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ELECTRON ION COLLIDER PROJECT AND CONTROL SYSTEM UPDATES FOR 2025*

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Abstract

As the Relativistic Heavy Ion Collider (RHIC) completes its final physics run in 2025, design activities for the future Electron Ion Collider (EIC) that will probe the building blocks of nuclear physics for decades to come have made critical advances. Recent improvements including a new Electron Injector System and updated Low Energy Cooler for electron-based cooling of hadron beams will be described. Advancements in the planning and demonstration activities for accelerator controls elements such as the Common Platform front-end computer designs and related infrastructure, EPICS-based software infrastructure, bridging tools to controls for legacy systems required to support hadron injector systems, and networking and computing infrastructure designs will be highlighted. Our analysis of potential scope of AI/ML integration with controls for the EIC accelerator and detector systems will be introduced.

COMPLETING THE RHIC ERA

The RHIC has been the workhorse since 2001 for Nuclear Physics research supported by the US Department of Energy (DOE) involving colliding beams of polarized protons or a range of heavy ions species between energies 3.85 GeV [1] and 255 GeV [2] for experiments that have themselves significantly improved in terms of capabilities over the last two decades [3]. The current expectation is that RHIC beam operations will permanently cease at the end of 2025, which amounts to a short delay of several months from what was predicted in our previous report.

Plans to reuse RHIC facilities and equipment have advanced in recent years. We still intend to adapt the RHIC Tunnel to host the Hadron Storage Ring (HSR) and Electron Storage Ring (ESR), where the HSR will primarily be comprised of magnetic elements from the existing Yellow Ring with modifications. A limited portion of the Blue Ring will be adapted to serve as the 41 GeV Bypass Line, though the location of that segment has moved to Arc Sector 1 to mitigate space concerns in the Collider Tunnel.

A REVISED INTRODUCTION TO THE EIC

The basic concepts of the EIC design remain close to those described in our 2023 report [4]. In addition to the previously described HSR and ESR machines that provide up to two Interaction Regions where physics experiments can be performed, EIC will require a photo-injector, a LINAC, and a Rapid Cycling Synchrotron (RCS) to accelerate polarized electrons that can be utilized in the ESR. Between 2024 and 2025, it was decided that physics and logistical issues involving tunnel installation of the new accelerator rings in the existing tunnel used by RHIC would require a revised set of designs for the Electron Injector Systems (EIS). This culminated in an updated design for the EIS that is comprised of an updated 750 MeV LINAC with a revised RCS Ring operating between 5 and 18 GeV and a newly added Beam Accumulator Ring (BAR) that are planned to be constructed in a new facility adjoining the Collider Tunnel in the existing 4 o'clock region. Figure 1 shows the updated cartoon layout for the entire EIC Project.

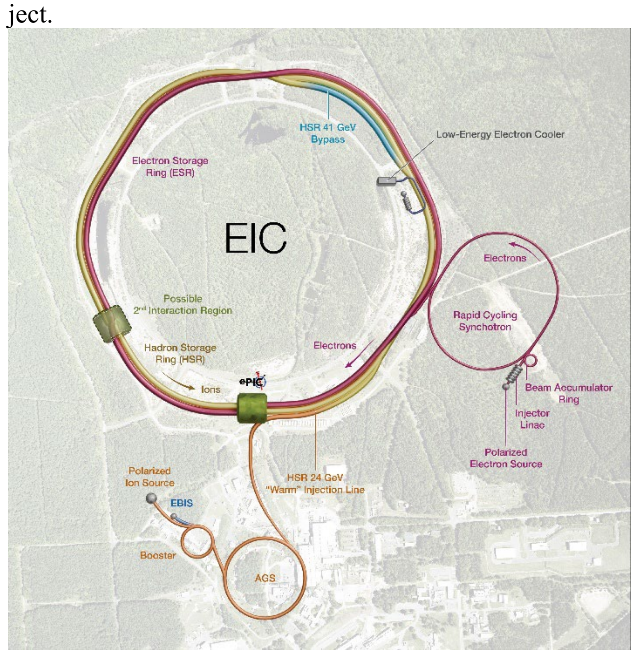

Figure 1: An updated cartoon layout of EIC as of September 2025.

Another set of strategic decisions that have been made recently is the removal of the Strong Hadron Cooler (SHC) systems from the Project and the concentration on providing a Low Energy Cooler (LEC) that uses a co-propagated electron beam to cool hadron beam in the HSR only at the injection energy for that Ring, which would still be installed in the 2 o'clock region of the Collider Tunnel. The motivation for these decisions is to reduce overall Project costs and has been supported by recent assessments of the limited projected benefit to beam luminosity yielded by the SHC design. The overall impact to Controls scope due to

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this set of changes is not particularly significant, as the scale of infrastructure needed for the LEC is comparable to what we had anticipating constructing for the SHC design.

In addition to the design changes required to progress towards the initial baseline approval process with the US Department of Energy, the EIC Project embarked in 2024 on a process of updating the organization of the scope into subprojects. This is expected to help lower the yearly budget expenditures throughout the Project lifetime and to hasten progress on portions of the original plan that currently enjoy a higher design maturity towards the construction approval process. Controls Systems support in various forms is anticipated for each of subproject, which will be addressed in a future Project update.

Beam commissioning activities are currently anticipated to begin in 2032, and the physics program utilizing the Electron-Proton/Ion Collider (ePIC) Detector that will be installed in the 6 o'clock Interaction Region is expected to start in 2035. Full Project completion is now anticipated to occur after FY38.

UPDATE ON EIC COMMON PLATFORM HARDWARE

Since our previous report, significant progress has been made in the design efforts for the EIC Common Platform and demonstration activities have notably reached a critical threshold. Table 2 shows a list of major components that are being managed by the Controls team and their current design and demonstration statuses.

Current estimates are that we will ultimately require approximately 1000 Common Platform chassis to support all applications across the spectrum of Controls, Instrumentation, RF, and Vacuum subsystems. Many of those units are expected to serve the Beam Position Monitor digitizer role, which will rely on a custom Daughter Card that is under development by the EIC Instrumentation team. Each chassis can host either one or two application-specific Daughter Cards, including the set shown in Table 1 that are the responsibility of the Accelerator Controls team or additional Daughter Cards developed by other groups for their own custom applications.

The Common Platform Carrier Board provides SFP connectivity for external clocking and synchronization integration via the proprietary Timing Data Link [5]. A separate SFP connection supports integration with a Machine Protection System Link, both of which operate at 8 Gb/s. We're currently performing the initial demonstration activities for the Carrier-to-Carrier timing communication that underpins both types of hardware links. These are expected to support most applications on the Project that involve nanosecond-level synchronization, including bunch-by-bunch beam instrumentation measurements and Low-Level RF controls applications. Figure 2 shows an image of a test stand currently in use for demonstrating functionality required for communications involved in both the Timing Data Link and MPS Link.

Table 1: EIC Common Platform Component Statuses

Component	Design Status	Status
Carrier Board	Ready (RevB)	Testing Done
SFP Breakout Daughter Card	First Article Ready	Under Test
DIO Daughter Card	In-Process (RevB)	Under Test (RevA)
Baseband ADC Daughter Card	First Article Ready	Under Test
Baseband DAC Daughter Card	Conceptual Design	N/A
Extended Carrier Interface Module	First Article In-Process	N/A

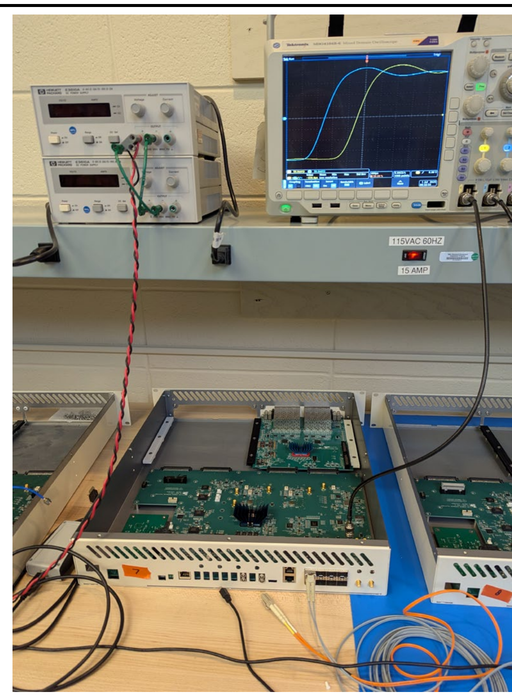

Figure 2: An image of a test fixture where bi-directional communication functionality associated with the Timing Data Link and Machine Protection System Link is under demonstration using two EIC Common Platform Carrier Boards and an SFP Breakout Daughter Card.

Remote interface development has reached a key milestone where we have functioning control and readback demonstrations between a Carrier Board and a CS-Studio Operator Interface screen using an EPICS Soft IOC and the pscDrv [6] module that is commonly used by the community. Figure 3 shows an interface in use for demonstration activities.

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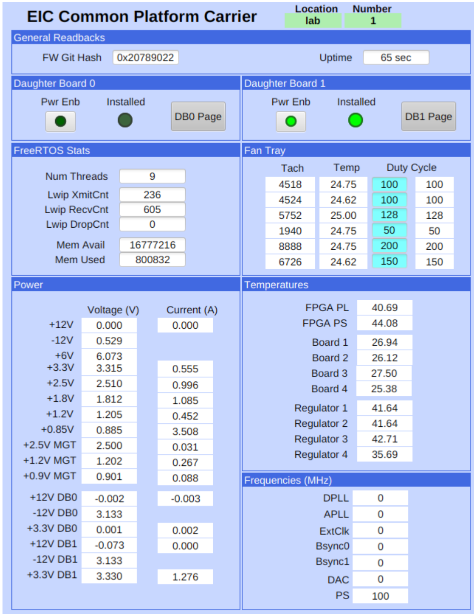

Figure 3: A sample Operator Interface (OPI) Screen for the EIC Common Platform Carrier hardware showing live information from a test setup using the CSS Studio Phoebus application.

FPGA gateware has been developed using the FWK FPGA Firmware Framework developed at DESY [7, 8]. We have found that this toolchain is a good method for standardizing our designs, though we still have more to learn on using all the functionality that it provides and on how it may be leveraged within our future Continuous Integration / Continuous Development (CI/CD) environment [9].

Before the end of the RHIC Program, team members associated with the Instrumentation Group hope to complete a set of parasitic tests using the EIC Common Platform and the BPM Daughter Card that is currently being assembled. This will accelerate our demonstration activities, bringing together a functioning high-performance data acquisition device with the base platform that will integrate the application with the future EIC Controls System. Our limited tests will require integration with the legacy RHIC beam synchronous timing system to allow for comparisons between the RHIC-era equipment data collection and the new EIC hardware without requiring full integration with the EIC Timing Data Link that is under development.

UPDATE ON EPICS SOFTWARE INFRASTRUCTURE

The design of the core software infrastructure for the EIC Project remains EPICS version 7 [10], using CS-Studio Phoebus [11] as the primary user interface application suite. Our focus since 2023 has been on understanding what primary options we might leverage for the core software services, and how those services will need to integrate with the off-project facilities that will eventually support EIC beam commissioning through the hadron injector chain that relies on the existing Controls System in use for RHIC, the Alternating Gradient Synchrotron (AGS), the AGS Booster, and the associated Pre-injector facilities. These systems rely on Accelerator Device Object (ADO) [12] software that will be maintained for some period that is expected to overlap with EIC commissioning activities. Development work has included testing two separate forms of bridging tools that can be used to interact between ADO software-controlled equipment and client software in the EIC EPICS-based Controls System called adoSrv and adoEpics. These two tools provide different mechanisms to support a scalable architecture allowing systems to interoperate in a controlled and well-monitored fashion across the physical and protocol-based boundaries between machines [13]. We are also currently testing a Restful service that would enable agnostic communication between ADO and EPICS PVs to support client-facing interactions.

A mechanism to transmit alarm notification messages between the ADO software infrastructure and client applications within the EIC Controls System is under development and demonstration (Fig. 4).

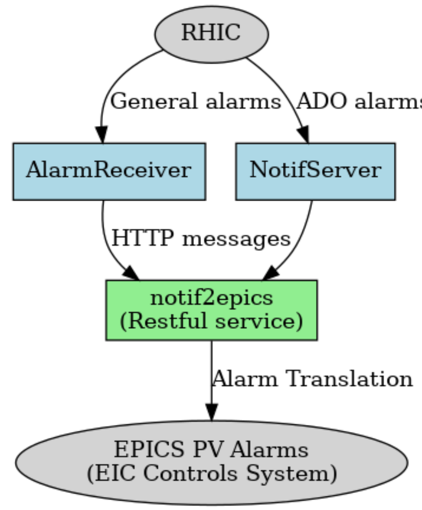

Figure 4: A diagram of a bridge interface for alarm notifications that has been demonstrated between RHIC ADO software and EPICS Process Variables via a new Restful service, notif2epics.

Originally developed to provide higher visibility and greater control to RHIC operations for sequenced sets of actions within the Controls System, the Tool for Automated Procedure Execution (TAPE) Sequencer [14] application has gone through some adaptation to demonstrate a new Python-based formatting for sequences. The hope is to utilize the new scheme to develop expanded sequencing capabilities that will enable complex machine operations for the EIC Complex to be developed, executed on demand, and managed effectively by operators and other personnel who have a use for this form of automation and are not trained programmers.

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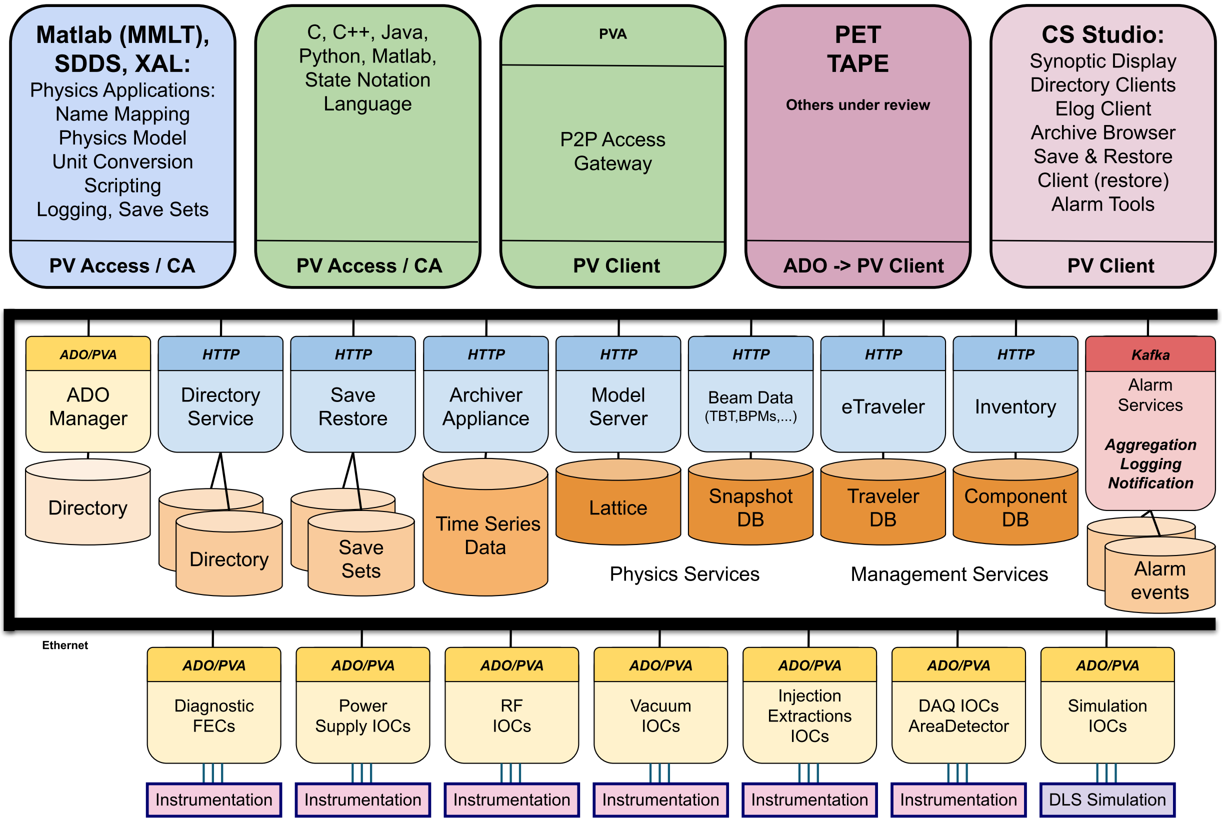

Figure 5: An EIC software architectural diagram that incorporates minor changes that have been made since our previous report.

In addition to performing design and demonstration activities for the software infrastructure required for the EIC, elements of the system including EPICS, a set of Input/Output Controllers (IOCs), and Archiver [15] have been deployed to a new facility at BNL that will eventually support a beampipe coating system used to process sections of the HSR vacuum pipe as a necesssary upgrade from the RHIC beampipe to allow us to achieve the expected beam performance with higher numbers of bunches and beam intensities. This is giving us an early opportunity to exercise a subset of our services by integrating a small number of field devices with standard user interfaces.

Our software architecture has only changed in minor ways since the previous report (Fig. 5).

NETWORKING AND TIMING INFRASTRUCTURE PLANNING

It was recently identified that it will be crucial to relocate the planned Distribution Hub for the EIC Project that would host fiber connections, master timing and machine protection system equipment, and servers for hosting remote interfaces for field equipment in a space within a newly constructed building that is geographically near the center of the overall Project. This would have small advantages on minimizing latencies for high performance communications across each subproject and would avoid longer communication pathways for remote interfaces that might benefit from being closer to the equipment. Centralized services are still planned to be hosted from a separate facility further away from the EIC portion of the BNL Campus. We include a cartoon of the revised fiber plant for the Collider portion of the EIC Project (Fig. 6). Development of similar plans to extend the fiber plant to the newly added Electron Injector Systems facility are underway, leveraging the same Distribution Hub that is planned to be built during the initial ASR subproject.

PLANS TO SUPPORT AI/ML FUNCTIONALITY

Prompted by developments within the greater accelerator controls community, stakeholder questions, and internal team questions, evaluation of potential scope related to Artificial Intelligence and Machine Learning (AI/ML) started in 2024 and has increased during 2025. These activities included the assembly of a Working Group by the Technical Director of the Project that is tasked with assessing the potential use cases and strategies that may be useful to employ during the construction and commissioning phases of the EIC. While a decision on whether to directly include AI/ML scope on the Project has not been made in advance of this report, we are currently considering off-project efforts and funding sources that would put us in the best possible position to be ready to implement AI/ML toolchains for physics, engineering, and administrative applications impacting both the EIC Accelerator and ePIC Detector datasets. We anticipate that there will be significant usage of

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such tools during the Project phase and throughout the life cycle of the EIC Complex based on both state of demonstration at existing accelerator facilities and on our own discussions with stakeholders and we feel that we should have a strategy in place that would allow us to safely and effectively utilize our future AI/ML infrastructure to enhance development efforts on the Project and systems performance [16]. In addition to considering centralized data processing for AI/ML applications that would involve tagging and training, we are considering potential applications for fast inference processing that may require some form of direct integration with the EIC Common Platform hardware [17]. Higher performance applications could be implemented, where the hardware deployment would be optimized by locating the equipment in the Distribution Hub planned for building 1003A.

CONCLUSION

Extensive progress has been accomplished by the EIC Project team since our previous report in 2023. This includes a significant accelerator strategic decision whereby the RCS and Pre-injector facilities have been removed from the Collider Tunnel and refreshed in a slightly different form in a new complex adjoining the existing Tunnel that is currently in use for RHIC beam operations. Additionally, hadron beam cooling designs no longer incorporate the SHC but will instead utilize the LEC for cooling of beams at injection energy only.

Regarding accelerator controls developments, we have built and performed basic testing on the Common Platform Carrier Board and chassis and have started testing three different application Daughter Cards that the Controls Group will be responsible for supporting across multiple subsystems including RF, Instrumentation, Power Supplies, and Vacuum. We've selected a location for a future central Distribution Hub for our main networking, timing, and machine protection services that will scale to meet the needs of each subproject.

EPICS-based IOCs and software services have been successfully deployed within our development environment, and we are actively documenting performance of bridging tools that support integration of the existing proprietary ADO infrastructure used at RHIC and the hadron injector chain with the proposed EIC controls system infrastructure that are in common use at other EPICS-based facilities.

While providing AI/ML functionality is not officially included in the scope of the EIC Project at this stage, we continue to consider what strategies we should employ to maximize our readiness to effectively deploy such services at an early point in construction and commissioning processes.

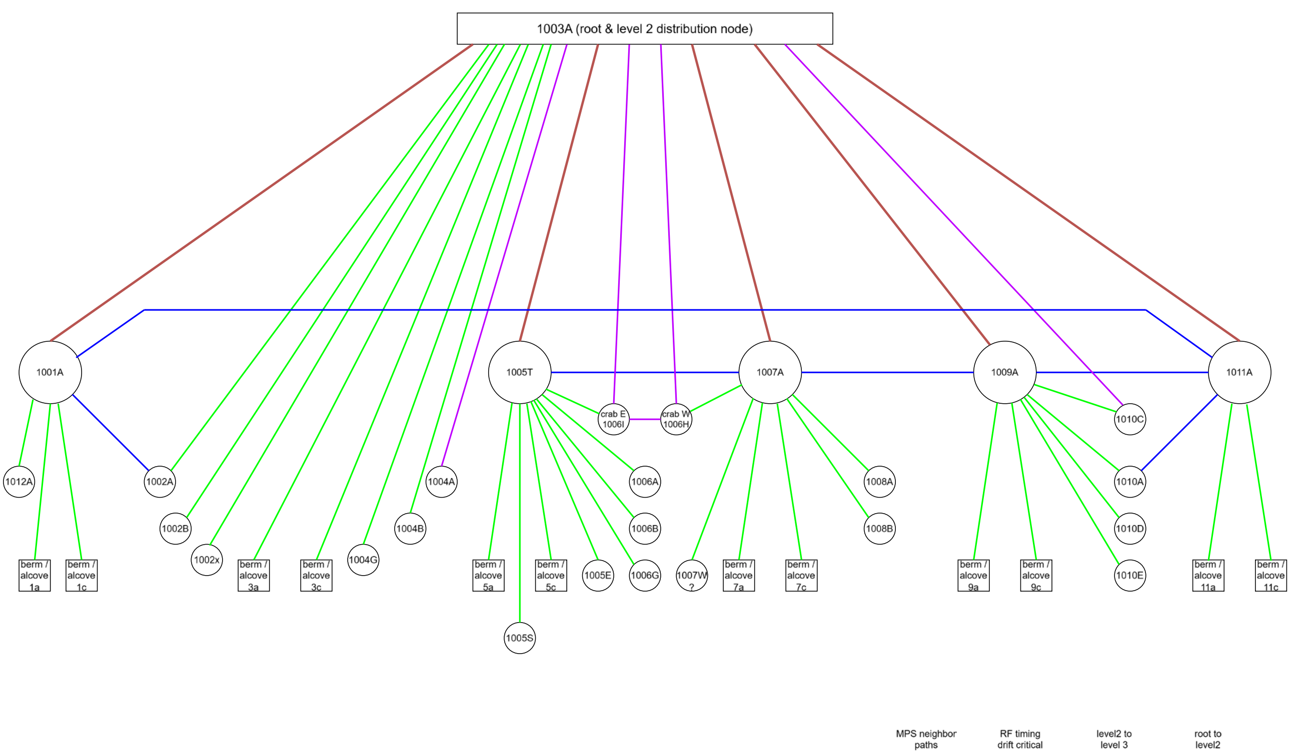

Figure 6: A cartoon showing a new fiber distribution topology that incorporates a central Distribution Hub in building 1003A and shows the pathways required for the Collider portion of the EIC Project.

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