

Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

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Introduction

The Nuclear Science Advisory Committee (NSAC) of the Department of Energy (DOE) Office of Nuclear Physics (NP) recommended in the 2015 Long Range Plan (LRP) for Nuclear Science that the proposed Electron Ion Collider (EIC) be the highest priority for new construction. This report noted that, at that time, two independent designs for such a facility had evolved in the United States, each of which proposed using infrastructure already available in the U.S. nuclear science community.

The key EIC machine parameters identified in the LRP were:

- Polarized (~70%) electrons, protons, and light nuclei,
- Ion beams from deuterons to the heaviest stable nuclei,
- Variable center of mass energies ~20-100 GeV, upgradable to ~140 GeV,
- High collision luminosity $\sim 10^{33}$ - 10^{34} cm $^{-2}$ sec $^{-1}$, and
- Possibly have more than one interaction region.

The LRP further noted that these requirements would push accelerator designs to the limits of available technology and would, therefore, need significant research and development investment. The LRP also noted certain technical areas that would require development; cooling of the ion beam, development of intense polarized electron sources, challenges in maintaining beam polarization for both electrons and ions, integration of the detectors to address demands on kinematic coverage, and detector technology.

In March 2016 NP management presented to NSAC a strategy for the process that could lead to advancing an EIC project. This strategy included the following four key points:

- *National Academy of Sciences (NAS) Study*: Initiate an eighteen-month NAS study entitled “US-based Electron Ion Collider Science Assessment.”
- *FY16 Funding Opportunity Announcement (FOA)*: Publish a competitive FOA in March 2016 with proposals due May 2, 2016, to select 1-year only awards toward Accelerator R&D for Next Generation NP Facilities.
- *NP Community Panel Review*: Conduct an NP community EIC R&D panel review charged with generating a report as basis for FY17 to FY20+ EIC accelerator R&D funding.
- *Bi-Annual FOA starting in FY17*: Publish bi-annual FOA for competitive accelerator R&D beginning in FY17 based on R&D priorities established in the EIC panel report with a target funding level of approximately \$7M per year.

This report represents the work of the panel assembled to address the third element of this strategy.

The detailed charge to the panel is available in Attachment A, with the essential charge elements summarized as follows:

“...assess the following:

- Status of EIC R&D to date: Evaluate current state of EIC-related accelerator R&D supported to date by NP competitive accelerator R&D funds and by individual NP laboratory funds;
- EIC design concepts: Examine the current IEC design concepts under consideration in the U.S. and identify a risk level (High, Medium or Low) for the realization of each concept;

- Technical feasibility: For each EIC design concept, identify key areas of accelerator technologies that must be demonstrated or advanced significantly in order to realize the technical feasibility of the concept;
- Priority list of R&D: Generate a list of R&D areas for each EIC design concept, prioritized (High, Medium, Low) in the context of associated risk and impact of activity to value engineering and technical feasibility. Identify R&D items that have relevance to multiple EIC design concepts; and
- Cost and schedule range: To the extent possible and within the time constraints of the meeting, provide an estimate of cost and schedule range for each item on the R&D list above.

The prioritized list of R&D activities for each EIC design concept and the associated information generated by this panel will be used as a key metric in evaluation of proposals submitted to future NP biennial Funding Opportunity Announcements (FOA) for conducting accelerator R&D for next generation NP facilities.”

General Observations

The panel notes that over the past ~10 years a considerable body of work has been accomplished on proposed EIC concepts. Many novel concepts have been proposed and developed including harmonic RF kickers, Gatling and inverted guns, Coherent Electron Cooling (CeC), harmonic crab cavities, in-situ coating of beam lines, and energy recovery linear accelerators (ERL) based on Fixed Field Alternating Gradient (FFAG) magnets. The research and development that has already been conducted is impressive; it provides a strong basis for both realizing and maximizing the performance of a future EIC and is also of great interest to many other future accelerator projects.

The panel was presented with three pre-conceptual design options, two from Brookhaven National Laboratory (BNL) and one from the Thomas Jefferson National Accelerator Facility (JLAB). BNL has invested considerable effort into the linear accelerator (Linac) – Ring concept (LR), while the more recently initiated Ring-Ring concept (RR) is less mature. JLAB has invested considerable effort in a novel figure-8 design concept (JLEIC). The panel notes that the beam pulse structures for the BNL and JLEIC concepts are quite different, and that the interested nuclear physics community should carefully evaluate the effects of the pulse structures on proposed experiments.

Electron-cloud effects will have quite different characteristics for each of the proposed options. The JLEIC ion beam may trap and accumulate electrons liberated by gas ionization, possibly leading to a classical electron-proton two-stream instability that might be counteracted by feedback. The BNL rings will create an electron cloud by beam-induced multipacting. Copper coating might mitigate this, but it is not obvious that copper will provide a lower secondary emission yield than stainless steel.

The machine-detector-interface should be given more attention in all designs. This includes the choice of β^* , space allocation for luminosity monitors, polarimeters, the effects of the detector solenoid (and the possible need for and integration of compensating and shielding solenoids) together with solenoid fringe fields in presence of a relative large crossing angle that could have effects on polarization, synchrotron-radiation background, vertical emittance, and so on. Synchrotron radiation background in the detector could be important as demonstrated by the Hadron-Electron Ring Accelerator (HERA) at the Deutsches Elektronen-Synchrotron. This should be examined including the possibility of reflected photons generated further upstream. Mitigation of synchrotron radiation background may impose constraints on

the final-focus optics, the final quadrupole design, and the vacuum chamber dimensions in the interaction region (IR), among other considerations. A masking system similar to those developed for past lepton colliders (the Large Electron-Positron Collider [LEP], Positron-Electron Project phase II [PEP-II], and the Japanese electron-positron collider facility [SuperKEKB]) will likely be needed and must take into account the specific needs of the EIC physics detectors. The need to avoid higher-order mode (HOM) excitations in the IR region (detector chamber) can further constrain the inner, incoming and outgoing IR beam-pipe dimensions. In addition, a movable collimator system may be needed at suitable optical locations (elsewhere in the lepton ring or lepton linac) to control beam tails at large amplitudes and associated detector background.

The complementary expertise and operational experience at each of the proponent laboratories establishes a unique situation. Simply put, each proponent laboratory has a different experience base deeply relevant to the type of facility that is envisaged. JLAB is the world leader in recirculating electron linacs, ERLs and Superconducting Radio-Frequency (SRF) technology that are required for the BNL designs, while BNL masters collider technology, proton- and ion-beam operation, and superconducting (SC) magnets that are required for the JLEIC. There are also obvious opportunities for joint R&D on other key components common to all collider proposals, such as crab cavities and high-current linacs. This situation presents unique opportunities for collaborative R&D that will benefit the realization of the next generation EIC machine.

The recently initiated study by the National Academy of Sciences (NAS) should further clarify the EIC technical requirements to support the desired program of forefront nuclear physics and any additional guidance should be incorporated into consideration of Funding Opportunity Announcement (FOA) awards. Arguments presented to the panel indicated that significant new physics could be accessed at center of mass energies below 100 GeV, but the panel was unable to judge the merit of this point. In particular, new guidance may clarify the need identified in the NSAC LRP for center of mass energy of a minimum of 100 GeV with the capability to upgrade to a center-of-mass energy of 140 GeV.

Some important technical components that represent significant advances over the current state-of-the-art have not yet been demonstrated and their performance seems to be taken for granted by the proponents – examples include crab cavities and high current multi-pass ERLs. These issues are addressed in detail in the report.

Constraints on available funding dictate that investment choices should be made to maximize technical progress while reducing long-term project risk. The current fiscal climate encourages the proponent laboratories to maintain a flexible approach to addressing important technical challenges while improving concept development.

Key academic institutions are engaged in EIC R&D, but the program may benefit from broadening such engagement. Many National Laboratories and Universities have substantial infrastructure and expertise in accelerator science and technology, and NP is encouraged to promote strong collaborations between the proponent laboratories and these related national resources to improve concept development and solve technical challenges. In particular, complex-wide opportunities exist for collaboration between national laboratories and interested and capable universities to further refine EIC concepts in the following topical areas:

- Hadron cooling techniques,
- Polarized electron sources,
- Ring magnet demonstrations,
- Interaction region magnet design and prototyping,

- Machine-detector interfaces,
- Superconducting RF technology,
- Large scale cryogenics technology,
- High current SC linacs,
- Crab cavity design, fabrication and testing (with beam),
- Beam and spin dynamics and benchmarking of simulation tools, and
- Electron cloud mitigation techniques.

The weighting of the performance criteria based on science requirements should be taken into consideration when evaluating R&D thrust areas. NP is encouraged to look to the NAS study to inform refinement of technical parameters to maximize new science. This will be particularly important for the machine-detector interface, including beam collision rates, pulse structures, the balance between luminosity and center-of-mass energy, and number of interaction points. Some clarification may be required for collision luminosities for preferred ion species. Given the current understanding of science criteria, the panel suggests that the requirements relating to beam polarization and e-p luminosity should carry more weight when evaluating the technical scope of R&D proposals.

Finally, comparing the two ring-ring collider proposals, BNL RR and JLEIC, at the same proton and electron beam energies of 100 and 10 GeV respectively (see Table 5 below), the designs are surprisingly similar in terms of the number of bunches, bunch frequency, and the peak luminosity. However, the panel notes that:

- The peak luminosity is similar despite the fact that two different hadron cooling schemes are employed, the “weaker” conventional cooling of JLEIC resulting in smaller emittances, and
- While the BNL RR design is near the beam-beam limit, JLEIC is far from such a limit operating with much smaller IP beta functions.

These observations suggest that neither design is fully optimized and that one could enhance the performance of JLEIC, e.g., by accepting higher beam-beam tune shifts, and the performance of the BNL RR design by further squeezing the beta functions. Depending on the acceptable IP divergence, the luminosity of either design could possibly be raised by a factor of 2-3. The panel suggests that similar design parameter optimizations could be performed for other beam energies.

Summary and Recommendations for Prioritization of Research and Development Activities

Charge Element I – Status of EIC R&D to Date

Since 2010 NP has issued four FOAs aimed at accelerator R&D for next-generation NP facilities and made 12 awards totaling over \$14M (including modest reserve funds) to individual and partner institutions comprising 5 national laboratories and 5 universities – the funds requested exceeds funds awarded by a factor of about 2.5. A majority of the proposals were focused on a proposed EIC. The proponent laboratories have done a commendable job of identifying important work and investing therein with programmatic funds (a total of ~\$3.4M/year) and Laboratory Directed Research and Development (LDRD). Non-federal investments are being leveraged to the extent possible (the Cornell-BNL Fixed Field Alternating Gradient [FFAG]-Energy Recovery Linac [ERL] Test Accelerator [CBETA]). The breadth of research performed so far is gratifying and some of it has been high risk – high reward, but as the concepts mature the research should be more focused on realizing technical solutions. Organizations receiving funding should have adequate resources to bring funded activities to a well-defined close with definitive deliverables and accountability for performance before embarking on new work (unless well justified).

While much has been accomplished the panel cautions that work is not fully complete until validation is performed; a number of initiatives are near this point and should be brought to conclusion as soon as possible. It is important that future work must focus on supporting technical decisions to increase confidence in concept definition. A reasonable balance of investment between simulation and modeling and technical demonstrations is needed; simulations in some areas could benefit from increased attention.

Charge Element II – EIC Design Concepts

The panel was presented with three pre-conceptual design options, two from BNL and one from the JLAB. BNL has invested considerable effort into the linear accelerator (Linac) – Ring concept (LR), while the more recently initiated Ring-Ring concept (RR) is less mature. JLAB has invested considerable effort in a novel figure-8 design concept (JLEIC). The panel evaluated the risk of the current state of each concept with regard to delivering an EIC facility that could satisfy the objectives stated in the NSAC LRP. The panel judged the overall concept risks as follows:

BNL Linac-Ring

High risk-high reward with a limitation of one interaction point; some high risk items can be mitigated with compromises to achieve the lower range of the NSAC requirements.

BNL Ring-Ring

Medium risk largely justified by the existing hadron machine, with **higher risk** associated with the electron ring, dependent on the electron injector scheme that is chosen.

JLEIC

Medium risk for the machine proposed, with risks associated with the machine-detector interface for the number of bunches and some technical aspects of the hadron cooling ERL system and the first

implementation of a figure-8 machine, and a **higher risk** based on fundamental limitations on fully addressing the technical requirements presented in the long range plan.

General

Life cycle cost and/or value-engineering aspects related to life-extension of the existing accelerator infrastructures will be relevant to all concepts.

The panel notes that its assessment of risk is generally more conservative than that self-identified by the concept proponents.

All three concepts have high-risk elements in common. While these elements differ in detail, they are similar enough to warrant common analysis. They include:

- Bunched-beam cooling of the hadron beams in the collider rings. The coolers will all require high average current energy-recovery linacs.
 - The BNL designs are based around CeC, which can use an unmagnetized electron beam, but as they require microbunched beams (effectively requiring them to be FELs, or a new design intended to amplify the microbunching instability) they will have the energy recovery process complicated by the significantly increased beam energy spread.
 - The JLAB design requires a high-average-current magnetized beam source. They are proposing a novel multi-turn accumulator ring to “recycle” the ERL beam, which to date has not been tested. The alternate approach requires a much higher average current magnetized source.
- Interaction region design. All IR designs include crabbed beams and very challenging magnet designs.
- Crab cavities with large integrated shearing voltages. Given the fact that these cavities have not been demonstrated in a hadron machine, it is important to study an alternative option for an interaction region design with bent electron beams and without the use of crab cavities to evaluate methods to address synchrotron light inside the detector and the need for synchrotron light absorbers to minimize the background inside the experiment.

Charge Element III – Technical Feasibility

The panel identified the following technologies and/or design concepts that present technical risks common to all concepts and that should be demonstrated:

- Crab cavity operation in a hadron ring,
- High current single-pass ERL for hadron cooling,
- Strong hadron cooling,
- Benchmarking of realistic EIC simulation tools against available data,
- Validation of magnet designs associated with high-acceptance interaction points by prototyping, and
- Polarized ^3He source.

BNL Linac-Ring (LR) Concept

The panel identified the following technologies and/or design concepts that address technical risks relevant to the BNL LR concept and that should be demonstrated:

- High current polarized and unpolarized electron sources,
- CeC proof of principle,

- High-current multi-pass ERL,
- Concept for 3D hadron CeC beyond proof of principle, and
- SRF high power HOM damping.

BNL Ring-Ring (RR) Concept

The panel identified the following technologies and/or design concepts that address technical risks relevant to the BNL RR concept and that should be demonstrated:

- Complete design of an electron lattice with a good dynamic aperture and a synchronization scheme and complete a comprehensive instability threshold study for this design,
- High peak current multi-turn electron linac,
- Necessity to triple the number of and shorten the bunches in the proton/ion ring,
- Beam pipe copper coating with plasma ion bombardment, and
- Simulation of the effect of electron bunch removal on the hadron beam.

JLEIC Concept

The panel identified the following technologies and/or design concepts that address technical risks relevant to the JLEIC concept and that should be demonstrated:

- Complete and test a full scale suitable superferric magnet,
- A high current magnetized electron injector,
- High power fast kickers for high bandwidth (2ns bunch spacing) feedback,
- Complete the design of the gear change synchronizations and assess its impact on beam dynamics,
- Integrated magnetized beam/kicker circulation test using the existing ERL infrastructure, and
- Operate the JLAB Continuous Electron Beam Accelerator Facility (CEBAF) in the JLEIC injector mode.

Charge Element IV – Priority List of Research and Development Activities

The panel received a self-assessment of the priorities of 34 R&D items identified by JLAB and 19 unique R&D items identified by BNL – these were binned into the categories of High, Medium and Low.

In particular the panel identified 9 items it considered high priority that were not explicitly identified for action by the proponent laboratories. These are summarized as follows.

Technologies and/or design concepts that address technical risks common to all concepts that must be demonstrated:

- High current single-pass ERL for hadron cooling,
- Benchmarking of realistic EIC simulation tools against available data, and
- Polarized ^3He source.

Specific R&D activities for the BNL Linac-Ring Concept:

- High-current multi-pass ERL, and
- Concept for 3D hadron CeC beyond proof of principle.

Specific R&D activities for the BNL Ring-Ring Concept:

- Synchronization scheme for the electron lattice and complete a comprehensive instability threshold study for this design,
- High peak current multi-turn linac, and
- Simulate effects of the electron bunch removal on the hadron beam.

Specific R&D activities for the JLEIC Concept:

- High power fast kickers for high bandwidth (2ns bunch spacing) feedback.

The panel cross-walked the elements identified in Charge Element III with the self-assessment provided by the proponent laboratories – there was substantial agreement but some differences were identified.

The discussion above on Charge Element III - Technical Feasibility summarizes the technical elements that the panel considers pose the most significant risk to realizing all or each of the EIC concepts presented, and must hence be considered high priority for R&D to reduce risk. Note that some of these technical elements represent generalizations of specific topics proposed by one or both of the proponent laboratories. In the table below (Table 1) these items are tabulated in rows 1-22, and are identified as originating from the panel by the insertion of “PANEL” in the proponent column. These R&D elements are all assigned high priority.

The R&D elements that the panel judged to be applicable to **all** concepts presented are identified by “ALL” in the concept/proponent identifier column and are assigned sub-priority A. **These are considered most important to be addressed to reduce overall design risk.**

The R&D elements that the panel judged to be applicable to individual concepts presented are identified by the appropriate concept identifier in the concept/proponent identifier column (e.g., LR, RR or JLEIC) and are assigned sub-priority B. **These are considered to be second in importance to reduce overall design risk, but important to reduce the risk associated with a specific concept.**

The R&D elements self-identified by the proponents are tabulated in lines 23-75 with the priority as deemed by the panel. Specific self-identified high priority R&D elements that have substantial correlation with the high priority global and concept-specific sub-priority A and B elements identified by the panel are denoted as sub-priority C to permit ready cross-reference when evaluating future R&D proposals.

Row No.	Proponent	Concept / Proponent Identifier	Title of R&D Element	Panel Priority	Panel Sub-Priority
1	PANEL	ALL	Crab cavity operation in a hadron ring	High	A
2	PANEL	ALL	High current single-pass ERL for hadron cooling	High	A
3	PANEL	ALL	Strong hadron cooling	High	A
4	PANEL	ALL	Benchmarking of realist EIC simulation tools against available data	High	A
5	PANEL	ALL	Validation of magnet designs associated with high-acceptance interaction points by prototyping	High	A
6	PANEL	ALL	Polarized ^3He Source	High	A
7	PANEL	LR	High current polarized and unpolarized electron	High	B

Row No.	Proponent	Concept / Proponent Identifier	Title of R&D Element	Panel Priority	Panel Sub-Priority
			sources		
8	PANEL	LR	Completion of the ongoing CeC demonstration (proof of principle) experiment	High	B
9	PANEL	LR	High-current multi-pass ERL	High	B
10	PANEL	LR	Concept for 3D hadron CeC beyond proof of principle	High	B
11	PANEL	LR	SRF high power HOM damping	High	B
12	PANEL	RR	Complete design of an electron lattice with a good dynamic aperture and a synchronization scheme and complete a comprehensive instability threshold study for this design	High	B
13	PANEL	RR	High peak current multi-turn electron linac	High	B
14	PANEL	RR	Necessity to triple the number of and shorten the bunches in the proton / ion ring	High	B
15	PANEL	RR	Beam pipe copper coating with plasma ion bombardment	High	B
16	PANEL	RR	Simulation of the effect of electron bunch removal on the hadron beam	High	B
17	PANEL	JLEIC	Complete and test a full scale suitable superferric magnet	High	B
18	PANEL	JLEIC	Develop a high current magnetized electron injector	High	B
19	PANEL	JLEIC	High power fast kickers for high bandwidth (2ns bunch spacing) feedback	High	B
20	PANEL	JLEIC	Complete the design of the gear change synchronizations and assess its impact on beam dynamics	High	B
21	PANEL	JLEIC	Integrated magnetized beam/kicker circulation test using the existing ERL infrastructure	High	B
22	PANEL	JLEIC	Operate the JLAB Continuous Electron Beam Accelerator Facility in the JLEIC injector mode	High	B
23	BNL	LR-A-1	R&D and Prototyping on the 6.2mA Polarized Electron Gun	High	C
24	BNL	LR-A-2	Study of Beam-Beam Effect with Crab Cavities	High	
25	BNL	LR-B-1	CBETA Project	High	C
26	BNL	LR-B-2	Waveguide HOM Couplers for the BNL (eRHIC) ERL	High	C
27	BNL	LR-C-2	Crab Cavity Prototype	High	C
28	BNL	LR-C-4	Design and prototyping of actively shielded IR quadrupole and dipole magnets	High	C
29	BNL	CeC	Completion of the ongoing CEC demonstration experiment	High	C
30	BNL	RR-A-1	Beam-Beam Parameter Validation	High	
31	BNL	RR-A-2	Study of Electron Spin Polarization in the Storage Ring	High	
32	BNL	RR-A-3	Stability Study of Beams with Crab Cavities	High	

Row No.	Proponent	Concept / Proponent Identifier	Title of R&D Element	Panel Priority	Panel Sub-Priority
33	BNL	RR-A-4	Synchrotron Radiation Background Assessment	High	
34	BNL	RR-A-5	Electron-Cloud Study	High	
35	BNL	RR-C-5	Improved Cu coating of the stainless steel RHIC cold Beam Pipe	High	C
36	BNL	RR-C-6	Design and prototyping of actively shielded IR quadrupole magnet	High	C
37	JLAB	BDD1	Spin tracking in ion and electron rings	High	
38	JLAB	BDD2	Beam-beam simulation with gear changing	High	C
39	JLAB	ECL1	Electron cooling simulations	High	
40	JLAB	ECL3	ERL Cooler design for single and multi turn operations	High	C
41	JLAB	ECL4	Magnetized source for the e-cooler 36mA	High	C
42	JLAB	ECL5	Fast kicker prototype for multi turn cooler	High	C
43	JLAB	INJ6	Test of CEBAF electron injection mode	High	C
44	JLAB	IRS1	IR design and detector integration	High	
45	JLAB	MAG1	Super-ferric 3T fast ramping short prototype	High	C
46	JLAB	MAG4	IR compact large aperture, high radiation magnets	High	C
47	JLAB	SRF1	SRF cavity systems	High	
48	JLAB	SRF2	Crab cavity design, simulations, and prototype	High	C
49	BNL	LR-B-3	Study the use of 5-cell 647 MHz cavities in the BNL (eRHIC) electron storage ring	Medium	
50	BNL	LR-C-1	Development of an BNL (eRHIC) ERL cryomodule	Medium	
51	BNL	LR-C-3	BNL (eRHIC) Crab Cavity Prototype	Medium	
52	BNL	RR-C-3	Design of fast kickers for electron and Hadron Injection	Medium	
53	JLAB	BDD3	Nonlinear beam dynamics in ion and electron rings	Medium	
54	JLAB	BDD4	Instabilities and feedback systems	Medium	
55	JLAB	BDD5	Large dynamic range BPM	Medium	
56	JLAB	ECL2	Bunched beam cooling experiment at IMP	Medium	
57	JLAB	ECL6	Fast kicker test with beam	Medium	
58	JLAB	ECL7	Integrated test of multi-turn circulator ring	Medium	
59	JLAB	ECL8	Magnetized source for the e-cooler 200mA	Medium	
60	JLAB	INJ2	Space charge in ion complex	Medium	
61	JLAB	INJ3	Ion beam formation	Medium	
62	JLAB	IRS2	Ion and electron ring background and vacuum	Medium	
63	BNL	RR-C-4	Conceptual Layout of the Electron Storage Ring Vacuum System	Low	
64	JLAB	BDD6	Large dynamic range luminosity monitor	Low	
65	JLAB	BDD7	Electron polarimetry	Low	
66	JLAB	BDD8	Ion polarimetry	Low	
67	JLAB	INI4	Alternative ion injector complex design	Low	
68	JLAB	INJ1	SRF linac high power operations	Low	

Row No.	Proponent	Concept / Proponent Identifier	Title of R&D Element	Panel Priority	Panel Sub-Priority
69	JLAB	INJ5	Ion sources	Low	
70	JLAB	IRS3	Collimation and machine protection	Low	
71	JLAB	MAG2	Alternate SC 3T fast ramping magnets	Low	
72	JLAB	MAG3	Full length prototype magnet and cryostat	Low	
73	JLAB	MAG5	Cooler solenoids	Low	
74	JLAB	MAG6	Spin rotator solenoids	Low	
75	JLAB	SRF3	Universal modular cryomodule	Low	

Table 1: Prioritized List of Proposed R&D Activities.

Charge Element V – Cost and Schedule Range

Based upon the level of cost and schedule information provided prior to and during the EIC review of each of the three EIC options, the cost and schedule estimates were deemed to be “reasonable” for the current pre-conceptual stage of this effort.

The cost and schedule estimates are considered to be within plus to minus 25% of the anticipated executed cost and schedules parameters.

Table 2 below provides a summary of the R&D cost proposals by organization.

Laboratory	Number of Proposals	Total Estimated Cost (\$k)
BNL	18	21,830
BNL	CBETA [*]	32,640
JLAB	36	45,676
JLAB	ERL Test [#]	19,900

Table 2: Summary of proposed R&D costs by organization.

Detailed discussions, risk, and recommendations for consideration by DOE NP may be found in the following sections.

Detailed Response to Charge Questions I-V

In response to charge questions I, II and V the panel provides a detailed discussion, assessment of risks, and some points based upon the discussion and identified risks for consideration by NP and the proponent laboratories/supporting universities.

The panel carefully evaluated a number of critical technology elements that are important to a future EIC machine. Each of these is discussed in detail in the response to charge question III below. For each

^{*} Funded by NY State through Cornell University

[#] Indicated separately due to cost relative to other proposals

technology element, there is a discussion, summary of risks identified by the panel, and a set of recommendations based on the discussion and risks for consideration by both NP and the proponent laboratories/supporting universities.

The outcome of the prioritization process for charge question IV is provided in the summary and recommendations section above.

I. Status of EIC R&D to date

Discussion

The state of EIC-related accelerator R&D is appropriate to the level of funding provided and the pre-CD0 state of the proposed EIC project itself. That is, effort is generally being coordinated within individual National Laboratories that are interested in submitting a proposal to host the EIC, with such research being directed to activities most likely to advance design concepts.

The quality of the research is generally high, and the individual laboratories and design teams have done a good job of identifying and addressing both “low-hanging fruit” areas of the design to reduce technical risk, and potential problem areas. Neither the JLAB nor BNL design efforts are “green-field.” The BNL design variants both make use of the existing RHIC facility for the hadron ring and injection complex, and to house the electron injector and either ring or ERL. The JLEIC design variant makes use of the existing CEBAF accelerator to serve as a full-energy electron injector, and while not making use of an existing tunnel their collider design is constrained by the space available on their current site.

A considerable amount of high-quality work has already been done to establish a design basis for the three concepts. This includes fundamental design work (e.g., establishing basic parameters for the accelerators), technical risk reduction, and R&D that can be expected to lead to higher performance or lower cost.

R&D of polarized electron sources has advanced the strained lattice GaAs photo-emitter technology, in particular by use of techniques to limit damage and improve quantum efficiency (QE). Performance remains significantly below the required average current, primarily limited by poor QE lifetime from thermal effects and ion back-bombardment of the cathode. Combination of the multi-layer deposition and use of large-area cathodes appears to hold promise for efficient low average-current photo-emitters that may be combined into a high average current beam. Overall, the development of such sources remains a high-risk item.

Concepts for fast cooling of hadron beams using interactions with bunched electron beams have been developed:

- CeC using a free-electron laser process to amplify charge modulation imprinted on an electron beam by stochastic distributions of the hadron beam, followed by further interaction of the electron beam with the same hadron beam to correct for the initial charge density fluctuations, and
- Use of a bunched and magnetized electron beam in a circulating cooler ring (CCR).

A proof-of-principle CeC experiment is under way at the BNL Relativistic Heavy Ion Collider (RHIC). A test of the CCR concept is proposed at the JLAB LERF. Both approaches provide direct longitudinal cooling, and techniques to convert longitudinal to transverse cooling need to be developed.

Recirculating and energy recovery linacs for high average current electron beams have advanced in the conceptual design; however, experimental validation is needed of the control of beam quality and efficient energy recovery at the average currents required for the EIC ring and injector concepts and cooling schemes. Development of optimized SRF cavities and cryomodules is part of the required R&D, and is also applicable to the ring design in some EIC concepts.

Simulation tools for beam dynamics studies of proposed EIC concepts need to be developed to include the many important physics aspects of these complex machines. Beam-beam effects, instability thresholds, detector backgrounds, intra-beam scattering, beam halo formation and losses, beam crabbing, feedback systems, and cooling systems will all eventually need to be modeled and well understood using validated codes, prior to the final design of lattices and hardware.

Crab cavity concepts to avoid crossing-angle-induced luminosity loss at the IP have been developed into hardware tested in SRF test facilities; however, they have not been inserted into an accelerator to test with a hadron beam. Demonstration of hadron beam crabbing is planned at the Super Proton Synchrotron (SPS) at the European Organization for Nuclear Research (CERN). The panel notes that these activities have benefited from the High-Luminosity Large Hadron Collider (HL-LHC) and related US LHC Accelerator Research Program (USLARP) developments.

Risks

There is often a tendency to focus on aspects of a new machine design that may be thought of as “interesting” – typically new concepts, higher-risk designs, etc. These are often very attractive both from a “pure” accelerator-physics perspective and from that of potentially dramatic improvements to eventual machine performance. As such they should be pursued, but should not be allowed to overshadow the developmental work required to transition foundational technologies towards lower risk solutions needed to assure a successful EIC design.

All three concepts rely at some point upon the high-average-current energy-recovery linac technology, which in turn requires a high-average-current beam source. The default option for ERLs, for both historical and technical reasons, is a photocathode electron gun using a high QE photocathode. (The gun itself is typically direct current [DC], although both normal-conducting radiofrequency [NCRF] and superconducting radiofrequency [SRF] guns have been proposed and tested.) The lifetime issues associated with high-QE photocathodes are well known and represent significant technical challenges in terms of replacement intervals, both from a hardware-and-technology perspective, and from an operational perspective, e.g., the beam dump recovery time.

Average current demonstrated from polarized electron beam sources is currently 1-2 orders of magnitude below the needs for some of the proposed EIC options, presenting a significant risk in achieving the luminosity requirement with these approaches.

High-current recirculating and energy recovery linacs are the critical components in all of the proposed EIC concepts. Untested performance limitations of these complex systems present a risk to luminosity and energy reach. In particular, for the BNL LR design, instabilities and beam losses could result in current limitations in superconducting multi-turn ERL operation.

SRF cavities and cryomodules for both electron and hadron rings and linacs are critical components with demanding requirements. Failure to realize highly robust designs of these systems presents risks in energy, high beam current, and luminosity reach.

Achieving the highest luminosities requires the development of fast hadron cooling techniques with cooling times of a few minutes, 1-2 orders of magnitude beyond capabilities already demonstrated at existing facilities. Without the successful development of fast cooling techniques the EIC designs proposed will reach only the lower end of the required luminosity.

The designs for full aperture detectors with a large crossing angle rely on crab cavities to maintain luminosity, presenting a risk that luminosity will be reduced if the performance of these devices, as yet untested with a hadron beam, is compromised. Synchrotron radiation in the detector, particularly for the BNL RR design, presents a risk.

The utilization of crab cavities near the IR presents a risk – these are untested in the hadron beam environments.

All EIC concepts need to be modeled and beam dynamics well understood using multi-physics, high-resolution codes, validated as much as practical using experimental data from other facilities, prior to the final design of the hardware. Not having high-fidelity models of EIC performance presents a risk in achieving the required luminosity. Conversely, extrapolation from simulations or proof of principle demonstrator experiments to a full-blown implementation over orders of magnitude of critical parameters can introduce risk.

Limited availability of the R&D funding will lead to the risk that costly and complex R&D items may not be completed adequately to inform future decisions.

General Considerations

- Develop technical options to meet the requirements without Crab Cavities. This is common for all designs.
- Validation experiments to test new concepts should have high priority. In particular, it is important to finalize critical experimental demonstrator experiments before taking critical decisions (e.g., Crab Cavity tests with beam at the CERN SPS in 2018 or the CBETA multi-turn, high current ERL experiment).
- Pursue R&D in integrated activities that can demonstrate those concepts most likely to result in significant breakthroughs targeted at the technical needs for an EIC.
- As the JLAB and BNL designs have matured, it has become evident that all three designs have common elements that can probably benefit from pooled R&D resources.
- Perform the R&D required to establish and strengthen the feasibility of fundamental concepts to meet performance goals for EIC. The NAS study may provide refined guidance on the desired EIC performance parameters, which should guide such research.
- It may be fruitful to consider the use of thermionic cathodes for both magnetized and unmagnetized electron cooling applications. In the context of klystrons, high-current thermionic cathodes can operate for tens of thousands of hours without maintenance; they generally have graceful failure modes; the overall system complexity is usually much less than a photocathode-based system; and there should be no issues with magnetized beam production using such

cathodes. In light of these potential advantages, thermionic cathode-based ERL beam sources are worth exploring for this application. The Super Photon Ring – 8 GeV (SPring-8) Compact Self Amplified Spontaneous Emission (SASE) Source (SCSS) X-ray FEL made very effective use of a thermionic cathode, demonstrating that such a cathode can produce a beam of very high quality if suitable care is taken, and the appropriate beam manipulations can be tolerated in the intended context. Specifically, the SCSS application clipped the head and tail of the beam, which may not be feasible for a high-average-current application. Unfortunately, expertise in thermionic-cathode guns is increasingly rare, so the development of such a source may require additional resources for reestablishing the technological base for performing the required R&D.

II. EIC Design Concepts

A. BNL Linac-Ring Concept

Discussion

The BNL stated preference is for the LR design as they believe it presents a potentially more cost effective solution. The concept is based on use of the existing RHIC hadron facilities, plus a new recirculating energy recovery electron linac accelerating a high average current polarized electron beam in multiple passes through the linac. The design covers all physics requirements as stated in the NSAC long-range plan and in the white paper. This design concept includes one interaction region only.

This is a high-risk concept that carries with it commensurate reward in terms of overall cost. Much of the risk centers on the electron injector complex. The injector must provide a 50-mA average current bunch train, composed of 5-nC polarized electron bunches. These are merged longitudinally, bunch compressed, and injected into the LR ERL. The ERL accelerates the bunches to 18 GeV in 6 passes, and, following collision, decelerates them through another 6 passes and finally directs them into a beam dump.

This design hinges on high current polarized electron source with sufficient QE lifetime. Demonstration of such a source is therefore a vital pre-requisite for this design. R&D is being re-directed into a concept for combining beams from multiple lower-current sources, rather than continuing development of a single high-current source. An accumulator ring is being considered in case the performance of polarized electron source cannot meet the requirement of the parameter list for the LR concept.

Strong cooling of the hadron beam is required to obtain the highest luminosities; CeC is being pursued in a proof-of-principle experiment at RHIC. The implementation of CeC is expected to require development of a high average current ERL. Recirculating ERL R&D is being focused at the CBETA facility at Cornell, not supported by the DOE NP. This approach utilizes significant investments in ERL technology already made at Cornell, and pauses much of the ERL development previously planned at BNL. The CBETA facility is primarily planned to demonstrate a multi-pass ERL using FFAG recirculation arcs, potentially a cost-saving approach. Achieving the CBETA objective key performance parameters would also move forward the demonstration of high average current operations of an ERL. However, the re-formulation of the CBETA test to a FFAG demonstrator appears curious after the early termination of a high current ERL experiment at BNL.

SRF R&D is pursuing development of cavity HOM damping in the beam line, based on current BNL experience with storage ring cavities. This approach dissipates heat close to the superconducting cavities and limits the number of cavities in a cryomodule.

The linac-ring IP assumes round beams, e.g., emittances in both transverse planes are approximately equal, for both the hadron and electron beams. This is a reasonable assumption for the electron beam given that it is provided by an ERL rather than a storage ring. That said, the high-brightness electron beam community has, over the course of the past several decades, advanced the design of flat-beam transform techniques for high-brightness electron guns. These were developed specifically for collider applications.

Risks

To meet the performance goals for an EIC requires development of:

- A high average current polarized electron source,
- Strong cooling of the hadron beam, and
- Recirculating and high average current energy recovery linacs (ERLs).

Failure to demonstrate technical validity for these key elements is a significant risk. The design is most likely the lowest cost option of all three concepts presented but has the highest technical risk.

There is no currently operating linac or ERL comparable to the proposed linac-ring electron accelerator. It will exceed current records by approximately an order of magnitude in terms of average beam current, and number of beam passes; and the accelerator-to-arc length ratio is also smaller than any other ERL designed to date. Risks associated with this overall design include single- and multi-bunch instabilities, SRF HOM power, energy loss, energy spread increase and emittance corruption in the arcs from coherent and incoherent synchrotron radiation, beam halo control, and beam energy and fractional energy spread during transport to the dump.

The polarized beam source is highly challenging, in terms of charge-per-bunch as well as average current. To obtain at least feasible cathode lifetimes, specifically on the order of a fill time, the BNL scheme intends to merge the beams from at least 8 separate polarized beams into a single stream.

The electron beam power at the IP is 0.9 GW. While this is within the expected range for an EIC, it is important to note that while an electron storage ring can be compared to a capacitor, with limited stored energy, an ERL is closer conceptually to a combination of a transmission line and a step-up transformer. If the beam is interrupted, the energy-recovery process will stop and the output beam energy will drop, but the linac will still attempt to operate as a high-average-power linac until beam generation at the source is halted. This will require a different approach to machine and personnel protection systems than is typical of most storage ring injectors.

While it is seen as a cost remediation measure, the CBETA experiment (in conjunction with Cornell) would, if successful and adopted, introduce new areas of concern to the linac-ring configuration. Specifically, rather than each energy having its own arc, all beam energies would circulate within the same pipe, raising the average current in a single pipe by a factor of 6. This will require, for instance, additional scrutiny of the impedance budget, vacuum beam pipe design, etc.

CeC is not required to meet the minimum luminosity goals of the linac-ring EIC; however, its use would provide significant benefits to the collider's performance. A CeC system relies on a presently unverified technique (coherent electron cooling), and will also require a high-average-current energy-recovery linac for efficient operation.

General considerations for BNL regarding this concept

- Prepare an alternative parameter set and operation mode that could get by without CeC.
- Encourage completion of the CBETA experiment to assure successful demonstration of high-current, multi-turn ERL operation. It would be a pity if the CBETA experiment fails to achieve either a high-current operation or multi-turn operation 'just' because of difficulties arising from the FFAG return arcs. Integrate approaches with the CCR proposal at JLAB, for understanding of recirculating and ERL concepts.
- Perform front-end simulations for the electron beam with full beam-beam interaction, realistic errors (including offsets of the two beams at the interaction points) and realistic HOM spectra in the SC cavities.
- Continue the CeC experiment, while studying alternate approaches such as strong electron cooling.
- Continue to pursue polarized electron gun R&D aimed at demonstrating technical requirements while managing risk.
- Develop collaborative approaches in SRF R&D, based on the best experiences and state-of-the-art in the SRF community.
- Continue to pursue and carefully monitor the high-current, high-bunch-charge polarized gun development. Initiate an early program to demonstrate the merger technique; note that this need not be done, initially, with polarized beams, or even identical guns.
- Begin preliminary failure-mode analyses of the ERL.
- Consider whether the luminosity, or other aspects of a linac-ring EIC, might be improved by adopting a flat-beam collision. If so, consider whether a flat-beam transform can be effectively performed on beam from a polarized electron gun.
- The JLAB magnetized DC photoinjector experiments provide a potential test-bed (given an energy booster to avoid space-charge issues), and the flat-beam transform topic could serve as a point of collaboration between the JLEIC and BNL LR teams.
- Determine the scale of change necessary to the BNL ring-ring concept to provide an upgrade path toward the linac-ring design that could take advantage of possible technology breakthroughs down the road in high-current polarized sources with good lifetime.

B. BNL Ring-Ring Concept

Discussion

The current BNL RR concept is still at a preliminary conceptual design stage. This design is relatively new, not found in their most recent design report. For example, there is no electron ring lattice design and related beam dynamics study, and the synchronization scheme has yet to be developed. However, it is an interesting and quite necessary alternative design for the high-risk / high-gain BNL LR design. This design covers all physics requirements as stated in the NSAC long-range plan and in the white paper. The baseline design can support two interaction regions.

This appears to be a medium-risk concept overall, with additional risk centered on the desire for single-bunch replacement in the electron ring. The concept as presented requires injection of a single 50-nC electron bunch into a dumped single bucket in the electron ring and refilling each bucket every 3 minutes, corresponding to a linac pulse rate of 1 Hz. An alternate injection scheme is conceptually similar to the “top-off” modes currently operated at many X-ray light source storage rings, wherein the charge in a given bucket is supplemented, as opposed to being dumped and replaced.

Some of the design beam parameters appear as quite demanding (e.g., high proton and electron bunch intensities, electron beam-beam parameter) when compared to achieved parameters in the only previous e-p collider (HERA) and other lepton colliders (e.g., LEP) while imposing new injection procedures such as the bunch exchange injection during the beam collision process. Validation of the presented parameter choices and operation mode depends to a large extend on scaling from past colliders and on beam simulations.

Copper coating of the exiting RHIC vacuum chamber would be required to limit heating due to resistive wall current, and also to limit electron cloud effects.

While pursuing two designs simultaneously dilutes the design effort available for each concept, developing the RR concept further is a necessary step to allow for an internal down select between the two BNL technical concepts.

Risks

The lack of a complete electron ring design with integrated IR optics prevents making progress toward a credible BNL RR EIC design.

Not being able to achieve the envisaged beam parameters due to fundamental limitations such as transvers mode coupling instabilities (TMCI) or beam-beam related beam size blow-up.

The inability to achieve design luminosity due to intense beam instabilities.

The electron injector for the ring-ring concept embodies several risk areas, particularly the single-bunch replacement paradigm.

The electron accumulator ring to collect, damp and merge polarized electron bunches must operate at higher charges and lower energies than comparable rings, for instance the particle accumulator ring (PAR) at the Advanced Photon Source (APS).

The resulting 50-nC electron bunch must be successfully accelerated through multiple passes of the linac prior to injection, while undergoing bunch compression and transport through very long return arcs. The bunch charge is 1 – 2 orders of magnitude higher than the most comparable linac designs at the same peak current based on 1.3-GHz TESLA-type cryomodules, suggesting 2 – 4 orders of magnitude higher wakefield effects for the same peak currents; switching to 650-MHz cavities should help to address HOM concerns but must still be evaluated thoroughly. Collective effects, such as coherent synchrotron radiation and the microbunching instability, also pose a potential risk.

General considerations for BNL regarding this concept

- Complete the electron ring lattice design as soon as possible.
- Develop an extensive simulation tool box for both the electron and the proton beams and validate the simulation tools through benchmarking with existing data (either data from past colliders and storage rings or simulation data from other codes).
- Continue to pursue recirculating and high average current ERL demonstrations, for example at CBETA.
- Mature an alternate injection scheme for top-up operation of the electron ring, which can make use of considerably lower bunch charges; this would address both the risk associated with 50-nC bunches and another concern identified by the panel, that of the effects of a newly injected (and thus undamped) electron bunch interacting with the proton beam.
- Perform bunch stacking, storing and damping experiments with relevant bunch charges at relevant accelerators, e.g., the APS PAR, to demonstrate technical feasibility of a key portion of the injector chain.
- The technical design needs to be developed further to allow for a comparison and down select between the two options for the RHIC site.

C. JLEIC Concept

Discussion

JLEIC was generally seen by the panel as a medium risk option, assuming the JLAB injector complex can serve as an on-energy injector for the electron ring. The hadron injector front-end has been well studied in the context of the Argonne Rare Isotope Accelerator (RIA) design; booster technology also seems to be fairly well established.

The JLEIC intends to use bunch-train incremental fills into the electron ring, which will readily facilitate top-up operation if the polarization lifetimes support operating times significantly longer than the stored beam lifetimes.

The figure-8 design of the storage rings, and in particular for spin preservation in the hadron ring, is a novelty in the accelerator landscape. Adopting this scheme for the JLEIC scheme bears therefore a non-negligible risk without experimental validation. However, given past validation of spin related accelerator tools (e.g., Siberian snakes) the likelihood of success appears rather high and the risk mainly arises when weighed against the implied high infrastructure investment and the importance of the high beam polarization levels for reaching the NSAC EIC goals.

The potential benefits of the figure-8 configuration for polarization are well recognized. However, this design is less efficient in using the circumference due to the need of more arc sections to complete the loop. The total bending angle is $2\pi(1+n)$ with $n = 0.45$ (for a recent design of 81.7 degree of the crossing angle). There are some important issues that should be addressed:

- For a given circumference, a larger net bend angle is used, leading to an increased synchrotron radiation power. This in turn limits either the maximum energy of the electron machine, or the maximum beam current, or some combination of both.

- Compared with the BNL RR design, JLEIC electron ring circumference is effectively smaller by a factor of: $(3.835\text{km}/2.15\text{km} * 1.45) = 2.58$, which means that JLEIC ring may be more limited by the total synchrotron radiation power.
- Both increasing the CM energy and optimizing luminosity can benefit from a larger electron ring. Setting aside the cost, however, the JLEIC suffers from limitations relating to the available acreage at the site adjacent to the CEBAF (the proposed injector).

Fast electron cooling using a bunched, magnetized electron beam and recirculating linac is needed for the hadron beams. A circulator cooling ring demonstration experiment using high average current recirculating and energy-recovery linac is proposed at the JLAB Low Energy Recirculator Facility (LERF) and is very important for demonstrating the feasibility of reaching the high-end of the projected JLEIC performance spectrum.

The existing CEBAF facility would be used as the electron injector. JLAB experience with SRF has resulted in high-efficiency HOM damping, allowing several cavities to be incorporated in a cryomodule. Existing RF and vacuum systems built for the PEP-II B-factory at the Stanford Linear Accelerator Center (SLAC) could be used in the electron ring. The hadron ring baseline uses super-ferric magnets, superconducting $\cos(\theta)$ magnets are considered as risk mitigation option. The energy reach of the baseline and upgrade design is lower than that defined in the NP Long-Range Plan. An upgrade including new magnets would be required to reach the higher end of the energy goals.

The design covers two of three physics requirements as stated in the NSAC long range plan and in the white paper. The design can reach the required luminosity, and can deliver polarized ions and electrons, but falls short of the nominal maximum center of mass energy desired at the ultimate facility (140 GeV). The baseline can support two interaction regions in its design. An upgrade path is proposed that would increase the energy of the accelerator, but the final energy would still be lower than what is stated in the NSAC report as a desirable upgrade target.

The project team has further refined the design in the last few years and has made trade-off studies that assess the impact if high risk R&D items do not succeed and these studies show that the design would still be competitive even without hadron cooling.

Risks

To meet the performance for an EIC requires the development of:

- Strong cooling of the hadron beam, which in turn requires
- Recirculating and high average current energy recovery linacs (ERLs).

The figure-8 design for both the main rings and booster is, to date, untested. Given the cost of accelerators it is unlikely the pre-CD0 budget will support a large subscale model, so the design must be exceptionally well validated by both theoretical and computational approaches.

The figure-8 design's symmetry has led the JLAB team to conclude that strong spin control is not necessary, and they are therefore relying on new, relatively weak spin-control technologies.

The CEBAF accelerator is assumed suitable as-is for operating as a top-up electron injector for JLEIC. In terms of average beam current this is true, however, JLEIC injection mode is very different from the

quasi-CW CEBAF operating mode, requiring higher average current bunch trains and differential beam loading that the RF system must compensate for. While these should be surmountable issues, an early demonstration of JLEIC injector-mode operation would mitigate this risk entirely.

There is limited experience with super ferric magnets in colliders especially for fields above 2.5 T. A 6 T magnet would be a high-risk item following this design concept. Therefore it is important to clarify how important the CM energy for an EIC collider is since it might increase the risk of the JLAB design.

There is risk in the area of reaching higher center of mass collision energy and maximizing luminosity at higher electron energies.

General considerations for JLAB regarding this concept

- Define and perform a demonstration of adequate hadron cooling with clear, pre-defined demonstration goals.
- Evaluate the possibility of experimental demonstration of spin conservation in a figure-8 storage ring arrangement.
- Continue to pursue development of the CCR proposal and other recirculating and high average current ERL demonstrations, for example at CBETA.
- Continue the development of fast cooling with bunched magnetized electron beams, while studying alternate approaches such as CeC.
- An early test of the JLEIC injector scheme on the existing CEBAF accelerator would retire a significant technical risk.
- An improved understanding of the center of mass energy requirement for the baseline design is critical to this concept.
- Assess whether the JLEIC design takes on more risk than necessary by pursuing mainly superferric magnet design concepts.
- Ensure that ongoing tests of pulsed beam cooling are relevant to the goal of hadron cooling for JLEIC.

III. Technical Feasibility

Critical Technology Elements

A. General Accelerator Technology

Discussion

Some novel accelerator concepts, such as crab cavity operation in hadron beams and high-current (multi-turn) ERL operation and strong hadron beam cooling are common to all EIC concepts. The successful validation of these key concepts through demonstrator experiments is a vital prerequisite for the successful implementation of a future EIC.

Risks

Inability to achieve crab cavity operation in hadron storage rings, high current ERL operation or strong hadron beam cooling would severely limit the performance reach of the currently envisaged EIC design concepts discussed above.

Achieving the EIC performance in any of the proposed approaches requires the development of several critical accelerator technologies.

Recommendations

- Studying alternative options for these key accelerator technologies would help to mitigate the associated risk of not meeting the required EIC performance levels. For example, one could look at interaction region design with bent electron beams and without the use of crab cavities and highlight the resulting implications such as synchrotron light inside the detector and the need for synchrotron light absorbers to minimize the background inside the experiment.
- Organize R&D plans to build on community experience and expertise, collaborating where possible to make best use of existing expertise, experience, and infrastructure.

B. Beam Dynamics and Simulation

Discussion

Several of the proposed EIC beam parameters and operation modes are rather demanding when compared to experience in past colliders. For example, proton and electron bunch intensities and electron beam-beam parameters appear as rather high when compared to what has been achieved in the only previous e-p collider HERA and other lepton colliders such as LEP. The extrapolation from previous colliders is even more challenging when the new EIC colliders introduce new operation concepts that have never before been demonstrated in an operational facility. These new operation concepts include beam-beam interactions with crabbed beams in asymmetric e-p collisions, Gear Cogging interactions between the electron and hadron beams and bunch-by-bunch swap out injections of high intensity electron bunches during the collision process. Validation of these demanding parameter choices and operation modes relies

mainly on validation through beam simulations. The development of new and the adaptation of existing (and already validated) simulation tools represent therefore an essential part of the EIC design process.

It is important that these concepts are validated through simulations in due time, before critical technical decisions are taken for the different EIC designs, which implies in turn that the required simulation tools should be validated through benchmarking with existing data early on in the EIC design process. The list of novel operation modes that requires the development of new tools includes:

- Collisions with crabbing,
- Collisions with multi-bunch operation and swap-out injection of individual bunches, and
- Multi-bunch collisions with Gear Changing collisions.

The above list of required new simulation tools needs to be complemented by a list of required simulation studies that can rely on existing simulation tools:

- Simulation of single bunch intensity limitations for short bunch operation (e.g., TMCI threshold calculations and simulations for multi-bunch operation),
- Estimation of impedance budgets for the targeted beam and bunch intensities,
- Simulation of dynamic aperture and resulting field quality specifications for the new storage rings (including the insertion magnets), and
- Simulation of instability thresholds in high intensity ERLs.

Complete front-end simulation for multi-turn ERL operation with realistic HOM spectrum and impedance model for the SRF, beam-beam interactions and realistic errors (beam offset at the IR, orbit errors and offsets inside the cavities, phase and voltage errors in the cavities etc.) are of critical value for the BNL Linac-Ring design. In time developments of the required tools would also allow predictive simulations for the new CBETA test facility.

The development of the required tools seems to progress at the moment rather independently for the different EIC concepts. A closer collaboration between the different EIC concepts for the development of new tools might provide more synergies and added value and performance capabilities for the new tools. For example, the development of the simulation tool for the Gear Changing operation mode is clearly tailored towards the needs of the JLEIC concept proposal. However, a closer involvement or discussion with the other EIC concept teams could result in a more flexible tool that is also capable of simulating the impact of beam-beam interactions with crabbed bunches and individual bunch swap-out injection with beam-beam interaction on the beam stability.

Risks

Not developing the required simulation tools in sufficient time (early on in the EIC pre-conceptual design process) and in too much isolation for the individual EIC studies bares the risk of not having key operation concepts and parameter choices validated when the design decision needs to be finalized.

Not validating new tools though proper benchmarking before applying the new tools to the EIC studies bares the risk of taking design decisions based on faulty or incomplete simulation results.

Recommendations

- Pursue as a high priority the development and validation of simulation tools that are required for design validation of the EIC concepts.
- Encourage a closer collaboration between all partner laboratories and universities for the development of the simulation tools and the development of a central simulation toolbox that can be shared by all design teams.

C. Crab Cavities

Crab cavities are a vital ingredient for all EIC concepts. While operation of crab cavities within a hadron storage ring has never been demonstrated, all EIC project proposals take this concept for granted. One should encourage the different EIC proposals to study and estimate alternative operation modes without crab cavities (e.g., insertion design with deflected electron beam and resulting synchrotron radiation through the detector, integrated dipole field in the detector, etc.).

Discussion

Crab cavities are needed for both BNL concept (LR and RR) and JLEIC for both protons (hadrons) and electrons. Crab cavities give the BNL concepts an increase in luminosity about a factor 33. For JLEIC the luminosity increase is about a factor of 10.

The required number of crab cavities and required voltages are still evolving as the interaction region designs have changed somewhat over the past year. The BNL concepts need about 10 to 15 crab cavities per side of the IR for hadrons and about 2 to 3 per side for electrons. JLEIC needs about 6 to 8 cavities per side for the hadron beam and about 2 per side for electrons.

The crab cavity development at BNL has been mainly focused on LARP for the high luminosity LHC project but should be highly applicable to the BNL concepts. Attention has been placed on the crab cavity test in the SPS at CERN but those tests will likely come late to BNL's self-imposed linac-ring / ring-ring down select timeframe. However, as both options require crab cavities, such a down select would be equivalent to a crab cavity frequency down select. Design work for BNL concept crab first harmonic cavities has started. The required crab cavity locations in the BNL accelerator lattice seem quite mature. Work on the third harmonic crab cavities has not yet started, but these concepts are expected to be similar to the crab cavities required for the electron beam.

For the JLEIC collider design, there are presently two locations in the rings where crab cavities could be located leading to two sets of crab specifications. Both vertical and horizontal crab cavities are used to correct for detector solenoid rotation effects. The JLEIC crab specifications will likely solidify in the coming year. There is presently dispersion at the location of the crab cavities in JLEIC. The committee was concerned about potential beam dynamic issues that may arise from dispersion; these issues should be studied.

Crab cavity work at Old Dominion University (ODU) on design and fabrication has been excellent. ODU is investigating several cavity shapes, cell apertures, and the number of cells per cryomodule for JLEIC.

More extensive simulations of hadron beams with strong crab cavities, long bunches, and beam-beam collisions need to be done, which will lead to improved specifications. These simulations should include phase jitter tolerances, voltage variations, beam rotations due to the detector solenoid, transverse beam offsets in the cavities, dispersion, IR upstream-downstream cancelation, and third harmonic cavities.

Crab cavity tests with hadron and/or high current electron beams will be important at the Critical Decision (CD)-1 stage for an EIC. This is a sizable effort so care must be taken to do the right and most productive test. This experiment could be done at several accelerators, including the future potential bunch cooler ring test facility at JLAB, at RHIC at BNL, or CBETA at Cornell, as well as at the SPS at CERN where there are upcoming possibilities to contribute to the crab cavity tests.

Risks

As crabbing is required to reach ultimate luminosity goals, there is the risk that the cavities do not achieve the required performance, including peak voltage and degradation with time. In particular, the presence of the crabbing cavities on the dynamics of the high-current electron and ion beams (for example instabilities, beam loading, and multipole components) need to be explored. Various degradation effects should also be investigated.

Recommendations

- Continue crab cavity design, simulation, and prototype development efforts.
- Foster collaborative design efforts between the ODU, JLAB and BNL design teams.
- More tightly integrate crab cavity activities into the broader design effort, specifically ring dynamics studies and detailed IR design.
- Given the fact that these cavities have not been demonstrated in a hadron machine, it is important to study an alternative option for an interaction region design with bent electron beams and without the use of crab cavities to evaluate methods to address synchrotron light inside the detector and the need for synchrotron light absorbers to minimize the background inside the experiment.

D. Diagnostic Devices

Discussion

From the presentations from both JLAB and BNL, little time was devoted to beam diagnostic issues. This may be consistent with the current stages of the accelerator designs. However, going forward issues in this area should not be taken for granted. Here, some observations and comments are given.

For JLEIC, the review presentations mentioned the following diagnostics:

- high-resolution electron detection downstream of IR,
- Compton polarimetry integrated with the IR design, and
- Beam dynamics and diagnostics (BDD) but not with great specificity.

For BNL, no specific mention of beam diagnostics is found.

High-power bunch-by-bunch feedback for the electron beam (more important for the figure-8 ring with a high bunch rate).

At KEKB, it is observed that both longitudinal and transverse bunch-by-bunch feedbacks are available. The operational parameters at KEKB, 2.6 A of e+ and 1.1 A of e-, circumference 3.016 km, and RF frequency 509 MHz, are very similar to those of the EIC electron rings. KEKB developed and operated wide-band (250 MHz) bunch-by-bunch feedback systems for transverse and longitudinal damping, but have reported that even though such capabilities were installed and operated, the system has not been used in routine operation.

The panel was more interested in aspects of the longitudinal feedback. Broadband bunch-by-bunch longitudinal feedback systems based upon the FPGA technology have been widely used at light source storage rings, with bandwidth from 100 to 250 MHz (5 ns to 2 ns bunch spacing). Typically, the bandwidth required is $\frac{1}{2}$ of the bunch rate, e.g., for a 500 MHz bunch rate (2 ns), the required BW is 250 MHz (there are some benefits to have a wider BW in some cases). Most recently developed RF kickers are waveguide-overloaded cavities with a broad bandwidth, high shunt impedance, and reduced higher-order-mode (HOM) effects. However, the shunt impedance is reduced in order to realize a larger bandwidth by using more RF feed-throughs. While it is prudent to investigate the damping needs for the bunch-by-bunch feedback systems as soon as feasible from the design point of view (it needs to know the required stability growth rates which are only possible after having completed a version of the vacuum chamber design), it is very likely a solution can be found by either using more powerful broadband RF amplifiers or more than one RF kicker.

High-resolution electron detector downstream of IR and Compton polarimetry

Input from the nuclear physics scientific community is needed to better define the needs and performance specifications for these diagnostics.

Risks

An implicit assumption has been made that beam diagnostics are conventional, based upon demonstrated technologies.

The risks for bunch-by-bunch feedbacks are likely manageable for EIC electron rings provided suitable analysis and R&D is performed.

Recommendations

- Gain a better understanding of the specific beam diagnostic needs in IR for different types of physics experiments.

E. Electron Cooling

Discussion

Various mechanisms, including intra-beam scattering (IBS), beam-beam interactions, multiple coulomb scattering, etc., would lead to emittance growth of hadron beams in the EIC, with IBS being the dominant one. To attain the highest design luminosity ($\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$), both EIC concepts require strong hadron beam cooling, with cooling times of approximately a few minutes or less. Present state-of-the-art electron cooling and microwave stochastic cooling are insufficient in the EIC regimes. Unproven “strong” beam

cooling techniques are proposed by both laboratories in order to reach luminosity of 10^{34} in an EIC. Both of these approaches require ERL technology to provide the high average current bunched electron beam.

A proof-of-principle CeC experiment is under way at the BNL RHIC facility, and is planned to complete by the end of 2018. This technique uses a high average current bunched electron beam in a free-electron laser (FEL) as a microwave amplifier, with longitudinal bunching induced by stochastic fluctuations in a hadron beam co-propagating through a “modulator” beamline. Amplification of the electron beam bunching follows in an FEL undulator beamline. After the FEL, the hadron beam is re-introduced to overlap the electron beam with the appropriate phase such that the strong modulation in the electron beam “kicks” the hadron distribution longitudinally to compensate for the charge fluctuations initially imprinted on the electron beam. In complete analogy to conventional microwave stochastic cooling, the $1/e$ momentum cooling time can be expressed as

$$\tau_{cool} \approx \frac{N_b}{W} k$$

where N_b is the number of protons per bunch ($\sim 10^{11}$), W is the bandwidth ($\sim 10^{12}$ Hz) and k ($>>1$) is a numerical degrading factor, associated with various processes, such as non-optimal amplification gain, reduced momentum cooling range, e-p bunch overlap, etc. The CeC proof-of-principle experiments mentioned above are aimed to demonstrate only longitudinal cooling.

Another approach to “strong” electron cooling is more conventional in using a bunched electron beam co-propagating with the hadron bunch in a solenoid channel. To reduce the demands on the electron accelerator, JLAB has proposed interacting each electron bunch with multiple ion bunches via a recirculator ring. A proof-of-principle experiment is proposed at the JLAB LERF, using existing ERL infrastructure and a new high average current gun producing magnetized beam, multi-pass circulator cooling ring including fast kickers, solenoid channel, and diagnostics and instrumentation.

All of the bunched-beam coolers proposed for EIC designs will require an ERL driver accelerator, both for efficient operation and to avoid extremely high beam dump powers. Table 3 presents a summary of key parameters for the JLAB 10-kW ERL-driven FEL, a high-average-power FEL driver designed for the US Navy (the INP-FEL), the BNL Linac-Ring injector ERL, and the three bunched-beam electron cooling strategies proposed for the EIC designs.

The column in green indicates an operating ERL. The column in yellow has been extensively studied via modeling and simulation. The cells in orange represent derived or extrapolated parameters. Publicly available references are provided for values not taken from the EIC technical review presentations.

Parameter	Units	JLAB FEL ^a	INP-FEL ^b	LR inj	BNL CEC ^c	JLAB recirc	JLAB direct
I _{avg}	[A]	0.01	0.1	0.05	0.13	0.075	0.2
Q _b	[nC]	0.135	1	5.3	13	3.2	0.42
E _{max}	[MeV]	115	100	13.0E+3	136	55	55
E _{dump}	[MeV]		~5				
P _{beam}	[MW]	1.15	10	650	17.68	4.125	11
Notes		1	1	2	1,4	3,5,6,7	3,5,8

Note 1: Free-electron laser

Note 2: Multiple passes both increasing and decreasing energy

Note 3: Requires magnetized beam source

Note 4: Requires high-brightness source (1-micron norm. emit.)

Note 5: Cooler will have to run from 4.3 - 55 MeV depending on proton beam energy

Note 6: Beam power does not reflect 25x amplification from recirculator ring

Note 7: Specifications are from the presentation; parameters in 2015 MEIC report and R&D summary differ somewhat

Note 8: I_{avg} of 200 mA based on JLAB ECL-8 R&D plan

Table 3: Summary parameters for various ERLs based on superconducting linacs.

Broadly speaking, the higher the average current, and the higher the peak beam power, the more challenging the design of an ERL will be. The higher the bunch charge, the more challenging the injector design in particular will be, and the greater the possibility for space-charge and other collective effects to introduce deleterious effects. All three electron cooler ERLs have beam currents and average beam powers comparable to the INP-FEL design, which is approximately an order of magnitude higher in current, beam power and bunch charge than the JLAB ERL-FEL.

One of the foremost challenges in the design of an ERL is managing the energy spread of the beam as it is decelerated down to the dump voltage. If simply decelerated on-trough, the beam's absolute energy spread will remain constant, while its mean energy decreases and thus fractional energy spread increases. The increasing fractional energy spread poses increasing challenges to the beam transport and extraction to the dump, especially as in a high-average-power machine beam loss must be minimized for both radiation safety and machine protection considerations. If the ERL is used to simply accelerate and then decelerate a beam, with minimal changes to the bunch parameters at the maximum beam energy, this is generally not a difficult challenge so long as collective effects (e.g., CSR, the microbunching instability, etc.) do not significantly degrade the beam quality during transport. However, ERLs that drive FELs, or other mechanisms that can induce large energy spreads on the beam, pose notable challenges.

^a S. Bensen et al., "High power operation of the JLAB IR FEL driver accelerator," Proceedings of PAC07, Albuquerque, New Mexico, USA

^b J. Blau, K. Cohn, W.B. Colson, "High average power free-electron lasers," Opt. Eng. 52(2), 021013 (Nov 15, 2012). doi:10.1117/1.OE.52.2.021013

^c BNL-101286-2013-CP

For instance, the INP-FEL design (Table 3) has a maximum beam energy of 100 MeV, and was intended to drive an FEL. Assuming the FEL process induced a 5% energy spread on the beam at 100 MeV, after deceleration to the beam dump the energy spread would be an unacceptable 100%.

There are several methods available to mitigate this problem. First, the beam can be dumped at a higher energy, trading simplicity of design against higher dump power and, potentially, higher activation if the beam energy at the dump is above 7-10 MeV. High-beam-power FEL-driver ERLs are usually designed to decelerate the beam off-crest, which when combined with other phase-space manipulations helps to reduce the absolute energy spread as the beam is decelerated. To maintain the power balance in the ERL, the beam must also be accelerated off-crest; some designs also incorporate harmonic linearizers and various bunch length manipulations.

The JLAB “direct” cooler has the potential to be workable with a simple on-crest/on-trough acceleration/deceleration scheme, depending upon how much energy spread a single pass will impose on the electron beam. Depending upon the imposed energy spread, the recirculating design might also work with a simple on-crest/on-trough scheme; this will require additional study. However, both JLAB cooler designs rely on magnetized electron beams, which have not previously been tested in ERL loops; there is a possibility of the angular momentum in the beam introducing additional coupling terms for the ERL that may, for instance, affect the beam breakup stability criteria.

The BNL CeC design is arguably the most technically challenging, with the highest beam current and by far the highest bunch charge at 13 nC per bunch (270 ps bunch length, 50 A peak current). To be effective for the highest energy proton beams, the CeC cooler will also require bunch emittances on the order of 1 μ m transverse normalized emittance, which may prove challenging to maintain depending upon the beam source technology and cathode.

The panel notes that an ex-parte communication obtained by a panel member following the panel’s meeting indicates that there could be significant challenges in achieving the required transverse cooling rates for one or more of the proposed designs.

Risks

Practical difficulties of each proposed strong electron cooling approach need experimental demonstration. The challenges include:

- Spatial and temporal overlap of both beams in the CeC “modulator” section,
- Tuning of the CeC FEL to the optimal gain, center frequency, and bandwidth,
- Spatial and temporal overlap of both beams in the CeC “kicker” section,
- Matching of the magnetized beam delivered to the CCR solenoid channel,
- Fast injection and extraction in the CCR,
- Development of the high average current ERL for required cooling rates, with transport and efficient energy recovery of the beam exiting the cooling section and returning through the SRF linac, and
- Development of transverse cooling based on emittance exchange for the CeC.

Initial CeC experiments are designed to demonstrate longitudinal cooling; transverse cooling schemes that are based on this approach are yet to be developed, and significant effort is required.

SRF technology for the required ERLs also needs development, as discussed in a later section.

Recommendations

- Maintain efforts to complete the CeC experiments at RHIC.
- Continue to pursue high average current ERL demonstrations, for example at CBETA.
- Continue to pursue CCR demonstration at LERF.
- Further develop models for strong electron cooling including transverse cooling.

F. Polarized Electron Sources

Discussion

Beam polarization is a key parameter for the EIC listed in the 2015 LRP. The required polarization for beams is listed as: Polarized (~70%) electrons, protons, and light nuclei. The injection requirements for polarized electron beams are, for the three designs under consideration:

TJNAF	JLEIC	Direct electron injection
BNL	LR	50mA, Direct electron injection
BNL	RR	Accumulator/Damper Ring injection

Table 4: Injection conditions for polarized electron beams.

The BNL EIC concepts require the development of a polarized electron source providing an average current of several mA.

Development of polarized electron sources has taken strained lattice GaAs photoemitters and advanced by the use of the following:

- Reduce the impact of QE degradation due to ion back-bombardment by emitting from an annular area off the axis of the photocathode,
- Cool the cathode to limit thermal degradation with high average drive laser power,
- QE enhancement by deposition of multi-layer optically reflective surfaces below and above the GaAs layer,
- Combine beams produced from multiple photocathodes within a single accelerating structure into a high average current output, and
- Interleave beams from multiple lower rate sources to combine them into a high average current beam.

The development of high QE and large area sources producing several mA beam may provide a path to high average current polarized electron beam production required for an EIC.

In the JLEIC proposal, the CEBAF 12 GeV accelerator is used as a direct injector with very little modification. The CEBAF accelerator has been in operation since 1995, first at 4 GeV, then 6 GeV, and now at 12 GeV, serving the nuclear physics program at JLAB. The CEBAF accelerator routinely operates with high availability. There are no proposals for R&D funding to continue the development of or modifications to the CEBAF accelerator. The only R&D element related to electron injection is to test the

CEBAF electron injector mode, which is expected to reduce the risk level to low. The JLEIC beam could be tested into a CEBAF beam dump at the earliest opportunity to demonstrate this mode of operation. The electron injector will inject two polarization states and achieve currents in the JLEIC electron ring of up to 3A at 7 GeV.

For the BNL LR concept, accelerated electrons originate in a high-current polarized source and are accelerated to 20 MeV in the injector accelerator. Using recirculating loops inside the RHIC tunnel the electrons make multiple passes through the ERLs, gaining up to 3 GeV of energy per turn. The electrons can be extracted at any energy from 3 to 18 GeV into a high-energy transport beam line that brings them into collision with the hadron beam.

The requirements for the polarized injector for the LR concept are quite demanding. Polarized electrons are required at an average current of 50 mA and a bunch repetition frequency of 9.4 MHz. Individual bunches are therefore 5 nC charge, and a bunch length of 1.5 ns yields a peak current of ~3.3 Amperes. The pulses originate in an 8 photocathode gun array, one pulse per gun sequentially, 1.5 ns long with ~105 ns between pulses (1.4% duty factor total, not per gun). The pulses from the 8 individual guns are transported through a series/parallel array of benders/combiners, (a total of 14 dog-leg benders and 7 combiners) to form a single longitudinal pulse train on a single beam line. This beam passes through a Wien Filter for spin manipulation, is longitudinally compressed via 84 MHz and 252 MHz cavities, and then is accelerated to 20 MeV in a 647 MHz cavity. The LR concept proposes to employ eight parallel polarized guns, each with inverted geometry of the JLAB style, each operating at ~350 kV in a common vacuum vessel.

The surface gradient at the GaAs crystal of JLAB gun is ~2.1 MV/m. The LR concept gun expects to achieve a cathode field gradient of between 2.7 and 4.3 MV/m. It is far from clear that the factor of ~2 increase in cathode surface gradient will permit extraction of this high charge density. The standard Pierce geometry would indicate only a factor of 2.8 increase in the peak current limit. The BNL team may be planning to use a uniform illumination scheme of the large area photocathode or employ the Massachusetts Institute of Technology (MIT) “hollow beam” concept, either of which could help with the surface charge limit on photoemission. These limits can be explored experimentally once the new gun is operational.

The LR concept gun needs to achieve 1.2 MHz, 6.3 mA average, 3 Amperes peak current for each of the 8 guns. The JLAB gun generated 4 mA average current, 53 mA peak current with a laser spot size of 0.3 mm on the cathode. This gun spot size was quoted as 1 mm in the design report but 25 mm in the presentations. According to BNL, each gun of the LR concept source could generate 6-10 mA average, 3.3-5.5 Amperes peak current.

Fast kickers are proposed to longitudinally stack bunches from the individual guns thereby creating a 9.6 MHz, 50 mA average current bunch train. However, each gun switch and laser element only operates at 1.2 MHz, so it takes all 8 guns to produce the 9.6 MHz pulse bunch train.

The 8-gun array will be located inside the RHIC tunnel. All of the Ultra High Vacuum (UHV) elements that transport GaAs crystal cathodes for activation, re-activation and removal must be remotely controlled. There was no description of how this will work in practice. Cathode manipulation is extremely complicated and does not lend itself easily to remote control. An error in one of the 8 guns will impact all the other seven cathode crystals in adjacent guns unless they are isolated with UHV valves. The MIT

group reports a significant loss of QE in activated crystals when UHV valves are actuated nearby. So, it is very important for the LR concept polarized gun team to address how remote control crystal manipulation and vacuum isolation will take place. (Even should a failure in one electron gun fail to adversely impact the other guns, it is far from clear what impact the resulting non-uniform bunch train would have upon ERL operation, specifically the higher-order-mode spectrum.)

The BNL LR concept team has launched a R&D program to address these issues. The team proposes to:

- Upgrade vacuum system of the existing Gatling gun prototype (previous R&D);
 - Use this gun for bench marking of beam dynamic simulations, and optimization and commissioning of the diagnostic beam line, and
 - Complete the build-up of diagnostic beam line and beam dump.
- Build up a single, new inverted gun with optimized geometry, ultra-high vacuum quality for high gun voltage (350 kV) with a large cathode diameter ~25 mm;
 - Fabricate and assemble the new inverted gun with an optimized geometry, ultra-high vacuum quality for high gun voltage (350 kV) with a large cathode diameter ~25 mm Gatling gun.
- Complete laser parameter optimization.
- Perform systematic measurements on the completed gun (FY18).
- Perform the simulation of beam extraction and transport (underway).
- Work out, optimize and simulate the bunch-stacking scheme.
- With the RF kicker electrical design available, work has already started for alternative stacking schemes.

To date there has been some R&D related to different approaches to polarized sources. BNL has supported the development of the Gatling gun (24 photocathodes in a single vacuum enclosure) concept. However, this approach is not the primary one for the BNL LR concept. The Gatling gun will use a single photocathode to benchmark beam dynamic simulations, and optimize and commission the diagnostic beam line and beam dump.

The requirements for the polarized injector for the BNL RR concept are less demanding than the LR version. The team proposes a recirculating linac inside the RHIC tunnel as the polarized full-energy injector for the electron storage ring. In the interest of risk reduction and cost saving the BNL team proposes to use existing 1.3 GHz SRF technology that is virtually identical to the European XFEL, LCLS-II at SLAC, and the proposed ILC. Alternatively, a 650 MHz ERL could be used as an injector, with 6 GV of total accelerating voltage installed in two adjacent straight sections of the RHIC tunnel. Two recirculation loops would then suffice to reach 18 GeV. This would also support arbitrary spin patterns in the electron ring, realized by full-energy injection of polarized electron bunches with the desired spin direction (“up” or “down”) and frequent bunch “swap-out” to ensure a high degree of polarization.

In the BNL RR injector concept, the electron gun emits a bunch of polarized electrons, which enters the pre-injector linac, is bunched and is accelerated to the energy of 200 MeV. This energy is suitable for preservation of the polarization in the damping/accumulator Ring, which accepts the electrons after the Spin Rotator. Once the required charge is achieved by stacking of successive bunches from the pre-injector, the damped bunch is extracted towards the bunch compressor that consists of the RF section and a chicane that ensures that the bunch length is suitable for acceleration in the 1.3 GHz RF linac. After passing the first linac section the beam energy increases to 3 GeV. A second stage of compression yields a shorter bunch that circulates around the RHIC ring to reenter both linac sections until the desired injection energy is achieved. Long (total of 3 km)

transport lines provide a mild amount of compression to reach the required beam parameters at the injection point of the storage ring.

The current design relies on the SLAC SLC type gun that has demonstrated reliable performance delivering several nC of polarized electrons (70-75% polarization) at a 120 Hz repetition rate. A damping Ring (DR) is necessary to increase the charge per bunch from several nC available from the SLC-type gun to the specification for the BNL ring of 50 nC. If the accumulation mode is feasible for the BNL Ring-Ring operations the DR can be bypassed, and the 200-MeV beam from the injector can be injected to the first 1.3 GHz Linac for acceleration.

The R&D to develop polarized photoelectron sources that have the performance required by the BNL linac ring accelerator specifications has not yet been successful. This is a high risk item for this concept as acknowledged by the BNL team and continues to be the top priority to validate this design approach. Three parallel avenues are being pursued – longer-term cathode developments at Cornell, large cathode developments with a ring-shaped laser beam at MIT, and a recent BNL-initiated effort to develop a large area photocathode at RHIC.

Risks

The R&D to develop polarized photoelectron sources that have performance characteristics required by the BNL LR accelerator specifications has not yet been successful. This is a high-risk item for this concept as acknowledged by the BNL team and it continues to be a top priority for them to validate this design approach. Three parallel avenues are being pursued – longer-term cathode developments at Cornell, large cathode developments with a ring-shaped laser beam at MIT and recently BNL has initiated an effort to develop a large area photocathode at RHIC.

The only R&D element related to the electron injection is to test the CEBAF electron injector mode, which is expected to reduce the risk level to low.

The spin polarization and luminosity, critical to the science goals of an EIC, are at risk while a suitably high current polarized electron source has not been demonstrated to support either BNL concept.

The BNL LR team is building a single, new “JLAB style” inverted gun with an optimized geometry, ultra-high vacuum quality for high gun voltage (350 kV) with a large cathode diameter. The LR concept design study listed a 1 mm cathode, but presentations showed 25 mm. When operational, in late 2017, they will install this new gun on the diagnostic beam line. The planned finish for this effort is February 2018. This approach requires per pulse charges from 130 to 1000 times higher than what has been achieved at JLAB. There does not appear to be a fallback alternative design. The risk for this design concept is high.

The new “JLAB style” inverted gun approach for the RR concept, unlike the LR concept, can utilize charge accumulation and damping to provide the high charge per bunch needed. The risk for this design concept is medium. The fallback position is a SLAC style gun.

Recommendations

- The cathode emission saturation effects with the new JLAB style gun under construction should be studied.
- The BNL LR concept team also discussed the transverse stacking of the 8 guns that would require all 8 to fire on every pulse, but would gain a factor of 8 in per pulse charge density with possible increases in emittance from this approach, which could affect beam halo and transport to the ERL. They should either pursue this alternative seriously or abandon it.
- There is no explicitly directed R&D that focuses on the UHV manipulation, remote control or vacuum isolation of the polarized electron gun. The practical issues related to how this array will be operated must also be addressed as the equipment becomes available.
- The MIT group has many components to conduct experiments towards a high intensity gun developed, but this research will require at a minimum of 2 more years and an investment of \$1-2M before relevant results can be expected. More direct participation of the BNL group in the experimental set-up, engineering and the actual experiments might be beneficial for both groups to accelerate progress in this area.

G. Injectors

Discussion

Each proposal uses some part of the host laboratory infrastructure, with minimal modification: JLAB would use the CEBAF facility as the electron injector, and BNL would use the RHIC facility as the hadron injector.

Recirculating and energy recovery linacs are required for the BNL concepts. The electron injector for the LR concept is a recirculating energy recovery linac, and for the RR concept a recirculating linac is proposed.

The JLAB hadron injector would use the ERL technology to cool the hadron beams using a magnetized bunched electron beam.

For the JLEIC, the injector (CEBAF) is used to fill trains of bunches spaced by 7 buckets, and it will take many fill cycles to stack the beam current in the electron ring. It is unclear whether this injection scheme is compatible for the top-off injection (to mitigate electron beam depolarization at a higher energy) for parity-violation experiments in which bunch trains with opposite polarizations should have very similar degrees of polarization.

For the BNL RR concept, the injection scheme has not been designed yet.

Risks

To meet the EIC performance objectives the injectors must have high average current polarized electron sources, and in the case of BNL concepts, recirculating and high average current energy recovery linacs (ERLs).

The CBETA ERL experiment at Cornell is a critical part of the R&D plan; however it is funded and managed by other institutions and funding agencies. Demonstrating FFAG in the return arcs is a complication and could obscure those problems related only to recirculating ERLs.

There is certain risk that the JLEIC top-off injection may not be compatible with parity-violation experiments at high electron energies. This may limit these experiments to lower center of mass energies.

For the BNL RR concept, risk needs to be determined based upon a concrete design concept.

Recommendations

- Continue to pursue recirculating and high average current ERL demonstrations, for example at CBETA. Integrate approaches with the CCR proposal at JLAB, for understanding of recirculating and ERL concepts.
- Continue to pursue polarized electron gun R&D aimed at demonstrating technical requirements while managing risk.
- Continue the development of fast cooling with bunched magnetized electron beams, while studying alternate approaches such as coherent electron cooling.
- For both JLEIC and the BNL RR concepts, the injection schemes should be thoroughly studied to understand their impact on physics programs.

H. (Polarized) Ion Beam Sources

Discussion

The EIC requires ion species from light ions to heavy ions to support its wide range physics program. Polarized light ions are essential to achieve the physics goal of the EIC, and therefore a core requirement for the accelerator design. To broaden the reach of the physics program polarized deuterons and/or ^3He ions together with heavy ions up to uranium are required.

The existing source technology is available for the heavy ion injector to support operations of all three concepts. The current RHIC ion injector complex can provide the required beams, beam intensities and time structures without changes or technical upgrades. One exception, discussed further below, is the production of polarized helium beams that is one of the ongoing R&D topics.

A state-of-the-art Electron Beam Ion Source (EBIS) is used at RHIC for the heavy ion injection. This source can be directly utilized also for the JLEIC concept and has demonstrated the required emittance, time structure and intensity over the whole operational range. In addition, the state-of-the-art high frequency ECR ion sources are available as a viable alternative for the ion injector. The JLEIC heavy ion injector linac design is compatible with both heavy ion beam sources. The final selection of the heavy ion source can be done in the next stage of the project – there is no urgency for pre-CDR R&D in this area.

Similarly, two source types are available to support operation with polarized ions and both have demonstrated the required source parameters. At this stage of the proposal there is no urgency to develop this technology any further through pre-project R&D.

The only ion beam species that requires R&D and experimental demonstration is the generation and acceleration of a polarized ^3He beam. A robust and high quality R&D program is underway as a collaborative effort between BNL and MIT and results are very promising. This R&D (if successful)

could already contribute to the existing science program at BNL. It is proposed to accelerate a polarized ^3He beam in RHIC in 2020, which will provide a full validation of this technical component for the EIC. This proposed R&D includes upgrades to the EBIS that could result in higher ion beam intensities for heavy ions as well. This work will benefit all concepts that have been proposed.

Risks

The risks associated with ion beam sources are low.

Recommendations

- It is important to continue the pursuit of the excellent polarized ^3He ion source R&D program. Preliminary injection tests of the polarized ^3He vapor should be accelerated using the existing off-line test EBIS if possible. This would provide valuable experience and data for the design of the injection scheme of the extended EBIS even if the beam polarization or acceleration cannot be achieved in this off-line test stand.
- Proceed with proposed ^3He polarized beam injection into RHIC.

I. Interaction Regions

Discussion

The key machine parameters of the EIC as identified in the NSAC Long Range Plan dictate that the interaction region (IR) design includes:

- Ion beams from deuterons to the heaviest stable nuclei,
- Variable center of mass energies $\sim 20\text{--}100\text{ GeV}$, upgradable to $\sim 140\text{ GeV}$,
- High collision luminosity $\sim 10^{33\text{--}34}\text{ cm}^{-2}\text{sec}^{-1}$, and
- The possibility to have more than one interaction region.

The present IR designs of all three EIC concepts (JLEIC, BNL LR, and BNL RR) are partly based on either beam dynamics performances that are to be demonstrated or novel concepts and/or technologies that are to be validated.

All three EIC concepts should address the same physics identified in the NSAC LRP, which in turn constrains the integrated design of the IR and the detectors. The IR design must address key detector design aspects including the energy range, collision frequency, angular divergence, and background issues.

The machine-detector-interface should be given more attention for all designs. This include the choice of β^* , space allocation for luminosity monitors and polarimeters, the effects of the detector solenoid (and the possible need for and integration of compensating and shielding solenoids) together with solenoid fringe fields in presence of a crossing angle (with possible effects on polarization, synchrotron-radiation background, vertical emittance, etc.). Synchrotron-radiation background in the detector can be important (for example, HERA). This should be examined, including the possibility of reflected photons generated further upstream. The mitigation of such reflected photons could impose constraints on the final-focus optics, the final quadrupole design, the vacuum chamber dimensions in the IR, and so on. A masking

system will need to be conceived similar to what has been done for past lepton colliders (LEP, PEP-II, and SuperKEKB), but taking into account the specific requirements of the EIC physics detectors. The need to avoid HOM excitation in the IR region (detector chamber) can further constrain the inner, incoming, and outgoing IR beam-pipe dimensions. In addition, a movable collimator system may be needed (elsewhere in the lepton ring or lepton linac) to control beam tails at large amplitudes and associated detector background.

Crab crossing plays an important role in all three design concepts allowing minimum luminosity reduction in the presence of large crossing angles. As crab crossing has never been demonstrated for a hadron beam, alternative scenarios should be explored for all three concepts, such as flat-beam collisions (possibly with a crab waist scheme) and using a detector-integrated dipole (as foreseen for the LHeC) bending the electron beam for a zero-angle crossing provided that complications from synchrotron radiation background can be mitigated. At crab cavity operation with high current (>0.5 A), KEKB initially observed large-amplitude oscillations of beams and the crabbing field, resulting from a combination of beam loading in the crab cavities and the beam-beam force. The possibility of such instability should be investigated in combined simulations of beam-beam collisions and crab-cavity responses for the various EIC designs.

Novel optics schemes including Achromatic Telescopic Squeezing (ATS) and Chromaticity Correction Block (CCB) should continue to be pursued for compensating the chromatic aberrations due to large beta-functions inside the focusing quadrupole magnets, so that minimum beta* can be achieved at the interaction point (IP) for luminosity gains.

The Table below shows major machine parameters pertaining to the interaction region for the three design concepts at the center of mass energy of 63 GeV.

	BNL RR Concept		JLEIC		BNL LR Concept	
	p	e	p	e	p	e
Energy [GeV]	100	10	100	10	100	10
CM Energy [GeV]	63		63		63	
Bunch freq [MHz]	112		158.7		9.4	
N (bunch)	1320		1113		111	
Bunch intensity [10^{10}]	7.5	15.4	3	2.8	30	3.3
$\beta^* h/v$ [cm]	112/5.3	130/15	15/3	4/0.8	5/5	5/5
rms norm emit [μm]	2.4/0.5	188/34	0.8/0.16	560/112	0.27/0.27	50/50
IP rms beam size, h/v [μm]	160/16	160/16	33.6/6.7	33.6/6.7	11/11	11/11

IP rms angular spread, h/v , [μr]	140/310	120/110	224/224	846/846	225/225	225/225
rms bunch length [cm]	6	0.8	2	1.2	5	0.3
Full crossing angle [mr]	22		50		14	
Max. b-b parameter	0.014	0.092	0.007	0.02	0.015	1.4
Luminosity [$10^{33} \text{ cm}^{-2} \text{s}^{-1}$]	3.4		3.5		5.8	

Table 5: Comparative machine parameters for the three proposed concepts.

Comparing the two ring-ring collider proposals, BNL RR and JLEIC, at the same proton and electron beam energies, the designs are surprisingly similar in number of bunches, bunch frequency, and the peak luminosity. In particular, we observe the following two aspects: (1) The peak luminosity is similar despite the fact that two different hadron cooling schemes are employed. The “weaker” conventional cooling of JLEIC results in small emittances. (2) While BNL RR is at the beam-beam limit, JLEIC is far from such limit operating with much smaller IP beta functions. This observation suggests that neither design is fully optimized and that one could enhance the performance of JLEIC, e.g., by accepting higher beam-beam tune shifts, and the performance of the BNL concepts by further squeezing the beta functions. Depending on the acceptable IP divergence, the luminosity of either design could possibly be raised by a factor of 2-3. We further speculate that similar design parameter optimizations can be performed for other beam energies.

JLEIC:

From the luminosity point of view, JLEIC design is optimized for a lower center-of-mass energy (CME) (e.g., peak luminosity of $19.5 \text{ cm}^{-2} \text{s}^{-1}$ at 45 GeV versus $3.5 \text{ cm}^{-2} \text{s}^{-1}$ at 63 GeV, respectively). At a lower energy, JLEIC design assumes three times higher bunch frequency (collision frequency) as compared to the JLEIC operation at 63 GeV CME. However, at a higher energy constraints from the synchrotron radiation power of the circulating electron beam limit the bunch frequency and intensity. This effect is relatively strong with JLEIC due to the relatively tight bending radius contributed by the smaller machine circumference (a factor of 1.8 smaller than the RHIC circumference) and the choice of figure-of-eight layout that further reduce the effective circumference by a factor of about 1.5. At center-of-mass energy of 63 GeV, the performance limitation is expected to be due to the small β^* at the collision point that demands a challenging chromatic compensation, challenging design of IR magnets of large aperture and high gradients and fields, and large beam angular divergence at IP that may compromise the detector design. The Chromaticity Correction Block (CCB) scheme of the JLEIC design has yet to be analyzed in detail (e.g., the dynamic aperture analysis) and demonstrated. Large aperture superferric quadrupoles of high gradient and superferric dipoles of high field are yet to be demonstrated. As pushing the center-of-mass energy upward to 100 GeV and beyond is even more difficult, it is prudent to consider magnets of better-established technology (e.g., magnets used in HERA and LHC) with a design that do not require high ramp rates.

BNL LR:

The BNL Linac-Ring (L-R) concept requires collision of a single-pass electron from an energy recovering linac with a circulating hadron beam. As the first linac-ring collider, unknown beam-dynamics mechanisms and possibly unknown performance-limiting phenomena are expected. For example, it is not clear whether the energy recovering process will function efficiently in the presence of the large beam-beam disruption at IP. Furthermore, it is not straightforward to accommodate more than one IP in the design.

BNL RR:

Comparing with the BNL LR concept, the BNL Ring-Ring (RR) concept is largely based on known design concepts and established technologies. Challenging R&D required for the LR concept may no longer be necessary, including high-performance electron guns and coherent electron cooling. From luminosity point of view, the RR concept, similar to the LR concept, is appropriate for the entire center-of-mass energy range from 20 to 100 GeV with an upgrade path to 140 GeV. However, the beam-beam envelope that the design assumes has not been demonstrated at the prior e-p collider HERA. As the RR concept is similar to the JLEIC concept at center-of-mass energy of 63 GeV, it is prudent for the RR concept to develop back-up scenarios possibly including trading the risks associated with the beam-beam limit with those of β^* limit, and developing bunched electron cooling with a large bunch charge similar to those for JLEIC in case progress in CeC is further delayed. Finally, the RR IR optics has a nonzero dispersion at the location of crab cavities. This could give rise to additional instabilities, with or without beam-beam force. For example, a small momentum offset will lead to a transverse offset at the crab cavity, which will result in an additional energy change due to acceleration or deceleration from the fundamental crab-cavity mode.

Risks

JLEIC:

The design concept relies on the operation of large aperture, high gradient superferric quadrupoles together with superferric dipoles of high fields to support a beam center-of-mass energy that can be extended to 100 GeV. As the performance of the superferric magnets at these energies has not been demonstrated, these magnets present significant risk.

The detector design and IR design integration must be emphasized to accommodate the planned high collision frequencies and high angular divergence.

Chromaticity Correction Block beam dynamics and performance must be evaluated.

The crab crossing implementation to meet the IR design specifications will be challenging (see section on Crab Cavities).

BNL LR Concept:

The performance of the linac-ring beam collisions given the current design parameters to support design criteria.

The energy recovery efficiency in the presence of the large beam-beam disruption at the IP could be problematic.

Accommodating a second IP is problematic.

The crab crossing implementation to meet IR design specifications will be challenging (see section on Crab Cavities).

BNL RR Concept:

The beam-beam parameter envelope has not been demonstrated at the prior e-p collider HERA and so presents a risk.

Non-zero dispersion at the location of crab cavities can lead to additional instabilities.

The crab crossing implementation to meet the IR design specifications will be challenging (see section on Crab Cavities).

Recommendations

All designs:

- Perform a detailed machine-detector-interface design optimization including the choice of β^* , space allocation for luminosity monitors and polarimeters, effect of detector solenoid together with solenoid fringe fields in presence of a crossing angle, synchrotron-radiation background in the detector including possibly reflected photons.
- Validate the crab crossing of both hadron and electron beams at design specifications.
- Develop back-up solutions for crab cavities including flat-beam collisions (possibly with a crab waist scheme) and using a detector-integrated dipole bending the electron beam for a zero-angle crossing.

JLEIC:

- Perform a detailed detector conceptual design and IR design integration including the detector response time and background consideration pertaining to the high collision frequencies and high angular divergence.
- Develop IR large aperture, high gradient quadrupoles and IR high field dipoles that correspond to a beam center of mass energy which can be extended to 100 GeV.
- Consider alternative, better-established magnet technology for IR large aperture quadrupoles of high gradients and IR dipoles of high fields for beam center-of-mass energy range from 20 to 100 GeV.
- Perform detailed beam dynamics verification including dynamic aperture analysis of the Chromaticity Correction Block (CCB) scheme.
- Develop backup chromaticity compensation schemes like the Achromatic Telescopic Squeezing (ATS).
- Optimize collider parameters (tune shift).

- Validate the crab crossing of both hadron and electron beams at design specifications. Given the fact that these cavities have not been demonstrated in a hadron machine, it is important to study an alternative option for an interaction region design with bent electron beams and without the use of crab cavities to evaluate methods to address synchrotron light inside the detector and the need for synchrotron light absorbers to minimize the background inside the experiment.

BNL LR Concept:

- Perform an integrated IR optics design addressing issues pertaining to machine – detector interfaces.
- Perform detailed beam dynamics modeling and analysis of linac-ring collisions including the electron beam energy recovery efficiency in the presence of the large beam-beam disruption at IP and realistic errors in the machine and orbit at the IP and crab cavity errors.
- Consider an experiment to validate energy recovery in situations where strong transverse beam perturbations are present; this could represent a possible collaboration with JLAB.
- Perform conceptual design of a second IP.
- Validate the crab crossing of both hadron and electron beams at design specifications. Given the fact that these cavities have not been demonstrated in a hadron machine, it is important to study an alternative option for an interaction region design with bent electron beams and without the use of crab cavities to evaluate methods to address synchrotron light inside the detector and the need for synchrotron light absorbers to minimize the background inside the experiment.

BNL RR Concept:

- Develop back-up scenarios trading risks associated with beam-beam limit with those of β^* limit.
- Develop bunched electron cooling with a large bunch charge similar to those for JLEIC as a backup to CeC.
- Validate the crab crossing of both hadron and electron beams at design specifications. Given the fact that these cavities have not been demonstrated in a hadron machine, it is important to study an alternative option for an interaction region design with bent electron beams and without the use of crab cavities to evaluate methods to address synchrotron light inside the detector and the need for synchrotron light absorbers to minimize the background inside the experiment.

J. Magnet Technology

Magnet Technology R&D is required for the ion ring facilities of the JLEIC design, the interaction region magnets for all designs and the solenoids for electron cooler and spin control. The development and demonstration of different magnet technologies provides collaboration opportunities between national laboratories and interested and capable universities. Conventional magnet technology is generally available for the EIC ion and electron acceleration complex. The panel identified the validation of magnet designs associated with high-acceptance interaction points by prototyping as a key area that is common for all EIC concepts. More specific for the JLEIC concept are the fast ramped 3 T superferric dipoles for the ion booster ring and the exploration of 6 T magnets based on this concept.

3 T superferric magnets are proposed for the JLEIC design as a value engineering option with a possible path to 6 T superferric magnets. This magnet design option has the advantage of fast ramp rates as well as cost savings, but the technology is not as well established as the conventional state-of-the-art $\cos(\theta)$

magnets and there is little operational experience in existing facilities. It was not clear from the technical information provided whether the fast ramp rate is really a critical item. Assessing the use of more conventional magnets as an alternative design solution could reduce this risk.

Permanent magnets used in an FFAG lattice are being proposed for the electron accelerator complex as a potential cost saving option for BNL.

Discussion

There are 6 R&D projects on magnet technology proposed by JLAB and one by BNL. The panel agrees with the JLAB ranking of the IR magnet and the superferric magnet R&D as the highest priority. The panel ranks all other magnet R&D activities with low priority. The panel ranks the BNL IR magnet R&D as high priority in contrast to the BNL decision for medium priority of this R&D topic. In case of JLEIC a relatively large crossing angle of 50 mrad allows the efficient detection of reacting particles with dipoles in the forward direction where the central solenoid is not effective. The large crossing angle and the forward direction detection concept require strong large aperture final focusing magnets. The smaller crossing angles in the BNL concepts (14 mrad for LR and 22 mrad for RR) require the penetration of the electron beam through the yoke of the magnets for the ion beam in the IR and therefore ‘sweet spot style’ magnets.

The JLEIC magnets flanking the IR require a challenging high magnetic field strength (up to 6 T tip field) and gradient (up to 90 T/m) and large apertures (up to 12 cm radius) for large acceptance. These superconducting magnets are exposed to high heat loads and radiation effects from Synchrotron Radiation (SR) and ion losses and are also affected by the fringe fields of adjacent magnets, including the main solenoid. In collaboration with Texas A&M the most challenging magnet types are addressed with various conceptual designs. A large-aperture high-gradient quadrupole for the innermost lens on the ion beam, a large-aperture dipole that must serve as a spectrometer for forward-going particles near the ion beam direction and a high-gradient, modest-aperture superconducting quadrupole that can operate with high gradient uniformity over a large dynamic range. The panel fully supports the R&D to select the magnet conductor material and to assess the field quality, the space constraints and the operational parameters in particular the robustness to the radiation load.

Concerning the ion ring dipoles in JLEIC there is the need to achieve 3T dipole field and fast ramp rate of 1 T/s in the Booster Ring. The dipole ramp rate of 0.1 T/s in the collider ring is relaxed. The collaboration with Texas A&M University's Accelerator Research Lab (TAMU-ARL) on superferric magnets provides potential cost savings for JLEIC arc magnets. The panel rates the work on the 1.2 m prototype as high priority to infer data on the challenging requirements of $<10^{-4}$ field quality over the 6 cm x 10 cm cross section and over the full dynamic range and on the multipole strength over the ramp range. The superferric magnet is using a cable-in-conduit technology with the strands in direct contact with the cooling medium. Texas A&M did the magnet design, produced the tooling for the coil winding and performed a mock-up coil winding of a 1.2 m prototype magnet. As plan B, JLAB pursues a $\cos(\theta)$ concept for the 3 T dipoles. As the Helmholtzzentrum für Schwerionenforschung (GSI) did prove the technology with a 4.5 T magnet for the synchrotron SIS300 of the Facility for Antiproton and Ion Research (FAIR), the panel ranks this development as lowest priority.

The goal of the BNL R&D effort is to develop the technology for superconducting sweet spot style IR magnets for the BNL concepts. The requirements are large apertures and strong magnetic fields for the hadron beam while providing nearby a protected low field strength aperture for the electron beam to pass through with $>10^{-4}$ attenuation of the main coil field. The proposed sweet spot geometry can accomplish

this goal by passing the electron beam through a passive magnetic shield located in the specially configured dipole or quadrupole coil structure.

Since the field in a quadrupole sweet spot coil structure changes more significant than for a dipole, the quadrupole sweet spot coil structure needs more attention. It is required to reduce the local field strength to a level that can be handled via passive shielding. Some preliminary R&D to support the development of sweet spot coils for these concepts has been done in terms of magnetic field and mechanical stress modeling and also physically in terms of performing an extensive upgrade of the existing BNL direct coil wind machine. BNL has the magnet development capabilities and the according test infrastructure.

An open question for a study, common to the dipole and quadrupole sweet spot work, is the use of mu-metal or a ‘Meissner shield’ (superconducting shield) for passive magnetic shielding. The geometric advantage for cold shielding is much less radial space required. However, shield geometries can be tested inside existing BNL magnets.

Superferric magnets use iron yokes and superconducting coils (typically operated at 4 K) together to produce high-quality, high-strength magnetic field. For the 3T magnet design, the requirements for the relative multipole strengths are $b_n < 10^{-4}$ (n is the order of the multipole). Superferric magnets are a relatively new technology, with the first known production for FAIR at GSI. However, only 2 T dipole magnets have been built for the SIS-100 ring at FAIR. The field specifications for the JLEIC and GSI magnets are likely not identical, and extrapolations from 2 T to 3 T are not trivial. For example, the measured performance of the 2 T FAIR prototype magnet showed a much stronger b_3 multipole at higher field (b_3 rises from 10^{-4} to $\sim 8 \times 10^{-4}$ from 1.7 to 2 T^a). A recent paper (2016) on the production magnets reported that “The field measurements have shown unexpected large not allowed field components, in particular skew quadrupole and skew sextupole.”^b This is concerning, as the JLEIC 3 T magnets apparently demand more stringent multipole requirements.

Much has yet to be done for the JLEIC IR magnets, in particular, to determine the level of allowed residual fields, in particular, multipole components, for the (other) coasting beam, based upon the limitations imposed by beam dynamics. IR magnets need to be designed to realize these field specifications.

Extrapolation from 3 T magnets to 6 T magnets (for both dipoles and IR magnets) is highly non-trivial.

For the BNL concepts (LR and RR), very little information has been provided regarding the high-field IR magnets. In the presentations, superconducting IR magnets (at 4.2 K) were mentioned, however, it seems that very little design has been performed in this area.

The choice of the magnet technology enables several opportunities for value engineering R&D and is pursued for all three concepts.

The permanent FFAG concept for the ERL is an attractive option to reduce space requirements, cost and complexity – however this concept still needs experimental validation. The experiment planned in Cornell (CBETA) is a necessary step.

^a Egbert Fischer et al. “Design and Test Status of the Fast Ramped Superconducting SIS100 Dipole Magnet for FAIR,” IEEE Trans. Appl. Superconductivity, v.21, n.3, p. 1844 (2011).

^b Anna Mierau et al. “Testing of the Superconducting Magnets for the FAIR Project,” IEEE Trans. Appl. Superconductivity, v.26, n.4, 4401605 (2016).

Permanent magnets are also proposed for the BNL RR concept electron storage ring as a cost reduction option. With the preliminary work completed, the remaining R&D can be explored post CDR.

It is unclear if the higher-ramp-rate superferric magnets are critically needed for JLEIC (ramp rate specification is 1 T/s; for FAIR, 4 T/s). By emphasizing value engineering it seems that the JLEIC assumes more risk than necessary compared to using conventional cosine-theta magnets with a ramp rate of 0.1 T/s.

For 3 T superferric magnets, it is unclear if other important performance parameters have been taken into account properly, and to what degree, in the design process, such as mechanical stability of coil windings, AC losses, field saturation of the bulk, edge field changes due to field saturation, hysteresis effects, etc., just to name a few.

Risks

The risks concerning the magnet technology are medium given existing technology and prototypes.

The fast ramped 3 T superferric magnets bear the risks that the precision of the coil winding and of the yoke geometry cannot be reached and therefore multipole strength reaches a level above the required 10^{-4} . These magnets need to achieve 3 T dipole field and fast ramp of 1 T/sec in the booster ring. A fallback position is the $\cos(\theta)$ technology in case the superferric magnets cannot achieve the required performance. The 3 T $\cos(\theta)$ magnet are within the range that has been demonstrated in the past for the SIS300 dipoles for FAIR at GSI, but at the level of prototypes built and tested in laboratories. 6 T dipoles are required for the collider ring, in case the facility is required to deliver a center of mass collision energy of 100 GeV. As the ramp rate of the collider is low, the risk on this magnet technology is medium, as the LHC magnet technology would be suitable. The 3 T superferric magnets require experimental validation through prototyping and the extrapolation to 6 T is a high-risk item.

The special magnets flanking the IR in the JLAB design bear the risks of insufficient beam quality due to the large aperture and large gradients required. In addition, the high heat load from lost particles and the according radiation damage can lead to quenching and short magnet lifetimes. The mechanical stress from the operation in the fringe field of the superconducting spectrometer solenoid can have impact on mechanical stability and positioning of the magnet.

The risk of the BNL IR magnets is that these systems may fail to simultaneously meet conflicting design goals. The experiment needs both large acceptance for forward directed particles and magnetic field reduction at the position where the electron beam penetrates the ion beam magnets. The simulation results for the shielded area can differ significantly from measured data in particular in low field regions.

The JLAB collaboration with Texas A&M has been productive, but given the importance of the magnets to the JLEIC concept, JLAB should ensure that it develops appropriate in-house expertise to bolster this collaboration and to also consider alternative magnet designs.

For BNL, the development of IR magnets and study of their impact on the beam dynamics are less mature. This must be corrected very soon as it is important for the creation of credible EIC conceptual designs.

Recommendations

JLEIC:

- A booster magnet study must be performed to validate the superferric technology with respect to the JLEIC arc magnet requirements. The panel recommends the fabrication of a 1.2 m superferric dipole cold mass, the coils and cryostats and the according vacuum chamber. The high field quality relies on a high accuracy of the yoke geometry and a precise coil winding. A prototype cold test and magnetic field measurements at different field level need to demonstrate the required field quality, the ramp rate and the quench performance. In addition, the prototype can provide a good basis to estimate the costs of the booster magnets. A full-length magnet prototype proposed is low priority R&D.
- To reach the final center of mass collision energy of 100 GeV, dipoles with a field strength of 6 T in the collider are required to reach the 200 GeV proton energy. As the collider requires a ramp rate of 0.1 T/sec only, the magnet design can follow LHC magnet design. However, the panel recommends the exploration of 6 T super ferric magnet as value engineering option.
- The panel recommends to prototype the critical magnets that flank the IR in the JLEIC design. These are the final focusing quadrupoles in the ion beam line. Because of the combination of high field and large aperture the coil field is at the limit or above what can be achieved with conventional NbTi technology. In addition, the proximity of the electron beam limits the available space and requires a very compact mechanical and flux return structure. The dipoles in the ion beam line have a large aperture. The proximity to the electron beam requires the effective suppression of the fringe field in that area and high radiation resistance.
- The SC magnet R&D for JLEIC can profit from collaboration with DOE laboratories that have strong expertise in this type of magnet technology.

BNL:

- The panel recommends the fabrication and cold testing of a short dipole and the prototyping of a short quadrupole with a ‘sweet spot’ area. With these prototypes the shielding performance of the sweet spot coils can be evaluated. In addition, the development and testing of warm and cold options for passive magnetic shielding for use in these ‘sweet spots’ need to be addressed in R&D with high priority. Having measured parameters from this R&D, detailed engineering designs for actual IR magnets in cryostats can be derived as well as reliable cost estimates.

K. Polarization Manipulation

Discussion

The following comments focus on the issues related to electron beam polarization, and its impact for possible parity violation experiments at EIC at high cm energies.

JLEIC:

Observation: for parity violation experiments, sub-trains of bunches with opposing polarizations will be filled in the figure-8 electron ring. At high energies, the depolarization effects due to the main dipole field

(when the electron polarization is in parallel with the dipole field in one of the two loops in the figure-8) are significant. As a benefit of the figure-8 configuration, this depolarization effect can be made to be the same/similar for two sets of electron bunches with opposite polarizations using a set of properly arranged spin rotators as proposed, which can help significantly reduce the polarization dependent systematic errors in experiments. Continuous top-off injection at higher energy may be needed to maintain a high degree of polarization. It is unclear how this nice feature (the same depolarization effects for bunches with opposite polarizations) can be preserved in the top-off injection scenario.

BNL RR Concept:

Unlike the figure-8 ring, for the RR design, the electron depolarization effects will be different for bunches with opposite polarizations. At higher energies, depolarized bunches will need to be replaced regularly. Again, it is unclear how this can be done in a transparent manner for a parity violation measurement.

Risks

In both ring-ring designs (JLEIC and BNL RR), the depolarization effects at high electron energy (therefore, a high cm collision energy) can have a significant impact on parity violation experiments which demand very high degrees of consistency of polarizations of the bunches with opposite polarizations. It is important to first obtain the requirements from nuclear physicists, and then develop suitable injection and operational schemes.

Recommendations

- Parity violation experiments place the most stringent requirements on the polarization control. The nuclear physics community should identify the related experimental needs as soon as possible to inform the accelerator designers so that appropriate solutions can be devised.

L. SRF Technology (Excluding Crab Cavities)

All the proposed EIC concepts rely on high duty factor SRF acceleration of both electrons (main beam, electron cooling) and ions. SRF is a mature technology and its choice for both cases is optimal for both performance and overall cost reasons.

Discussion

Each of the proposed EIC concepts involves use of SRF technology operating in regimes beyond those currently demonstrated, in particular at higher required HOM damping powers.

SRF cryomodules represent the largest capital investment among the involved technologies. In addition, the required cryogenic infrastructure is among the largest items affecting both capital and operational costs as well. Therefore, a high potential exists for cost savings SRF R&D avenues. In particular, the choices of the operational accelerating gradient and assumed cavity quality factor, both having a strong effect on the costs, should be carefully made in light of the state-of-the-art developments (e.g., high Q techniques based on nitrogen doping and magnetic flux management) implemented by contemporary SRF-based projects such as LCLS-II at SLAC.

There are common goals for technology development and in cost reduction approaches that would benefit from close collaboration between the proponents of the different concepts as well as with other Office of Science labs. The development of multi-pass linac and energy recovery linac technology for the proposed EICs will address the need for handling of the beam wakefield effects, including HOM damping techniques and cryomodule optimization for dissipation.

Risks

High average current, multi-pass acceleration and energy recovery in a collider linac present challenges in control of instabilities driven by long-range wakefields, and drive the need for CW SRF cavities and cryomodules optimized for handling the significant beam-induced power. Similar challenges exist for electron cooling energy recovery linacs (ERLs), although these are single-pass machines. In the case of CeC the large energy spread induced by the SASE FEL process presents additional risk in transport and efficient energy recovery of the beam exiting the cooling section and returning through the SRF linac.

Maintaining beam quality in high bunch charge acceleration in a pulsed collider injector drives the need for careful control of energy spread, through the optimization of cavities with relatively small wakefield and/or by longitudinal phase space compensation techniques. Multi-pass acceleration adds challenges in control of long-range wakefields. The accelerating cavity frequency and geometry, and HOM damping technique, require careful optimization. Efficient integration of SRF systems into a cryomodule is needed to provide a small physical footprint and cost savings for production.

Recommendations

- Pursue experimental demonstrations of high average current, single- and multi-pass ERLs in integrated systems.
- Evaluate and pursue possible capital and operational cost savings opportunities enabled by state-of-the-art developments in SRF cavity R&D (e.g., nitrogen doping).

IV. Priority List of R&D

General Comments

The panel considers the R&D elements identified in the General Comments section of Part III of this report (Charge Element 3) to be high priority but notes that they can be sorted in the order of importance.

The panel received a self-assessment of the priorities of 37 R&D items identified by JLAB and 19 R&D items identified by BNL – these were binned into the categories of High, Medium and Low.

The panel cross-walked the elements identified in Charge Element 3 with the self-assessment provided by the proponent laboratories – there was substantial agreement but some differences were noted.

In particular the panel identified 9 items it considered high priority that were not identified for action by the proponent laboratories. These items are identified in bold italic text below.

Technologies and/or design concepts that address technical risks common to all concepts that must be demonstrated

- Crab cavity operation in a hadron ring
- Strong hadron cooling
- Validation of magnet designs associated with high-acceptance interaction points by prototyping
- ***High-current single-pass ERL for hadron cooling***
- ***Benchmarking of realistic EIC simulation tools against available data***
- ***Polarized ^3He source***

Specific R&D activities for the BNL Linac-Ring Concept

- High current polarized and unpolarized electron sources
- CeC proof of principle
- SRF high power HOM damping
- ***High-current multi-pass ERL***
- ***Concept for 3D hadron CeC beyond proof of principle***

Specific R&D activities for the BNL Ring-Ring Concept

- Complete the design of an electron lattice with a good dynamic aperture and a ***synchronization scheme and complete a comprehensive instability threshold study for this design***
- Necessity to triple the number of and shorten bunches in the proton/ion ring
- Beam pipe copper coating with plasma ion bombardment
- ***High peak current multi-turn linac***
- ***Simulate the effect of electron bunch removal on the hadron beam***

Specific R&D activities for the JLEIC Concept

- Complete and test a full-scale suitable superferric magnet

- High current magnetized injector
- Integrated magnetized beam kicker/circulation test using existing ERL infrastructure
- Complete design of the gear change synchronizations and assess its impact on beam dynamics
- Operate CEBAF in JLEIC injector mode
- ***High power fast kickers for high bandwidth (2ns bunch spacing) feedback***

The outcome of the panel's prioritization process is found in the Summary and Recommendations section of this report.

V. Cost and Schedule Range

General Cost and Schedule Range Comments

The following general comments are applicable to all three EIC R&D activities:

- Clearly defined scope, including assumptions, limitations, and boundaries, was not provided for each of the R&D activities.
- Clearly defined benefits and consequences associated with each R&D activity were not fully described.
- Clearly defined deliverables were not provided for each of the R&D activities.
- Interrelations and dependencies between various R&D activities were not provided, but this is not unreasonable given the pre-conceptual status of the work.
- There were no apparent high level schedule guidance objectives provided to any of the activity development teams to be used for their independent schedule development efforts.
- It was not apparent whether or not any level of “contingency” was included in any of the R&D activity cost and schedule information.

General Cost Range Comments

The following general cost range comments are applicable to all three EIC R&D activities:

- There was no “basis of estimate” (BOE) information provided for any of the EIC R&D activities, making it quite difficult to assess the quality of the assigned cost estimate.
- “Detailed” labor resource information for all required resources along with their applicable labor rates was not provided on a consistent basis. This made it difficult to assess the quality of provided labor estimates.
- In most instances burdened labor rates were not specifically used for labor being provided by collaborating laboratories and other institutions. In most cases “outside” labor was estimated using the same labor rates as resources belonging to the proposing institution.
- There was no attempt to include escalation impacts in any of the R&D activities. The impact of escalation on the total R&D proposal, especially in the out-years of funding could be substantial.

General Schedule Range Comments

The following general schedule range comments are applicable to all three EIC R&D activities:

- There was no specific rationale provided to support schedule details presented for any of the EIC R&D activities during the R&D review process.
- The majority of the R&D activity schedules appeared to be highly success oriented.
- Although it was stated that several of the existing R&D activity schedules were in fact “resource loaded” none of these schedules were made available for review and evaluation during the review process.
- Only summary level R&D schedules were presented during the review. Due to the interdependences between various R&D activities it is suggested that integrated, more detailed schedules, be developed and presented for future consideration.

BNL R&D Activity Cost and Schedule Details

The table below provides a breakdown of the BNL R&D activity cost and schedule data, where LR represents the Linac-Ring Concept and RR represents the Ring-Ring concept.

Critical Technical Element	Activity ID	Activity Name	BNL Priority	TRL Before	Level Before R&D	TRL After	Level After R&D	FY16 Labor Cost (\$K)	FY16 M&S Cost (\$K)	Total FY17 Cost (\$K)	Year Start	Year End	Duration
Polarized Electron Source	LR-A-1	R&D and Prototyping on the 6.2mA Polarized Electron Gun	1-highest	1 to 3	Low	5	Medium	\$2,000	\$1,000	\$3,060	FY17	FY19	2.16
Crab Cavities	LR-A-2	Study of Beam-Beam Effect with Crab Cavities	3-high	2	Low	3	Low	\$235	\$20	\$260	FY16	FY18	2.00
Electron Cooling/FFAG, ERL	LR-B-1	CBETA Project	4-medium-high	3	Low	5	Medium	\$32,000		\$32,640	FY17	FY21	4.00
Superconducting RF	LR-B-2	Waveguide HOM Couplers for the eRHIC ERL	4-medium-high	4	Medium	6	Medium	\$180	\$290	\$479	FY16	FY18	2.00
Superconducting RF / Beam Dynamics	LR-B-3	Study the use of 5-cell 647 MHz cavities in the eRHIC electron storage ring	5-medium	1	Low	2	Low	\$29	\$0	\$30	FY17	FY17	0.25
Superconducting RF	LR-C-1	Development of an eRHIC ERL cryomodule	4-medium-high	4	Medium	6	Medium	\$799	\$4,000	\$4,895	FY16	FY19	3.00
Crab Cavities	LR-C-2	Crab Cavity Prototype	almost completed	5	Medium	7	High	\$0	\$0	\$0	FY15	FY17	2.00
Crab Cavities	LR-C-3	eRHIC Crab Cavity Prototype	5-medium	3	Low	7	High	\$588	\$322	\$928	FY17	FY19	2.16
Magnets	LR-C-4	Design and Prototyping of actively shielded IR quadrupole and dipole	5-medium	4	Medium	6	Medium	\$1,800	\$1,800	\$3,672	FY17	FY21	4.00
Electron Cooling	CeC	Completion of the ongoing CeC demonstration experiment	2-high	2	Low	3	Low	\$1,350	\$1,350	\$2,754	FY12	FY19	6.50
Beam Dynamics Simulations	RR-A-1	Beam-Beam Parameter Validation	3-high	3	Low	5	Medium	\$355	\$0	\$362	FY16	FY18	2.00
Beam Dynamics Simulations	LR-A-2	Study of Electron Spin Polarization in the Storage Ring	3-high	2	Low	3	Low	\$235	\$0	\$240	FY17	FY18	1.00
Beam Dynamics Simulations	RR-A-3	Stability Study of Beams with Crab Cavities	3-high	2	Low	3	Low	\$235	\$0	\$240	FY16	FY19	2.00
Interaction Regions	RR-A-4	Synchrotron Radiation Background Assessment	3-high	3	Medium	4	Medium	\$117	\$0	\$119	FY17	FY17	0.50
Accelerator Technology	RR-A-5	e-Cloud Study	3-high	3	Low	4	Medium	\$295	\$0	\$301	FY16	FY19	3.00
Pulsed Devices	RR-C-3	Design of fast kickers for electron and Hadron Injection	5-medium	5	Low	6 to 8	High	\$470	\$542	\$1,032	FY17	FY18	1.00
Accelerator Technology	RR-C-4	Conceptual Layout of the Electron Storage Ring Vacuum System	6-low (small effort)	5	Medium	5	Medium	\$588	\$0	\$600	FY17	FY17	0.50
Accelerator Technology	RR-C-5	Improved Cu coating of the stainless steel RHIC cold Beam Pipe	5-medium	5	Medium	7	High	\$202	\$100	\$308	FY17	FY17	0.50
Magnets	RR-C-6	Design and Prototyping of actively shielded IR quadrupole	5-medium	4	Medium	6	Medium	\$800	\$1,700	\$2,550	FY17	FY21	4.00
							Totals	\$42,278	\$11,124	\$54,470			
							CBETA	\$32,000		\$32,640			
							Total Remaining Cost w/	\$10,278	\$11,124	\$21,830			

Table 6: Overview Cost and Schedule Summary of Proposed BNL EIC R&D Activities.

JLAB R&D Activity Cost and Schedule Details

The table below provides a breakdown of the JLAB R&D activity cost and schedule data.

Overview of JLAB R&D

CTE	PRIORITY	CTE Title	TRL	Level before	TRL	Level after	Year start	Year end	Years	Total cost
										K\$
ELECTRON COOLING R&D										
ECL1	first	Electron cooling simulations	3	low	7	high	2017	2019	3	488
ECL2		Bunched beam cooling experiment at IMP	4	medium	7	high	2017	2018	2	248
ECL3		ERL Cooler design for single and multi turn operations	2	low	5	medium	2017	2018	2	1,710
ECL4		Magnetized source for the e-cooler 36mA	3	low	5	medium	2016	2018	3	0
ECL5		Fast kicker prototype for multi turn cooler	4	medium	6	medium	2017	2018	2	911
ECL6	second	Fast kicker test with beam	6	medium	7	high	2019	2019	1	473
ECL7		Integrated test of multi-turn circulator ring	5	medium	8	high	2019	2021	4	0
ECL8		Magnetized source for the e-cooler 200mA	5	medium	7	high	2019	2021	3	4,026
MAGNET R&D										
MAG1	first	Super-ferric 3T fast ramping short prototype	3	low	5	medium	2017	2018	2	1,147
MAG2	second	Alternate SC 3T fast ramping magnets	4	medium	6	medium	2017	2018	2	904
MAG3		Full length prototype magnet and cryostat	5	medium	7	high	2018	2021	4	4,059
MAG4	first	IR compact large aperture, high radiation magnets	3	low	6	medium	2017	2020	4	4,203
MAG5	third	Cooler solenoids	4	medium	7	high	2019	2022	4	3,047
MAG6		Spin rotator solenoids	4	medium	7	high	2018	2021	4	3,096
SRF TECHNOLOGY R&D										
SRF1	first	SRF cavity systems	3	low	6	medium	2017	2019	3	2,998
SRF2		Crab cavity design, simulations, and prototype	3	low	6	medium	2017	2019	3	2,511
SRF3	third	Universal modular cryomodule	4	medium	7	high	2018	2020	3	1,499
INJECTORS R&D										
INJ1	third	SRF linac high power operations	4	medium	7	high	2018	2019	2	465
INJ2	first	Space charge in ion complex	4	medium	7	high	2017	2018	2	646
INJ3		Ion beam formation	3	low	6	medium	2017	2018	2	1,711
INI4	third	Alternative ion injector complex design	3	low	6	medium	2017	2018	2	0
INJ5		Ion sources	7	high	8	high	2018	2019	2	4,238
INJ6		Test of CEBAF electron injection mode	5	medium	8	high	2019	2019	1	195
INTERACTION REGIONS R&D										
IRS1	second	IR design and detector integration	5	medium	7	high	2017	2018	2	733
IRS2		Ion and electron ring background and vacuum	3	low	6	medium	2017	2018	2	733
IRS3	low	Collimation and machine protection	5	medium	7	high	2018	2019	2	586
BEAM DYNAMICS AND DIAGNOSTICS R&D										
BDD1	first	Spin tracking in ion and electron rings	5	medium	8	high	2017	2018	2	977
BDD2		Beam-beam simulation with gear changing	4	medium	8	high	2017	2021	5	404
BDD3	second	Nonlinear beam dynamics in ion and electron rings	5	medium	8	high	2017	2018	2	977
BDD4		Instabilities and feedback systems	3	low	6	medium	2017	2018	2	488
BDD5	third	Large dynamic range BPM	3	low	6	medium	2018	2020	3	553
BDD6		Large dynamic range luminosity monitor	3	low	6	medium	2017	2020	4	863
BDD7		Electron polarimetry	5	medium	8	high	2018	2019	2	300
BDD8		Ion polarimetry	6	medium	8	high	2019	2020	2	489
Total JLAB R&D without ECL7										45,678

Table 7: Overview Cost and Schedule Summary of Proposed JLEIC R&D Activities.

General Considerations for NP and the Proponent Laboratories/Supporting Universities

For future EIC cost and schedule reviews the following is recommended:

- Improve the quality of scope definition of R&D activities including a description of assumptions and constraints.
- Provide detailed basis-of-estimate information along with estimate classification information to the extent possible.
- Prepare cost estimates using appropriate labor rates for supporting organizations where possible.
- Provide resource loaded schedules at a summary level.
- Provide estimates of the cost and schedule contingency.
- Provide an overall integrated schedule showing dependencies between the various R&D activities.

Acknowledgements

The panel wishes to thank Brenda May and Cassie Dukes and those supporting them for the critical logistical support that enabled a smooth and productive meeting of the panel.

The chair thanks Ferdinand Willeke (BNL) and Fulvia Pilat (JLAB) for coordinating the significant effort required by the proponent laboratories to prepare and provide materials to support the work of the panel. The chair also thanks the presenters from Cornell University, the Massachusetts Institute of Technology, Old Dominion University and Texas A&M University for their willingness to attend and present at the panel meeting.

The chair thanks Jehanne Gillo and Manouchehr Farkhondeh for their guidance, patience and support as the panel moved through this process, and trusts that the information the panel has provided will be of use to the Office of Nuclear Physics.

Appendix A: Panel Membership

Name	Affiliation
Oliver Brüning	CERN
John Corlett	Lawrence Berkeley National Laboratory
George Dodson	Oak Ridge National Laboratory
Daniel Jones (for John Tapia)	Los Alamos National Laboratory
Kevin Jones (Chair)	Oak Ridge National Laboratory
Oliver Kester	TRIUMF
Daniela Leitner	Lawrence Berkeley National Laboratory
John Lewellen	Los Alamos National Laboratory
Sergei Nagaitsev	Fermi National Accelerator Laboratory
Alexander Romanenko	Fermi National Accelerator Laboratory
John Seeman	Stanford Linear Accelerator Center
Jie Wei	Michigan State University
Ying Wu	Duke University
Frank Zimmerman	CERN

Appendix B: Panel Meeting Agenda

Hilton, 1750 Rockville Pike, Rockville, MD

Nov. 29 – Dec. 2, 2016

Event contact	Brenda May, 301-903-0536 (office); brenda.may@science.doe.gov		
Time	Event/Activity	Lead	Attendees
Tuesday, November 29, 2016			
8:00-8:30 am	Executive Session		Panel Only
8:30-9:15 am	Office of Nuclear Physics Perspective on EIC-Related R&D to Date and Discussion	Manouchehr Farkhondeh	Panel Only
9:15-9:30 am	Break		
9:30-10:30 am	Opening Remarks, Charge to the Panel, Status of the Process and Related Discussion	Kevin Jones	All
10:30-11:30 am	BNL Introduction and ERL-based Linac-Ring Concept Overview	Ferdinand Willeke	All
11:30 am – 12:30 pm	Working Lunch		Panel Only
12:30-1:30 pm	R&D Program for Linac-Ring Concept	Ferdinand Willeke	
1:30-2:30 pm	Discussion of BNL Linac-Ring Concept		Panel, Presenters, Relevant Support Experts
2:30-3:00 pm	BNL Ring-Ring Concept Overview	Ferdinand Willeke	All
3:00-3:15 pm	Break – Refreshments		

Event contact	Brenda May, 301-903-0536 (office); brenda.may@science.doe.gov		
Time	Event/Activity	Lead	Attendees
Tuesday, November 29, 2016 (continued)			
3:15-3:45 pm	R&D Program for BNL Ring-Ring Concept	Ferdinand Willeke	All
3:45-4:15 pm	Discussion of BNL Ring-Ring Concept		Panel, Presenters, Relevant Support Experts
4:15-6:15 pm	Panel Discussion		Panel Only

Time	Event/Activity	Lead	Attendees
Wednesday, November 30, 2016			
8:00-9:00 am	Follow-up Questions and Additional Discussion for BNL Concepts		Panel, Presenters and Relevant Support Experts
9:00-10:30 am	JLAB JLEIC – Overview Presentation	Fulvia Pilat	All
10:30-10:45 am	Break – Refreshments		
10:45 am – 12:15 pm	JLAB JLEIC – Critical Technology Elements and R&D	Fulvia Pilat	All
12:15-1:15 pm	Working Lunch		Panel Only
1:15-2:30 pm	Discussion for JLAB JLEIC		Panel, Presenters, Relevant Support Experts

Time	Event/Activity	Lead	Attendees
Wednesday, November 30, 2016 (Continued)			
2:30-3:00 pm	MIT Presentation 1	Robert Redwine	All
3:00-3:30 pm	MIT Presentation 2	Richard Milner	All
3:30-3:45 pm	Break - Refreshments		
3:45-4:15 pm	Cornell Presentation	Luca Cultrera	All
4:15-4:45 pm	Old Dominion University Presentation	Jean Delayen	All
4:45-5:15 pm	Texas A&M University Presentation	Peter McIntyre	All
5:15-6:00 pm	Discussion of University EIC R&D Presentations		Panel, Presenters, Relevant Support Experts
6:00-7:30 pm	Panel Discussion		Closed Session

Time	Event/Activity	Lead	Attendees
Thursday, December 1, 2016			
8:30-9:30 am	Follow-up Questions and Additional Discussion for JLAB JLEIC		Panel, Presenters and Relevant Support Experts
9:30-10:30 am	Follow-up Questions and Additional Discussion for University EIC R&D Presentations		Panel, Presenters and Relevant Support Experts

Time	Event/Activity	Lead	Attendees
Thursday, December 1, 2016 (Continued)			
10:30-10:45 am	Break - Refreshments		
10:45 am-12:30 pm	Panel Breakout Work		Closed Session – Presenters to be Available
12:30-1:30 pm	Working Lunch		Panel Only
1:30-3:30 pm	Panel Breakout Work		Closed Session – Presenters to be Available
3:30-4:00 pm	Break - Refreshments		
4:00-6:30 pm	Panel Breakout Work		Closed Session

Time	Event/Activity	Lead	Attendees
Friday, December 2, 2016			
8:30-10:00am	Panel Report Preparation		Closed Session
10:00-10:15 am	Break – Refreshments		
10:15-11:30 am	Panel Report Preparation		Closed Session
11:30 am-12:00 pm	Close-out Discussion with Office of Nuclear Physics		Panel and DOE/NP

Attachment A: Charge to the Panel



Department of Energy Washington, DC 20585

June 23, 2016

Dr. Kevin Jones
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831

Dear Dr. Jones:

Thank you for agreeing to chair the Office of Nuclear Physics (NP) Community Review of Electron Ion Collider (EIC) Accelerator Research and Development (R&D). The Nuclear Science Advisory Committee (NSAC) recommended in the 2015 Long Range Plan (LRP) for Nuclear Science that the proposed EIC be the highest priority for new construction. This panel is asked to provide guidance to the NP Office on the current status of accelerator R&D efforts and the priorities for future accelerator R&D that will enable an EIC pre-conceptual design which will deliver the scientific objectives, while simultaneously minimizing technical risk and promoting cost effectiveness.

The key machine parameters of the EIC as identified in the LRP are:

- Polarized (~70%) electrons, protons, and light nuclei
- Ion beams from deuterons to the heaviest stable nuclei
- Variable center of mass energies ~20–100 GeV, upgradable to ~140 GeV
- High collision luminosity ~10³³-34 cm⁻²sec⁻¹
- Possibly have more than one interaction region

As the Chair, you will assemble a panel of experts to assess the following:

- Status of EIC R&D to date: Evaluate current state of EIC-related accelerator R&D supported to date by NP competitive accelerator R&D funds and by individual NP laboratory funds;
- EIC design concepts: Examine the current EIC design concepts under consideration in the U.S. and identify a risk level (High, Medium or Low) for the realization of each concept;
- Technical feasibility: For each EIC design concept, identify key areas of accelerator technologies that must be demonstrated or advanced significantly in order to realize the technical feasibility of the concept;
- Priority list of R&D: Generate a list of R&D areas for each EIC design concept, prioritized (High, Medium, Low) in the context of associated risk and impact of activity to value engineering and technical feasibility. Identify R&D items that have relevance to multiple EIC design concepts; and

- Cost and schedule range: To the extent possible and within the time constraints of the meeting, provide an estimate of cost and schedule range for each item on the R&D list above.

The prioritized list of R&D activities for each EIC design concept and the associated information generated by this panel will be used as a key metric in evaluation of proposals submitted to future NP biennial Funding Opportunity Announcements (FOA) for conducting accelerator R&D for next generation NP facilities.

We are requesting the panel's final report no later than January 9, 2017. Please provide us with information regarding the review approaches you will use (face-to-face panel), video, teleconference and the corresponding meeting schedules. The NP Office can provide support with logistics of the review. To provide input to your panel, you may consider inviting for presentation, representatives from lead NP Labs and universities working on current concepts of EIC and/or on key R&D efforts for these concepts. The 2015 NSAC Long Range Plan and the 2015 report of the NSAC subcommittee on EIC costs are additional sources of information for the panel to consider. Our Office can provide you with details on EIC R&D funds provided to applicants to biennial FOAs published under "R&D for Next Generation NP Facilities" since 2010.

Dr. Manouchehr Farkhondeh, Program Manager for Advanced Technology Research and Development for the Office of Nuclear Physics will act as the office representative to work with the panel during the meeting. If you have any questions about the review, please contact Dr. Manouchehr Farkhondeh at (301) 655-6895, or E-mail: Manouchehr.Farkhondeh@science.doe.gov.

I greatly appreciate your willingness to assist us in this review and look forward to very informative and stimulating discussions.

Sincerely,



Jehanne Gillo
Director
Facilities and Project Management Division
Office of Nuclear Physics

Enclosure