SMART-ReAD: AI-driven detector readout for physics experiments

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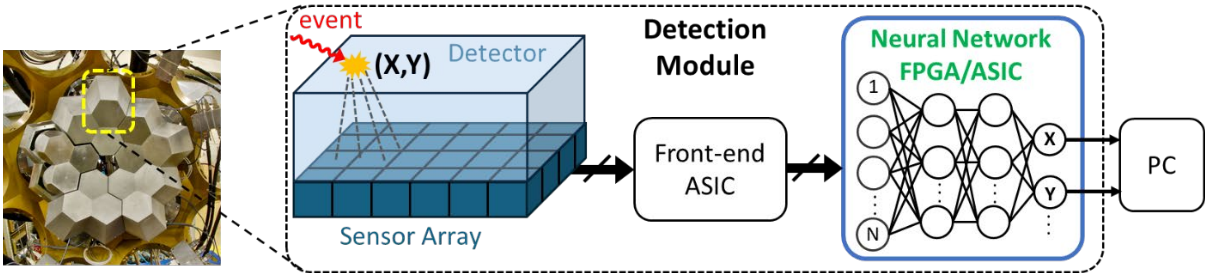
1. Research objectives



Scope of this project is the development of an electronics platform to implement an embedded processing of detector signals by means of AI techniques and its deployment in physics experiments infrastructures. The proposal starts from the experience gained by the proposing team in the framework of processing the detector signals by means of AI algorithms, in particular Machine Learning (ML), such as, for example, Neural Networks (NNs) and Decision Trees (DTs). Such processing can be used to extract, at the very early stage of the data processing chain, relevant features of the event (position, energy, timing), with implementation very close to the detector and Front-End electronics. This approach would allow to simplify the event processing and to reduce the computational resources, compared to a more traditional extraction of all the detector signals and full event processing by external computational units. The use of FPGA and, more recently, custom ML-ASICs allows to embed the event processing close to or even integrated to the detector module. In the proposing team, we have already explored the possibility to process events, in particular generated in scintillators readout by SiPMs and in LGAD silicon detectors, using NN and DT for the extraction of the position of interaction of the event [1,2,3]. More recently, the full ML processing has been integrated in FPGAs. Moreover, in the last three years, we have been developing an ASIC (ANNA: Analog Neural Network ASIC) where the NN adopted to reconstruct the center of gravity of the event in a pixelated detector is implemented with an analog integrated circuit [4]. This ASIC directly processes the analog detector signals, with the advantage to avoid the use of ADCs and digital processing, as in the case of digital accelerators AI platforms, targeting an improvement of the energy efficiency (n.operations/s/W) [5].

The main detector types addressed by this proposal are semiconductor detectors in which charge sharing among different pixels is used to estimate the position of interaction of charged particles. A demonstrator will be built using RSD silicon sensors, which exploit signal sharing to achieve excellent spatial resolution even with large pixels [3]. In recent studies, a resolution of about 20 μm has been measured for a 500 μm pixel pitch—approximately 4% of the pitch. Compared to traditional silicon detectors, RSD reduce the number of electrodes by about a factor of 100, ideal for very low-power low-material applications. Since one hit generates signals on multiple electrodes (typically 4–8), NN techniques can be used to reconstruct the hit position from the measured signals. For this reason, the combination of RSD sensors with the ANNA ASIC is of particular interest. We plan to develop matrices of RSD sensors and connect them to ANNA ASICs using custom-designed interposers with the final aim to build a small tracker demonstrator as first proof-of-concept for a new type of very low-power tracker.

The electronic platform could also be used for other detector technologies, e.g. high-Z semiconductor detectors (Ge and CdTe/CZT) and scintillator-based detectors for gamma-ray spectroscopy, imaging and for calorimetry. Particle identification is also a topic which can be suitably addressed by this development, for instance implementing an embedded, on-line PSA (Pulse Shape Analysis) of the detector signals by ML techniques.

The project plan includes validation and deployment of prototypes in infrastructures for physics experiments. The proposed approach aims to contribute to improve the efficiency of the IT infrastructures required to process the very large amount of data generated by the complex detection apparatus of hadron physics experiments, especially those based at particle accelerators. The developed platform will be conceived to work both as stand-alone unit and to be integrated in the detector systems.

The proposal aims to address the following Scientific Cases mentioned in the call for LoIs: *Short-term R&D, AI technologies, Applications and links with industry*. Furthermore, it aims to address the award criteria formulated in the work programme: .. *improve the services the infrastructures provide and to further develop their on-line services*. Although not specific target of the program, the proposed approach may have relevant outcomes also in applied physics applications, as nuclear medical imaging (e.g. PET, Range Verification in Hadron Therapy), as well as towards the development of innovative industrial instruments.

Publications

[1] T. Ferri et al., "Gamma-Ray Position-of-Interaction Estimation in a Thick Monolithic LaBr3 Detector Using Artificial Neural Networks," in IEEE Transactions on Radiation and Plasma Medical Sciences, vol. 9, no. 3, pp. 284-295, March 2025.

[2] M. Agnolin et al., "A γ-Ray Detector Based on a 3" LaBr3:Ce:Sr Crystal With SiPM Readout for 80 keV–16 MeV Energy Range With Position Sensitivity for Doppler Correction," in IEEE Transactions on Nuclear Science, vol. 70, no. 10, p. 2337, 2023.

[3] F. Siviero, et al., "Machine learning for Precise Hit Position reconstruction in resistive Silicon Detectors," in JINST, 19 C01028.

[4] S. Di Giacomo, et al., "Experimental Validation of ANNA: Analog Neural Network ASIC for Event Positioning in Monolithic Scintillation Detectors," in IEEE Transactions on Radiation and Plasma Medical Sciences, vol. 9, no. 5, pp. 542-552, May 2025.

[5] M. Ronchi, et al., "Design, Implementation, and Analysis of an Integrated Switched Capacitor Analog Neuron for Edge Computing AI Accelerators," in IEEE Transactions on Circuits and Systems I: Regular Papers.

2. Connection to Transnational Access infrastructures (TAs) and / or Virtual Access projects (VAs)

The proposing team is participating since more than 25 years in physics experiments taking place at LNF-INFN (SIDDHARTA, study of Kaonic atoms) and CERN. Moreover, the first test of position sensitivity of a large $LaBr_3$ scintillator using ML techniques, to correct for Doppler broadening, has been made at the IFIN-HH accelerator at Bucharest (Romania) [2]. The demonstrators will be validated during dedicated beam tests at CERN, LNF Frascati, LNL Legnaro, Bucharest and Krakow.

3. Estimated budget request

The budget required for the project is 445keuros, including the following costs: 4 FTEs for designers (140k), 1 FTE for detector development (35k), ASIC runs (80k), sensors production (60k), FPGAs, PCBs, components (30k), beam tests and travels (40k), Overheads (60k).

4. Participating institutions

Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria
Università degli Studi di Milano, Dipartimento di Fisica
INFN, Sezione di Milano / INFN Sezione di Torino
UPO, Università del Piemonte Orientale