Report of the 22nd Meeting of Collider-Accelerator Department Machine Advisory Committee (C-AD MAC)

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BNL / hybrid meeting

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Remote: Richard Scrivens (CERN)

The committee members are grateful to the C-AD management and staff for the well-organized meeting, excellent presentations and open discussion. We appreciate the team responding to all recommendations from MAC-21.

The MAC was requested to review and advise on (i) the plans for maintaining and upgrading the hadron injector complex over the next 3 years, and (ii) the strategy and efforts of the C-AD R&D efforts. We answered the following charge questions and provided comments on other aspects of the C-AD accelerator operation and R&D:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.
b) Are the C-AD plans aligned with the EIC goals over the next decade?
c) Are the present efforts well executed, and future work well planned?

Overview

The RHIC accelerator complex is the only operating collider in the U.S. The very flexible machine was designed for investigating the QCD phase diagram and proton spin, and has been delivering heavy ion and polarized proton collisions at the highest luminosity. Over the 25 years of operation, the machine has attained spectacular performance far exceeding design parameters.

C-AD is concluding the final RHIC Run with the new sPHENIX and upgraded STAR detectors: the last Au-Au collisions ended on December 8, 2025, and as of the time of this report the machine delivers polarized proton-proton collisions to sPHENIX. The run will terminate no later than January 28, 2026. After the completion of the RHIC physics program, C-AD will assume responsibility for the removal of equipment not needed for the EIC from the RHIC tunnel and experimental halls, will maintain the hadron accelerator complex in a ready state, operate the hadron injectors for isotope production at BLIP and space radiation studies at NSRL, and will continue R&D in accelerator science and technology. This constitutes a major transformation for C-AD as well as for the entire Laboratory.

C-AD developed a plan for transitioning from RHIC to EIC covering the period from the end of the RHIC program to the start of EIC operations. In this phase, the BNL Nuclear Physics (NP) operations constitute an important part of the EIC portfolio, outside the scope of the construction project. The effort will include maintenance and operation of the hadron injectors, their regular upgrades and modernization, and experimental support. The accelerator safety documentation will be reviewed and updated to conform with the current DOE accelerator safety order, and Accelerator

Readiness Reviews will be conducted. The accelerator R&D is a major component of NP Operations and was a significant focus of this review. Additionally, the RHIC Removal and Repurposing Project is an effort to prepare the RHIC tunnel and infrastructure for the EIC, and plans for four Large Upgrade Projects needed for EIC have been developed, although the alignment of these efforts with the overall EIC schedule was not presented.

Beam parameters for EIC injectors have been defined and captured in the functional requirements document. Most of the parameters have been achieved during RHIC operation. The expected availability of EIC beam operation is 85%, which requires attention to the machine and system reliability.

A model has been developed parametrizing Hadron Injector Chain availability as a function of operations funding investment. The model uses several point estimates and will be further refined to enable informed programmatic decisions.

Comments

- We congratulate the team for their outstanding achievements in the RHIC operation and development. Machine evolution has been truly spectacular, and we are grateful for the opportunity to observe it and provide guidance.
- The thorough approach to developing the plan for transition from RHIC to EIC is highly commendable. We encourage C-AD to continue working with the EIC Project on the definition and alignment of plans.

Charge questions responses:

a) **Comment on possible models of availability as a function of funding, and risks associated with single points of failure.**
    - Accelerator research infrastructure at high tech facilities requires regular maintenance and modernization. Any reduction in the required maintenance is not a saving but a delay in spending that builds up the investment backlog. As this backlog develops there will be a reduction of availability and an increased risk of extended downtimes (up to years). The committee agrees with the conclusion from the availability vs. cost analysis performed by C-AD. We welcome this step and encourage cross-laboratory collaboration on the subject potentially aiming to develop a common approach to maintenance and modernization.

b) **Are the C-AD plans aligned with the EIC goals over the next decade?**
    - **Yes**

c) **Are the present efforts well executed, and future work well planned?**
    - **Yes**

Recommendations: None

RHIC Performance in Run-25

Findings

For the past three years the physics program at RHIC focused on sPHENIX, while accommodating other detectors as possible. This year's Run-25 started in March and continued until the time of the review. The physics program had a delayed start, however, minimal downtime during the summer months was incurred. The luminosity goals for Au-Au run have been met, and the p-p run is ongoing and expected to achieve the additional sPHENIX request. Additional experiments may run if approved and if time allows.

The 2-month delay to the start of the run was caused by a dipole magnet developing a short to ground on a repaired cable splice. The repair required opening a cryostat and was executed expeditiously. Additionally, 14 days of beam operation were lost due to a power line failure that caused significant effort. Further, an 11-day downtime period was caused by the abort kicker misfire sending ⅔ of a bunch train into a section of flange. The repair was executed efficiently.

Overall, RHIC availability to date in Run-25 was 81%, which is higher than the Run-25 target of 80%, but lower than the availability goal for EIC of 85%.

APEX studies are highly relevant during the final year of RHIC operations. The APEX workshop was held early in the year (January 2025) to develop and review a comprehensive plan for the studies. To date, all of the high priority experiments have been completed. The progress will be formally evaluated in January 2026. One example is the flat beam acceleration that demonstrated the transverse emittance ratio of 11:1 maintained through acceleration to top energy.

In response to a recommendation of MAC-21, work was done to understand the nature of beam instabilities and it was determined that emittance growth was caused by insufficient damping in the 56 MHz cavity.

The 56 MHz cavity development and operation had to be terminated early due to the failure of a forward power coupler and the insufficient time to repair. The demonstrated benefit was positive for a short period.

The source of experimental background was tracked to a legacy mask restricting aperture in the upstream section with respect to the triplets. Once the mask was removed, the background was eliminated.

For the remainder of the run the priority is to reach the p-p luminosity goal. Other studies may be afforded depending on the remaining time.

Comments

- The team is congratulated for delivering the required integrated luminosity to sPHENIX despite a number of significant challenges.
- The correct identification – from tracking modeling the observed behavior – of the aberrant mask upstream of the detector as the source of the background is particularly noteworthy.

Charge questions responses:

d) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

e) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **Yes**

f) Are the present efforts well executed, and future work well planned?
   - **Yes**

Recommendations: None

Injector upgrade plans over next 3 years

Findings

The presentation of the injector upgrade plans over the next decade is a response to Recommendation no. 6 from the previous C-AD MAC, which asked for an optimized modernization plan and a prioritized list of tasks. In the injectors, IRRs (Internal Readiness Reviews) and ARRs

(Accelerator Readiness Reviews) are planned for the Linac/Booster combined (June 2026), for the SRF Test Facility (September 2026) and for the AGS (October 2027).

A Technical Infrastructure Upgrade Plan has been initiated in 2018 for RHIC with a view towards EIC. It aims at performance upgrades and work on obsolete systems and components. Technical infrastructure should be maintained in good order and the hadron injector complex should be ready for EIC when commissioning starts while also running for external users (e.g. NSRL and BLIP). Upgrades are prioritized based on funding and staff availability. A list of hardware groups that have end-of-life systems with obsolete or unsupported components was presented.

It was decided to suspend the execution of the Technical Infrastructure Upgrade Plan in FY22 and no funding from the Accelerator Improvement Projects (AIP) or the Capital Equipment (CE) was allocated. Funding was directed into RHIC operation instead. This has contributed to a backlog of maintenance and modernization.

It is now assumed that annual allocation of about $3M of combined AIP and CE funding will begin again in FY26. High Priority Hadron Injector Upgrades (to be funded from CE, AIP and Ops) were prioritized for each equipment group based on reliability of the present system, the number of recent failures, obsolescence of system components, spares availability, cost, and funding availability. Prioritized work was listed for the linac, the booster, the AGS, facilities and EIC-related equipment for a total investment of $3.5M per year. Additional funding would allow the execution of the following upgrade projects:

- Central Cryo Plant Upgrade for EIC ($34.0M)
- SRF Test Facility in Building 912 ($17.6M)
- Linac RF upgrade: replacing RF tubes with solid state devices initially for 1 tank and further with 7 out of 9 replaced ($12.7M/tank)
- Main Magnet Cooling System Upgrade for the AGS ($9.1M)

The extra investment would add up to $149.6M. A detailed list of high priority hadron Injector upgrades was presented with the estimated funding profile from FY26 to FY33, grouped by systems. Upgrades and major maintenance work were presented in more detail for the next 3 years.

Challenges mentioned involve aligning the upgrade work with funding availability and C-AD staff availability. The full scope of work may not be complete before EIC operations begin, requiring co-operation of old and new systems. It was mentioned that the cost estimate for AGS cable tray replacement needs more work and may be significantly higher than the $2M presently estimated for the most critical tasks.

<u>Comments</u>

- The committee congratulates the C-AD staff for developing a very convincing and sound plan for injector upgrades and modernization measures required for the EIC operational phase.
- The committee fully supports the presented work plans and proposed investments. It notes that the planned yearly investment seems low in view of the work to be done, the backlog from suspended maintenance, the importance of EIC availability and also if compared to similar efforts at other labs.
- The strategy for modernization of the 65-year old AGS cabling should be sharpened, to define the modernization needs for the next 30 years and the work to be done now versus work to be done later.
- The presented photos of old rusted exterior disconnect switches highlight the need for regular maintenance and replacement. We appreciate the effort to include the required modernization of electrical safety equipment into the work plan with high priority.
- The additional project list is a heavy lift and the overall package should be analyzed and resource-loaded in view of the other work to be done.

- The RF amplifier modernization is timely and important.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?

- **Yes.** The injector upgrade and modernization plan is fully aligned with the goal to prepare EIC operation and performance at high availability.

c) Are the present efforts well executed, and future work well planned?

- **Yes.** The required injector upgrade and modernization work for the EIC era is well analyzed and well planned. This work is just starting and we cannot yet comment on its execution. We agree with the risk mentioned that work will not advance fast enough and recommend considering an increased funding rate for this work.

Recommendations:

1. **Execute the proposed injector upgrades and modernization with high priority. In consultation with the funding agency and lab management, consider an accelerated plan with increased funding.**
2. **Consider an option that modernizes the full 65-year old AGS cabling in well defined steps, such that it will be adequate for the next 30 years.**

200 MeV H- Linac RF amplifier upgrade plan

Findings

- The existing RF system using triodes, while still working satisfactorily, is becoming difficult to maintain and there is significant risk of the tubes becoming unavailable in the foreseeable future (approximately 4 years).
- BNL has a stock of spares for about 6 years, and tubes can be refurbished once per core, but the quality of tubes and their lifetime has degraded in recent years.
- The RF team has investigated and compared several alternatives to the existing tubes, including diacrodes used at LANL, klystrons, and Solid-State Amplifiers (SSA). The team settled on SSA as the most compelling long-term upgrade. This decision is based on space considerations, performance and long-term sustainability.
- The presented plan is to purchase and install one amplifier to replace RF tank #9 and acquire experience with running it, with an option of purchasing the remaining balance of amplifiers if performance is satisfactory.
- The low-level RF system was upgraded a few years ago and will be able to accommodate the change in dynamic behavior of the new amplifiers with a relatively straightforward tuning of its parameters.
- The SSA will be specified with enough overhead to deliver full rated power with 20% of the modules being off.

Comments

- The review committee found the argument for SSA upgrade compelling and concurs with the project on choosing this path. It should be recognized that besides the technical transition, a switch to SSA technology also requires a commensurate change in the workforce qualifications.

- That said, there are a number of potential pitfalls to be aware of. In discussions it became clear that the RF team is indeed aware of these.
    - SSA can be sensitive to cyclic (pulsed) operation. Care is important when developing the specifications to ensure this requirement is understood and handled in a flexible manner with enough range to cover all possible operation scenarios.
    - Reverse power from the cavities (that may exceed the forward power generated due to beam-induced power) can present issues to the SSA. These are usually mitigated by a common circulator per cavity plus circulators for the individual power modules, plus possibly circulators for the individual output transistors. Reverse power protection is a key specification in ensuring reliable operation in the field.
- The power margin aimed for appears reasonable. However, it needs to be ensured (by interlocks or limiters) that a fully functional amplifier (at 125% output) does not damage the RF structures.
- The plan for a comprehensive review with external reviewers before procurement documents are finalized is commendable.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?

- **Yes**. The EIC will require a reliable injector chain to meet its overall availability goal of 85% (of both hadron and electron injector complexes combined). Addressing the risk deficit of spare tubes, or tubes of bad quality, will become an important component in meeting this goal.

c) Are the present efforts well executed, and future work well planned?

- **Yes**. The investigation leading to the upgrade decision was conducted well.

Recommendations:

3. The team is encouraged to engage in discussions with other labs about relevant experience with SSA technology, especially in pulsed operation and with control of beam loading, etc. For example, CERN has had mixed experience with implementing high-power SSA.

C-AD R&D strategy and plans

<u>Findings</u>

The C-AD R&D strategy and plans were presented. The strategy is (1) to maintain leadership and expertise in key areas, (2) to align mid-term R&D with EIC needs and future EIC performance and capabilities, (3) to pursue advanced accelerator R&D (external funding using FOA and LDRDs). (4) AI/ML applications shall be actively pursued at various C-AD accelerators to optimize beam controls, automate machine tuning and data analysis, improving reliability and operations.

The overarching goal presented is to use mid-term R&D in a coherent strategy to maintain leadership in technology needed for the EIC, for future EIC capabilities and upgrades, and possibly the next generation of NP facilities. Topics presented were ion sources, electron sources, polarization and polarimetry, and beam cooling.

Goals for focused mid-term R&D efforts were presented:

- In ion sources to fully establish EIC requirements, including polarized He-3 source development, and to develop future EIC capabilities.
- In electron sources to develop polarized and high-current cathodes for the EIC and to develop a high-current electron gun suitable for the EIC.
- In polarization and polarimetry to maximize polarization through the accelerator injector chain and to develop robust polarimetry at various stages of acceleration.
- In high-energy cooling (HEC) to develop a HEC system for the EIC to maximize luminosity and to fully optimize the EIC potential.

Those focused mid-term efforts were partially presented in this talk and further details followed in subsequent talks. Highlights and future plans were presented per topic. Several plans, but not all of them, were presented with some deliverables, and years in which they are to be delivered. Finally, the C-AD plans for machine learning in accelerators were introduced.

Comments

- The C-AD team is congratulated on the important achievements and the excellent capabilities in accelerator R&D. The committee agrees that it is important to maintain those capabilities and put them into use to attain the best EIC performance.
- The committee agrees on the ion and electron sources, polarization and polarimetry, and ML/AI as important and focused activities. The urgency of HEC work is lower, as presented.
- The NP Operations funded personnel engaged in accelerator R&D was presented to be below 10% of the total workforce in C-AD. This seems about adequate but tight. The progress in the prioritized activities should be closely monitored and, if advancements fall behind the plans, further prioritization should be implemented. We commend the leveraging of external funding, which is appropriately managed.
- The department is successfully executing a limited number of R&D projects on diverse and exciting topics that are not directly related to future EIC performance. These developments have a potential to contribute to the EIC in the long-term. In the short term, efforts should be made to bring on board external partners, especially universities and students, in order to strengthen these topics.
- Experience has shown that achieving the high level of polarization and operating with polarized beams requires long-term preparation and commitment to bear fruit. Polarized beams are one of the distinguished features of the EIC and require for the polarized-beam team to be strong.
- Machine learning (ML) algorithms and software, especially Bayesian optimization, are being developed at BNL. We encourage focus on providing tools to speed up EIC beam commissioning as much as possible.
- We view the APEX framework as a very successful endeavor and encourage its extension into the transition era to define and execute the studies in the hadron injector chain.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **Yes.**

c) Are the present efforts well executed, and future work well planned?
   - **Mostly yes**, see comments on individual presentations

Recommendations:

4. **Execute the accelerator R&D plan with high urgency, closely monitoring the progress versus planned milestones. If delays are encountered, e.g. due to the tight personnel, prioritize further.**

Plans for EIC polarimetry

Findings

The EIC will use polarized protons and helions (^{3}He), and later on polarized deuterons, and heavier nuclei like lithium (^{6,7}Li) may be needed. The EIC promises to provide proton beam polarizations of $P \geq 0.7$ with a relative uncertainty of $\Delta P/P \leq 1\%$. Polarization calibration is needed for each ion species. The beam polarization will be deduced from the known target polarization. Absolute proton beam polarization calibration relies on measured nuclear polarization of an atomic jet using a Breit-Rabi polarimeter. The polarimeters shall determine the bunch polarization profile in x,y,z, the polarization lifetime, and the polarization vector per bunch. With polarized beam and polarized target, all components of the beam polarization can be determined from spin-dependent cross section. The instruments are a hadron polarimeter in IP4 for absolute polarization measurements and a pC polarimeter in IP6 for relative determination of the polarization. At EIC the bunch repetition rate is much higher than at RHIC, therefore the beam-induced depolarization of target atoms has to be investigated.

At present, polarization in the AGS is measured at discrete energies using sweeping carbon-fiber targets. A storage-cell target would provide continuous polarimetry along the ramp. In the AGS an openable storage cell would provide a high areal target density for CNI pp elastic polarimetry and related reactions. Initially, the cell could be filled with unpolarized gas, e.g., H_2, to generate the required target densities for a variety of polarimetry reactions. At a later stage, a polarized H (or D) atomic beam can be used to feed the storage cell and provide a polarized internal target. Required equipment for a storage-cell based internal polarimeter in the AGS is available at Ferrara University including a target chamber, thin-foil openable cell, test chambers, detector system, etc., and could eventually be transferred to BNL.

The ^{3}He atomic beam polarimeter development is performed in a collaboration with MIT/BATES and BNL to develop an absolute ^{3}He beam polarimeter for the EIC based on a polarized ^{3}He atomic beam source. It will be installed and tested in the AGS first.

Comments

- The committee appreciates the idea of a co-location for carbon, polarized H, and ^{3}He atomic beam targets at a single IP in the EIC. This setup would minimize spin transport between devices and allow for the use of common services, such as unified slow controls and DAQ. It could also perform functional roles such as carbon ribbon(s) for fast relative polarization scans and polarized HJET and ^{3}He for absolute polarization calibration.
- The committee fully supports installing a storage-cell target at the AGS, based on proven technology to provide fast, high-precision, and energy-resolved polarization measurements during the ramp. This capability would greatly enhance the EIC's performance in efficiently preparing a highly polarized beam by enabling continuous polarization measurements throughout the entire AGS ramp. This development will undoubtedly advance the AGS's polarized beam technology and has a strong connection to AI/ML.
- It must be clarified how equipment from Ferrara can be transferred to BNL and what

resources are required to set up, commission, and operate this installation in the AGS.
- Is assistance of experienced external specialists for the setup and commissioning of the polarimeter required?
- The committee is concerned about maintaining the polarized beam community and attracting and training a sufficient number of scientists for this field until the start of the EIC and beyond. Many scientists are close to retirement or have already retired.

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **Yes.**

c) Are the present efforts well executed, and future work well planned?

   - **Maybe**: Are the required resources in terms of funding and experienced personnel available for the various tasks in the AGS and EIC?

   - **Maybe**. Are there efforts to strengthen the polarized beam community for the development of polarized beams in the EIC? Are there efforts to attract and educate young scientists in this field?

Recommendations:

5. Execute the development of the storage-cell target polarimeter to enable significant advances in the polarization transmission of the AGS.

ML - results to date and plans

Findings

- BNL effort is well integrated with the efforts ongoing in other labs, including university involvement.
- EIC provides a focal point for the BNL effort.
- Efforts are ongoing for transfer lines (BtA, LtB).
- An LtB case shows an about 20% increase in transmission from an as-found state.
- A digital-twin (DT) application for NSRL shows the ability to optimize a beam distribution using the DT.
- A 4x4 quad scan application was developed.
- The SLAC-developed Badger GUI front-end for Xopt was implemented at BNL.
- Several application programs are operational for use in the control room. At this point they are mostly used by accelerator physicists.

Comments

- The focus on control-room applications is truly commendable!
- It was not clear how much polarization optimization was done in the AGS since the last presentation. Apparently the team is now waiting for the new, faster, polarimeter.
- We encourage polishing the software deployed in the control room to the point that the

operators are able to use them without risk of accidentally tuning the machine into an unusable state.

- Opportunities will exist after the completion of RHIC run in the injector complex but the work will be slower. Is there work that could be done at other facilities?
- The integration with the efforts at other labs is commendable and will keep the effort relevant on a broader scale and avoid duplication.
- The digital-twin approach is an expansion of earlier efforts, at many facilities, of model-building for existing machines, on a much more detailed level. This may prove to be very useful for new machines like the EIC.
- It was pointed out that reinforcement learning (RL) can potentially keep a machine optimized in a way many human operators would not be able to sustain. The benefits of this are obvious.
- It appears that ^{3}He polarization commissioning is a perfect application of the developed AI/ML techniques, e.g. to automate some of the more tedious tuning tasks.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **Yes.** The ML efforts presented are crossing the threshold to application in the control room and can be expected to play a significant role in EIC beam commissioning.

c) Are the present efforts well executed, and future work well planned?
   - **Yes.** Several examples of application were shown as well as of software that is being deployed in the control room.

Recommendations:

6. **Train and encourage operators to begin using the application programs, beginning with the least complex ones, to build confidence.**
7. **Prepare a list of desirable AGS experiments, together with the software work that has to be completed, to be launched whenever the AGS will be running in the future.**
8. **Define and have a set of application software ready and tested in time to support EIC beam-commissioning.**

Polarized He-3 source development

Findings

Polarized ^{3}He ions are required for the EIC, approximately five years after EIC operation starts. The polarization fraction of ~85% is needed at the source output to meet the 72% requirement for injection into the EIC.

The production of polarized ^{3}He atoms has been demonstrated in a high magnetic field using an RF driven discharge with optical pumping, in a collaboration between MIT and BNL, with a very high polarization fraction. A critical point is suppression of impurities in the ^{3}He gas, to which end purification has been developed and improved significantly. Nevertheless, purity still requires attention as the full system is implemented.

A full set up compatible with the RHIC EBIS is in the final stages of production, and a plan was presented to install it in the summer of 2026, after which the tests for production of ^{3}He polarized ions can begin. This plan represents the response to R13 from MAC-21.

On the operational ion linac, a polarimeter has been [confirm] installed at 6 MeV/u which will allow the polarization to be measured and optimized.

Comments

- It is good to see there is a plan for installation of the ^{3}He polarization system onto the operational EBIS, and the committee looks forward to seeing some results at the next MAC.
- These developments are really unique in the world, and it is important to keep advancing now as the personnel and hardware are available, and make sure the development time on the EBIS and Linac are allocated. Furthermore, it will be important to well document all aspects of this work.
- Source developments typically require several iterations, and further equipment modifications after the first tests can be expected.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?
  - **Yes**.

c) Are the present efforts well executed, and future work well planned?
  - **Yes**.

Recommendations:

9. Investigate if optimization tools developed elsewhere can help in the fine tuning of the MEOP and EBIS parameters to reach the best intensities and polarization fractions (but not as a replacement for expertise).

Maximizing He-3 polarization

Findings

Polarized ^{3}He beams will be produced at the Electron Beam Ion Source (EBIS) with an expected intensity of 2.5×10^{11} ions/pulse and 85% polarization. The ion linac accelerates the beam to 2 MeV/u ($|G\gamma|$ =4.1932), the Booster accelerates it further to either $|G\gamma|$ = 7.5 or 10.5. The AGS then accelerates the polarized beam up to $|G\gamma|$ =49.5, avoiding the strong $|G\gamma| = 60 - \nu_y$ intrinsic resonance. HSR will finally accelerate and store the beam up to $|G\gamma|$ = 820. This is significantly higher than polarized protons with $G\gamma$ = 487. The EIC requires ^{3}He with a store intensity of 0.8×10^{11} ions/bunch and 70% polarization.

The commissioning plan spans to 2030 and includes several objectives and priorities. The objectives are:

1. Commission polarized ^{3}He up to $|G\gamma|$ = 7.5 in Booster.
2. Commission polarized ^{3}He up to $|G\gamma|$ = 10.5 in Booster after the A5 kicker upgrade.
3. Commission polarized ^{3}He up to $|G\gamma|$ = 49.5 in AGS.

The resulting priorities are:

1. Identify the maximum achievable efficiency to determine the number of bunch merges required to satisfy EIC intensity requirements.
2. Identify the maximum achievable polarization transmission with the proposed techniques and ensure the EIC polarization requirements can be satisfied.
3. Fully study the proposed alternatives in Booster and AGS if Priority #2 cannot be satisfied.
4. Identify and propose upgrades as needed to satisfy EIC requirements.

Polarized ^{3}He are currently requested at the EIC after the first five years of physics/commissioning.

Comments

- The committee appreciates that optimal configurations for the Booster and AGS have been identified and that a timeline and goals have been set through 2030. Should the intended configurations fall short of EIC requirements, potential upgrades have been identified.
- The committee supports the team's consideration of the beam studies modality.
- The committee strongly agrees that improving the AGS polarimetry and utilizing the capabilities of AI/ML will reduce the time needed for polarization optimization and maintaining the level of polarization during experimental time. See previous sections on polarimetry and ML for more information.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **Yes**.

c) Are the present efforts well executed, and future work well planned?
   - **Yes**

Recommendations: None

Fast Cycling Permanent Magnet Fixed Field Alternating (FFA) Synchrotron (LDRD24-010)

Findings

A fast-cycling permanent magnet synchrotron and a permanent magnet gantry have been studied for the FLASH Radiation Cancer Therapy Facility at Stony Brook University Hospital. The main limitation to accelerate protons in fast cycles within the non-relativistic energy range is the limiting speed of magnetic field response to the change of energy. This limitation can be eliminated by using the permanent magnets for the same energy range. This reduces the estimated cost of the proposed FLASH radiation therapy facility to roughly $40M to be compared to approximately $200M (Varian Facility in New York city in Harlem). The power consumption with permanent magnets will be reduced as they do not require electrical power. Reliability is improved by reducing power supply failures, radiation shielding is reduced due to less beam losses in the synchrotron, smaller magnet sizes and weights, and especially the gantry weight is significantly reduced. It also allows simplified operation as there is not a need to change the magnet settings for different proton energies.

Project status:

1. The magnets were assembled on an aluminum plate, positions adjusted by the surveying team and covered by the aluminum chamber with Kevlar windows at the entrance and exit.

2. The magnet assembly was transported to the NSRL laboratory and positioned for the first part of the experiment 50-250 MeV proton beam transport. The proton beam with energies between 50 MeV and 250 MeV was propagated through the assembly with radial horizontal positions adjusted for each energy. The proton beam positions were measured with two sequential flags in front and at the exit.
3. The second part of the experiment was performed at the Tandem BNL accelerator using deuterons to provide equivalent proton kinetic energies between 10 and 50 MeV.

Beams at all energies were transmitted through the 4-cell test girder (22.5° or 1/8 arc) for protons at NSRL and deuterons at Tandem in the range of 10 to 250 MeV, a factor of 5.3 in momentum.

Comments

- The committee congratulates the team on their experimental confirmation that the available momentum range is very large for a non-scaling FFA, particularly for one with a flattened tune. A factor of 5.3 in momentum could be reached. A beam energy of 250 MeV is the highest ever reached energy in any NS-FFA line.
- The single-pass measurements showed a degree of aberrations that could be consistent with the simulated, multipass, dynamic aperture. There are some larger discrepancies between measured and estimated tunes especially at lower energies. It has been stated that this can be explained by a larger beam offset in structure during the experiment.
- The committee strongly supports the two requests for additional beam time, primarily to improve beam alignment. A better vacuum should be used for the next beam times.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?

- **N/A**. This effort is not directly related to EIC.

c) Are the present efforts well executed, and future work well planned?

- **Yes**. There are currently some inconsistencies between the measurements and the simulation that should be resolved in upcoming beam times. The next obvious milestone towards realization would be to provide a conceptual design for the proposed facility.

Recommendations:

10. Publish the results in reputable journals as planned.

BNCT lithium beam driver (LDRD 24-046)

Findings

The project is a successful and well-integrated effort combining high-current lithium beam acceleration, inverse-kinematics neutron production, and BNCT applications. This is based on the demonstrated acceleration of a 35 mA $^{7}Li^{3+}$ beam (a world record) representing a major technical milestone; importantly, the presentation indicates that significantly higher currents, on the order of 100 mA, should be achievable, providing a substantial performance margin for future operation.

The development of inverse-kinematics nuclear cross-section data, their implementation in Monte Carlo simulations, and experimental validation with multiple neutron detectors form a coherent and convincing technical framework. Neutron measurement experiment at BNL has been performed to characterize neutrons from the inverse kinetic-kinematic reaction, and to validate its PHITS simulation system. The observed agreement between simulation and experiment strongly supports the reliability of the modeling tools for beam shaping assembly (BSA) design and BNCT optimization. The inverse-kinematics approach, with its forward-directed neutron emission, offers clear advantages in reducing unwanted radiation and shielding requirements, directly benefiting clinical feasibility.

The team proposed FY2026 activities as refining BSA design, experimental demonstration of ^{7}Be separation, and dissemination at international conferences.

Comments

- This project is well justified based on the team activities and as a response to Recommendation 12 of MAC-21.
- While effectively leveraging international collaborators, the project clearly demonstrates that BNL leads in all core technical elements, underscoring its unique capabilities in ion sources, linacs, and neutron source development. The collaboration should be enhanced not only in academia but in industry through a public awareness campaign.
- The proposed FY2026 plan is a natural step toward a practical BNCT system.
- The committee strongly supports continuation of this program, recognizing its high technical quality and clear societal impact. We can expect that the project will establish and promote BNL's leading role in compact accelerator-driven neutron sources.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **N/A**

c) Are the present efforts well executed, and future work well planned?
   - **Yes.**

Recommendations: None

Ion trap test stand for ultra-low emittance beams (LDRD 24-006)

Findings

The project is a seed for crystalline ion beams for accelerators. Schemes in the past have considered creating crystalline beams in rings through cooling in the ring. This proposal researches the concept of producing an ultra-low emittance, crystalline ion collection in a Paul trap coupled with laser cooling, before extracting and transporting the ions to an accelerator.

Some potential applications were shown that might be realized by focusing the beam to very small sizes even at moderate energies, including implantation for q-bits and precise radiation effect studies, among others.

Simulation studies of the crystal beam formation in the trap were shown, as well as studies within rings to study the parameter space where the crystals would remain stable, or break-up.

The simulations of the formation of ionic crystals need to be compared to experiments, where construction of a Paul trap is in preparation, including an electron gun for ionization and detectors. An addition of a laser to allow cooling is necessary to start experiments on producing crystal ion configurations in the trap, and then really start to test the simulation results.

Comments

- There is a long path from the present status to any future applications, and this work has to be considered as a long-term investment.
- Incorporating a laser for ion cooling will necessarily require a substantial increase in the time devoted to experimental operations.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?
  - **N/A**. This specific topic is not part of EIC, and will not have an impact on the EIC the next decade.

c) Are the present efforts well executed, and future work well planned?
  - **Yes**. Within the scope of the present grant, it is well planned and executed.

Recommendations:

11. Evaluate if the experimental programme could be pursued in collaboration with a university, as the scope and complexity of the work appear well aligned with a doctoral research project.

Tunable monoenergetic neutron beam (LDRD C)

Findings

The project on a tunable neutron beam through deuteron disassociation was presented. The method was first described in 1947 and relies on a disassociation reaction that strips the loosely-bounded deuteron into a (p + n) pair with similar energies. A 2% efficiency is expected with a 100 MeV/n deuteron beam that impacts on a 1 cm Be target. The goal is to develop a tunable neutron beam at 15-200 MeV energy reaching a flux of 10^{10} neutrons/cm^2/sec.

A project on this concept was approved for FY2025 (LDRD-C $75k), that covers 8 hours of beam time at NSRL, engineer time, etc. Results of a beam test performed on September 3, 2025 were presented, obtained with deuteron beams at 100 MeV/u. The experiment includes a dipole behind the target that separates the charged protons from the neutral neutrons.

A calorimeter in the forward direction was installed to measure the neutron beam. However, the recorded data was mostly charged particle background. The neutron signal could not be verified. A new LDRD-C proposal was submitted for FY2026. An open-slot dipole magnet is defined to sweep away all primary beam deuterons and the breakup protons, scintillator strip detectors shall be used to tag the breakup protons and a neutron telescope detector (multi-layer segmented scintillators) shall be used for defining a charge-veto and flight-time, combined with a range-telescope. Event-by-event tagged neutrons are planned for a clear demonstration.

In questions it was clarified that the term “mono-energetic” relates for a 100 MeV/u deuteron beam to an expected neutron energy of about 50 MeV with ± 5 MeV energy spread (10%).

Comments

- The final deliverables of the proposed neutron source are not fully specified. The proposed neutron source should be modelled, including all of its components and relying on adequate models for physics, beam transport, scattering and detectors (e.g. using the FLUKA or similar simulation code).

- A detailed parameter table was not presented but would allow the committee to assess the expected neutron beam properties and the requirements from neutron applications. The table should define the energy properties and beam quality provided to users.

- An event-by-event tagging of p-n pairs for users, as presented in the discussion, seems a priori not adequate for user needs and should be explained in more detail.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **N/A.** There is no relevance of this work for the EIC programme, as far as we understand.

c) Are the present efforts well executed, and future work well planned?
   - **Partially**, see recommendation.

Recommendations:

12. Verify performance, user relevance and applicability of the proposed neutron source with analytical and numerical methods.

Production and acceleration of molecular ion beams at EBIS (LDRD 25-043)

Findings

As an alternative to delivering (unpolarized) protons to the Booter from the 200 MeV Linac, they could be delivered from the ion linac.

Tests were performed using the EBIS to deliver protons to the Booster through the ion linac, but showed limited success, with poor transmission through the chain understood to be due to the low magnetic fields at the lower injection energy into the Booster.

A way to increase the injection fields is to accelerate the H_2^+ or H_3^+ molecular ions in the Booster. Tests to produce these at the EBIS led to relatively low intensities of H_2^+, and no H_3^+. Nevertheless, the concept of accelerating H_2^+ in the Booster to 1 GeV/u was shown to be successful.

A higher intensity of H_3^+ has been demonstrated with other source types, and the team have chosen the route of a 2.45 GHz ECR source, which can be developed into a highly reliable source even at high duty factors. ECR sources are now the preferred source type for light ions.

The group has set an objective of 10 mA of H_3+ from the source, which in a 40 us pulse significantly exceeds the present proton intensity delivered to NSRL, leaving a large margin for transmission losses.

Presently an ECR source is being designed, with the aim to complete an offline bench to test the performance of H_3+.

Comments

- An ECR ion source for producing H_3+ on the ion linac has the prospect to reduce the operation cost for NSRL physics. But it does not replace the 200 MeV linac for polarized proton production, nor for Isotope Production.
- The addition of this source to the ion linac needs to be checked for operability, as the area is already very crowded.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **N/A**.

c) Are the present efforts well executed, and future work well planned?
   - **Yes**.

Recommendations:

13. Clarify the operational scenarios for H_3+ to NSRL, and how much operation of the 200 MeV linac could be spared.

Electron Sources: cathodes R&D

Findings

Electron beams are required for EIC in order to provide hadron cooling. Epitaxial photocathodes shall provide for the required high intensity electron sources. Those photocathodes shall have an ordered surface, low physical roughness and large grain or single crystal photocathodes with reduced grain boundaries. The gun must provide electrons with low emittance and high QE. Goals include high average current, high bunch charge, long lifetime and low emittance.

The presented 5-year project started in August 2021 and aims at completion in July 2026. The project is now in its final, fifth year. The completed project tasks are (1) single crystal photocathode development for K2CsSb in year 3 and Na2KSb in year 4, (2) the upgrade of the growth chamber with RHEED in year 2 and (3) incorporation of in situ x-ray characteristics with offline techniques in year 1 and year 2.

Epitaxial growth of Cs3Sb, K2CsSb and Cs2Te materials were performed on various lattice matched substrates. High quantum efficiency, ultrasmooth and epitaxial thin film photocathodes were achieved. Epitaxial growth of Na2KSb with an ultrasmooth surface (with EIC cathode evaporator configuration) was successfully realized. The experimental chamber was equipped with a new evaporator design same as the EIC HC cathode growth system, to grow the cathode material in the same deposition conditions as will be used for EIC. The new evaporators were conditioned and tested, with successful growth demonstrated.

Sodium potassium antimonide (NaKSb) photocathodes are one of the cathode choices for high-brightness applications. This material offers high QE, fast response, and good thermal stability, making it a viable candidate for high-brightness, high-average-current photoinjectors.

Presently ongoing is the fabrication of the cathode transfer chamber between growth and analysis tools with design, procurement, modification and fabrication completed. The cathode transfer chamber now needs to be further assembled and fully commissioned.

Finally, the high current test (in line with gun schedule) needs to be performed, including a lifetime test for the single crystal K2CsSb cathode and measurement of transverse emittance of the electron beam generated by this cathode. At present, simulation work continues for emittance measurements. A LabView based control and data acquisition system for emittance measurement is developed. The high current test is presently planned for 2026~2027 at Stony Brook University.

At the end of the project the characterization of damaged cathodes and investigation of recovering methods are planned.

An extensive list for potential long-term future work in cathode R&D was presented with topics in hardware & infrastructure development, in engineering for heterostructure photocathodes, in surface engineering for enhanced stability, and in continued High current test for cathode materials.

<u>Comments</u>

- The committee congratulates the cathode R&D team on their systematic approach in cathode R&D and the important progress achieved. This R&D topic is of high importance for the EIC performance in hadron cooling.

- The next steps, in particular the cathode high current tests, seem well prepared and we acknowledge the preparational work in simulations and in controls for the emittance measurement.

- The development of the Na2KSb cathode from a QE of 2.8% to 8% is supported, as well as the plans to confirm its high current performance and cathode lifetime.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.
b) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **Yes**.
c) Are the present efforts well executed, and future work well planned?
   - **Yes**.

Recommendations:

14. Perform the well prepared high current tests on cathodes as presented.
15. Work on a longer-term plan for cathode R&D in electron sources.

Proposal: Polarized deuteron ion source

<u>Findings</u>

The statement from the executive summary of “Realizing the Scientific Program with Polarized Ion Beams at EIC” (The EPIOS Scientific Consortium) demands: The EIC accelerator design team must make it a priority to develop ion spin control and manipulation from source to collisions of the deuteron, ^{3}He, ^{6}Li and ^{7}Li nuclei". It identifies polarized ^{2}H, ^{3}He, ^{6}Li, ^{7}Li ion beams as critical enabling technology for key measurements [Slated to appear in Physical Review C (Perspectives)].

A promising way to get polarized deuterons is to install, commission and operate the available COSY polarized deuterium ion source at the BNL Tandem Van de Graaff Facility. For polarized D^- beams polarization routines and measurements have to be established and could be a basis for follow-on AGS/EIC applications. A proposal has been submitted on 12/10/25, concluding that it will take 2 years and cost $2 million. The final layout of the ion source at the Tandem, the beam line design, the layout for the polarimeter at the high energy end of the Tandem, and polarization transfer in the Tandem to Booster (TtB) transfer line has to be worked out. Polarization preservation in the EIC has been investigated [Phys. Rev. Accel. Beams, 23:021001, 2020].

<u>Comments</u>

- Various types of polarized ions are requested at different times by the EIC. However, there is a considerable time overlap in the development, maintenance, and operation of polarized sources and polarimeters for different ions.
- The beam requirements of the EIC will certainly help to disentangle polarized beam developments, but a long-term vision and plan is required for making and keeping the source operational in the longer term (beyond delivery and installation). Polarized deuterons injection into EIC might be a phase three project for the physics program after collisions with polarized protons in the first phase and polarized ^{3}He in phase two.
- The transfer and setup of the polarized deuteron source from COSY may be time-critical because it may no longer be available once the time window for obtaining it has expired.
- The committee would like to point out that it would be desirable and, moreover, probably even necessary to get the support of experienced external specialists in order to transfer the knowledge to the next generation.
- Besides the COSY polarized deuteron source, other laboratories have developed this technology and the committee encourages the team to evaluate the pro and contra of the various approaches for the AGS/EIC facility.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.
b) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **Maybe**. It should be clarified if polarized deuterons are a part of the EIC goals and when would such a beam be needed?

c) Are the present efforts well executed, and future work well planned?
   - **Yes**.

Recommendations:

16. Clarify if the performance of the COSY source is compatible with the needs of the EIC.

Proposal: High-current Ion Sources - demonstration with niobium beam

<u>Findings</u>

The proposal is to achieve the highest intensity of highly charged Nb beam (5.0 × 10^10 Nb15+ ions/pulse) and to overcome the EEBIS actual performance. It builds on BNL's demonstrated world-record performances, including 58 mA Al11+ and 96 mA C6+ beams, establishing strong technical credibility and a low-risk foundation for the proposed Nb-focused program.

The choice of niobium as a pilot species is motivated: it is experimentally accessible, strategically relevant, and provides a clear pathway towards very heavy ions, with direct applicability to EIC commissioning and future accelerator upgrades.

The Direct Plasma Injection Scheme (DPIS) combined with advances in laser technology and RFQ design represents a distinctive and internationally leading approach, where BNL clearly holds core intellectual and technical leadership.

The demonstrated capability of the variable-structure 4-rod RFQ, designed for ~100 mA-class peak currents, provides strong confidence that the proposed performance targets are achievable within the proposed 2-year-timeframe.

Comments

- The committee recognizes the proposal as addressing a critical need for next-generation high-current, highly charged ion sources.
- The proposed R&D plan is well structured, technically sound, and scalable, progressing logically from plasma optimization to RFQ commissioning and long-term stability tests, with clear milestones and deliverables.
- The choice of niobium as a pilot species is helpful for effective EIC commissioning.
- Beyond the immediate Nb demonstration, the committee notes the broad impact potential of this work, including potential applicability to other heavy ions and relevance to future inter-disciplinary applications.
- The work is technically compelling, strategically aligned, and positions BNL to maintain leadership in high-current heavy-ion source development. The committee strongly supports this proposal and recommends its favorable consideration.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.
b) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **Yes.**
c) Are the present efforts well executed, and future work well planned?
   - **Yes.** The plan appears quite ambitious for the resources currently allocated.

Recommendations: None

Proposal: ERL-based high energy cooler

Findings

The proposal that was recently submitted to the DOE was presented. The objective of the proposed work is to design a non-magnetized RF-based electron cooler that employs an energy recovery linac to provide cooling of EIC protons at all collision energies. The present base EIC design makes use of the Low-Energy Cooling for reducing the initial proton beam vertical emittance at injection energy from 2 down to 0.3-0.5 micrometers. An addition of a high-energy cooling system to maintain beam emittance in collisions is highly desirable, however such a system has not been demonstrated and is currently not in the baseline design.

The EIC cooling rate requirements are driven by the intrabeam scattering which has a lifetime in the range of 2-4 hours for the transverse emittance. The implementation of a high-energy cooler is challenging because of the scaling of the cooling rate with energy and beam intensity, demanding a long interaction section and high electron current. Two technologies currently under consideration are the Ring Electron Cooler, which has matured to the conceptual design level after several years of work, and the ERL-based electron cooler (ERLEC), which is the subject of the present proposal. The primary benefit of the ERL-driven cooler over the ring-driven cooler appears to be an extension of the cooling to the lower hadron beam anergy, where the ring has the disadvantage of not enough synchrotron-radiation damping.

The stages for achieving a CDR have been identified and include optimization of e- beam parameters, optimizing the source, injection, ERL, recirculator ring and addressing the design challenges of fast kickers.

A first round of high-level parameter optimization has been performed aiming at obtaining the desired cooling with a reasonable beam. The cooler requires an average electron-beam current of the ERL of 60 mA (4.8 nC/bunch) with small normalized emittance of 2 um, which is considered challenging. To maintain enough cooling at higher hadron beam energy while keeping the electron beam current below 60 mA, the electron beam makes up to 9 passes before dumping and refilling. The concept is based on the established design of the LEReC DC electron gun, which is also chosen for the Low-Energy Cooler. The ERL design could be based on recent experience with a 150 MeV machine at JLab/BNL. Key physics effects critical for the optimization of the recirculator ring have been identified. Two technological solutions for the kickers are being evaluated.

The team has developed a workflow for iterating on the design options and plans to start work from the most demanding case of 275 GeV protons. The rough timeline spanning over two years was presented and is based on the team's experience with similar design studies in the recent years. This would allow the design to be brought to a state where a meaningful comparison of the ERL and the ring designs can be made.

<u>Comments</u>

- The proposed R&D is outside of the EIC Project scope, and at this time it is not clear if the benefits to the cooling rate at lower hadron energy are commensurate with the effort expended on producing two competing designs. As we were told by the presenter, high-energy cooling is most important for the high hadron energy case.

- While it is prudent to bring this design to the same level of maturity as the Ring Cooler, a set of comparison criteria and a path to a decision were not shown.

- Both designs carry performance risks. The ring-driven cooler requires a 2 A beam-current ring at low beam energy with complicated wigglers, whereas the ERL-driver cooler requires an ERL operating at 60 mA (which is high for an ERL) and possibly novel harmonic kicker systems to inject and dump the beam.

- The level of maturity expected at the end of the study has not been identified along with the analysis of the proposed effort.

Charge questions responses:

a) Comment on possible models of availability as a function of funding, and risks associated with single points of failure.

b) Are the C-AD plans aligned with the EIC goals over the next decade?
   - **Not clear**. A ring-based design exists and is deemed to be developed enough to write a CDR, with performance risks addressed as far as possible.

c) Are the present efforts well executed, and future work well planned?
   - **Maybe**. The presentation of the current plan was very clear. However, we were not shown a path towards a decision based on established criteria.

Recommendations:

17. The Department leadership is encouraged to review the study plans and, in discussions with the EIC project, verify that increased cooling at lower hadron-beam energy is a sufficient reason to embark on the ERL-based design study and justifies the required effort. If there is a consensus that the ERL design study should continue, clear comparison criteria and risk-quantification methods should be developed in a timely manner. Effort should be focused on addressing these criteria and risks.