Report of the 21st Meeting of Collider-Accelerator Department Machine Advisory Committee (C-AD MAC)

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BNL / hybrid meeting

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Present in person: Ralph Assmann (GSI), Andreas Lehrach (Aachen University), Yoichi Sato (KEK/J-PARC), Richard Scrivens (CERN), Alexander Valishev (FNAL), Uli Wienands (ANL)

Excused: None

Charge questions: The committee was asked to advise on (i) the operation with sPHENIX and STAR in the final Run-25, (ii) the plans for maintaining and upgrading the hadron injector complex over the next decade for EIC, and (iii) the presented R&D efforts.

For items (i) and (ii), we were presented with the following charge questions:

a) Are the technical goals realistic to meet the stated goals?
b) Are there any technical issues that were missed or need additional attention?

For item (iii), we addressed, in addition, the following charge question:

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

Overview

The committee members are grateful to the Collider-Accelerator Department (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-20.

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 delivers heavy ion and polarized proton collisions at the highest luminosity. The RHIC science program will conclude in 2025, after which the transition to the Electron-Ion Collider (EIC) construction will begin. Injector machines of the 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 academic applications at the tandem, further enhancing the nationwide impact of the lab. C-AD is also engaged in accelerator R&D aiming at developing technologies for future facilities and broad applications.

C-AD is preparing for the last year of RHIC operation focusing on delivering Au+Au collisions at 100 GeV/nucleon for the sPHENIX and STAR detectors, while also considering other operation modes (proton-proton, proton-Au, etc.) and studies relevant to the EIC development.

After the completion of the RHIC program, C-AD will continue maintaining and operating the hadron accelerator complex to support the growing Isotope Program and NSRL and keep the machines in a state of readiness for the EIC. To accomplish this, a substantial, well-coordinated program of maintenance and modernization is being executed. A major effort for C-AD in the past three years was the preparation for and the execution of Accelerator Readiness Reviews for all legacy accelerators, the work that will continue through 2027.

C-AD will support the EIC Project, both through staff transfer as well as by matrixed employees.

The accelerator R&D portfolio of C-AD is vast and relevant: the department is engaged in beam cooling research, source development, polarized beam dynamics research, AI/ML, and pursues novel concepts. There and well justified opportunities to continue using machines of the accelerator complex including AGS after the completion of RHIC physics run.

Comments

- C-AD is focused on the remaining RHIC operations and maintaining the hadron injector complex. Appropriate attention should be given to the transfer of knowledge about long-term reliability of RHIC components and systems that will be utilized by the EIC.
- Maximum exploitation of RHIC for science and accelerator development up to the end of 2025 calendar year within the allocated resources must be ensured. A premature, budget-driven end of the RHIC run would forgo valuable opportunities.

Recommendations: None

RHIC Performance in Run-24 and planning for Run-25

Findings

The sPHENIX detector came in new in 2022 and installation was completed in 2023. In 2023 a failure in the valve feedthrough happened and was repaired. In April 2024 sPHENIX was completed. From April to September a polarized p+p 200 GeV run took place. From September to December the Au+Au 200 GeV engineering run took place. The emittances at the start of luminosity production were optimized, from typically around 5 micron to about 2 micron. A scrubbing run was needed at the start of the run. Instabilities were encountered. Beam polarization was optimized and reached essentially the same level as in 2015.

A special challenge are the auto-recovery events in MVTX. They appeared already in 2023 during the first sPHENIX run. Then in Run-24 they had a massive impact. The MVTX detector trips and takes 15-20 seconds to recover. The beam pipe in sPHENIX is quite misaligned.

Concerning availability, the goal from DOE developed over the recent runs ranged from 82.5% to 85%. During the FY24 RHIC run an availability of 80.4% was achieved. The average availability over the last 10 years was 85.2%.

In answer to a homework question the breakdown of run statistics was presented. Downtime is dominated by issues from power supplies, pulsed power and electrical systems. In Run-23 the valve box failure had a strong impact. Run-24 showed the influence of accesses to sPHENIX and of Linac failures with increasing rate due to no

Linac maintenance done. Linac maintenance was performed before the upcoming Run-25.

The FY25 run will start at the end of March 2025. By that time the budget will be known. The availability goal for FY25 is 80%. The nominal crossing angle will be 1.5 mrad and is constrained by detector requirements from sPHENIX.

In an answer to a homework question it was clarified that the luminosity goal for Au+Au is 7 nb^{-1} within +-10 cm. During Run-23 a total of 3 nb^{-1} of commissioning data was collected, not counting towards the goal. In Run-25 it is expected to collect 0.36 nb^{-1} per week, so that 20 weeks of operation (6 days per week for sPHELIX) are required. The auto-recovery problem can at most mean a factor 4 reduction in physics reach for certain channels. At the same time operation in triggered mode leads to a factor 13 reduction in auto-recovery events.

There are two scenarios for run length: 20 or 28 weeks (from which 2 weeks were already spent), depending on budget. The predicted delivered luminosity ranges from 1300 to 2300 ub^{-1} per week. In an answer to a homework question it was clarified that the Associate Lab Director asked for 20 week and 28 week plans. 2 weeks were already spent on the Run-24 extension. The run length will be determined by the budget. Budget clarity is required to optimize run plans. The department can plan until the end of the calendar year, even with the end of the budget year in between. It is also a possibility that running in July and August is skipped due to issues with systems operating in hot weather.

It was shown that the machine protection system of RHIC had been successfully improved and upgraded. Presently there are no issues any more. The 56 MHz cavity was shown some years ago to improve the longitudinal bunch shape such that higher longitudinal peak current can be achieved. This resulted in a >15% increase in luminosity in 2016.

The RHIC Accelerator Safety Envelope (ASE) expires on 31 December 2025. This defines the firm end date for RHIC operation. Alternatively one would need to start working now on its extension.

<u>Comments</u>

- The RHIC team has successfully completed Run-24 and the results obtained are applauded.
- Several issues have been encountered, limiting the achieved collider availability, which still remained acceptable at 80.4%.
- Major issues included running during summer months and the auto-recovery events in the sPHENIX MVTX detector.
- A detailed breakdown of the downtime would be useful for the committee and was presented in answer to a homework question.
- The experience from the scrubbing run and lessons for future scrubbing needs were not presented in detail.
- The FY25 run seems well prepared.

Charge questions responses:

a) **Are the technical goals realistic to meet the stated goals? – Yes**, the goals seem to be realistically defined. A risk remains due to the auto-recovery events. The priority for the Au-Au run is supported by the MAC.

b) **Are there any technical issues that were missed or need additional attention? – Maybe**
It was not clear if a further scrubbing effort is required. Instabilities could be analyzed in more detail but this will probably not put the goals into risk.

Recommendations:

1. **The nature of the instabilities encountered should be described in more detail.**
2. **Define a strategy for the 56 MHz cavity before the start of the run, that achieves an optimal trade-off between invested time and expected performance gain.**

Experimental background in Run-24 and sPHENIX MVTX experimental background task force

Findings

The MVTX in sPHENIX is the detector closest to the beam pipe, consisting of three layers of the detector with about 0.5-1 cm radial distance between layers. The detector was designed to operate in full-streaming mode, i.e. reading out constantly. If any of the staves is overloaded with charge, the entire stave goes into auto-recovery mode, which is a 20-second time period. Such an event can be triggered by a single ion striking the beam pipe. The proton-proton collisions do not saturate the staves, this problem is specific to Au-Au collisions background. There is also significant asymmetry between the backgrounds from Yellow and Blue beams, yellow beam being the dominant source.

Calculations have been performed to determine which particles could be hitting the beam pipe; it was found that such events would be caused by very large (larger than 10 beam sigma) transverse amplitude particles. The beam longitudinal structure was also studied. The beam pipe misalignment between the North and the South ends of the detector is about 1 cm.

A program of beam studies was executed during Run-24 to determine the best mitigation strategy, when the average auto-recovery rates were measured for different bunch patterns and combinations of Blue and Yellow beams, optics changes and orbit position scans. Large amplitude orbit bumps in IP8 and kicker prefire protection bump resulted in a significant reduction of the auto-recovery rate with 12 bunch operation, however that solution does not scale to a larger number of bunches. The studies point at the off-momentum particles as the source of this background.

The detector plans to operate in Run-25 in the triggered mode, in which the auto-recovery rate could be as much as 100 times lower than in the full-streaming mode and conditions could be suitable for Au-Au operations.

A task force has been formed to investigate the experimental background affecting sPHENIX. It includes accelerator and detector physicists. Data from Run-24 were analyzed to identify the source, find ways to mitigate the losses and to improve instrumentation and monitoring. Various tools were involved, e.g. FLUKA, GEANT, etc.

The blue beam has more material outside the beam pipe than the yellow beam. And the blue beam has much less of a problem than the yellow beam. Source of the background could originate from outside of the beam pipe but in the insertion region. Asymmetry also exists in the support of the vacuum pipe. Dispersion in the yellow beam is about 15 cm.

A solution was studied using the increase of dispersion in a warm section to intercept losses. The figure of merit is 0.12 at the location of possible collimator in IR4 and 0.1 in IR8 where sPHENIX is located. To increase the horizontal dispersion, the Gamma-t quadrupoles need to be rewired. Complications include the tight space in IR4 and bakeout requirement. Possible locations in other IR's have their own issues and problems.

Concerning the source of particle losses, beam-gas scattering was considered with GEANT studies. No asymmetry is seen in the vacuum pressure that could explain the yellow versus blue beam difference. Showering studies were done with FLUKA. No location/source identified yet, but studies point at the second taper potentially being the source of the problem. Multiple scattering of harmful ions is considered as a possibility.

Installation of 2 m of Polyethylene shielding could result in a factor of 10 improvement, according to FLUKA predictions. GEANT studies do not see an impact of "cable shielding" versus "no cable shielding", opposite to the observation. GEANT simulations with the Polyethylene are in progress but seem to indicate promising effects.

Higher order focusing fields (sextupole and octupole) have also been studied for background mitigation. Sextupoles would correct the 2nd order chromaticity. Measurements show a significant difference between the two rings. At the moment it is unclear if this can explain the different background issues for the two beams.

Additional monitoring includes donut detectors, which are essentially repurposed detector modules including photomultipliers and scintillators.

Beam emittance does not seem to influence the rate of auto-recovery events in the sPHENIX experiment.

In answer to a homework question the status of task force recommendations, decisions and actions was summarized:

1) Better monitoring - decided
2) Internal shielding - to be decided and to be installed, both by the experiment
3) Momentum collimation - decision by C-AD management on a proposal by the task force. Time for implementation is very critical. If it would be done, the process should start immediately.
4) Higher order fields - C-AD management will need to approve a few shifts of beam studies early in Run-25.

The target date for an official recommendation from the task force was not presented.

In response to a homework question, additional info on momentum collimation was shown.

<u>Comments</u>

- The task force to study the origin of the sPHENIX MVTX experimental background and possible mitigation measures is a good idea and is fully supported by the MAC. The task force team is making important progress, though it is not yet clear what the detailed source of the problem is and how it can be mitigated.

- The situation is complicated by RHIC not having a dedicated momentum collimation system.
- Large orbit bumps also generate dispersion waves, which should be incorporated into the lattice modeling considerations.
- The MAC agrees with the strategy to not correct the beam pipe misalignments in IP8.
- It was alluded that one significant difference between the two rings is the sign of 2nd order chromaticity, which could be changed. This could be a relevant direction to study in preparation and during Run-25.
- It is not obvious if the effect is bunch intensity-dependent.
- The impact from neutral particles was not presented but as a far away bump helps, it seems unlikely that neutral particles could be the cause of the problem.
- The influence of horizontal collimator settings on losses at sPHENIX was not presented in detail.
- Normalized momentum and betatron apertures were not shown. The Figure-of-Merit data misses this information, as it only relies on the beam beta-x function and on the horizontal dispersion.
- If a decision is made to implement momentum collimation, a commissioning scenario is required. It should be based on realistic simulations that take into account the fine-ring-aperture model and the beam loss distribution of scattered particles.

Charge questions responses:

a) **Are the technical goals realistic to meet the stated goals? – Maybe.** It is unclear if a low enough rate of auto-recovery events in the sPHENIX experiment can be achieved. No goal was presented.

b) **Are there any technical issues that were missed or need additional attention? – No**
The task force made a rather complete review. No missed sources can be identified. Mitigation studies should include orbit bumps that are dispersion closed, the impact of the horizontal collimator settings and a quick view on a vertical momentum collimation.

Recommendations:

3. **Calculate the overall aperture bottleneck for a betatron halo particle (at a setting of horizontal collimator, e.g. 8 sigma-beta-x) that at the same time has an energy offset at the momentum aperture (e.g. 4.5 sigma-E). Use the known local aperture, the horizontal beta function and the horizontal dispersion to see if such a particle can get lost at the second taper in front of sPHENIX or at another "high impact" location that can shine into the detector. Only if this is true, a global momentum collimation can safely protect the experiment. Otherwise, local origins of off-momentum ions might be responsible, to be counteracted by local protection measures.**
4. **Check the dependence of background on bunch intensity and horizontal collimator settings.**
5. **The addition of local shielding in sPHENIX seems like a good idea and should**

be done before Run-25 if at all possible.

Injector upgrade plans over the next decade

Findings

Detailed responses to the recommendations regarding the Injectors from the 2023 MAC were presented.

Detailed lists were presented with M&S cost estimates given for a significant number of upgrade tasks, both large and small. The labor costs were said to be covered by the anticipated departmental funding.

The team decided to descope the cryo-plant upgrade ($17M) and the Booster power supply upgrade ($35M) as each of these would exceed the expected available funding ($3M p.a. AIP funding).

Solid-State Amplifiers are considered as a replacement for the tube amplifiers for the linac. Tube procurement is becoming difficult (single-vendor). This item is driven by BLIP requirements and funding by the isotope production program is being sought.

Comments

- The Injector performance and repair plan appears comprehensive and well thought out.
- While the list of maintenance and upgrade tasks appears comprehensive and the M&S cost estimates shown were helpful in assessing the size and scope of the tasks, there was no priority given, which makes it difficult to assess the likelihood of a given task to be actually completed.
- The correlation between investment in hardware repairs and upgrades, and the downtime caused by such systems could have been made more explicit.
- Since the total anticipated AIP funding is not sufficient to cover all the tasks deemed necessary, the RHIC cryo-plant upgrade is left not covered and negotiations with the EIC team for alternative funding are aimed for. The committee finds this approach reasonable for the anticipated funding level.
- Likewise, the Booster Power Supply replacement ($35M) is being pushed out towards the beginning of EIC running. The committee notes that Booster power supplies do not appear to cause much downtime, and we are confident that the team has a reasonable plan of action to avoid undue impact on EIC commissioning and running, although details were not provided.
- The pulsed nature of linac operation may drive specifications and costs of SSA amplifiers for the linac.

Charge questions responses:

a) **Are the technical goals realistic to meet the stated goals? – Yes.**
b) **Are there any technical issues that were missed or need additional attention? – No.**
   For evaluation of the SSA alternative for the linac power amplifiers, make sure the

vendor understands the details of the pulsed operation.

c) **N/A.**

Recommendations:

6. **Continue optimizing the modernization plan and produce a prioritized list of tasks for next year's review.**

CeC status and plans for Run-25

Findings

Over the course of the years, the CeC experiment has achieved several key milestones along the path to a final cooling demonstration. Up to now, the CeC experiment at RHIC has achieved an SRF accelerator generating a high brightness electron beam, with peak current up to 75 A at 14.6 MeV. Over the past two years, the new laser profile has been tested to provide better final temporal distribution uniformity and key beam parameters have been established and worked on to improve beam quality.

Predicted by 3D simulations, beam properties (peak current, slice energy spread, uniformity in about 10 – 15 ps) are critical for achieving observable longitudinal cooling and the peak-to-peak variation should be less than 10%. Recent efforts have been made to achieve better uniformity in the beam properties and elimination/compensation of all undesirable time-dependent kicks from cavities. Studies of individual beamlet's properties have been performed. A list of laser system fixes/upgrades has been presented and a new 500 MHz bunching cavity was installed and made fully operational in Run-24 to eliminate unwanted time-dependent transverse kick, which degrades beam quality.

The key beam parameters (except slice emittance) required for cooling demonstration have been experimentally measured. Simulations show that temporal uniformity can be achieved using a modified initial laser pulse shape with peaks on the sides and a dip in the center. A new laser profile has been developed to have intensity/delay control over individual Gaussian beamlets.

The aim for Run-25 is to demonstrate longitudinal Coherent electron Cooling.

Comments

- The CeC accelerator still suffers from a lack of reliability: both in terms of beam parameter jitter and the poor repeatability of operation set-ups. This is a major challenge to overcome in the beginning of Run-25.
- The new laser profile should be established for Run-25.
- A new operating mode for the CeC accelerator with 10 MeV electron beam has been proposed to relax the electron beam requirements for observing cooling. Beam dynamics and cooling simulations for the new mode are underway. This development should be put into operation.

Charge questions responses:

a) **Are the technical goals realistic to meet the stated goals? – Yes**

b) **Are there any technical issues that were missed or need additional attention? – No**

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

Recommendations:

7. **Overcome the lack of reliability: both in terms of beam parameter jitter and poor repeatability of operation set-ups.**
8. **Develop a Plan B to continue the CeC development after the RHIC shutdown.**

Polarization increase with AGS skew quads in Run-24

Findings

Magnets and power supplies were delivered and installed in time for commissioning in Run-24.

All commissioning tasks were completed successfully: polarity checks, proof-of-principle experiment, orbit centering, demonstration of correction effect during acceleration.

Gain factors in dedicated experiments of up to 15% polarization have been measured. The long-term average is 12.6%. This exceeds the performance of the tune jumps in the dedicated measurements and is similar to the performance of tune jumps in longer-term ~~operation~~ average (in the first commissioning run).

The correction effect is consistent enough in operation to replace the tune jump as the default system for horizontal resonance correction.

Run-25 AGS development time is planned for most of the run (including behind Au operation). Up to 8 weeks of RHIC operation is possible for polarized protons. AGS survey and realignment is planned for this shutdown between Run-24 and 25.

Comments

- The MAC is truly impressed by the significant progress that the project has made in recent years.
- Competing methods have been developed to overcome horizontal spin resonances. Thus, the timing of jumps seems to be a critical issue that could be further investigated.
- Further improvements/studies should be identified to improve the performance, including improved orbit control and alignment.
- Resonance correction is highly model-dependent. The developed models with realistic machine errors include continued development of the Bmad version of the lattice for inclusion of all effects rolls and vertical displacement in sextupoles.
  All model efforts are synergistic with the overall Machine Learning/digital twin effort (see G. Hoffstaetter's talk) to fully characterize other sources of polarization loss.
- More precise characterization of low and high energy resonance contributions and corrections is useful and we agree with the plan to perform more single resonance crossing experiments. Simulation is required to fully understand effects of slow crossings.

- The team fully recognizes that helical dipoles are complicated magnets and lead to large optical effects at low energy (see also G. Hoffstaetter's talk and recommendation below).
- In order to develop common and more efficient correction schemes, resonance crossings with a similar number of parameters (# skew quads) should be grouped.

Charge questions responses:

a) **Are the technical goals realistic to meet the stated goals? – Yes**
b) **Are there any technical issues that were missed or need additional attention? – No**
c) **Is the accelerator R&D effort well executed and future work well planned? – Yes**

Recommendations:

9. **Consider installing a polarized gas target to get an absolute polarization measurement that would help to track the polarization in the accelerator chain.**
10. **In Run-25, prioritize addressing model inaccuracies at energies below transition.**

Physics-informed ML for polarization increase in injectors (FOA)

Findings

Three optimization routines were developed to aid Booster injection tuning, AGS injection tuning and AGS bunch merges. These are declared to be ready for use in the control room. The group has expressed a commitment to support these tools in operational use.

Examples of the result from applying the routines to the machines were given. The results were restoration of the performance prior to a deliberate disturbance of some elements.

Besides the direct polarization optimization, effort has been spent on developing Bayesian-Optimization tools for Booster injection and AGS injection and a Reinforcement-Learning tool for bunch splitting/merging.

Application of ML/AI tools is considered to the optimization of the depolarizing-resonance-correcting skew quads, especially at low energy where the machine-model accuracy is poor.

Comments

- Recommendations from the prior MAC meeting were responded to adequately.
- Providing tools for control-room use is commendable and represents the return on BNL's investment. The committee is looking forward to hearing reports of their successful application at the next MAC meeting.
- The skew-quad system to reduce the effect of depolarising resonances is now being commissioned and is showing promise for increasing polarization.

- Model building appears to be focused on single-particle type of beam dynamics. We suggest to start including collective effects in the model building to guide the optimization routines being developed towards mitigating the undesirable effects arising from these.
- The work and plans appear driven by academic-type research, and a concise overall plan for next year's work was not presented.

Charge questions responses:

a) **Are the technical goals realistic to meet the stated goals? – Mostly.** This is a Cornell FOA funded R&D activity.
b) **Are there any technical issues that were missed or need additional attention? – No.**
c) **Is the accelerator R&D effort well executed and future work well planned? – Yes.** The plans are appropriate for each subtask.

Recommendations:

11. **At the next MAC, present a summary of the usage of the optimization tools created for BNL accelerator operations.**

BNCT lithium beam driver (LDRD 24-046)

Findings

Boron Neutron Capture Therapy (BNCT) is a new trend in cancer therapy. Boron compound IV infusion reaches and accumulates only in cancer cells. Irradiation with a neutron beam results in reactions with boron and destroys only the tumor cells. Accelerator based BNCT (AB-BNCT) facilities have been operated for patient care in Asia and Europe. However, the cost of the AB-BNCT facility is still high using the present technology of neutrons produced by a proton beam into Li target.

The BNL proposal is to realize the 8m-long compact accelerator system for AB-BNCT by adapting their Laser Ion Source (LIS) technology with direct injection into the RFQ (35 mA of $^7Li^{3+}$ beam - a world record for RFQ linac - has already been demonstrated). The lithium ions would need to be accelerated to the 14-20 MeV/nucleon range to act as a Li-beam driver impinging on a proton target to generate a highly oriented neutron flux. The high directionality of the neutrons enables much smaller shielding, leading to a compact facility and a cost reduction.

With international collaboration, this project has already performed several Monte Carlo simulations. They show promising results for this scheme as a conceptual design of an accelerator-based neutron source. However, the nuclear reaction models are not suitable for this inverse kinematic reaction.

The project adopted Frag data (user-defined data) and obtained reasonable results in the first simulation attempt. Further investigation is under development.

A neutron production experiment was conducted using the Tandem van de Graaf accelerator at BNL to evaluate an angular neutron distribution in the case of the inverse kinematic reaction. In the experiment, a beam of $^7Li^{3+}$, < 56 MeV, < 65 nA hits a polypropylene target. The inverse kinematic reaction p (Li7, n) Be7 was induced on the target and neutron production by the collision between the lithium beam and polypropylene was observed. By comparing the radiation signals from different setups, the neutron flux from the target can be calculated. Sharp directivity was confirmed and data analysis is ongoing.

In the near future, a set of high aperture RFQ electrodes will be installed and tested, and the multi-physics design of a high-current, large-acceptance, IH drift tube linac will be completed. More detailed neutron production experiments are planned at the BNL Tandem and Dresden Tandem.

Neutron target design study will be completed in two years. Detailed accelerator design will be completed.

Comments

- The recommendations from previous MAC were properly addressed.
- This new project will contribute to maintaining the LIS technology initiative at BNL. Monte Carlo simulations have shown promising results for this project, but there are no reasonable benchmarks yet. We commend the budgeting process for the proposal of experiments at BNL, which is reasonable for building simulation benchmarks. We hope that this plan will provide key technologies for the BNCT linac.
- For medical use, it is important to evaluate the reliability of the entire system. There are strict criteria for passing the evaluation. The durability of the neutron target material is one of the important issues that must be evaluated. However, it is not realistic for BNL to possess all the technologies for the entire medical system. It is necessary to clarify the scope of responsibility among collaborators.
- An exploration of further possibilities is also expected for maintaining the LIS technology initiative at BNL, using the high current capability of LIS.

Charge questions responses:

a) **Are the technical goals realistic to meet the stated goals? – Yes.**
b) **Are there any technical issues that were missed or need additional attention? – No.** The team knows the issues and has measure plans.
c) **Is the accelerator R&D effort well executed and future work well planned? – Yes** for this initial stage

Recommendations:

12. **For MAC-22, clarify the scope of responsibilities among collaborators and highlight the BNL part.**

Ion trap test stand and laser cooling for ultra-low emittance beams (LDRD 24)

Findings

This project is the start of R&D to develop tests of crystalline Ca+ beams, with very low emittances. In the long term they could be a candidate for irradiation on the nano-scale.

In order to create the Coulomb crystal of ions, the proposal is to contain them in a Paul trap and use laser cooling to create milli-kelvin temperature ions, which then arrange in a periodic structure to minimize the Coulomb energy.

Within this LDRD project, the objective is to simulate the cooling and crystal formation process and assemble a test-stand at BNL.

The simulation results already show the creation of a Coulomb crystal, and when compared to the University of Hiroshima measurements, they could explain several of the features observed including a heterogeneous structure.

For the creation of a test set up at BNL, the objective is presently to try and trap and extract Cs+ ions, due to the fact that a laser for cooling is presently beyond the project scope. Most of the equipment required for this stage is in-house, and assembly is on-going.

A response was given to Recommendation 12 from MAC-20. It was stated that long permanent magnets would be best created through short magnets that are individually tuned.

Comments

- For longer term development beyond the scope of the present project, consideration will need to be given on how to maintain the crystalline structure during acceleration and potential storage in rings.
- For future funding proposals, some more attention should be given to concretize uses and applications at the lower energy range.

Charge questions responses:

These are answered from the point of view of the stated aims of simulation, and the first stages of a test stand creation.

a) Are the technical goals realistic to meet the stated goals? – Yes.
b) Are there any technical issues that were missed or need additional attention? – No.
c) Is the accelerator R&D effort well executed and future work well planned? – Yes.

Recommendations: None

EBIS Status and Performance

Findings

The EBIS has been extended to include two solenoids (now called EEBIS), with the aim to increase the intensity of Au beams, and allow a 3He polarization gas cell to be incorporated.

The EEBIS has been installed in the Linac for more than a year. It was successfully recommissioned and was able to supply the large range of ion species needed for NSRL users. However, when pulsing the electron beam with 5 Hz repetition rate for 12 pulses that is required for Au production for RHIC, discharges develop, and the EEBIS must be stopped for ~30 minutes to recover. Due to this, RHIC has been using the Tandem for Au filling (and will start Run-25 with the Tandem).

Following the recommendation from the previous MAC, tests showed that the electron beam was significant in the initiation process of the discharges.

During the end of year maintenance period, modifications to the short trap and gas injection regions will be made - the proposed changes are to increase the smallest electrode apertures with the aim of avoiding electron beam loss, and change some connections that could be seed areas for discharges. Time has been allocated in the schedule for the recommissioning, before users require the beam.

Additionally, use of a BaO cathode was tried, but the electron current could not be maintained over multiple pulses, so the IrCe cathode was re-installed.

Due to the above work, the development of the 3He polarization has been slowed, and it is not planned to install it into the EEBIS in this maintenance period. After Run-25, the priority will be for this 3He development.

Nevertheless, the two individual traps have been shown to work, and measurements show that the two traps can be emptied in succession, or even the ejected ions over-lapped in time.

Comments

- The EBIS source with its array of injection ion sources is a highly flexible supplier of ions for users.
- Ion sources are well known to suffer from discharges, which can be erratic, and sources are often run with parameters to limit their occurrence. In order to study and mitigate these, sufficient testing time is needed. The one month commissioning time for the EEBIS in 2025 is a good step in this direction.

Charge questions responses:

a) **Are the technical goals realistic to meet the stated goals? – Yes.**
b) **Are there any technical issues that were missed or need additional attention? – No.**
c) **Is the accelerator R&D effort well executed and future work well planned? – Mostly.** Nevertheless, it is well planned for the immediate EEBIS modifications and recommissioning.

Recommendations:

13. **At the MAC-22 present the plans and schedule for the polarized 3He development.**

FFA synchrotron for medical applications (LDRD 24-010)

Findings

So far, only conventional proton therapy is available in the USA. A new accelerator setup called FFA Fixed Tune Synchrotron has been established. A collaboration between C-AD and the Radiation Oncology Department and a second collaboration with Stony Brook University for FLASH therapy has been established.

FLASH requires 4 Gray in 100 ms in an energy scan in the range of 70 to 250 MeV with 600 nA proton beams. Existing facilities are not capable of delivering beams with a large change in beam energy in a very short time, as is required for Flash.

FFA are well known for many decades and need large magnets. Non-scaling FFA Fixed Tune Synchrotron has been proposed with permanent magnets, covering an energy range from 10 to 250 MeV.

A proof of principle has been performed at Cornell. It was shown that the beam could be transported without loss. To achieve the fixed betatron tunes the new concept has non-linear fields (multipole contributions in the magnets).

Further goals of the LDRD are to transfer the existing technology to the FLASH therapy cancer radiation facility at the Radiation Oncology Department of the Stony Brook University Hospital. The results will be used as a proof-of-principle for the concept of fast-cycling permanent magnet synchrotron for obtaining funding to complete the synchrotron. The current collaboration includes the FLASH therapy experiments on mice at the BNL TANDEM accelerator using 28.5 MeV proton beam.

Comments

- A large dynamic aperture is essential to achieve the anticipated performance. The most critical point is the field quality. Also, fringe fields can be very detrimental to the performance of this type of accelerator. Therefore, realistic 3D magnetic fields including tolerances should be included in the beam simulation. Magnet alignment requirements may also be examined in detail. It may be necessary to include magnetic field correctors.
- Single-pass experiments are planned to prove the principle. The question arises, if it is possible to get enough information from a single-pass experiment for a multi-pass application, especially concerning higher-order corrections.
- This type of accelerator has the potential to be used as proton drivers, muon collider accelerators, and for ADS, if high-power operation can be demonstrated. It would be an important step if, at some point in the future, high-power operation with electrically driven magnets could be demonstrated.

Charge questions responses:

a) **Are the technical goals realistic to meet the stated goals? – Maybe.** A demonstrator would be useful.
b) **Are there any technical issues that were missed or need additional attention? – Yes.** 3D field maps should be incorporated in beam simulation.
c) **Is the accelerator R&D effort well executed and future work well planned? – Yes**

Recommendations:

14. 3D field maps including fringe fields should be incorporated in beam

simulation, and the necessary dynamic aperture demonstrated. Correction schemes should also be investigated.

High Energy Cooling R&D

Findings

A discussion of cooling requirements for the EIC was presented. The suite of tools will consist of Low-Energy Cooling (LEC) and High-Energy Cooling (HEC), which was the subject of the present report. While CeC made progress in recent years, there are crucial unresolved issues related with extremely tight tolerances on timing for electron and hadron beams in the cooler and cooling diagnostic.

Alternative HEC systems based on the well-established technology of Electron Cooling were considered in the past and two of the approaches with most promise are being explored in greater detail by C-AD:

1) the storage Ring Electron Cooler (REC) where electron bunches which provide cooling of protons are being cooled themselves via synchrotron radiation in a storage ring.
2) ERL-based Recirculator design where electron bunches are supplied by a high-brightness electron source.

It is envisaged that high-energy cooling would be located in IR2, where some real estate will also be taken by the LEC.

The ring-based cooler would be realized via a racetrack-shaped electron storage ring of 426 m circumference and a 170 m long cooling section. The electron beam would be cooled by strong wigglers in the opposite long straight section. The recent design optimization considered important criteria such as the cooling requirements, effects of proton-electron beam interaction, self space charge in the electron beam, etc. The present design iteration aims to achieve the electron bunch of 21 nC charge, 7.8 nm transverse emittance and 34 cm length. Several different codes were used to optimize the parameters of circulating beam, cooling section optics, RF, injection and so on. A large number of challenges associated with this option still needs to be addressed such as the considerations of collective effects and instabilities, vacuum requirements, proton-electron beam interaction, magnetic errors and misalignments, beam loading and so on.

The recirculator concept has some advantages over the ring-based design: intrabeam scattering and self space charge are not significant, as well as the proton-electron beam-beam interaction; enhanced radiation damping is not required because bunch parameters are defined by the dynamics in the injector and ERL. The most important challenges of the option were identified to be the high-current gun and ERL (up to 60 mA), requisite high quality bunches with high charge (emittance less than 2 um at 2.5 nC), and fast kickers. The team established overall requirements for the system and identified the next steps for the physics and engineering evaluation.

A response to MAC-20 recommendation was presented: the EIC Project change control process is underway to include Low Energy Cooling in the project scope and remove the high energy CeC-based cooler. As part of HEC R&D, the plan is to develop the most promising scheme, evaluate risks and costs and choose the most reliable and cost-effective approach for the EIC. It is estimated that the effort at the level of 2-3

Accelerator Physicist FTE over several years will be needed to develop a robust HEC system for the EIC.

Comments

- The progress with the REC option is commendable. The inclusion of a more realistic wiggler model and the associated design optimization are relevant.
- The team recognizes the challenges associated with both HEC options and possesses the necessary expertise to tackle them.
- The timeline and estimated effort for future work were presented as a response to a homework question. The work pace will be driven by the availability of resources. The C-AD beam cooling group's priorities in FY25 are on other projects: CeC, high-current R&D, LEC, and other EIC tasks. It is realistic to complete the REC dynamic aperture studies with realistic errors by the end of 2025 and have CDR-level maturity in 2-3 years. A CDR-level study for the ERL-based option would be the next goal 2-3 years later.

Charge questions responses:

a) **Are the technical goals realistic to meet the stated goals? – Yes**
b) **Are there any technical issues that were missed or need additional attention? – No**
c) **Is the accelerator R&D effort well executed and future work well planned? – Yes,** in the short term

Recommendations:

15. **Consider engaging external partners (e.g. university faculty, graduate students) to accelerate the work on HEC options.**
16. **Begin work towards an integrated assessment of beam dynamics in EIC hadron cooling (i.e. start-to-end simulation) for the HEC options.**