Report of the 20th C-AD Machine Advisory Committee meeting

December 19-21, 2023
Hybrid format meeting

Present: Andreas Lehrach (Aachen University), Yoichi Sato (KEK/J-PARC), Richard Scrivens (CERN), Andrei Seryi (JLAB), Alexander Valishev (FNAL), Uli Wienands (ANL)

Excused: None

Charge questions: The committee was asked to advise on (i) the operation with sPHENIX and STAR, (ii) the plan to maintain the hadron injectors for EIC, and (iii) the presented R&D initiatives, and in particular, for items (i) and (ii), to address the following charge questions:

a) Are the technical goals realistic and is the progress appropriate to meet the stated goals?

b) Are there any technical issues that were missed and/or need additional attention by the team?

And for item (iii), to also address the following question:

c) Is the accelerator R&D effort well executed and future work well planned?

Overview

The Committee thanks the C-AD management and staff for organizing a well-prepared hybrid meeting and all the presenters for their excellent talks and staying within the time limit. The Committee appreciates that the C-AD management responded to all recommendations from the previous 19th MAC, and included them in corresponding presentations, or in the overview talk.

The RHIC accelerator complex is a uniquely flexible and only hadron collider in the US for exploration of QCD phase diagram and proton spin, capable of providing heavy ion and polarized proton collisions with highest luminosity. The RHIC science program will be completed in 2025, at which point the transition to the Electron-Ion Collider construction will begin.

The Collider-Accelerator Department (C-AD) is preparing for two more years of running with the new sPHENIX and the upgraded STAR detectors. The remaining 2024-25 runs will focus, correspondingly: Run-24 on p+p at 100 GeV, and Run-25 on Au+Au at 100 GeV/nucleon collisions for the new detector sPHENIX and STAR. The most recent RHIC Run-23 was ended on 1 August 2023, 6 weeks early, initiated by a helium leak in a valve box and subsequent damage to a superconducting DX magnet. The DOE Office of Science has approved a carry-forward of 6 weeks Au+Au operation from Run-23.

After completion of the RHIC program the C-AD will maintain the hadron accelerator complex in a ready state while transitioning the majority of the staff to the Electron Ion Collider (EIC) Project. Substantial and well-coordinated efforts are ongoing aimed to maintain and enhance the RHIC injector complex for EIC operation.

The elements of RHIC accelerator complex are also used for a variety of impactful application programs such as isotope production using LINAC/BLIP, space radiation studies at Booster/NSRL, industrial and medical applications at tandems, further enhancing the nationwide impact of the lab. The above mentioned efforts include all elements of the RHIC injector complex except AGS.

However, there are additional and well justified opportunities to continue using AGS during the period when RHIC physics will end, and before EIC will start operating. In particular: operation of AGS for 3-4 weeks/year can significantly boost polarized 3He development for EIC, as well as development of high intensity polarized proton beams. AGS operations can be also helpful for development of the alternative schemes for transition crossing, or for polarimetry development with a jet target. The committee is endorsing the efforts to develop the plans to continue running AGS after completion of RHIC runs.

Recommendation:

Develop technical and resource plans for continuing to run AGS after completion of RHIC physics runs.

RHIC Performance and repair status

Findings

The RHIC Run-23 goal was to commission the sPHENIX detector and to deliver Au-Au collisions at the center-of-mass energy of 200 GeV to sPHENIX and STAR detectors. The sPHENIX PD-4 project approval was achieved on 12/12/22. The late start of the run demanded operating into the summer. Beam was injected into RHIC on schedule by May 10, 2023, and the team demonstrated a very fast pace of commissioning to collisions by May 18. The alternating APEX (Accelerator Physics Experiments) and maintenance program started on May 24. The collider provided a wide variety of beam conditions thus enabling sPHENIX commissioning and successfully meeting all requirements. Collisions at STAR were provided with the crossing angle of 1 mrad and luminosity leveling and resulted in the collection of 30% of combined Run-23 and 25 minimum-bias statistics goal. On August 1 the Blue Ring 1004B valve box failure forced an early run termination, 6 weeks earlier than planned.

Machine availability in Run-23 was 74.4%, lower than the 10-year average of 85.8%. In addition to the critical failure ending the run, reliability in Run-23 was affected by factors stemming from the operation during summer months, including heat, humidity, and power outages. Inflation and supply chain issues, most prominently the abrupt rise in the cost of He, also created operational challenges.

The APEX program in Run-23 focused on experiments to inform EIC design and beam cooling studies and allocated a total of 44 hours to 6 experiments over four experimental periods. The highlighted results include the demonstration of operations with a large (11:1) horizontal to vertical emittance ratio and the snake aperture optimization.

An extensive program of analysis and repair of the valve box and splice failure is progressing with the goal to recover collider operations by early March 2024. At the time of the review, the 1004B valve box feedthrough pressure and electrical tests are complete, a new feedthrough tube and bellows have been installed. The spare DX magnet was tested and installed, the wiring in splice cans is proceeding.

The RHIC science mission in the remaining two years of operations assumes 20 cryo weeks of polarized proton collisions and 6 carryover weeks of Au-Au collisions in Run-24, 24 cryo weeks of Au-Au program in Run-25. Since the schedules of both runs include operating in the summer months, an extensive program of preventive maintenance and upgrades of the systems necessary to support this mode is executed.

In addition to the core physics program, the APEX studies dominated by EIC related R&D are planned for Runs 24 and 25. At present, a total of 36 hours of beam time is requested, which can be accommodated by allowing 2 shifts every other week.

<u>Comments</u>

- The rapid startup of beam operations and the success with the sPHENIX detector commissioning in Run-23 are significant accomplishments and a testament to the strength of the C-AD team and well established tools and operational processes.
- The APEX program made good progress in Run-23 despite a smaller than usual beam time allocation. The APEX process is well established; we agree with the approach of intertwining collider luminosity delivery with accelerator R&D time over a single large time block towards the end of a run as a strategy to mitigate risk of a single failure. The focus of APEX on studies informing the EIC design is appropriate. Yet we encourage the team to engage with national and international

partners to explore research opportunities of broader scope - as the only operational collider in the US, RHIC could potentially allow the exploration of concepts for future facilities.

- The failure mode of the 1004B valve box and subsequent damage to the wiring in the splice cans are well understood. The strategy for mitigating risk in the short term by improving current lead flow control is reasonable, and we encourage work on the prevention of recurrences in EIC operation.
- The work on modernizing obsolete systems and on making RHIC capable of operating in the hot months makes good progress. The downtime categorization by the responsible system is tracked, however the breakdown was not presented and it is unclear how much of the 15.6% downtime in Run-23 was caused by impacts of heat, humidity and other such factors. The experience of operating in the summer in runs 23, 24 and 25 should be analyzed from this perspective.

Charge questions responses:

a) **Yes.**
b) **No.**
c) **Yes.**

Recommendation:

- **Plan a long-term program of inspections and/or repairs relevant to the failure mode realized in the 1004B valve box incident, aiming to prevent recurrence in the EIC era operation.**

<u>p+p luminosity maximization for sPHENIX</u>

<u>Findings</u>

The Run-24 program comprised of up to 26 cryo weeks will be dominated by the polarized proton collisions with up to 16 weeks of physics. A key feature of the new sPHENIX detector, the relatively small luminosity region of +-10 cm requires the optimization of collider configuration to fit a high percentage of interactions within this vertex. The scheme with a crossing angle of 2 mrad was chosen to achieve this goal.

The best RHIC performance with polarized proton beams at 100 GeV was demonstrated in Run-15. Assuming the Run-24 luminosity delivery at the same rate as in Run-15, meeting the sPHENIX data collection goal would require 22 weeks, hence the luminosity must be increased by approximately 40% to reach the goal in 16 weeks.

Two paths for the luminosity increase were identified: through the reduction of beta* and by increasing the beam intensity. In Run-15, head-on beam-beam effects caused performance degradation, which was compensated by the electron lenses. These studies established a limit on the tune spread, which predicts that with the 2 mrad crossing angle the bunch intensity can be raised to 3e11, some 40% higher than with head-on collisions. For the beta-function reduction, an option of 50cm (from the current 85 cm) was evaluated. The effect of such a change on luminosity within +-10 cm is ~50%. An optics solution exists using a beta-wave to realize such a squeeze while also providing sufficient physical aperture clearance.

Preliminary studies of the dynamical aperture have been performed and indicate issues at the high beam intensity in the optics with beta* of 85 cm. The dynamical aperture in the 50 cm optics is insufficient at beam intensities above 1.8e11. Further optimization is in progress and will involve betatron tune scans or intermediate beta* values.

The capability of the injector chain to generate higher bunch intensities (3.4e11 at AGS extraction) was evaluated. Two basic options were considered: via using two Linac pulses and a subsequent two-bunch merge, or with a more intense Linac pulse, the former being more efficient in terms of the overall performance due to the higher polarization. Several technical challenges exist on the path to higher implementing beam intensity, including the longitudinal RHIC acceptance and the dependence of polarization on intensity. The campaign of improvement of the polarization transmission in AGS via cancellation of horizontal resonances with skew quadrupoles and by AI/ML applications may result in relaxed requirements on the beam intensity.

A comprehensive program of simulations and studies of the various options is being executed. It is believed that a combination of the beta-function squeeze and higher beam intensity will allow to reach the sPHENIX integrated luminosity goal in the allocated time.

In response to the MAC-19 recommendation, the consequences of a quench protection diode failure were presented: the worst-case scenario could result in downtime of up to 40 days.

<u>Comments</u>

- We agree with the approach to push for better luminosity performance by exploring several directions, even partial success in each one will contribute to the desired overall outcome and also inform future developments for the EIC.
- The impact of dynamical effects on performance is potentially a concern. While baselines for some configurations were established by previous runs, the Run-24 scenario proposes to enter a sufficiently uncharted territory in terms of the beam intensity (10-20% up from the demonstrated maximum) coupled with larger momentum spread, and collisions with a large crossing angle. Even if these factors are not limiting separately, their combination may be significant.
- In view of this, the decrease of beta* seems to be the most promising approach.

Luminosity leveling by squeezing the beta* in several steps is the baseline strategy for Run-24. The model for integrated luminosity within +-10cm vertex assumes a squeeze to beta*=50cm 3 hours into a store We advise to prioritize the investigations of lattice tuning aiming at achieving reasonable dynamical aperture, since the tools are well established.

Charge questions responses:

a) **Yes.**
b) **Maybe. We are concerned about i) the collective beam stability in RHIC at bunch intensities above 2.4e11; ii) the possible emittance degradation caused by high-intensity beam collisions at large crossing angle.**
c) **Yes.**

Recommendation:

- **Prioritize the modeling of beta*=50cm (and intermediate) optics aiming at achieving the desirable dynamical aperture before Run-24.**

Injector upgrade plans for EIC

Findings

This presentation well replied to the recommendation of the 18th C-AD MAC, "Perform an assessment of components and spares needed to continue running in the EIC era".

25+ year technical infrastructure upgrade plan is well organized to match the schedule of Accelerator Readiness Reviews planned in the following over the next few years, Linac/Booster combined (2025), AGS (2026). Specific work required for successful Linac/Booster ARR has mostly been identified. AGS work still in the process of being identified. Documentation is in the process of being prepared. Tandem ARR was successfully completed in 2022.

Capital equipment and operations funded upgrades are well discussed. Necessary of Chipmunks (very early design phase) upgrades are reported. These radiation monitors are old and difficult to maintain; and spares are very limited. In AGS – Siemens Main Magnet Power Supply Cycloconverter, we have to note the manufacturer no longer supports the present system. The estimated cost to replace is $5 Million Total, but $2.5M AIP funding presently is available. Alternatives are being explored as a result of cost increase. The Cryo System Upgrades also requires additional funding on Central Plant and 912 Upgrade.

For Booster main magnet power supply, the existing system induces significant disturbances on the power line, and it affects RHIC magnet power supplies resulting in beam perturbation. The replacement cost is ~ $35M and 6-month shutdown. The Upgrade would include capacitive energy storage (used for CERN PSB and PS, and for J-PARC MR) includes Booster creates disturbances in the electrical grid due to the load changes.

Linac RF Tubes – 40-year supply needed. Existing tube RF amplifiers are the most cost effective as long as we can ensure that they are available. Replacing the present RF system with klystrons was evaluated as an alternative but cost is significantly higher.

All upgrades will be scheduled based on priorities and funding availability

Comments

All cost estimates are based on reasonable arguments, including requests for additional funding. To measure the AGS- Siemens Main Magnet Power Supply Cycloconverter, the team refers CERN case as a good success story. The replacement of the booster main magnet power supply is based on a robust scenario. Although it imposes a severe burden in terms of both cost and long-shutdown, it is worthy to improve the long-term operation efficiency.

Charge questions responses:

- **a) Yes.**
- **b) No.**
- **c) N/A**

Recommendation:

Booster PS replacement will be beneficial for increasing performance and reliability of running in the EIC era. Attempts should be made to allocate funding for this item, following the refrigerator upgrade efforts. Schedule the replacement of the booster main magnet power supply carefully, including off-line commissioning before beam operation.

EBIS status and performance ramp-up plan

Findings

The Extended EBIS (EEBIS) provides space to install a 3He polarization cell, necessary for the EIC polarized He beam. The extra trapping length also opens the possibility of higher Au intensity.

The EEBIS has been moved from the test area and installed onto the Linac, and a first beam was extracted after a very fast commissioning, representing an important milestone.

Improvements in the vacuum system to avoid cryogenic pumps looks to have been successful, in particular the move to new NEG strips which can be rejuvenated in a relatively short time.

However, pressure rises have been observed that limit the intensity of Au^{32+} ions with 5 Hz rep-rate 12 pulses per supercycle operational mode which is required for efficient ion injection into RHIC. The lifetime of new oxide cathode is found to be shorter than initially expected, but it is still adequate for reliable Extended EBIS operation for both RHIC and NSRL.

There is still significant technical, installation and commissioning work to be done to obtain polarized 3He from the EBIS. The gas polarization cell development needs to be completed in the offline solenoid, and the layout needed to fit inside the gas injection region also needs to be demonstrated to work. At that stage the installation into the EEBIS solenoid can be made during a stop of a couple of months, and the full ion production testing can start. Due to the injection of gas, the commissioning might not be compatible with operation of some ion types (especially the higher charges).

Comments

This R&D for polarized 3He from an EBIS is really unique, and the advances made so far are impressive.
Au beam intensity is presently lower than the single EBIS, and the impact of this for Run2024 needs to be clarified.

Charge questions responses:

a) **Maybe. The installation of the extended EBIS and putting it into operation on the Linac is a very significant milestone. We note that the time necessary for repairs, installation and commissioning polarized 3He, needs to be allocated.**
b) **No.**
c) **Yes (applicable for R&D only).**

Recommendation:

1) For the issue of discharges observed in the short trap, consider a dedicated conditioning test under consistent conditions, of the order of half a day, to clarify if the discharges can be conditioned or not, and to understand the "decay time" of this discharge.
2) Make sure the polarized cell integration is ready for installation into the EBIS for a likely installation date at the end of 2024, and that commissioning time for polarized 3He from in the EBIS is allocated.

Polarization increase in AGS with skew quads - update

Findings

All 15 skew quadrupole magnets have been delivered, 14 have been installed and power supplies have started to arrive and will be delivered on time. Analysis and measurements to characterize the eddy current effects are underway. The commissioning plan has been discussed. An overall scaling of the correction will be performed and the effects on tuning and coupling will be verified. The effects will be characterized using measured average polarization and polarization profiles measurements. Simulations predict an AGS flattop polarization of 75% with a full skew quadrupole correction scheme.

A more comprehensive Bmad model will be developed to include additional effects and improve optimization.

Comments

The project is progressing well, and the concept of adding magnets as their power supplies arrive sounds reasonable. The overall scaling of the correction will be an important milestone for an efficient correction scheme. The AGS flattop polarization of 75% seems to be an ambitious goal. In this context, the collaboration with Cornell on the AGS's Bmad model is crucial, as the SPRINT functionality has been imported into Bmad, allowing for improved optimization schemes (see AI/ML based methods of GH's talk). The measurement of the driving terms for the coupling should be included in the optimization process of the skew quadrupole settings (see R6 of MAC-19).

Charge questions responses:

a) **Yes**
b) **No**
c) **Yes (applicable for R&D).**

Recommendation:

1) After applying the overall scaling of the correction, polarization measurements should be performed at several intermediate energy steps where the largest polarization losses are expected. In addition, horizontal spin resonance driving terms should be measured at these intermediate energies.
2) Study remaining sources of depolarization by weaker higher order snake resonances or weak hybrid resonances.

ML for beam polarization increase (FOA)

Findings

About 20% of the polarization is lost from the source to the RHIC experiments. Even 5% more polarization would be a significant achievement, since the polarized luminosity for longitudinal collisions scales with P^4. The modelling of the accelerator chain takes place from the extraction Linac to the booster, the AGS and the RHIC ramp. The main issues to improve polarization are emittance reduction, more accurate timing of tune jumps and reduction of resonance driving terms. Detailed models of various subsystems in the accelerator chain are currently being built. Places where AI/ML will be used in the booster are ORM, dispersion, tune and chromaticity measurements. In the AGS projects are a detailed model of AGS including differentiable snakes, symplectic tracking, orbit and optics compensation of snakes for all energies and timing of tune jumps. Regular meetings are held with all the collaborators from BNL, Cornell, JLAB, SLAC, RPI, SUNY, etc.

Comments

ML is very powerful for an approximate model and a step-by-step model-guided optimization using the model to select the next optimization point, as it is also applied by the team. The starting model should contain all available information. Field overlap of nearby magnets is an important topic at other medium-energy hadron accelerators (J-PARC RCS, COSY) and should be included in the model based on field calculations.

Beamtime for machine experiments plans are available at the AGS booster and beam lines. Sufficient time for beam studies at the AGS or related developments is also available when RHIC will be transitioning to EIC.

Charge questions responses:

a) **Yes.**
b) **Yes. (see comment about the overlapping fields)**
c) **Yes (applicable for R&D).**

Recommendation:

Include at least the first-order effect of field overlap between nearby magnets (change in effective magnet field length) in the model.

ML for luminosity maximization (FOA)

Findings

This proposal has made good progress since last year. An existing package (GPTune) has been adapted for use and tested first on the luminosity formula, and then on a tracking model for sPHENIX with reasonable output. A test of the script to change the waist location was done in IR12 on the machine to assess the effect on beam lifetime.

A separate model was made for EBIS and used in machine studies with good results. Even with noisy data the fitting process converged to a stable solution with total improvement claimed at the 30% level from the starting point, using up to 19 parameters fitted first in two groups of 9 and 10 parameters, resp., acting on two different charge monitors, yielding 22% improvement. A third fitting step using all 19 parameters yielded another 7% increase.

Comments

Upon request the committee was shown a list of the parameter changes during the optimization process. However, there was no analysis of the changes seen and their significance.

The model used for EBIS could be useful in further tuning-up EBIS and be a useful operational tool.

We were told there is a communication process with sPHENIX management about the tuning parameters and limits. The committee is pleased to be able to acknowledge the constructive response to the recommendations made at the MAC-19 meeting, and we are looking forward to the results of application at sPHENIX at the next MAC meeting.

Charge questions responses:

a) **Yes.**
b) **Mostly No,** but the team is encouraged to pay close attention to the resulting parameters after an optimization run in order to gain insight into the overall behavior of both the machine as well as the optimizer.
c) **Yes.**

Recommendation:

Pay more attention to the results of the optimization runs in order to gain insight of the process as well as better characterize the system being optimized (sPHENIX luminosity, or EBIS as the case may be).

High-current LION (FOA)

Findings

The LION project will develop a high current laser ion source (LIS) and a Radio Frequency Quadrupole (RFQ) to provide ion beams with very high current and highly charged states. The species will first be light to medium mass ions.

LIS can provide high current beam with low temperature after adiabatic expansion, uniform density of beams, and low emittance growth, and can provide high charge state ions using high laser power density. LIS does not require a strong magnetic field like conventional high-current highly charged ion sources such as ECRIS, and can inject ions directly into RFQ. Its key technology, Direct Plasma Injection Scheme (DPIS), was invented by the project team, and the team have provided various ion beams without major maintenance since 2014. They have reliable experiences for stable and reliable operation, reproducible high current beams, and well-controlled beam emittances. The LIS technology is applicable for carbon therapy and neutron source, and its worldwide collaboration is expanding.

Newly designed RFQ electrodes are aimed to achieve over 100 emA peak current, 50 kV extraction voltage, output energy 280 keV/n, and max m/q = 7/3, which is suitable for 7Li3+ ion beams. A variable aperture was used to provide variations in resonant frequency and electrode voltage. These strategies are based on reasonable simulations for the initial design.

The test RFQ successfully provided 20 mA Mg10+ and 10 mA Mg12+, fully stripped ion, and achieved world records of peak currents of 11B5+ and 26Mg10+, and of particle number of 12C6+. After further acceleration to medium mass ions in 2024, the team aims to accelerate high current heavier mass ions with DPIS.

Comments

The Laser Ion Source is suitable for next generation accelerators, providing short-pulses of high current highly charged beams, and the potential for well-controlled beam emittances. The project team possesses all the technology necessary for stable and reliable operation. The world-wide collaboration demonstrates the social importance of this project. Powerful lasers, necessary for LIS, are still expensive to manufacture, however, the laser technology is developing year by year, and costs will come down in near future.

This project is closely related to the "Laser Ion Source (LDRD 23-007)" project. We expect both projects to develop new technologies for pulsed neutron sources.

Charge questions responses:

a) **Yes.**
b) **No.**
c) **Yes (applicable for R&D).**

Recommendation:

The LIS technology initiative must be maintained at BNL. Report further achievements in 2024

Laser Ion Source (LDRD 23-007)

Findings

The application concerns laser ion source development for a compact neutron source from a reaction of 14 MeV lithium ions on a proton target.

The potential for generating the required high currents of lithium ions is well suited to a laser ion source. The team has already demonstrated 35mA of 7Li3+ out of an RFQ.

This project's objective is to study a liquid target surface for the high repetition rate laser as a mitigation to the issue of craters formation on a solid target; this is a logical path to try. A significant part of the study will be to try to mitigate the impact of vibrations on the surface, and a few ideas were shown.

The liquid target test set-up has been designed, and after a safety review production and testing are planned for 2024.

Comments

Development for such a system has a very high potential reward.
A liquid Li surface may turn out not to be a viable solution, but the present investigation is very worthwhile at this stage, and will allow the team to gain experience in liquid Li handling.

Charge questions responses:
a) **Yes.**
b) **No.**
c) **Yes (applicable for R&D).**

Recommendation:

Further contacts with potential users of the neutrons to better understand the future requirements.

Photocathode development (ECA FOA)

Findings

The team presented results on epitaxial growth of multiple alkali-based photocathode materials. As demonstrated at measurements, performed at NSLS-II and test stands, the cathode films are showing exceptional qualities and performance in crystallinity, surface roughness and QE in a varied thickness range. The next steps of the study will include measurements of the emittance for epitaxial K2CsSb photocathode, gun test aiming for up to 100 mA average current (meeting EIC hadron cooling requirement), and development of mitigations for damaging mechanisms and cathode lifetime improvements. The requirement for QE is minimum 3% and up to 8% and above, creating a range where the laser power can be adjusted. The demonstrated photocathode met these requirements.

Comments

The team is commended for great efforts toward developing the path to meet the needs of EIC in unpolarized photocathodes. The committee understands that there are several parallel efforts on development of photocathode production. It is recommended to cross-check the parallel efforts to maximize the prospects for success by learning from each other.

Charge questions responses:

a) **Yes**
b) **No**
c) **Yes (applicable for R&D).**

Recommendation:

Review parallel efforts on photocathode production to cross-disseminate lessons learned and maximize community's success towards establishing photocathode production for EIC and beyond.

Permanent magnet applications (LDRD 22-013)

Findings

Prototypes of open-midplane permanent magnets for FFA beamlines, relevant for CEBAF upgrade, have been developed and measured. The magnets feature about 1.5 T maximum field combined with about 50T/m gradient, in the +-7.5mm vertical aperture with good field region +-10.5mm. The magnet consists of 24 permanent magnet wedges, assembled in Halbach configuration. Assembly procedures have been developed. The prototype magnet slices are about 50mm long. Fieldmap measurements procedure have been developed, and demonstrate achievement of 1E-3 field quality after tuning. Assembly and tuning involve using brass wedges and iron tuning rods, inserted into the magnet aperture. The prototypes exhibit thermal sensitivity of around 1E-3/K, consistent with the properties of the materials.

Comments

The committee is pleased to see great progress in development and field measurements of FFA magnet prototypes. In discussion with the team the committee also learned that long magnets will be integrated from thin slices, and there are several options considered for field quality tuning of the long magnets. The NSLS-II upgrade design efforts consider similar magnets, and integration of the vacuum chamber can be very similar (based on splittable magnets). While perhaps beyond the LDRD project scope, the committee believes that procedure of tuning the long magnets and integration of vacuum chambers need to be developed quite soon, as they may impact the approach for design and assembly of short slices, as well as the choice of the vendor. These integration studies will need to be done together with the CEBAF collaborating team. The thermal expansion characteristics and thermal stabilization approaches need to be developed further.

Charge questions responses:

a) **Yes**
b) **No**
c) **Yes (applicable for R&D).**

Recommendation:

Working with collaborators, a) develop practically realistic procedures for tuning long magnets, taking into account the need to integrate magnets with vacuum chambers, while maximizing vertical aperture for the beam; b) Develop practical methods for integrating vacuum chambers into long magnets, possibly taking into account NSLS-II upgrade design efforts.

Ring cooler feasibility study for EIC

Findings

In 2023 the Dept. launched a study of an electron-storage-ring-based high-energy electron cooler for EIC, as backup to the baseline of coherent electron cooling. A 150-MeV race-track electron ring with eighteen 4.2-m long wigglers and a dual-frequency rf system to prepare the necessary beam emittances and dimensions would drive a 180-m long cooling section. An electron-beam current of 3 A (average) is needed to achieve cooling times equal to or shorter than the IBS growth rates at 275 GeV proton energy. Such schemes have been discussed in the literature before but have not been realized so far. The study has undergone a feasibility review in June 2023 with a number of recommendations made to point out areas of investigation needed to assess practicality of the scheme.

The scheme presents several accelerator-physics challenges, most notably the wiggler section and its effect on the optics and the dynamic aperture. The study group has focused on the wiggler section and made notable progress since the Feasibility Review, refining the description of the wigglers and optimizing the design to significantly reduce the chromaticity added to the ring lattice by the wiggler section. Dynamic aperture of 5-6 beam-sigma has been shown in modeling; these are initial results and the expectation is that it can be further improved upon.

First investigations of vacuum requirements suggest that a pressure less than 1E-9 torr (with beam) may be needed for useable beam lifetime. While potentially challenging, modern NEG coatings should be able to achieve such pressures.

<u>Comments</u>

The committee understands that results may be needed in Q2, FY25, if there is a case to be made for changing the EIC project baseline to include the REC. To facilitate this, the study team will need to determine feasibility of the wigglers and the key parameters of the other systems needed to make such a ring work: Injector and injection/extraction, vacuum system, the dual-frequency rf system and the ring-magnet parameters. On the beam-physics side, the wiggler work needs to continue to gain confidence the optics of the wiggler section is described correctly and completely, and collective effects need to be assessed as well as the extent to which stabilization of the dual-frequency rf system against beam loading is needed.

Charge questions responses:

- **a) Maybe.** This being a status report there were no stated goals. Overall feasibility of the REC still needs to be established.
- **b) Yes.** The work has focused on the wiggler and single-particle beam dynamics; most other accelerator physics questions, and all engineering/implementation questions, remain to be addressed.
- **c) N/A.** The work presented is detailed and appropriate. A plan for future work was not presented.

Recommendation:

The Dept. and the study group are encouraged to assess and provide the effort needed to determine the required design details in line with the EIC project needs.