available in 3D hybrid bonding, provide an excellent signal to noise ratio with moderate power consumption. This combination enables fabrication of integrated sensors and electronics with both excellent position and time resolution. In this white paper, a discussion will be presented on the advantages of 3D integration, ongoing projects, and prospects in high energy physics and beyond.

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Executive summary

In the past years, high-energy physics experiments have been mostly relying on bump bonding for high density pixel to ASIC connection. The bump bonding technology was proven to be reliable and is currently used in many large silicon detector systems; however, it is known to have several limitations. It can be applied only down to 20-50 μm of pitch and has yield issues for finer connections. Furthermore, the solder balls used for the connection inevitably increase the input capacitance to the amplifier and hence the noise. In order to provide a planar connection to a bump-bonded sensor, either an interposer is required or the sensor/chip needs to have suitable

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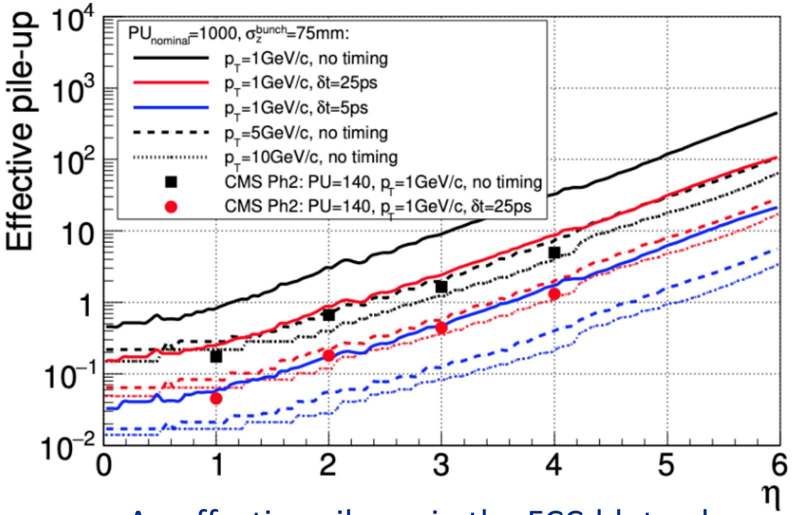
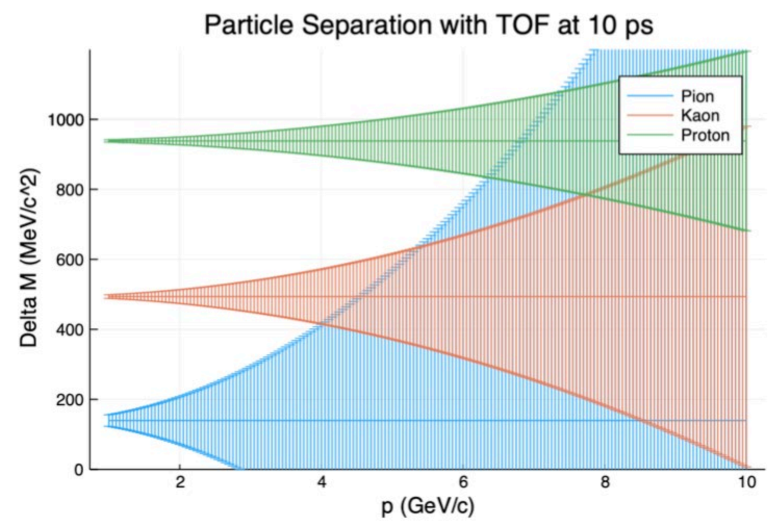
4D trackers and precision timing

- Contact persons: **R. Heller and A. Schwartzman**
- Applications of timing detectors:
  - Hadron colliders, e^+e^- colliders (ILC, CLIC, C3), muon colliders, EiC
  - Survey specifications required for each machine type, usage in each machine (PU, PID, BIB, etc)
- Sensor technologies:
  - LGADs, AC-LGADs, LGAD optimizations (buried layer, double-sided, thin, etc), 3D sensors, MAPS, Induced Current sensors
  - A comprehensive survey of novel directions, limitations and opportunities in sensors technologies



An effective pile-up in the FCC-hh tracker



Mass resolution for a TOF system with 10 ps in SiD

4D trackers and precision timing

- Electronics for fast timing detectors: current chips (ALTIROC, ETROC) and what's next
  - Advances in detector technology and the direction of HEP experiments will require development of new specialized readout electronics.
  - Overview of the current technologies and limitations that they pose
  - The entire pixel electronics will need to be designed with low power techniques and with novel timing extraction architecture, and more advanced edge-computing paradigms
  - Requirements of the next machines will need major advances in the ASIC development and approaches: some of these will be covered in IF7
- Layout optimizations
  - Key considerations are the optimizations of excellent time-and-position in all layers, vs excellent time in some and excellent position in others
  - Alternative approaches such as alternating spatial with timing layers, or 4D with 3D layers could help improve the overall physics performance.
  - Tracking material and pseudorapidity coverage.

Integration and Packaging

- Contact persons: **S. Mazza, R. Lipton, R. Patti**
- Electronics and sensor advanced packaging offer technologies to meet the needs of future particle physics experiments.
  - Collaboration between research groups and industry is crucial for the successful introduction of this technology in the research community
  - State-of-the art packaging and integration technologies now available can significantly extend the reach and effectiveness of future detectors, enabling lower mass, finer pitch, and lower noise systems
- Advantages of advanced packaging
  - Footprint, speed, performance, power, heterogeneous integration, robustness,
- Commercial availability
  - Variants of the 3D integration technology have been adopted by a number of foundries available to HEP
  - Examples of capabilities and successful collaborations with NHanced Semiconductors and Cactus Materials

Integration and Packaging

- Description of currently active 3D R&D projects for HEP and related fields.
  - These include single-photon avalanche diode 3D integration on CMOS,
  - High granularity LGADs,
  - 3DIC SiPM with sophisticated processing with active quenching for each pixel, inter-micropixel communication and pattern recognition etc.
  - Edgeless Tile Arrays, Small Pixel Induced Current Detectors, Double Sided and Small Pixel LGADs,
  - 3DIC for high performance Pattern Recognition: massive three-dimensional network for data communication with shorter traces and low parasitic capacitance
  - Zero mass tracker, 2D Interconnects and Interposers, etc
- Results and ongoing projects
  - An overview of several latest results from FNAL and UCSC+Cactus materials
- Path for future development

Novel Sensors for Particle Tracking

- Contact persons: **S. Seidel**
- Five contemporary technologies with potential application to particle tracking in future high energy physics experiments are discussed.
- Silicon and Diamond Sensors in 3D Technology
  - Shows promise for compensation of lost signal in high radiation environments and for separation of pileup events by precision timing.
  - Sensors with improved uniformity, timing resolution, and radiation resistance.
  - Present research aims for operation with adequate signal-to-noise ratio at fluences approaching 10^{18} n_{eq}/cm^2, with timing resolution on the order of 10 ps.
- Submicron Pixels with a Quantum Well for Vertexing
  - Development of sensors with submicron position resolution for vertex detector for the future linear collider experiments
  - Quantum well gate is made with a Ge layer deposited on a silicon substrate.

Novel Sensors for Particle Tracking

- Thin Film Detectors
  - Thin-flim transistor technology uses crystalline growth techniques to layer material
  - Monolithic detectors may be fabricated by combining layers of thin film detection material with layers of amplification electronics using vertical integration.
  - Offer optical transparency, mechanical flexibility, high spatial resolution, large area coverage, and low cost relative to traditional silicon-based semiconductor technology.
  - Monolithic sensors can be fabricated using layers of thin film materials for particle detection with layers for amplification electronics
- Scintillating Quantum Dots in GaAs for Charged Particle Detection
  - Charged-particle tracking using novel ultra-fast scintillating material utilizing semiconductor stopping media with embedded quantum dots
  - First prototype detectors have been produced, and initial studies published
  - Significant exploratory research and development is required to accurately assess expected performance of these detectors in future high-energy physics applications

Simulation tools

- Contact persons: **B. Nachman**
- Models for single quantities
  - Annealing (e.g. Hamburg Models), Straggling (e.g. Bichsel Model)
- TCAD simulations for detector properties
  - Commercial TCAD packages are capable of full simulations of device fabrication, including epitaxy, implantation, annealing, deposition and oxydation.
  - The accuracy and detail provided by these simulations can be invaluable in the development of new sensor technologies or in understanding the behavior of existing devices.
  - Many multitrap models for radiation damage
  - Lighter-weight alternatives: TRACS and Weightfield2
- Testbeam
  - Pixelav, Allpix2, and similar specialized MC programs for beam tests
- Full detector systems
  - Within large HEP collaborations, silicon detector simulation is typically performed using proprietary software (Athena, Gaudi, and CMSSW)
  - Different approaches to modelling of radiation damage in LHC experiments

Simulation tools

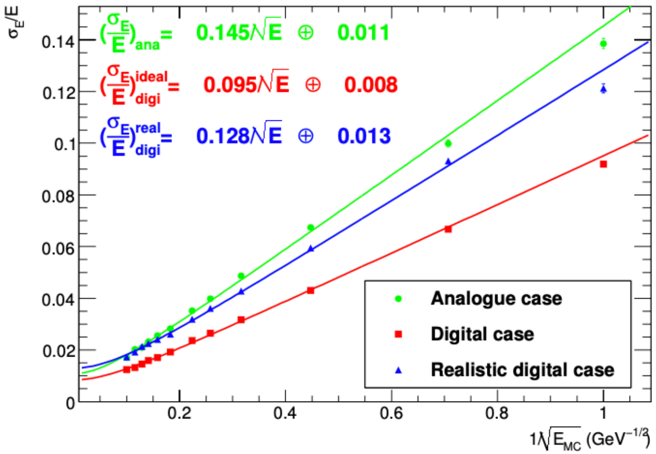
- Challenges and Needs
  - Unified radiation damage (TCAD) and annealing model
  - Prescription for uncertainties in TCAD models
  - Measurements of damage factors (many of the inputs in the RD50 database are based on simulation or less)
  - Update to basic silicon properties? https://cds.cern.ch/record/2629889
  - How to deal with proprietary software and device properties?
  - Feedback between full detector systems and per-sensor models
  - Extreme fluences of future colliders

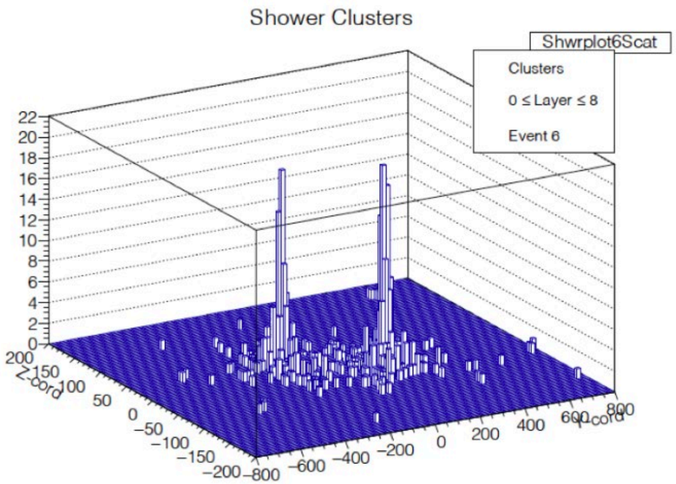
Monolithic integrated silicon detectors, CMOS (MAPs)

- Contact persons: **C. Vernieri**
- Address the challenges of the future trackers and calorimeters by utilizing CMOS Monolithic Active Pixels (MAPs)
  - Si diodes and their readout are combined in the same pixels, and fabricated in a standard CMOS process
  - Integrating sensors and front-end electronics on the same die removes the need of interconnections, thus reducing complexity and mass.
  - The close connection of sensor and front-end amplifier reduces input capacitance which reduces the achievable noise floor and thus for the same S/N ratio allows for a reduction in signal and therefore sensor thickness, which also reduces mass.
- Develop two types of fully depleted MAP sensors with characteristics suitable for Trackers and Electromagnetic Calorimeters.
  - Requirements of the SiD detector for ILC are used as the strawman specifications

Monolithic integrated silicon detectors, CMOS (MAPs)

- Possibility and advantages of a wafer-scale device production, which will significantly simplify detector construction for future trackers
- R&D needs for the wafer-scale MAPS to investigate the challenges with power-pulsing, power distribution, yield and stitching techniques
- Detailed simulation studies for ECAL application of similar MAPS sensors presented
- Large volume of data provided by ECal reveals details of particle showers.
  - The extraction of the most pertinent information, for example particle energy, particle type, and the separation of nearby and overlapping showers, provides an opportunity to apply Machine Learning techniques.





Cooling and Mechanics

- Contact Person: **A. Jung**
- Increased segmentation leads naturally to larger power densities; in order to minimize material, solutions with integrated services and cooling are necessary.
- Addresses challenges of cooling and structural stability required for future tracking systems through:
  - A holistic approach to design, simulation and manufacturing
  - Novel materials, new cooling and composite manufacturing techniques
- Cooling developments currently is driven by European colleagues.
  - It is necessary for the US community to engage more in order for our tracking systems to be successful

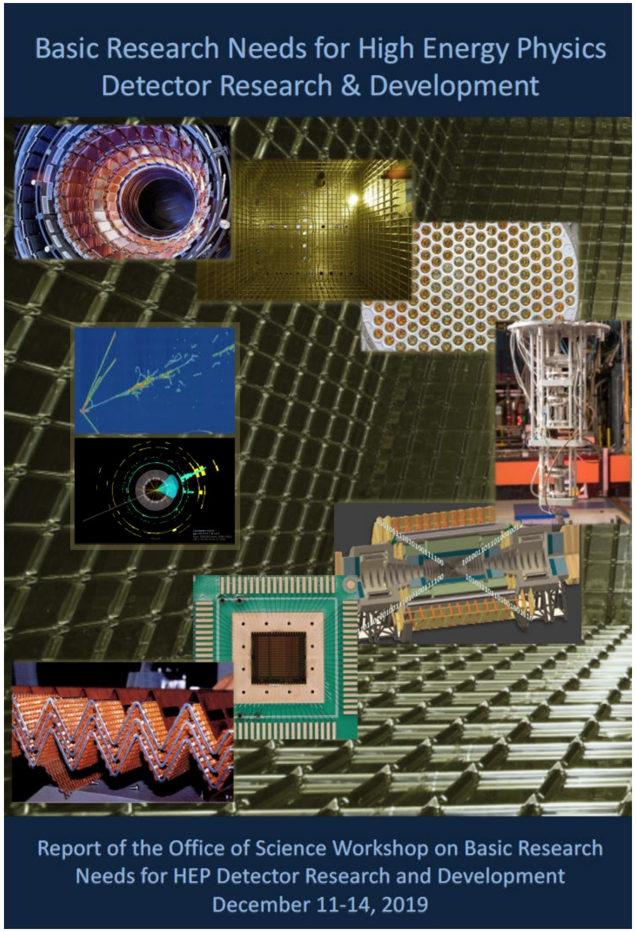
Summary

- Achieve 4D-capability from timing sensors with fine segmentation
  - Large area sensors with improved uniformity
  - Ability to cope with high occupancies
  - Major advances in the ASIC development and approaches
  - New materials for sensor and electronics
- Advanced packaging and edge-computing paradigms
  - Vertical integration of multi-tier processing electronics and sensors
  - Industry partnerships and adoption of new technologies
- Radiation hard technologies and more effective cooling
- Advances and maintenance of simulation tools

BRN for HEP Detector R&D

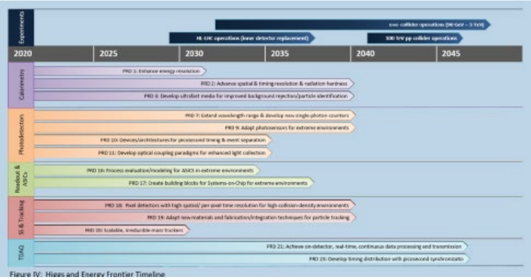
Guidance and structure of BRN report is excellent resource to start and structure our future plans

- PRD: Priority Research Directions
  - PRD 17: Create building blocks for Systems-on-Chip for extreme environments
    - Thrusts for low power I/O, wireless control systems, power management, MAPS/SPADs/SiPM
  - PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking
    - Thrusts for non-silicon/novel-configuration sensors, readout electronics and post-processing
  - PRD20: Realize scalable, irreducible mass trackers
    - Thrusts for MAPS, low-mass services and supports, special applications (space, rare processes dark matter)
  - PRD21: Achieve on-detector, real-time, continuous data processing and transmission to reach the exascale
    - Thrusts for high bandwidth low power data links, real-time processing hardware, advanced feature extraction for trigger



Conclusions

- Significant need for low mass trackers for future physics programs
- We need to work together to find solutions
  - Time to start is now
    - R&D timescale of 10-20 years to develop technologies for LHC and LH-LHC systems
  - Will require extra R&D funds (BRN, base grants, LBRD), industry-academic partnerships (SBIR,..)
- How do we develop to our future needs through near term experiments?
  - Technology road-map?
- How to we organize? How do we maintain and develop expertize and facilities?
  - SNOWMASS, CERN RDs,…
- Next step for SNOWMASS process will be to define and outline Whitepapers
  - More inputs can be collected at IF03 meetings (https://indico.fnal.gov/category/1183/)



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