Snowmass 2021 Letter of Interest:

High-speed Instrumentation for Data Acquisition and Processing

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Thematic Areas:

- IF4: Trigger and DAQ
- IF7: Electronics/ASICs

Abstract:

Future high-energy and nuclear physics detectors will generate ever-increasing amounts of data, typically collected in extreme environments and at very high data rates, which will require both significant R&D to advance current DAQ solutions as well as the development of new technologies and paradigms. To optimally leverage these huge physics datasets, DAQ solutions which in the past were typically implemented in successive layers of interconnected PCBs populated by many different types of dedicated chips will need to subsume much of this functionality into a single ASIC capable of onboard feature extraction and data reduction while meeting demanding technical specifications such as e.g. low-power, low-mass, small footprint, fast timing, radiation hardness, etc. Similarly, triggering solutions optimized for such advanced DAQ will require the ability to deploy powerful inferential ML/AI algorithms in hardware at or in close proximity to detector front-end electronics.

The “DOE Basic Research Needs (BRN) Study on Instrumentation”[1] presented to HEPAP in July 2020 identified 26 different Priority Research Directions (PRDs) required to advance the science of high-energy physics. These PRDs were defined through a community process that:

- Initially considered the particular technical requirements needed to enable discovery physics in several disparate areas of HEP, such as e.g. LHC/Higgs, DUNE/neutrinos, Dark energy & Inflation/Cosmic, as well as in nuclear physics experiments such as those that will be realized at the recently approved Electron-Ion Collider; and then

- Subsequently identified the many different technologies which will be needed to ultimately enable physicists and staff at universities and labs, along with industry partners, to meet the technical demands of experiments with transformative and cost-effective technical solutions.

In particular, PRDs 16 and 17 addressed the need to develop high-speed ASICs for data acquisition and processing to meet the demanding needs of current and upcoming HEP experiments, while PRDs 21-23 were directed at developments which will be required in trigger and DAQ applications to address HEP’s main science drivers:

- PRD 16: Evaluate process technology and develop models for ASICs in extreme environments;

- PRD 17: Create building blocks for Systems-on-Chip for extreme environments;

- PRD 21: Achieve on-detector real-time, continuous data processing and transmission to reach the exascale;

- Develop technologies for autonomous detector systems; and

- Develop timing distribution with picosecond synchronization.

The conclusion of the HEP Instrumentation BRN study neatly dovetailed with the Snowmass 2021 process and the BRN panel concluded their report to HEPAP by *“encourag[ing] the particle physics community to build on the research plans presented in this BRN study by developing and refining them further and introducing and developing new instrumentation ideas during Snowmass 2021.”*

The TDAQ technology panel, in particular, identified several common themes across the breadth of HEP and also noted cross-cuts among these into areas outside of HEP:[2]

- Moving (traditionally) software-based processing into front-end hardware;

- Integrating sensor and readout/processing technology;

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[1] https://science.osti.gov/-/media/hep/hepap/pdf/202007/11-Fleming_Shipsey-Basic_Research_Needs_Study_on_HEP_Detector_Research_and_Development.pdf
[2] https://agenda.hep.wisc.edu/event/1430/contribution/0

- Implementing real-time ML/AI with hardware acceleration;

- Parallelization through new technologies/architectures;

Nalu Scientific LLC (NSL) was formed in 2016 specifically to develop ASICs and supporting technologies to address many of the technical challenges outlined above. Starting from design and evaluation of System-on-Chip (SoC) waveform sampling data acquisition front-end ASICs through Phase I DOE SBIR projects in 2016 and 2017 (in collaboration with Prof. Gary Varner, University of Hawaii). NSL has raised over $10M in grants and contracts for a variety of synergistic SoC projects and has continued to refine and develop SoC ASICs. NSL was recently awarded a FY20 Phase IIA SBIR and over the next two-year period of the award, it will continue development of an SoC ASIC in conjunction with university, national lab and industry partners which will have the following capabilities:

- Full-waveform sampling with self-triggering capability at 10-15 GSa/s;
- Management of complex multi-hit scenarios without user intervention;
- High background rejection via in-situ triggering and waveform discrimination;
- Compact design for high spatial resolution;
- Feature extraction for data compression;
- Self-test and self-calibration ;
- Timing resolution of 5 ps or less;
- Architectural mechanisms to reduce radiation impact;
- Long trigger buffering (3-5 microseconds);
- Low-cost standard commercial CMOS fabrication process.

Beyond the above, the next few years of development will include select improvements to meet additional TDAQ technical drivers of HEP and NP physics, such as e.g. early zero-suppression mechanisms based on feature extraction, deadtime reduction through pre-triggered smart event tagging, support for streaming modes, and development of an ML/AI integrated development environment to support hardware-based on- or near-detector ML/AI inference (e.g. TensorFlow->TensorFlowLite->Edge devices). Ultimately, such inferential devices will allow high-speed, high-throughput image analysis of detector data which has not yet been processed by high-level reconstruction software into physics objects.

The development of modularized ASIC and inferential technologies to implement a broad array of DAQ solutions meeting the several PRD and technical goals stated above has the promise of being transformative not just for HEP and NP but also for a diverse cross-section of industries including, e.g., autonomous vehicles, fusion energy, time-of-flight positron emission tomography (PET-TOF), along with many others. We welcome new opportunities to join with scientists and staff at universities and national laboratories, as well as industry partners, to define, pursue and overcome the technical challenges which the effective, and cost-effective, pursuit of next-generation discovery physics will entail.