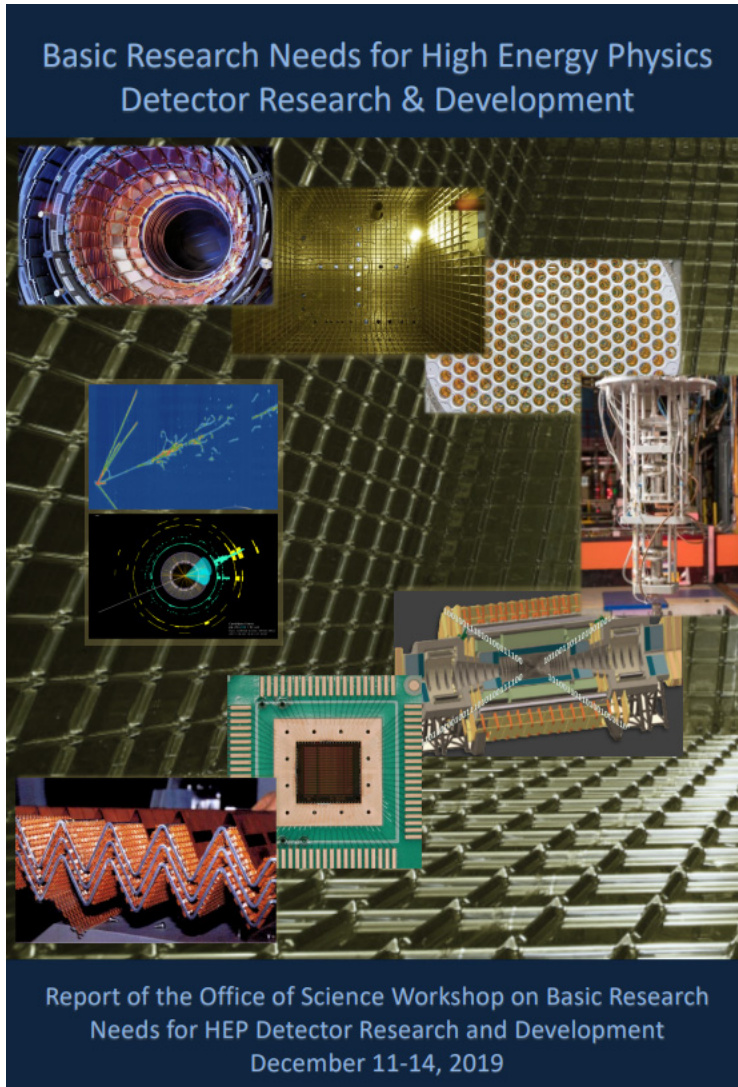


Community efforts: Basic Research Needs and Snowmass

Gabriella Carini
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2022/05/19

Basic Research Needs for High Energy Physics Detector Research and Development

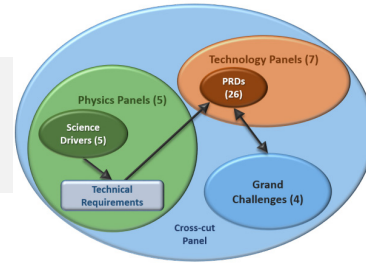


DOE Basic Research Needs Study on High Energy Physics
Detector Research and Development

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Held during 2019, report
released in August 2020



Grand Challenges:

1. Advancing HEP detectors to new regimes of sensitivity
2. Using integration to enable scalability for HEP sensors
3. Building next-generation HEP detectors with novel materials and advanced techniques
4. Mastering extreme environments and data rates in HEP experiment

Readout and ASICs

4.5 Readout and ASICs

4.5.1 Introduction

An Application-Specific Integrated Circuit (ASIC) is an integrated circuit explicitly designed for a specific purpose, in other words, is a chip developed for doing one thing extremely well. ASICs continue to replace discrete electronics to a point that entire systems are now integrated in a chip (system-on-chip). The shrinking of feature size (gates) with the advancement of technology (nodes) has enabled the integration of increasingly more functionalities with higher density and performance.

A majority of the R&D tasks described in this BRN report will require some form of ASIC development to support the research goals. Most will need to be compatible with an extreme environment, e.g. high radiation, cryogenic temperature, or space. Current and future custom integration allows higher density, enhanced circuit performance, lower power consumption, lower mass, much greater radiation tolerance or better performance at cryogenic temperatures than is possible with commercial ICs or discrete components. Transistors, invented in the 1940s became commercialized as discrete components in the 1950s and soon after specialized function circuits with multiple transistors on the same substrate became available. By the end of the 20th century complex Printed Circuit Boards (PCBs) with broad and sometimes programmable functionality were commonplace. Today much or all of the analog and digital functionality once relegated to a PCB can be found on a single substrate (see Figure 36).

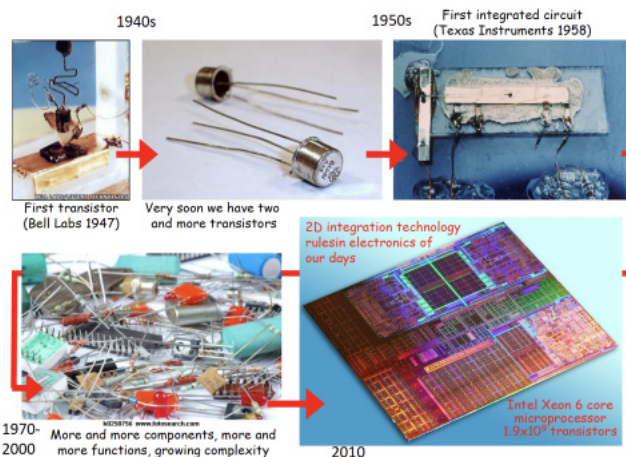


Figure 36: Highlights of the development of single transistors to Systems-on-a-Chip. The past 70 years have seen amazing developments in the performance and versatility of integrated circuits. The history above gives a sense of this progression which continues to evolve.

The Microplex chip, designed in 1984 at SLAC for the MARK II detector is perhaps the first example of how integrated circuits technology can enable breakthroughs. Four 128 channel Microplex chips placed side by side were used to read out the newly developed silicon strip sensor with 512, 25 μ m pitch channels

Priority Research Directions	Thrusts	Technical Requirements
PRD 16: Evaluate process technology and develop models for ASICs in extreme environments	Develop models, standard cell libraries, and demonstrators for extreme rate and radiation; Develop models, standard cell libraries, and demonstrators for intermediate cryogenic range; Develop models, standard cell libraries, and demonstrators for quantum sensor controls and data acquisition for deep cryogenic range; Investigate emerging design and verification methodologies; Investigate CMOS with integrated photonics nodes when commercially available; Investigate processes with Internet of Things (IoT) technology to enable self-assembly or assembly-free very large scale detectors; Adopt Artificial Intelligence (AI) and Machine Learning (ML) techniques	TR 1.1, TR 1.2, TR 3.47, TR 5.3, TR 5.6, TR 5.8, TR 5.11
PRD 17: Create building blocks for Systems-on-Chip for extreme environments	Develop advanced low power high speed I/O protocols; Develop wireless blocks beginning with control and monitoring; Develop power management blocks (DC/DC) converters, regulators, pulsed power; Circuit development for monolithic designs with sensor and readout integrated (MAPS, SPADs, SiPM); Develop Single Event Effects flows and techniques relevant for new technologies; Develop analog and multiplexing blocks for 4K environments and below; Develop fault tolerant communications for long lifetime inaccessible readout; Develop precision clock and timing circuits (PLL, DLL, Timing Discriminators, Delay Lines, Picosecond TDCs); Develop multi-channel RF digitizers	TR 1.5, TR 2.1, TR 2.3- 2.5, TR 2.6- 2.7, TR 4.3- 4.4, TR 5.3, TR 5.6, TR 5.8, TR 5.11

Table 19: Summary of Priority Research Directions, Thrusts and Technical Requirements for Readout and ASICs.

Instrumentation Frontier conveners and scope



Phil Barbeau	Duke University	psbarbeau[at]phy.duke.edu
Petra Merkel	Fermi National Accelerator Laboratory	petra[at]fnal.gov
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The Instrumentation Frontier group is geared to discussing detector technologies and R&D needed for future experiments in collider physics, neutrino physics, intensity physics and at the cosmic frontier. It is divided into more or less diagonal sub-groups with some overlap among a few of them. The sub-groups are Calorimetry, Cross Cutting and Systems Integration, Electronics/ASICs, Micro Pattern Gas Detectors, Noble Elements, Photon Detectors, Quantum Sensors, Solid State Detectors and Tracking, and Trigger and DAQ. Synergies between the different sub-groups, as well as with other Frontier groups and research areas outside of HEP will be paid close attention to.

IF topical groups and co-conveners



Topical Group	Co-Conveners			
Quantum Sensors	Thomas Cecil (ANL)	Kent Irwin (SLAC)	Reina Maruyama (Yale)	Matt Pyle (Berkeley)
Photon Detectors	Juan Estrada (FNAL)	Mayly Sanchez (ISU)	Chris Rogan (Kansas)	
Solid State Detectors and Tracking	Tony Affolder (UCSC)	Artur Apresyan (FNAL)	Steve Worm (DESY)	
Trigger and DAQ	Darin Acosta (Florida)	Wes Ketchum (FNAL)	Stephanie Majewski (Oregon)	
Micro Pattern Gas Detectors	Bernd 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)	Roxanne Guenette (Manchester)	Jen Raaf (FNAL)	
Cross Cutting and System Integration	Jim Fast (PNNL)	Maurice Garcia-Sciveres (LBL)	Ian Shipsey (Oxford)	
Radio Detection	Amy Connolly (Ohio State)	Albrecht Karle (Wisconsin)		

IF Liaisons

Liaisons are providing high-level and bi-directional communication b/w Frontiers

IF Liaisons:

- Energy Frontier: Caterina Vernieri (SLAC), Maksym Titov (CEA Saclay)
- Neutrino Physics Frontier: Mayly Sanchez (ISU)
- Rare Processes and Precision: Marina Artuso (Syracuse)
- Cosmic Frontier: Kent Irwin (SLAC), Hugh Lippincott (UCSB)
- Accelerator Frontier: Andy White (UTA)
- Computational Frontier: Darin Acosta (Florida)
- Underground Facilities: Eric Dahl (Northwestern), Maurice Garcia-Sciveres (LBNL)
- Community Engagement: Farah Fahim (FNAL)

A long journey



- Started in 2020 paused because of COVID
- Before the pause:
 - Defined possible overlaps and boundaries between topics
 - Engaged community with several topical workshops leading towards the community meeting
 - We had received 343 LOIs and had started to work on white papers
- After the pause:
 - Slightly reorganized topical groups
 - Focus on white papers – submitted to arXiv
- Currently working on sub-topical and topical summary
 - Preparing for the meeting in July

Electronics / ASICs



Trace: • instrumentation • **electronics**

IF7: Electronics/ASICs

co-Conveners:

Name	Institution	email
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Description

Most R&D will need to be compatible with an extreme environment - e.g. high radiation, cryogenic, space. Current and future custom integration allows higher density, enhanced circuit performance, lower power consumption, lower mass, much greater radiation tolerance or cryogenic temperature performance than is possible with commercial ICs or discrete components. Designs that in the past required significant area on a printed circuit board with many types of specialized chips can potentially be replaced by a single integrated circuit and in some cases, notably pixel detectors, both sensor and readout can be fabricated as part of the same ASIC saving significantly on cost, power per channel and material burden, while improving spatial resolution and potentially replacing highly inefficient data transfer off detector with abstracted parameters.

Electronics / ASICs



Received 32 LOIs

Consolidated/coordinated on a few areas

IF7 - Connection established with:

- TDAQ/Triggering (IF4)
- Solid State Detectors /Tracking (IF3)

Relevant IF7 related contributions merged into IF3 and IF4 white papers

- AI/ML
- Calorimetry
- Data handling
- Deep cryogenic readout
- Design for reliability analytical techniques
- Monolithic sensor readout
- Photodetector readout
- Pixelated Liquid Noble readouts
- Optical links
- Timing
-

Cross Cutting and System Integration



Foundries and foundry access

Calibration & Test beams and irradiation facilities

Facilities for unique environments

- Low environmental noise
- Cryogenic facilities (LAr to mK)
- Low-background LOIs will be covered by Underground Facilities working group

Final white papers

Transcendental Preprint
April 18, 2022

Enabling Capabilities for Infrastructure and Workforce in Electronics and ASICs

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Carl Grace, Timon Helm
LAWRENCE BERKELEY NATIONAL LABORATORY
Angelo Dragone, Ryan Herbst, Lorenzo Rota
SLAC NATIONAL ACCELERATOR LABORATORY
Gabriella Carini, Grzegorz Deptuch
BROOKHAVEN NATIONAL LABORATORY
Mitch Newcomer
UNIVERSITY OF PENNSYLVANIA
Kevin Flood
NALU SCIENTIFIC LLC

ABSTRACT

The impressive progress in data rate capabilities, pattern recognition, and spatial resolution of current detectors in experimental particle physics has been possible thanks to the availability of sophisticated analog and digital signal processors implemented in custom made front end application specific integrated circuits (ASICs). The performance requirements and increasingly smaller feature size chosen for these devices pose significant challenges to the designers. In order to meet these demands, we need to educate and retain a skilled work force, as well as aggregate and disseminate design tools and acquired knowledge. We propose a multifaceted initiative to ensure that these needs are met.

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

arXiv:2204.07285v1 [physics.ins-det] 15 Apr 2022

April 4, 2022

Readout for Calorimetry at Future Colliders: A Snowmass 2021 White Paper

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JULIA GONSKI, COLUMBIA UNIVERSITY
JAMES HIRSCHAUER, FERMI NATIONAL LABORATORY
JAMES HOFF, FERMI NATIONAL LABORATORY
GABRIEL MATOS, COLUMBIA UNIVERSITY
JOHN PARSONS, COLUMBIA UNIVERSITY

ABSTRACT

Calorimeters will provide critical measurements at future collider detectors. As the traditional challenge of high dynamic range, high precision, and high read-out rates for signal amplitudes is compounded by increasing granularity and precision timing the readout systems will become increasingly complex. This white paper reviews the challenges and opportunities in calorimeter readout at future collider detectors.

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

1 Introduction

Nearly all particle detectors foreseen at future colliders, from detectors at the High Luminosity Large Hadron Collider (HL-LHC) currently under construction, to potential future circular and linear colliders, include some aspect of particle calorimetry. The need is clear. Calorimeters are the primary detectors used to measure the energy of neutral particles produced in collisions, and also provide an important measurement of charged particle energies, in addition to measurements of particle position and timing. Calorimeters are often split between two sections, an electromagnetic calorimeter (ECAL) in the front, followed by a

arXiv:2204.00098v1 [physics.ins-det] 31 Mar 2022

Final white papers

arXiv:2204.00149v1 [physics.ins-det] 1 Apr 2022

Electronics for Fast Timing

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March 31, 2022

ABSTRACT

Picosecond-level timing will be an important component of the next generation of particle physics detectors. The ability to add a 4th dimension to our measurements will help address the increasing complexity of events at hadron colliders and provide new tools for precise tracking and calorimetry for all experiments. Detectors are described in detail on other whitepapers. In this note, we address challenges in electronics design for the new generations of fast timing detectors.

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

1 Introduction

Time resolution in particle physics has steadily advanced from microseconds in the 1950s to nanoseconds in the 60s to picoseconds today. This progression has allowed our detectors to utilize the steady increase in instantaneous luminosity in colliders. This has provided

Transcendental Preprint
March 30, 2022

Fast (optical) Links

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ABSTRACT

In this write-up we focus on fast data links that read out particle detectors. This includes developments of ASICs, optical modules, identifying passive components such as fiber and connector, and a link system design. A review of the current status is provided. The goal of R&D is to double (near term) and quadruple (longer term) the present data transmission rate for particle detectors, enabling a wide range of physics exploration and measurements.

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

1 Introduction and Current Status

The past-decade has seen tremendous advances in particle detector developments, exemplified in pixel sensors [1], high-granularity calorimeters [2] and time (of arrival) detectors [3, 4] for MIPs in a jet. R&D efforts are also seen in dedicated sensor readout ASICs [5, 6], on-detector readout electronics and data transmission to off-detector processing units [7]. In data transmission we have progressed from tens of mega-bits per second (Mbps) per channel to the present 10 Gbps per channel, and migrated from mainly coaxial-cable based transmission medium to optical fibers. At the beginning of the LHC experiments optical link systems were constructed using custom components, COTS (commercial off the shelf) ICs (example: the G-Link chip-set [8]) that are tested to be radiation tolerant, and ASICs developed by CERN (example: the GOL serializer [9]). The transmission speeds range from 80 Mbps to 1.6 Gbps per fiber. With the increase of requirements in data rate and radiation tolerance, and the limit on power dissipation, ASICs become the only choice in constructing the on-detector side of the optical links with a data rate about 5 Gbps [10] per fiber for the Phase-I

arXiv:2203.15062v1 [physics.ins-det] 28 Mar 2022

Final white papers

arXiv:2204.13223v1 [physics.ins-det] 27 Apr 2022

Transcendental Preprint
April 29, 2022

Smart sensors using artificial intelligence for on-detector electronics and ASICs

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ABSTRACT

Cutting edge detectors push sensing technology by further improving spatial and temporal resolution, increasing detector area and volume, and generally reducing backgrounds and noise. This has led to a explosion of more and more data being generated in next-generation experiments. Therefore, the need for near-sensor, at the data source, processing with more powerful algorithms is becoming increasingly important to more efficiently capture the right experimental data, reduce downstream system complexity, and enable faster and lower-power feedback loops. In this paper, we discuss the motivations and potential applications for on-detector AI. Furthermore, the unique requirements of particle physics can uniquely drive the development of novel AI hardware and design tools. We describe existing modern work for particle physics in this area. Finally, we outline a number of areas of opportunity where we can advance machine learning techniques, codesign workflows, and future microelectronics technologies which will accelerate design, performance, and implementations for next generation experiments.

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

RF Electronics

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ABSTRACT

For many decades High Energy Physics (HEP) instrumentation has been concentrated on detectors of ionizing radiation – where the energy of incident particles or photons is sufficient to create mobile charge in gas, liquid, or solid material, which can be processed by front end electronics (FEE) to provide information about the position, energy, and timing of the incoming radiation. However, recently-proposed HEP experiments need to sense or control EM radiation in the radiofrequency (RF) range, where ionization detectors are unavailable. These experiments can take advantage of emerging microelectronics developments fostered by the explosive growth of wireless data communications in the commercial sector.

Moore's Law advances in semiconductor technology have brought about the recent development of advanced microelectronic components with groundbreaking levels of analog-digital integration and processing speed. In particular, RF "System-on-Chip" (RFSoc) platforms offer multiple data converter interfaces to the analog world (ADCs and DACs) having bandwidths approaching 10 GHz and abundant digital signal processing resources on the same silicon die. Such devices eliminate the complex PC board interfaces that have long been used to couple discrete ADCs and DACs to FPGA processors, thus radically reducing power consumption, impedance mismatch, and footprint area, while allowing analog preconditioning circuits to be eliminated in favor of digital signal processing. Costed for wide deployment, these devices are helping to accelerate the trend towards "software defined radio" in several high-volume commercial markets. In this whitepaper we highlight some HEP applications where leading-edge RF microelectronics can be a key enabler.

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

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Final white papers



Transcendental Preprint
May 19, 2022

Cryogenics Readout

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ABSTRACT

A benefit of integrated electronics is to relocate the first stages of signal processing or control as close as possible to the sources, where these signals arise, or, correspondingly, where controls are suitably needed. This implies, that for sensors that require operation at cryogenic temperatures, this integrated electronics must also be ready for cryogenic. Transferring the operating temperature of integrated circuits from temperatures for commercial applications, for which process design kits contain trustably characterized model parameters, is not evident and the difficulties increase as the temperature decreases. Luckily MOSFETs operate all the way down to even subkelvin temperatures, HBTs keep pace with them. However, in the work of active elements, new phenomena are revealed, such as the dominance of tunnel conduction, freezing of carriers, or increased susceptibility to damage by hot carriers, etc. Designing integrated circuits for operation at cryogenic temperatures requires increased efforts. However, in applications such as reading out noble liquid TPCs, mating with sensors whose operation is based on quantum phenomena, qubit control, or reaching for other manifestations of interaction of radiation with matter, e.g. phonon detection, put cryogenic readouts in the center point of interest. The ongoing efforts and opening on new avenues for the cryogenics readout are discussed.

Final remarks



Our CPAD community discussion concluded that there was movement towards direct support for instrumentation and, in fact, two FOA's from DOE appeared in the Spring that included some wording from the 2019 BRN Instrumentation report

- *Microelectronics Co-Design Research* LAB opportunity
- *Traineeship in High Energy Physics* University Program
- We have participated in discussions with ASIC foundry representatives to explore opportunities for multi-party NDA's
 - Notably: *Skywater & TSMC*
- DOE-led effort for EDA tools
- We expect to continue to pursue opportunities through the HEPIC and follow the progress of the 3 funded Traineeship programs

Thank you!

