Precise central silicon tracking and calorimetry with integrated parallel and continuous readout for an EIC detector

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Abstract

Our interests in support of the realization of an EIC detector include development and production of central electromagnetic and hadronic calorimetry and large area, multi-layer silicon (MAPS and/ or LGAD) tracking detectors including all mechanical support structures, cooling and power, coupled to an integrated continuous readout system featuring on-the-fly data processing, using a full systems

engineering approach and professional project management. Such an integrated systems management approach is essential to achieve an optimized experiment-wide, common back-end, continuous readout system to significantly improve performance and reliability, while reducing overall integrated costs. The silicon tracking subsystem provides micro vertex location, timing resolution, and momentum resolution over the full momentum range consistent with the Yellow Report and will include all interfaces needed for central PID subsystems, which are not directly included in this EOI. Likewise, the electromagnetic and hadronic calorimetry meet the requirements of the Yellow Report concerning resolution and electron/photon discrimination. Our Consortium has a demonstrated track record spanning several decades realizing such tracking and calorimetric subsystems in large existing and previous ONP experiments at the AGS, CERN SPS, RHIC, and the LHC.

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2 Institutions

- Oak Ridge National Laboratory
- Florida State University
- University of Tennessee
- Vanderbilt University
- Wayne State University

3 Narrative

The Electron Ion Collider (EIC) will explore new frontiers in quantum chromodynamics to investigate gluon dynamics over a broad kinematic range including the saturated gluon density regime and emergent properties of the nucleon and hadronic matter. The physics case is extensively presented in the EIC Whitepaper[1]. The EIC[2] is now the highest priority new user facility construction project according to the 2015 NSAC Long Range Plan. The site selected for the facility is Brookhaven National Laboratory.

The technological ideas presented in this Expression of Interest follow directly from the underlying EIC physics motivations and are completely consistent with the Detector Requirements identified in the EIC Yellow Report[3].

The EIC detector requirements present technical challenges requiring state-of-the-art solutions. These requirements include hermetic 4π detector coverage, excellent spatial resolution for tracking and secondary vertex detection, excellent momentum resolution, excellent particle identification with 3 to 4 σ K-pi separation (up to 50 GeV/c in the forward region), and a very low material budget. Restricting our attention to the central region, these performance requirements are widely recognized to include, at a minimum, the necessity of a multi-layer silicon detector system with high channel count for both precise primary and secondary vertexing and tracking, very low power and low cost per channel, and both electromagnetic and hadronic calorimetry. The large channel count and need to avoid trigger biases require a continuous readout scheme with on-the-fly processing and data reduction. In our expression of interest, the requirements are met by a multi-layer, hermetic silicon detector system including, among present actively considered technologies, new generation Monolithic Active Pixel Sensors (MAPS) similar to those under development for ALICE ITS-3 for high spatial resolution tracking including the inner vertex trackers, and Low Gain Avalanche Diode (LGAD) layer(s) to provide both tracking and particle ID via ultra-fast silicon time of flight. Research and development of MAPS sensors is, as noted, part of the development for the planned upgrade of the Inner Tracking System (ITS-3) of the ALICE Experiment, in which some of our Consortium members currently participate. (ORNL played a leading role in the MAPS-based ITS upgrade, ITS-2, for LHC Run 3.) R&D for LGAD sensors is part of the development for the CERN CMS Endcap Timing Layer in which we intend to participate, and in general for experiments at the high luminosity CERN LHC.

For central electromagnetic calorimetry, we consider silicon pixel-tungsten, a technology for which we have experience, which allows very high spatial shower reconstruction with correspondingly excellent electron/ photon/ neutral-pion discrimination. Alternatively, we consider tungsten powder and/or machinable tungsten alloy as absorber material combined with scintillating fibers as the active medium. This latter approach is presently less costly, but R&D on the silicon tungsten approach is needed to fully understand the cost/benefit of potentially using common sensors and readout in electromagnetic calorimetry and tracking. The sampling hadron calorimeter will use steel absorbers, doubling as the magnetic flux return, and low cost scintillator with tile-fiber readout with good spatial resolution.

The far-forward detector system is also of interest and a system for which we have relevant experience. Current development of the EIC Zero-Degree Calorimeter (ZDC) is based on technologies proposed for the ALICE FoCal Si-W tracking calorimeter, for which we play a leading role in the development. We are a collaborating institute for the EIC Far-Forward Detector EoI cross-referenced in Section 10 below.

Beyond the very front-end topology and sensor readout, the back end of the readout and data acquisition chain can be common across subsystems for a given detector. Our Consortium proposes an integrated systems management approach for the complete suite of silicon detectors and other compatible subsystems to provide an optimized experiment-wide common back-end continuous readout system. Such an integrated systems-level approach will improve performance and reliability, while reducing overall integrated costs. Our national laboratory-scale resources and experience have a demonstrated track record of delivering such large state-of-the-art nuclear physics detectors and associated readout systems required for this endeavor.

In addition to hardware and readout components, the software and computing needs for the EIC will present new challenges. Solutions for these challenges will include continuous readout, common software, federated and accelerated computing, and machine learning. Ongoing research related to these and other computing considerations are required for the long term success of the project. Our available national laboratory expertise and resources will contribute to addressing unique computational challenges that the EIC project will face.

4 Items of interest for potential equipment cooperation

The items of potential equipment cooperation include the effort to design, develop, and deliver the multilayer, hermetic central silicon detector system, central electromagnetic and hadronic calorimetry, including the continuous readout system and associated ASIC design, production, and testing; firmware and software; mechanical support structures and alignment systems; power and cooling systems; slow controls and calibration instrumentation and software; and overall professional Project Management, Project Controls and ES&H teams. All of these contributions leverage our substantial recent R&D and design and construction experience in similar activities at the AGS, SPS, LHC and RHIC.

Our Consortium is also interested in collaborating broadly with the EIC Software Consortium in addressing several software and computing challenges for the EIC. Ongoing activities include common software development with the ACTS (A Common Tracking Software) track reconstruction package[4] and accelerated Celeritas particle transport[5] for detector simulation of physics events. Machine learning will play an important role in EIC computing and ORNL already has significant expertise in ML applications in ALICE that we would apply at the EIC. Also, there is interest in R&D for accelerating Monte Carlo event generation and detector simulations to take advantage of leadership computing facilities. Available federated computing facilities can contribute to offline data processing, which we have already demonstrated with the ALICE Experiment.

5 Potential contributions for each item of interest

The average level of effort from our Consortium for the silicon tracking and calorimetry systems, associated readout electronics, and all the associated scope described in Section 4 above, averaged over 5 years, is shown in Table 1. Additional collaborators are welcome. Funding for the research staff and postdocs is assumed to be from continuing ONP research funds.

The full scope of work is not certain at this very preliminary pre-conceptual design phase and therefore the required labor resources are similarly uncertain. We continue to seek additional collaborators, but for the present, we associate the full scope of work with Consortium member institutes with ORNL supplying the bulk of the engineering and technical workforce as needed.

INSTITUTION	Professor	Research Professor	Staff Scientist	Postdoc	Graduate Student	Undergraduate Student	Engineer	Designer	Technician	Total Sum
ORNL	0	0	5.7	2.0	0.7	0	2.7	0.6	1.2	12.9
FLORIDA STATE	0	0.5	0	0	0	0	0	0	0	0.5
U. TENNESSEE	0.6	0	0	0.7	0.5	0	0	0	0.2	2.0
VANDERBILT U.	0.2	0.5	0	1.0	2.0	2.0	0	0	0.2	5.9
WAYNE STATE U.	1.0	0	0	1.0	2.0	2.0	0	0	2.0	8.0

Table 1. Anticipated time commitment of members of each institute for the EIC efforts described in this EoI. The values represent the average annual fractional full time equivalent (FTE) for each category, averaged over FY22 through FY27.

6 Assumptions about items of interest coming from EIC Project or other labs

The full costs for engineering labor and hours for matrixed technicians discussed in Section 7 would rely on funds from the EIC Project.

7 Labor Contributions for Experimental Equipment Activities

As shown in Table 1, the anticipated collaborative effort of ORNL to cooperate on the EIC Project is to include (on an annual basis during the indicated period) 5.7 full-time equivalent FTEs of research staff, 2.0 FTE of postdoctoral researchers, and 0.7 FTE of Ph.D. students. As indicated in Section 5, the preceding contributed effort does not require Project funds. The ORNL technical collaborative effort available, given appropriate project support, is estimated, for the scope in this EOI, to include up to 6.0 FTE-years total of senior electronics engineers, 3.0 FTE-years of electronic designer, 3.0 FTE-years of electronics technicians, 4.0 FTE-years of mechanical engineers, 3.0 FTE-years of mechanical technicians, 1.0 FTE-years of computer engineers, and 2.5 FTE-years of a project engineer, plus project controls and project management. As indicated in Section 6, this technical effort assumes Project support.

It is anticipated that the collaborative effort of Florida State Univ. to cooperate on the EIC Project, contributed without requiring Project funds, is to include (on an annual basis) 0.5 FTE of a research professor.

The anticipated collaborative effort of the Univ. Tennessee to cooperate on the EIC Project, contributed without requiring Project funds, is to include (on an annual basis) 0.6 FTE of a physics professor, 0.7 FTE of a postdoc, 0.5 FTE of a graduate student, and 0.2 FTE of a mechanical technician.

It is anticipated that the collaborative effort of Vanderbilt Univ. to cooperate on the EIC Project, contributed without requiring Project funds, is to include (on an annual basis) 0.7 FTE in senior personnel shared among 2 professors and one research professor, 1.0 FTE of postdoctoral fellow, 2.0 FTEs of graduate student work shared among 6 graduate students, and 2.0 FTEs of undergraduate researchers with research projects during the academic year and full time in the summer. Vanderbilt would also provide 0.2 FTE of a machine shop technician.

It is anticipated that the collaborative effort of Wayne State Univ. to cooperate on the EIC Project, contributed without requiring Project funds, is to include (on an annual basis) 1.0 FTE in senior personnel shared among three professors, 1.0 FTE of a postdoctoral fellow, 2.0 FTEs of graduate students, and 2.0 FTEs of undergraduates. The Physics Building at WSU has its own machine shop including several large Fadal CNC machines and thousands of square feet of available laboratory space including a 500 ft^2 clean room and overhead cranes. Wayne State Univ. successfully collaborated with UTK/ORNL on the ALICE Barrel Tracker Upgrade project, and is presently participating in the sPHENIX TPC construction which will conclude in mid-2021.

We anticipate the duration of this collaborative effort to cooperate on the EIC Project to start at the design phase and to be for a minimum period of five years.

8 Timing Constraints

Some members of our team have obligations on other experiments (ALICE, sPHENIX, CMS), but the timing of those obligations has been considered in the labor estimates provided above and will not constrain the work proposed here. The FTEs listed in Table 1 represent an average level of effort over the indicated period as obligations elsewhere ramp down and effort towards the EIC ramps up.

9 Other Information

ORNL has extensive experience and extensive resources relevant for the work described in this Expression of Interest. This includes decades of experience developing advanced detector and readout systems for major experiments in the field (multiple STAR and PHENIX subsystems, ALICE EMCal, TPC and ITS, sPHENIX MVTX), as well as complex online processing (ALICE HLT and O2 facilities). We have significant resources needed for the development and integration of silicon vertex/tracking and calorimeter subsystems, advanced continuous readout with on-the-fly data processing, integrated full-systems engineering, professional project management, and leadership-scale advanced computing with hardware acceleration. We have electronics engineers and technicians with experience in ASIC design, PCB design, and integrated systems engineering. Vanderbilt has an established track record of successful detector design, construction, and operation (Pad Chambers and Time-of-flight for PHENIX, and GEMs for sPHENIX).

10 Cross-reference to other EOI's

The following EIC Expressions of Interest include direct participation by ORNL. Collectively, they coherently respond to the overarching goals described in the Abstract and Narrative sections above and help us span the full scope of this Expression of Interest.

1. This Expression of Interest.

2. EOI, submitted by EIC Silicon Consortium including ORNL, LBNL, Univ. Birmingham, Rutherford-Appleton Laboratories, BNL Instrumentation Div., CCNU (Wuhan), JLAB.

3. ECCE, Electron ion Collider Consortium Expression of interest (using selected components of the sPHENIX Experiment), submitted by consortium including ORNL, BNL, Catholic Univ. of America, Columbia Univ., George Washington Univ., Iowa State Univ., Livermore National Lab, Massachusetts Institute of Technology, Rice Univ., Rutgers Univ., Stony Brook Univ., TAU, Univ. Connecticut, Univ. Illinois Urbana-Champaign, UMA, Univ. New Hampshire, Univ. Virginia, Vanderbilt Univ.

4. EOI for Precision Timing Silicon Detectors for a Combined PID and Tracking System, submitted by consortium including Rice U., ORNL, and U. Kansas.

5. EOI for high resolution Zero-degree Calorimeters, submitted by a Far Forward Detector consortium including U. Kansas, LBNL and ORNL.

6. EOI for EIC Common Software, submitted by EIC Software Consortium including ORNL, ANL, BNL, CEA/Partons, JLAB, LANL, Radiasoft LLC, Stony Brook Univ., Univ. Manitoba.

In addition, the following selected EIC Expressions of Interest are relevant to the work described above.

1. EOI for EIC Streaming Readout, submitted by consortium including BNL, Catholic Univ. of America, JLAB, Massachusetts Institute of Tech., Stony Brook Univ.

References

[1] A. Accardi et al. “Electron Ion Collider: The Next QCD Frontier: Understanding the glue that binds us all”. In: *Eur. Phys. J. A* 52.9 (2016). Ed. by A. Deshpande, Z.E. Meziani, and J.W. Qiu, p. 268. DOI: `10.1140/epja/i2016-16268-9`. arXiv: `1212.1701 [nucl-ex]`.

[2] Brookhaven National Laboratory. “An Electron-ion Study”. In: (2020). URL: `https://wiki.bnl.gov/eic/upload/EIC.Design.Study.pdf`.

[3] EIC Users Group. "EIC Yellow Report". In: to be submitted (2020). URL: http://www.eicug.org/web/content/yellow-report-initiative.

[4] X. Ai (for the ACTS Developers). "Acts: A common tracking software". In: Oct. 2019. arXiv: 1910.03128 [physics.ins-det].

[5] T. Evans et al. "Celeritas". In: (2020). URL: https://www.snowmass21.org/docs/files/summaries/CompF/SNOWMASS21-CompF2_CompF1-053.pdf.