October 13, 2018

Technical core of the proposal "High intensity CBETA tests for electron cooling"

This proposal was jointly submitted by BNL, Cornell and JLAB to the Department of Energy in January 2018, in response to a Funding Opportunity Announcement focused on Electron-Ion Collider research and development. This document, which contains only the technical core of the proposal, is public.

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1.0 Introduction

The unique foundation for the proposed work is the Cornell-BNL ERL Test Accelerator, CBETA, the world's first multi-turn SRF ERL. This proposal highly leverages previous funding by the National Science Foundation (NSF) for existing Cornell University equipment, and single-shot funding by New York State Energy Research and Development Agency (NYSERDA) for the construction of CBETA.

The major challenge in reaching luminosities of $L=10^{34}cm^{-2}s^{-1}$ and higher in an electron-ion collider (EIC) is the realization of strong hadron cooling with electron beams. The most efficient way of producing the strong CW electron beams needed for cooling is through the use of energy recovery linac (ERL) technology. However, the state of the art in ERL technology falls short by a factor of 10 to 100 in intensity, compared to what is needed for strong hadron cooling. We propose to address the necessary development of ERL technology by studying the accelerator physics and technological issues using the CBETA facility, which will begin to be available for experimental beam tests in 2019. The community panel on R&D priorities for EIC recommended that such studies to be performed with highest priority.

Construction of CBETA, an accelerator capable of 4-pass ERL operation, will be completed in 2019. Commissioning to achieve the relatively modest Key Performance Parameters shown in Table 1 will continue until April 2020 [1]. This proposal covers a program of CBETA work over the two-year period from October 2018 to October 2020, with the central goal of understanding and increasing the average current and single bunch charge limits for the different electron-cooling concepts for EICs. Initially the program focuses on simulation studies, beam diagnostics development, and Low Level RF (LLRF), evolving towards enhanced commissioning and extraction design during the second year.

Table 1: Key Performance Parameters (KPP) defined in the construction contract with NYSERDA, and ultimate anticipated design parameters.

Parameter	Unit	KPP	Design
Electron beam energy	MeV		150
Electron bunch charge	nC		0.123
Electron source current	mA	1	40
Bunch repetition rate (source)	MHz		325
RF frequency	MHz	1300	1300
Injector energy	MeV		6
RF operation mode			CW
Number of ERL passes		1	4
Energy aperture of arc		2	4

Limits for the average current and the bunch charge in CBETA are expected to be set by:

a. Higher-Order Mode (HOM) absorber heating in the Main Linac Cryomodule (MLC).
b. Beam-Breakup Instability (BBU).
c. Halo losses and associated equipment damage and radiation exposure.
d. Emittance degradation for high bunch charges.
e. LLRF control issues with a very high ratio of circulating beam power to installed RF power.

These same processes will limit the current and bunch charge in any ERL-driven electron cooler for the EIC. CBETA is therefore an excellent – and unique – test-bed accelerator.

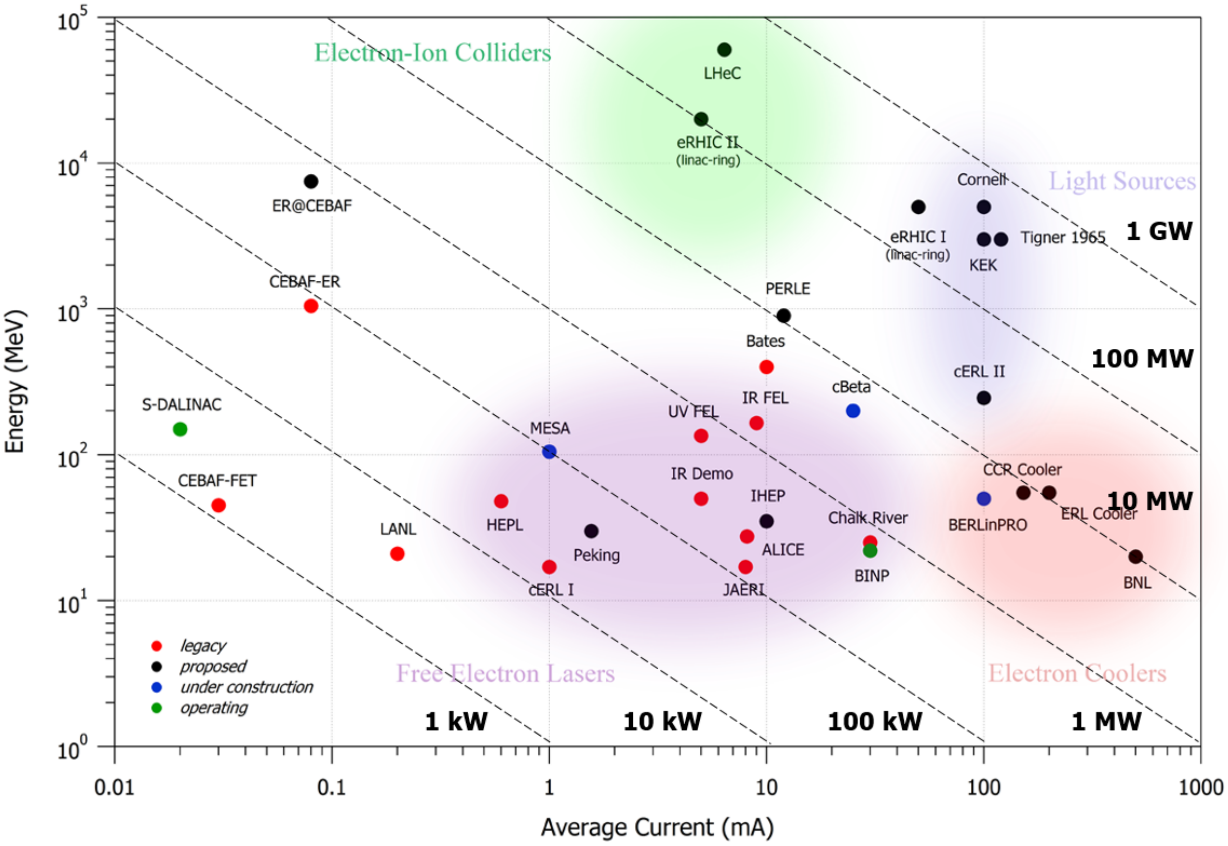
CBETA is designed for a 150 MeV electron beam with a bunch repetition rate of 1.3 GHz. The maximum average current is anticipated to be 40 mA, based on:

1. an extrapolation of HOM heating measurements obtained by sending an electron beam through a single MLC cavity, and
2. simulating the BBU instability under beam loading in the 6 cavities of the MLC, assuming realistic errors.

Further CBETA studies are needed, including:

a. HOM heating of other beamline components.
b. Simulations of longitudinal and the quadrupole BBU.
c. Beam loss due Touschek and rest-gas scattering.
d. Halo losses from space charge forces and field emission.
e. Coherent Synchrotron Radiation (CSR).
f. Microbunching.
g. Nonlinear dynamics.
h. RF control of the SRF cavities with strong reactive beam loading.

Figure 1: The ERL landscape, showing the location of CBETA in the trend towards higher average beam power. The single bunch charge is also an important parameter in EIC cooler applications. (Graphic by courtesy of C. Tennant).

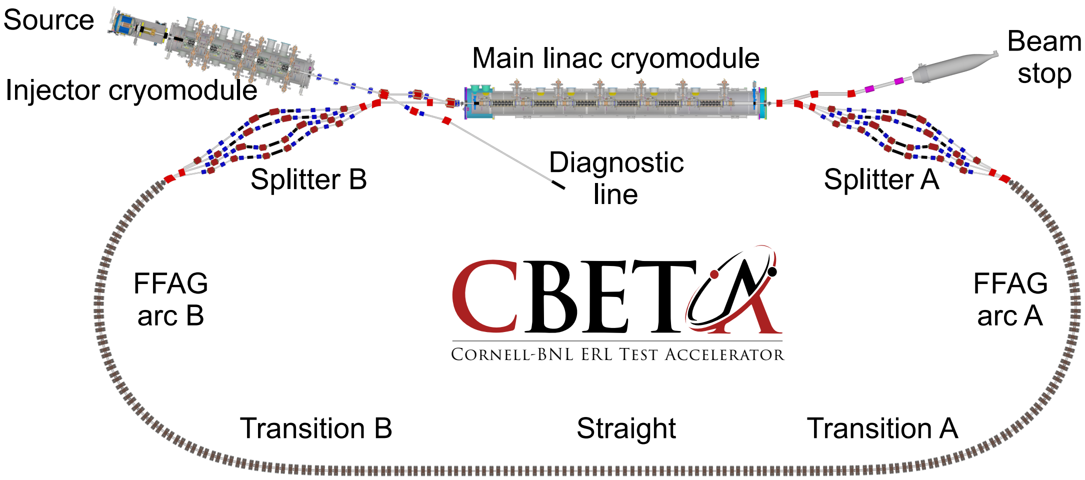


Interest in ERL technology is becoming widespread in both development and design, as shown by the ERL landscape plot shown in Figure 1. Other state-of-the-art ERLs that are also currently in construction, at the Helmholtz Zentrum Berlin (BerlinPRO) and in Mainz (MESA), will begin commissioning significantly after CBETA. It is likely that a collaboration between Orsay and CERN will eventually take the PERLE@Orsay design into construction, although it is currently only at the proposal stage.

Large-scale ERLs are being considered for high-energy physics applications (such as the LHeC), for nuclear physics (eRHIC) [2], for X-ray light sources, and for bunched-beam electron cooling, as in eRHIC and the JLEIC. The research program proposed here will benefit all of these ERLs. It will also help high-current conventional linear accelerators (such as PIP-II and ESS) to understand their sources of particle loss and their phase-space dynamics.

A unique feature of CBETA is the use of very strong focusing optics in a return arc to enable a single beam pipe to transfer electrons with a broad range of energies – 42, 78, 114, and 150 MeV – from the exit of the MLC back to its entrance for another acceleration (or deceleration) pass. This is illustrated in Figure 2, which shows the racetrack layout created by connecting splitters A and B on either end of the MLC to two fixed field alternating gradient (FFAG) arcs A and B, thence to a straight section on the opposite side of the ring. The return beam line uses Halbach type permanent magnet quadrupoles in a non-scaling fixed field alternating gradient configuration that adiabatically matches the arcs to the straight section, parallel to the linac. Electron energy recovery and acceleration is controlled by adjusting the time-of-flight and the R_{56} matrix element (which measures the rate of change of path length with respect to the relative momentum deviation), using the electromagnets in splitters A and B.

Figure 2: CBETA installation in experimental hall L0E at the Cornell Laboratory for Accelerator StudieS and Education. The DC gun and source sends electrons through the 6 MeV injector cryomodule into the main linac cryomodule or the beam diagnostics line. After passing through the MLC on each of 4 passes the beam enters the return loop for further acceleration or energy recovery, eventually ending in the beam stop.



The scaling fixed field alternating gradient principle, which was developed during the 1950's in the MURA (Midwest University Research Association) group and independently in Russia and Japan [3, 4, 5], allows acceleration with extremely large momentum dynamical aperture, zero chromaticity, fixed horizontal and vertical tunes. Non-scaling fixed field alternating gradient optics allow for the magnets to be reduced in size by an order of magnitude, as in CBETA [6, 7]. The Electron Model for Multiple Applications (EMMA), built in Daresbury Laboratory in the UK, was the first non-scaling fixed field accelerator [8]. More recently a momentum acceptance aperture of ± 60% was achieved in a non-scaling fixed field alternating gradient beam line experiment at the BNL ATF [9].

CBETA uses sophisticated components that were developed, constructed, and commissioned at Cornell under NSF funding. These pre-existing components, shown in Figure 2, include the world's highest current (75 mA) DC photocathode gun, the minimal emittance 6 MeV SRF injector linac [10, 11], the 10 m long SRF MLC for high-current continuous wave (CW) beams, an ERL merger between injector and the MLC, and a phase-space diagnostics line with a high-power beam stop. Besides being an ideal venue for accelerator physics studies, CBETA will also produce beam parameters potentially relevant for nuclear physics experiments that need medium-energy, high-current beams [12] and for a compact hard-X-ray source based on Compton back scattering [13].

1.1 Collaborative Structure

The program will be performed in a collaboration of three peer institutions: Brookhaven National Laboratory (BNL), Cornell University (CU), and Jefferson Laboratory (JLab). The team members will work largely at their home institutions, but will send a significant workforce to Cornell during times of CBETA commissioning and operation.

The BNL-CU collaboration that planned, designed, and is now building CBETA was formed in the summer of 2014, wrote a white paper in December 2014, began receiving construction funding from NYSERDA in November 2016, and will use this grant to commission to Key Performance Parameters by spring 2020. The BNL-CU collaboration functions by holding weekly internet meetings of the full team, by regular and as-needed phone meetings of subgroups, by biannual collaboration meetings, and by a significant amount of travel. We will continue and develop these modes of exchange – of simulation results, component design, operation plans, and labor sharing – when JLab members join the team.

There is considerable joint interest and coordinated activity on common topics between the three labs, following from the tight collaboration that is already in place between BNL and CU, for the construction and initial commissioning of CBETA. Nonetheless, the three labs have leading interests.

BNL will simulate strong electron cooling in eRHIC for parameters that can be achieved in CBETA, will participate in beam dynamics simulations, will send people to CBETA commissioning runs, and will work on extraction designs. BNL will further analyze how CBETA intensities can be increased towards the values required for eRHIC cooling.

Cornell University, where CBETA is located, is responsible for maintaining and operating the facility. CU scientists will put together the core operations team, will simulate beam dynamics and instabilities, halo losses and collimation, and will implement new diagnostics components into the accelerator and the control system. CU engineers will implement LLRF and microphonic suppression and will push the DC gun current and bunch charge as high as permitted by radiation limits. Cornell will simulate CBETA operation at high currents and large bunch charges, and will push CBETA commissioning to the highest possible currents.

JLab will design and develop high-current and beam-halo diagnostics. JLab personnel will participate in beam dynamics simulations, and in CBETA commissioning runs. JLab will simulate and analyze magnetized beam transport through CBETA. No hardware development for magnetized beams is included in this proposal, as the Cornell DC photo-emitter gun cannot be replaced in the timeframe of this proposal. However, a follow-up proposal may address such hardware installation and beam operation. The incoherent electron cooling proposed for JLab requires very large currents at 100 MeV. CBETA runs at this reduced energy are therefore proposed, while pushing the beam current to the highest possible values.

2.0 Project Objectives

The research program builds on the technical expertise and depth of the accelerator teams at BNL, Cornell, and JLab.

BNL brings expertise in beam simulation and accelerator operation, including very strong focusing permanent magnet optics. BNL also has significant experience with high charge and high current electron guns, SRF cryomodules, HOM simulation, microphonic control and remediation, and precision LLRF.

Cornell brings expertise in design, simulation, construction, and operation of electron guns, SRF cryomodules, and ERLs.

JLab brings essential expertise in the operation and simulation of DC electron guns, magnetized beams, and operations of the JLab IR Upgrade Free Electron Laser (FEL).

We propose to work on five main tasks:

1) Simulations
    a. Develop halo simulations to compare loss mechanisms with experiments.
    b. Simulate bunch-charge limitations for CBETA
    c. Design a chicane and simulate beam studies of the microbunching instability.
    d. Simulate a CBETA magnetized gun, possibly with a round-to-flat transformer to allow transport through the FFAG lattice.
2) Diagnostic development
    a. Develop halo diagnostics for high current and high bunch-charge operations.
    b. Develop coherent synchrotron radiation and microbunching diagnostics.
    c. Develop time-resolved diagnostics for post-mortem analysis of beam loss mechanisms.
3) Low Level RF
    a. Construct a model of the RF system to simulate the behavior of noise and transient behavior over a range of beam currents.
    b. Optimize the loop gains and frequency response to provide stable operation at the highest possible CW and pulsed currents.
    c. Test the RF control system on the MLC using pulsed and CW beams to benchmark the simulations. Re-optimize as needed to maintain stability.
4) Commissioning to high-intensity
    a. Push to the highest possible current in 4-pass ER mode with an energy of 150 MeV.
    b. Optimize LLRF controls for stable high current operation with headroom for beam noise.
    c. Operate with increased single bunch charge, pushing toward 1 nC per bunch.
    d. Find where halo is lost with high (1 nC) single bunch intensities.
5) Extraction design
    a. Design one or more 150 MeV beam-extraction lines.
    b. Drive the high-energy beam (alone) to large orbit oscillations in beam-extraction studies.
    c. Demonstrate 110 MeV operation in 3-pass ER mode for later JLEIC cooling studies.
    d. Push the beam current to the largest possible values (50 mA?) in 3-pass ER mode.

3.0 Proposed Research and Methods

This section describes the five main topics of proposed work in more detail. Section 4 discusses the "Broader Impacts of the Proposed Work", while the milestones associated with the topical goals are described in Section 5, "Timetable of Activities".

3.1 Simulations

Future ERLs and linacs require high currents, including those in eRHIC, JLEIC, LHeC, PIP-II and ESS. However, beam instabilities in the high-intensity regime are largely unexplored. This topic focuses on the simulation of CBETA current limits, with the general goal of using simulations to design experiments to study phase-space evolution, instabilities, and particle-loss mechanisms when beam interactions with the environment dominate.

The current in CBETA will be limited by the interactions of the beams with itself and with its environment, characterized by impedances that influence the phase-space dynamics of the charge distribution and drive instabilities. Both types of interaction cause particle loss and increase the emittance, and both will be studied. BBU simulations of threshold currents and potential optical remediation to increase thresholds will be simulated and studied as part of William Lou's PhD thesis research.

Particle-loss mechanisms will be simulated, including residual gas scattering, Touschek scattering, and dark current effects. Simulations will include a study of the impact of each loss mechanism on characteristics observable in available beam diagnostics. Coherent synchrotron radiation simulations will include microbunching, the study of beam emittance and beam-size increases, and particle loss rates.

Beam loss

Goal: Develop halo-simulations to compare loss mechanisms, including ghost pulses from the laser, field emission at the cathode and in cavities, and Touschek (residual gas) scattering.

It is of primary importance to diagnose and control unintended light that is incident on the photoinjector cathode. Stray light at the level of one part in a thousand can come from a single scratched, dirty, or otherwise poorly chosen optical element in the laser path, limiting CBETA performance through electron beam losses at high currents. This effect is primarily controlled by restricting the size of the active area of the photocathode to be only slightly larger than the laser spot, so that stray light does not directly lead to photoexcited electrons. However, single or multiple reflections in the surrounding vacuum chamber or nearby optical elements make it possible for light to hit even this small active area, at an unintended time. Such "ghost" pulses excite electrons, which are then accelerated.

Ghost pulses may be accelerated through the rest of the machine, but are likely to be lost due to an energy or betatron mismatch within the lattice. In addition to photo-emitted ghost pulses, electrons that are field-emitted from the cathode or from the RF cavities can similarly lead to beam losses after acceleration. Studying these effects and estimating the location and amount of beam loss is straightforward, using an end-to-end model of the accelerator and a detailed model of the laser flight path.

Residual gas interactions

A second mechanism for beam loss is electron interactions with residual gas molecules, either through elastic scattering or bremsstrahlung. Elastic scattering changes the trajectory of the electrons and excites betatron oscillations. If the scattering angle is larger than an angle aperture set by a collimator, the electron is lost transversely at the collimator [14, 15]. In the process of bremsstrahlung, an electron scattering off a gas nucleus emits a photon and suffers an abrupt energy change. If the energy change is too large, the electron is lost longitudinally.

Analytical estimates have been made for electron beam losses through elastic scattering and bremsstrahlung, as a function of the transverse or longitudinal aperture. Different gas species are assumed for initial commissioning and for later routine operations. If the limiting transverse aperture is at the last linac pass, the analytical estimates show that in the initial operation stage, the beam loss due to elastic scattering ranges from 2.16 pA (2.5 cm aperture) to 13.4 pA (1 cm aperture) and the beam loss due to bremsstrahlung ranges from 0.22 pA (0.1 MeV energy aperture) to 0.14 pA (1 MeV energy aperture). At the stable operation stage, the beam loss due to both processes reduces by a factor of 2. Further simulation work will focus on more accurate estimates achieved through element-by-element simulation with detailed lattice design and environment parameters.

High-bunch-charge

Goal: Simulate bunch-charge limits for CBETA, including coherent synchrotron radiation, microbunching, longitudinal space charge, and wakes.

Nearly all ERLs built and operated so far have been used to drive an FEL by leveraging the ability to run high repetition rates in SRF cavities to generate high beam powers while operating with modest bunch charges. Electron coolers, on the other hand, require aggressive bunch charges of several nanoCoulombs. Investigating the high-charge limits of CBETA operation is therefore vital to bridging the gap between the bunch charges that have successfully run in past ERLs (of order 0.1 nC) and those necessary for coolers (of order 1.0 nC). Experience at the Jefferson Laboratory ERL-driven FELs (the IR Demo, IR Upgrade and UV) provided ample opportunity to observe, measure and diagnose a variety of collective effects at bunch charges of around 0.1 nC. With an order of magnitude increase required for electron coolers, one of the primary challenges is to understand and control collective effects, to maintain and deliver beam of the quality needed at the cooling channel. The three effects that pose the biggest challenge are CSR, space charge and the microbunching instability.

CBETA is ideally suited to investigate these issues by virtue of its multi-turn capability – a feature no other SRF ERL currently possesses (or will possess in a reasonable time frame). For example, the evolution of CSR can be studied over many turns-worth of bending, and the multiple passes provide long transport distances over which space charge can accumulate. And finally, the presence of both CSR and space charge, together with a small energy spread within the bunch, provides the potential to seed the microbunching instability.

Other important beam dynamical processes, such as Touschek scattering, halo, intrabeam scattering and other loss mechanisms are discussed elsewhere. Here we consider only the ways in which the beam interacts with itself.

Coherent synchrotron radiation

Coherent synchrotron radiation poses a significant challenge for high brightness accelerator beams. When a bunch travels along a curved orbit, fields radiated from the tail of the bunch can overtake and interact with the head. Because the interaction takes place in a dispersive region, the energy redistribution is correlated with the transverse positions in the bend plane, potentially leading to projected emittance growth. Further, because the tail loses energy while the head gains energy, CSR leads to a distortion of the longitudinal phase space. This is particularly problematic for cooler applications where the energy spread must remain very small.

CSR-induced transverse emittance growth can be managed with careful lattice design [16]. The CSR wake-induced distortion in the longitudinal plane, however, is more difficult to ameliorate. We propose to simulate and understand how these effects scale with bunch charge and with the number of recirculations, and to understand how lattice adjustments can be used to mitigate them. This will provide much needed guidance in cooler lattice design.

Space charge

Recent work has shown that space charge is not particularly detrimental during the traversal of a single, generic recirculation arc, even at single bunch charges of several nanoCoulombs [17]. However, space charge may become problematic after multiple recirculations, because it is an integrated effect. Once again, CBETA offers an attractive test bed for understanding the degradation of beam quality due to space charge, as it is the only SRF ERL with multi-turn capability. We propose to study and understand how much space charge can be tolerated over multiple recirculations.

Microbunching instability

In the microbunching mechanism an initial density modulation, either from shot noise or from the drive laser, is converted to energy modulations through short-range wakefields such as space charge and CSR. The energy modulations are then transformed back to density modulations through the momentum compaction (R_{56}) of the lattice. Danger arises when a positive feedback loop is formed, and the initial modulations are enhanced. This phenomenon has been studied extensively, both theoretically and experimentally, in bunch compressor chicanes. However, only recently has there been a concerted effort to study the microbunching instability in recirculating arcs [18].

ERLs are particularly susceptible to microbunching, in part because of the native momentum compaction of the lattice (in arcs, splitters, chicanes, et cetera). Low energy injected beam is influenced by space charge forces. Multi-pass energy recovery with substantial bending ensures that ERLs are subject to CSR effects that – unlike space charge – do not diminish at high energy. CSR can drive the microbunching instability; in addition to its potential for emittance and energy spread growth.

Simulating the microbunching instability in the time-domain (via particle tracking) presents multiple challenges. The initial density modulation needs to be small enough to remain in the linear regime but large enough to overcome numerical artifacts. This requires tracking a large number of particles. Due to the computational burden, it becomes difficult to exercise parametric studies and/or model an entire accelerator complex. On the other hand, a semi-analytical Vlasov solver that works in the frequency-domain and models relevant collective effects such as LSC, CSR and linac geometric effects using analytic impedance expressions has led to insights on lattice constraints in controlling the microbunching instability [19]. The development of a fast Vlasov-solver has been an invaluable asset in the design and development of arc lattices.

Preliminary estimates using the Vlasov code show a modest microbunching gain for a single CBETA pass [20]. However, the gain will grow exponentially with each additional pass, up to a maximum of 4 passes. Therefore very high bunch charges may not be necessary to observe and measure the microbunching instability. Regardless of the bunch charge, a more thorough analysis of the instability is required.

Magnetized beam-transport simulation

One of the most critical features of JLEIC is the luminosity, which requires cooling the ion beams. In the proposed design, this is achieved when an electron beam and ion beam of the same average velocity but different temperatures co-propagate. The cooling rate such an interaction achieves can be improved by approximately two orders of magnitude if the interaction occurs within an appropriate solenoid field [21]. The design of the Circulating Cooling Ring (CCR), consequently, intends for the cooling to occur in four long solenoids. One difficulty in effecting electron cooling is the fringe field the electron beam encounters upon entering a long solenoid. Derbenev [22] suggested that the detrimental impact of the fringe field on the cooling rate is removed if the electron beam is created in a similar field; this is called a magnetized electron beam.

While magnetized electron beams have been studied at the Fermilab Photoinjector Laboratory [23, 24, 25], none are a CW beam of high average current that is required for the CCR, which is supplied by a magnetized electron beam ERL. Currently, magnetized electron beams are being studied at JLab. While the experiments and simulations contribute to the understanding of magnetized beam dynamics and demonstrate an agreement between simulation and measurements, the necessary CW, high average current beam has not been demonstrated [26]. The opportunity to produce a magnetized electron beam fulfilling these criteria would be provided by installing a DC high voltage photogun and solenoid (such as the magnetized gun currently in use for the JLab beam experiments) at the beginning of the CBETA injector. The magnetized beam could then be passed through the injector and the merger.

Such an undertaking requires thorough simulation work to ensure that the beam will travel through the beamline while remaining magnetized, as well as determining the proper scope of the experiment. The simulation work can be separated into three successive phases: the injector, the merger, and the FFAG arcs. If simulations fail to successfully pass a magnetized beam through a given section, the design of that section will be altered until a magnetized beam is successfully transported or until the design features that prevent a transport are clearly identified. The experimental desire would be to measure the magnetization of the beam, which requires additional space.

The main obstacle to simulating a magnetized injector is the limitation of the existing construction. Simulations that have already been performed demonstrate a magnetized electron beam passing through a typical ERL injector, modeled on the JLab FEL. The difficulty comes in the form of magnet strengths, cavity voltage limits, and physical room in the beamline for either additional magnets or diagnostics, especially before the merger.

If an experimental set-up can be created that allows for a magnetized beam to retain its characteristics while passing through the merger, this would allow for thorough beam characterization to be performed on the diagnostic beamline in the existing CBETA layout. The challenge in this section is that the merger is not axially symmetric – a known source of degradation for magnetized beams [27]. This is first challenge likely to degrade the magnetization of the beam. Even if that degradation were unavoidable, an opportunity to quantify the degradation experienced in relation to the axial asymmetry of the beamline would provide valuable information on the beam dynamics of magnetized beams. A comparison of flat beam properties will be made for transporting a magnetized beam through the merger, performing a flat beam transform and transporting a flat beam through the merger.

After successfully designing a merger section that makes the required net bend and retains beam magnetization, the beam will be tracked through the main MLC and at least one FFAG arc. However, as beam magnetization is unlikely to be preserved without significant modification, the goal of this phase is to identify the sources of magnetization degradation and, if possible, determine requirements for an FFAG design that will retain beam magnetization. A full re-design is not the goal, nor is it possible in the proposed timeline. Simulations for the evolution of a flat beam through the MLC and FFAG arc will be performed.

The total anticipated time spent on the entire magnetized beam simulation design is 12 weeks – 4 weeks on each section – during FY19, in three successive phases:

1. Modify the existing CBETA injector until a magnetized beam is successfully transported in simulation.
2. Simulate the magnetized beam from the altered injector design through the merger.
3. Simulate the magnetized beam from the altered merger design through the MLC and at least one of the FFAG arcs.

Nonlinear dynamics

Maintaining a high-quality longitudinal distribution is important for avoiding particle loss and maintaining energy recovery efficiency. The longitudinal dynamics are controlled by the RF force, by the dependence of time-of-flight on energy created by the return loop, and by collective effects such as wake fields and coherent synchrotron radiation. The fixed field alternating gradient return arc has a significant second-order contribution to time-of-flight. Further, the compact nature of the splitter lines requires them to have significant second-order terms in order to match the linac to the return arc. Very short magnets also contribute significant nonlinear terms due to magnet end effects.

We will compute time-of-flight as a function of energy including nonlinear and magnet end effects. Combining this with the linac, we will produce a model for the longitudinal dynamics of the full machine, and use this model to study the impact of the RF phase choices on the longitudinal dynamics.

As the current increases during enhanced commissioning, coherent synchrotron radiation and wakefields modify the longitudinal dynamics of the system. These effects will be included in the longitudinal modeling, to determine how best to adjust the RF phasing scheme as a function of current, and to determine whether they limit the current. If so, we will explore lattice design changes that could raise the current limit. For instance, nonlinear magnets could be added to the splitters to correct higher order optical terms.

The very high chromaticity of CBETA may have an impact on transverse instabilities. This will also be studied, for comparison with beam studies experiments.

3.2 Diagnostic development

Both setup and benchmarking of an accelerator require comprehensive diagnostics that allow the beam physicists to set up the machine and to compare the beam behavior with simulations. In a high current ERL with a bright beam, several important beam properties cannot be measured with typical accelerator diagnostics (viewers, beam position monitors, scanning wires, et cetera.). This effort will develop and install diagnostics that are uniquely useful to a high current ERL, in three topical areas.

Halo diagnostics

Though some models allow halo predictions, they are usually not effective in predicting the halo for any given machine. One must therefore measure halo as carefully as possible. Conventional diagnostics typically do not have the dynamic range or noise floor to see current densities that are four to six orders of magnitude below the core beam density. But, since this halo has a much larger area, it might have a net current of microamperes, which is much more than can be lost anywhere in the accelerator.

A High Dynamic Range (HDR) transverse beam profile monitor was developed for both the Jefferson Lab FEL and for the running of the Dark Light experiment at JLab FEL [28]. A version of this device is proposed to image the tails of the core beam by having it pass through a hole in the center of the Optical Transition Radiation (OTR) and only image the halo. This system will also be evaluated for use of a YAG screen with or without a hole. A stepped fork in the transverse plane has been successfully used at the JLab FEL, in an arrangement that allows a variable-size aperture to be used with a CW beam. This device also allows the core of the beam to pass unimpeded, while imaging the halo. The forks can be either phosphor coated or direct OTR. The HDR beam viewers, which come with a telescope to remove the video camera from the plane of the beam path, allow the beam loss sources to be located.

CSR and microbunching diagnostics

ERL beams start with very bright beams, which are very susceptible to microbunching. The relatively high charge also leads to an enhancement in coherent synchrotron radiation that can lead to a growth in both the energy spread and transverse emittance. Standard emittance measurements may be used to get some idea of the emittance growth and BPMs at a dispersive location can characterize the energy loss due to CSR [29]. The best way to see microbunching is to look for the coherent radiation enhancement at short wavelengths. A spectrometer can be used to characterize the short wavelength fall-off in the coherent radiation for comparison with the models.

The CSR effects can be imaged CW with synchrotron light, the effect is seen and the electron beam begins to separate out to distinct filaments. Passing the signal into a visible/near IR spectrometer can quantize the effect. These devices use a tangential port and telescope for a video imaging camera & a fiber optic collection system that diverts the CSR signal to a small spectrometer, Ocean Optics are an example [30].

Time-resolved beam-loss diagnostics for machine protection post-mortem analysis

Machine protection systems must prevent damage from the extremely high power densities in the core beam. Instabilities can cause the beam to trip off when losses suddenly rise. The problem of determining the cause of the beam loss can be aided by “first fault” capability in the machine protection system logic chain, but it can be determined even more sensitively by monitoring some key parameters with sampling scopes and triggering on a loss event. One can then look back to the time before the trip to see what led to the event.

This effort by JLab, in collaboration with a Cornell graduate student, will provide expertise and engineering support for the development of this beam loss monitor. A beam loss monitoring system was developed during operation of the JLab FEL that allowed for archiving the last faults, using 12 channel VME boards (x4 for 48 channels) that gave warning alarms prior to faults and captured the sequence of beam loss pattern around the machine. An updated copy of this system is proposed. Based on Photo-Multiplier Tubes (PMT), the integration constant is fixed and controlling the high voltage sets the gain. The system is periodically calibrated with known beam conditions, to counteract PMT aging issues.

3.3 Low Level RF

RF Stability in the Injector Cryomodule (ICM) and the Main Linac Cryomodule (MLC)

ERL operation is similar to electron time of flight spectrometers [31]; consequently stability of electric fields in the SRF cavities is an important issue. Amplitude and phase stabilities of better than $1\text{x}10^{-4}$ and 0.1° have been targeted for CBETA operations in the presence of very high beam loading. This calls for the development of advanced field control and fast detuning compensation algorithms to be incorporated in its low level RF control system. The major factors affecting stability are vibrations of the SRF cavities, beam loading and noise coming from the RF power sources.

Vibrations result in transient deformations of the cavity walls leading to microphonics detuning. Strong microphonics place large transient RF power demands in order to maintain stable accelerating field in the cavities. Both the injector and the main linac cryomodules incorporate fast tuners based on piezo-electric actuators to compensate for transient detuning. Microphonics compensation algorithms monitor cavity detuning and vibration signals from sensor piezos to calculate actuation signals used by the fast tuner. Feedback control based on two ideas – digital filter banks [32] and Least Mean Square techniques [33] – are under development and will be used in CBETA operation to compensate for detuning and significantly reduce peak power demands, especially on the MLC cavities.

Large beam currents in both pulsed and CW operation will induce ripples in the accelerating fields, due to high beam loading. Detailed simulations will be performed incorporating these effects, including microphonics and noise from various sources, in order to understand the behavior of the cavity field and to optimize the LLRF for maximum stability.

“Perfect” energy recovery would be ideal but is not always possible [34]. Imperfect energy recovery drives the need for excessive RF power or the need to vary the tuner as a function of beam current. Additionally, there is an issue of beam “slippage” between the injected beam at about 5 MeV, and the decelerated beamlets at more than 40 MeV.

Lastly there is the issue of path length drift. Path lengths changes as small as 0.6 mm are probably sufficient to exceed the available RF power limitations. Detailed simulations will be performed to better understand the effect of imperfect energy recovery that can be calculated as a function of beam current and cavity location in the linac. Analysis will be performed as to the need for, and the design of, a feedback system that would stabilize the path length to an acceptable level.

Tune up beam is generally a macro pulsed beam of some tens of microseconds long (necessary for diagnostics such as beam position monitors) at some 10 Hz (in order to eliminate the risk of burn through) with a micro pulse repetition rate of 42 MHz or about 2.6 mA of peak current. RF loading due to this beam is further complicated by the concept of interceptive beam diagnostics. Thus if one were to put a viewer in the beam line just after the last accelerating pass, then the linac will have 4 times the tune beam current in the linac. The concept of beam loading under such conditions also needs to be simulated and may require reduction in the micropulse repetition rate of 42 MHz, or implementation of a feedforward beam loading compensation algorithm in the LLRF.

Ramping the DC current up to the maximum value will present important problems with beam scraping and halo, as well as with beam loading. The approach used at JLab in their moderate current ERL was to first tune with a pulsed beam of 2 Hz 250 us beam, then to change the pulse repetition rate from 2 Hz to 60 Hz, and finally to increase the pulse width until achieving good transport without tripping the beam loss monitor system. Additionally, JLab had a vernier control on the micro pulse repetition rate. For example if one had a 42 MHz bunch repetition rate with a maximum bunch repetition rate of 1300 MHz one would put one pulse every 23.8 ns. One can increase the current by adding another 770 ps pulse every 23.8 ns, ramping up to full current in 30 steps. The first activity is to review the drive laser system to determine if this approach can be implemented.

The project will develop a beam mode table that defines all of the required time structures and bunch charge parameters. This is necessary to define the machine protection system and to understand the RF drive requirements.

3.4 Commissioning to high-intensity

Commissioning to the highest intensities requires a variety of skill sets spread across many people. Some of those people are naturally resident at Cornell: for example those with specialized support roles for cryogenics, vacuum, injector, ion mitigation, and controls. In other cases, expert collaborators from BNL and JLab will be effective in the control room, in data analysis, and in importing hardware such as beam diagnostics. External collaborators from BNL and JLab need travel support, especially in recognition of the need to avoid inefficient short-term participants.

BNL personnel performed much of the lattice design work for CBETA; therefore their participation in commission and operations of CBETA is essential. This is particularly important when machine configurations change as required to achieve the proposed goals.

Experience at Jefferson Lab has shown that three classes of activity are vital for successful high-power ERL operation: operations planning, RF drive analysis on optimization, and power flow management. The RF drive analysis was discussed in the last section. Jefferson Lab will carry out studies necessary to define operational procedures and characterize the power flow management.

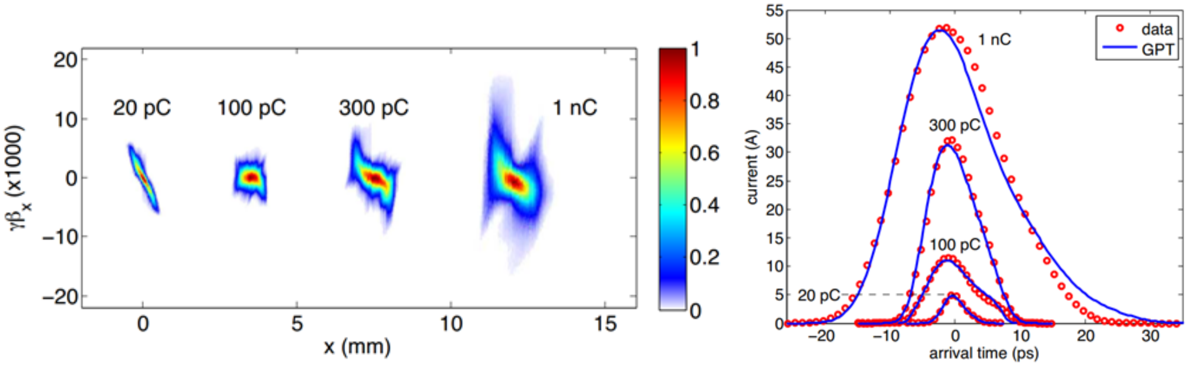
Integrated planning of high-power operations is needed to insure that project goals are consistent with the installed machine, to reduce risk, and to ensure safe operation. The team will – at the outset – develop a set of operational goals that can be met within the operational envelope using existing hardware and generate a beam operations plan that will serve as a framework supporting activities in pursuit of these goals. The information provided by subsequent activities will be codified in test plans and procedures on which actual beam operations will be based.

At high beam powers, beam halo and synchrotron radiation (primarily coherent synchrotron radiation) can result in substantial power deposition. Control of these effects is critical to successful operation of any nonequilbrium system, and the effort involved consumes much – or even most – of the beam time devoted to high power operation. Before high power operation commences, an assessment of halo sensitivities [35], CSR effects [36], and associated operational implications [37] must be performed. Collimation may be required and – given the multivariable couplings involved in FFAG transport – care must be taken in the development of the tuning algorithms used to mitigate halo losses.

Operating with a 1 nC bunch charge at a reduced repetition rate

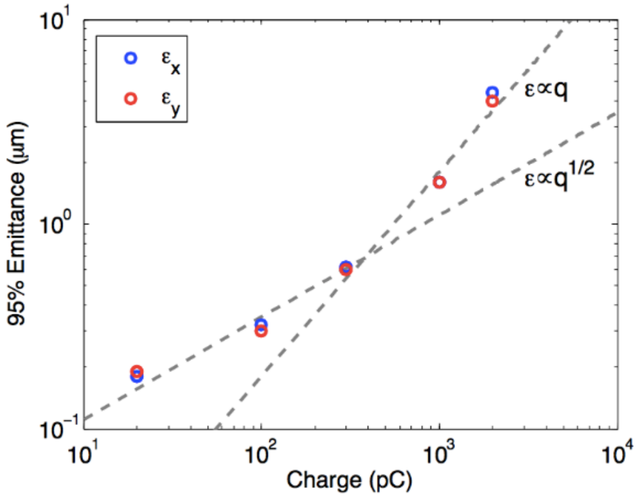
Our strategy in pushing for high average current includes first demonstrating that we can transport a high bunch charge beam (of about 1 nC) around CBETA, with and without energy recovery. A reduced repetition rate of high charge bunches will serve as a perfect test of beam halo diagnostics prior to pushing for higher average currents, in addition to being directly relevant to electron cooling.

Figure 3: Left: Longitudinal current profiles for corresponding bunch charges. Right: Horizontal phase spaces for bunch charges from 0.02 nC to 1 nC.



Previously, the Cornell photoinjector has produced low emittance bunches with charges up to 2 nC per bunch at about 9.5 MeV. Figure 3 shows the measured (horizontal) phase spaces and longitudinal current profiles for bunch charges up to the desired 1 nC targeted in this proposal. Bunches with a charge of 2 nC tended to have significantly larger tail than 1 nC bunches. The injector settings for these measurements were established using detailed multiobjective genetic algorithm optimizations of the 3D space charge dynamics in the injector using the space charge code General Particle Tracer (GPT) [38, 39]. All electromagnetic fields in the injector were modeled using realistic field maps, and all relevant laser and injector parameters (such as laser spot size, longitudinal shape, and magnet and cavity settings) were varied during the optimization. Figure 4 shows the best emittances measured over a wide range of bunch charge Q on a logarithmic scale. Low bunch charges (Q) the trend.

Figure 4: Trend of emittance versus bunch charge out of the Cornell photoinjector.



The emittance scales like $Q^{1/2}$ at low charges, and roughly linear with Q at higher charges. A charge of about Q = 0.3 nC separates the two regimes. The final emittance is dominated by the intrinsic emittance of the photocathode below 300 pC, with noticeable contributions from optical aberrations (mostly emittance compensating solenoids and SRF cavities) at higher charges. The 95% and 100% emittances at 1 nC are 1.6 and 2.3 microns (consistent with CBETA design specification), with the formation of large halo tails that become even larger with 2 nC bunches [39].

CBETA operation with nanocoulomb bunches will require re-optimizing the injector optics, to account for the lower injector energy of 6 MeV, and for the fact that the second ICM is turned off in this configuration, because this cavity reaches its frequency tuning range limit. The plan is to accelerate 1 nC low repetition rate beam in a 1-pass ERL configuration, as well as in a 4-pass recirculation configuration in which high energy beam is dumped in a Faraday cup (small) beam stop. We may also attempt 4-pass energy recovery at either 1 nC or at a reduced bunch charge, as limited by beam losses.

Care must be taken in constraining the bunch length and the longitudinal tails delivered by the injector to be compatible with the downstream optics, including potential energy recovery. The resulting optimized 1 nC bunches will then be tracked through the single pass ER CBETA lattice using BMAD, which includes a relativistic Gaussian space charge model and CSR effects as well as the final 4-pass configuration. End-to-end tracking will establish where beam losses are expected to occur, including (if possible) energy recovery after the MLC. If necessary, full 3D space charge tracking of the final 6 MeV beam transport will be performed from the MLC to the main beam stop using GPT.

The first step in experimentally realizing 1 nC bunches in CBETA will be upgrading the CBETA drive laser system. We will re-install the existing rod amplifier into the laser system to boost the laser power and will set up the long set of longitudinal shaping crystals and mirrors to lengthen the laser pulse to the values of about 25 ps rms required for nC bunches. A high performance multi-alkali photocathode is also required, with a large centered active area, when operating at reduced duty factor for the initial production of 1 nC bunches.

Once the laser upgrades and cathode production and installation are completed, the injector will be tuned to the optimized 1 nC optics setting. The beam will then be characterized using the emittance measurement system that is located in the diagnostic line before and adjacent to the MLC, directly measuring both the transverse and the longitudinal phase spaces, in turn providing a measurement of the transverse emittance and Twiss parameters as well as the longitudinal emittance.

Then the beam will be accelerated though the MLC, threaded through the first splitter line (set for single pass ER mode) and injected into the return loop. Beam losses will be monitored along the beam line using BLMs and radiation monitors. Similarly, the 4-pass CBETA configuration will later be explored with 1 nC beams. Beam losses will be characterized using the beam loss monitoring system that consists of numerous discrete radiation monitors and a network of scintillating fibers connected to PMTs around the transport loop.

Pushing to the highest possible current in the 1-pass ERL configuration at 42 MeV

The highest average current in superconducting ERLs achieved to date is 9.1 mA, demonstrated at the JLab IRFEL-DEMO [40]. At Cornell, CBETA is uniquely poised to explore the regime of higher average currents, with CW currents of more than 50 mA already demonstrated in the Cornell photoinjector. As a first goal, we will push to the highest possible average current with CBETA set up as a single pass, 42 MeV ERL.

By running in a single pass mode configuration, we benefit from a simpler bunch time structure, so diagnostics will not have to deal with multiple spatially overlapping beams. The control system will be able to fine-tune the machine optics for a single beam without worrying about the optics at other energies, as will be necessary in multipass running. The complex requirements on the bunch pattern structure required to prevent temporal overlap of multi-pass beams are also essentially removed. Under these conditions we can use a 1.3 GHz bunch train, allowing for the same high current operation at significantly reduced bunch charges, as compared to bunch repetition rates of tens of MHz.

Reduced bunch charge operation mitigates the issues related to increased radiation levels originating from unwanted beam losses. The primary strategy to increase the electron beam current will focus on this high repetition rate. Prior to these proposed experiments, all operations in CBETA will have been at a reduced repetition rate of about 42 MHz, chosen to allow multi-turn operation. At 1.3 GHz bunch charges can be reduced by a factor of 1300/42=31 for the same average current in the machine, mitigating both the long-term and short-term issues of operating permanent magnets in the presence of high radiation levels.

The permanent magnet arcs require a properly matched beam to achieve a transport that will not degrade the beam parameters to the point where they significantly affect the energy recovery efficiency. Initial experiments will be performed at a very low duty factor using the diagnostic line, to verify that the beam is correctly matched to the rest of the lattice, in order to fine-tune the machine settings.

Every change in bunch charge requires such a brief low-current tuning period. After that, the beam is threaded at low current through the rest of the arc, adjusting the path length to fully recover the energy, and guiding the beam into the beam stop. Then, increasing the laser duty factor gradually raises the average current. At 1.3 GHz the laser duty factor can be set anywhere in the range from 0% to 100%.

The laser spot on the photocathode is adjusted and matched to the active area on the cathode in order to minimize the radiation beam losses from halo. The active area is also sufficiently far from the electrostatic center to mitigate ion back bombardment effects that limit the cathode lifetime. Care is taken to ensure that the active area is positioned not too far off the center, in order to minimize beam aberrations while still allowing the drive laser to be cleanly reflected without inducing spurious reflections and contributing to the unwanted beam losses.

While increasing the machine duty factor, we will perform studies aimed at mitigating already known primary limitations in the production and transport of high average electron beam currents: the cathode degradation by ion back bombardment and vacuum trips induced by machine trips, ion trapping, long-range higher-order mode effects in SRF cavities, as well as radiation losses from beam halo or incomplete energy recovery. As we push into an unexplored high current territory we also anticipate facing new and unexpected challenges.

We hope to improve the cathode lifetime by operating the biasable anode on the new DC electron gun. This may reduce the gun trip rate at high currents. Ion accumulation is not expected to be a significant problem below average currents of 10 mA. Higher currents will present an opportunity to further explore ion clearing methods previously developed at Cornell [41]. Beam break up from higher-order modes in SRF cavities is not expected to be relevant until currents larger than 100 mA, although the heat dissipation from the HOMs is expected to be measureable at currents of less than 10 mA.

Finally, the largest impediment to high current is likely to be beam loss both from halo and incompletely energy-recovered beam (i.e. temporal tails). We detect these two effects using local radiation monitors and a network of scintillating fibers connected to PMTs around the recirculating arc. Understanding and mitigating beam losses will require guidance from the simulations as discussed elsewhere.

Some minor hardware modifications will be required in order to operate CBETA in this mode. Specifically, vacuum pipes will need to be replaced on the first splitter lines, to reach the correct path length required for energy recovery. Changes to the laser system are also required to produce the 1.3 GHz bunch rate. Both of these required modifications have been already designed and will not require any new infrastructure.

Pushing to the highest possible current in the 4-pass ERL configuration at 150 MeV

To date no multi-pass ERL has operated at significant levels – milliamps – of current. CBETA is uniquely poised to target this gap, due to its high intensity photoinjector and the large energy acceptance of its return loop. Multi-pass high average current operation is significantly more complicated than single-pass operation, due not only to the complexity of beam diagnostics that must work simultaneously on overlapping beams, but also to the inherent challenges in controlling orbits, energies, and beam halo losses of each individual beam when using a shared control system that affects them all. Our goal is to explore the challenges posed by multimode operation with as many as 4 passes, and to identify average current limitations. This will build not only on the experience with high-current single pass operation, but also on the high bunch charge operation detailed previously.

We will begin with a 2-pass configuration, incrementally activating additional one pass at a time. Two-pass operation is the simplest configuration that will introduce new issues, a necessary step for success with larger numbers of passes. Operation in a 3-pass configuration is of particular interest to JLab because its beam energy of 114 MeV is directly comparable to the energy required by the JLab high current electron source designed for strong hadron beam cooling.

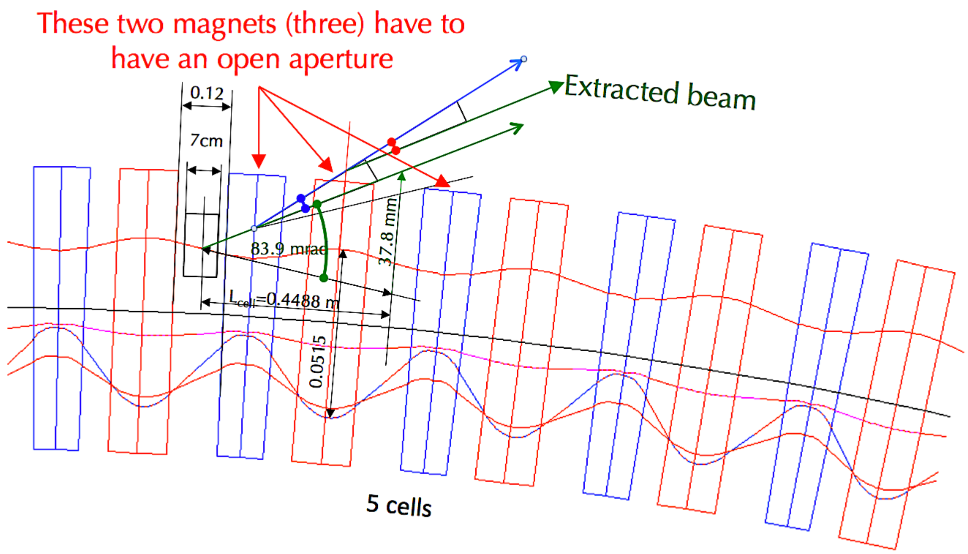
Each change in the number of passes requires dedicated vacuum hardware replacement to both splitters, to add or subtract the half RF wavelength of additional path length that is needed for energy recovery. However, no other hardware modifications or upgrades are required, and only minor changes to the beam optics settings are foreseen.

All multipass operations require the use of the existing 42 MHz laser to drive the photoinjector, in order to provide a bunch structure that is compatible with multiple beam diagnostics. At this lower frequency, the laser duty factor can be smoothly adjusted from 0% to 100% duty factor, increasing the average current at a fixed bunch charge.

3.5 Extraction design

CBETA will support 4-pass acceleration to 150 MeV, followed directly by 4-pass deceleration. At a later stage, after this proposal is complete, CBETA could be used for EIC R&D or other purposes in a configuration in which beam is extracted at 150 MeV, and also returned for subsequent energy recovery. A number of concepts have been proposed for high-energy beam extraction, but none of them have been developed far enough to evaluate their performance and practicality. The goal of this topic is to develop these concepts further, supported where possible by preliminary beam studies.

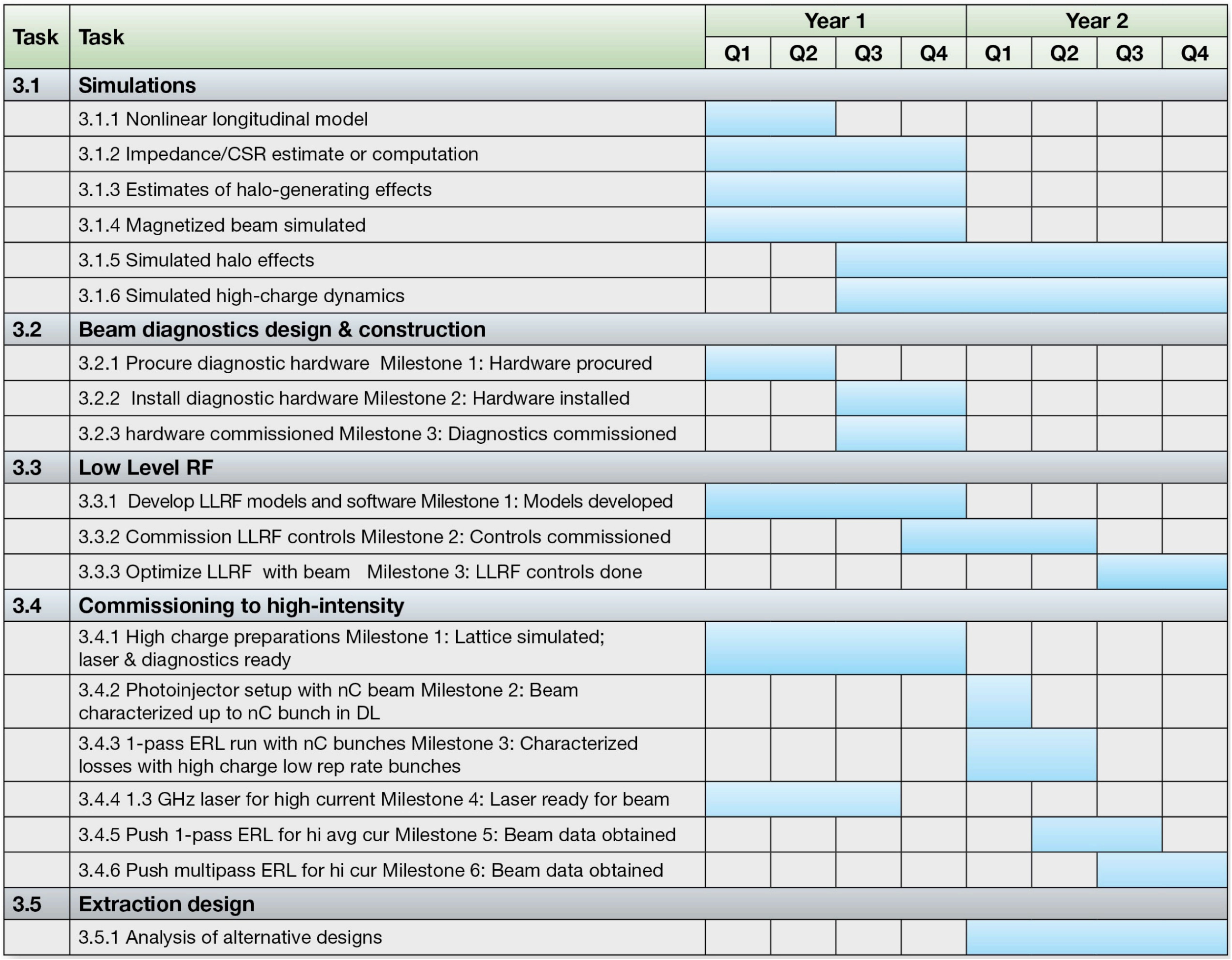
Figure 5: Concept of 150 MeV beam extraction from the CBETA return arc.



One concept for high-energy extraction is shown in Figure 5. Extraction from the arc to an experimental line is achieved by using a couple of special open mid-plane magnets. Prototypes of such open-midplane Halbach-style magnets have already been built and successfully tested at BNL.

4.0 Timetable of Activities

Figure 6: Timeline of activities for the tasks described in this proposal.



Task	Task	Year 1				Year 2			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
3.1	**Simulations**								
	3.1.1 Nonlinear longitudinal model	🟦	🟦						
	3.1.2 Impedance/CSR estimate or computation	🟦	🟦	🟦	🟦				
	3.1.3 Estimates of halo-generating effects	🟦	🟦	🟦	🟦				
	3.1.4 Magnetized beam simulated	🟦	🟦	🟦	🟦				
	3.1.5 Simulated halo effects			🟦	🟦	🟦	🟦	🟦	🟦
	3.1.6 Simulated high-charge dynamics			🟦	🟦	🟦	🟦	🟦	🟦
3.2	**Beam diagnostics design & construction**								
	3.2.1 Procure diagnostic hardware Milestone 1: Hardware procured	🟦	🟦						
	3.2.2 Install diagnostic hardware Milestone 2: Hardware installed			🟦	🟦				
	3.2.3 hardware commissioned Milestone 3: Diagnostics commissioned			🟦	🟦				
3.3	**Low Level RF**								
	3.3.1 Develop LLRF models and software Milestone 1: Models developed	🟦	🟦	🟦	🟦				
	3.3.2 Commission LLRF controls Milestone 2: Controls commissioned				🟦	🟦	🟦		
	3.3.3 Optimize LLRF with beam Milestone 3: LLRF controls done							🟦	🟦
3.4	**Commissioning to high-intensity**								
	3.4.1 High charge preparations Milestone 1: Lattice simulated; laser & diagnostics ready	🟦	🟦	🟦	🟦				
	3.4.2 Photoinjector setup with nC beam Milestone 2: Beam characterized up to nC bunch in DL					🟦			
	3.4.3 1-pass ERL run with nC bunches Milestone 3: Characterized losses with high charge low rep rate bunches					🟦	🟦		
	3.4.4 1.3 GHz laser for high current Milestone 4: Laser ready for beam	🟦	🟦	🟦					
	3.4.5 Push 1-pass ERL for hi avg cur Milestone 5: Beam data obtained						🟦	🟦	
	3.4.6 Push multipass ERL for hi cur Milestone 6: Beam data obtained							🟦	🟦
3.5	**Extraction design**								
	3.5.1 Analysis of alternative designs					🟦	🟦	🟦	🟦

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