The CEBAF II/ELIC Upgrade of CEBAF

A Report to the NSAC Subcommittee on Categorizing Proposed Facilities

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CEBAF II/ELIC Upgrade — Project Summary

A strong physics case has been established for constructing an extremely high luminosity ($\sim 10^{38}$ cm^{-2} sec^{-1}), CEBAF-like accelerator with energies in the 20-30 GeV range. There have also been a series of studies investigating the scientific potential of an electron-light ion collider (ELIC) operating in the 20-65 GeV center-of-mass energy range. The facility at Jefferson Lab can be upgraded to provide either (or both) of these options in a straightforward manner. An energy upgrade of CEBAF to 25 GeV would support extensions of the CEBAF 12 GeV program to smaller x and higher Q^2, and, in particular, support a program of deeply virtual meson production that would permit the flavor separation of the Generalized Parton Distributions that characterize the nucleon's properties. A high-luminosity electron-light ion collider (ELIC) in the center-of-mass energy range $\sqrt{s}$ of 20-65 GeV, would build on the physics insights obtained from the CEBAF 12 GeV upgrade, and expand on our understanding of the structure of the nucleon and nuclear binding. While questions remain on the details of the science program and on technical aspects of the facility design, we expect that the facility's research program will be **absolutely central** to the field of nuclear physics. In particular, such a facility will provide a unique tool to:

- *Complete our quantitative understanding of how quarks and gluons provide the binding and the spin of the nucleon.* There are still glaring gaps in our knowledge of the QCD structure of the proton. How large is the role of gluon and quark angular momentum in the description of the proton's spin? Can we fully disentangle the contribution of up, down, and strange quarks to the proton's momentum and spin? The 12 GeV Upgrade concentrates on the moderate to high-x structure of the proton – the regime where the valence structure emerges. The ELIC facility would concentrate on the small-x regime ($10^{-4} < x < 10^{-1}$) with high luminosity, reaching the regime where gluons become prevalent. The combination of precision measurements at moderate Q^2 and high-x (from the 12 GeV Upgrade) and data at small-x and relatively large Q^2 (~ 10 GeV^2) (from ELIC), using techniques ranging from "deep inelastic scattering" to "deep exclusive scattering", will permit us to disentangle the exact quark-gluon structure of the nucleon, over a wide range of x.

- *Understand how quarks and gluons evolve into hadrons via the dynamics of confinement.* Another fundamental question is: "How does a quark (and the associated glue) struck by a virtual photon in a high-energy electron-quark scattering evolve into a hadron?" This process, known as hadronization, is complex, and is related to both the structure of hadronic matter and the long-range dynamics of confinement. In an astrophysical context, hadronization emerges as a key aspect of the transition from the deconfined state of free quarks and gluons in the Big Bang (the quark-gluon plasma) to stable hadronic matter. Dramatic increases in our knowledge of this aspect of nucleon structure are expected, with measurements of the spin-dependence of this process as the main theme.

- *Refine our understanding of how the nuclear binding arises from QCD.* The interaction between protons and neutrons is responsible for nuclear binding. It may be described with good success using effective theories in which exchanged mesons (predominantly pions) mediate the interactions. How does this binding effect manifest itself in the underlying quark and gluon degrees of freedom? The modification of the momentum distributions of quarks in a nucleus has been demonstrated unambiguously, but not much is known about other properties of quarks (and gluons) in a nucleus. A series of measurements aims at elucidating the complete spin-flavor structure of the modifications to quarks and gluons in nuclear systems.

The April 2002 Long-Range Plan for the Next Decade, developed by the 2001-2002 Nuclear Sciences Advisory Committee (NSAC) Long Range Planning Process, noted that a "ring-linac option where a linear electron beam is incident on a stored ion beam" is one of two classes of machine design for an electron-ion collider (the other is a ring-ring design). Since then, conceptual design studies for the facility have continued, and our latest results indicate that luminosities of up to 10^{35} cm^{-2} sec^{-1} are within reach, with a combination of a high-intensity, energy-recovered linac and a ring that has been optimized for this physics. A number of technical challenges remain, and several R&D projects have been started. These include: electron cooling of protons/ions (in collaboration with BNL/BINP); the design of an interaction region and detector that, taken together, support the combination of the very high luminosity and very high detector acceptance and resolution essential to carry out this physics program; and the demonstration of the feasibility of energy recovery at high current and high energy. For the latter, an early test on the GeV scale will occur at JLab in March, 2003. Given the level of R&D remaining to be done, the readiness of this project should be categorized as **"scientific and engineering issues still need to be resolved."**.

1 The Electron-Light Ion Collider — Science

Three decades after the establishment of QCD as the theory of the strong nuclear interaction, understanding how QCD works in practice remains one of the great puzzles in nuclear physics. QCD stipulates that colored quarks are the basic constituents of strongly-interacting matter, and gluons are the mediators of this interaction through the exchange of color between quarks. The most important difference between QED and QCD is the "non-abelian" character of the latter, which means that gluons interact with gluons, whereas photons, the mediators of the electromagnetic interaction, do not interact with other photons. The direct implication of this unique phenomenon is that, unlike any other many-body system, the individual quark and gluon constituents making up a proton cannot even be removed from the system and examined in isolation.

This built-in non-linearity of QCD makes calculations and theoretical predictions difficult, as the world we encounter consists of nucleons and mesons, rather than the fundamental degrees of freedom of QCD — quarks and gluons. This remarkable and unique feature of QCD at long distance scales (between the quarks and gluons) is termed quark confinement. On the contrary, at short distance scales the quarks and gluons behave essentially as free particles, termed asymptotic freedom, and QCD renders reliable predictions in the high-energy limit.

A great achievement of nuclear and particle physics has been the quantitative verification of the QCD theory in hard scattering processes, at distance scales several times smaller than the size of the proton. At these short distances, the quarks and gluons have a very clear experimental signature, and their dynamics follows the prediction of perturbative QCD calculations. Such experiments have, e.g., established that the quarks carry about 50% of the proton's momentum, and only 30% of the proton's spin. Even the modification of the momentum distributions of quarks in a nucleus has been demonstrated (although not yet understood), but not much is known about other properties of quarks (and gluons) in a nucleus. Yet, at some level the quarks and gluons must be responsible for the binding of nuclei. Similarly, there are still glaring gaps in our knowledge of quarks and gluons inside the proton. How large is the role of gluons and angular momentum in the description of the proton's spin? In addition, although the knowledge gained on regions where quarks and gluons behave as essentially free is impressive, we know that no free quarks exist, and the quarks and gluons must have strong correlations in certain kinematic regions.

Recent advances in computational technology, lattice field theory algorithms, continuum model building, accelerator beam quality, and detector design have led us to the threshold of developing a true understanding of the fundamental mechanisms of QCD and the ability to solve QCD, also at a long distance scale, quantitatively. However, such an understanding requires an extensive series of precise measurements, utilizing a hard electron-quark collision not only to access deep inelastic scattering processes, but also the more selective (and hence having a smaller cross section) semi-inclusive and deep exclusive processes. For the latter, the consensus is that a momentum transfer squared $Q^2 \sim 10$ GeV^2 would be optimal, thus leading to the requirement for high luminosity. A large range in energy is similarly required, to cover the full region of x (the momentum fraction of the struck quark), from the region where gluons dominate to where solely quarks remain.

The feasibility of a high-luminosity (up to 10^{35} cm^{-2} sec^{-1}) electron-light ion collider in the center-of-mass energy range $\sqrt{s}$ of 20-65 GeV, in combination with data that will have been obtained from a 12-GeV Upgrade fixed target facility, is optimal to finally solve the elusive structure of the nucleon. In particular, such a facility will provide the perfect tool to:

- develop a quantitative understanding of how quarks and gluons provide the binding and spin of the nucleon based on QCD,

- understand how quarks and gluons evolve into hadrons via the dynamics of confinement,
- and, develop a basic idea how the nuclear binding originates from quarks and gluons.

1.A Kinematics

The collider geometry offers two major advantages over fixed target e-p studies. First, the collider delivers increased energy to the center of mass providing a larger range in x and Q^2 in the primary collision. Secondly, the collider eases the requirements for particle detection. In a fixed target experiment relativity boosts the reaction fragments to small laboratory angles, a problem that is absent in a collider geometry. In addition, low-energy nuclear fragments might not escape the fixed target nuclear environment, whereas these fragments can easily escape in the lower-luminosity e-p collision area. Nonetheless, for some of the smallest cross sections, especially in *precision longitudinal/transverse separations* or *deep exclusive* reactions, a 25-GeV fixed target geometry has distinct advantages.

Figure 1 shows the x-Q^2 range accessible with ELIC. Similarly, Fig. 2 shows, both for ELIC and a 25-GeV fixed target facility, the x-Q^2 range accessible for precision longitudinal/transverse separations (here, one disentangles the nuclear response according to to whether the mediator of the electromagnetic scattering process, the photon, has longitudinal or transverse polarization). Such separations greatly enrich the access to the quark-gluon substructure of nucleons.

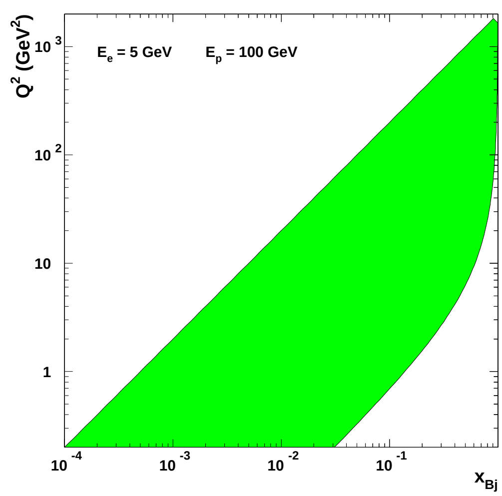

Figure 1: The x-Q^2 range of the proposed electron light-ion collider, for a center-of-mass energy of 45 GeV. Only the range beyond the nucleon resonance region ($W^2 > 4$ GeV^2) is indicated.

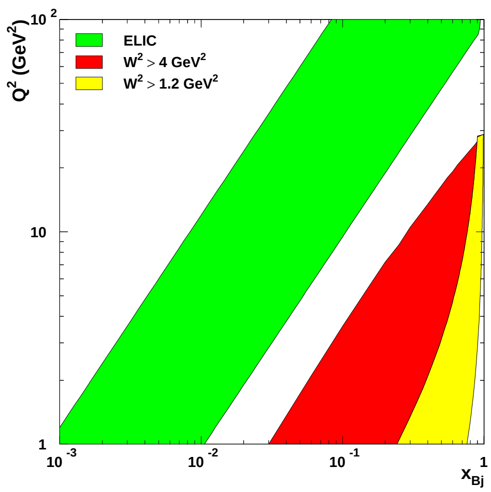

Figure 2: The x-Q^2 range accessible for longitudinal/transverse separation of nucleon structure functions with ELIC (green) and a 25-GeV fixed target facility (red). The nucleon resonance region is indicated in yellow.

It is important to realize that already at the center-of-mass energy shown in Fig. 1, 45 GeV (a 65 GeV energy case has not yet been worked out in detail), it will be possible to access values of x down to 5×10^{-4}, for $Q^2 > 1$ GeV^2, the typical kinematic limit for the deep inelastic scattering region (in deep inelastic scattering, the collision is assumed to occur on a free quark).

The final design luminosity corresponds to an integrated luminosity of over 5,000 (pb)$^{-1}$ per day, whereas significant results can, for inclusive electron scattering experiments (only the scattered electron is detected), already be obtained for an integrated luminosity of 200 (pb)$^{-1}$. This high luminosity will also allow for unprecedented measurements of deep exclusive reactions (reactions where one puts a lot of energy transfer into the nuclear system, but still detects all fragments) over a large range of x. Here, results with similar statistical precision require an integrated luminosity typically a factor of 1,000 larger than for inclusive scattering.

1.B The Quark-Gluon Structure of the Nucleon

Following the seminal work of Freedman, Kendall, and Taylor at SLAC in the early 70's, three decades of deep inelastic scattering experiments have mapped the momentum distributions of light quarks (up, down, and strange, with diminishing precision). Altough the gluons carry no charge, indirect (and thus less precise), information on the gluons originates from a precise mapping of the Q^2 dependence of the measured (at high Q^2 predominantly transverse) structure function F_2. Due to quark-gluon interactions, the exact quark momentum distributions at finite Q^2 also depend on the gluon distributions.

Over the last decade, these unpolarized (or spin-averaged) electron scattering measurements have been extended to precise spin-dependent measurements, rendering data on the g_1 structure function over a large range in x and about one decade in Q^2. Recently, the dependence on Q^2 of the structure function g_1 has been used to constrain the gluon contribution to the proton spin. However, the precision and range in Q^2 are far from optimal for this procedure to precisely map this gluon spin distribution. In addition, there has been one direct measurement of the gluon spin distribution at $x \approx 0.2$ by the HERMES collaboration measuring a pair of hadrons, both with large momentum transverse to the momentum transfer direction. Lastly, there has been some progress in disentangling the contributions from different quark flavors to the proton spin by flavor tagging in semi-inclusive scattering.

Still, many puzzles remain on the exact role of the various contributions to both the nucleon momentum and spin. In particular, the proposed ELIC setup, in combination with the 25-GeV fixed target facility, will provide:

- A measurement of the (purely longitudinal) F_L structure function over a large range in x and Q^2, enabling also a precise determination of the *moments* of gluon distributions, given the existing measurements of F_2.
- An indirect determination of the gluon spin distribution via a precise map of the g_1 structure function over 2 decades of Q^2.
- A direct determination of the gluon spin distribution over a large range of x (between 0.02 and 0.5) by measuring pairs of high-transverse momentum hadrons.
- A precise, final, map of the contribution of the up, down, and strange quark contributions to the nucleon's momentum and spin, by a series of flavor tagging experiments in semi-inclusive scattering, down to $x \approx 10^{-3}$.
- A first measurement over one decade of Q^2 of the *transversity* distributions of the quarks. These distributions describe the quark polarizations within a transversely polarized proton, and do not mix with gluon distributions (there is no transversity of gluons in a nucleon). In the non-relativistic quark model, the transversity distribution $\delta q(x)$ should be equal to $\Delta q(x)$, the longitudinal spin distribution mentioned earlier, and this provides a "baseline" for our understanding of this, as yet unmeasured, distribution. The transversity distribution $\delta q(x)$ encodes, more general, information about the relativistic effects in the nucleon's transverse spin content. The first moment of $\delta q(x)$, termed the tensor charge of the proton, offers a promising point of comparison with theory.

- A series of fully exclusive processes, in which all of the reaction products are reconstructed, to unravel the complete internal dynamics of the proton in the framework of "*Generalized Parton Distributions*" (GPD's): The recently developed GPD formalism describes hard scattering processes that involve the *correlations* between quarks and gluons. This formalism offers an exciting bridge between elastic and deep inelastic scattering: in different limits of the GPD's, one recovers the familiar elastic form factors (where the quarks act coherently, and the proton remains intact) and quark (and gluon) distributions accessible in deep inelastic scattering. Clearly, a mature description of the quark-gluon substructure of the proton, beyond the naive picture of asymptotically free quarks, must involve a description of these correlations. Even more important, the GPD's have a direct connection to the, as yet unknown, quark angular momentum. Electroproduction measurements of charged pions can be extended to reach the limit, $Q^2 > 10$ GeV^2, where we can safely believe access to GPD's is feasible; electroproduction measurements of vector mesons, such as ρ mesons and ϕ mesons, can be extended to reach into the lower x domain (at lower Q^2), where the gluon GPD's can be probed.

As mentioned, the GPD's relate the two type of quantities which have been the major sources of our present knowledge of nucleon structure: quark distributions which tell us about the longitudinal momentum structure of a fast-moving nucleon, and form factors which contain information on its transverse structure, such as its charge radius. In general, the GPD framework assumes a quark to be extracted from the nucleon in the primary collision process, and returned with a different momentum fraction. The GPD's have an intrinsic region in x where a quark-antiquark pair or a gluon pair is emitted from the initial nucleon. The dynamics of this region reveals aspects of the nucleon structure that can not be accessed with the usual quark and gluon distributions.

Since GPD's describe also transitions between the nucleon and different hadrons, this allows one to probe the overlap of their respective wave functions. This opens the way to study hadrons not available as beam particles. The great advantage of GPD's is, generally speaking, that their large information content allows one to connect different observables and to determine quantities of physical interest which one cannot extract directly from individual observables. The most prominent of these quantities is the total angular momentum of the quarks. This is an essential ingredient for the complete understanding of the nucleon's spin.

To realize this program is both an experimental and a theoretical challenge. Factorization proofs (similar to that used in deep inelastic scattering to separate the hard electron-quark collision from the underlying nucleon structure) guarantee that the GPD's are well-defined QCD objects. In the last few years tremendous progress has been made in raising their theoretical treatment to levels approaching that achieved in over three decades of intense studies of the usual quark distributions.

1.C How Do Quarks and Gluons Evolve into Hadrons

A fundamental question is how a quark (and the associated glue) struck in the primary high-energy electron collision evolves into a hadron. This process is known as *hadronization*, and is a clear manifestation of confinement: the asymptotic physical states detected in experiment must be color-neutral hadrons. In the asymptotic energy limit, the measured cross section for detection of an electron scattering off a nucleon in association with the production of a *fast* hadron factorizes into a structure function, giving the probability to find a quark in the nucleon, and a quark $\rightarrow$ hadron fragmentation function. These fragmentation functions provide another snapshot of hadron structure, and map how the struck quark evolves into the detected hadron (in principle, there also exist *target* fragmentation functions that map how the spectator quarks evolve into color-neutral hadrons).

Hadronization is a complex, non-perturbative process which is related to both the structure of hadronic matter and to the long-range dynamics of confinement. Understanding hadronization from first principles has proven very difficult. However, over the last two decades, progress has been made in phenomenological descriptions of hadronization, such as the Lund model. However, our knowledge of this hadronization or fragmentation process is still rudimentary. For example, according to our present understanding of the process, it should not matter whether a quark with longitudinal or transverse momentum was selected in the electron scattering process. However, to date there exists no experimental verification of this. In the future, understanding of fragmentation in spin-dependent processes, use of fragmentation as a tool for hadron structure study, and probing of the global structure of the hadronic final state are likely to be the main themes of investigation in this direction. Especially the question how, and to what extent, the spin of a quark is transfered to its hadronic daughters is intriguing. The possibility of measuring all reaction products in the collider geometry will allow a dramatic increase in our knowledge of the target fragmentation process.

In nuclear physics, hadronization has emerged over the last 5 years as a *tool* of profound importance in the analysis of hadronic structure functions: A new generation of experiments is exploiting the fact that semi-inclusive deep inelastic scattering measurements may, through the use of the fragmentation functions, "tag" particular flavors of struck quark.

1.D The Quark-Gluon Origin of Nuclear Binding

Most of the observable matter in the universe is contained in the form of atomic nuclei, with the interaction between protons and neutrons is responsible for the *nuclear binding.* How does this binding manifest itself in the underlying quark and gluon degrees of freedom? The natural energy scale of QCD is of the order of hundreds of MeV, whereas the nuclear binding scale is relatively small, of the order of 10 MeV. Hence, one is led to believe that this small scale arises from complicated details of near cancellations of strongly attractive and repulsive terms in the nuclear interaction, or is there some deeper reason?

Due to the small scale of the nuclear binding, it was a surprise when the European Muon Collaboration demonstrated a significant modification of the quark momentum distributions in the nuclear medium. To date, this remains the single unambiguous experimental result highlighting that a nucleus is not merely a simple set of nucleons. Three separate physics regions emerge: (i) for $x > 0.2$ one obtains a reduction of F_2 in nuclei, followed by a steep rise at $x \approx 0.7$. This is the original "EMC effect", where the rise at large x is due to Fermi smearing effects; (ii) at $x \approx 0.1$ there is a small enhancement of the nuclear structure function F_2 with respect to the free nucleon. This region is termed the *anti-shadowing* region; (iii) at lower x the nuclear ratio drops to below unity (the *shadowing* region), ultimately reaching a saturation limit at $x \approx 10^{-3}$.

The EMC and enhancement regions presumably arise, at least partly, due to nuclear binding effects. To date, no quantitative calculation starting from a nucleon-meson framework has been able to explain the full effect. The shadowing region is thought to arise from the specific space-time characteristics of the primary collision. The photon can, due to quantum mechanics, fluctuate into a $q\bar{q}$ pair, which can strongly interact with the nuclear medium. Hence, part of the photon flux gets absorbed in the nucleus.

The Drell-Yan process (essentially a quark-antiquark annihilation process) has been used to study the sea quark distribution in nuclei. No significant nuclear modification has been found in the region of $x \approx 0.1$, which remains one of the interesting puzzles of nuclear physics. If the nuclear force is considered to be predominantly mediated by pions, why do we not find any signature for them? What is the cause of the enhancement found in the regular nuclear structure function ratio at this value of x? Lastly, the precise nuclear structure function ratios of Sn and C as measured by the New Muon Collaboration at CERN, and their detailed Q^2 dependence, have been used to constrain our knowledge of the gluon densities in nuclei.

Short of a breakthrough in our understanding how nuclear binding originates from the underlying quarks and gluons, the best approach seems to be to accumulate precise data for the modifications of the momentum and spin distributions of quarks, antiquarks, and gluons in the nuclear environment. The combination of ELIC and the 25-GeV fixed target facility will provide:

- Precise ratio measurements down to the region of *saturation* at small x ($\approx 10^{-3}$), for a large range of nuclei.
- An indirect, more precise, determination of the gluon distribution in the nuclear environment, via a map of the ratio of nuclear F_2 structure functions over a large range of x and Q^2.
- A direct measurement of the gluon distribution in the nuclear environment, by J/ψ detection in the collider facility, extended into the region where gluon shadowing, if indeed confirmed, is expected to saturate.
- A precise longitudinal/transverse separation in the region of low x, to independently confirm the gluon shadowing expectation.
- A host of measurements that will "tag" particular flavors of the struck quark, in an attempt to disentangle the spin-flavor dependence of the measured nuclear effects, and pick apart the origin of the EMC effect.

2 The Electron-Light Ion Collider — Design

2.A Overview

To probe the hadronic structure of matter and reach the full parameter regime of the physics described earlier, we propose an upgrade to CEBAF beyond 12 GeV, which is comprised of an Electron-Light Ion Collider (ELIC) facility, and of the capability to produce up to 25 GeV electrons for experiments in external target geometry in advantageous situations. This Section outlines the conceptual description of the proposed integrated facility. The CEBAF-based design concept for the collider appears to offer significant advantages with respect to a colliding storage rings configuration. In particular, much higher luminosities appear feasible and flexibility with respect to spin manipulations is greatly enhanced. Conceptual design studies of the ELIC collider indicate that luminosities up to 10^{35} cm^{-2}sec^{-1} are within reach, with both beams longitudinally polarized at 80% in the interaction region (and, optionally, transversely polarized ions). The center-of-mass energy can be variable between 20 and 45 GeV, a result of collisions of 3 GeV electrons on 30 GeV ions, up to that of 5 GeV electrons on 100 GeV ions (note that while a particular worked-out-in-detail design exists for these energy ranges, a possible energy reach of 65 GeV center-of-mass energy has not been worked out in such detail yet). Ion species include protons, deuterons, and ^{3}He (and, perhaps unpolarized, heavier ions). Spin-flip of both beams, which is extremely desirable to reduce systematics, is possible.

The proposed electron-light ion collider would accelerate the electron beam to 5 GeV using the CEBAF recirculating linac with upgraded accelerating structures, in energy recovery mode. After colliding with protons/light ions circulating in a storage ring at energy of 100 GeV, the electrons are re-injected into the CEBAF accelerator for deceleration and energy recovery. Furthermore, the same accelerator that provides 5 GeV electrons for the collider mode can also provide up to 25 GeV for fixed target experiments for physics.

2.B The Electron-Light Ion Collider proposal

A schematic layout of the ELIC collider, for 5 GeV electrons colliding with 100 GeV ions, is shown in Fig. 3. Parameters for this facility are listed in Table 1. Longitudinally polarized electrons generated from a high current polarized source are injected into the CEBAF accelerator. With CEBAF Upgrade-style cavities, operating at a gradient of 18 MV/m, installed in the tunnel, a single pass recirculation through CEBAF results in an electron beam energy of approximately 5 GeV. To ease the high current polarized photoinjector and Energy Recovering Linac (ERL) requirements, a circulator ring, in which electrons circulate for a small number of revolutions (about 100) while colliding with the ion beam, may be used. In such a scenario, the 5 GeV electrons are injected into the circulator ring, after acceleration in the ERL, and circulate for 100 revolutions while they continuously collide with the ions. They are subsequently extracted, transported back to CEBAF for deceleration and energy recovery, and are dumped at approximately their injection energy. Might a very intense polarized electron source become available, the circular ring can be dropped and the electrons would still follow the same transport, but circulate only once before being reinjected to CEBAF for energy recovery.

All ion species are injected longitudinally polarized and accelerated in a conventional ion RF linac with maximum energy of 200 MeV. Currently, two options are being considered for the ion beam stacking and acceleration after the linac. The first option comprises the conventional scheme of a 2 GeV kinetic energy "Figure-8" pre-booster ring (approximately 70 m in circumference, not shown in Fig. 3) followed by a large booster (coincident with the "Figure-8" electron circulator ring). Stripping injection of the polarized negative ions can be used to accumulate the polarized protons and deuterons in the pre-booster. However, this method is not applicable to the polarized ^{3}He (positive ion source). For polarized ^{3}He an alternate scheme is considered that includes a small, up to $\sim$15 m in circumference, 200 MeV accumulator ring, with conventional electron cooling, following the linac and before the pre-booster. In this scheme, all ion species can be accumulated using positive polarized sources. Another important advantage of this option is the possibility to cool the ion beam after acceleration in the linac in order to reduce the transverse emittance.

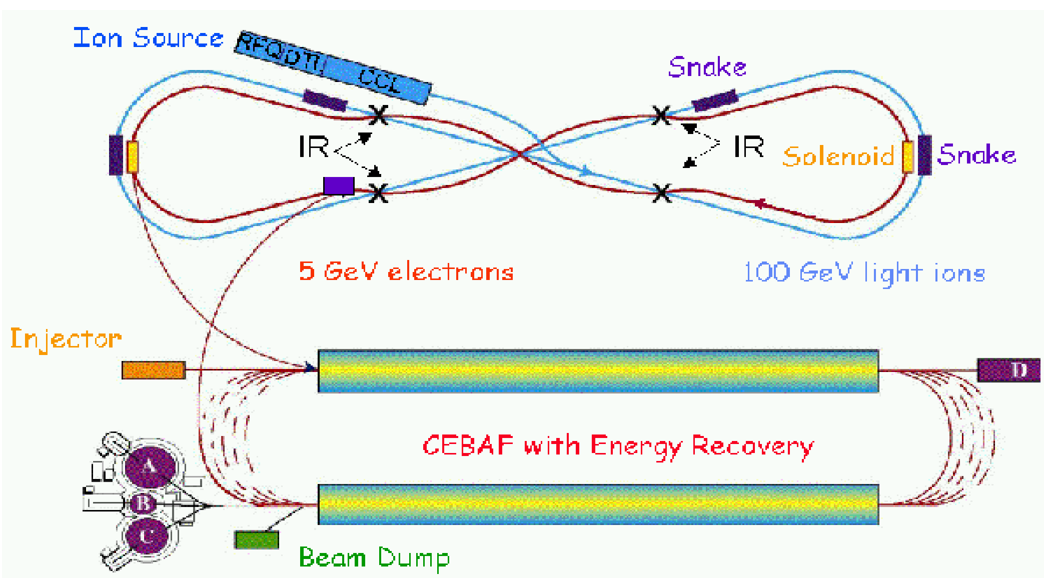

Figure 3: ELIC layout.

As mentioned earlier, the circulator ring can also be used as the booster ring bringing the ion energy up to 10-20 GeV. The ions are then injected and stored in the "Figure 8" storage ring housed in the same tunnel with the CR. "Figure-8" rings, including pre-booster, booster and storage ring, are used for the

Table 1: ELIC Top-Level Parameters

Parameter	**Units**	Electrons	Ions
Energy	GeV	5	50/100
Cooling	–	–	Yes
Luminosity	$cm^{-2}sec^{-1}$	$\mathbf{6 \times 10^{34}}$ / $\mathbf{1 \times 10^{35}}$	
N_{bunch}	ppb	1×10^{10}	1×10^{10}
f_c	MHz	1500	
I_{ave}	A	2.5	2.5
σ^*	μm	4.5	4.5
ε_n	μm	10	0.1
β^*	cm	2	1
σ_z	cm	0.1	1
ξ_e/ξ_i	–	0.2	0.01
$\Delta\nu_L$	–	–	0.09

ions for spin preservation and flexible manipulation of all species of interest. Specifically, "Figure-8" rings have zero spin tune, as a result of which intrinsic spin resonances and spin resonance-crossing are avoided. In the "Figure-8" storage ring, longitudinal polarization for all ion species at all energies is possible by introducing solenoids in the straight sections or horizontal dipoles in the arcs. Spin rotators around the interaction points would not be needed. For protons, up to 4 simultaneous interaction regions (IRs) can exist with longitudinal polarization. For D and ^{3}He up to 2 simultaneous IRs can exist with longitudinal spin. To ensure that the electron spin remains longitudinal at the IRs, a Wien filter in the injector or one Siberian snake (i.e. superconducting solenoid) is required for two IRs, and a Wien filter plus 2 Siberian snakes, or three Siberian snakes without the Wien filter for 4 IRs.

It has been determined that electron cooling of the ions is neccessary for luminosities above 10^{32} cm^{-2} sec^{-1}. To arrive at the parameters of Table 1, a series of evolutionary upgrades to the collider facility are envisioned. Thus, a first milestone may be at a luminosity of 10^{33} cm^{-2} sec^{-1}, which could be reached if the polarized electron injector current is 2.4 mA, assuming that we use the circulator ring configuration. A next milestone, at a luminosity near 10^{34} cm^{-2} sec^{-1}, may be reached by utilizing the extremely short, $\sim$1 cm, ion bunches resulting from electron cooling, which allow the use of "crab crossing" resulting in an increase of the collision frequency and reduction of parasitic collisions. With the use of the circulator ring, the polarized electron source is required to provide about 16 mA. The maximally attainable luminosity, corresponding to the parameters of Table 1 (at a polarized electron current of 25 mA), is obtained at the beam-beam limit of the ion ring, together with a maximum, equal to the rf frequency, collision frequency. Finally, a luminosity of 10^{35} cm^{-2} sec^{-1} or greater is feasible when the ion beam energy is 100 GeV or above.

2.C Integration with 25 GeV Electrons for Fixed-Target Experiments

The same electron accelerator that is used in the collider mode can also provide up to 25 GeV electrons for fixed target experiments for physics. This scheme requires the implementation of a 5-pass recirculator at $\sim$5 GeV per pass as in present CEBAF. It is a subject of further investigation whether the collider and fixed target modes could run simultaneously, or in alternating modes. The emittance growth due to synchrotron radiation in the CEBAF arcs at the higher energies has been addressed with a novel optics design for the higher arcs, resulting in a significant reduction in emittance growth. The beam spot sizes will thus be between 0.3-0.5 mm at 25 GeV.

2.D Accelerator physics and technology challenges

Although luminosities up to 10^{35} $cm^{-2}sec^{-1}$ look indeed promising at the proposed CEBAF-based electron-ion collider facility, and the integration with a 25 GeV fixed target program appears to be straightforward, there are a number of technical challenges that need to be resolved, before construction commences. These challenges include the demonstration of the high average current polarized electron source, high energy electron cooling of the ions, high current and high energy demonstration of energy recovery, and integration of the IR design with a real detector geometry.

A significant challenge for the realization of ELIC is the high charge per bunch and the high average current polarized electron source. The highest average current that has been demonstrated to date is approximately 1 mA at Jefferson Lab. The circulator ring concept appears promising in easing this requirement.

Cooling of the intense ion bunches contemplated here requires high electron beam current (hundreds of mA). Electron cooling at such high energy can only be conceived in the context of superconducting rf ERLs demonstrated and routinely used in the Jefferson Lab IR FEL. The BNL/BINP collaboration is seriously pursuing the design and prototyping of an ERL-based electron cooling device for RHIC. Jefferson Lab had initiated informal collaboration with BINP for over two years, and has recently formally joined a collaboration with BNL.

Energy recovery has been demonstrated reliably at the JLab IR FEL with average current up to 5 mA and energy up to 50 MeV. Establishing feasibility and high-efficiency operation of ERLs at an average current of order 100 mA, as required both for the electron cooling device and for the collider itself, and at an energy of several GeV, requires the experimental investigation and understanding of a number of issues. To directly address the feasibility of energy recovering a GeV-scale beam, one of the cornerstones of the ELIC proposal, we have proposed and are scheduled to execute an energy recovery experiment at CEBAF in March 2003. This experiment aims to investigate the ability for phase space management and to quantify beam quality degradation in GeV scale ERLs. The experimental investigation of high average current effects is planned at the JLab FEL Upgrade (10 mA), the Cornell/JLab ERL prototype, and the BNL electron cooling prototype (both 100 mA).

2.E Why at JLab

There are many reasons why Jefferson Lab is the optimum site for the future electron-ion collider, four of which are particularly compelling: First, the "green field" design of the ion complex, together with the ERL-based electron complex, allows for an unprecedented luminosity, and great flexibility in manipulating and maintaining the polarization for all ion species of interest. In addition, an optimum cooling design can result in very short ion bunches, which, in turn, make advanced concepts of the interaction region design applicable and can result in maximum attainable collision frequency and therefore luminosity. Second, the interaction regions are highly simplified allowing for a wide energy variability of both beams and all ion species, without sacrificing the high degree of polarization. Third, Jefferson Lab has pioneered the key technologies required for a high luminosity electron-ion collider: large scale superconducting recirculating and energy recovering linacs (required for both the collider and the electron cooling process), and high average current, high polarization electron sources. Fourth, an electron-ion collider based at CEBAF can be fully integrated with external beams for a fixed-target program, largely enhancing and complementing the physics scope of the facility.