FY27 NPP LDRD Type B Pre-Proposal

Research & Development of a Hybrid Digital–Analog Computing Framework for Advanced Artificial Intelligence Methods

Wen Guan (NPPS) • Meifeng Lin (CDS)

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Proposal title:

- Research & Development of a Hybrid Digital–Analog Computing Framework for Advanced Artificial Intelligence Methods

Primary Investigator:

- Wen Guan (NPPS)

Other Investigators:

- Meifeng Lin (CDS)

Cross-directorate proposal:

- Yes [X] No [ ] (NPPS + CDS)

Other directorates/organizations:

- Computational Data Science (CDS) Directorate

Proposal Term:

- From: 10/1/2026 To: 9/30/2028 (FY27–FY28)

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Proposal title and brief abstract:

Research & Development of a Hybrid Digital–Analog Computing Framework for Advanced AI Methods

Hybrid digital–analog computing promises significant gains in performance and parallelism, but effective strategies for mitigating noise and hardware non-idealities—especially at scale—remain unclear. This project will investigate noise-aware learning methods, hybrid digital–analog training strategies, and scalable approaches to reducing the impact of analog noise. To support this research, the project will develop a software framework that integrates emerging analog simulators and accelerators into scientific AI workflows with reproducible and quantitatively characterized error behavior.

Program:

Multiprogram (cross-cutting AI & computing aligned with NP/HEP/ASCR needs)

Return on Investment:

Follow-on proposals in hardware–software co-design, efficient AI, and scaling research.

Reusable stack to evaluate future accelerator options and partner with vendors/centers.

Broader impact on laboratory activities:

Accelerates adoption of heterogeneous compute for BNL science workflows (CPU/Analog).

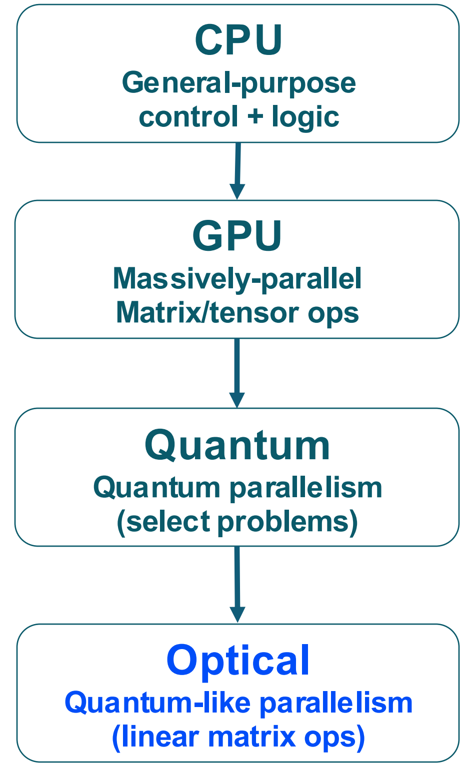
Builds internal capability for benchmarking, validation, and integration of novel accelerators.

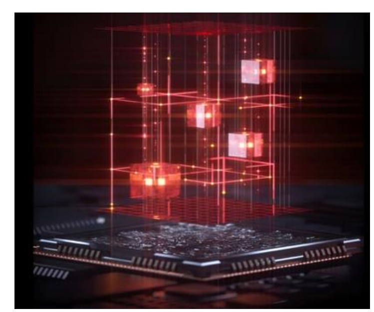
Fiscal Year	Planned Funding	Notes
FY27	220k	Method study and framework dev
FY28	220k	Scale-up + integration + dissemination

Description of the LDRD (1/3): Motivation

Motivation

- AI progress requires rapidly growing compute (e.g., LLM training at multi-million GPU-hour scale).
- New technologies
  - Quantum computing
    - Quantum parallelism and entanglement
    - Remain challenging:
      - Noise and error accumulation
      - Degree of freedom: entanglement reduces local freedom
  - Analog Computing (especially optical computing)
    - Energy efficiency
    - Quantum-like parallelism
    - Extremely good at matrix operations (to replace GPU)
    - Nonlinearities are hard
    - Hybrid is the realistic future
      - Optical (linear, fast, parallel) + electronic (nonlinear, control, memory)
    - challenges:
      - Noise, error accumulation
    - Optical computing R&D has progressed rapidly in recent years





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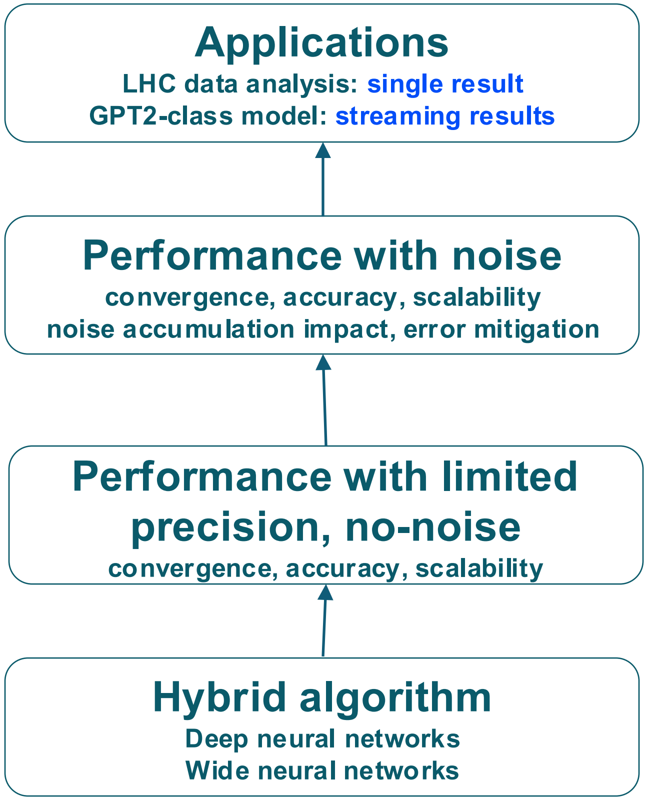
Description of the LDRD (2/3): R&D

Research Objectives

- Analyze ML algorithms under limited-precision analog computing
- Quantify the effects of analog noise and hardware non-idealities on training dynamics, convergence behavior, inference accuracy, and scalability limits.
- Develop principled, hardware-aware training and error-mitigation methods
- Explore noise-robust and scalable neural network architectures, including novel designs that **mitigate noise accumulation during scaling**, as well as hybrid digital–analog optimization and mixed-precision training strategies.
- Establish the feasibility, performance envelope, and fundamental limits of analog and hybrid computing for scientific workloads and large language model (LLM) applications.

Technical Approach

- **Project Objective:** Enable a systematic study of hybrid digital–analog computing by developing an integrated research framework that combines analog and optical computing concepts with machine learning workflows.
- **Evaluation:** The framework will be benchmarked on representative large-scale scientific workloads—including LHC data analysis—and on natural language processing tasks using GPT2–class models.



Description of the LDRD (3/3): Deliverable

Deliverable:

- Quantitative characterization of analog computing with limited precision and accumulated noise
- Validated mitigation strategies and hybrid training workflows
- Extensible research framework for analog AI
- Scalable methods for analog AI
- Publications and proposal-ready results

Fiscal Year	
FY27 Q1-Q2	Develop hybrid algorithms integrating diverse optical computing simulators and IBM electrical analog computing hardware (no optical hardware), and representative LHC workload development
FY27 Q3-Q4	Conduct performance evaluation and hybrid algorithm optimization; GPT2-class application development
FY28 Q1-Q2	Perform systematic performance evaluation and hybrid algorithm optimization under error-mitigated execution
FY28 Q3-Q4	Scalability evaluation and dissemination through publications

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Summary: Motivation, Approach & Deliverables

Motivation	R&D	Key deliverable
• Advancing technology demands new computing paradigms • Quantum computing remains challenging • Optical computing offers quantum-like parallelism, well suited for matrix ops • Optical computing has advanced rapidly in recent years, making it a promising near-term alternative	• Hybrid framework with optimized algorithms for analog AI • Quantify the impact of precision limitation and noise • Explore error-mitigation methods on scale • Demonstrate on representative scientific AI workflows.	• quantitative characterization of analog computing with limited precision and accumulated noise • Error mitigation and hybrid training workflows • Extensible framework and scalable methods for analog AI • Publications and proposal-ready results

Personnel	Risks
0.5 FTE (NPPS) 0.5 FTE (CDS)	Performance for scale (new algorithm developments) GPT2-class evaluation may be still big for this project (to use a smaller but not too small model)