TOMATO (end-TO-end siMulation fAst deTectOrs): *And end-to-end simulation framework for fast detectors at the EIC*

Applicant/Institution: The University of Kansas Center for Research, Inc.

Street Address/City/State/Zip: 2385 Irving Hill Rd., Lawrence, KS 66045-7552

Principal Investigator/Contact person: Daniel Tapia Takaki (jdtt@ku.edu)

Co-PIs: None

Collaborators: Alexandre Camsonne (JLab) and Dave Gaskell (JLab), Tommaso Isidori (KU) and Nicola Minafra (KU)

Address: 1082 Malott Hall, 1251 Wescoe Hall Dr.

Telephone Number: (785) 864 1272

Administrative Point of Contact: Alicia M. Reed, (785) 864 3441, kucrpropmgmt@ku.edu

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Abstract:

This project consists in developing an end-to-end simulation framework for fast detectors R&D for the Electron Ion Collider (EIC). While special emphasis will be put in R&D studies of an electron Compton polarimeter for the EIC, the proposed simulation framework is expected to simplify the design of a wide variety of fast detectors within a generic detector design. Funding is requested to support a computer science-oriented graduate student to develop the simulation framework, in close collaboration with the University of Kansas and the Jefferson Lab teams.

Project Description

This project will develop an end-to-end simulation framework to support the R&D work required for fast detectors at the Electron-Ion Collider [1, 2]. Fast detectors with good time precision are an integral part of a generic detector at the EIC: there are ongoing R&D work for Low-gain avalanche diodes (LGADs), AC-LGADs, and diamond detectors. The use of fast detectors is also needed for EIC projects like the electron Compton Polarimerer (ECP). To conduct R&D work for the fast detectors, the simulation studies need to model the detector, the particle transport, the induced current, and the transfer function of the front-end electronics. At present, these simulation tasks are done as independent separate steps when characterizing fast detector sensors. Since there are several sensor solutions for fast detectors to be tested, a simulation framework will make the characterization work, and thus the R&D studies, more effective and efficient, thus leading to detailed systematic studies of the spatial and time precisions required for the detectors. For the ECP project, the following sensors will be tested (DUTs: Devise under test): single crystal chemical vapour deposition (CVD) diamond, polycrystalline CVD diamond, 2D CVD graphitized diamond, 3D CVD graphitized diamond, 3D Silicon sensors, the calypso family of ASICs, LGADs, and AC-LGADs.

In particular, the University of Kansas (KU) team is working on the R&D of fast detectors for the ECP project. Recently, the PI has received funding from the U.S. Department of Energy (DOE), Office of Science, Nuclear Physics, Heavy-Ion Physics program to contribute to early R&D work for this project. KU CERN-based postdoctoral researcher Dr. Tommaso Isidori is working on this project at 0.5 FTE. The PI has also secured funding for material and equipment costs to carry out this preliminary work. For this R&D, the KU team is collaborating with Thomas Jefferson National Accelerator Facility (JLab) personnel: Dr. Alexandre Camsonne and Dr. Dave Gaskell (ECP project leader).

This proposed project will develop an end-to-end simulation framework that will be named TOMATO (end-TO-end siMulation fAst deTectOrs). Indeed, a robust simulation framework that includes all the necessary components will greatly facilitate the development and characterization of the various sensors. Figure 1 shows an overview of the proposed simulation framework. The following three components will be integrated into the framework:

- Step 1: The electron beam transport and detector model simulations are built using GEANT4 [3]. This C++ based toolkit provides a reliable architecture to simulate the passage of particles trough matter. GEANT4 is at the core of the EIC beamline simulation framework used to generate the electron beam distributions expected at the ECP. This toolkit will also be used to model their interaction with the DUT to characterize important features of the detectors geometry;

- Step 2: Weightfield2 [4] sensors response simulations. This open source tool, also implemented in the C++ programming language, uses the Ramo theorem to calculate the diffusion of the free carriers inside the sensors. For our simulation chain, this is used to effectively convert the energy deposit generated in the previous step into output current signals. Weightfield2 has a graphical users interface based on the ROOT interface TGUI, which allows to easily modify the sensors qualities (such as type, or doping densities) and the environment conditions.

- Step 3: Finally, the currents output by the senors are read out by a Front-End Electronic schematic that can be modeled using LTSpice [5]. This is an analog electronics simulator software based on SPICE and widely exploited in physics, as well as in industry. It uses SPICE libraries to model most of the commercially available electronics components and simulate their response to input currents. This last step is fundamental for optimizing the required detectors performance (time resolution, time integration).

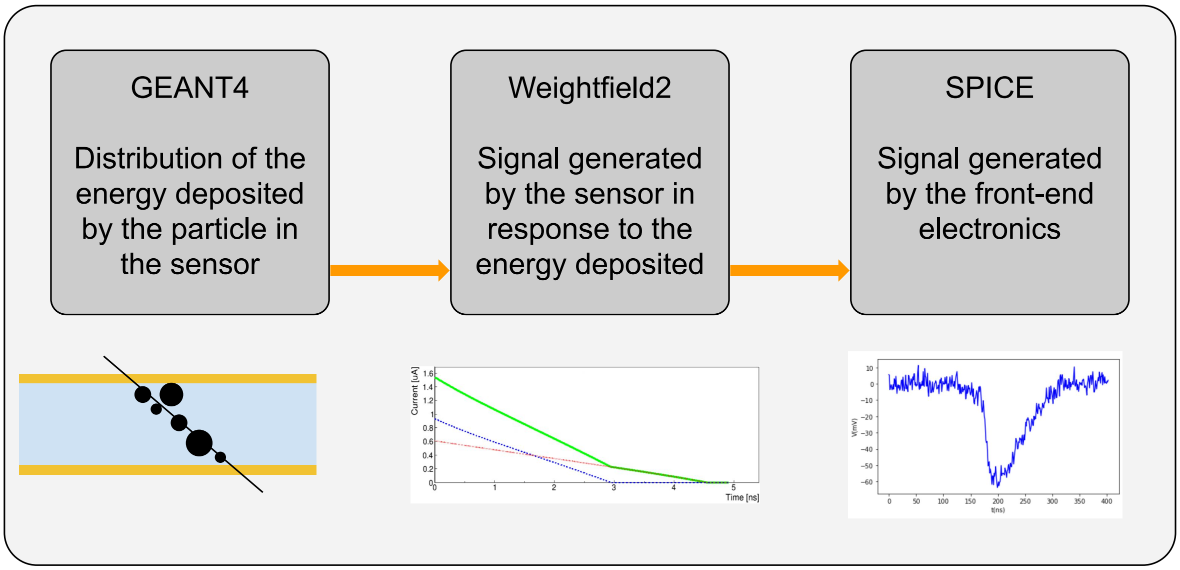

Figure 1: Diagram illustrating the three different components that will be integrated in the TOMATO end-to-end simulation framework for fast detectors.

Funding is requested for about $46,000 for a period of 12 months in the form of participant support costs. Thus, no ovearhead costs are required. The computer science–oriented student will be recruited from a pool of students that applied to PhD student programs at CERN (both from physics or technical/engineering background) or to a dedicated open call application that will be managed by the University of Kansas team. The graduate student will be based at CERN to collaborate closely with Isidori and to have close interaction with the team working on the sensors characterization. Minafra is also a CERN-based researcher. The student will be registered at CERN as a “guest” to the ALICE Collaboration to gain access to CERN premises. The KU team is a member of the ALICE Collaboration, and CERN is developing synergies with the EIC project for R&D purposes. The PI has office and research laboratory space where this work will be conducted. We expect that such a student can then be recruited to join a graduate program at the University of Kansas or at another EIC participating institution.

Milestones And Tasks For The TOMATO Project

- **Milestone 1: Development of an optimized detector model**
  1. Task 1.1: Coordinate with Isidori on the sensing technologies to be studied.
  2. Develop a simulation model to evaluate the performance of fast diamond detectors.
  3. Task 1.2: Develop a simulated model to evaluate the performance of fast silicon detectors.
  4. Task 1.3: Evaluate the most optimized read-out geometry for the sensors needed for the requirement imposed by the ECP.
  5. Task 1.4: Evaluate the performance of the sensors as a function of the collected radiation dose expected for the ECP detectors.
- **Milestone 2: Integrate the Front-End Electronics (FEE) design into the simulation framework.**
  1. Task 2.1: Coordinate with Isidori to gather the latest requirements for the development of the FEE.
  2. Task 2.2: Model the FEE response to characterize the detectors output signals.
- **Milestone 3: Benchmark testing for the user case (EPC at the EIC)**
  1. Task 3.1: Coordinate with the project leader of the ECP to gather the latest technical requirements for the generic detector.
  2. Task 3.2: Integrate the detector models in the general simulated EIC beamline environment for benchmark testing.

The proposed project will be based on the recent experience that Isidori has obtained working for the AGILE (Advanced enerGetic Ion eLectron tElescope), NASA supported project [6], during his PhD studies.

The simulation chain utilized during the AGILE studies employs the same tools referenced in this proposal. However, for AGILE the various steps of the simulations were done independently, with no continuity between the consecutive steps. As mentioned earlier, TOMATO proposes the first development of a more user friendly interface, embedding the various components of the simulation in the same, end-to-end framework. The PI has also experience in developing software. He has recently contributed to the development of nOOn, an after-burner for the generation of forward neutrons in ultra-peripheral heavy-ion collisions [7]. The PI requests funding for recruiting a computer science-oriented graduate student to develop TOMATO, exploiting the expertise developed by the KU team. This is a timely opportunity since the R&D studies for the fast detector sensors for the ECP has already started.

As per solicitation requirements, there are three budget scenarios: A) Realistic nominal budget (baseline budget). In this case, the three proposed milestones should be met. For budget scenario B) Nonimal budget minus 20%, only 9 months of support for the graduate student will be possible. In this case, the milestone 3 will not be realized. For budget scenario C) Nominal budget minus 40%, the proposed project will support only 7 months of the student's work. This implies that task 1.3 and task 1.4 of milestone 1 will not be carried out.

Case Study: The Electron Compton Polarimeter (ECP)

As the EIC design phase is currently advancing, the development of a performing technology for the quality monitoring of the electron bunch-by-bunch polarization is required for achieving the wide set of the physics program goals [2]. Among the proposed methods (Mott polarimeter, Moller scattering polarimetry), Compton polarimeters are widely regarded as the most promising option for highly energetic beams. The electron Compton polarimeter measures the asymmetry of laser photons scattered from the electron bunches.

Monitoring the longitudinal and transverse polarized bunches with less than 1% uncertainty is however challenged by the short spacing between consecutive bunches of about 9 ns, drastically increasing the particle rates on the forward detectors used for the counting of the scattered photons.

To improve the capabilities of current employed technologies [8], the PI proposes the use of fast read-out electronics [9] for the development of novel counters based on Low Gain Avalanche Diodes or upgrade the capabilities of Diamond detectors. Both technologies displayed timing precision better than 50 ps and unprecedentedly short dead-times and these radiation-hard promising solid-state devices rapidly became the technology of choice for many timing applications in high energy physics and related fields.

The KU team led by the PI relies on previous experiences in the use of both LGAD and diamonds and their employment in particle detection in high-rate facilities. Isidori has ample experience in this work. The single particle identification capabilities of a detector designed at KU have already been demonstrated and published in [10]. Additional related experience includes the test and installation of Chemical Vapor Diamond (CVD) and LGADs housed in Roman Pots for the detection of sustained rates of energetic protons, at the Large Hadron Collider [11, 12, 13]. The development of TOMATO will be carried out in parallel to the R&D work for the EIC ECP project. For reference, the detailed list of tasks, timeline and workforce assigned for the DOE funded project led by the PI are presented in Table 1.

EIC Compton Polarimeter detectors R&D milestones	
Year 1 (June 2022 - May 2023)	
month 1 - 4	Investigate the most promising detector technologies (sCVD, pCVD, 2D CVD graphitized, 3D CVD graphitized, 3D Si, LGAD)
month 5 - 8	Electronics simulations (power consumption, pulse features, etc..) and geometrical simulations (rate, occupancy, segmentation)
month 9 - 12	Sensors (for prototype) production, quality control, and radiation hardness test campaigns (publish irradiation results)
Year 2 (June 2023 - May 2024)	
month 1 - 3	Design and development of the analog Front End Electronic prototype
month 4 - 6	First prototype production with reduced number of channels
month 7 - 10	Lab test for quality control and comparison with simulations
month 8 - 12	Test beam (publish hardware results)
Year 3 (June 2024 - May 2025)	
month 1 - 4	Start the design of the digital part of the read-out (fast discrimination and data digitization of FPGA)
month 5 - 8	Production of read-out prototype (reduce number of channels) and lab test
month 9 - 12	Full chain test (lab test, test beam)

Table 1: Detailed milestones for the R&D studies for the ECP R&D sensor characterization project.

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Budget And Budget Justification

A total budget of 46,423 USD is requested for a period of 12 months. The student will be supervised by the PI, and will work closely with KU CERN-based postdoctoral researcher Isidori. While the student will be recruited via an open application process, priority will be given to applicants that are studying at an institution with an interest to join the project. Thus, the engagement of new institutions in the EIC ECP project can be promoted.

A. Senior Personnel

None

B. Other Personnel

None

C. Fringe Benefits

None

E. Travel

None. We anticipate that travel to/from CERN will be provided by the student's institution.

G. Other Direct Costs

Participant support costs. The PI requests an allowance for a graduate student for a period of 12 months. Such an allowance will support only subsistence costs (lodging and meals) and a comprehensive health insurance that include insurance for accident and disability. Since the graduate student will be based at CERN, the requested allowance is the same as that offered by the official CERN program for CERN-paid graduate students, which is 3,719 Swiss Francs (CHF) per month. This is also consistent with the guidelines established by the General Services Administration (GSA).

- **Realistic nominal budget (baseline budget)**: 46,423 USD
  12 months of support for a graduate student at 3,719 CHF / month
- **Nominal budget minus 20%**: 34,817 USD
  9 months of support for a graduate student. Tasks 1.3 and 1.4 will not be realized.
- **Nominal budget minus 40%**: 27,080 USD
  7 months of support for a graduate student. Tasks 1.3, 1.4 and 3.1 and 3.2 will be not be realized.

H. Indirect Costs

None

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