

STATUS OF COMPACT ERL

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Abstract

Compact ERL (cERL) at KEK has been dedicated to R&D for industrial applications as a test facility since FY2017, such as the EUV-FEL project for the future lithography light source. Two undulators were installed at the cERL to demonstrate the SASE-FEL with the ERL scheme. We successfully observed the infrared (IR) light in FY2020 as a primary result, which was demonstrated with a 5 MeV injector energy without energy recovery. As the next step, the energy recovery was demonstrated with 3-3.5 MeV injector energy: the high current operation with a low electron charge, and beam tuning for FEL with a high electron charge. We report the results of one-month beam commissioning in FY2023 in the proceedings.

OPERATION PARAMETERS IN FY2023

The compact ERL was constructed as a test facility for a future light source [1]. The main parameters of the beam commissioning in FY2023 are summarized in Table 1. We are aiming for 10 mA for the future EUV-FEL project, however, the maximum average beam current is limited to 1 mA due to the radiation safety regulation of the cERL at present. It is critical to reduce the beam loss at the full recirculation beam energy for high current operation. The sensitive loss monitors are used for the beam optics optimization and the collimator tuning in the low current burst mode before going to the high current operation.

For high current operation, we chose the parameter set of the small bunch charge to prevent it from being affected by the severe space charge effects and to maintain the small beam size along the whole beamline. The injector energy is set to 3.0 MeV, which is the same as FY2018 operation. It is necessary to make the bump height of the recirculation beam small and reduce the beam loss in the injector and dump chicanes, in which the ratio between injector and recirculation energy is 1:6.

For the IR-FEL demonstration, the bunch charge is set to 60 pC, which is the same as the EUV-FEL project. In the previous demonstration [2-3], the injection energy was set to 5 MeV. It was demonstrated by turning off the chicanes and without energy recovery because the energy ratio is unacceptable in the chicanes. The IR-FEL demonstration in FY2023 is performed at the 3.5 MeV injector energy, which is acceptable for energy recovery. It is slightly larger than 3.0 MeV in the high current operation to minimize the transverse and longitudinal emittance growth at the low energy region. The high current operation is limited because the orbit in the chicanes needs to be slightly distorted and it causes a beam loss.

HIGH CURRENT OPERATION

In FY2023, the high current operation was necessary for the machine inspection every five years. Although the beam stability is critical for keeping the radiation level low, we found the beam fluctuation, which was not seen at the previous commissioning. The large fluctuation can be suppressed by replacing the unstable power supply for the steering magnets while the other small fluctuation at the other frequency cannot be suppressed. In addition, there was an unknown spiky beam position shift.

The parameters of the beam optics tuning are shown in Table 1. At the low energy region of the injector, the Q scan responses are matched with that of the design optics optimized with the simulation code General Particle Trace (GPT) to suppress the emittance growth [4]. On the other hand, at the recirculation loop, the linear optics matchings are performed with the tool of the code ELEGANT. At the middle energy region of cERL, magnet standardization is imperative to deal with magnet hysteresis. However, the reproducibility of the standardization was poor due to an unknown reason, so it took a long time to find the best beam optics.

Table 1: Main Operation Parameters in FY2023

Parameter	CW operation for high current	Beam tuning for high current	IR-FEL w. energy recovery
Recirculation energy	17.2 MeV	→	17.5 MeV
Injection energy	2.9 MeV	→	3.5 MeV
Energy ratio at chicane	1 : 6	→	1 : 5
Bunch charge	~ 0.77 pC (max)	1 pC	60 pC
Bunch repetition	1300 MHz	→	81.25 MHz
Operation mode	CW	burst	burst
Pulse duration	-	1 μs	1 μs
Pulse repetition	-	5 Hz	5 Hz
RF frequency	1300 MHz	→	1300 MHz

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CBETA: ACHIEVEMENTS, CHALLENGES, STATUS, AND PLANS*

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Abstract

The Cornell-BNL ERL Test Accelerator, CBETA, is an energy recovery linac (ERL) capable of accelerating electrons to 150 MeV in 4 linac passes. It uses a fixed field alternating gradient return arc to return all 4 energies, from 42 to 150 MeV, to the linac. CBETA was operated in two modes, with one accelerating pass to 42 MeV and with four accelerating passes to 150 MeV. I describe the unique features of CBETA, and summarize what was achieved in our studies. I will outline some of the difficulties we faced which we would like to address in future operations. Finally, I will describe some possible future studies using CBETA.

MACHINE OVERVIEW

CBETA (Fig. 1), the Cornell-Brookhaven ERL Test Accelerator [1], is an energy recovery linac (ERL) accelerating to as high as 150 MeV in 4 passes through a superconducting linac. It consists of

- A 6 MeV injector, capable of 0.5 MW beam power
- A 6-Cavity 1.3 GHz superconducting linac (MLC), which accelerates or decelerates the beam by 36 MeV on each pass
- A fixed field alternating gradient (FFA) return arc, which returns the beam after being accelerated or decelerated by the linac back to be reinjected in the linac. This is a single beam line capable of returning beams at all the relevant energies, from 42 to 150 MeV.
- Splitter (SX) and recombiner (RX) lines which have individual beam lines for each design energy in the return FFA. They connect the MLC to the FFA return arc, and manage betatron matching, time of flight, and R_{56} for each of the four design energies in the return arc.

The return arc thus has 4 design energies: 42, 78, 114, and 150 MeV. The SX and RX lines can be configured so that any of these energies is the maximum energy that the beam is accelerated to in the ERL. I use the language n -pass to refer to the number of accelerating passes in the linac: so for instance, the 1-pass configuration accelerates to 42 MeV, makes one accelerating and one decelerating pass through the linac, and one pass through the return arc. CBETA was operated in the 1-pass configuration and the 4-pass configuration.

Some unique features of CBETA are

1. CBETA is the first 4-pass ERL using a superconducting linac. While a 4-pass ERL has been built before [2],

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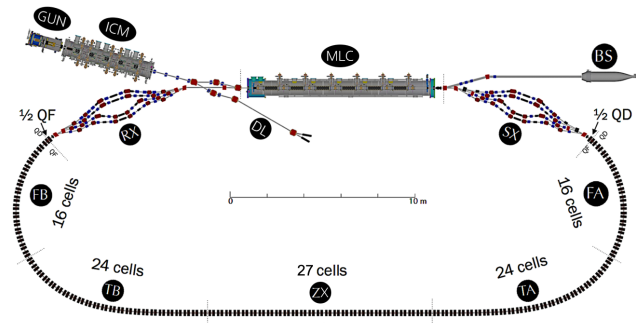


Figure 1: Layout of CBETA.

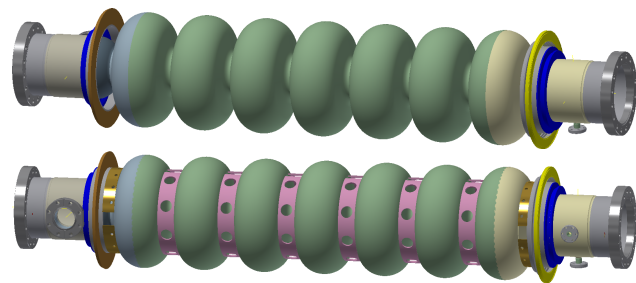


Figure 2: Unstiffened (top) and stiffened (bottom) cavities in the MLC [5].

it used room temperature RF cavities. The low losses in superconducting cavities are needed to get good efficiency in an ERL, but superconducting cavities are significantly more challenging to operate than room temperature cavities, so this is a significant advance. Other ERLs have operated with a superconducting linac, but never with so many passes.

2. CBETA uses a single FFA arc to return the beam to the linac for all the design energies. This idea can be very advantageous for an ERL with a very large number of passes, as was proposed for an early design of an electron-ion collider at Brookhaven National Laboratory (BNL) [3].
3. The FFA return arc is constructed from Halbach-like permanent magnets [4] surrounded by window frame magnets for orbit correction.

MAIN LINAC CRYOMODULE

The main linac cryomodule contains 6 cavities, which alternate between two cavity designs, one with stiffener rings and one without (see Fig. 2). The cavities were supplied with either 5 or 10 kW power amplifiers, for the stiffened and unstiffened cavities, respectively.

Significant effort was put into the reduction of detuning in these cavities. Vibration sources were removed, and active microphonics compensation was introduced [6] (see Fig. 3).

STATUS OF THE S-DALINAC WITH FOCUS ON ERL OPERATION*

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Abstract

The S-DALINAC is a thrice-recirculating electron accelerator at Technische Universität Darmstadt. It can be operated as an energy-recovery LINAC (ERL) besides the conventional acceleration scheme serving various nuclear-physics experiments. One-turn and two-turn energy recovery was achieved at the S-DALINAC. A study on the three-turn ERL mode was conducted. A setup for laser Compton backscattering is under commissioning and will be introduced. This contribution will give an overview of the facility with a focus on its ERL activities.

INTRODUCTION

The superconducting Darmstadt linear accelerator S-DALINAC is in full operation since 1991 at the *Institut für Kernphysik at Technische Universität Darmstadt* [1]. The accelerator is mainly developed and operated by students and serves as important building block for the hands-on education of the future generation of accelerator scientists. The S-DALINAC can be operated as an energy-recovery LINAC (ERL) since 2016 [2], while serving various nuclear-physics experiments in fixed-target operation with up to three recirculation beamlines.

Overview of the S-DALINAC

Figure 1 shows the floor plan of the facility. The beam is generated by the thermionic gun and pre-accelerated with 250 kV. The beam is then prepared for an acceleration in the superconducting radio-frequency (SRF) cavities with a repetition rate of 3 GHz in the normal-conducting chopper-buncher section. The superconducting injector LINAC houses a six-cell capture cavity with a reduced β of 0.86 [3] and two 20-cell SRF cavities ($\beta=1$). Downstream of the injector LINAC, a beam with a total energy of up to 10 MeV and a beam current of up to 60 μ A can be provided. This beam can be used for nuclear-resonance fluorescence experiments at DHIPS [1, 4, 5]. Alternatively, the beam can be deflected into the main LINAC housing eight 20-cell SRF cavities for further acceleration. The beam can pass through the main LINAC up to four times using the three recirculation beamlines. A total energy of 130 MeV with 20 μ A can be reached. The extracted beam can be used for electron scattering experiments at the two spectrometers LINTOTT [6, 7] and QCLAM [8–11], the photon tagger NEPTUN [12, 13] or for tests of devices at the detector test setup.

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Path-Length Adjustment System

The distance travelled by the electrons from the exit of the main LINAC through a recirculation beamline until reentering the main LINAC is called path length. Each recirculation beamline of the S-DALINAC houses a path-length adjustment system (PLAS), see orange circles in Fig. 1. These systems are driven remotely from the control room to adapt the path length of each recirculation beamline depending on the beam momenta and the operation mode: Conventional acceleration or ERL. A full RF wavelength ($= 360^\circ$) corresponds to a distance of 10 cm at the RF frequency of 2.997 GHz of the S-DALINAC. The following strokes are available for the different beamlines and are given as an equivalent of an RF period:

- First recirculation beamline: Approx. 265°
- Second recirculation beamline: Approx. 360°
- Third recirculation beamline: Approx. 360°

The second recirculation beamline is used to operate the S-DALINAC in one- or two-turn ERL mode [14]. For the two-turn ERL operation the first recirculation beamline is used additionally. The PLAS in the third recirculation beamline was upgraded to allow for the three-turn ERL mode [15] that is under study at the moment.

ONE-TURN ERL OPERATION

The beam is accelerated in the injector LINAC, bent into the main LINAC and accelerated once. The separation dipole magnet downstream of the main LINAC deflects the beam directly into the second recirculation beamline. A change in the total path length of a multiple of the RF wavelength plus or minus half a wavelength is applied during the transition to achieve a phase shift leading to deceleration. The beam is reentering the main LINAC on the decelerating phase. As a consequence, there are two beams superimposed in the main LINAC. The electrons are decelerated during their second transition through the main LINAC, thus they are returning their kinetic energy. Finally, the beam is dumped at injection energy. The RF phases and amplitudes of the main LINAC as well as the longitudinal dispersion of the arcs and the PLAS setting of the second recirculation beamline can be used as degrees of freedom during the setting.

The energy of the injector LINAC was set to 2.5 MeV, the energy gain of the main LINAC to 20 MeV during the one-turn ERL run. An initial current of 1.2 μ A was used. At that time, the beam loading could only be measured for the first main LINAC cavity A1SC01 (see Fig. 1), see Table 1. For comparison purposes, the S-DALINAC was operated in four different operation modes:

PROGRESS ON TERAHERTZ LIGHT PRODUCTION AT TRIUMF e-Linac

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Abstract

In addition to the TRIUMF 520 MeV cyclotron, the superconducting e-Linac serves as a new primary beam driver of the Advanced Rare Isotope Laboratory (ARIEL) project, delivering high-power electron beams to generate neutron-rich rare isotope beams (RIB) through photo-fission. Electron beams are initially produced by a thermionic gun at 300 keV, and are subsequently accelerated in a superconducting linear accelerator to 30 MeV. Present gun capacity is specified at up to 15 pC per bunch at a repetition rate of 650 MHz. The minimum bunch length can be reduced to a few millimeters with the current buncher and injector system. This holds substantial potential as a source of terahertz (THz) radiation. This work discusses the first demonstration of THz light production and detection from the ARIEL e-Linac. To produce more intense THz light for broader future applications, an upgrade of the current e-Linac beamline to include a magnetic compressor is under consideration. This study encompasses preliminary parameters and simulations of bunch compression to estimate the coherent synchrotron radiation production towards a future photo-gun driven THz source.

INTRODUCTION

TRIUMF e-Linac is a driver accelerator developed as part of the ARIEL project, which was initially proposed in 2008 [1]. The current e-Linac beamline consists of a thermionic electron gun (e-gun) that generates an electron beam with an energy of up to 300 keV [2], an injector module that accelerates the beam to 10 MeV, and an accelerator module (EACA) that further accelerates the beam to 30 MeV. The current layout of the ARIEL e-Linac is shown in Fig. 1.

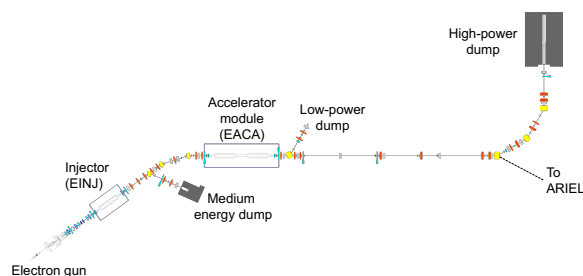


Figure 1: Current layout of the ARIEL e-Linac.

PRESENT STATUS

In September 2021, the first 10 kW beam was directed to the high-power dump, marking the first successful high-power beam delivery from this machine [3]. At that time, the 10 kW beam lasted only about 15 minutes, and it was not possible to maintain high-power beam operation for several hours. To address this limitation, several upgrades were implemented.

Installation of a New Power Converter System

First, a turbine-generator assembly was installed to generate power from the flow rate and head of deionized water, automating the battery charging process. This upgrade enabled uninterrupted, extended operation of the e-gun. Additionally, the e-gun matching circuit was redesigned, and the defective connection to the e-gun tuner was replaced. As a result of these improvements, we successfully demonstrated continuous beam delivery for 3 days at approximately 1 kW in early 2024.

Auto-Regulation of Beam Current

The success of continuous beam delivery also revealed a new challenge: the fluctuation of the beam current due to variations in the surrounding temperature (as shown in Fig. 2). To address this issue, we implemented a feedback control system (PID loop) that uses the current reading from the AC current transformer (ACCT) downstream of the e-gun, along with RF attenuation, to regulate the beam current. The results of this improvement are shown in Fig. 3, where the peak current remains stable and is now insensitive to external temperature changes.

TRIUMF TERAHERTZ PROJECT

The potential of the ARIEL e-Linac as a THz-based light source was discussed in [4] and further elaborated by Victor Verzilov, the THz project leader at TRIUMF [5]. In 2023, CFI funding for this THz project was approved. The collaboration includes TRIUMF, the University of British Columbia (UBC), and the University of Waterloo. The primary objective of the project is to demonstrate the generation of high-intensity, high-strength broadband radiation in the THz region, with a pilot experiment scheduled for completion by 2028. To achieve this goal, a series of plans at different stages have been outlined for the next few years.

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ADVANCEMENTS AND CHALLENGES IN LARGE-SCALE CRYOGENICS FOR ACCELERATOR FACILITIES

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Abstract

Large-scale 4.5 K and 2.0 K helium cryogenic systems are a foundational support system for modern superconducting accelerator facilities. These are highly energy intensive systems. Large-scale efficient helium systems presently require approx. 800 W/W of cooling at 2 Kelvin (30 mbar) and 250 W/W at 4.5K. Due to the nature of the application, these systems require very high reliability. Over the last few decades, progressive and synergistic advancements in cryogenic system operating efficiency and reliability have been made – starting from development of warm compressor skids with wide range operation, to development and implementation of the Ganni floating pressure process for efficient and high turn-down of the refrigeration systems (NASA-JSC, 12 GeV-JLab, FRIB etc.). These design and developments are successfully utilized with high turn-down capacity and substantial energy savings for large-scale helium cryogenic systems at many US Labs. The design and successful implementation of superconducting magnet quench recovery and management helped preservation of helium inventory and improved beam availability. There are still several challenges, e.g. efficient and reliable operation of small-scale 2.0 K cryogenic systems, helium recovery and purification systems that can affect reliable cryogenic system operation. In this paper, the operational experience, progress made to date, recent challenges, and the path forward are discussed.

BACKGROUND

Cryogenics is a critical sub-system for present and future particle physics facilities utilizing superconducting magnet or superconducting radio frequency (SRF) technology. These systems are very complex, unique, and involve highly energy-intensive processes. Currently, these superconducting magnets and SRF resonator cavities are designed to operate at 4.5 K or below. Helium was first liquefied by Heike Kamerlingh Onnes in 1908 [1]. The initial helium liquefaction concepts were very difficult and unreliable. Peter Kapitza (1934) was the first to apply adiabatic expansion to drop the temperature of helium below the inversion point [2]. In 1946, Collins and his colleagues at MIT built a simpler version of a helium liquefier which produced liquid helium without the need for pre-cooling (although liquid nitrogen pre-cooling is used to increase the capacity of the machine) [3]. In the late 1960s, the first Collins helium refrigerator located at Brookhaven National Laboratory (BNL) (~200W at 4.5K) and the refrigerator at Stanford University (300W at 1.8K), designed by Sam Collins, were considered as large cryogenic plants [4]. In these

earlier systems the input power was of secondary importance to a working plant (*i.e.* reliability and stability) and achieving the desired capacity. By the late 1980's the plant sizes grew substantially to more than 25 kW at 4.5K (BNL) and 4.6 kW at 2.0 K (Jefferson Lab, or JLab) [4]. Thus, there was a relatively rapid change to large systems that were not consistently used at their maximum capacity and/or were used for modes different than those for which they were designed. These later systems were designed based on a modified Claude-Brayton cycle (*i.e.*, constant-pressure process) and operated with the philosophy of the earlier systems. Presently, the input power requirement can vary between 250 W or above per W of cooling provided at 4.5 K, and between 800 – 1100 W or above per W of cooling provided at 2.0 K. Due to the niche field of application, many of the key components have been traditionally adopted from other industries and the refrigeration / liquefaction systems are designed at specified maximum (cooling) capacity operating point(s).

Over the years, it has been recognized and proven that a system design based on a constant pressure ratio (known as the '*Ganni Floating Pressure*' process cycle, patented) will lead to an optimal system design and improved efficiency of operating systems with the added benefits of stability [5]. In this paper, the progressive and synergistic advancements in helium cryogenic process system components (*e.g.* warm compressors, turbo-expanders, liquid nitrogen pre-cooling system, heat exchangers, cryogenic centrifugal compressors) leading to the deployment and operation of a refrigeration system based on the Ganni Floating Pressure process cycle has been discussed in detail. The present challenges with the design of sub-atmospheric (2.0 K) refrigeration systems, and other sub-systems (namely, helium recovery and purification systems) are also discussed with potential paths for advancement of the technologies.

DESIGN FOR EFFICIENT WIDE-RANGE OPERATION

Design of a cryogenic system that is efficient over a wide range of operating loads requires a thermodynamic process cycle that can adjust to the varying loads, as well as development of efficient system components. Advancements in both these areas are discussed below.

Ganni Floating Pressure Process Cycle

The constant pressure ratio process (instead of a constant pressure process), as implemented in the Ganni Floating Pressure process cycle [5], is a variation to prior cryogenic refrigeration and liquefaction cycle designs that allows for

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MACHINE LEARNING FOR HIGH CURRENT BEAM OPERATION AT COMPACT ERL

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Abstract

The compact ERL (cERL) has been operated at the mid-energy region of approximately 17 MeV since 2017, thus facilitating the execution of beam studies on industrial applications. A R&D issue that has been identified is the high average beam current operation, which is carried out with a low bunch charge (0.77 pC). In 2023, machine learning was employed to optimise the beam tuning process, with the objective of maintaining a high current beam while reducing radiation levels. The application of machine learning represents a promising approach to the realization of automatic tuning. This provides the current status of the machine learning study for beam tuning at cERL.

INTRODUCTION

In the realm of accelerator beam operation, beam adjustment stands as a pivotal component. Achieving the requisite beam characteristics often poses a significant challenge due to the complexity inherent in adjusting accelerator parameters. At cERL, the process of beam tuning, which aims to minimize radiation and ensure efficient energy recovery, is particularly arduous. This is primarily due to the intricate interplay between tuning parameters and the need for specialized expertise in beam adjustment. The integration of machine learning emerges as a promising avenue for facilitating automatic tuning. In the context of beam tuning for high current CW operation, Bayesian optimization has been utilized as a tool for this purpose. Bayesian optimization is a method of estimating the shape of a black box function and of obtaining the global maximum (or minimum) from a limited set of observed data. We are currently exploring the potential of implementing machine learning algorithms to enhance the operational efficiency of the beamline at cERL.

COMPACT ERL

As shown in Figure 1, the compact ERL's layout includes a photo-cathode DC gun that generates a low-emittance electron beam with a voltage of 450 kV [1]. In the low bunch charge beam operation, the beam is induced by a high repetition rate pulse laser and subsequently directed to an injector system that accelerates it to a beam energy of 2.9 MeV. The beam is then accelerated to 17.2 MeV by a main superconducting cavity, and it traverses a recirculation loop. Subsequently, the beam passes through the undulator section, and it returns to the main SC cavity, where

it is decelerated to the same energy as the injection energy of 2.9 MeV. The energy generated by the deceleration of the previous beam is recovered and utilized to accelerate the subsequent beam. The beam is then directed to a beam dump.

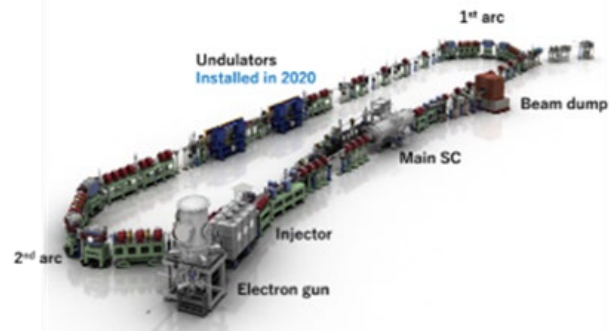


Figure 1: Layout of cERL.

MACHINE LEARNING APPLICATION AT cERL

In the high-current continuous wave (CW) operation at cERL, the objectives are as follows:

- To maintain a high beam current.
- To suppress radiation due to beam loss.

In the context of CW operation, beam loss can result in elevated radiation levels, which can lead to the termination of beam operation. It is essential to acknowledge the necessity of beam tuning to ensure compatibility between the two conditions.

The utilization of a loss monitor is essential for the detection of beam loss. Nevertheless, in the event of substantial beam loss during machine learning optimization, PMT with HV near the loss point has the potential to result in interlock or operation termination. Therefore, optimization is pursued while evading "dangerous" parameter searches. The algorithm is subsequently employed to automatically estimate the "safe" parameter space. Bayesian optimization is then implemented within that parameter space [2].

The design of the evaluation function represents a fundamental aspect of Bayesian optimization. In order to achieve equilibrium between the aforementioned conditions, a linear combination of two components is incorporated into the evaluation function. These components represent the high-current retention and loss reduction parts, respectively. The equilibrium between these two components can be modulated by adjusting the weights appropriately. Bayesian optimization is a method of searching for parameters that maximize such an evaluation function.

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BEAM DYNAMICS OF THE STRONG HADRON COOLER ERL AT THE ELECTRON-ION COLLIDER

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Abstract

The Strong Hadron Cooler Energy Recovery Linac (SHC-ERL) for the Electron-Ion Collider (EIC) is required to produce an electron beam with a bunch charge of 1 nC, an average current of 100 mA, and a beam energy of both 150 and 55 MeV, with strict requirements for the transverse emittance, slice energy spread, and longitudinal distribution. This paper covers the design in detail, including preliminary considerations of higher order effects and diagnostics.

INTRODUCTION

The Electron-Ion Collider (EIC) is a partnership project between Brookhaven National Lab (BNL) and Thomas Jefferson National Accelerator Facility (TJNAF) to be constructed at BNL, using much of the existing infrastructure of the Relativistic Heavy Ion Collider (RHIC); a layout of the EIC is shown in Fig. 1. Collisions occur between the hadrons in the Hadron Storage Ring (HSR) and the electrons supplied by the Electron Storage Ring (ESR); in order to maintain a high average polarization of the ESR, bunches are frequently replaced using the Rapid Cycling Synchrotron (RCS). While most of the magnets for the HSR are repurposed RHIC magnets, already installed in the existing tunnel, both the ESR and RCS will have to be installed. In the current scope of the EIC, only one interaction region (IR) is supported, sited at the current IR6 of RHIC; however, it is highly desired that a second IR may be supported at IR8 in the future, and design efforts support that eventuality [1].

In order to achieve the design emittances of the hadron beam and average luminosity, a two-stage cooling system is necessary. First, hadron beams are injected into the HSR and cooled to the desired emittances. After the design emittances are achieved, the HSR is ramped to the collision energy, and the hadron beam is cooled during collision in order to maintain the beam emittances; preserving the design emittances is critical to achieve the desired average luminosity of the EIC. The electron cooler which provides cooling to the hadron beam is located in IR2 [1, 2].

STRONG HADRON COOLER ERL

The Strong Hadron Cooler Energy Recovery Linac (SHC-ERL) is intended to cool the hadron beam during collision of 275 and 100 GeV protons, which requires 150 and 55 MeV

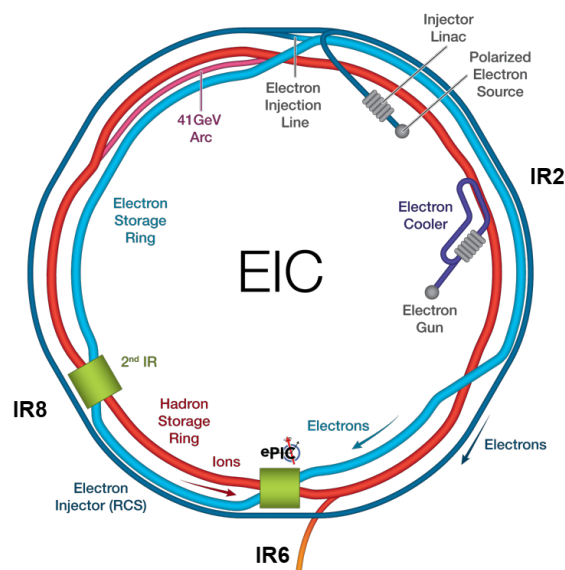


Figure 1: The current layout of a portion of the Electron-Ion Collider (EIC). The Hadron Storage Ring (HSR), Electron Storage Ring (ESR), and the Rapid Cycling Synchrotron (RCS) labels are color-coded to their respective rings; the current and proposed IRs are shown at IR6 and IR8, with the electron cooler in IR2.

electrons, respectively. The necessary beam parameters for both energies are given in Table 1; for an explanation of the development of these parameters, please see [3]. Given the significant beam power necessary, it is clear that an energy recovery linac (ERL) is required - the operational power to produce the same beam parameters with a linac is prohibitive; additionally, using an ERL reduces the radiation considerations at the beam dump. Closed optics exist for both operational modes, shown in Figs. 2 and 3.

LAYOUT

A representative layout of the SHC-ERL is shown in Fig. 4. In beamline order during energy recovery, the sections are the injector, the merger, the booster, the bunch compressor and high energy bypass lines (PX), the main linac, the beam dump, the laser heater, transport to the cooling section, the cooling section (modulator, amplifier, and kicker), the first turnaround, the return line, and the second turnaround

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FAST ENVELOPE TRACKING FOR HIGH INTENSITY LOW ENERGY ELECTRONS

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Abstract

Particle-in-cell (PIC) tracking codes such as GPT and ASTRA are commonly used for simulating and understanding the initial stages of electron beam creation and acceleration, typically up to the first few hundred kilovolts. However, these simulations are often slow and require precise input of details that are not essentially needed. An alternative is envelope tracking using numerical integration, which offers rapid results and is handy in early-stage design. This study presents beam dynamics simulations from two electron sources: the photocathode gun at cERL-KEK and the thermionic gun at TRIUMF e-Linac. It compares results from both methods and validates them against experimental data. In these two cases, despite being orders of magnitude faster than conventional multi-particle PIC codes, the envelope method delivers comparably accurate results for rms measures of beam dimensions, even under strong space charge (SC).

INTRODUCTION

When calculating beam optics, two common types of simulations are typically used: the envelope method and multi-particle particle-in-cell (PIC) codes. The envelope equations were originally derived by Kapchinsky and Vladimirsky (K-V) for a continuous beam with uniform charge density and elliptical cross-section [1]. These equations were later generalized by Sacherer in the 70's to accommodate arbitrary charge distributions with elliptical symmetry, as well as bunched beams with ellipsoidal profiles [2]. The envelope method represents the beam using statistical moments, whereas the PIC approach tracks each macro-particle individually. In comparison to the $6 \times N$ degrees of freedom required in a PIC code (where N is the number of macro-particles), the envelope method only requires solving 21 sets of envelope equations. This significantly simplifies the calculations and provides a computationally efficient alternative. Table 1 presents a comparison of the computational time taken to simulate a 300 keV beam at the start of a 200 cm-long electron beamline at TRIUMF, using both a PIC code (GPT) [3] and the envelope code (TRANSOPTR) [4].

The results, shown in Fig. 1, demonstrate that the TRANSOPTR simulation closely matches the results from GPT with 10,000 particles, yet is approximately 2 order of magnitude faster. This ultra-fast tracking not only enhances design

efficiency but also enables real-time simulations and model-based tuning, offering valuable insights during actual beam delivery and operational adjustments.

Table 1: An Example Comparing the Simulation Time for the Similar Layout at the Injection Beamline of TRIUMF e-LINAC

Type of Simulations	CPU time (s)	No. particle
Envelope	0.06	-
Multi-particle	8.4	10000
	1.4	1000
	0.08	100

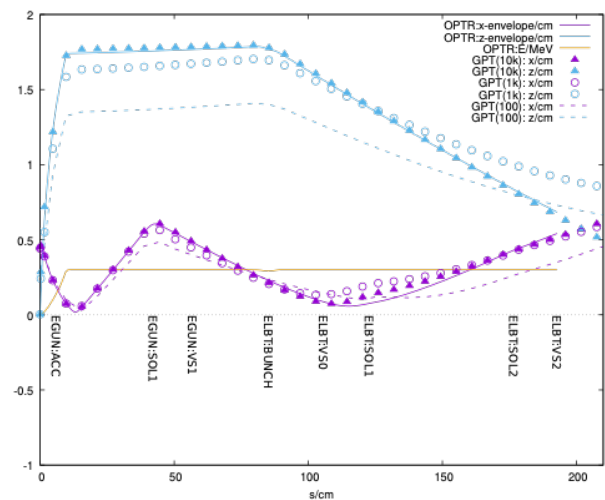


Figure 1: The comparison of envelope results using multi-particle tracking code (GPT) and envelope code (TRANSOPTR) at different no. of particles. The beam energy is 300 keV and the bunch charge is 14 pC.

Despite its fast turnaround, the envelope method is not typically the primary choice for studying beam optics in low-energy regimes, such as the injection beamline. This is because the envelope method includes only linear terms, which lead to potential discrepancies when space-charge effects become prominent and highly non-linear at low energies. This work investigates the feasibility of using an envelope code to model the beam optics of high-space-charge electron beams, including a comparison with other simulation tools and experimental results.

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PHASING AND CALIBRATION OF THE MAIN LINAC CRYOMODULE CAVITIES FOR THE CBETA ENERGY RECOVERY LINAC*

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Abstract

I describe the method used for calibration and phasing of the Main Linac Cryomodule (MLC) for the CBETA energy recovery linac at Cornell University. The cavities are powered one at a time, and the phase of each cavity is set to a uniformly spaced set of values over a full 360 degree range, with cavity voltages set to one or more values. For each cavity, voltage, and phase, arrival time measurements are taken at BPMs upstream and downstream of the linac. No magnets lie between the linac and the BPMs. These measurements are used to obtain a least squares fit to the parameters of a model. The model is based on integrating through a fieldmap that was generated from a finite element computation. The parameters to be fit are the scaling factors between the programmed and actual cavity voltages, the offset between the programmed and actual cavity phases, and the energy of the beam coming into the linac. The fitting process is accelerated by constructing a good initial guess for the parameters, and by computing the arrival time and its derivatives with respect to the parameters so that Newton's method can be used to solve for the fitting parameters.

LINAC MODEL AND MEASUREMENT

When first operating an RF cavity, there is an unknown relationship between the phase and amplitude settings in the control system and the corresponding phase and voltage in the model of the cavities in the linac. Thus a measurement must be performed to determine that relationship. We expect that the relationship between amplitude and voltage should be relatively stable, and thus can be calibrated rather infrequently. Depending on how the timing in accelerator is handled, the phase relationship may also be stable, but for CBETA [1], that relationship was different every time the accelerator was started, so the calibration process was used regularly.

The Measurement

The linac cavities will be calibrated using time of flight data measured on a BPM at the end of the linac. While bunches are injected at the entrance to the linac at a constant energy, the phase of a single cavity in the linac is varied in uniform steps over 360°. At each phase, a number of readings are taken to reduce the statistical uncertainty in the arrival time value. This is repeated for each cavity, always

with all other cavities off. One additional measurement of the arrival time is made with all of the cavities off, typically with more readings taken than when a cavity is on, since the additional readings have a small impact on the measurement time while having a significant impact on the uncertainty.

The voltage of the cavity is set to a compromise between two extremes. If the voltage is too low, then the uncertainty in the calibrated phase and voltage is large due to a small variation in time of flight relative to the uncertainty in the time of flight measurement. If the voltage is too high, then the low beam velocity at maximum energy loss leads to significant space charge and beam steering from imperfect alignment, creating a systematic error in the readings. The former is a greater concern at the end of the linac, the latter a greater concern at the beginning. A good starting point is a voltage corresponding to half the injection energy into the linac. This assumes that the cavity voltages are at least approximately calibrated to start with. One could use a different voltage at each cavity, though in our calibrations for CBETA we did not do so. One can also use multiple voltages for each cavity.

The Linac Model

The linac is a sequence of n cavities in a straight line with no intervening magnets, plus a BPM at the entrance and the exit. I model the particle motion solely in the longitudinal plane. The evolution of time and energy for a particle within an RF cavity is governed by

$$\begin{aligned} \frac{dt}{ds} &= \frac{E}{c\sqrt{E^2 - (mc^2)^2}} \\ \frac{dE}{ds} &= qVG(s) \cos(\omega t + \phi + \phi_r) \end{aligned} \quad (1)$$

Here V and ϕ are the voltage and phase, respectively, that parametrize the state of the RF cavity. $G(s)$ is proportional to the longitudinal electric field at the position s in the cavity. It is normalized such that

$$\int_{-\infty}^{\infty} G(s) \cos(\omega s/c + \phi) ds = \cos(\phi + \phi_c), \quad (2)$$

in other words such that the maximum possible energy gain of a particle moving at the speed of light according to Eq. (1) would be qV . I define ϕ_r , on the other hand, based on a particle at the design injection energy E_r . If the cavity has an infinitesimally small voltage applied (mathematically, if the particle's velocity doesn't change), then the value of ϕ for which it has its maximum energy gain should be $\phi = 0$. Thus

$$\int_{-\infty}^{\infty} G(s) \cos(\omega s/(\beta_r c) + \phi + \phi_r) ds = A_r \cos(\phi) \quad (3)$$

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HIGH AVERAGE CURRENT HVDC ELECTRON GUN FOR EIC HADRON COOLING*

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Abstract

A critical R&D initiative for the Electron Ion Collider (EIC) involves the design of an electron gun capable of generating a high average current and high-brightness electron beam for the hadron cooler. This is essential to preserve hadron beam quality and achieve the collider's luminosity target of $1 \times 10^{34} \text{ s}^{-1} \text{ cm}^{-2}$. For an energy recovery linac (ERL)-based hadron cooler, the gun must deliver a high average current of 98.5 mA, a normalized transverse emittance of less than 2 mm-mrad, and a bunch charge of up to 2.5 nC. This proceeding outlines the high-voltage design of a DC gun operating at 500 kV, with conditioning capability up to 600 kV. The design incorporates several unique features, including the use of inverted ceramic at this voltage level, active cooling for the cathode, and large single-crystal multi-alkali cathodes grown on a silicon carbide substrate. High-brightness electron sources are also pivotal for other advanced applications, such as high-intensity gamma sources, future e^+e^- colliders, and ultra-deep UV sources for the semiconductor industry. Additionally, this paper provides an overview of the hadron cooling approaches planned or proposed for the EIC.

INTRODUCTION

To achieve and sustain the high luminosity target of $1 \times 10^{34} \text{ s}^{-1} \text{ cm}^{-2}$, the Electron Ion Collider (EIC) requires advanced hadron cooling capabilities. Two hadron cooling systems are planned for the EIC: a low-energy cooler designed to cool hadrons at the injection energy of 24.5 GeV, and a high-energy cooler intended to maintain luminosity at collision energies of 100 GeV and 275 GeV. Both systems will require high-average-current, high-brightness electron sources, particularly if single-pass linac or energy recovery linac (ERL)-based designs are employed for the hadron cooler. The schematic layout of the EIC, including the electron cooler, is shown in Fig. 1.

Building on the successful tests of the polarized gun R&D at the EIC, we are developing a HVDC gun to serve as the electron source for the hadron cooler. This gun is designed to deliver up to 98.5 mA of average current at voltages exceeding 500 kV. The design incorporates several advanced features, including an inverted feedthrough structure and an upgraded active cathode cooling system using fluorinert

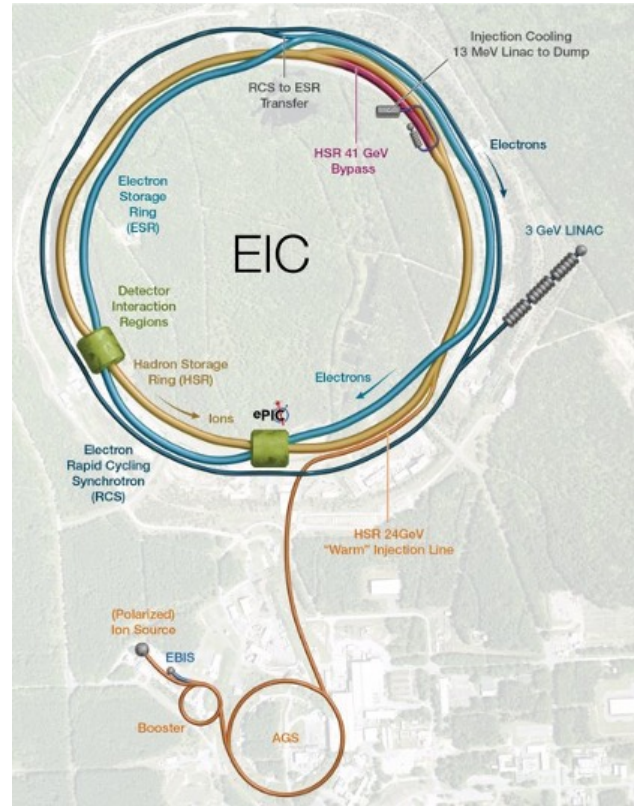


Figure 1: EIC schematic layout.

(FC72). To achieve high brightness, the gun will utilize novel large-crystal K_2CsSb photocathodes grown on 4H-SiC substrates. The design and analysis of the HVDC gun have been completed, and the construction is currently underway. High-voltage conditioning is targeted for 2025, with beam commissioning anticipated in 2026–2027.

In this report, we will discuss the ERL-based hadron cooler proposals for the EIC, followed by an overview of the HVDC gun's design concepts, considerations and novel features. Additionally, the major components of the HVDC gun will be described in detail.

VARIOUS PROPOSALS OF THE ERL-BASED HADRON COOLERS FOR EIC

The EIC low-energy cooler (LEC) is designed to reduce the injection rms normalized vertical emittance from 2 mm mrad to a range of 0.3 mm mrad to 0.5 mm mrad, as

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DESIGN OVERVIEW OF THE STRONG HADRON COOLER ERL AT THE ELECTRON-ION COLLIDER

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Abstract

The Electron-Ion Collider (EIC) is currently under development to be built at Brookhaven National Lab and requires cooling during collisions in order to preserve the quality of the hadron beam despite degradation due to intra-beam scattering and beam-beam effect. An Energy Recovery Linac (ERL) is being designed to deliver the necessary electron beam for Coherent electron Cooling (CeC) of the hadron beam, with an electron bunch charge of 1 nC and an average current of 100 mA; two modes of operation are being developed for 150 and 55 MeV electrons, corresponding to 275 and 100 GeV protons. The injector of this Strong Hadron Cooler ERL (SHC-ERL) is shared with the Injection Cooler ERL, which cools lower energy proton beams via bunched beam cooling, as used in the Low Energy RHIC electron Cooling (LEReC). This talk introduces the layout and presents a high-level overview of the design.

INTRODUCTION

The Electron-Ion Collider (EIC) is a partnership project between Brookhaven National Lab (BNL) and Thomas Jefferson National Accelerator Facility (TJNAF) to be constructed at BNL, using much of the existing infrastructure of the Relativistic Heavy Ion Collider (RHIC); a layout of the EIC is shown in Fig. 1. Collisions occur between the hadrons in the Hadron Storage Ring (HSR) and the electrons supplied by the Electron Storage Ring (ESR); in order to maintain a high average polarization of the ESR, bunches are frequently replaced using the Rapid Cycling Synchrotron (RCS). While most of the magnets for the HSR are repurposed RHIC magnets, already installed in the existing tunnel, both the ESR and RCS will have to be installed. In the current scope of the EIC, only one interaction region (IR) is supported, sited at the current IR6 of RHIC; however, it is highly desired that a second IR may be supported at IR8 in the future, and design efforts support that eventuality [1].

In order to achieve the design emittances of the hadron beam and average luminosity, a two-stage cooling system is necessary. First, hadron beams are injected into the HSR and cooled to the desired emittances. After the design emittances are achieved, the HSR is ramped to the collision energy, and the hadron beam is cooled during collision in order to maintain the beam emittances; preserving the design emittances is

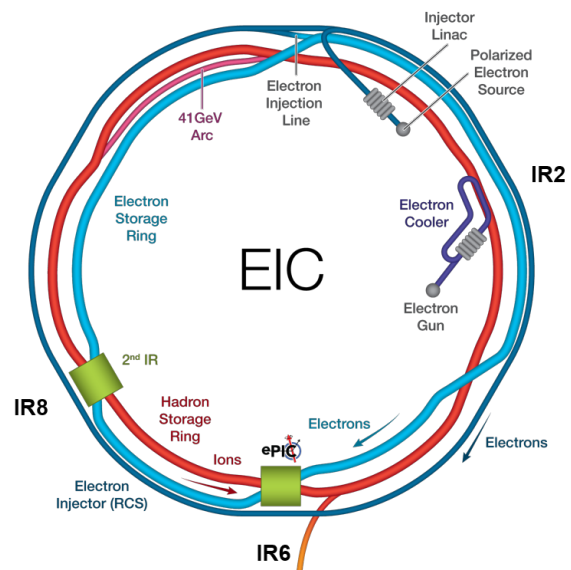


Figure 1: The current layout of a portion of the Electron-Ion Collider (EIC). The Hadron Storage Ring (HSR), Electron Storage Ring (ESR), and the Rapid Cycling Synchrotron (RCS) labels are color-coded to their respective rings; the current and proposed IRs are shown at IR6 and IR8, with the electron cooler in IR2.

critical to achieve the desired average luminosity of the EIC. The electron cooler which provides cooling to the hadron beam is located in IR2 [1, 2].

MICROBUNCHED ELECTRON COOLING

Coherent electron cooling (CeC) uses an electron bunch to “measure” the position of the protons, then uses the same electron bunch to apply corrective energy kicks to reduce the emittance of the proton bunch in the longitudinal and transverse directions. For the EIC, it is anticipated that the protons will be stored on the order of ten hours, but intra-beam scattering (IBS) and beam-beam effect will cause emittance growth on the order of two hours, reducing luminosity over the duration of the store. Consequently, to preserve the emittance of the proton beam and increase the average luminosity over the store, cooling during collisions is required to counteract emittance growth.

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PRELIMINARY DESIGN AND BEAM DYNAMICS SIMULATION STUDIES OF THE PHOTO INJECTORS FOR EicC

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Abstract

A project for a polarized electron-ion collider in China (EicC) is planned based on the high intensity heavy ion accelerator facility (HIAF), which is currently under construction. According to the electron beam parameters from the white-paper of EicC, two electron injectors are required, one is polarized electron beam for the collider and another one is for the energy recovery linac (ERL) used for the electron cooling (e-cooler) of high energy ions. For the polarized electron beam, a DC high voltage photocathode gun is used; for e-cooler ERL, a quarter wave length resonator (QWR) SRF photocathode gun is considered. The preliminary considerations and designs of both injectors with beam dynamics simulation studies are presented here.

INTRODUCTION

The polarized electron ion collider in China (EicC) aims at achieving the highlighted physics goals presented in reference [1] and the layout is shown in Fig. 1. It will be based on the existing High Intensity heavy-ion Accelerator Facility (HIAF). HIAF is the major national facility focusing on nuclear physics, atomic physics, heavy ion applications and interdisciplinary researches in China. The construction is scheduled for seven years, and the beam commissioning is planned for 2025. HIAF is a completely new facility that a series of upgrades for EicC in the future have been taken into consideration during the design stage, and its capability to run with EicC concurrently is also reserved.

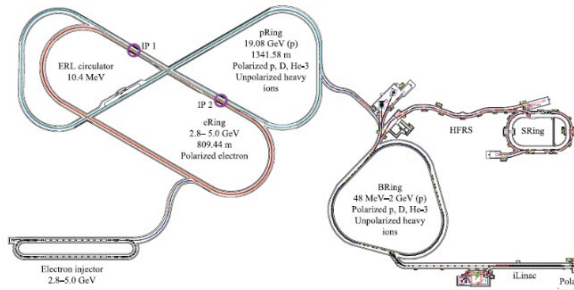


Figure 1: The layout of the EicC accelerator facility [1].

There are several key technologies for the EicC project. Two of the most challenges are polarized electron source and energy recovery linac based electron cooling for high energy ions. There are two SRF linacs, one requires polarized electron injectors with high beam quality and high polarization rate and another one needs high repetition rate and high bunch charge. Considerations of electron source

for the EicC project are referred to [2], where a DC photocathode injector is considered for the polarized electron source for the electron and ion collider and a QWR SRF photocathode injector considered for the ERL based electron cooling. In this paper, we present the preliminary considerations and designs of both injectors with beam dynamics simulation studies to investigate the possible solutions. The technologies of the both injectors are within the state of art and the structures design of the guns are referred as some mature designs from the world's labs.

POLARIZED ELECTRON PREINJECTOR DESIGN

Currently, for the polarized electron beam, due to its unique cathode material (GaAs) and some critical demands, especially for the high vacuum (10^{-10} Pa) conditions, the high voltage DC photocathode electron gun is the most possible choice [3]. The photocathode for polarized beam is strained GaAs. Currently the QE, life-time and polarization rate are still big challenges. For high average current polarization electron gun, the cathode problem should be solved firstly. For the high voltage DC photocathode gun, the gun voltage higher is better for generating high quality beam, normally 500 kV is preferred. For polarized electron gun, 300-200 kV is chosen because of lower field emission and beam energy for longer cathode lifetime and easy polarization manipulation. Here we choose 300 kV high voltage, the same with JLab inverted insulator DC gun structure [4]. The polarized electron injector layout based

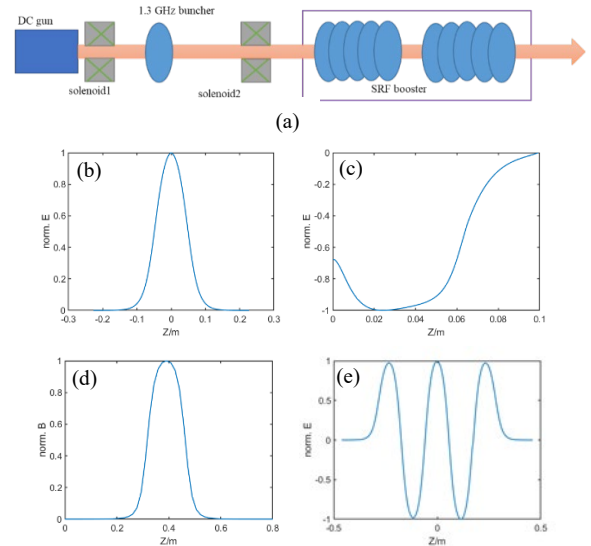


Figure 2: The polarized electron injector layout based on the DC gun structure (a) and the field maps(b-e).

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DESIGN OF A CONDUCTION-COOLED 2.856 GHz Nb₃Sn SRF CAVITY AND COMPACT CRYOMODULE FOR ELECTRON ACCELERATOR*

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Abstract

This paper introduces the design of a conduction-cooled Nb₃Sn 2.856 GHz cavity and compact cryomodule. The cryomodule incorporates a single-cell Nb₃Sn cavity for electron beam acceleration, featuring a dual-function ring that serves as both a conduction cooling interface and a tuner, along with thermal shielding to efficiently maintain cavity cooling and magnetic shielding to minimize exposure to external magnetic field. Nb₃Sn cavities have shown higher efficiency at 4 K compared to pure niobium cavities when cooled using a conduction cooling system. This increased efficiency makes them suitable for more compact and cost-effective accelerators. Conduction-cooled SRF cavities, operating at 4 K, do not require large-scale helium refrigerator systems, enhancing the compactness and efficiency of accelerators. Currently, a conduction cooling cryomodule is under optimization process. The study includes a thermal study of the conduction cooling system, magnetic shielding considerations, the tuner system design, and preliminary measurement results.

INTRODUCTION

Superconducting radio-frequency (SRF) cavities are essential components in modern particle accelerators, enabling efficient acceleration of charged particles with minimal energy loss. Traditionally, SRF cavities are constructed from high-purity niobium and are cooled with liquid helium to reach superconducting states. However, the development of Nb₃Sn (niobium-tin) conduction-cooled cavities represents a significant advancement over pure niobium, offering several advantages in terms of operational temperature, thermal stability, and efficiency.

Nb₃Sn has a higher critical temperature ($T_c \sim 18$ K) compared to niobium ($T_c \sim 9.2$ K), allowing operation at higher temperatures, such as 4.2 K. With a critical temperature of (twice that of Niobium), enables RF cavities to operate at 4 K with the same BCS losses as Niobium at 2 K [1]. This thermal efficiency allows for conduction-cooled systems powered by cryocoolers, removing the infrastructure requirements and complexities associated with liquid helium [2]. This feature dramatically reduces cryogenic infrastructure costs and complexity [2]. These properties make Nb₃Sn conduction-cooled cavities a strong candidate for next-generation particle accelerators. They are particularly

suitable for compact systems and energy-efficient designs. As a result, they offer significant potential for advancing accelerator technology.

This paper explores the design and addresses the challenges associated with the development of a conduction-cooled Nb₃Sn cavity. A beam acceleration test of a Nb₃Sn superconducting cavity will be conducted at t-ACTS, RARiS, Tohoku University, with the cavity operating at the S-band frequency of 2856 MHz. A conduction-cooled cryomodule using a GM cryocooler has been developed for this purpose. In the tests, a 200 W RF amplifier will drive the cavity at an acceleration gradient of 20 MV/m, achieving an acceleration voltage of 1.05 MV per cell. The 20 MeV electron beam will gain ~ 1.0 MeV, with the energy gain measured via beam position changes in the dispersion section [3].

2.856 GHz CAVITY DESIGN

The 2.856 GHz cavity design was scaled from 1.3 GHz Tesla shape design as shown in Fig. 1. CST Studio [4] was used for the simulation calculations.

2.856 GHz Cavity Design

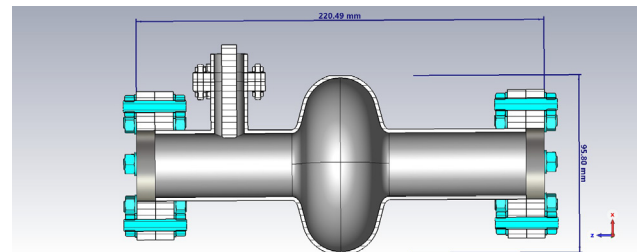


Figure 1: Schematic design of 2.856 GHz cavity.

Table 1 summarizes the electromagnetic RF parameters of the 2.856 GHz cavity for an accelerating gradient of 20 MV/m. The Table 1 provides key insights into the cavity's performance, aiding in the design and evaluation process for integration with the linac system. The E_{pk}/E_{acc} and B_{pk}/E_{acc} ratios are similar to 1.3 GHz Tesla shape cavity parameters. Figure 2 illustrates the electromagnetic field profiles of the 2.856 GHz cavity for the fundamental accelerating mode, TM₀₁₀.

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INVESTIGATING PERMANENT MAGNET RESILIENCY TO RADIATION – A STUDY AT JEFFERSON LAB’S CEBAF*

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Abstract

Jefferson Lab is currently studying the feasibility of an energy upgrade based on FFA technology. The concept will use a pair of permanent magnet-based multipass recirculation arcs to increase the total number of passes through the current linacs. The increased number of recirculations will increase the final achievable nominal energy to over 20 GeV. No existing Fixed Field Alternating Gradient (FFA) machines have ever approached the energy levels proposed for this upgrade. This raises concerns as to the radiation hardness of the permanent magnet materials to be used. The lab has therefore provided a two-year Laboratory Directed Research and Development (LDRD) grant to study the permanent magnet materials in a radiation environment similar to those in which they will operate. Samples of permanent magnet materials (namely neodymium iron boron and samarium cobalt) will be installed around the CEBAF facility in a variety of different radiation environments, along with appropriate dosimetry. Over time, as allowed by the CEBAF operational schedule, we will measure the magnetic degradation and radiation doses at each location. We will then use this data, along with data from other similar studies, to extrapolate the degradation these materials may experience over time when operating in the upgraded CEBAF facility.

BACKGROUND

Jefferson Lab is currently performing an energy upgrade feasibility study, referred to as the FFA@CEBAF study, the goal of which is to increase the energy of the Continuous Electron Beam Accelerator Facility (CEBAF) from a nominal 12 GeV electron beam to over 20 GeV using fixed field, alternating gradient (FFA) permanent magnet arcs [1]. The permanent magnets proposed for the upgrade have not been tested in a radiation environment similar to those expected to be present in the upgraded CEBAF machine. Furthermore, the specific type of permanent magnet material to be used in the FFA magnets has not yet been decided, so a comparative study is also important, as it will aid in the assessment of the materials. Placing samples and assemblies of samples of selected permanent magnet materials in different radiation

regions of the operational 12 GeV CEBAF will allow us to gather data, which when combined with simulations, external studies, and calculations, will allow us to evaluate the radiation hardness, and thus the lifetime, of the materials to be used for the FFA arcs.

The work being performed in this LDRD project is intended to provide input into the overall design prior to the manufacture and purchase of the FFA magnets. While radiation resiliency tests have been performed elsewhere, the results often only cover a very small part of the parameter space required to gain a full understanding of the impact of radiation on permanent magnet materials. Please see Ben Shepherd’s work [2] for a comprehensive survey on similar studies that have been performed, including resources and references. These studies will contribute to ongoing worldwide studies of permanent magnet degradation due to radiation exposure.

PLANS AND METHODOLOGY

This section will describe the plans and methodology for our work, including setup, acquisition of data, and simulations.

Radiation Environment Characterization

To determine the accumulated doses that our samples will be exposed to, we needed to determine where to place them and get preliminary dose measurements. The first step was to map the CEBAF machine in likely installation locations, and measure the integrated doses. Then, we will install at a variety of locations which will give a range of different doses and radiation profiles. The following list summarizes the work.

- Dosimeters (optichromic rods and optically stimulated luminescence (OSL) area monitors) were placed around the CEBAF accelerator based on historical radiation data, institutional knowledge, and estimates from known beam physics in the regions. Figure 1 shows where dose information was gathered, and where permanent magnet samples will be installed.
- Integrated dose rates were determined by dosimeter readings after known exposure periods ranging from two to six weeks.
- The NDX system (Neutron Dose Rate Meter with Extended Capabilities [3], Fig. 2) will be utilized to pro-

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SUMMARY OF ERL2024 WORKING GROUP 1, BEAM DYNAMICS AND INSTRUMENTATION*

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Abstract

Working Group 1 of the ERL2024 Workshop was devoted to beam dynamics and instrumentation. Optimization techniques played a prominent role in the session, and were applied to injector design and machine operations. There were presentations on designs of future ERLs, including the beam dynamics studies required to verify machine performance. We heard about simulation techniques for beam breakup instability and injectors lines. In many of the presentations, measurements played an important role, and in particular one presentation focused on techniques for simultaneously measuring accelerating and decelerating beams in an ERL return loop.

OVERVIEW

The beam dynamics and instrumentation working group encompassed a wide range of topics. There were presentations on machine optics design, both for machines that are yet to be operated [1–6] and for existing machines [7, 8]. Many of those studies used advanced optimization techniques [3–8], often inspired by modern machine learning techniques, frequently but not exclusively applied to the injectors of the ERLs [3–8]. While injectors are often simulated with multiparticle tracking codes to incorporate space charge forces, one presentation showed that computationally efficient fast envelope tracking methods could match the accuracy of multiparticle tracking simulations [9].

Multiparticle beam dynamics simulations are important for ERL design. Clearly the space charge effect must be considered in injector design, and a large number of presentations described simulations of this phenomenon [1, 2, 4–9]. Presentations also showed simulations of the beam breakup instability [1, 10] and coherent synchrotron radiation [2].

There were presentations on instrumentation in operating ERLs [11–13]. In some cases optimization techniques were combined measurements to improve machine performance [11] or calibration [13].

ADVANCED OPTIMIZATION

We heard about optimization techniques being used for both machine design and tuning. These included the use of genetic optimization [3, 5–8], Bayesian techniques [4, 11],

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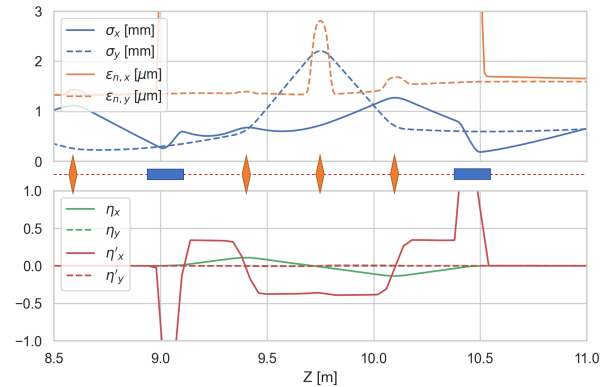


Figure 1: Merge dogleg, simulated with ASTRA [14] for BriXSinO [15, 16] after optimization with GIOTTO [3].

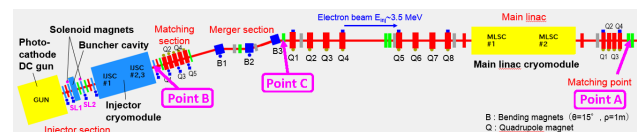


Figure 2: cERL injection line through just downstream of the main linac. Labeled points show where performance criteria were evaluated during the optimization process [8].

and a more traditional local minimization based on Newton's method [13].

Injector Design

Injector design was the application to which optimization techniques were most frequently applied.

Rossetti Conti and colleagues developed a tool for genetic optimization called GIOTTO [3] that is tailored to accelerator lattice design applications. Unlike traditional multi-objective genetic optimization routines that scan a wide parameter space and attempt to find a Pareto front, GIOTTO creates a single fitness function, that is based on a sum of Lorentzian functions representing the objectives, optimizes that single function, and tends to lead to searching in a desired direction in the parameter space. Using ASTRA [14] as the underlying tracking engine, they presented results of applying their software to the BriXSinO [15, 16] injector [3]. Optimizations were done for the gun through the end of the injector cryomodule, and for the achromatic merge dogleg (Fig. 1). To accomplish the latter, a post-processor, RotnSlice, was implemented to GIOTTO to handle physical coordinate system rotations and thus better enable dispersion optimization. GIOTTO is also capable of optimizing target parameters at multiple locations in the beam line.

SUMMARY OF WORKING GROUP 5 - FACILITIES

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Abstract

Since the postulation of the ERL principle by Maury Tigner in 1965, there have been many ERLs in operation. At the current time, there are three operational SRF ERLs: cERL (Japan), CBETA (USA) and S-DALINAC (Germany). The next generation of ERLs is under construction with bERLinPro (Germany), MESA (Germany) and PERLE (France). There are future projects, thinking about using an ERL, e.g.: at the TRIUMF e-Linac (Canada) and BriXSino (Italy).

INTRODUCTION

In working group 5 (WG5) session, we organize the facility report at ERL2024 workshop. There are 8 talks in WG5 at ERL2024 workshop. In this report, we will overview our WG5 talks.

ERLS IN OPERATION

cERL

Compact ERL (cERL) at KEK has been dedicated to R&D for industrial applications as a test facility since 2017, such as the EUV-FEL project for the future lithography light source [1–3]. In FY2023 commissioning, we demonstrated the high current CW operation with a low electron charge, and IR-FEL demonstration with energy recovery at a high electron charge, respectively.

For a high-current CW operation, it is critical to reduce the radiation level, in other words, the signals of the photomultiplier loss monitors should be reduced by beam tuning with a low-current burst operation. The locations of the loss monitors are shown in Fig. 1. In 2023, we successfully operated at approximately 1 mA beam current after installing the two undulators with small beam losses, which are achieved by manual optics tuning with the beam loss monitor. However, predicting the beam halo and tail formation is difficult, therefore, we introduced the Bayesian optimization to minimize all the signals simultaneously. Figure 1 shows an example of machine learning, in which the two collimators are used as variable parameters. For evaluating machine learning, the collimator tuning is demonstrated without manual tuning from a bad condition, in which the maximum current is

limited to 0.14 mA. It works well and finds successfully a condition for 0.6 mA and almost 1 mA step by step.

We tried IR-FEL demonstration with energy recovery while the first light in 2020 was observed without energy recovery. It is challenging because the injection energy should be small to transport the merger and dump chicane. We succeeded in observation of the IR-FEL signal and energy recovery although the transmittance is very low.

In addition, the preparation is underway to realize 10 mA operation by intensifying the power supply of the electron gun and the radiation shield of the collimators. We plan the regenerator FEL scheme to improve the IR-FEL intensity.

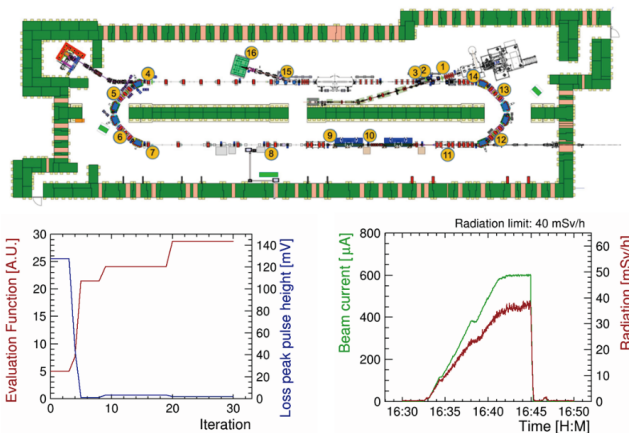


Figure 1: Top: Location of the loss monitor with high sensitivity for low current beam tuning. Bottom left: Trend of the evaluation function and the loss monitor response during the Bayesian optimization. Bottom right: Average beam current and the area monitor during the high current operation.

CBETA

CBETA [4], the Cornell-BNL ERL Test Accelerator (Fig. 2) is a 4-pass energy recovery linac built at Cornell University [5]. It accelerated beam to 150 MeV in four passes through the linac, and was capable of being configured for fewer accelerating passes if desired. It used a single fixed field alternating gradient (FFA) return arc for all four design