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El-Pho: Electro-Photonic Integrated Platform for Near-Sensor Processing in Extreme Environments within the MEERCAT MSRC

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The El-Pho project, part of the DOE-funded MEERCAT Microelectronics Science Research Center, is developing an integrated electro-photonic platform for near-sensor processing in extreme environments encountered in High Energy Physics (HEP), Nuclear Physics (NP), photon science, and space applications. Future detectors in these domains—such as Monolithic Active Pixel Sensors (MAPS) for ultra-granular tracking and vertexing —must address rapidly increasing data volumes under strict constraints on material budget, power dissipation, and cooling. Conventional copper-based readout architectures are ill-suited to meet these demands in next-generation experiments.

El-Pho addresses this by co-designing electronic and photonic subsystems to deliver low-latency, high-bandwidth, and energy-efficient readout. Through heterogeneous 3D integration of MAPS with silicon photonics, electrical data transport from pixel arrays can be replaced or augmented with optical links using micro-ring modulators, wavelength-division multiplexing, and photonic wire-bonding. This significantly reduces cabling mass, mitigates electromagnetic interference, and improves scalability to multi-megapixel systems.

A central innovation is embedding AI/ML-enabled processing directly within the electro-photonic readout chain, with a focus on Graph Neural Networks (GNNs) for real-time charged-particle tracking and classification. GNNs are ideally suited to the sparse, irregular hit patterns produced by tracking detectors. In El-Pho, we employ publicly available physics-based tracking datasets and representative synthetic datasets derived from experiment-like conditions, enabling rigorous benchmarking of hardware-accelerated GNN inference against realistic detector outputs. This ensures that algorithm–hardware co-design choices directly map to deployable solutions in upcoming HEP and NP experiments.

Hardware partitioning between electronic and photonic domains is guided by performance–energy trade-offs:

Photonic accelerators execute parallel, low-latency operations such as message passing and feature aggregation across graph nodes.

CMOS electronics handle local control, data conditioning, and dynamic resource allocation.
This hybrid approach maximizes throughput per watt while preserving flexibility to adapt to diverse detector geometries and topologies.

The platform also incorporates event-selective data handling to avoid idle bandwidth use, further improving energy efficiency without constraining architectural choices to a single readout protocol. By tightly coupling sensing, optical data movement, and intelligent processing, El-Pho reduces the data burden on downstream DAQ, simplifies infrastructure, and improves robustness in high-rate, high-radiation environments.

The project's development pipeline integrates:

Electro-Photonic Detector Units —vertically integrated, pixelated detectors with direct optical readout.

Mixed photonic-electronic DAQ —optimized for modular scaling and bandwidth adaptation.

AI/ML co-design —driven by standardized datasets and reproducible benchmarking workflows to ensure portability of solutions across experiments.

By merging advanced MAPS technology, integrated photonics, and embedded intelligence, El-Pho offers a holistic near-sensor processing platform that minimizes power and mass, accelerates pattern recognition, and enables new detector concepts for DOE-mission-aligned science. Its scalable architecture also opens a pathway for industrial adoption in domains where high data rates and constrained form factors demand both performance and efficiency.

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