FUTURE STABLE-PARTICLE ACCELERATORS FOR NUCLEAR PHYSICS *

L. Harwood**, TJNAF, Newport News, VA 23692, USA

Abstract

Several projects that would be used for nuclear physics research are at various stages of development or construction. The fixed target projects include a hadron facility now under construction at JAERI and an upgrade of the CEBAF 6 GeV electron facility at Jefferson Lab to 12 GeV. eRHIC is the proposed electron-ion collider at Brookhaven National Laboratory. Jefferson Lab also investigating the feasibility of a facility that combines a 25 GeV fixed target capability with an electron-ion collider, eLIC. The conceptual layouts for all the projects are presented as is the utilization of superconducting rf technology. The R&D opportunities are discussed.

INTRODUCTION

The spectrum of proposed accelerator projects around the world is broad, ranging from small light sources to multi-kilometer linear colliders. Midrange in this spectrum are proposed facilities for nuclear physics. Some of these facilities will focus on the production of beams of rare isotopes. Others will use stable-particle beams to study nuclei in extreme states (quark-gluon plasma at RHIC) or "strong-QCD" (at CEBAF and possible electron-ion colliders). Exciting R&D opportunities are presented by each project. SRF technology is critical to almost all.

JAPANESE ATOMIC ENERGY RESEARCH INSTITUTE (JAERI)

In collaboration with KEK, JAERI is constructing a new facility called the Japanese Proton Accelerator Research Complex (J-PARC) [1]. The facility will be multi-disciplinary and be build in phases.

Phase I of the project supports material science and nuclear physics programs. Construction is underway at JAERI's Tokai campus in Ibaraki Prefecture. It will consist of a 400 MeV proton linac injecting a 3 GeV booster ring which then feeds a 50 GeV storage ring. The 3 GeV beam from the booster will be used to produce neutrons for material science studies. The 50 GeV protons will be used to create secondary beams (kaons, pions, hyperons, muons, and anti-protons) for nuclear physics studies in a dedicated research area. This phase of the project is expected to be complete in 2006.

Phase II of the project adds neutrino and waste transmutation programs. The 50 GeV protons will be used to produce a beam of neutrino's aimed at the Super-K detector. Linac capability will be expanded, with an srf-based booster linac, to provide high-current beam to a radioactive waste transmutation research facility.

* This work was supported by U.S. DOE under contract DE-AC05-84ER40150.

** Harwood@JLAB.ORG

BROOKHAVEN NATIONAL LAB (BNL)

RHIC-II

The relativistic heavy-ion collider (RHIC) at BNL [2] is the world's preeminent facility for the study of high-temperature, ultra-dense nuclear matter. A core goal for RHIC is the identification and study of a quark-gluon plasma. RHIC has produced many exciting results on the road to understanding this state of matter that existed in the early moments of the universe. 100+ GeV ions (protons through Au) circulate in interlaced rings. Four of the six interaction regions are presently instrumented with detectors.

Increasing RHIC's luminosity garnered support in the 2002 Long Range Plan (LRP) of the US Nuclear Science Advisory Committee (NSAC) [3]. BNL has developed a specific proposal to increase RHIC's luminosity by 9x for Au-Au collisions at 100 GeV/u (Fig. 1) and 3x for polarized proton collisions. The heart of the luminosity enhancement is the addition of electron cooling of the circulating beams. The cooler would use an srf-based energy recovering linac (ERL) and would be the first linac-based, bunched electron beam cooling system used at a collider. (See a later section of this paper for discussion of the e-cooling development project). At this time, R&D for the e-cooler is underway.

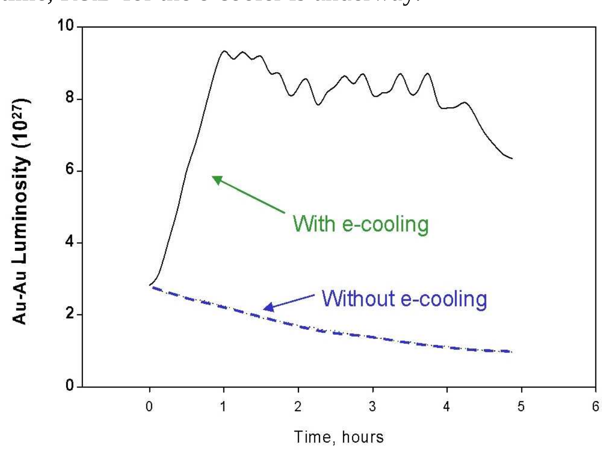

Figure 1: Luminosity of RHIC with and without benefit of electron cooling.

eRHIC

Theoretical studies have indicated an electron-ion collider (EIC) would provide the opportunity for important new insights into the nature of hadronic matter and non-asymptotic QCD. NSAC's 2002 LRP endorsed preliminary exploration of concepts for such a facility.

While the specific characteristics for the EIC have not been finalized, among them are:

- Center-of-mass energy between 20-100 GeV
- Energy asymmetry of ~10
- CW luminosity >10^{33} $cm^{-2}sec^{-1}AMU^{-1}$
- Ions spanning the entire periodic table
- Polarized beams (electrons and light ions)
  - Longitudinal polarization ≥ 50%
  - Transverse polarization of ions extremely desirable
  - Spin-flip of both beams extremely desirable

BNL has determined that they would like to add this research program to that of RHIC. They would modify the RHIC facility to include production and storage of electron beams which would collide with the ion beams circulating in the RHIC ring. The new facility would be called eRHIC [4].

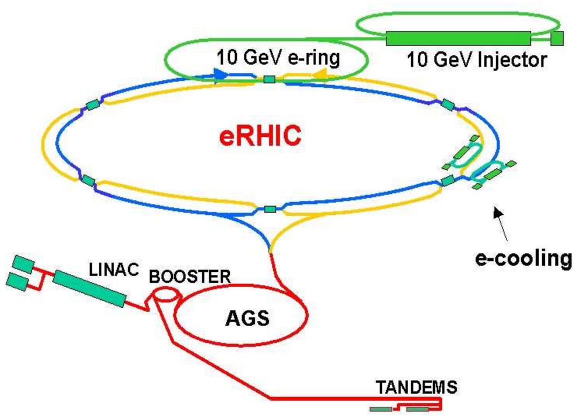

Figure 2: Proposed eRHIC complex.

The evolution of RHIC-II into eRHIC would entail the addition of production and acceleration capability for polarized electrons. The present plan calls for using a pulsed electron source followed by a two-pass recirculating linac (which utilizes srf cavities) for full-energy injection into the electron storage ring at ~10 GeV (Fig 2). This scenario is referred to as the ring-ring option, for fairly obvious reasons. One electron-ion interaction region would be added to the four ion-ion interaction regions. ~0.5 A of stored current in the electron ring would lead to a projected luminosity of ~10^{33}. Electron polarization would be accomplished with super-bends with maximum polarization being reached after ~15 minutes. The RHIC collision rate is 9 MHz. It would be increased to 28 MHz for eRHIC.

An alternative design would use an srf-based 2-pass ERL (Fig 3). It has been dubbed the linac-ring option. The advantage of this approach is that it simplifies some of the accelerator physics limitations, specifically it eliminates the beam-beam disruption issues with the electron beam. It also makes electron polarization changes much easier. On the other hand, it greatly pushes the requirements on the electron source if it is to be competitive with the ring-ring option. In order to reach a luminosity of 10^{33}, the required electron current is 130 mA, which greatly exceeds the present state of the art for polarized electron sources. The present analysis indicates that this option would be somewhat more expensive than the ring-ring option.

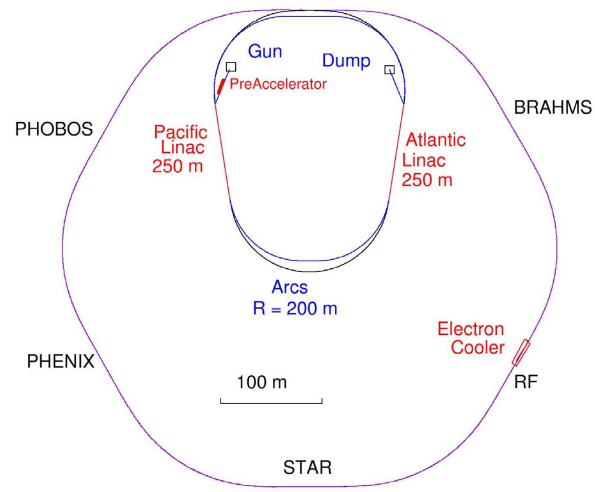

Figure 3: Alternative linac-ring layout for eRHIC. The five currently occupied interaction regions are labeled.

JEFFERSON LAB

12 GeV Upgrade

The CEBAF facility has led to substantial new advancements in our understanding of hardonic matter, including the recent discovery of the penta-quark. Lattice QCD calculations have indicated that experiments made possible by an increase of it's 6 GeV beam to 12 GeV beam might lead to the explanation of the reason for quark confinement. The upgrade of CEBAF to 12 GeV [5] has been strongly endorsed by NSAC in the 2002 LRP.

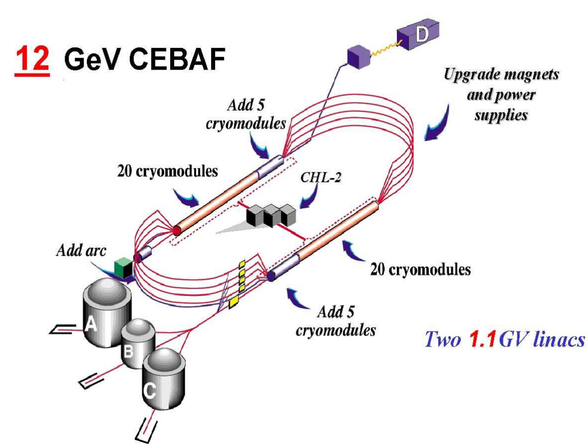

Figure 4: CEBAF 12 GeV Upgrade.

The 12 GeV Upgrade would incorporate the following modifications of the present facility [6]:

- Installing 10 new 100+ MV cryomodules, plus associated rf systems
- Doubling the cryogenic plant's capability

- Modifying the beam transport system to accommodate the increased beam energy
- Building a new experimental hall specifically for the exotic meson program plus the beam transport to get the beam to the new hall.

With the addition of the 10 new cryomodules, the CEBAF linac voltage would increase from 1.2 GV to 2.2 GV. Five-pass recirculation through these linacs makes 11 GeV beam available to the existing three experimental halls. An additional pass through one of the linacs would make 12 GeV beam available for the exotic meson program in the new experimental hall.

The original CEBAF cryomodules had a performance specification of 20 MV using eight 5-cell cavities. The new cryomodules will have eight 7-cell cavities. The new gradient specification is 19.2 MV/m where the original was 5 MV/m (on average, the existing cavities operate at 7.5 MV/m). The new specification includes a 10% allowance for some cavities being off-line or performing below specification. Q_0 needs to exceed $8x10^9$.

Cryomodule development is proceeding apace. The first one using 7-cell cavities is operational in CEBAF. A second, for use in JLab's FEL, is under construction. A third [7], which has tuner design changes and some modifications based on lessons-learned from the first 7-cell cryomodule, will be completed in 2004. This cryomodule will use cavity shapes which differ from that used previously for CEBAF[8].

The 12 GeV Upgrade project is in the R&D phase. JLab is awaiting funding approval from the US Department of Energy. Should approval come soon, first 12 GeV beam would occur around 2010.

25 GeV and eLIC

If all the cryomodule "slots" in CEBAF were populated with 100 MV cryomodules, the total voltage would be 5.0 GV. This level of acceleration could be used as the basis for a fixed target program, part of an EIC, or both.

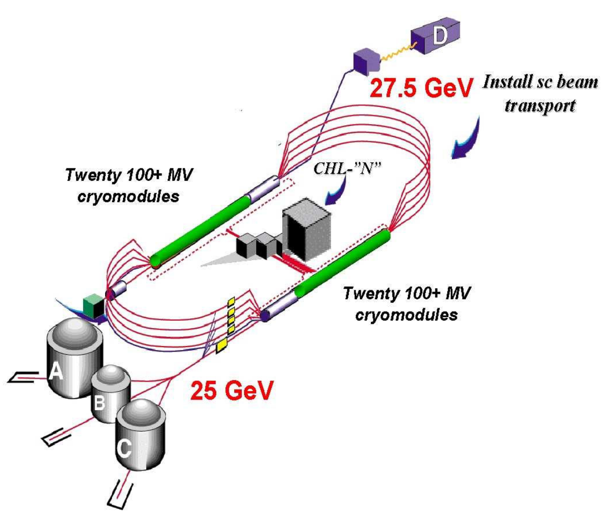

Figure 5: CEBAF upgraded to 25+ GeV.

With new magnets, likely superconducting, in the recirculation beam transport, the 5 GV linacs would make 25+ GeV beams available for fixed target research programs. 27.5 GeV would, in fact, be available for Hall D. The potential research program for this facility is quite promising and may become more so with additional study.

A more intriguing utilization of the 5 GV of acceleration would be as part of an EIC. JLab has developed an EIC concept called The electron Light Ion Collider (eLIC) [9]. It would use the linacs to provide full-energy injection of the polarized electrons into a 5 GeV ring. Ions, up to ~100 GeV, would circulate in a separate ring. Both would be figure-8's in order to simplify polarization dynamics. As with eRHIC, electron cooling would be used in the ion ring.

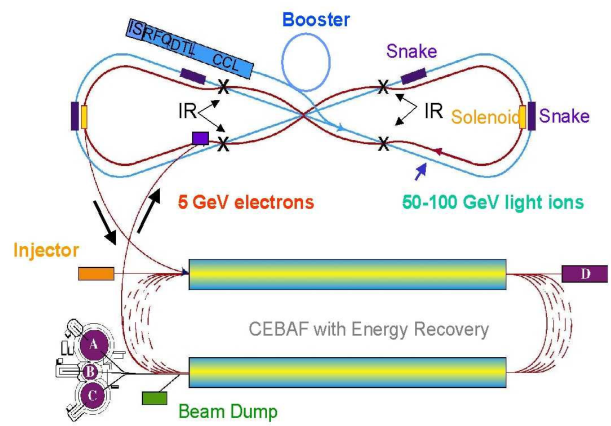

Figure 6: eLIC (electron-ion collider at JLab).

One of the unique features of eLIC is its proposed use of a circulator ring (CR). The electrons would circulate in this ring for ~100 turns, thereby reducing by 100x the required average current from the polarized electron source relative to that needed for a linac-ring concept. It also carries the benefit, relative to the ring-ring option, of reducing the constraints coming from beam-beam-collision induced disruption of the circulating electron beam, although not as much as with the linac-ring option. Design calculations indicate inclusion of crab-crossing might enable collision frequencies of 1.5 GHz; this would make a luminosity of $\sim 10^{35}$ a possibility.

The use of srf technology in the linacs is critical for eLIC. Even though the average beam currents in the electron linacs would be much smaller than for a linac-ring option, a luminosity of 10^{35} would still require ~50 mA. Without energy recovery, the rf power requirements would be prohibitive.

JLab is pursuing the feasibility of getting "double duty" out of the 5 GV linacs and thereby leverage the required investment in those linacs. 25+ GeV beam could be provided for the fixed target program during the ~99% of the time when the linacs are not being used to fill eLIC's CR.

Like eRHIC, 25GeV/eLIC is only in its nascent R&D phase. It is hoped that NSAC will endorse robust funding for EIC planning and R&D in its next long-range plan.

Table 1: R&D opportunities presented by the projects described in this report.

	RING-RING	LINAC-RING	LINAC/CR-RING	ACTIVE R&D
Luminosity potential	10^{33}	10^{33}	10^{33} 10^{34} 10^{35}	
Electron cooling	Yes	Yes	Yes	
"¼A" cw gun				BNL, Cornell
"½A" cavities				BNL, Jlab
Radiative polarization	Yes	—	—	BNL
Polarized-electron gun current	—	130 mA	5 mA 16 mA 25 mA	JLab
ERL's	—	Yes	Yes	JLab
Circulator ring accelerator physics	—	—	Yes	Jlab

R&D OPPORTUNITIES

The projects at BNL and JLab require R&D before they can be realized. Table 1 summarizes the R&D opportunities.

Non-srf R&D

Electron cooling:

Electron cooling in the ion ring is required for all the EIC projects. BNL has an active program for development of an electron cooler [10, 11]. Its goal is to establish the viability of all the requirements for electron cooling of the RHIC beam by investigating the following issues:

- Electron velocity must match the ion velocity—This means the RHIC cooler will have an electron beam energy ~150 times higher than any existing cooler.
- Minimizing rf power consumption.
- The electron beam needs to be "cold" and at a high current (>0.1 A).
- Issues of bunched beams in injector, magnetized beam transport and cooling.
- A very long, super-precise solenoid is needed (30 m long, 1 Tesla, 8x10-6 error).

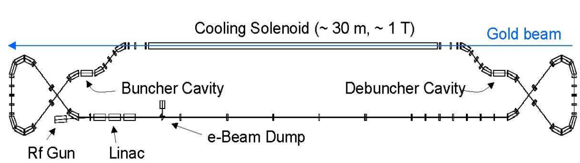

Figure 7: Schematic of BNL electron cooler.

BNL proposes to use an ERL for the electron cooler. BNL and Advanced Energy Systems are collaborating on a room-temperature rf photo-injector for the ERL. BNL is pursuing the precision solenoid and accelerator physics issues.

Cornell is pursuing an ERL-based next-generation light source demonstrator [12]. Its beam current requirements are similar to those for electron cooling. As such it is developing both high-current accelerator modules (see below) and a high-current source [13].

It has been suggested that utilization of a circulator ring could alleviate the requirement for a high-current source [14]. The "one-up/one-down" ERL would be morphed into a configuration similar to that proposed for eLIC with beam circulating for 100 (or more) turns thereby reducing the average beam current from the source by a factor equivalent to the number of turns in the circulator ring.

Circulator ring beam physics:

No circulator ring has been built; neither has an extensive study of the beam physics issues been carried out. It would be very advantageous if the nominal 100 turns of storage could be pushed to 1000 or higher. Positive results from such an intense investigation of circulator ring beam physics would be very beneficial to eLIC planning and electron cooling projects.

High energy, high current ERLs:

Both the linac-ring and linac/CR-ring options for an EIC rely on ERL's providing the vast majority of the electron beam's acceleration. Maximizing the ratio of Injector/dump energy and linac energy is very advantageous as it minimizes the required rf power. JLab has demonstrated 10:1 ratio at 5 mA in its IR FEL (lasing at 1.7 kW) [15]. More recently, it has successfully demonstrated energy recovery with ratios as high as 50:1 [16], but not at high current, and plans follow-on experiments. Extension to 1000:1, or higher, and at high current would be beneficial for ERL expanding the potential for broad utilization of ERL's.

High-current polarized electron guns:

The linac-ring and linac/CR-ring versions of the EIC will require significant advances in polarized electron source currents in order to reach desired luminosities. The present state-of-the-art is ~1 mA. The linac-ring option needs >100 mA for a luminosity of 10^{33}. Using a circulator ring reduces the requirement to ~5 mA for the same luminosity. If 25 mA could be produced, then a luminosity of 10^{35} might be possible with a CR. JLab is working to push polarized electron gun capabilities.

Radiative polarization:

The ring-ring scenario for the EIC relies on radiative polarization of the electron beam. Super-bends are proposed for enhancement of this process. BNL is pursuing studies to determine potential polarization levels and times. They are working toward a goal of 70-80% polarization in 15 minutes.

SRF R&D

SRF technology is key to all the US proposals. The performance requirements (current, gradient, Q_0, net rf power) vary somewhat between the different applications.

Cavities useful for electron-cooling:

Electron cooling does not require high energy beam. The electron beam energy is 0.05% of the ion beam's energy/nucleon. High gradients are thus not required. Rather high currents, i.e. ~1 A, are needed however. As such, it is possible to focus the development/design effort on insuring the cavities have extremely good damping of their high-order modes and not have to "push" the gradient or Q_0.

BNL is developing a 5-cell 0.7 GHz cavity [17]. It uses large, extended beam tubes with ferrite dampers. TDBBU calculations indicate that the design has acceptable HOM damping for over 1 A.

The Cornell ERL planning includes two different cryomodule designs. One [18], for the injector, will use five 2-cell 1.3 GHz cavities operating at 4.3 MV/m. They plan on including variable rf coupling so as to enable operation at 13 MV/m when running lower currents. They share with BNL the large-aperture/ferrite scheme for HOM damping. The main linac's cryomodules' cavities will be multi-cell [19].

Cavities for large ERL's:

The ERL's being proposed as main drivers anticipate more moderate beam currents (≤200 mA) than the electron coolers. On the other hand, they must deliver much more total voltage and will require construction of new tunnels. Thus higher gradient ("floor gradient", not "cavity gradient") is needed to minimize the tunnel length. High Q_0 is then required for those cavities that will operate in cw machines. The relative importance of gradient/Q_0 and HOM damping are thus reversed with respect to those for electron coolers. Varying concepts have been proposed [20,21] which appear capable of reaching high gradient with good "floor gradient".

SUMMARY

Nuclear physics remains a field with exciting unanswered questions. Answering those questions will require upgrades to existing facilities (RHIC-II and JLab's 12 GeV Upgrade) and/or construction of new facilities (J-PARC, eRHIC, eLIC). Construction of these facilities will be feasible only after successful completion of R&D efforts that hold the potential to be as exciting for the accelerator community as the subsequent nuclear physics measurements will be to the nuclear physics community.

REFERENCES

[1] http://j-parc.jp/

[2] http://www.bnl.gov/RHIC/

[3] http://www.sc.doe.gov/production/henp/np/nsac/nsac.html

[4] http://www.phenix.bnl.gov/WWW/publish/abhay/Home_of_EIC/

[5] http://www.jlab.org/div_dept/physics_division/GeV.html

[6] L. Harwood and C. Reece, "CEBAF at 12 and 25 GeV", SRF2001.

[7] Reece, et al., "Design and Construction of the Prototype Cryomodule for the CEBAF 12 GeV Upgrade - Renascence", this conference.

[8] Kneisel, et al, "First Cryogenic Tests with JLab's New Upgrade Cavities", this conference.

[9] Merminga, et al., "ELIC: An Electron-Light Ion Collider Based at CEBAF", EPAC2002.

[10] Ben-Zvi, et al., "Electron Cooling for RHIC", PAC2001.

[11] I. Ben-Zvi, "R&D on Electron Cooling of RHIC", Workshop on Beam Cooling and Related Topics, Mt. Fuji, Japan, May 19-23, 2003.

[12] C. Sinclair and G. Hoffstaetter, "The Cornell ERL Prototype Project", PAC2003.

[13] C. Sinclair and I. Bazarov, "High Brightness, High Current Injector Design for the Cornell ERL Prototype", PAC2003.

[14] S. Derbenev, private communication.

[15] Neil, et al, Phys. Rev. Lett., 84 (2000) 662.

[16] Tennant, et al., "CEBAF-ER: Extending the Frontier of Energy Recovery at Jefferson Lab", this conference.

[17] Calaga, et al., "Study of Higher Order Modes in 5-Cell SRF Cavity for E-Cooling at RHIC", this conference.

[18] Padamsee, et al., "Overview of the Cornell ERL Injector Cryomodule", this conference.

[19] M. Liepe, "Conceptual Layout of the Cavity String of the Cornell ERL Main Linac Cryomodule", this conference.

[20] Rimmer, et al., "Strongly HOM-Damped Multi-cell RF Cavities for High-current Applications", this conference.

[21] Sekutowicz, et al., "Development of Superstructures for High Current Application", this conference.