

# ERL 2024

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on Energy Recovery Linacs

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## Working Group

Beam dynamics

Sources

Superconducting RF

Applications

Facilities

Sustainability

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# 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<br>for high current | Beam tuning<br>for high current | IR-FEL<br>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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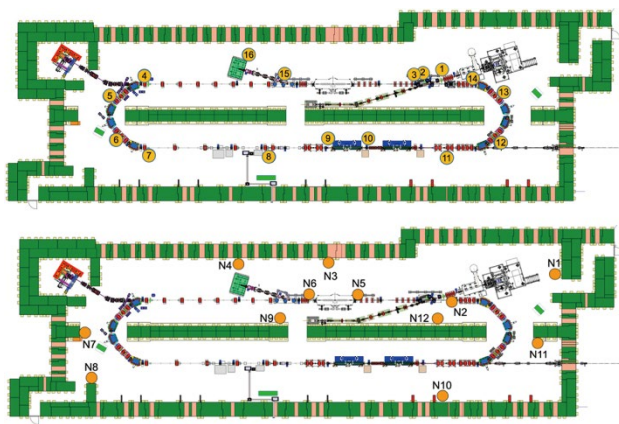


Figure 1: Location of loss monitors. Top: Photomultiplier loss monitor with high sensitivity, Bottom: Area radiation monitor for high current operation.

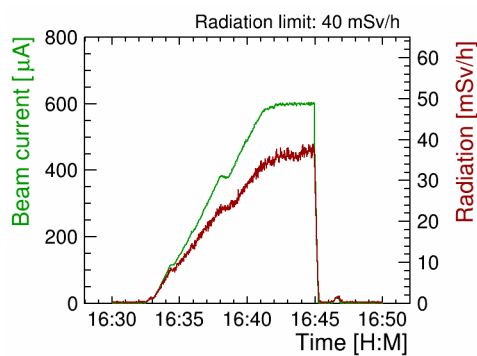


Figure 2: Average beam current and area monitor during the high current operation.

In such a severe condition, almost 100% core beam is transported to the main dump with energy recovery at the low current. For an average beam current of 1 mA, the beam loss at the recirculation loop should be maintained at less than  $10^{-4} \sim 10^{-5}$ , however, it is impossible to estimate the beam loss less than a few percent with the Faraday cup current monitor at the main bam dump. Therefore, the sensitive beam loss monitors are used in the beam tuning at a low current to treat the beam halo and tail. The locations are shown in Fig. 1 (top).

Two collimators around the injector chicane are used to cut the beam halo and tail at low energy region. It should be carefully tuned not to cut the beam core. After fixing the beam optics and collimators, the beam current is increased by checking the 12 area monitors in Fig. 1 (bottom). Figure 2 shows an example of the response of the area monitor, which is not should exceed the safety threshold.

At the previous beam commissioning in FY2022, the maximum average beam current is limited to less than 0.25 mA due to the severe beam loss. It is difficult to predict the halo and tail formation, especially at the undulators, therefore, machine learning with the Bayesian optimization is used for optics optimization, in which the quadrupole magnets are used as variable parameters to reduce the loss monitor response [5].

The halo and tail should be removed at the collimators, otherwise, most of them are lost after accelerating up to the full recirculation beam energy and increase the radiation level. On the other hand, the radiation shields of the collimators are insufficient. To take into account the balance, we also used machine learning using the collimator position as variable parameters.

The first 1 mA operation was successful with the conventional manual tuning for machine inspection. For evaluation of the machine learning, the collimator tuning is demonstrated without manual tuning from the bad condition, in which the maximum current is limited to 0.14 mA. It works well and successfully finds 0.6 mA and almost 1 mA step by step. The evaluation function during the beam tuning at 0.6 mA is shown in Fig. 3. Figure 2 shows the beam current during the high current operation.

At the beam condition optimized for high current, the photomultiplier loss monitor has almost no signal. Nevertheless, there are cases, in which the area monitors exceed the threshold at the high current operation. Therefore, the gafchromic films are used to precisely identify the beam loss position, which depends on the beam optics and orbit at every tuning.

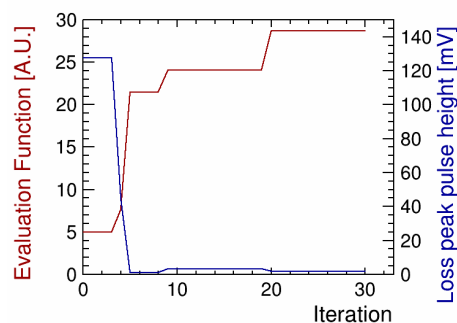


Figure 3: Trend of the evaluation function and loss monitor response during the collimator tuning.

## FIRST TRIAL OF SASE-FEL WITH ENERGY RECOVERY

Another laser system at 81.25 MHz for the electron gun is equipped for SASE-FEL demonstration. The repetition rate of the burst is controllable with the same pulse intensity. It makes it possible to maintain the bunch charge constant with 60 pC from low to high average beam current. It is important for the high current operation because the best optics and collimator positions depend on the bunch charge. The laser system was moved to a new laser hutch.

To demonstrate the energy recovery with SASE-FEL, the injection energy is set lower than the previous commissioning even though the space charge effect increases. Figure 4 shows the signal of IR-FEL and the beam current monitored with the Faraday cups. The IR signal is successfully observed at the undulator. On the other hand, the transmittance is very low: 30 % and 3.6 % just after recirculation and energy recovery, respectively. It is considered to have occurred by the beam loading because the transmittance is different in the 1  $\mu$ s pulse duration as shown in Fig. 4.



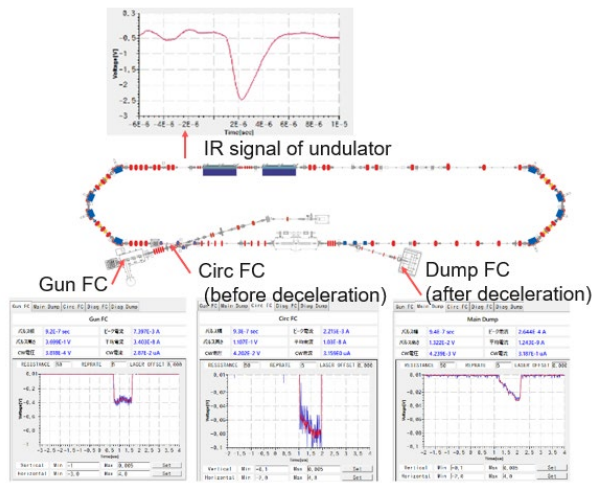


Figure 4: Energy recovery operation with SASE-FEL. Gun FC, Circ FC and Dump FC are located just after the electron gun, the recirculation loop, and after the energy recovery, respectively.

## OTHER RELATED BEAM STUDIES

The target of the average current is 10 mA. The preparation is underway to realize it by intensifying the power supply of the electron gun and the radiation shield of the collimators. At the limited beam commissioning time, three hours of operation is demonstrated at 0.8 mA without acceleration to verify the vacuum components and condition at the beam dump [6].

In addition, the efficiency of the energy recovery is measured at several pathlengths of the recirculation loop. The results are consistent with the simulation.

## FUTURE PLAN

The EUV-FEL is the candidate for the future light source for lithography because it has the advantage in terms of the upgradability to shorter wavelength (beyond EUV) and variable polarization control [7]. In addition, the electric power consumption per scanner is low compared to the conventional laser-produced plasma (LPP) EUV laser system. The schematic is shown in Fig. 5. The cERL is used as the platform for the development of key components such as the superconducting accelerator cavity and the electron gun. In addition, we are redesigning the whole scheme because it is essential to make the accelerators size down, which is larger than the LPP system. The double loop scheme and regenerative FEL oscillation [8] are proposed as options.

## CONCLUSION

Almost 1 mA CW operation is successfully demonstrated at cERL for the first time after installing the two undulators. At the other operation mode of SASE-FEL, the IR signal is observed with 3.5 MeV injector energy. The energy recovery is expected to be successful by the beam loading correction.

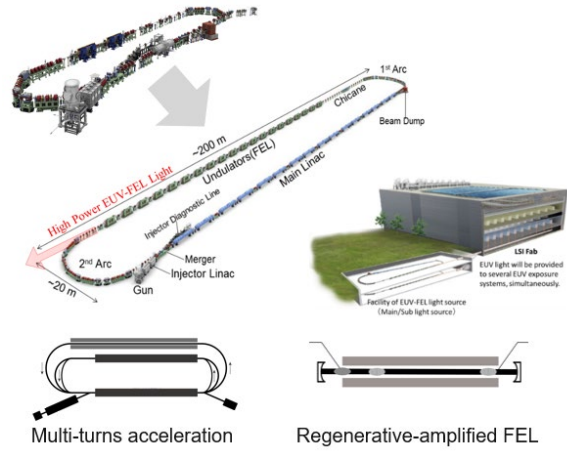


Figure 5: Schematic of the future EUV-FEL light source and the design works for reducing the accelerator size.

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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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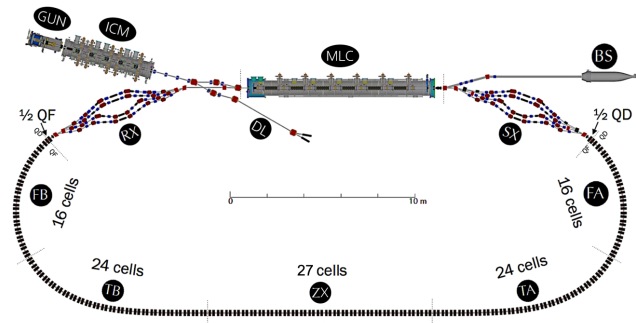


Figure 1: Layout of CBETA.

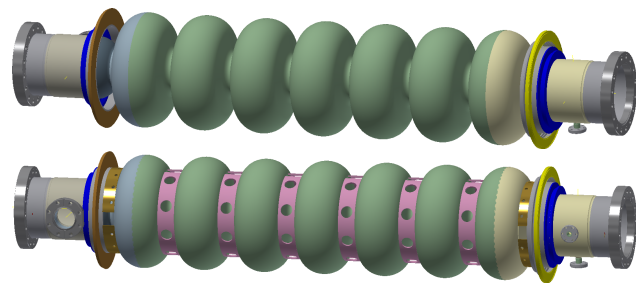


Figure 2: Unstiffened (top) and stiffened (bottom) cavities in the MLC [5].

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).



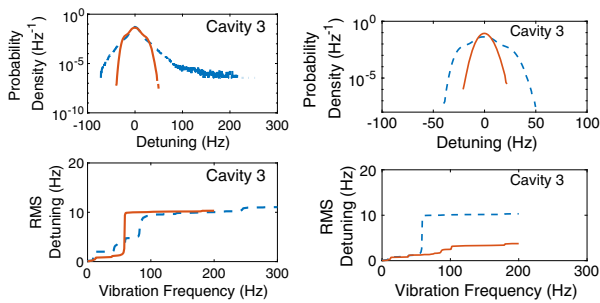


Figure 3: Impact of vibration reduction (left) and active microphonics compensation (right) on measured cavity microphonics [6]. Blue dashed lines are before compensation, solid orange lines are after.



Figure 4: The FFA return arc, showing individual magnets. Red magnets are the focusing quadrupoles, other magnets are defocusing, the color indicating which type of defocusing magnet is used. FA and FB contain the arc cells, ZX contains the straight cells, and TA and TB contain the cells making up the adiabatic transition.

### FFA Return Arc

The FFA return arc transports beams at all of the design energies for most of the circumference of CBETA. It accomplishes this by consisting entirely of doublet focusing cells with the defocusing magnet generally having a dipole component to its field. At the ends of the return arc, the cells bend by 5 degrees each, and in the center there is a straight section. In between these there are 24 cells on each side which adiabatically transform the arc cell lattice functions to those of the straight cell (Fig. 4). The return arc is constructed from Halbach style permanent magnets [4]. There are 5 types of magnets (Fig. 5): a single focusing quadrupole, one of which is used in each cell, and four types of defocusing magnets, three of which have a dipole component to their field. The straight cells use the defocusing magnets with no dipole component, the arc cells use one of the types, and the two remaining types are used in the transition region, with their displacements individually adjusted to optimally match the orbit over the entire energy range from its energy-dependent value in the arcs to zero in the straight [7].

Orbit correction for all passes simultaneously is managed with horizontal and vertical dipole correctors that surround each magnet.

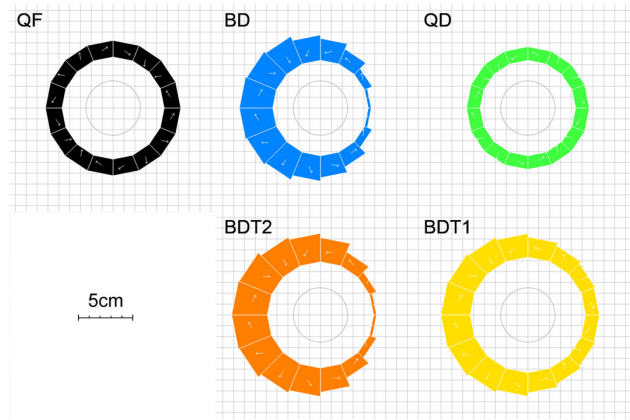


Figure 5: Permanent magnet arrangements and magnetization orientation in the five types of permanent magnets used in the FFA return arc [4].

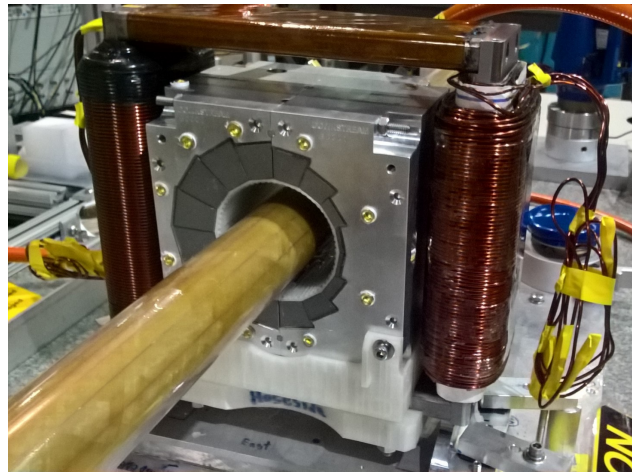


Figure 6: Permanent magnet within a rotating coils measurement apparatus. The permanent magnet blocks within the aluminum frame can be seen, as well as the Panofsky dipole corrector that surrounds the magnet [8].

### Permanent Magnets for the FFA

The permanent magnets used in the FFA return arc are Halbach style, meaning they have a number of permanent magnet blocks arranged around the beam pipe with their magnetization directions having different orientations around the aperture. There is no iron inside the permanent magnet blocks (before correction, see below), so the fields from the blocks almost exclusively determine the field within the aperture. Figure 5 shows the arrangement of the permanent magnet blocks in the FFA magnets. The blocks are supported in a aluminum frame whose temperature is maintained by a water flow system to avoid changes in magnet strength due to changes in the temperature of the environment (see Fig. 6).

After being assembled, each magnet has its field measured by a rotating coil (Fig. 6). To reduce the magnitude of unwanted multipoles and reduce the difference of the integrated strength of the design multipoles from their design

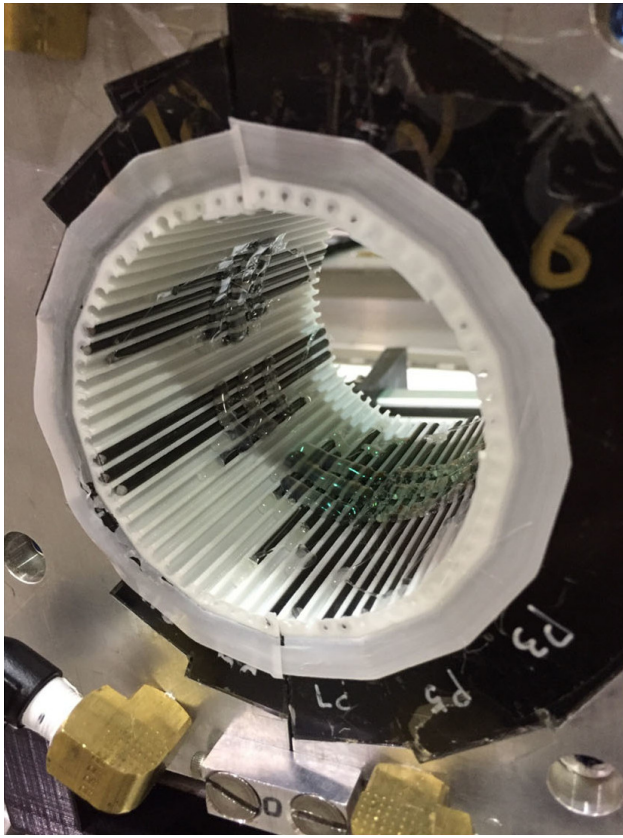


Figure 7: Plastic cylinder with iron rods for field error correction inside of a permanent magnet [4]. Water lines for temperature regulation can be seen at the bottom.

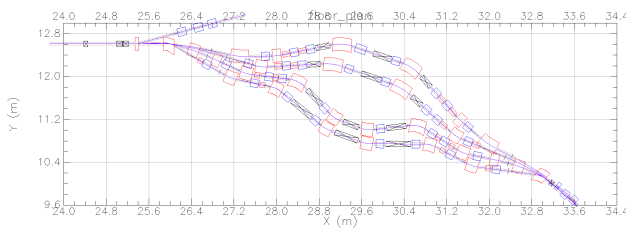


Figure 8: Splitter line layout. Blue rectangles are quadrupoles. The black rectangles in the central region are sliding joints for path length adjustment.

values, iron wires are inserted into a plastic cylinder that lies just inside the magnet aperture (Fig. 7). The magnet is then measured again, and the process repeated if necessary. The resulting field errors in the magnets were reduced by about an order of magnitude to an average of less than 3 parts in 10000 [4].

### Splitter and Recombiner Lines

For each design energy in the return loop, we need to achieve the following:

- The beam must return to the linac at the proper phase.
- $R_{56}$  must have the desired value for longitudinal dynamics and instability control.

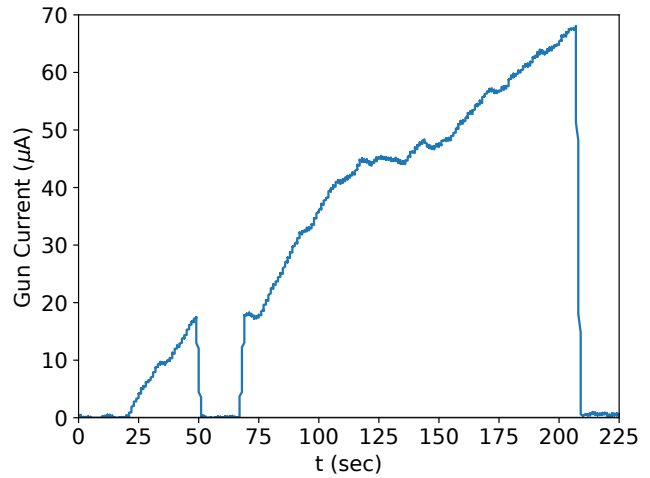


Figure 9: Average beam current at the gun during a test determining maximum operating current in 1-pass operation [9].

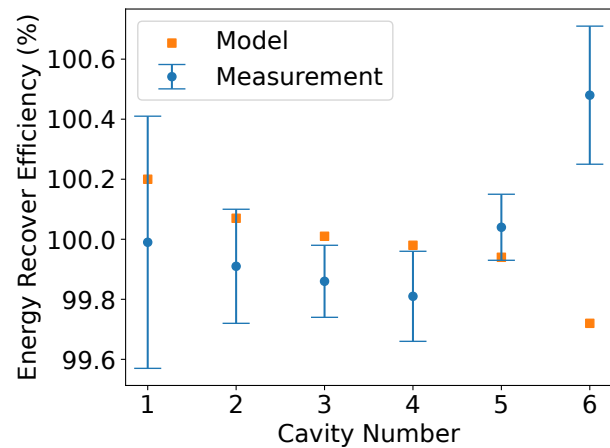


Figure 10: Measured efficiency of energy recovery for individual cavities in the MLC during 1-pass operation [9]. The efficiency is 1 minus the net energy delivered to the cavity divided by the energy delivered to the beam during acceleration. Results are corrected for particle losses. Values predicted by the machine model are also shown.

- The lattice functions at the linac must be matched to the lattice functions at the FFA arc.

These requirements must be met for each individual energy. Doing so mandates the use of individual beamlines for each energy, which are significantly shorter than the return loop. These are the splitter (SX) and recombiter (RX) lines that can be seen in Fig. 1. Figure 8 shows the splitter lines in more detail. Each line contains three sliding joints which allow for a small amount of path length adjustment. Each line also has 8 quadrupole magnets to match the lattice functions and set  $R_{56}$ . The vacuum chambers in each of the three lower energy lines can be replaced to configure CBETA for any number of passes.

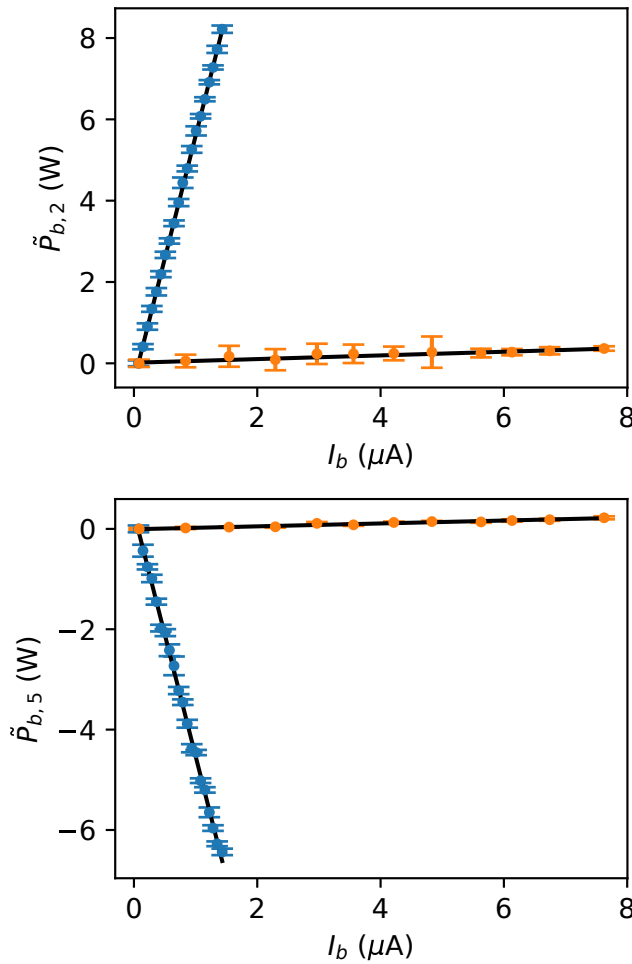


Figure 11: Measurement of net power delivered to the second (top) and fifth (bottom) cavities in the linac. Blue symbols are when only one pass is made through the linac, and the second cavity is accelerating and the fifth cavity is decelerating. Orange symbols are when both accelerating and decelerating passes are made through the linac. The slopes of the lines are used for the efficiency calculation [9].

## IMPORTANT ACHIEVEMENTS

CBETA was operated in 1-pass and 4-pass configurations. In this section I will summarize the primary achievements in each of those operating modes.

### 1-Pass

For 1-pass operation, the beam was injected at 6 MeV, accelerated to 42 MeV, then decelerated back down to 6 MeV [9]. The machine was able to operate with a current of nearly 70  $\mu\text{A}$  (Fig. 9). We believe we could have reached 1 mA, but the fast shutdown system was not operational, and the beam dump entrance was not fully shielded, so radiation limits prevented higher current operation.

During 1-pass operation, we measured the energy recovery efficiency in each individual cavity [9]. While we had designed a set of cavity phases so as to have energy balanced perfectly at each cavity, RF phase jitter made this operation

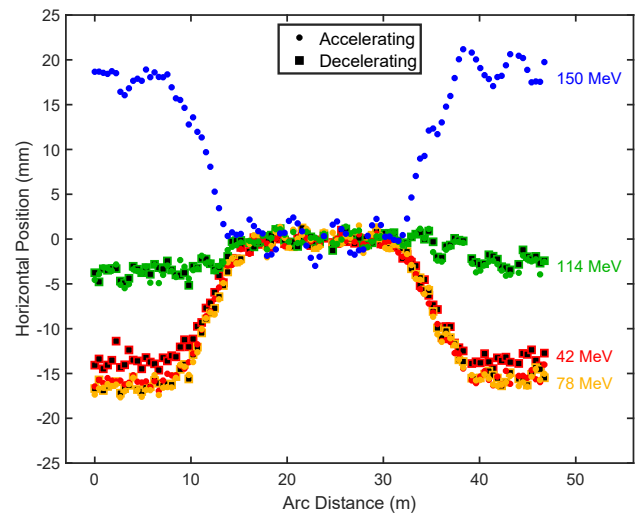


Figure 12: Beam positions at each cell in the FFA arc during 4-pass operation after correction [10]. Colors indicate the energies of the orbits. Both accelerating and decelerating beams are shown, indicated by symbol shape, for all energies except 150 MeV.

mode unstable. So instead we set all of the cavity acceleration phases to 1 degree to reduce the impact of phase jitter on beam energy, and performed our measurement in that configuration. In this configuration we do not expect a perfect energy balance at each cavity; Fig. 10 shows the expected efficiency of the individual cavities in the linac. This resulted in an energy at the dump line about 1 keV above the injection energy of 6 MeV. The measurement was performed by first configuring the linac for a single pass with 3 accelerating cavities followed by 3 decelerating cavities to calibrate the measurements of power delivered to the cavity for a given current. Then the machine was reconfigured for energy recovery, and the power was measured again. The measurements for two of the cavities are shown in Fig. 11. The efficiencies computed from those measurements, corrected for beam loss, are shown in Fig. 10, demonstrating that CBETA is capable of producing high power beams while delivering only a tiny fraction of that power to the beam through the MLC.

### 4-Pass

Operation with 4 accelerating and 4 decelerating passes was the most notable achievement of CBETA [10]. The machine ran in this mode with a low operating current (1 nA with 5 pC bunch charge). Operating in this mode required that the orbits would be corrected simultaneously at 4 different energies in the common FFA return arc (Fig. 12). With the exception of the final decelerating pass, accelerating and decelerating orbits with the same energy followed each other closely.

We demonstrated excellent agreement between our model of the machine and measurements. We measured tunes for a range of low energies and our design energies in the FFA return arc, and had excellent agreement with our machine



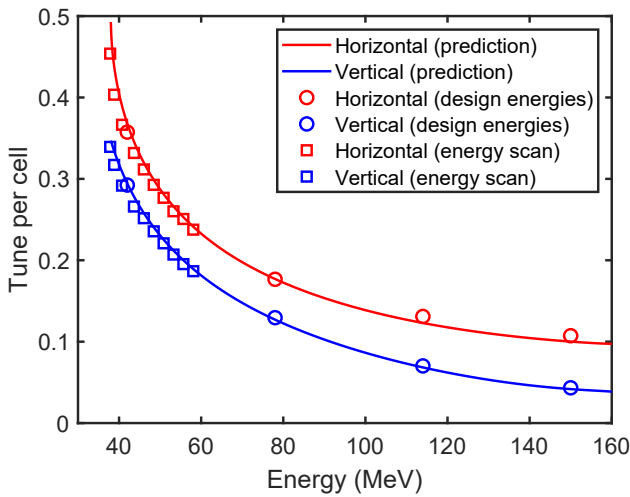


Figure 13: FFA return arc cell phase advances [10]. Symbols show measured values at the design energies from the beam circulating in 4-pass operation, and values measured at lower energies during a single pass energy scan [11]. Curves are from a model based on field maps for the FFA magnets.

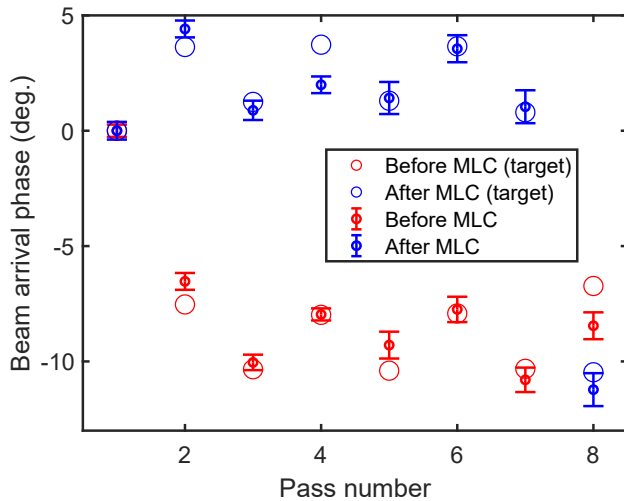


Figure 14: Arrival phases before and after the MLC for each pass in 4-pass operation [10]. Decelerating phases are relative to  $180^\circ$ . Measured and design values are shown.

model (Fig. 13) [10]. Linac phases agreed well with our design (Fig. 14), and adjusting the return path lengths to match those phases to the design was essential to transporting the beam through all passes [10].

## CHALLENGES

We encountered numerous difficulties operating CBETA. Many of those challenges were addressed, but other issues remained that could profitably be studied and addressed in future operations and upgrades.

### RF

RF stability and control created numerous problems during operation. RF phase and voltage fluctuations and often

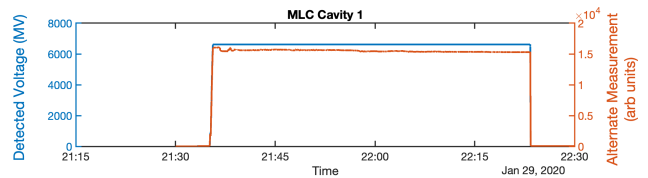


Figure 15: Two measurements of RF voltage in an MLC cavity versus time [12].

related RF trips made operation challenging in some configurations, made it difficult to operate the machine for long periods, and at times required us to operate some cavities at lower voltages than desired. Many of those issues were successfully addressed in our commissioning process [6]. However, there was a long-term drift in the RF voltage arising from an inconsistency in voltage measurements that impacted amplitude control [12] (Fig. 15). In operation this was addressed by adjusting splitter line magnet fields, but for long term operation it would be essential to correct the underlying problem.

We found that the MLC cavity axes were not aligned with the BPMs outside the MLC cryomodule [13]. We were able to determine the cavity positions via beam-based measurements, and we adjusted the height of the MLC cryomodule by 3 mm based on those results.

### Splitter Lines

The splitter lines presented numerous challenges. Many difficulties arose from their compact layout (Fig. 16). When changing fields in a magnet in one line, those fields could impact the adjacent line. We constructed linear combinations of magnet currents that would allow us to vary one magnet and leave transport in other lines relatively unchanged. We also saw hysteresis effects in our magnets, necessitating development of a degaussing procedure and making machine tuning challenging. We were unable to keep the beam centered in all splitter line quadrupoles, likely due to a mismatch with the model of beam trajectories into and out of the FFA lines and through common magnets in the splitters, which required steering adjustments when quadrupole strengths were changed. Our sliding joints for path length adjustment would not move freely, making path length adjustment very time consuming. The betatron function matches in the splitter lines were highly optimized yet required large quadrupole strengths and generated large amounts of chromaticity, largely due to the fact that the magnet layout was highly constrained and dictated almost entirely by space considerations.

In 4-pass operation, we found a significant loss between the last two return passes, which we believe occurred in the 78 MeV recombiner line (Fig. 17). There is also a smaller current loss in earlier passes. We do not fully understand the cause of this, and should address this in any future 4-pass ERL operation.



Figure 16: CBETA splitter lines, viewed from the linac end [14].

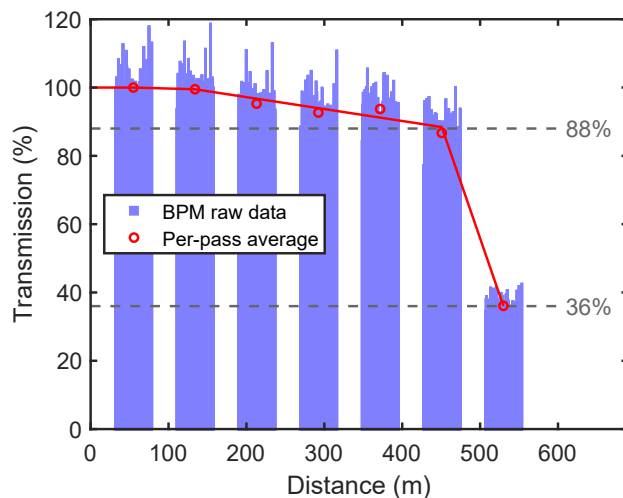


Figure 17: Beam current for each FFA return arc pass [10].

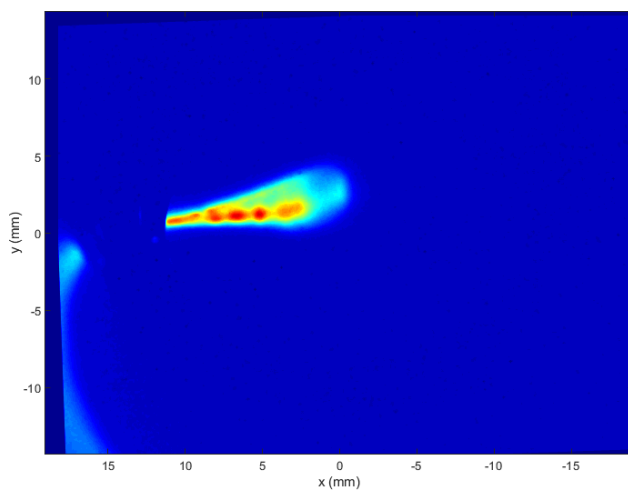


Figure 18: Beam distribution for a 2.5 pC bunch charge at the entrance of the second splitter line [15], showing evidence of microbunching. Microbunching is not visible at 1.3 pC bunch charge.

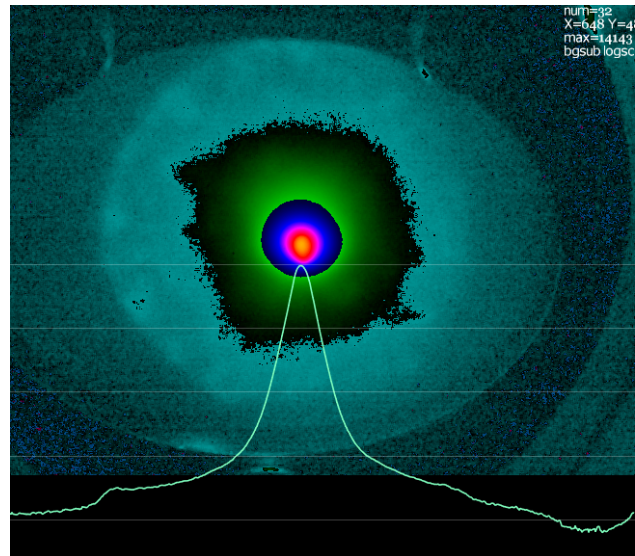


Figure 19: Composite image showing the beam halo in the injector line [16].

### Beam Dynamics

We observed evidence of microbunching at higher bunch charges (Fig. 18) [15]. We also saw evidence of beam halo (Fig. 19) [16]. Both these effects could lead to beam losses limiting the ability to run at high current. Beam halo likely was created at the cathode, and could be addressed with a cathode activated over a more limited area, or by collimating in the injector line.

## FUTURE POSSIBILITIES

CBETA is still intact, and operations could be resumed should funding become available. CBETA's capabilities are similar to those that might be needed for an ERL generating an electron beam for cooling in the Electron-Ion Collider (EIC) [17, 18], and thus studies at CBETA could assist in R&D for that project. The CEBAF 22 GeV upgrade plan uses a design with splitters and an FFA return arc that is very similar to CBETA [19]; studies on CBETA addressing the splitter line operation and the interaction with the FFA return loop would benefit that project. CBETA could be turned into a source for inverse Compton scattering photons by adding a new return line for 150 MeV (Fig. 20) [20].

## ACKNOWLEDGMENTS

This paper is summarizing the work of the entire CBETA collaboration; the references are a good representation of the contributors to these results.

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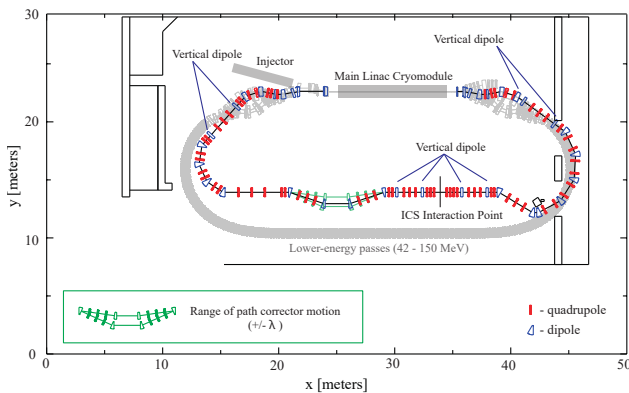


Figure 20: An inverse Compton scattering beamline that could be added to CBETA [20].

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# 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  $\beta$  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  $\mu$ 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  $\mu$ 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.  $265^\circ$
- Second recirculation beamline: Approx.  $360^\circ$
- Third recirculation beamline: Approx.  $360^\circ$

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  $\mu$ 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:

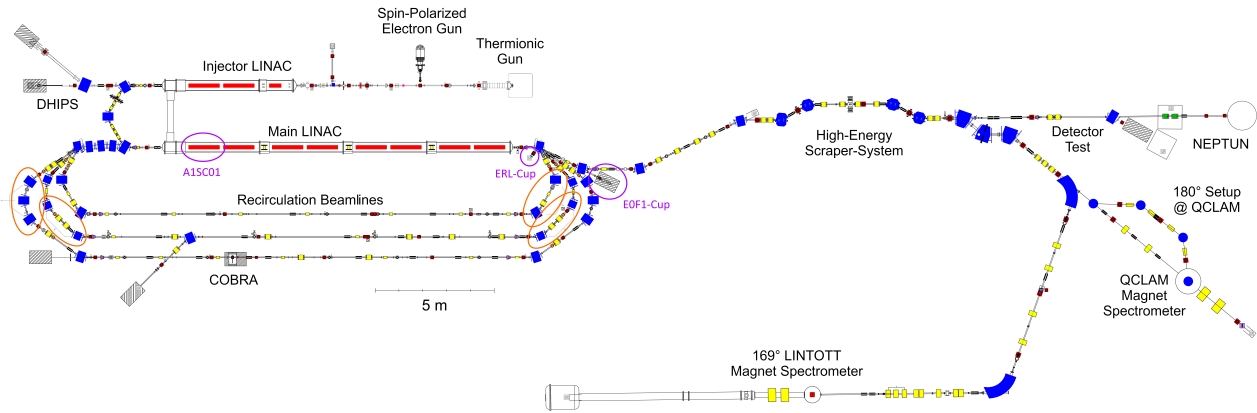


Figure 1: Layout of the facility S-DALINAC. Data was taken from the first main LINAC cavity A1SC01 (purple) and the beam dumps for ERL-mode (ERL-Cup, purple) as well as conventional acceleration mode (E0F1-Cup, purple) during the one-turn ERL measurement. The path-length adjustment systems (PLAS) of the recirculation beamlines are circled in orange.

- No beam: The RF system was running in steady state without beam. This was used as reference for the beam loading measurements.
- One beam (acc.): One beam was accelerated in the main LINAC.
- ERL operation, two beams (acc. + dec.): The machine was operated in one-turn ERL mode. In the main LINAC an accelerated and a decelerated beam have been superimposed.
- Two beams (acc. + acc.): The PLAS was tuned to change the operation mode from one-turn ERL to conventional acceleration. Two beams have been accelerated in the main LINAC here.

Table 1: Beam Loading Measured in First Main LINAC Cavity A1SC01

| Operation mode               | Load A1SC01 in W |
|------------------------------|------------------|
| No beam                      | $0.00 \pm 0.01$  |
| 1 beam (acc.)                | $4.51 \pm 0.16$  |
| 2 beams, 1xERL (acc. + dec.) | $0.45 \pm 0.03$  |
| 2 beams (acc. + acc.)        | $8.59 \pm 0.01$  |

The RF powers of the first main LINAC cavity A1SC01 as well as the beam current on the dumps corresponding to the one-turn ERL and the twice-accelerating mode have been measured during all four operation modes (for position of A1SC01 and both beam dumps see Fig. 1). The results are presented in Fig. 2. The energy recovery within the first main LINAC cavity A1SC01 can be calculated to  $(90.1 \pm 0.3) \%$ . Further details on the one-turn ERL run can be found in Ref. [16].

## TWO-TURN ERL OPERATION

In the case of a two-turn ERL, the setup is more complex: There is a higher number of superpositions in the main

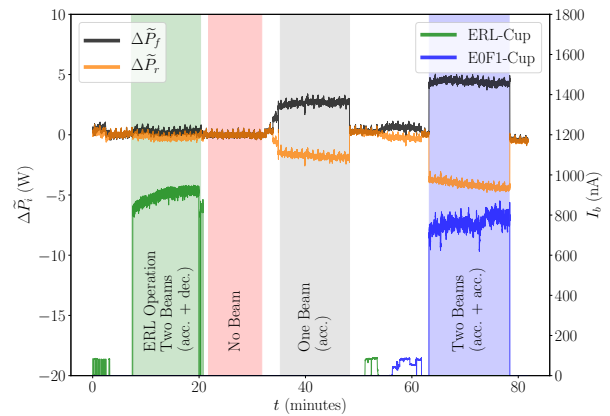


Figure 2: The changes in the forward power (black line) and the reverse power (orange line) have been measured during four different operation modes in the first main LINAC cavity A1SC01: The ERL operation with one accelerated and one decelerated beam (highlighted in green), as reference no beam (highlighted in red), one accelerated beam (highlighted in grey) and two accelerated beams (highlighted in blue). The beam current at corresponding beam dumps for ERL operation (green line) and two accelerated beams (blue line) was measured. Figure first published in Ref. [16].

LINAC section compared to the one-turn ERL, and a superposition in the first recirculation beamline. Thus, there is common recirculation transport of an accelerated and a decelerated beam [17]. As a result, quadrupole magnets located in this beamline have to focus two beams to ensure proper transport of both beams.

Furthermore, both beams traveling through the first recirculation beamline must have the same centroid momentum. The latter is influenced by the RF fields inside the cavities of the main LINAC, of which amplitudes and phases are tunable, as well as the path length covered during a recirculation. The latter can be tuned for all particles to the same extent via a PLAS and thus affects the path length of the design particle, as well. While the longitudinal dispersion can be

used to change the individual path length of the individual particles, which will have a minor influence on the centroid momentum, too, it is only used as degree of freedom to influence the correlation in the longitudinal phase space. Consequently, the most prominent difference to the one-turn ERL operation concerning longitudinal quantities is that in the case of the two-turn ERL operation the PLAS of the first recirculation beamline affects two beams. Thus, finding the correct setting for the S-DALINAC requires beam-dynamics simulations to ensure the correct momenta after each main-LINAC pass. The corresponding optimization problem can be described by [18]

$$\min \sum_{i=1}^4 f(\bar{p}_i(A_1, \dots, A_8, \phi_1, \dots, \phi_8, L_F, L_S), p_{0,i}, \epsilon_2) \quad (1)$$

subjecto to  $(A_1, \dots, A_8, \phi_1, \dots, \phi_8, L_F, L_S) \in M_2$ ,

where  $\bar{p}_i$  is the centroid momentum and  $p_{0,i}$  is the design momentum after main LINAC pass  $i$ ,  $A_j$  and  $\phi_j$  are the amplitude and phase of cavity  $j$ ,  $L_m$  is the length of a recirculation  $m$ ,  $\epsilon_2 = 1$  keV/c is the parameter defining the precision, and  $M_2$  is a set providing the technical limits of the degrees of freedom. The function

$$f(\bar{p}_i, p_{0,i}, \epsilon_2) = \begin{cases} 0, & |\bar{p}_i - p_{0,i}| \leq \epsilon \\ \left( \frac{|\bar{p}_i - p_{0,i}| - \epsilon}{\epsilon} \right)^2, & |\bar{p}_i - p_{0,i}| > \epsilon \end{cases} \quad (2)$$

is a penalty function that is utilized to provide a stop criterion in the algorithm. By formulating the optimization problem in this way, the tracking software ELEGANT [19] can be utilized for solving. After a solution has been found to the optimization problem (1), the longitudinal dispersions acting along the injector arc and along each recirculation beamline have been used as degrees of freedom to influence the momentum spread and the bunch length. Results are presented in Fig. 3. The solution of this two-dimensional optimization problem provides the longitudinal working point for the S-DALINAC, which was then tuned according to the details given in Ref. [20].

The beam tuning finally led to a stable two-turn ERL operation; operation took place for different beam currents slightly exceeding 7  $\mu$ A. For a wide range of beam currents, the beam loading of the main LINAC was measured and compared to values present in intermediate operation modes (see Fig. 4). Due to particle losses downstream of the third main-LINAC pass, not all electrons did participate in the second deceleration in the main LINAC. Thus, energy recovery was limited, which leads to a non-zero beam loading in the case of this two-turn ERL operation. The particle losses are the result of differences in Twiss parameters for the two beams traveling through the first recirculation beamline. For future beam times, the focusing has to be revised to avoid particle losses entirely. Further details on the two-turn ERL operation including numerical values are provided in Refs. [18, 20].

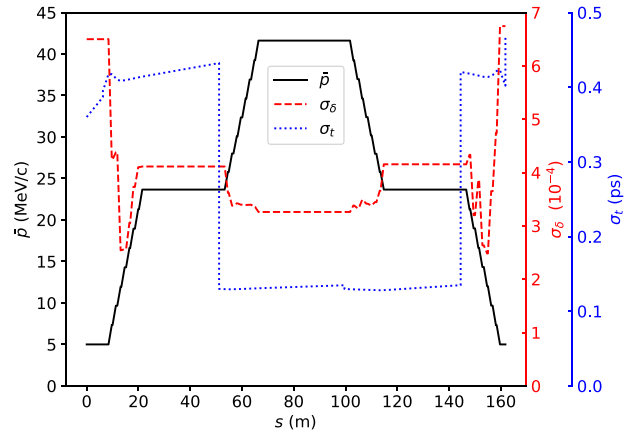


Figure 3: Simulated longitudinal quantities for the two-turn ERL, starting after the injector LINAC. Figure first published in Ref. [18]. Reproduced with permission from Springer Nature. All rights reserved.

### THREE-TURN ERL STUDY

In order to realize a three-turn ERL using all of the S-DALINAC's recirculation beamlines, the PLAS of the third recirculation had to be modified to ensure the required phase shift. This task was completed recently [15]. Furthermore, additional beam diagnostics has to be installed for beam tuning.

Similar to the two-turn ERL operation, beams are superimposed in the first and the second recirculation beamline in the three-turn mode. Ensuring appropriate transport of the electron beam requires now that the centroid of the electrons has a certain design value after six instead of four main-LINAC passes [21]

$$\min \sum_{i=1}^6 f(\bar{p}_i(A_1, \dots, A_8, \phi_1, \dots, \phi_8, L_F, L_S, L_T), p_{0,i}, \epsilon_3) \quad (3)$$

subjecto to  $(A_1, \dots, A_8, \phi_1, \dots, \phi_8, L_F, L_S, L_T) \in M_3$ .

Here, a further recirculation-path length as degree of freedom appears. The set  $M_3$  differs from  $M_2$  in its dimension since  $L_T$  has to be taken into account. The value of the parameter defining the precision  $\epsilon_3 = 630$  keV/c is larger than  $\epsilon_2$  because the number of objectives increased by two, but the number of degrees of freedom increased only by one compared to the case of the two-turn ERL. However, due to the increased number of main-LINAC passes and recirculations, the bunch's shape in the longitudinal phase space can be sheared more often, which thus supports a higher number of iterative shearings in the very phase space.

After a solution has been found to the optimization problem (3), the longitudinal dispersions acting along the injector arc and along each recirculation beamline have been used as degrees of freedom to influence the momentum spread and bunch length. Results are presented in Fig. 5.

Another outcome is that the phases and amplitudes of the RF fields of the main LINAC's cavities pairwise deviate more strongly in the case of the three-turn ERL compared to the two-turn ERL. Further details on the three-turn ERL



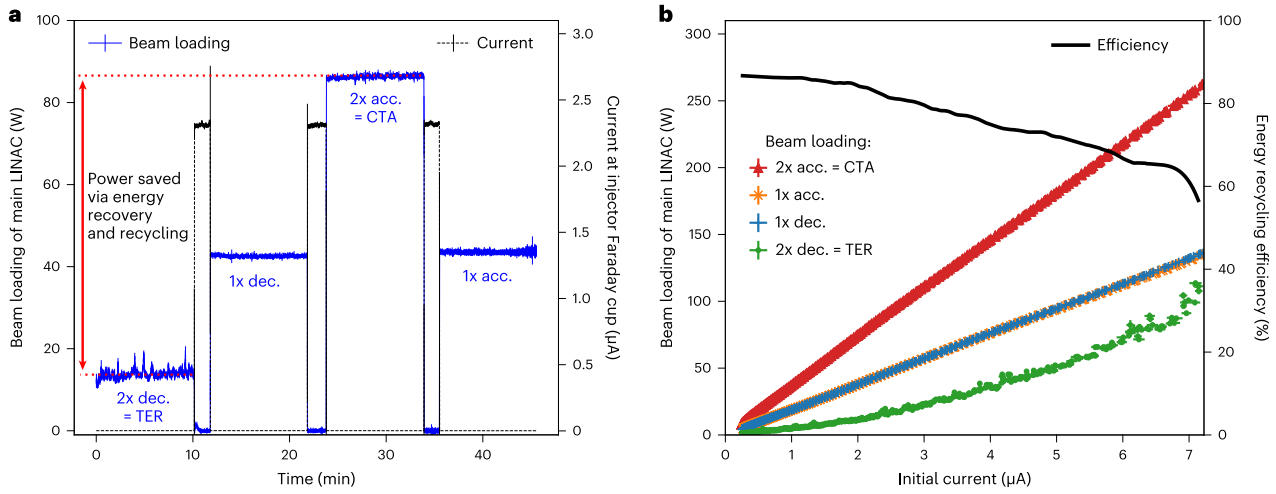


Figure 4: Beam loading of the main LINAC for (a) different intermediate modes at a given initial beam current, and (b) different intermediate modes and different initial beam currents. Highlighted saved power refers to the beam power only and does not address power saving of the entire facility. Figure first published in Ref. [18]. Reproduced with permission from Springer Nature. All rights reserved.

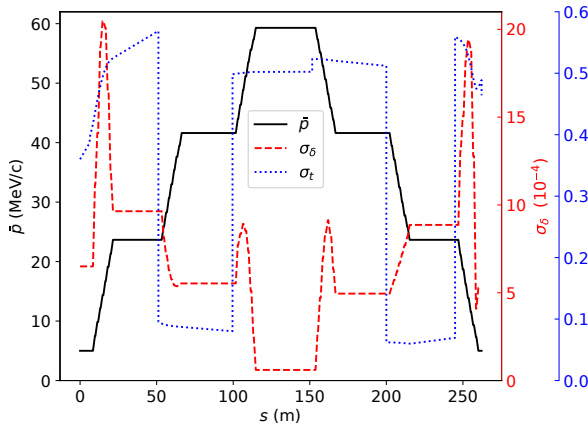


Figure 5: Simulated longitudinal quantities for the three-turn ERL, starting after the injector LINAC. Figure taken from Ref. [21].

study including numerical values are provided in Refs. [20, 21].

## COBRA: A SETUP FOR LASER COMPTON BACKSCATTERING

The ERL mode is a special operation scheme of a recirculating LINAC. On the one hand, R&D is very important to enhance the capabilities of this mode. On the other hand, the mode will be used as a sustainable driver for experiments that are suited for an ERL. These experiments have to fulfill the condition to affect the electron bunches only slightly. Thus the bunches can be guided back to the SRF system downstream of the interaction process and will be decelerated there. One possible experiment type is a collider application. At the S-DALINAC, it was decided to use a laser for the collision with the electron beam. In a Compton backscattering reaction a photon scatters off an ultrarelativistic electron and thereby gains energy in the laboratory

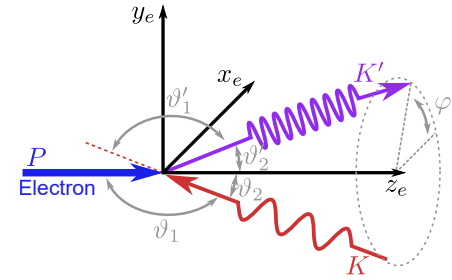


Figure 6: Compton backscattering of an incoming electron from the left (blue) with a laser photon (red) at a scattering angle  $\vartheta_1$ . The scattered photon (violet) is backscattered at the angle  $\vartheta_2'$ , at the azimuthal angle  $\varphi'$ . Figure taken from Ref. [22].

frame of reference. The process is sketched in Fig. 6. It can be exploited as non-destructive diagnostics for the electron beam.

Characterization of the electron-beam energy and energy spread is an important aspect for many experiments. In particular, laser-driven Compton backscattering (Laser Compton Backscattering (LCB)) at wavelengths in the visible range have the least influence on the electron beam. The maximum resulting energy  $E_{\max}$  of the photon after the collision can be expressed in a simple term using a double Lorentz transformation of the original photon energy  $E_p$  with  $E_{\max} = 4\gamma^2 E_p$ , where  $\gamma$  is the Lorentz factor given by the electron. The scattered photon has thus gained energy proportional to the square of the electron's total energy, the photon is boosted in energy. The detected energy of the scattered photon can therefore be used to recalculate the electron energy. However, LCB as a photon radiation source may also be of interest for applications in the field of photonuclear reactions, in particular nuclear resonance fluorescence and photoinduced nuclear fission [23]. Due to the Lorentz boost of the photons, the required photon energies in the MeV range can already be achieved for these exper-

iments with existing accelerator facilities. Nevertheless, it is worth investing in newer accelerator technologies to improve the beam quality, in terms of photon bandwidth at high flux. In addition, the energy distribution of the backscattered photons shows an angular dependence, which means that narrow-band electromagnetic radiation can be generated with simple collimation. The energy of the scattered photons  $E'_p$  can be calculated by

$$E'_p = \frac{(1 + \beta \cos \vartheta_2)E_p}{(1 - \beta \cos \vartheta'_2) + (1 - \cos \vartheta'_1) \frac{E_p}{E_e}}, \quad (4)$$

for electrons with kinetic energy  $E_e$  and the angles showed in Fig. 6. The maximum scattered photon energy only depends, apart from the incident particle energies, on the scattering angle. From Eq. (4) it can be concluded that the desired photon energy can be achieved by adjusting both the original electron and photon energy. The highest photon energy can be achieved by a head-on collision,  $\vartheta_1 = \pi$ .

The ongoing COBRA (COmpton Backscattering at a Re-circulating Accelerator) project at the S-DALINAC will in the future provide a beam diagnostics method and at the same time serve to further develop LCB sources in combination with ERLs. The COBRA project consists of three main components, in addition to the S-DALINAC itself, shown in Fig. 7: A CPA-Laser (Chirped Pulse Amplification) with beam position stabilization, the Compton backscattering source with the coupling chamber and the interaction point as well as the detector setup to measure the scattered photons.

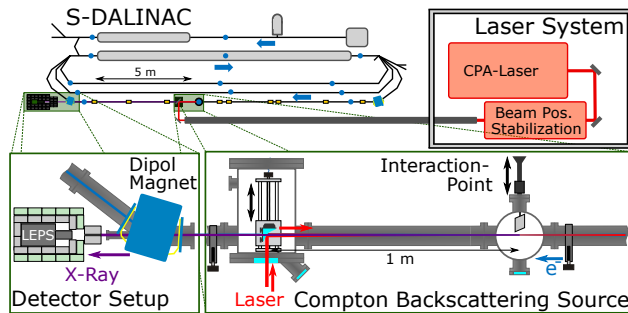


Figure 7: Schematic drawing of COBRA at the S-DALINAC. The three components of the Compton backscattering source can be seen: The laser system is located in a separate room outside the accelerator facility (top right in the drawing). The bottom right illustration shows the principle of the coupling chamber with the interaction point. The laser is brought onto the beam axis of the electrons via an off-axis parabolic mirror. The scattered photons are measured in a detector setup, shown below left. The electrons are previously deflected by the first dipole magnet in the second arc of the third recirculation. Figure taken from Ref. [22].

### Electron Beam

The coupling chamber and therefore the interaction point is located in the third recirculation beamline of the

Table 2: Parameters of the electron beam at the third recirculation of the S-DALINAC. Values taken from Ref. [22].

| Electron beam                |                           |
|------------------------------|---------------------------|
| Repetition Rate              | 2.997 GHz                 |
| Energy                       | 60 MeV to 99.45 MeV       |
| Energy spread                | 0.1 %                     |
| Bunch charge                 | <6.67 fC                  |
| Bunch length (rms)           | <1 ps                     |
| Emittance (normalized)       | 5 mm mrad                 |
| Spot size ( $\sigma$ ) at IP | 80 $\mu$ m to 143 $\mu$ m |

S-DALINAC, shown in Fig. 7. The achievable parameters at the current position of COBRA are listed in Table 2. The electron beam radius to be achieved at the interaction point is dependent on the geometric emittance of the electron beam in the third recirculation and the through-hole size selected in the parabolic mirror. Thus, with the current geometric emittance, for a round beam, of  $\epsilon_g = 4.3 \times 10^{-2}$  mm mrad for 60 MeV and  $2.5 \times 10^{-2}$  mm mrad for 99.45 MeV, a resulting minimum beam radius at the interaction point of 143  $\mu$ m or 80  $\mu$ m respectively can be achieved [22]. If a smaller beam radius is desired, the emittance of the accelerator must be improved accordingly. The electron-beam geometry and the positioning of the quadrupole magnets were optimized and checked using the tracking software ELEGANT [19]. The setup was also tested for robustness, i.e. for different electron beam dimensions (beam width and angular divergence) at the entrance to the straight line of the third recirculation, where it was shown that the beam can be focused in such a way that the same desired behaviour always exists between the IP and the hole in the parabolic mirror.

### Laser

The laser system is located in a separate laser lab and the laser beam is transported via vacuum beam transport pipes, shown in Fig. 7. The solid-state laser system (Yb:YAG), consisting of a fibre laser as oscillator and amplifier operating in a Chirped Pulse Amplification (CPA) setup, was chosen due to its good long-term stability in relation to the reference frequency of the master oscillator of the S-DALINAC and the good availability of high-quality optical components. The measured parameters of the system are listed in Table 3. In addition, a high average power, a high repetition rate and very good beam parameters such as narrow bandwidth, good beam profile and short pulse length are important characteristics for the laser system used. All parameters were measured and verified. Additionally, the beam profile and average laser power were recorded at three different positions in the beam transport line [22]. It can be seen that the laser beam retains its Gaussian profile up to the interaction point, see Fig. 8, and that the power at the interaction point has reduced minimally to 93 % of the original value.

### LCB Source

The LCB source consists of the interaction point located within a DN40CF vacuum cross and the coupling chamber

Table 3: Parameters of the CPA-Laser system for COBRA. Values taken from Ref. [22].

| Laser beam                   |                                      |
|------------------------------|--------------------------------------|
| Wavelength                   | 1030 nm                              |
| Bandwidth                    | <2 nm                                |
| Beam quality factor $M^2$    | 1.1                                  |
| Average output power         | 100 W                                |
| Pulse energy                 | 0.5 mJ                               |
| Pulse width                  | 0.8 ps                               |
| Repetition rate              | 0.2 MHz to 40 MHz                    |
| Spot size ( $\sigma$ ) at IP | 25 $\mu\text{m}$ to 50 $\mu\text{m}$ |

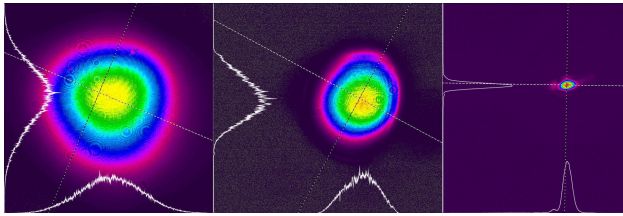


Figure 8: Laser beam profiles (from left to right) in the laser laboratory, after the beam transport and at the interaction point. It can be seen that the profile retains its Gaussian shape almost unchanged. Note that the scales of the profiles do not match as the beam images were taken for qualitative comparison. Figure taken from Ref. [22].

(DN300CF), in which the laser beam is aligned with the axis of the electron beam. Figure 9 shows the CAD model of the full vacuum setup. The electron beam, coming from the front right, first passes through the interaction point, reaches the coupling chamber, passes through a hole in the centre of the parabolic mirror and leaves the setup. Quadrupole magnets positioned in front and behind the setup are used to achieve a beam radius ( $1\text{-}\sigma$ ) at the interaction point of 80  $\mu\text{m}$  to 143  $\mu\text{m}$ . The laser beam, coming from above the coupling chamber hits the off-axis parabolic mirror, is reflected by 90° and focused at a distance of 1 m onto the interaction point with a beam size ( $1\text{-}\sigma$ ) of 25  $\mu\text{m}$  to 50  $\mu\text{m}$ . The alignment of the electron beam and laser beam to each other and relative to the structure is carried out with the aid of two scintillator targets and their imaging by cameras. If required, the targets can be moved into the beam path at the interaction point and at the location of the mirror. Since two points sufficiently define a straight line, it is possible to align the entire COBRA system at these two points with an adjustment laser beam, including the Low-Energy Photon Spectrometer (LEPS) detector and collimator.

The resulting LCB beam parameters for the scattered photons, calculated with the electron beam and laser beam parameters from Tables 2 and 3, are listed in Table 4. The resulting parameter range is given by the minimum and maximum possible electron energy and the resulting different minimum electron beam size at the interaction point.

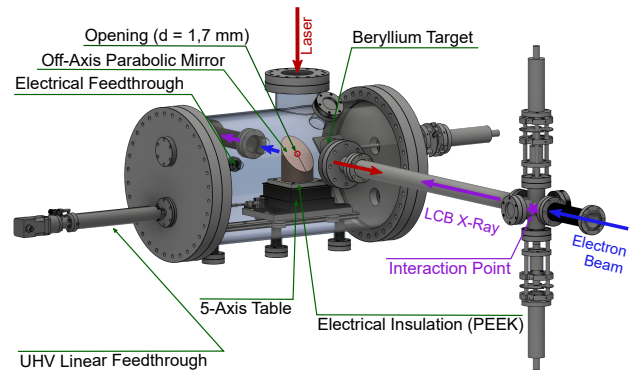


Figure 9: 3D model of the interaction area. A stainless steel vacuum chamber (the area between the flanges has been shown transparent for a view inside) with a diameter of 300 mm, called the coupling chamber is shown. Inside the chamber is the mounted off-axis parabolic mirror which directs the laser beam onto the electron beam axis. A DN40CF vacuum cross, in which the interaction point is located, is shown in the front right-hand area. Figure taken from Ref. [22].

Table 4: Design Parameters of the resulting LCB-beam for the COBRA project. Values taken from Ref. [22].

| LCB beam                 |                                          |
|--------------------------|------------------------------------------|
| Energy range             | 67 keV to 184 keV                        |
| Intrinsic bandwidth      | 0.37 % to 0.81 %                         |
| Total photon flux        | 10 837 ph/s to 32 487 ph/s               |
| Spectral density         | 0.192 ph/eVs to 0.206 ph/eVs             |
| Collimation angle        | 1 mrad                                   |
| Collimated photon flux   | 220 ph/s to 1748 ph/s                    |
| Bandwidth ( $\sigma$ )   | 0.7 % to 1.8 %                           |
| Source size ( $\sigma$ ) | 24.6 $\mu\text{m}$ to 23.9 $\mu\text{m}$ |
| Pulse length             | 1.28 ps                                  |

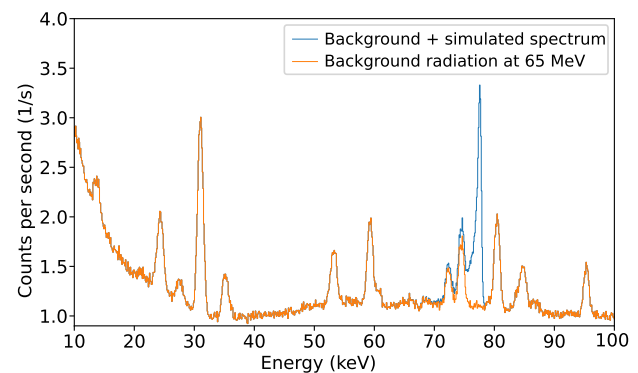


Figure 10: Radiation background spectrum at the S-DALINAC (running at 65 MeV energy and 5  $\mu\text{A}$  beam current) measured with the LEPS (orange). The same spectrum added with the simulated spectrum of the COBRA source (blue). The expected photon peak at 77.8 keV is clearly recognizable. Figure taken from Ref. [22].

### Detector Setup

The Low-Energy Photon Spectrometer (LEPS) is located directly behind the first dipole magnet of the second arc



of the third recirculation beamline. To protect the detector from the background radiation, a combined shielding of lead bricks in the inner part and polyethylene bricks in the outer part is used. The shielding was tested during a high-energy high-beam-current beam time by measuring the background radiation spectrum, shown in Fig. 10. In order to visualize the expected spectrum in comparison to the background, this was added to the background and is shown in Fig. 10. It can be seen that the spectrum of the scattered photons stands out above the background.

## CONCLUSION

An overview on the ERL-related activities at the S-DALINAC was presented. After the successful one-turn ERL mode, a two-turn ERL mode with beam currents slightly exceeding 7  $\mu$ A has been achieved. A study on the three-turn ERL mode is promising. Our research will intensify on further simulations for this setting. The LCB source COBRA as a collider-application for an ERL is under commissioning at the S-DALINAC. The first collision is expected to take place in 2025. Systematic measurements to characterize and further evolve COBRA are foreseen for the future.

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# 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.

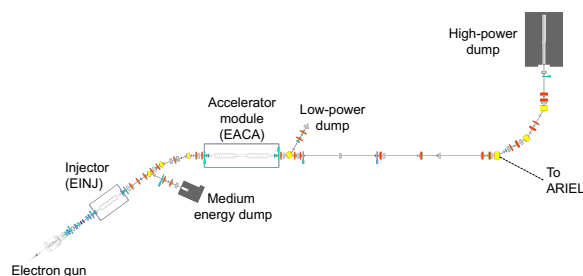


Figure 1: Current layout of the ARIEL e-Linac.

## 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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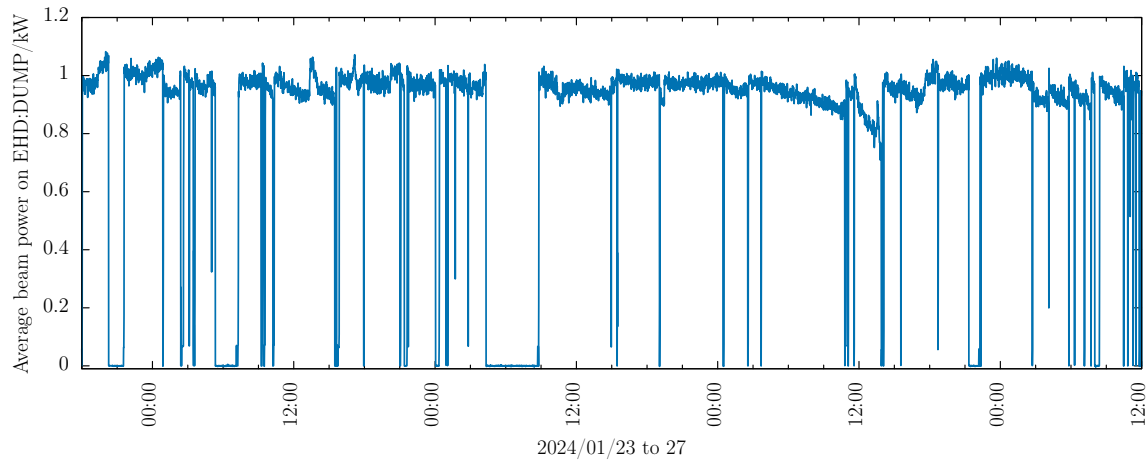
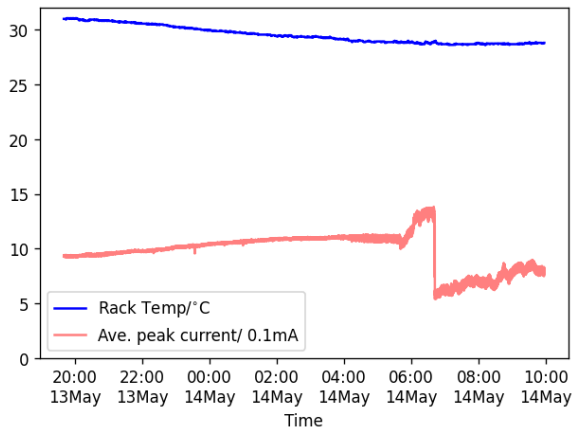
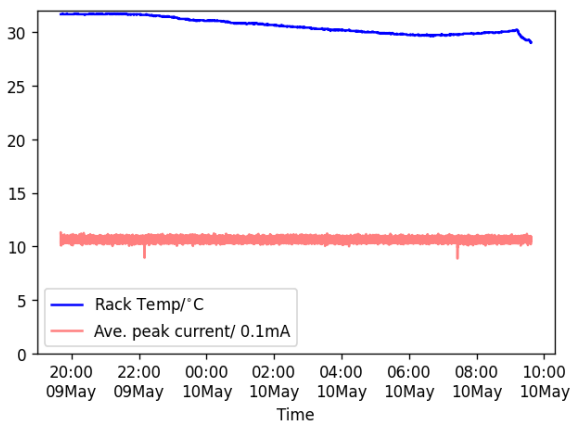


Figure 2: Average beam power on the beam dump after installing the new turbine and the re-designed e-gun matching circuit.



(a) Without PID loop



(b) With PID loop

Figure 3: After implementing PID loop, the rms of the average peak current is within 2 % regardless of any external factors, such as temperature changes.

### THz Instrumentation

As the first step in this project, we aim to demonstrate the first production of THz light using the current ARIEL

e-Linac settings. Since THz radiation intensity increases quadratically with the electron bunch charge [6], it is essential to maximize the beam current from the e-gun. To achieve this, we have pushed the e-gun to its limits to investigate the maximum achievable beam current. We successfully extracted a high-current beam of up to 17 mA (equivalent to 26 pC) at a reduced duty factor using the existing thermionic gun. Furthermore, we performed calculations to estimate the minimum achievable bunch size by optimizing the buncher and injector cavity. The results show that a sub-millimeter longitudinal beam is achievable with the present system, demonstrating substantial potential for THz light production. Consequently, we have set up a target assembly with a microwave detector downstream of the accelerating module to capture THz radiation emission.

### Magnetic Bunch Compression

The next step in this project is to install a magnetic bunch compressor. Ideally, the installation of the bunch compressor will provide hands-on experience with tuning the accelerator for bunch compression and allow us to test various THz generation schemes. A C-chicane is being considered for installation after a potential new accelerating module (EACB) and before the first split to the ARIEL target station and beam dump. The space constraint is further illustrated in Fig. 4, which shows the envelope plot of the high-energy section of the beamline.

To ensure the compressor fits within the limited space of approximately 600 cm between the EACB and the first dipole before the split, we studied its feasibility using various parameters for a typical C-chicane. Figure 5 shows examples of the results calculated using a 30 MeV beam and a 30 cm dipole effective length. Further work is currently underway to incorporate more detailed beam dynamics, such as incoherent dispersion, before finalizing the design and installation in the beamline.



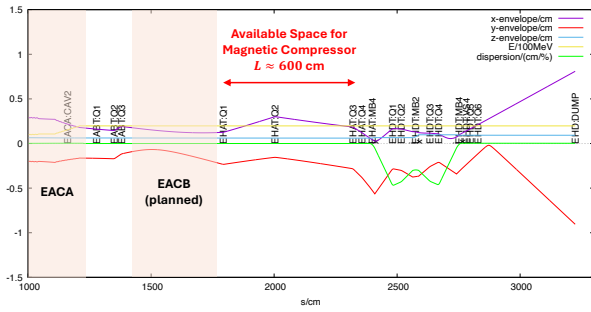
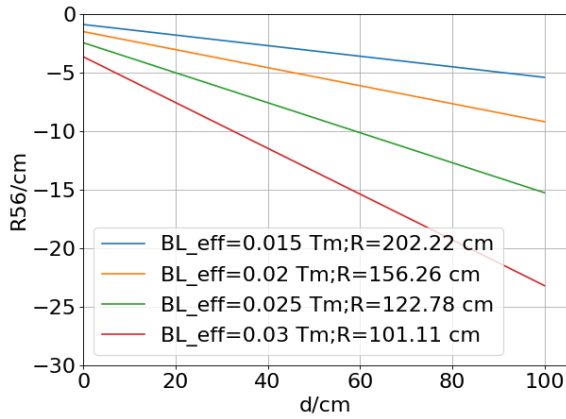
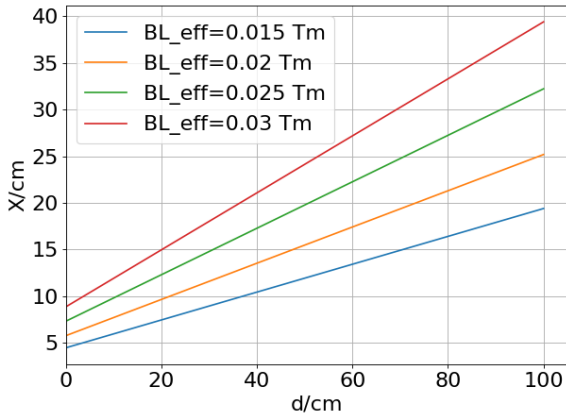


Figure 4: The envelope plot of the high energy section of the beamline. The magnetic compressor has a limited space of approximately 600 cm only.



(a) R56



(b) Horizontal offset ( $X$ ) from the main beam line

Figure 5: R56 and the horizontal offset from the main beam line plotted against the projected distance between the first two dipoles of the C-chicane.

### New High Brightness Photo-gun

The final step of this project is to install a new high-brightness photo-gun that runs perpendicular to the current low-energy beamline to produce sub-picosecond pulsed beams. This is necessary to meet the requirements for a high-brightness beam, which is essential for generating more intense THz radiation.

| Parameters                                            | Terahertz | ARIEL     |
|-------------------------------------------------------|-----------|-----------|
| Q per bunch (pC)                                      | 200       | 16        |
| Bunch length (ps)                                     | 0.1 ~ 1   | 10        |
| Beam Energy (MeV)                                     | ~ 20      | 30        |
| Energy stability                                      | $10^{-4}$ | $10^{-3}$ |
| RMS normalized transverse emittance ( $\mu\text{m}$ ) | < 10      | ~ 2       |

Table 1: Comparison of electron source requirements for ARIEL and THz project.

There are several key requirements for the new photo-gun. Table 1 summarizes and compares the key parameters of the electron beam delivered to ARIEL and the electron beam used for THz radiation production. Ideally, the bunch charge should reach up to 200 pC, and the bunch length should be less than 1 ps for THz light production. Given the high bunch charge and short bunch length requirements, a gun providing higher initial beam energy is highly desirable to mitigate the space-charge effect. We have now converged on an SRF gun as the preferred choice for the new photo-gun.

The proposed future beamline layout, which includes the new photo-gun and bunch compressor, is shown in Fig. 6. To ensure beam quality before the electron beam passes through the injector cavity, we are investigating the use of a compact achromatic bender, such as an alpha magnet, to merge the beam into the main beamline.

## CONCLUSION

The ARIEL e-Linac has made significant progress toward its goal of generating high-intensity electron beams for both rare isotope production and THz light generation. Key milestones, including successful continuous beam delivery and the implementation of a feedback control system to stabilize beam current, have demonstrated the system's reliability for extended operation. Following recent successes in high-current beam extraction and initial THz radiation tests, we are now preparing for the next phase of the project. We are evaluating two RF cavity designs as candidates for the new SRF photo-gun: a low-frequency quarter-wave resonator (QWR) operating at 4 K, and a multi-cell 1.3 GHz elliptical cavity operating at 2 K. Beam dynamics simulations are underway to identify the optimal choice between these two options. In the coming years, efforts will focus on refining the beamline design, installing critical components, and achieving the project's goals.

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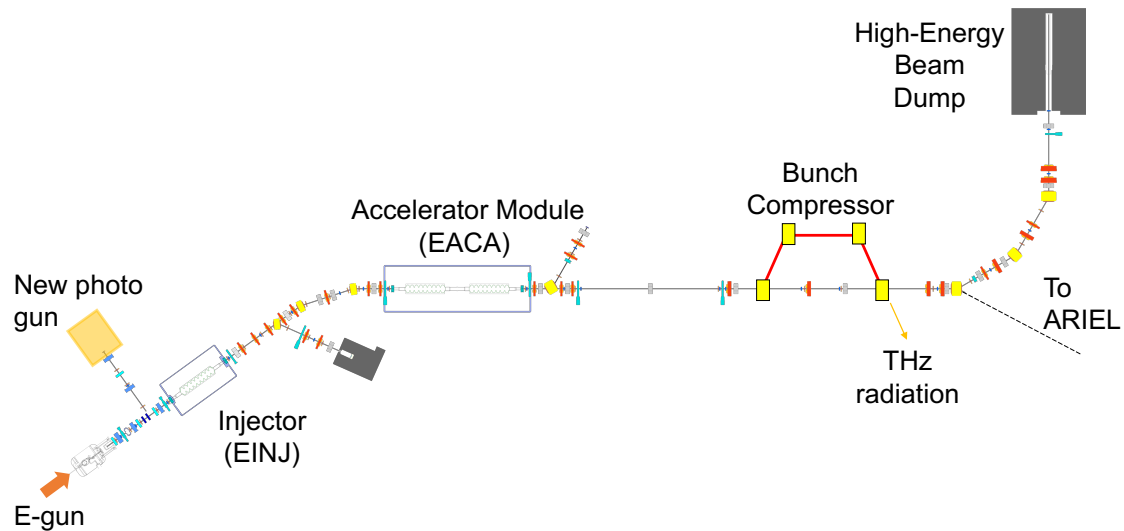


Figure 6: Sketch of a potential future e-Linac layout that enables simultaneous operation of THz light generation and beam delivery for ARIEL.

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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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optimal operation and design of helium refrigeration systems. This cycle is based upon the traditional process / equipment used for helium refrigeration system designs, *i.e.*, constant volume displacement compression and critical flow expansion devices. It takes advantage of the fact that for a given load, the expander (flow coefficient) sets the compressor discharge pressure, and the compressor sets its own suction pressure. This concept not only provides an essentially constant system Carnot efficiency over a wide load range but invalidates the traditional philosophy that the ( $T$ - $s$ ) design condition is the optimal operating condition for a given load using as-built hardware.

Fundamental aspects of the Ganni Floating Pressure process were originally conceptualized and subsequently applied to the cryogenic system for the Superconducting Super Collider Laboratory (SSCL) string test plant (known as ASST-A) in 1992 [6]. Appropriate design / modifications to existing (legacy) systems are technically feasible, as demonstrated by the BNL-RHIC cryogenic system [7]. During 2002-2007, phased modifications performed on this system (*e.g.* control system upgrade, process cycle modifications) caused an input power reduction from 9.4 MW to 5.0 MW for the same cryogenic load. However, with the scope, schedule and risks associated with different projects, it may not be always achievable.

To standardize the design of such a cryogenic system, development efforts in several areas have been carried out over multiple projects, minimizing the risk associated with a newly developed component. These developmental efforts are discussed in the following sub-sections. To date, this process cycle has been applied to several cryogenic systems including JLab [8, 9], MSU-NSCL [10], ORNL-SNS [11], NASA-JSC [12] and MSU-FRIB [13].

### Helium (4.5 K) Refrigeration System

**Helium (Warm) Compressors** The (warm) helium compressor system provides the required availability to the refrigerator / liquefier as well as the cryogenic loads and is considered the ‘heart’ of the cryogenic system. As such, the performance, reliability and maintainability of the warm compressor system are of paramount importance. Oil injected rotary screw compressors for helium refrigeration systems were introduced in the 1970’s following the recognition of their long-term operational reliability and effectiveness in approaching an isothermal compression process. At the present state of warm compressor system designs for helium refrigeration systems, typically two-thirds of the lost input power is due to the compression system. A well-matched compression system and refrigerator (cold box) system is essential for efficient operation of helium refrigeration systems, especially since there is typically a considerable uncertainties and margins involved in estimating the loads for a refrigeration system and in addition the manufacturers add their own margins to the components and system. Considering these limitations, designing a refrigeration system to a single design point goal is proved to be unwise. The conventional oil injected rotary screw helium compressor systems are restricted in the suction and discharge pressure ranges that they can operate; especially

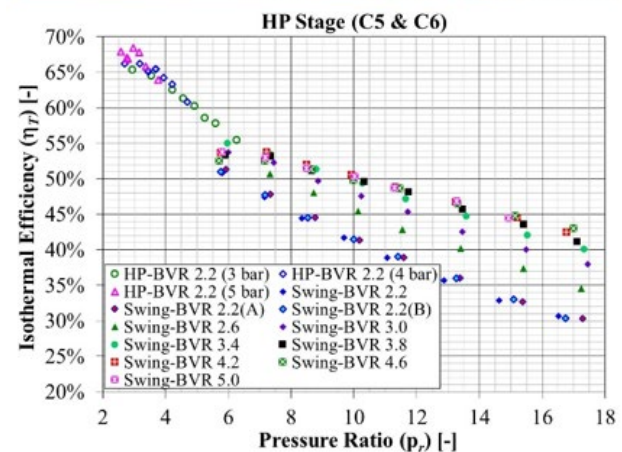


Figure 1: Installed compressor skids at FRIB (top) and measured isothermal efficiency of HP compressor skid under wide-range operating conditions (bottom).

regarding their bulk oil separation (BOS) process. The realization of the now patented Ganni – Floating Pressure Process Cycle [5] during the design of the cryogenic system for the Superconducting Super-Collider Laboratory (SSCL) became the primary motivation to design a warm compressor system capable of a wide range of operation of suction and discharge pressures. The opportunity to develop such a helium compressor skid arise during the design and specification of a 12 kW, 20 K helium refrigeration system for NASA-JSC [12] by US-DOE’s Jefferson Lab (JLab). Several modifications to the oil injection and re-circulation system (compared to traditional designs) were made. This compressor skid design was further refined for JLab’s 12 GeV upgrade project with the addition of a completely new type of bulk oil separator (BOS).

In 2013, the 12 GeV upgrade helium compression system was successfully commissioned, composed of compressor skids completely design by JLab and built-to-print by industry, demonstrating a very wide range of operation to allow full implementation of the Ganni Floating Pressure process cycle. At present, these compressor skids are being used at JLab (12 GeV cryogenic system, since 2013) [14], at the Facility for Rare Isotope Beams (FRIB) cryogenic system since 2017 [15] and at SLAC’s LCLS-II cryogenic system since 2020 [16]. Figure 1 shows the

compressor skids installed at FRIB and the measured isothermal efficiency of the FRIB HP compressor skid under a wide-range operating condition [15]. The FRIB swing stage compressor (C6) demonstrated operation from 6.0 bar to 18.0 bar of discharge pressure at approx. 1.05 bar suction pressure.

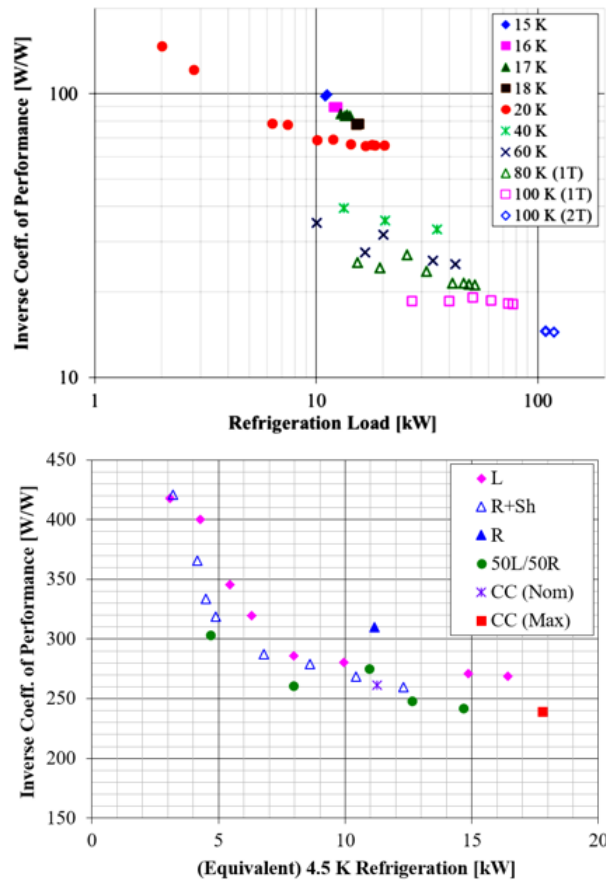


Figure 2: Measured inverse coefficient of performance as a function of the refrigeration load for the NASA-JSC cryogenic system (top) and JLab 12 GeV cryogenic system (bottom).

**Refrigerator Cold Box** Traditionally, a cold box design providing maximum efficiency (minimum operating cost) at a single design point(s) is referred to as the optimum system design. However, the demand on equipment sub-components varies substantially between the types of loads (e.g. efficient operation of a refrigerator is heat exchanger dominant, while that for a liquefier is expander dominant). Deviations from this design load involve not only a deviation in capacity, but often this indirectly also results in a deterioration in the type of load (e.g., refrigeration, liquefaction). As such, it is a superior approach to address these aspects directly in the design, and not as ancillary issues. The challenge is to envision a cycle considering these optimization goals, using real components, capable of operating close to maximum efficiency for a load varying from a maximum to minimum capacity and from full refrigeration to full liquefaction mode or in any partial load combinations. Most of the above goals can be accomplished with a system design based on a process which ‘naturally’ responds to

(follow, or track) the load. In general, pure liquefaction load (or liquefaction dominated load, e.g. a 4.5 – 30 K liquefaction required by 2.0 K compression system) governs the design / selection of expander flow coefficients and expander brake requirements, while pure refrigeration load (or refrigeration dominated load) governs the heat exchanger performance requirements and the cold end component sizing. The performance of the cryogenic system under other operating modes (e.g. minimum / stand-by capacity) are cross-checked for possible scenarios to verify that an unexpected condition does not occur. A balanced plant design considering these factors do not unnecessarily restrict the plant capacity under different modes.

The 20 K helium refrigerator installed at NASA Johnson Space Center’s Space Environment Simulation Laboratory (SESL) to support the ground testing of the James Webb Space Telescope (JWST) was the first of its kind to follow the design methodology mentioned above. The refrigeration system was designed to support a variable load from 100 kW at 100 K to 12.5 kW at 20 K, utilizing the Ganni Floating Pressure process cycle [12]. In addition to the warm compressor development, the design and requirements for turbo-expanders (nozzle, gas bearing and variable brake design) supporting such a wide range of load (approx. 2-25 kW at 20 K) was established by the vendor (Linde Process Systems) in collaboration with JLab. Figure 2 (top) shows the measured inverse coefficient of performance of this cryogenic system with various loads. The system can automatically support any loads at 20 K from 30% to 100% at practically constant efficiency without any manual interventions and with a temperature stability better than  $\pm 0.1$  K [12].

The cryogenic cold box for JLab’s 12 GeV project (Central Helium Liquefier 2) was also designed as a balanced plant taking full advantage of the Ganni Floating Pressure process cycle [17]. JLab performed the process design, sizing and selection of all major components, as well as the cold box internal component and piping design. Based on empirical data analysis by JLab during the commissioning of this system, an important parameter for the heat

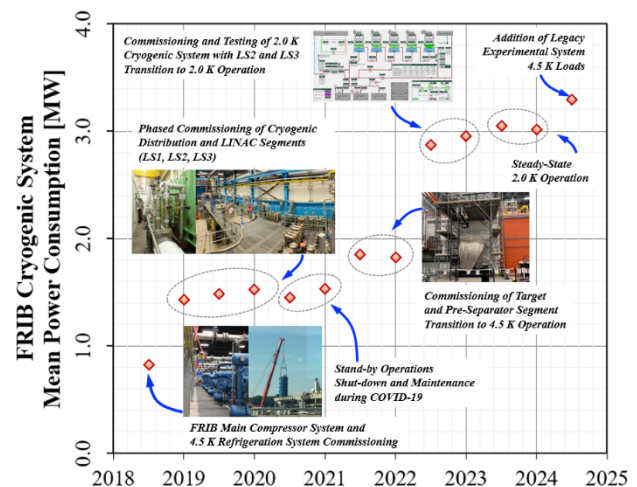


Figure 3: Progressive mean of power consumption for the FRIB cryogenic system with the increase of load over the years of accelerator commissioning and operation.



exchanger (HX) specification was realized and discussed in [9]. Based on this analysis, the 12 GeV cold box was modified by the vendor (Linde Kryotechnic) to meet the specification for the utility (LN) consumption for the LN pre-cooler stage of the cryogenic system. Figure 2 (bottom) presents the measured inverse coefficient of performance of this cryogenic system with varying (equivalent) 4.5 K refrigeration loads.

The FRIB 4.5 K helium refrigeration system is very similar to the JLab 12 GeV design [18]. Based on the lessons learned from the design and operation of the past systems, the JLab 12 GeV cold box design was adapted with minor equipment modification to match different types of loads which have approximately the same total load exergy (equivalent to approx. 18.5 kW at 4.5 K) [13]. Figure 3 shows the overall energy consumption by this cryogenic system as function of time starting from commissioning to present day (with increase of overall load due to phased commissioning of different sections of the accelerator).

### Sub-atmospheric (2.0 K) Refrigeration System

Advancement in the sub-atmospheric cryogenic compression technology over the last several decades has been driven by the increased interest in superconducting radio-frequency (SRF) cavities, which are generally required to operate at temperatures below the normal boiling point of helium (typically at 2.0 K or below, or at a saturation pressure of approx. 30 bar). The sub-atmospheric compression system is responsible for re-pressurizing (re-compression) the sub-atmospheric vapor returning from the 2 K load before injection into the main 4.5 K refrigerator at approx. 1.2 bar. Re-compression can be accomplished using cryogenic centrifugal (cold) compressors, warm vacuum compressors, or a combination of these two. For large capacity sub-atmospheric refrigeration systems (above ~ 2.0 kW at 2.0 K), the most practical approach to improve the overall system efficiency and minimize the equipment footprint, including both the refrigerator cold box size and the rotating machinery, is to use multi-stage cryogenic centrifugal compressors to fully recompress the sub-atmospheric helium returning from the load [19, 20] to above atmospheric (positive) pressure.

Since the first application of this technology in the mid 1980's [21], advancements in the turbo-machine design and manufacturing process have improved the overall efficiency of the centrifugal compressors utilized in the sub-atmospheric compression at low temperatures, increasing the isentropic efficiency of re-compression from 55 percent at Tore Supra [21] to nearly 75 percent at FRIB [22]. The recent technological developments in high-speed variable frequency motor drives with active magnetic bearings has significantly improved the operational stability and the turn-down capacity of the cold compressor train [23] compared to the systems designed in the 1990s [24] and 2000s [25].

As with turbo-expanders, although centrifugal compressors are typically designed around a single operating point, the system may not operate at the design point and at a point of maximum efficiency. It will seldom operate at a

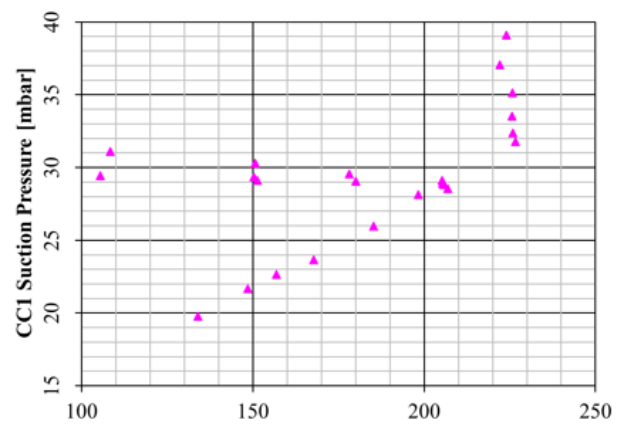


Figure 4: Variation of operating mass flow rate with sub-atmospheric system pressure for the FRIB 2.0 K cryogenic system.

single point. Hence, the overall isentropic efficiency of the cold compressor train is of secondary importance. Turn-down (and associated operational stability) of the centrifugal compressor mass flow rate is a major factor in terms of cost savings, although this may not be fully appreciated when focused solely on the sub-atmospheric system. A gram per second reduction in mass flow processed by the sub-atmospheric system can result in a 15 – 20 kW reduction of input power at the main compressor [26]. Therefore, while the centrifugal compressor train may not be locally operating at their peak efficiency, the overall cryogenic system operational cost savings from turning down the sub-atmospheric flow (liquefaction load) can significantly outweigh the energy cost savings of lower compressor efficiency. Energy savings for this kind of turn-down can only be realized if the 4.5 K refrigeration system can also turn-down efficiently over this range (as demonstrated by those using the Ganni Floating Pressure process cycle).

For full *cold-compression*, the current areas of research include optimized control with minimal complexity of multi-stage cryogenic centrifugal compressors during steady-state operation and during the transient ‘*pump-down*’ process from the normal boiling point to the sub-atmospheric load temperature (nominally, 2 K). Research interest is mainly driven by the desire for a wider range of efficient and stable operation of larger 2 K systems.

The FRIB cold compressor train was designed for a wide range of operating loads (based on the facility requirement) by the vendor (Air Liquide Advanced Technologies) in collaboration with the FRIB cryogenics department. As can be seen from Fig. 4, this system has a considerable operating range, and a turn-down of nearly 2 to 1 at the operating condition (approx. 30 mbar) [23]. The overall design and fabrication of this cold box (except the cold compressors) was performed completely in-house at FRIB. Further research and development of the pump-down, steady-state operation and control philosophy was carried out recently [26]. Predictive models based on theoretical principles were developed to eliminate reliance on empirical and statistical methods employed traditionally. Overall,



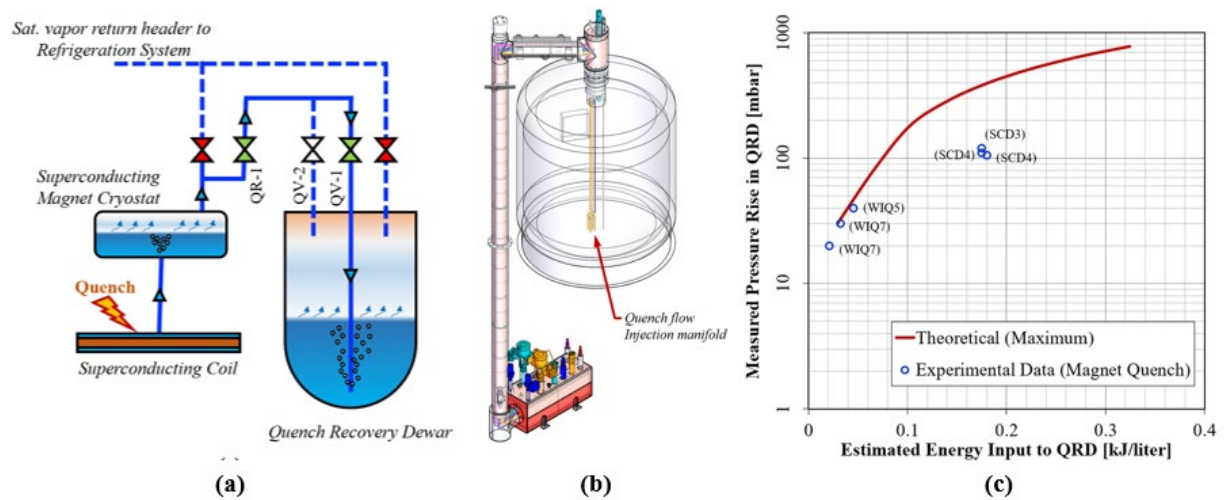


Figure 5: (a) Schematic diagram of the FRIB quench handling system, (b) 3D model of the associated cryogenic buffer vessel and (c) pressure rise in the buffer vessel from different LTS magnet testing / operation at FRIB as a function of the estimated energy input.

appreciable progress was made in understanding the physical characteristics of the multi-stage centrifugal cold-compressor sub-atmospheric system at FRIB during transient and steady-state operation. The methodology developed for the FRIB sub-atmospheric system can be applied to other large-scale sub-atmospheric cryogenic facilities utilizing cold-compression with the appropriate modifications for system and cold-compressor configurations.

### Helium Preservation Operational Stability

In low temperature superconducting (LTS) magnets built using (cryogenic) convection cooled superconductors, the operating stability and *quench* (sudden transition from superconducting to normal state) is a complex phenomenon. In most cases, the quenched LTS magnet is isolated from the rest of the cryogenic system and the cryogen (helium) is expelled from the LTS magnet cryostat via a pressure relief valve (PRV) to prevent over-pressurization. Under such conditions, this results in a loss of both the cryogenic coolant, which is release to atmosphere, and the associated stored refrigeration in the fluid. Consequently, this causes unnecessary operational cost to both replenish the helium and to recover the quenched LTS magnet. A novel method of using a cryogenic buffer volume to absorb both the mass and energy release during the quench of a LTS magnet was first conceptualized at SSCL for magnet string testing [6]. Typically, the boil-off helium generated during *quench* in a LTS magnet has a temperature in range of 4.5 - 15 K. There is a significant amount of cryogenic refrigeration stored in this boil-off flow. It can be directly injected into a pool of saturated liquid helium stored in a cryogenic buffer volume. The resulting direct contact heat exchange between the liquid helium and the flow released from the magnet quench cools the latter at the expense of generating more boil-off helium, thereby pressurizing the buffer volume. Once the boil-off flow (and energy) due to quench has been absorbed, the buffer volume and the quenched magnet can be depressurized slowly and subsequently reliquefied by the supporting cryogenic system.

This process has been designed and implemented for the FRIB experimental system superconducting magnets by incorporating a 10,000 liter (nominal) cryogenic dewar vessel [27]. The quench dewar volume is sized to store the FRIB experimental system superconducting magnet inventory in case of maintenance needs and to absorb the pressure pulse and energy released from these magnets because of a quench, while containing the helium without venting [28]. Following a quench, the stored refrigeration is recovered by the FRIB cryogenic refrigerator by depressurizing the buffer volume. This doesn't pose a risk to the refrigerator stability or operation of the rest of the loads, due to the implementation of the Ganni Floating Pressure process cycle. Schematic of the quench handling system along with the design of the associated dewar vessel are shown in Figs. 5(a) and 5(b). The quench handling system at FRIB was commissioned in April 2021 [28]. To date, there have been 20+ recorded events of a quench with the quench handling system absorbing each of these without affecting the cryogenic refrigerator or other operating magnets and without venting helium.

## PRESENT CHALLENGES

### Small-scale 2.0 K Refrigeration Systems

The optimal design of 2.0 K refrigeration system using full cold compression (*i.e.* higher efficiency, smaller footprint, and lower capital cost) becomes challenging at lower capacities due to reduced volumetric flow rates. Therefore, many modern small to medium scale systems are designed utilizing other methodologies than strictly full cold compression. Small 2.0 K (or superfluid) helium refrigeration systems, capable of providing several hundred Watts of refrigeration, are increasingly used for R&D activities associated with superconducting technology and quantum computing [29]. Typically, these are either custom design-engineered systems or what is known as direct vacuum pumping systems. The former are expensive as they are one-of-a-kind and require specialized engineering. The later are

less expensive yet quite inefficient and, in cases where the helium is not recovered because a purification system is not installed, are wasteful of a non-renewable resource that is becoming increasingly scarce within the U.S. They have the advantage of being relatively inexpensive to purchase and easy to implement but are quite power intensive. Many require more than 3200 Watts of input power per 1 Watt of cooling (at 2 K, or around 30 mbar), but can easily require twice this input power [29]. Additionally, many are plagued with contamination problems from either or both the compressor system and air in-leaks into the sub-atmospheric process, since the helium must be sub-atmospheric at some point in the process if the superfluid is being used at the load.

A preliminary process study [29] conducted at JLab indicates it is very reasonable to achieve a small-scale system efficiency of better than 1500 Watts of input per 1 Watt of cooling at 2.0 K and addresses the contamination issue. A build-to-print design for a small 2.0 K refrigeration system that can be implemented with a commercially available 4.5 K refrigerator, can combine the efficiency gains of a one-of-a-kind system with the cost savings of an off-the-shelf system.

### Helium Recovery and Purification Systems

Helium recovery and purification systems are necessary to support commissioning and operation of the cryogenic refrigerators, and associated sub-systems used in particle accelerators. These systems are typically designed for removing low level impurities (*i.e.*, in parts per million), since even the trace amount of impurities can block and/or change the flow distribution of refrigerant (helium) and be detrimental to the cryo. system and reliable operation of the accelerator. For low level contamination, experience suggests [30] elimination of the traditionally used molecular sieve bed, in favour of freezing out the moisture on a properly designed heat exchanger. Of course, the design of this heat exchanger is critical to maximize time between regeneration cycles (*i.e.*, maximizing the moisture and air removal capacity) and to minimize the liquid nitrogen consumption. However, the specifics of the heat and mass transfer involved in this process have not been sufficiently investigated to a sufficient level to provide adequate engineering direction in the design of such equipment. Consequently, commercially available helium recovery (compressor) and purification systems have significantly higher cost of operation (utilities – power and liquid nitrogen consumption) and have short times required between regeneration cycles, *i.e.*, they have low moisture and air removal capacities. These systems are also difficult to operate and regenerate, requiring complex operational scrutiny. Research and developmental efforts are presently being carried out at FRIB / MSU Cryogenics Initiative to better understand the underlying physics of contaminant freeze-out [31] and helium oil mixing process for small-scale compressors.

## SUMMARY

A set of progressive and synergistic development activities have been carried out over the last couple of decades that lead to the complete understanding and deployment of the Ganni Floating Pressure process cycle and complementary sub-systems at several cryogenic systems in the USA. The Ganni Floating Pressure process can be implemented for most refrigeration and/or liquefaction cycles (new or existing systems) to achieve improved efficiency at the design load as well as reduced loads and for mixed modes of system operation. In this cycle, the pressure ratio remains constant for all practical purposes and thus maintains the maximum efficiency over a wide operating range as compared to the other cycles. Additionally, these systems also result in maximum system stability, lower operating temperatures (pressures) at the load and thereby improving the experimental envelop. Stable and efficient long-term operation of several cryogenic system has been demonstrated at multiple US-DOE particle accelerator facilities. Some practical challenges relating to cryogenic sub-systems (helium recovery, purification) and scalability (small-scale 2.0 K) remains to date and are being actively pursued by the community. The MSU-FRIB Cryogenic initiative to train the future generation work force is actively involved in advancing the understanding and application of various modes of 2.0 K cold compressor operations, warm helium compressor efficiency improvements, helium recovery from magnet quenches without venting, helium purification and preservation of the helium inventory. These advancements are of critical importance to FRIB and the other existing and future superconducting accelerators.

## ACKNOWLEDGEMENT

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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.

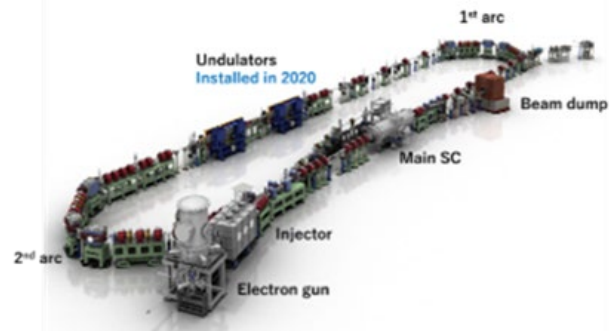


Figure 1: Layout of cERL.

## 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 Tuning at cERL – One Example

In order to address the issue of radiation level reduction, a series of trials have been conducted. These trials involved the tuning of both the beam and the collimator in burst mode, as well as the operation of the beam in CW mode. Figure 2 shows a comparison of the beam structure between burst and CW mode. In order to combat the occurrence of beam loss, the implementation of loss monitors at designated points along the beam line, as well as the installation of collimators at the entrance and the midpoint of the merger section, has been proposed.

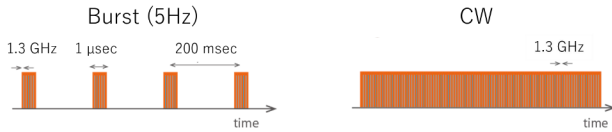


Figure 2: Burst mode and CW mode.

The following example illustrates the implementation of beam adjustment through the use of Bayesian optimization. cERL is equipped with two undulators, utilized for the generation of free-electron lasers (FELs). Due to the confines of the chamber's oval-shaped design, with a 50-millimeter major axis (horizontal) and an 8-millimeter minor axis (vertical), dedicated beam tuning is imperative. This is essential to ensure the reduction of radiation levels in the surrounding region, which is crucial for maintaining high current CW operation. The cERL beamline is equipped with sixteen loss monitors for interlock, and the undulator section is outfitted with four loss monitors to facilitate observation and monitoring of any associated losses.

The selection of the combination of 8 quadrupole and steer magnets around undulators is made for the purpose of beam tuning. Figure 3 shows the results of machine learning beam tuning. The direction of machine learning tuning is such that the evaluation function is increased and the loss signal is decreased at the undulator section as shown in the left figure. Concurrently, machine learning traverses a safe parameter space, thereby achieving optimization without interlock from loss monitors due to the explosion of the beam loss signal, as shown in the right figure.

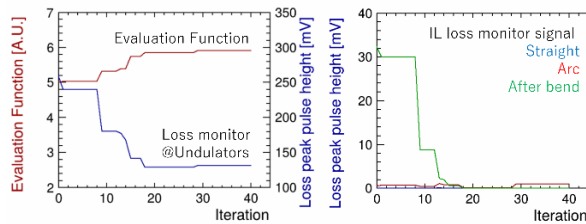


Figure 3: Machine learning beam tuning. The left figure shows the trend of parameter search iteration, and the right figure shows the loss monitor signals at three parts.

## AUTO-BEAM TUNING FOR CW OPERATION

The automatic beam tuning process was executed in a manner consistent with the manual tuning procedure. The initial condition manifested as some loss signals in burst mode.

To mitigate beam loss, magnet tuning was performed at undulator section, upstream of the dump bend, and before the dump. In addition, beam loss at the first arc was suppressed by collimator adjustment, which was realized also using machine learning.

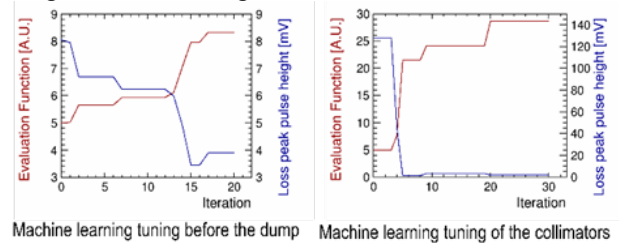


Figure 4: Machine learning beam tuning at cERL.

As illustrated in Figure 4, the Bayesian optimization process yielded two distinct outcomes. The left side of the figure depicts the tuning process in front of the dump, while the right side illustrates the simultaneous tuning of the two collimators. The machine learning demonstrates optimal functionality under conditions of loss signal suppression. It maintains beam transmission to the dump at approximately 100% during burst mode, while concurrently exhibiting effective reduction of loss monitor signal. As demonstrated in Figure 5, following the implementation of machine learning-based beam tuning, a comparative analysis of the loss monitor signals on the beamline was conducted. The results of this analysis indicated that the loss monitor signals were effectively suppressed subsequent to the beam tuning procedure, which was executed in burst mode. Subsequent to the implementation of machine learning beam tuning, CW operation was conducted, resulting in an augmentation of the beam current from 140  $\mu\text{A}$  to 600  $\mu\text{A}$ . A comprehensive study of hyperparameters is imperative to ascertain the efficacy of Bayesian optimization in enhancing optimization outcomes. Moreover, the development of a strategy for machine learning beam tuning is essential to achieve comprehensive overall beamline loss suppression, thereby enabling 1 mA CW operation following machine learning tuning.

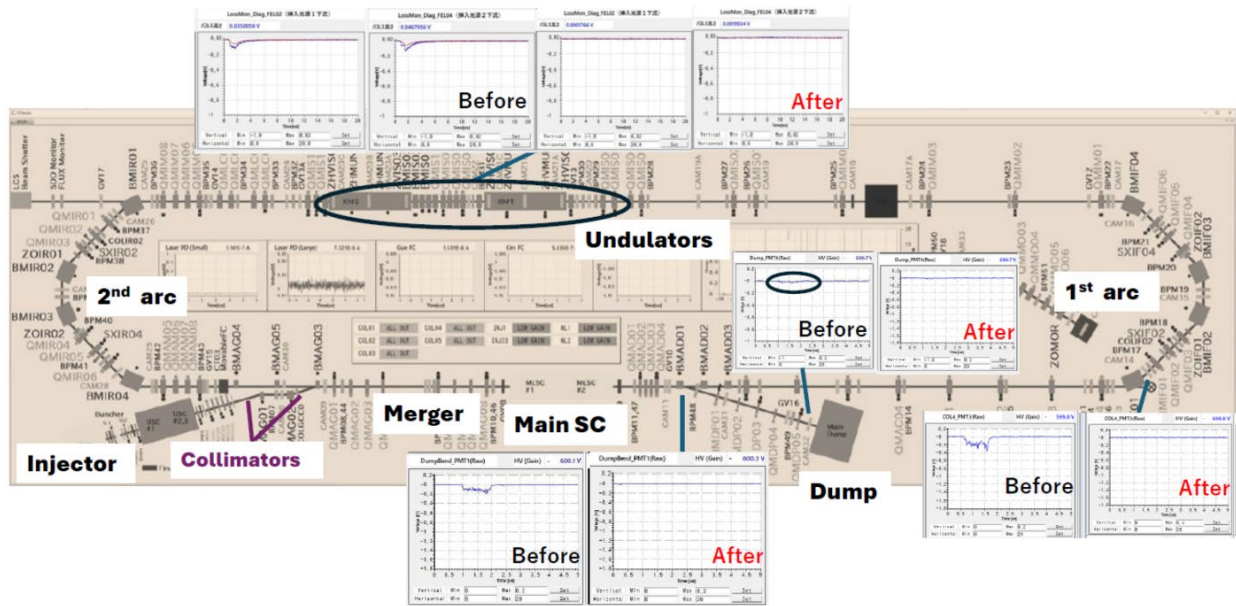


Figure 5: cERL beamline and the comparison of the loss monitor signals between before and after machine learning beam tuning.

## SUMMARY

The cERL is currently investigating the potential of implementing auto-tuning for high current and low beam loss operation. Preliminary findings suggest that this approach may hold promise in achieving the desired outcome. Machine learning has the capacity to balance the high current and loss reduction condition simultaneously. Thorough beam loss reduction is important and necessary for high current beam operation. To realize that, the following study is necessary:

- A detailed study of hyperparameters
- A strategy for efficient beam tuning

The subsequent steps will focus on the optimization speed and its application to more realistic scenarios. In the context of future high-current beam operations, such as

10 mA, the most significant challenge will be the integration of a beam loss signal strategy for the large number of loss monitors (O(100)) that are planned for installation.

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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

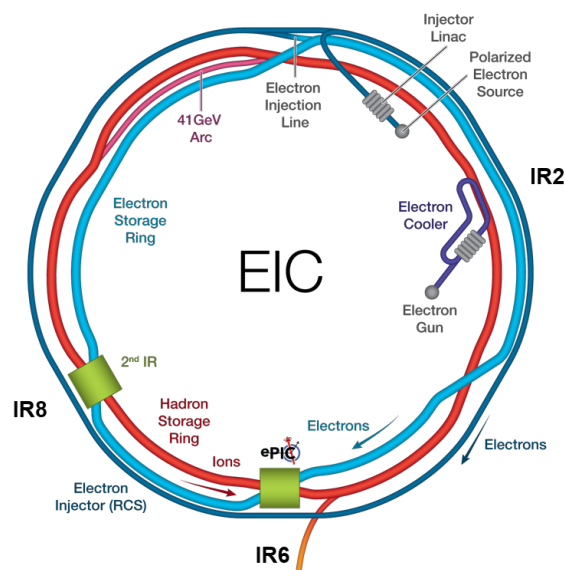


Figure 1: The current layout of a portion of the Electron-Ion Collider (EIC). The Hadron Storage Ring (HSR), Electron Storage Ring (ESR), and the Rapid Cycling Synchrotron (RCS) labels are color-coded to their respective rings; the current and proposed IRs are shown at IR6 and IR8, with the electron 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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Table 1: The electron beam parameters for the two proton beam energies. The electron beam longitudinal distribution is assumed to be a supergaussian of order  $\sim 4$ .

| Proton Energy                       | 100 GeV | 275 GeV |
|-------------------------------------|---------|---------|
| Gamma                               | 107.6   | 294     |
| Energy (MeV)                        | 55      | 150     |
| Bunch charge (nC)                   | 1       |         |
| Rep. rate (MHz)                     | 98.5    |         |
| Avg. current (mA)                   | 98.5    |         |
| rms bunch length (mm)               | 9       | 7       |
| Peak current (A)                    | 10      | 13      |
| Slice energy spread $dp/p(10^{-4})$ | 0.6–1.5 | 0.4–0.8 |
| Norm. trans. emit. (mm-mrad)        | 2.8     |         |

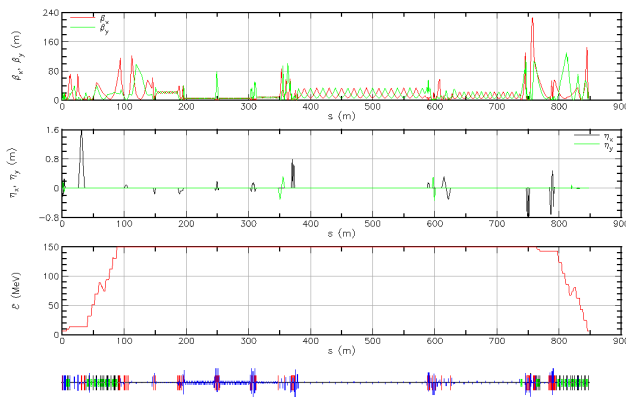


Figure 2: The closed design optics for the 150 MeV mode of the SHC-ERL. Shown are the beta functions in meters (top), dispersion in meters (middle), and the beam energy in MeV, all as a function of  $s$  in meters. Below the three plots is the component layout.

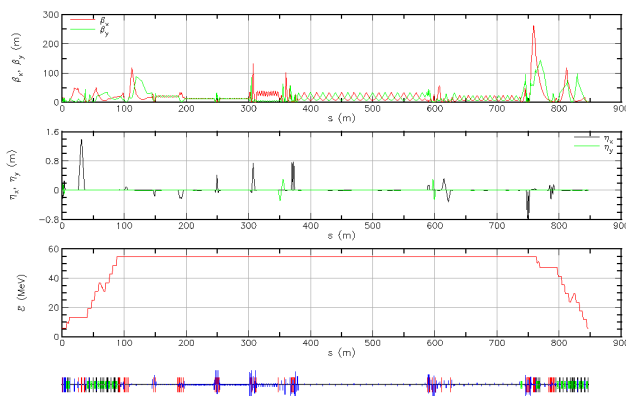


Figure 3: The closed design optics for the 55 MeV mode of the SHC-ERL. Shown are the beta functions in meters (top), dispersion in meters (middle), and the beam energy in MeV, all as a function of  $s$  in meters. Below the three plots is the component layout.

– after which, the beam begins energy recovery. Alternatively, the beam can be steered through the merger into the diagnostic line. The injector consists of a photocathode DC gun and a cryomodule containing three superconducting radiofrequency (SRF) cavities – two 197 MHz quarter-wave resonators (QWRs) and a 591 MHz single-cell cavity. The beam is accelerated to roughly 6 MeV and the accelerating cavities are run off-crest so that the bunch is chirped; the single cell cavity is at the third harmonic of the 197 MHz frequency and is used to linearize the longitudinal phase space.

The booster consists of two cryomodules, oriented so that the cavity order is two 197 MHz QWRs, two 591 MHz, and two 197 MHz QWRs. The beam energy is roughly 13 MeV, the bunch is significantly chirped, and the single cell cavities are again used to linearize the longitudinal phase space; however, the longitudinal phase space is evaluated after the bunch compressor in the following section.

Next, the beam enters the PX section, which consists of the P1, P2, and P3 lines. Each line is energy-specific and during the acceleration of both configurations, the 13 MeV beam goes down the P1 line, which compresses the bunch; bunch compression is tunable due to the quadrupole magnets included in the compressor.

Following the PX section is the main linac, consisting of eight 591 MHz five-cell SRF cavities and four 1773 MHz five-cell SRF cavities, with the 1773 MHz cavities placed in the center and four 591 MHz cavities on either side. The beam is accelerated to the top energy of either 150 or 55 MeV and is no longer chirped. Similar to the injector and booster, the longitudinal phase space is linearized with the 1773 MHz cavities.

The dump chicane and the laser heater chicane follow the main linac, after which the beam is transported to the cooling section, which consists of the modulator, amplifier, and kicker. After the cooling section, the beam separates from the HSR before entering a Bates bend and going down the return line.

At the end of the return line is a 591 MHz five-cell SRF cavity, which is run at the zero crossing and chirps the beam, minimizing the energy spread of the beam at the dump. Without this chirp cavity, the only way to minimize the energy spread is to have the beam energy at the dump to be significantly different than the 6 MeV injection energy.

After the return line is a second Bates bend – following this, the high energy line merges with the injection line, and the chirped beam begins deceleration and energy recovery. The beam is decelerated during the second pass through the booster, then enters the PX section. For the second pass through PX, the beam enters either the P2 or P3 beamline, corresponding to the 55 and 150 MeV modes, respectively. During the second pass through the linac, the beam decelerates to the injection energy and is transported to the beam dump.

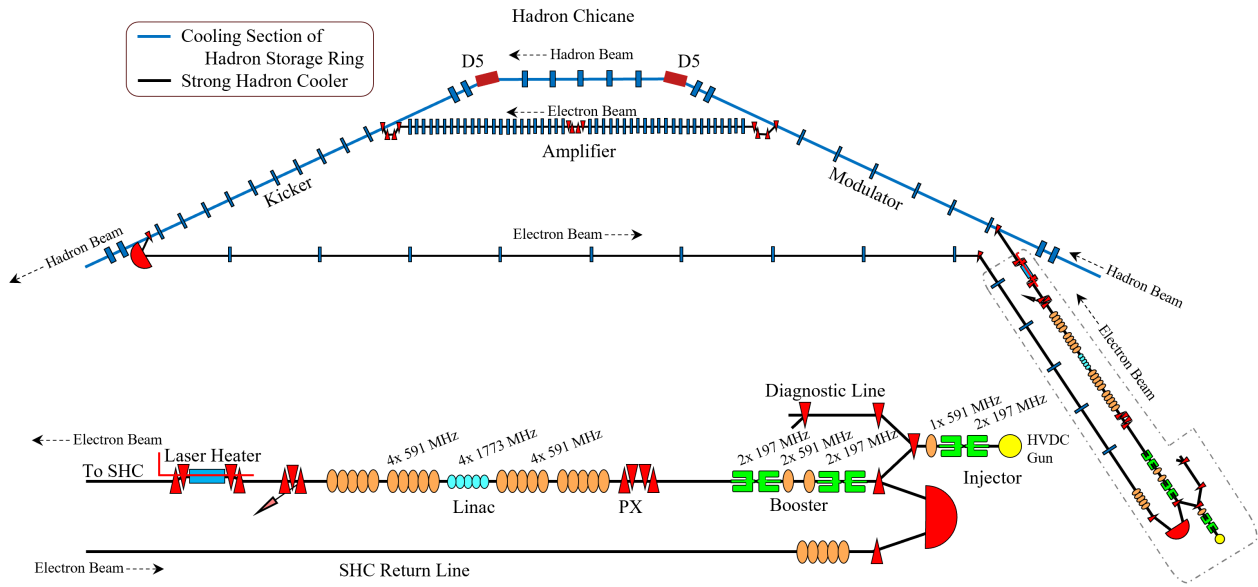


Figure 4: (Top) A representative layout of the cooling complex in IR2. The electron beam of the SHC-ERL begins at the HVDC gun, represented by a yellow circle in the bottom right. This beam is brought up to full energy before the electron beamline merges with the HSR in the cooling section, which consists of the modulator, amplifier, and kicker. At the end of the cooling section, the electron beam separates from the HSR, returns to energy recover, and is steered into the dump line. (Bottom) This is an enlarged view of the dashed gray box enclosing part of the SHC-ERL. Represented is the injector, followed by the merger, going to either the diagnostic line or the booster, the bunch compressor and high energy bypass lines (PX), the main linac (Linac), the dump chicane, the laser heater, the transport to the cooling section, and the return line from the cooler.

## TIME OF FLIGHT CONSIDERATIONS

Typically, ERLs have a single linac and consequently, only a single time of flight concern – the time of flight between the linac exit and the linac entrance. However, this machine has two accelerating sections, the booster and the linac, which means that there are two time of flight concerns. The first concern is the time of flight between the booster exit and the booster entrance; the second is the time of flight between the linac exit and the linac entrance.

The booster time of flight uses path length changes in the two Bates bends for flexibility, similar to the Jefferson Lab Free Electron Laser ERL drivers; correctors at the entrance and exit of the Bates bend allow for the beam to enter and exit on-axis, while the beam orbit through the the magnet is off-axis, changing the path length through the Bates bend [4]. At the 197 MHz fundamental frequency of the booster and a 2.5 cm maximum orbit excursion at the center of the bend, this translates to a range of  $\pm 11.7^\circ$  per Bates bend. However, the length of this machine introduces a complication – for a fixed path length on the order of 800 m, the time of flight for the two energies differs by roughly  $8^\circ$  at the booster frequency, but the time of flight between the booster exit and entrance is required to be the same for both modes. The second Bates bend was placed so that the relevant time of flight was roughly  $4^\circ$  from the requirement for both energies

and by design, both energies travel through the second Bates bend off-axis to achieve the requisite time of flight.

The linac time of flight is controlled by the path length through the appropriate high energy PX line. Both P2 and P3 have moving stages in order to physically move two dipoles and change the on-axis path length through the lines, similar to the moving stages in the CBETA splitters [5, 6].

## PX SECTION

The floor plan of the PX section, with the separate lines labeled, is shown in Fig. 5. The design of this section allows for the SHC-ERL to switch operational modes without requiring a change to the physical layout of the machine. While a simpler design would have a single high energy line which bypasses the bunch compressor of P1, such a design required either very large beam pipes or placing the first high energy dipole so close to the common dipole that the risk of field leaking into the P1 line was considered non-negligible.

Each line in PX corresponds to a specific beam energy; P1, P2, and P3 are designed for beam energies of 13, 48, and 143 MeV, respectively. P1 compresses the accelerating beam for both modes, while P2 and P3 transport the decelerating beams for the top energies of 55 and 150 MeV, respectively. While all lines are achromats, none is isochronous; though it would be ideal for  $R_{56}$  to be zero in P2 and P3, it is more critical to close dispersion, dispersion prime, and control



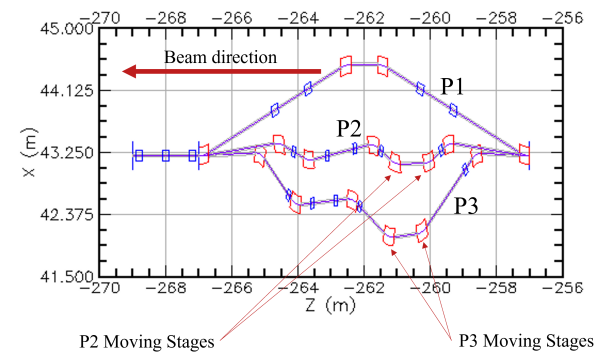


Figure 5: The floor layout of the PX section; the three separate lines are P1, P2, and P3, top to bottom (as labeled), which correspond to the beam energies of 13, 48, and 143 MeV, respectively. The “common” dipoles are the right most and left most dipoles, which is a common magnet for all three beam energies. In both the P2 and P3 lines, the second and third dipoles are on moving stages which can be remotely controlled to change the physical path length of the on-axis orbit.

the transverse optics through these lines. Given that the decelerating beam is chirped, the non-zero  $R_{56}$  of these lines does mean that some bunch stretching occurs. If necessary, the  $R_{56}$  of the second Bates bend can be tuned to compress the bunch, so that the bunch length during the second pass the linac is sufficiently short. In order for the time of flight requirement between the linac exit and entrance to be correct, the booster time of flight must be correct. This is driven by the limited range of the moving stages, i.e., the limited time of flight flexibility in the P2 and P3 lines, as well as the inherent geometry of the PX section; if the decelerating beam enters either high energy line at an energy significantly different than design, the beam will be lost on the beam pipe wall before reaching the first high energy dipole. While the 150 and 55 MeV configurations have very similar linac time of flight requirements, the P3 line has an extra wavelength of path length in order to remove geometry conflicts with the P2 line. As the two lines have different geometries, the time of flight flexibility is different. The P2 line has a range of  $+20^\circ/-10^\circ$ , while the P3 line has a range of  $\pm 55^\circ$ , both with respect to the 591 MHz fundamental frequency of the linac. The physical motion of the moving stages corresponding to these ranges is shown in Fig. 6.

The design before the main linac, particularly the booster and PX sections, is motivated by the need to produce a super-gaussian longitudinal distribution, with small slice energy spread and transverse emittance. At present, we achieve this by producing a very long bunch at the gun, which controls both the slice energy spread and transverse emittance, until the beam is at a sufficiently high energy that when the bunch is compressed to the requisite bunch length, these parameters are relatively unperturbed through the compression process.

The inclusion of a bunch compressor within the accelerating section of an ERL is not a typical configuration,

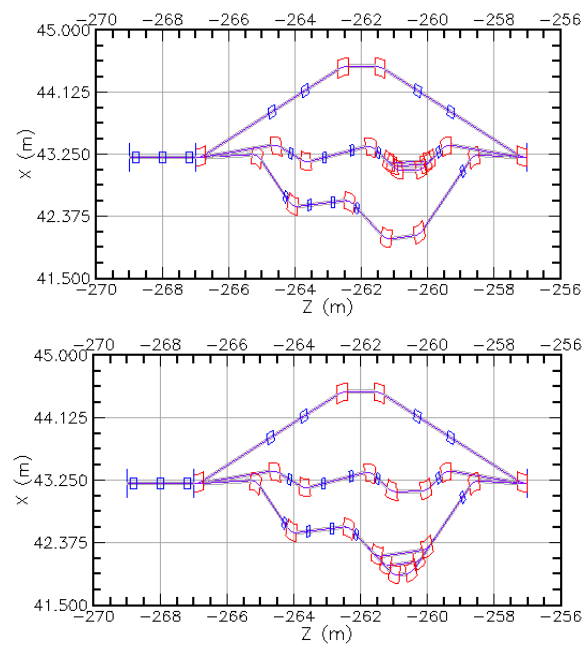


Figure 6: The floor layout of PX section demonstrating the full range of motion of the moving stages for lines P2 (top) and P3 (bottom).

and its inclusion makes the design more complex. As a design alternative, the injector energy could be increased to 13 MeV and the bunch compressed before the merger. This would have the benefit of returning to a more simple ERL layout, with a single time of flight requirement and no need for higher-energy bypass lines to transport the decelerating beam around the compressor chicane. However, this design comes with other drawbacks – lower energy efficiency and higher shielding requirements at both the dump and the diagnostics line. Another alternative is to compress the 6 MeV bunch in the injector – however, this approach does not produce the required beam parameters.

## BEAM BREAKUP INSTABILITY

At present, the lattice assumes the 591 MHz five-cell cavities in the main linac are BNL style – each cavity in its own cryomodule; alternatively, using PERLE style cavities would mean four of these cavities per cryomodule, significantly reducing the length of the main linac. While the cooling section is within the existing RHIC tunnel, the vault containing the SHC-ERL injector, booster, and main linac is new construction – reducing the length of the linac reduces the length of the vault, consequently reducing the infrastructure cost.

Initial evaluations of the beam breakup (BBU) instability have been performed using scaled higher order mode (HOM) parameters from both BNL and PERLE style cavities. Preliminary results show the BNL style cavities to be more stable and have significantly higher threshold currents than the PERLE style cavities, capable of handling the required average current of 98.5 mA; unfortunately, the

PERLE style cavities do not fulfill this requirement. However, the most dominant cavities are the highest frequency, ie, the 1773 MHz cavities; replacing these will not significantly reduce the linac length. It is possible that using PERLE style cavities only at the lower frequencies and BNL style for the higher frequencies may produce a significantly shorter linac while maintaining a sufficiently high threshold current [7].

## ENERGY BALANCE

In an ideal energy recovery design, each cavity would be energy balanced, meaning that the beam gains and loses the same amount of energy for the two passes through the cavity. While this design balances the energy across the booster and across the linac, the primary concern is achieving the requisite beam parameters, so none of the cavities are energy balanced; the deviation from energy balance for both modes is shown in Table 2.

Table 2: The deviation from energy balance for each cavity in the booster (top) and linac (bottom). The cavity number is given in the left column, while the deviation in kV is given for the 150 and 55 MeV modes in the center and right columns, respectively.

| Cavity Number | Energy Balance Deviation (kV) |        |
|---------------|-------------------------------|--------|
|               | 150 MeV                       | 55 MeV |
| 1             | 16                            | 15     |
| 2             | 10                            | 10     |
| 3             | -5                            | -4     |
| 4             | 3                             | 3      |
| 5             | -11                           | -11    |
| 6             | -14                           | -14    |
| 1             | 4                             | 12     |
| 2             | 13                            | 17     |
| 3             | 15                            | 18     |
| 4             | 16                            | 16     |
| 5             | -7                            | -4     |
| 6             | -7                            | -4     |
| 7             | -7                            | -5     |
| 8             | -7                            | -5     |
| 9             | 14                            | 14     |
| 10            | 12                            | 9      |
| 11            | 4                             | -4     |
| 12            | -49                           | -65    |

In the booster, no one cavity has a significantly higher absolute deviation than all others. In the linac, however, the final cavity has a significantly higher absolute deviation, which is not ideal in regards to having common RF requirements for all the linac cavities. Subsequent designs will

explore changing the linac time of flight to minimize the range of absolute deviation across the linac cavities, as well as examining how this changes the beam energy at the dump.

## CONCLUSION

An initial design exists for both energy modes of the SHC-ERL, which is capable of cooling high energy protons during collisions at the EIC. One critical success of this design is that the magnet layout is unchanged between configurations, so no vault access is required between switching energies. Though more complex than many ERLs, no show stoppers have been found. As collective effects and design alternatives are evaluated, we anticipate that a mature, robust design for an ERL-driven high energy cooler can be completed.

## ACKNOWLEDGMENTS

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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          |

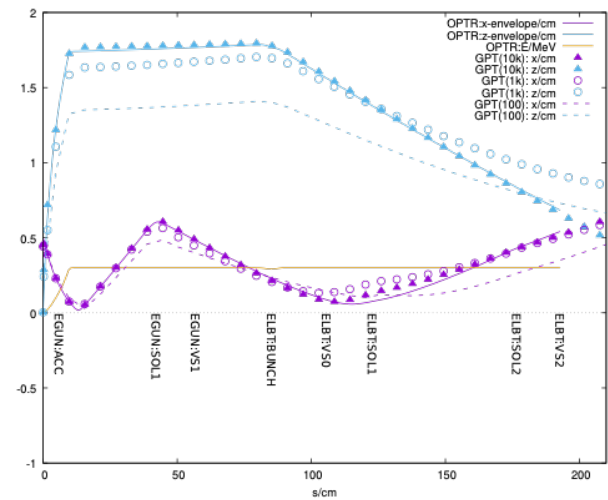


Figure 1: The comparison of envelope results using multi-particle tracking code (GPT) and envelope code (TRANSOPTR) at different no. of particles. The beam energy is 300 keV and the bunch charge is 14 pC.

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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## THEORY

### Infinitesimal Matrix and Hamiltonian Dynamics

An ensemble of  $N$  particles can be described by its second moment

$$\sigma = \frac{1}{N} \sum_{i=1}^N \mathbf{x} \mathbf{x}^T$$

where  $\mathbf{x} = (x, P_x, y, P_y, z, P_z)^T$ .

When the particles propagate through optical elements described by a transfer matrix  $\mathbf{M}$ , the change in the  $\sigma$  matrix can be obtained by differentiating it with respect to the longitudinal position  $s$ . This gives:

$$\frac{d\sigma}{ds} = \frac{1}{N} \sum_{i=1}^N \frac{d\mathbf{x}}{ds} \mathbf{x}^T + \frac{1}{N} \sum_{i=1}^N \mathbf{x} \frac{d\mathbf{x}^T}{ds} \quad (1)$$

Assuming that the infinitesimal matrix  $\mathbf{F}(s)$  is defined such that  $\mathbf{x}' = \frac{d\mathbf{x}}{ds} = \mathbf{F}(s)\mathbf{x}$ , and  $\mathbf{F} ds = \mathbf{M} - \mathbf{I}$ , eq. (1) simplifies to:

$$\sigma' = \mathbf{F}\sigma + \sigma\mathbf{F}^T \quad (2)$$

These constitute the 21 sets of envelope equations. By integrating these equations, we can obtain the envelope at any given point  $s$ .

Recall the Hamiltonian equations of motion, which describe the time evolution of a system. If we expand  $\mathbf{x}'$  to second order, we find that the matrix  $\mathbf{F}$  corresponds to the second-order partial derivatives of the Hamiltonian. In this case,  $\mathbf{F}$  can be expressed as a  $6 \times 6$  matrix:

$$\mathbf{F} = \begin{pmatrix} \frac{\partial^2 H}{\partial P_x \partial x} & \frac{\partial^2 H}{\partial P_x^2} & \frac{\partial^2 H}{\partial P_x \partial y} & \frac{\partial^2 H}{\partial P_x \partial P_y} & \frac{\partial^2 H}{\partial P_x \partial z} & \frac{\partial^2 H}{\partial P_x \partial P_z} \\ -\frac{\partial^2 H}{\partial x^2} & -\frac{\partial^2 H}{\partial x \partial P_x} & -\frac{\partial^2 H}{\partial x \partial y} & -\frac{\partial^2 H}{\partial x \partial P_y} & -\frac{\partial^2 H}{\partial x \partial z} & -\frac{\partial^2 H}{\partial x \partial P_z} \\ \frac{\partial^2 H}{\partial P_y \partial x} & \frac{\partial^2 H}{\partial P_y \partial P_x} & \frac{\partial^2 H}{\partial P_y \partial y} & \frac{\partial^2 H}{\partial P_y \partial P_y} & \frac{\partial^2 H}{\partial P_y \partial z} & \frac{\partial^2 H}{\partial P_y \partial P_z} \\ -\frac{\partial^2 H}{\partial y \partial x} & -\frac{\partial^2 H}{\partial y \partial P_x} & -\frac{\partial^2 H}{\partial y^2} & -\frac{\partial^2 H}{\partial y \partial P_y} & -\frac{\partial^2 H}{\partial y \partial z} & -\frac{\partial^2 H}{\partial y \partial P_z} \\ \frac{\partial^2 H}{\partial P_z \partial x} & \frac{\partial^2 H}{\partial P_z \partial P_x} & \frac{\partial^2 H}{\partial P_z \partial y} & \frac{\partial^2 H}{\partial P_z \partial P_y} & \frac{\partial^2 H}{\partial P_z \partial z} & \frac{\partial^2 H}{\partial P_z \partial P_z} \\ -\frac{\partial^2 H}{\partial z \partial x} & -\frac{\partial^2 H}{\partial z \partial P_x} & -\frac{\partial^2 H}{\partial z \partial y} & -\frac{\partial^2 H}{\partial z \partial P_y} & -\frac{\partial^2 H}{\partial z^2} & -\frac{\partial^2 H}{\partial z \partial P_z} \end{pmatrix} \quad (3)$$

This implies that, for any given system, knowing the Hamiltonian allows for the straightforward calculation of the  $\mathbf{F}$  matrix, which can then be integrated to determine the envelope at any given point  $s$ . This approach forms the basis of TRANSOPTR, the envelope code used in this study.

## RESULTS

### TRIUMF e-Linac

The first comparison was conducted for the low-energy beamline of the TRIUMF e-Linac, using a 300 keV, 14 pC beam. The results, obtained with varying computational times in GPT, are presented in Fig. 1. This comparison demonstrated good agreement between the two codes for 10,000 particles, with TRANSOPTR achieving a speed improvement of at least two orders of magnitude.

Futhermore, the beam sizes were measured using the a 300 keV and 14 pC electron beam at TRIUMF e-Linac. Figure 2 presents a comparison between the results calculated using the envelope code and the experimental data.

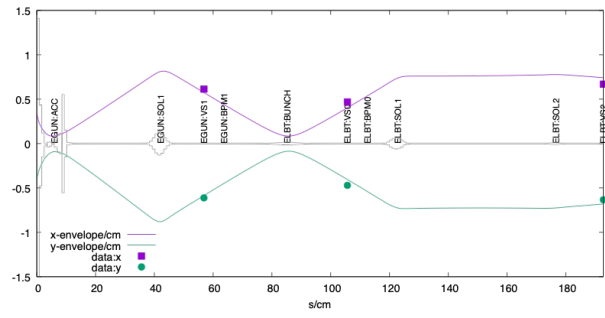


Figure 2: The comparison of envelope code against experimental data taken at low-energy beamline of TRIUMF e-Linac. The lines are envelope calculated by TRANSOPTR, whereas the points are measured at the respective viewscreen.

The initial beam conditions were first determined by fitting it with data taken from a solenoid scan.

Figure 2 shows a good match, with a deviation of less than 10 %. These results validate the envelope method as an effective tool for predicting the behavior of electron beams up to several tenths of a picocoulomb. Consequently, this work was extended to another machine that generates a more intense electron beam, with a stronger space-charge effect.

### cERL-KEK

A similar comparison was conducted using low-energy high-intensity electron beams at the injection beamline at cERL KEK. First, the beam envelopes were calculated with different simulation tools: GPT and TRANSOPTR. The results are presented in Fig. 3, where beams with different bunch charges (0 pC and 110 pC) were compared. The initial bunch length was 3 ps, and the beam energy from the source was 450 keV before being accelerated to 3 MeV by the injector. The injector phases were fine-tuned to achieve maximum energy gain. Figure 3 again shows good agreement for both cases, demonstrating the feasibility of using an envelope code to simulate the beam size of a high space-charge beam.

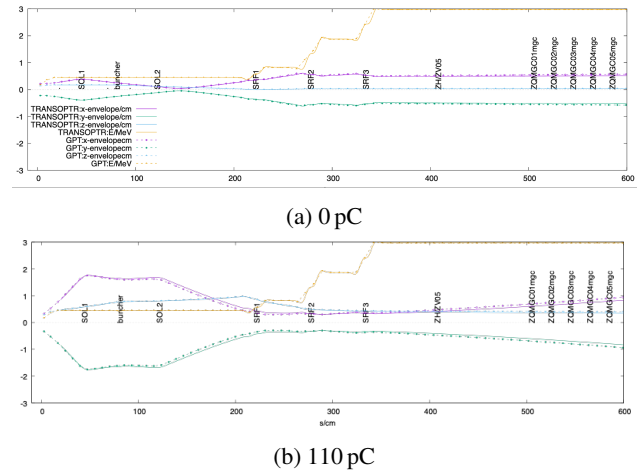
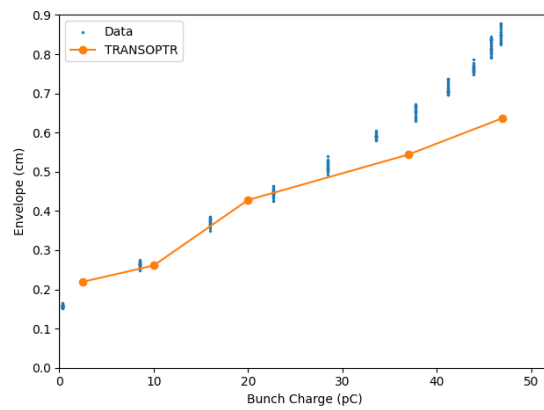
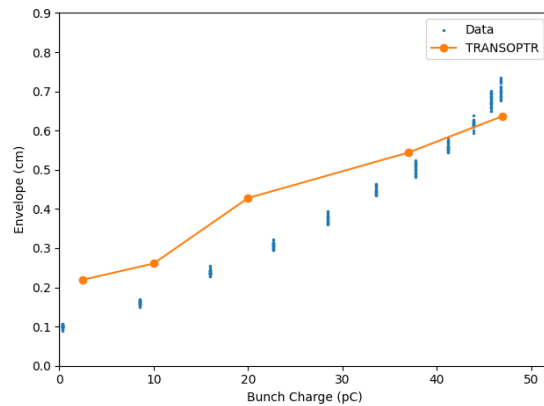


Figure 3: The comparison of envelope results using GPT at different bunch charges. The final beam energy is 3 MeV.



(a) X envelope



(b) Y envelope

Figure 4: Comparison of envelope results with experimental data obtained at cERL using the second viewscreen (CAM02).

Additionally, experimental data were taken at the injection beamline of cERL. Figure 4 shows the results of the

transverse beam sizes measured at the second viewscreens at cERL. The experimental data are represented by blue points, while the TRANSOPTR calculations are shown as orange lines. Note that the measured beam sizes were obtained by fitting a Gaussian function to the viewscreen images and taking the  $\sqrt{5}$  rms value. Overall, the TRANSOPTR calculations show good agreement with the experimental data, with a deviation of less than 25 %.

## CONCLUSION

Envelope tracking of the low-energy electron beam yields results that are consistent with those from multi-particle tracking codes up to 110 pC, while achieving over two orders of magnitude faster computational speed. The experimental data agree with the envelope tracking results within  $\pm 25$  %. The fast turnaround provided by the envelope code can greatly assist in live beam tuning and beamline design during the early stages of a project.

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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  $\phi$  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  $\phi_r$ , 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  $\phi$  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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The cavity fields do not overlap;  $G(s) = 0$  outside of the interval  $[s_-, s_+]$  (for convenience 0 should be within this interval). For modeling, I obtain  $G(s)$  on that interval from an eigenmode calculation of the cavity. The BPM before the linac is located at  $s = s_0$ , the BPM after the linac is located at  $s = s_{n+1}$ , and for cavity  $i$ , the field map  $G(s)$  is translated so its origin is at  $s = s_i$ .

If we integrate Eq. (1) starting at  $s = s_-$ , then at  $s = s_+$ , the results are given by the functions

$$\begin{aligned} t(s_+) &= T_c(V, \omega t(s_-) + \phi, E(s_-)) \\ E(s_+) &= E_c(V, \omega t(s_-) + \phi, E(s_-)) \end{aligned} \quad (4)$$

If at the upstream BPM, the arrival time is  $t_g$  and the energy is  $E_g$ , then if only cavity  $i$  is powered, the arrival time at the downstream BPM is

$$t_g + \hat{T}_i(V, \omega t_g + \phi, E_g) \quad (5)$$

where

$$\begin{aligned} \hat{T}_i(V, \phi, E_g) &= (s_i + s_- - s_0)B(E_g) \\ &+ T_c(V, \omega(s_i + s_- - s_0)B(E_g) + \phi, E_g) \\ &+ (s_{n+1} - s_i - s_+) \\ &\times B(E_c(V, \omega(s_i + s_- - s_0)B(E_g) + \phi, E_g)) \end{aligned} \quad (6)$$

and

$$B(E) = \frac{E}{c\sqrt{E^2 - (mc^2)^2}} \quad (7)$$

There is no common time reference for the upstream and downstream BPMs, so in practice one can only measure time differences at a BPM. So we will make a high precision measurement of the arrival times at the upstream and downstream BPMs with the cavities off. Then we will fit the data to the difference between the arrival times with the cavity on and with the cavity off. We will still take upstream and downstream times for each point and record their difference, so as to remove any global noise and drifts (we found that this was essential for noise reduction in measurements). Thus the model we are fitting this difference to for cavity  $i$  is

$$\begin{aligned} T_i(V, \phi, E_g) &= T_c(V, \omega(s_i + s_- - s_0)B(E_g) + \phi, E_g) \\ &+ (s_{n+1} - s_i - s_+) \\ &\times B(E_c(V, \omega(s_i + s_- - s_0)B(E_g) + \phi, E_g)) \\ &- (s_{n+1} - s_i - s_-)B(E_g) \end{aligned} \quad (8)$$

To find  $T_c$  and  $E_c$  for a given set of arguments, I integrate Eq. (1) using fourth order Runge-Kutta integration. The function  $G(s)$  is fit from field map data via least squares to a high-order spline function (for the CBETA cavity, 12th order B-Splines with 230 basis functions [2]). The fit uses field map data out to a radius of 15 mm combined with the expansion about the axis of the RF fields under the assumption of cylindrical symmetry (the field was generated for a cylindrically symmetric model of the cavity) to improve accuracy.

The integration step size (1536 steps for the CBETA cavity field map) is chosen to be that which gives the best precision for integrals (2) and (3) when computed via Simpson's method. While these choices of step size and spline order may seem excessive, the computation time required for the fitting is negligible relative to the measurement time, and thus doing so to minimize numerical noise and approximation errors in the computation is reasonable. A sufficiently high order spline fit should be made to the data to ensure sufficient continuity for the order of the integration method being used.

## FITTING THE MODEL

We fit the model parameters to the data via a least squares fit. The parameters we are fitting are the ratio of the control system voltage to the voltage in the model, the phase difference between the control system phase and the model phase, and the injected energy. For cavity  $i$ , we take measurements on cavity  $i$  indexed by  $j$ , with voltage  $V_{ij}$  and phase  $\phi_{ij}$  set in the control system. We measure arrival times  $t_{ij}$ , and we are comparing them to model values  $\tau_{ij}(\lambda_i, \psi_i, E_g) = T_i(\lambda_i V_{ij}, \phi_{ij} + \psi_i, E_g)$ ; we are fitting the calibration quantities  $\lambda_i$  and  $\psi_i$ , as well as the incoming energy  $E_g$ .

The model parameters will be fit using Newton's method. This will require repeatedly computing derivatives of the model functions, which involves integration of differential equations, as well as finding a good initial guess. The following may seem complex, but the benefit it provides is reliability: if data is successfully taken, the optimal solution will be found every time. The computation time for finding the parameters is only a couple of seconds, despite the excessive precision in the computation and the fact that the computation is being performed in an interpreted language (Matlab).

Much of this section is formulated generically to keep expressions as compact as possible; applying them to the specific case described requires rather simple algebra and differentiation. The formulations for least squares fit, derivatives of solutions to differential equations, and uncertainty in the parameters are not innovations, they are merely included here so that this paper contains the calculations required to implement the calibration computation.

### Least Squares Fit

A least squares fit to data  $t_i$  with uncertainties  $\sigma_i$  to find parameters  $p$  is trying to minimize the function

$$f(p) = \frac{1}{2} \sum_i \frac{(T_i(p) - t_i)^2}{\sigma_i^2} \quad (9)$$

with respect to  $p$ . The minimum of this function occurs when

$$0 = \frac{\partial f}{\partial p} = \sum_i \frac{\partial T_i}{\partial p} \frac{T_i(p) - t_i}{\sigma_i^2} \quad (10)$$

There are numerous methods for minimizing a general function, but if you are near the desired local minimum, the most

efficient method is generally to solve the equation for the derivative of  $f$ . The most efficient method of doing this (when near the local minimum desired) is to use Newton's method, which requires the second derivative of  $f$  and therefore  $T_i$ :

$$\frac{\partial^2 f}{\partial p_i \partial p_j} = \sum_k \sigma_k^{-2} \left\{ \frac{\partial^2 T_k}{\partial p_i \partial p_j} [T_k(p) - t_k] + \frac{\partial T_k}{\partial p_i} \frac{\partial T_k}{\partial p_j} \right\} \quad (11)$$

### Derivatives of the Model

For computing the derivatives of  $T_i$ , the only non-trivial derivatives required are those of  $T_c$  and  $E_c$ . I will show that the computation of these derivatives can be done simply by extending the set of ordinary differential equations that are integrated.

Consider a general differential equation for  $z(z_0, p, s)$  with initial conditions  $z(z_0, p, 0) = z_0$ :

$$\frac{dz}{ds} = g(z(z_0, p, s), p, s) \quad (12)$$

$p$  are parameters. Derivatives of  $z$  with respect to  $p$  and  $z_0$  are needed for the least squares fit. It is straightforward to take derivatives of this differential equation and the initial conditions with respect to  $p$  and  $z_0$ :

$$\frac{d}{ds} \frac{\partial z_i}{\partial p_j} = \sum_k \frac{\partial g_i}{\partial z_k} \frac{\partial z_k}{\partial p_j} + \frac{\partial g_i}{\partial p_j} \quad (13)$$

$$\frac{d}{ds} \frac{\partial z_i}{\partial z_{0j}} = \sum_k \frac{\partial g_i}{\partial z_k} \frac{\partial z_k}{\partial z_{0j}} \quad (14)$$

$$\left. \frac{\partial z}{\partial z_0} \right|_{s=0} = I \quad (15)$$

$$\begin{aligned} \frac{d}{ds} \frac{\partial^2 z_i}{\partial p_j \partial p_k} &= \sum_l \frac{\partial g_i}{\partial z_l} \frac{\partial^2 z_l}{\partial p_j \partial p_k} \\ &+ \sum_{lm} \frac{\partial^2 g_i}{\partial z_l \partial z_m} \frac{\partial z_l}{\partial p_j} \frac{\partial z_m}{\partial p_k} \\ &+ \sum_l \frac{\partial^2 g_i}{\partial z_l \partial p_j} \frac{\partial z_l}{\partial p_k} + \sum_l \frac{\partial^2 g_i}{\partial z_l \partial p_k} \frac{\partial z_l}{\partial p_j} \\ &+ \frac{\partial^2 g_i}{\partial p_j \partial p_k} \end{aligned} \quad (16)$$

$$\begin{aligned} \frac{\partial^2 z_i}{\partial p_j \partial z_{0k}} &= \sum_l \frac{\partial g_i}{\partial z_l} \frac{\partial^2 z_l}{\partial p_j \partial z_{0k}} \\ &+ \sum_{lm} \frac{\partial^2 g_i}{\partial z_l \partial z_m} \frac{\partial z_l}{\partial p_j} \frac{\partial z_m}{\partial z_{0k}} \\ &+ \sum_l \frac{\partial^2 g_i}{\partial p_j \partial z_l} \frac{\partial z_l}{\partial z_{0k}} \end{aligned} \quad (17)$$

$$\begin{aligned} \frac{d}{ds} \frac{\partial^2 z_i}{\partial z_{0j} \partial z_{0k}} &= \sum_l \frac{\partial g_i}{\partial z_l} \frac{\partial^2 z_l}{\partial z_{0j} \partial z_{0k}} \\ &+ \sum_{lm} \frac{\partial^2 g_i}{\partial z_l \partial z_m} \frac{\partial z_l}{\partial z_{0j}} \frac{\partial z_m}{\partial z_{0k}} \end{aligned} \quad (18)$$

Except for the case indicated, the initial condition for each derivative is zero.

### Initial Guess

To get an initial guess for the parameters, I begin with a simplified model of the linac with a single cavity powered: a drift from the upstream BPM to the center of the cavity, an energy gain at the cavity center, then a drift to the downstream BPM. From the data taken for a given cavity, we take the data points with the latest and earliest arrival times; I'll denote  $T_-$  to be the latest arrival time, arising from the smallest energy gain, and  $T_+$  the earliest arrival time. The guess for the phase offset will come from assuming the phases for these two times correspond to the phases of minimum and maximum energy gain, respectively. Then I solve the two equations

$$T_{\pm} - T_0 = \frac{(s_{n+1} - s_i)}{c} \left[ \frac{E_g \pm \lambda_i V_i}{\sqrt{(E_g \pm \lambda_i V_i)^2 - (mc^2)^2}} - \frac{E_g}{\sqrt{E_g^2 - (mc^2)^2}} \right] \quad (19)$$

for  $\lambda_i$  and  $E_g$ .  $s_i$  is the center of cavity  $i$  here. This can be done via Newton's method, for which we need an initial guess. The initial guess comes from expanding these equations to second order in  $\lambda_i$ :

$$\begin{aligned} \frac{c(T_{\pm} - T_0)}{s_{n+1} - s_i} &\approx \\ &\mp \frac{(mc^2)^2 \lambda_i V_i}{(E_g^2 - (mc^2)^2)^{3/2}} + \frac{3}{2} \frac{(mc^2)^2 E_g \lambda_i^2 V_i^2}{(E_g^2 - (mc^2)^2)^{5/2}} \end{aligned} \quad (20)$$

The guesses for  $E_g$  and  $\lambda_i$  can then be found through elementary means:

$$\frac{E_g \sqrt{E_g^2 - (mc^2)^2}}{(mc^2)^2} = \frac{4}{3} \frac{s_{n+1} - s_i}{c} \frac{T_+ + T_- - 2T_0}{(T_- - T_+)^2} \quad (21)$$

$$\frac{(mc^2)^2 \lambda_i V_i}{(E_g^2 - (mc^2)^2)^{3/2}} = \frac{c(T_- - T_+)}{2(s_{n+1} - s_i)} \quad (22)$$

From this starting point, Newton's method is applied to Eq. (19) to get  $\lambda_i$  and  $E_g$  for data from one of the cavities. The  $E_g$  found for each of the cavities are averaged to get the initial guess for  $E_g$  for the fit to all of the cavity data. This may seem like a lot of work for the initial guess, but since it only involves a few evaluations of elementary functions, the computational time required is a tiny fraction of the time needed for the full fit.

### Uncertainty

To show how to compute the uncertainty in the fit parameters, I'll discuss the generic formulation. Begin with Eq. (10) and take its derivative with respect to  $t_j$ . This results in:

$$\begin{aligned} \sum_{kl} \sigma_k^{-2} \left\{ \frac{\partial T_k}{\partial p_i} \frac{\partial T_k}{\partial p_l} + [T_k(p) - t_k] \frac{\partial^2 T_k}{\partial p_i \partial p_l} \right\} \frac{\partial p_l}{\partial t_j} \\ = \sigma_j^{-2} \frac{\partial T_j}{\partial p_i} \end{aligned} \quad (23)$$

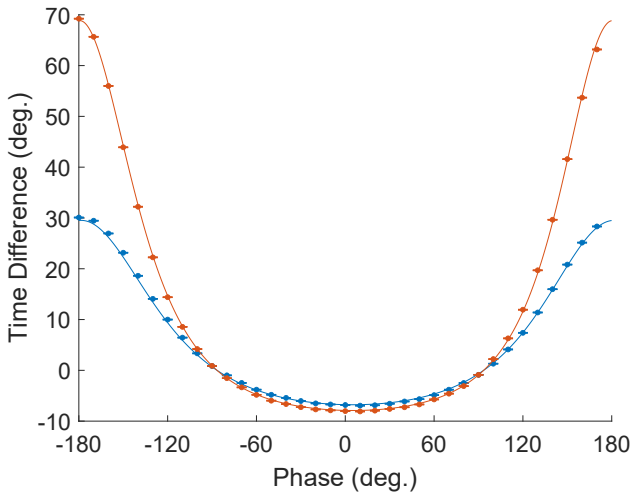


Figure 1: Measured data with RD1CAV01 powered (the last cavity) for cavity voltage set to 3000 (blue) and 4000 kV (orange). Curves show the model values using the fit parameters. Time is measured as a phase relative to the 1.3 GHz reference frequency.

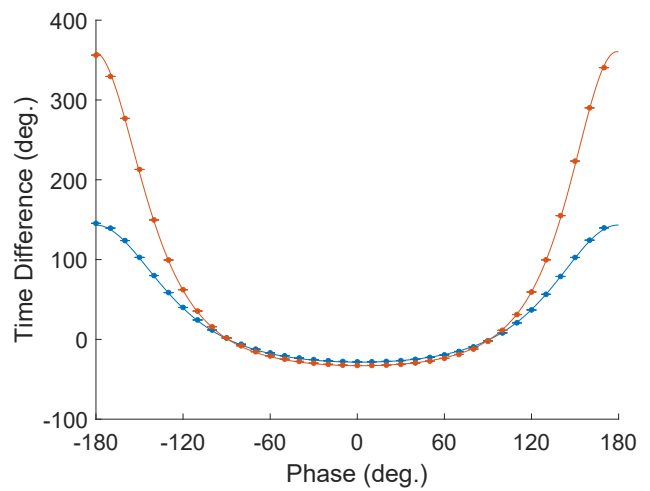


Figure 2: Measured data with RD1CAV06 (the first cavity) powered for cavity voltage set to 3000 (blue) and 4000 kV (orange). Curves show the model values using the fit parameters. Time is measured as a phase relative to the 1.3 GHz reference frequency.

The quantity in braces, summed over  $k$ , is a matrix that can be inverted to compute  $\partial p_l / \partial t_j$ , which are the quantities in the covariance matrix used to compute uncertainties in the parameters  $p$  from the uncertainties in the data  $t$ . All of the quantities required for the computation were already computed to apply Newton's method to solve the least squares problem.

There is one additional complexity, in that the  $t_k$  in Eq. (23) are, for our measurements,  $t_{ij} - t_0$ , where  $t_0$  is the measurement with the cavities off. Extending the calculation to take that into account is straightforward. To reduce the statistical uncertainty in the parameters for minimal cost in measurement time, many more readings are taken for  $t_0$  than for the  $t_{ij}$ .

## SAMPLE MEASUREMENT AND FIT

To demonstrate the capability of this technique, we measured cavity data at two voltage settings, 3000 and 4000 kV, with 10 degree steps in the phase setting. The cavity voltages and phases had already been calibrated, so the phase and voltage settings should already be close to their correct values. Figures 1 and 2 show the data at the last and first cavities, respectively (data were taken for all 6 cavities). For ordinary calibration, we would typically take data at only one voltage (usually 3000 kV) and using larger steps in phase (20 or 30 degrees). We fit the data to the model as described above, and the values for the model using those fit parameters are shown in those same figures. Note the significantly different scales in those figures. There is a significantly larger range in time difference for the first cavity compared to the last, owing to the significantly longer drift distance to the downstream BPM.

Figures 3 and 4 show the difference between the fit data and the model. There are error bars on the data points show-

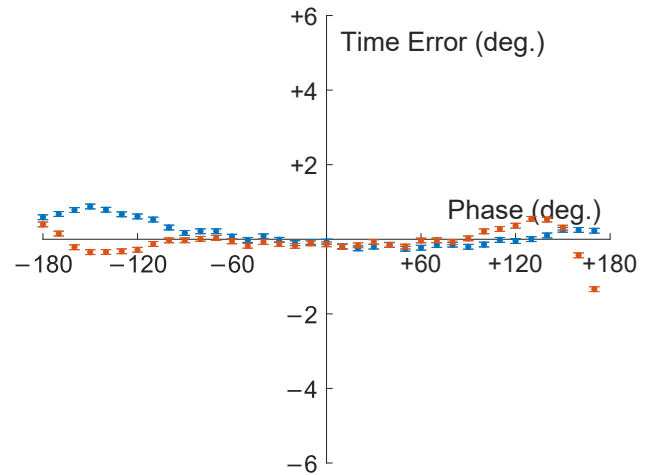


Figure 3: Difference between the data and the model fit for the data in Fig. 1.

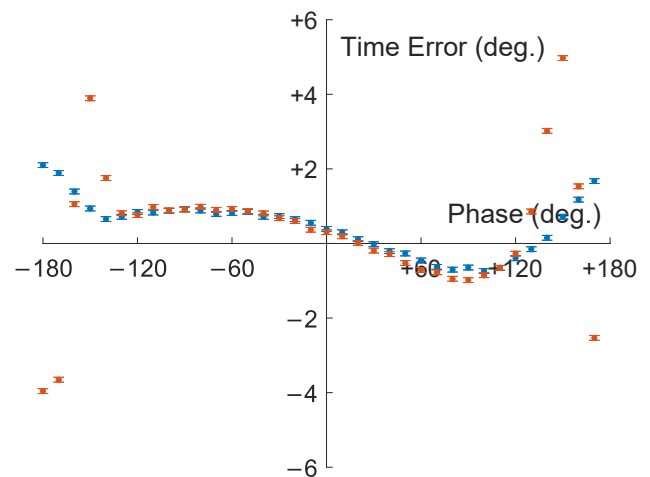


Figure 4: Difference between the data and the model fit for the data in Fig. 2.



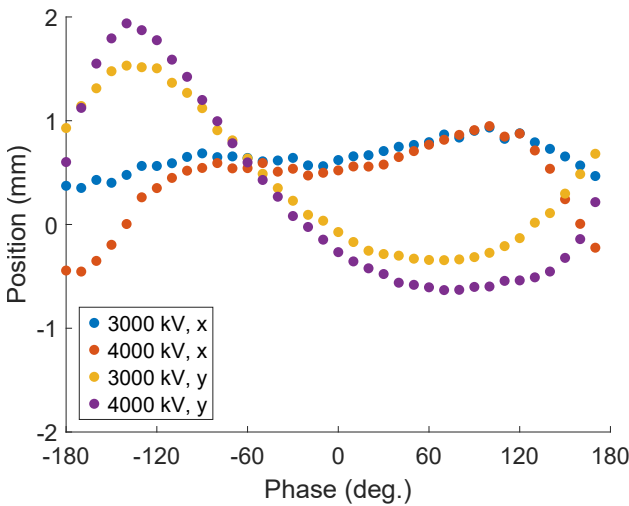


Figure 5: Position at the downstream BPM for the measurements from Fig. 1. Statistical uncertainties are negligible on this scale.

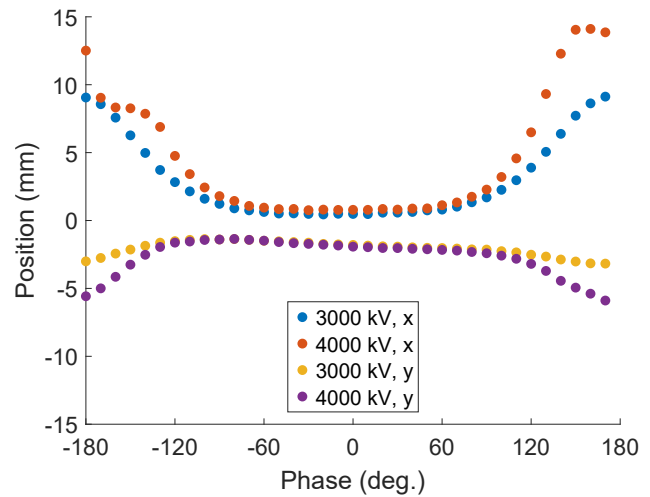


Figure 6: Position at the downstream BPM for the measurements from Fig. 2. Statistical uncertainties are negligible on this scale.

ing the statistical error on the measured arrival times, computed by aggregating all of the time of flight measurements and taking their standard deviation. What is clear from these differences is that the uncertainties in the parameter fits are not dominated by the statistical uncertainties in the data. Instead, other systematic uncertainties in the measurements or errors in the model are the primary contributors to the parameter uncertainties.

Systematic uncertainties in the measurements could arise in many ways, and I will not attempt to enumerate all of them here. One important measurement error we did observe was an apparent dependence of the measured arrival time on the transverse position at the BPMs. Unfortunately, despite extensive attempts at analyzing this effect we were unable to determine how the transverse position was correlated with the arrival time measured, or even whether there truly was a causal relationship. Attempts at measuring the correlation often led to contradictory results. We had indications that the MLC cavity axes were not aligned with the beam pipe axes outside the MLC, and therefore made measurements to determine the actual cavity axis transverse positions [3]. Due to transverse focusing in the cavities that depends on the cavity phase and voltage, this could therefore lead to systematic measurement errors if there was a correlation between transverse position and measured time of flight at the BPM. We therefore steered the beam down the linac such that its transverse offset matched the average center of the cavities.

Figures 5 and 6 show the positions at the downstream BPM corresponding to the measurements shown in the earlier figures. For the first cavity (Fig. 6), the position is correlated with the cosine of the phase, so the effect is not primarily arising from a focusing effect in the cavity due to a displaced beam, which would cause the position to be correlated with the sine of the phase. The input coupler is on the downstream side of the cavity and is oriented in the

horizontal direction, so while an input coupler kick could explain the horizontal displacement, it would not account for the vertical displacement. Furthermore, for the last cavity (Fig. 5), the correlation between phase and position is in the opposite direction. The displacement could also arise because the beam has a transverse momentum, and the change in the longitudinal momentum going through the cavity leads to a change in angle downstream of the cavity; but since the transverse momentum would have the same sign for each cavity, this effect should have a consistent sign, which is not what is observed. Furthermore, the measurements with the cavities off indicate a position difference of less than 1 mm between the upstream and downstream BPMs, which is too small to be consistent with this effect. The cavity axis could also be tilted, the transverse displacement arising from the resulting transverse component of the accelerating field; for the first cavity, this would correspond to a tilt of about 0.6 mrad, which is not unreasonable. If this is the case, then this technique also allows a measurement of the axis tilts of the cavities; tilts of this magnitude were also found in [3].

The field map for the cavity was generated from a cylindrically symmetric model of the cavity. A field map based on a more complete model (that included, for instance, the input coupler and other ports) may have produced somewhat different results. We found early in our studies of CBETA that using the field map rather than a simplistic model for the cavity gave significant improvements in the agreement between our measurements and the model, so the details of the field map are important.

We attempted to apply this technique to the injector cryomodule (ICM), a 5-cavity cryomodule in the injection line that accelerates the beam to 6 MeV [1,4], but were unsuccessful. The beam steering effect was much stronger in this line, and alignment of the beam through the ICM was difficult to control. Furthermore, space charge forces at the lower energies involved may have made measurements challenging.

Table 1: Cavity calibrations results for the example given here. The CBETA MLC cavities are numbered in reverse: RD1CAV06 is the first cavity, RD1CAV01 is the last. The injection energy was computed to be  $6055.3 \pm 6.6$  keV.

| Cavity Name | Amplitude Factor | Uncertainty   |              |
|-------------|------------------|---------------|--------------|
|             |                  | Amplitude (%) | Phase (deg.) |
| RD1CAV01    | 0.9516           | 0.51          | 0.21         |
| RD1CAV02    | 0.9739           | 0.28          | 0.11         |
| RD1CAV03    | 1.0031           | 0.20          | 0.07         |
| RD1CAV04    | 1.0098           | 0.18          | 0.05         |
| RD1CAV05    | 1.0031           | 0.17          | 0.04         |
| RD1CAV06    | 0.9873           | 0.17          | 0.04         |

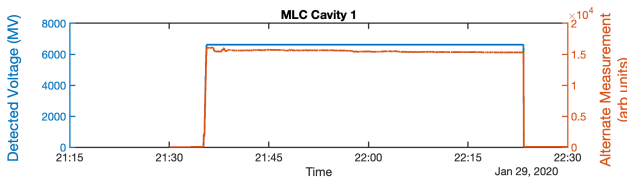


Figure 7: Two measurements of RF voltage in an MLC cavity versus time [5].

We used smaller voltages relative to the beam energy for the tuning, but this did not allow us to succeed. A modification of this technique with the phases ranging over some range around the crest may be needed to succeed at these lower energies.

The results and uncertainties from the calibration measurement shown above are given in Table 1. The table takes into account systematic uncertainties observed by multiplying the uncertainties computed via linear error propagation by the square root of  $\chi^2$  per degree of freedom computed from the fit (i.e., twice Eq. (9), divided by the number of measurements reduced by the number of parameters). Amplitude corrections were not applied regularly, only the phase offsets, since the latter were expected to change on every machine restart, while there is no reason to expect the former to change. Yet, over a period of months, the amplitude calibrations clearly did change, as can be seen in Table 1. This may not in fact have been a long-term drift in the amplitude calibration, but a shorter term one. We found that the beam energy coming out of the MLC changed throughout a day's operation. We typically corrected this via continual changes to the magnet fields in the splitter lines, based on position measurements in those lines. These drifts in the RF amplitude appeared to arise from an inconsistency in voltage measurements at the cavities [5] (see Fig. 7). The magnitude of the drift shown in Fig. 7 indicates that the calibration factors in Table 1 are to be expected.

## FINAL THOUGHTS AND ACKNOWLEDGMENTS

None of these measurements would have been possible without the entire team that designed and operated CBETA;

see the results reported in [6–8] for many of the members of that team. This work was motivated by the original phasing methods for the cavities that were based on finding the RF crest (see [6]); finding the phase value for a maximum is of its nature imprecise, and since the cavities were phased with their desired incoming energy, phasing the later cavities in the linac with time of flight was very difficult, and one used beam steering through a dipole instead. A re-thinking on how cavity phase was defined (i.e., relative to a 6 MeV beam, then using calculations to get the desired phases when the beam was accelerated) and phasing each cavity using the 6 MeV beam allowed these more precise measurements.

Further studies of the systematic errors in this technique could be made. One could continue to examine whether, and if so why, transverse position is having an impact on arrival time measurements. One could use a field map based on a more complete cavity model and determine if that gives a better fit to the data. One could even treat the on-axis field map as a function to be optimized to determine the field profile that best fits the data. As suggested above, one could use different voltage amplitudes in different cavities to take into account different distances to the downstream BPM. And one could attempt to use a smaller phase range in the injection cryomodule to enable applying this technique there.

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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

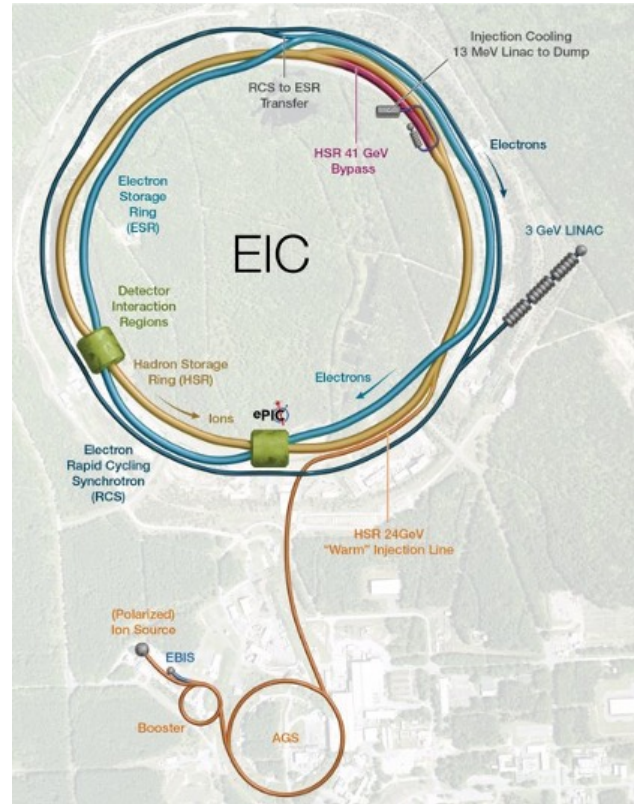


Figure 1: EIC schematic layout.

(FC72). To achieve high brightness, the gun will utilize novel large-crystal  $\text{K}_2\text{CsSb}$  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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reported in [1]. As illustrated in Fig. 2, the design concept is similar to that of the Low-Energy RHIC Electron Cooler (LEReC), includes an increased electron beam energy of 12.5 MeV, a higher beam current of 70 mA, and an extended cooling length of 170 m.

The high-energy cooler (HEC), however, presents more significant challenges. For traditional electron coolers, the cooling rate is inversely proportional to  $\gamma^2$ . To compensate for the reduction in cooling rate at higher energies, several approaches are considered:

- Increasing the six-dimensional phase space density of the electron bunch: Since the electron bunch must match the ion bunch, increasing the bunch charge is a viable strategy. At a repetition rate of 98.5 MHz, the average electron current in the cooling section must exceed 400 mA.
- Extending the cooling section length: Although longer cooling sections improve the cooling rate, they are typically constrained by the available drift space within the hadron ring.
- Pre-cooling the ion bunch: Reducing the transverse velocity spread of ions accelerates the cooling process. The LEC is specifically designed to achieve this pre-cooling.

To mitigate the limitations in cooling rates caused by higher beam energies, stochastic cooling has been developed. This method utilizes a system of pickups, amplifiers, and kickers to cool high-energy hadrons. For even higher cooling rates required for proton cooling, the Coherent Electron Cooler (CeC) has been proposed, leveraging electron plasma as the amplification medium [2, 3].

In recent years, several ERL-based electron cooling systems have been proposed. While storage-based electron cooling systems are also under development, they are not covered in this report as they are not relevant to ERL-based designs.

### *Strong Hadron Cooling Based On CeC*

Strong hadron cooling, as illustrated in Fig. 3a, was adopted in the EIC Conceptual Design Report and has been extensively studied in recent years. The cooling rate is sufficient to balance Intra-beam Scattering (IBS), but achieving precise electron and ion alignment, as well as implementing effective cooling detection, presents substantial challenges. Proposed methods, such as Schottky signal modification, demand detectors with extremely low noise and high gain, which are currently unavailable [4]. Other concerns include the absence of tunable knobs and the difficulty of maintaining a low-noise electron beam in the ERL [5–8]. Generating 1 nC bunch charge with 98.5 mA average current and a cooling section emittance of less than 3 mm mrad requires a high-brightness electron source that surpasses the current state-of-the-art. Consequently, this scheme will necessitate significant R&D efforts [9].

### *Recirculating ERL-based Electron Cooling*

The average current of 400 mA significantly exceeds the capabilities of demonstrated high-brightness electron sources. To date, the highest average current achieved is approximately 65 mA [10]. To address this limitation, the proposed concept involves using an electron beam to cool the hadron beam over multiple turns before being dumped after energy recovery. By ensuring the beam retains sufficient quality to provide adequate cooling over multiple turns, the average current required from the gun can be reduced proportionally to the number of turns. A harmonic kicker would be employed to remove one bunch and inject another for energy recovery [11]. The schematic illustration in Fig. 3b depicts the original concept developed for JLEIC, which utilized magnetized electron cooling. The electron cooler without using a magnetized beam has been discussed with the EIC team and appears feasible. However, a significant challenge lies in the beam quality degradation caused by multiple turns in the arc section, primarily due to coherent synchrotron radiation (CSR) and the effects of interactions with the high-intensity ion beam using multi-nano Columb high-intensity electron bunches.

### *Multiple Guns Beam Merging ERL-based Electron Cooling*

To address the limitation of single electron gun average current and mitigate the energy spread increase caused by CSR in multi-turn ERLs, this report proposes an alternative approach to achieve high average current, as illustrated in Fig. 3c. The proposed solution involves a multiple gun merging system. If each gun produces an average current of 100 mA, four guns would be needed to achieve the required 400 mA. Alternatively, using six guns would reduce the average current per gun to 67 mA, a value that has been experimentally demonstrated. The concept of a gun merging system was previously explored during the early EIC conceptual staging. This approach relies on a capacitor kicker to align and stack bunches along a single axis. For instance, to produce a 4 nC, 98.5 MHz beam, each gun would generate 4 nC bunches at a reduced repetition rate of 24.6 MHz. A 24.6 MHz kicker could be implemented using either an LC circuit-based capacitor kicker, as described in [12], or a cavity-based ferrite-dominated RF kicker [13]. After merging, the beam would be accelerated to an energy exceeding 10 MeV for injection into the ERL. This design represents a single-turn ERL system, which is expected to maintain superior beam quality compared to the multi-turn ERL-based electron cooling approach. However, the beam dump power, estimated at 4 MW, exceeds the capacity of typical high-power dumps. To address this, the beam can pass through an RF structure for deceleration. For improved efficiency, an RF output coupling port can be introduced to extract RF power, compensating for the main ERL cavity's power loss resulting from the beam energy recovery process.

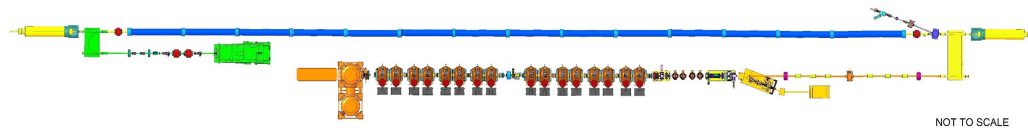
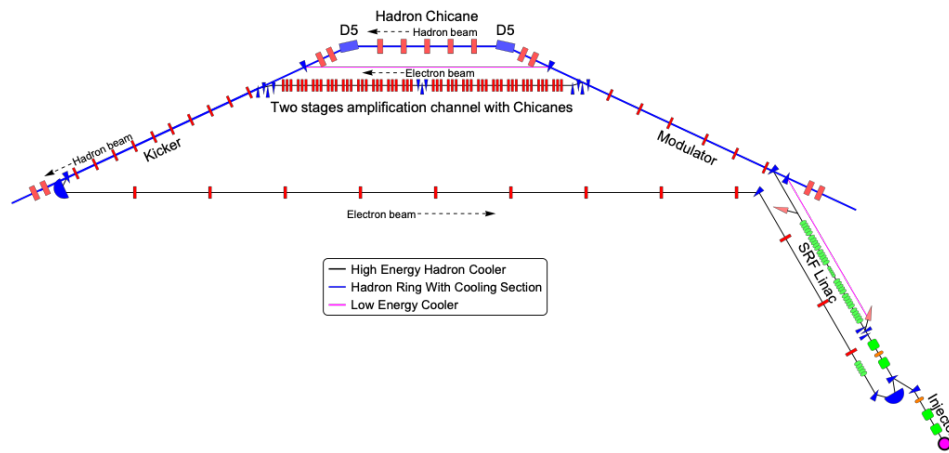
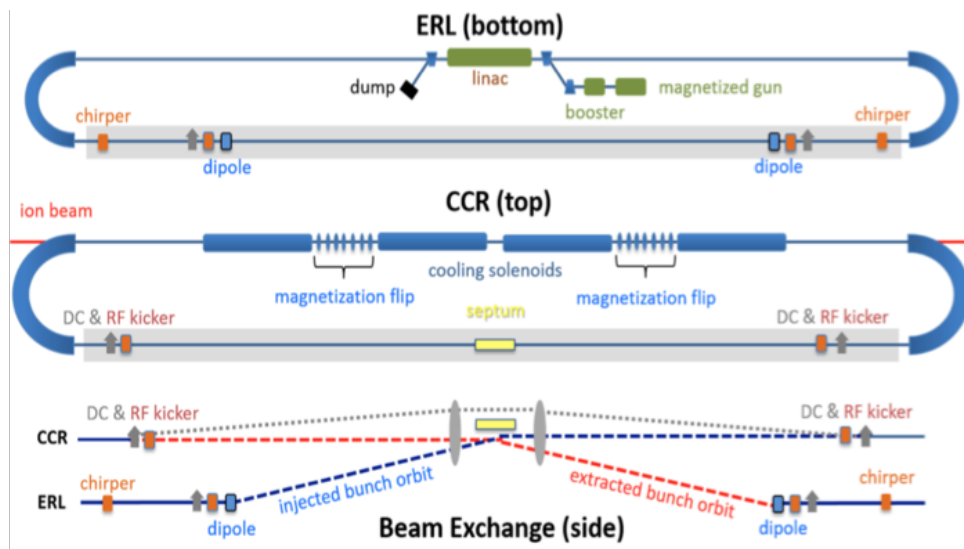


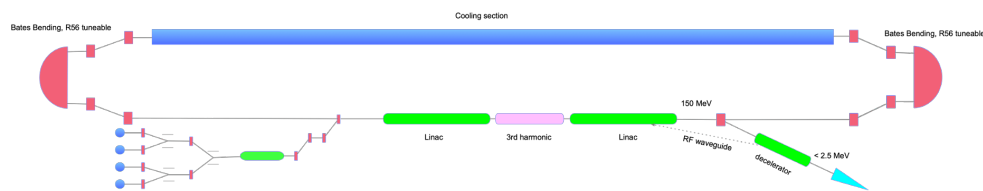
Figure 2: Low-energy cooler layout.



(a) Strong hadron cooling



(b) Multi-turn recirculating ERL cooler



(c) Multi-gun single turn ERL cooler

Figure 3: The schematic drawing of the proposed high energy cooler for EIC.

## ELECTRON SOURCE DEVELOPMENT

### Electron Source Requirements

All above schemes need high brightness, high average current, high-intensity electron source. We listed the electron

source requirements for each scheme as in Table 1. RF guns are generally better suited for generating high-brightness beams with bunch charges above several nC. However, within the EIC timeline, the development of a superconducting



Table 1: Comparison of Different HEC Electron Source Requirements

|                                   | Precooler | SHC-CeC   | HEC-recirculating | HEC-multi-gun single turn |
|-----------------------------------|-----------|-----------|-------------------|---------------------------|
| Average current, mA               | >70       | 90-100 mA | 60-100 mA         | 60-100 mA                 |
| Normalized Emittance rms, mm-mrad | 1.5       | 3         | 2                 | 2                         |
| Bunch charge, nC                  | 1.2       | 1         | 4                 | 4                         |
| Lifetime                          | 1 week    | > 3 days  | > 3 days          | > 3 days                  |

radio-frequency (SRF) gun capable of delivering 50 mA to 100 mA is not feasible [14]. Consequently, our approach involves the development of an HVDC gun to generate a pencil-shaped bunch, which is then compressed to the desired length before being injected into the Linac.

The HVDC gun R&D is guided by the following requirements:

- Development of an electron source capable of delivering a 98 mA beam with a single operational lifetime charge of 60 000 C.
- Operation at voltages exceeding 500 kV with an electric field gradient on the cathode surface of more than  $5 \text{ MV m}^{-1}$ .

The primary challenges of this R&D effort include the development of an efficient cathode cooling mechanism, achieving long stable operation at high voltages, reducing emittance, and generating high-bunch-charge beams [9].

### Gun Geometry

There are typically two HVDC gun configurations. The first involves placing the high-voltage feedthrough on top of the gun, while the second uses an inverted structure where the feedthrough is located inside the gun body.

The former feedthrough design offers the advantage of better control over the voltage potential along the ceramic, enabling the achievement of high voltages, such as above 500 kV [15]. However, this configuration has significant drawbacks, including a large physical footprint due to the required  $\text{SF}_6$  tank and the need to position the high-voltage power supply (HVPS) adjacent to the gun, often sharing the same  $\text{SF}_6$  tank. When the gun is placed in a high-radiation environment, such as a collider tunnel, the HVPS inverter is susceptible to radiation damage. Furthermore, challenges remain in developing an efficient cathode cooling system for this setup.

The inverted structure is more compact because both sides of the ceramic are enclosed neither in the atmosphere nor  $\text{SF}_6$ . This design allows for a shorter ceramic feedthrough. A polarized gun using this configuration has achieved 350 kV after only 20 hours of conditioning [16]. However, scaling this design to higher voltages, such as 500 kV, remains challenging due to uncontrollable potential distributions along the ceramic. We use the triple point shed on both the ground and high voltage sides to linearize the potential along the ceramic as shown in Fig. 4 [17]. The sheds also can avoid extremely high gradients at the vacuum-ceramic-metal joint.

The inverted structure facilitates cathode cooling and eliminates the need for  $\text{SF}_6$  in the entire system. The power supply, located far from high-radiation areas, can be connected to the gun through a high-voltage cable with a plug feedthrough.

A spherical chamber with a spherical electrode provides additional advantages in achieving high voltage. For a given chamber size, the minimum achievable electric field gradient can be optimized by adjusting the electrode size, as shown in Eq. 3:

$$V_{\text{cross}} = \int_{R_1}^{R_2} E(r) dr = \frac{q}{4\pi\epsilon_0} (R_1^{-1} - R_2^{-1}), \quad (1)$$

$$\frac{dE}{dR_1} = 0, \quad (2)$$

$$R_1 = \frac{R_2}{2}. \quad (3)$$

The Pierce-shaped cathode and anode system were optimized to achieve minimal emittance and maximize the laser spot size. Applying 550 kV to the electrode results in a cathode surface gradient of  $5.4 \text{ MV m}^{-1}$ , while all other surfaces maintain gradients below  $10 \text{ MV m}^{-1}$ . Even under conditioning up to 600 kV, the maximum surface gradient remains close to  $10 \text{ MV m}^{-1}$ . With a well-polished surface, field emission can be effectively mitigated. The optimized normalized emittance is 1.02 mm mrad for a bunch length of 250 ps.

To prevent gun trips caused by ion back bombardment, offsetting the laser from the center is essential. A laser offset of 3.5 mm results in approximately 3% emittance degradation. Additionally, 100 ppm HV variation increases emittance by approximately 1%. Emittance will be measured in the beamline using a multi-slit and viewer system. The main geometric design parameters for the gun operating up to 600 kV are summarized in Table 2.

### Cathode Cooling Set Up

Characterization of the  $\text{K}_2\text{CsSb}$  cathode material revealed that both the quantum efficiency (QE) and lifetime of the cathode significantly decrease above  $80^\circ\text{C}$ , particularly when the laser power exceeds 5 W, with QE dropping below 1% [18]. Cathode cooling is therefore essential to generate average currents in the 100 mA range, where laser powers typically exceeds 12 W.

We tested a cathode cooling scheme at BNL's polarized gun, which successfully maintained voltages above 300 kV for over two years without failure [16]. However, the cooling



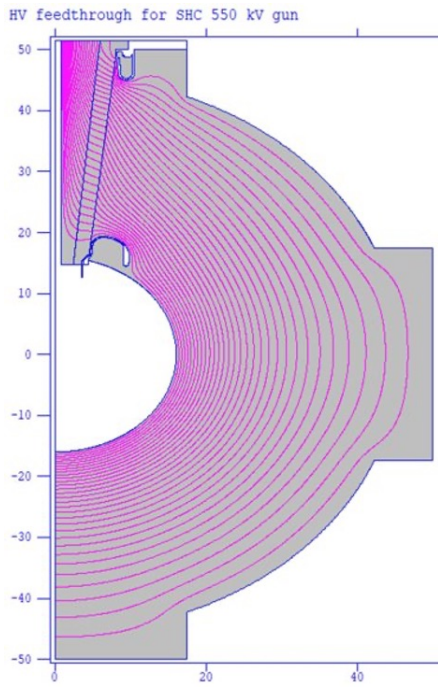
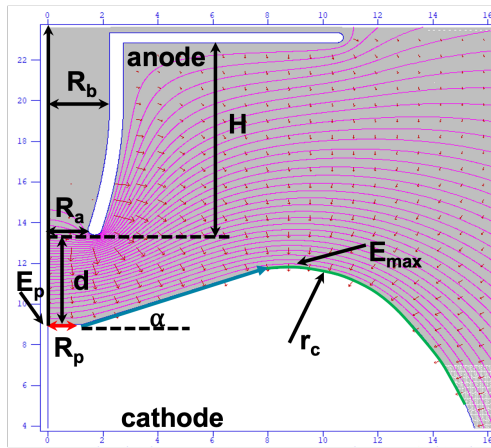
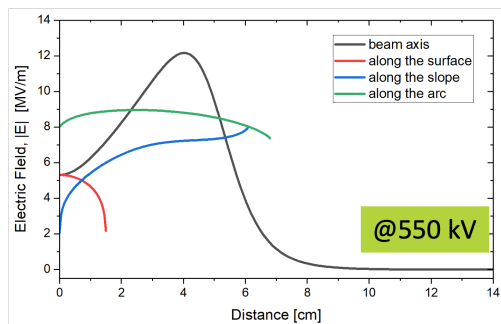


Figure 4: Triple point shielding set up in the gun.



(a) Super fish model of the gun field.



(b) Field gradient along the axis and electrode surface.

Figure 5: The HVDC gun field along the various surfaces at 550 kV after optimization

system, using FC72 as a fluid, increased maintenance complexity, as FC72 can dissolve the grease typically used to seal

Table 2: Main Gun Geometry, and Field Parameters, Responding to Fig. 5a

| Parameters                          | Values |
|-------------------------------------|--------|
| $R_1$ (cm)                          | 16     |
| $R_p$ (cm)                          | 1.26   |
| $r_c$ (cm)                          | 4.8    |
| $R_a$ (cm)                          | 1.45   |
| $R_b$ (cm)                          | 2.25   |
| $\alpha$ (°)                        | 23     |
| d (cm)                              | 4.4    |
| H (cm)                              | 9.5    |
| $E_{cathode}$ (MV m <sup>-1</sup> ) | 6.4    |
| $E_{max}$ (MV m <sup>-1</sup> )     | 9.8    |
| Voltage (kV)                        | 600    |

HV cable plugs and feedthroughs. Grease is commonly employed in industry to prevent air from being trapped between these components.

To mitigate the maintenance challenges and enhance cooling efficiency, our new approach involves creating a small gap between the ceramic feedthrough and the HV plug, which is filled with FC72. This not only prevents air entrapment but also provides cooling to the cathode. FC72 has a dielectric strength of 80 kV cm<sup>-1</sup>, allowing a length of 7.5 cm to withstand 600 kV. This setup is currently under testing, having already achieved voltage levels between 530 and 570 kV. Further tests focusing on stability and reliability are planned.

The cathode puck, designed with a large-waged base, is tightly attached to the cathode heat sink, which is made of oxygen-free copper. The cooling fluid reaches the heat sink, efficiently removing more than 20 W of thermal power. The cooling setup is still undergoing testing, as illustrated in Fig. 6.

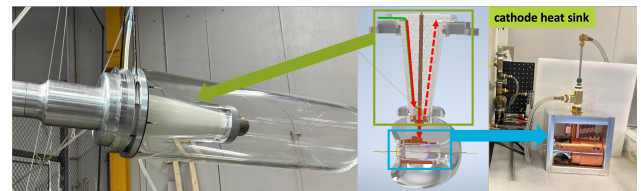


Figure 6: The cathode cooling set up. Left: the high voltage test with the FC72 flowing; Mid: the model shows how the cooling Fluid to the cathode heat sink and returns; Right: The cathode temperature set up using a heater and cooling fluid.

### Epitaxially Grown Large Crystal Photocathode

When a cathode is deposited onto a metal substrate, it typically forms polycrystalline crystal structures. The used cathode material must then be removed, and the substrate repolished to achieve a mirror-like smoothness. Recently, the BNL team developed a large crystal K<sub>2</sub>CsSb cathode,

epitaxially grown on lattice-matched 4H-SiC wafers, which demonstrates exceptional crystal quality, including ultra-smooth surfaces [19, 20]. Using 4H-SiC as the cathode substrate simplifies the replacement process, making it quick, cost-effective, and straightforward.

As discussed in the final section, the 4H-SiC substrate can potentially mitigate high-voltage breakdowns and reduce field emission. Additionally, doped 4H-SiC exhibits excellent thermal conductivity (4.2 W/cm-K), surpassing even copper. This property aids in efficient laser power transfer to the heat sink, helping to maintain the cathode temperature during high current operations. The intrinsic emittance is expected to be smaller than that of the polycrystalline crystal cathodes due to the smoothness of the 4H-SiC surface and the reduced scattering at grain boundaries in the cathode film with ordered crystal structure and large grains. Although the HVDC gun operates at lower gradients, the emittance increase due to surface smoothness may be difficult to measure. However, the reduction of emittance due to reduced grain boundary scattering could potentially be measurable using a slits system. The QE of these photocathodes could reach approximatively 9% when illuminated with a 532 nm laser, which satisfies the operational requirements for the gun. Similar to the cathode puck used in the polarized gun with GaAs wafers, we have designed a similar cathode assembly to accommodate the 4H-SiC wafers.

### High Voltage Cable and HVPS

The gun is designed to operate at 550 kV and is conditioned up to 600 kV. A 1 MV HV cable will be used to deliver the power, which simplifies the configuration compared to the scenario where both the power supply (PS) and the gun share the same SF<sub>6</sub> tank. However, the HVPS and the high-voltage cable's stored energy can potentially damage the gun if arcing occurs. For instance, the HVPS has a stored energy of 3.5 kJ, and a 9-meter 600 kV cable contains 80 J of stored energy. For a 400 kV cable, we have used a semiconductor jacket covering the cable to redistribute energy during discharge [16, 21], though this is not practical for the 1 MV cable. Our new approach involves placing a resistor between the gun and the HV cable.

During conditioning, the field emission current is uncontrollable. To mitigate this, we employ 66.7 MΩ voltage-dividing resistors to form a negative feedback loop, thereby protecting the gun. In high-current operation, the current becomes more controllable. To prevent the resistor from absorbing too much voltage drop, we use a 500 Ω resistor, which provides protection in case of a high-current HV trip. These resistors are capable of handling energies above 4 kJ, which is sufficient for both conditioning and operation of the gun. They are mounted in cylindrical assemblies designed to be directly affixed to the gun assembly. The energy storage between the resistor tank and the gun is negligible.

The HVPS is designed as a two-phase Cockcroft-Walton voltage multiplier, housed within a vessel that can either be pressurized with N<sub>2</sub> or operated with SF<sub>6</sub>, depending on the requirements. It can provide an average current of:

1) 150 mA at 400 kV; 2) 120 mA at 550 kV; 3) 12 mA at 600 kV.

The voltage multiplier is driven by an external power inverter that operates at a nominal frequency of 20 kHz. The combination of a stored energy of 3.5 kJ and the high-frequency inverter ensures that the output voltage ripple, caused by an instantaneous step of full-load current, remains below 1 kV, as shown in Fig. 7. The voltage drop/ripples due to beam energy variation are on the order of  $4 \times 10^{-4}$ .

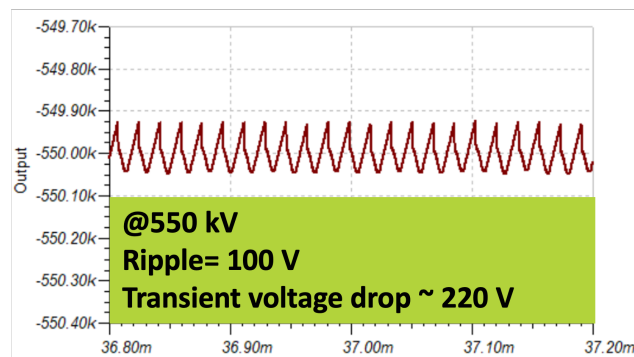


Figure 7: The transient voltage ripple expected at 550 kV operation.

### Vacuum

We are aiming to get a similar vacuum level as the polarized gun, about less than  $1 \times 10^{-11}$  torr, to avoid overnight QE degradation. For the R&D beamline which is short, it is important to block the outgassing from the beam dump. Differential pumping stage and beamline with NEG coating were simulated and is going to be used in the SHC R&D gun. Cathode vacuum pressure could achieve  $< 1 \times 10^{-11}$  Torr when beam dump is at  $1 \times 10^{-7}$  Torr with a full beam power of 55 kW as shown in Fig. 8.

## DISCUSSION: HV TRIP CONSIDERATIONS AND PROPOSED SOLUTIONS

One of the challenges in designing and operating the HVDC electron gun is the occurrence of undesired HV trips that disrupt the gun's operation. Specifically, the HVPS experiences more frequent trips when attempting higher current outputs. The following discussions are summarized detail the tech notes [22].

Several mechanisms have been proposed to explain HVPS trip, including downstream ion origin and cathode emitter bursts causing strong field emission. The ion back-bombardment sequence can be characterized as follows: 1) Electron beam ionizes residual downstream gases; 2) Positively charged ions or clusters flow back towards the cathode; 3) High-energy ions (100s keV) halt at the cathode center, fracturing the material and creating an irregular surface; 4) The roughened cathode surface induces field emission, triggering power supply trips. This mechanism explains

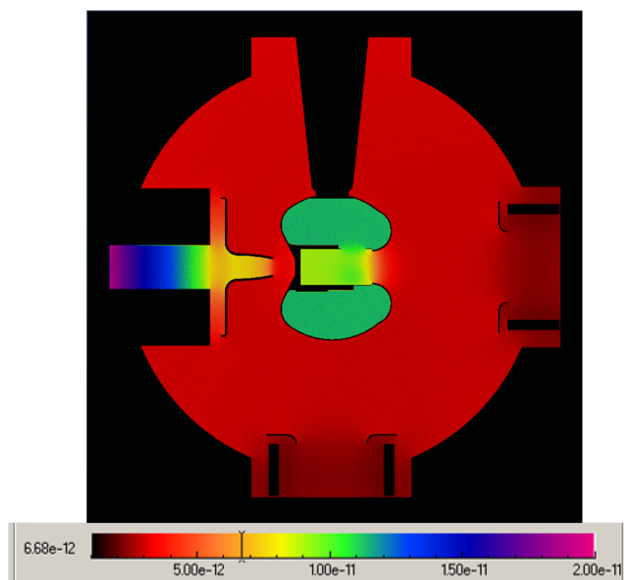


Figure 8: Monte-Carlo simulations shows the residual molecule distribution inside of gun vessel.

the increased trip probability with rising average current and damage concentration at the cathode center. Mitigation strategies such as anode biasing which we adopted and ion kicker electrodes have shown limited effectiveness, reducing trip probability only below 10 mA average current. Moreover, ions generated within the HVDC gap remain unaddressed through these methods. A notable contradiction emerges: some cathode damage spots are away from its center, which is the only location that downstream ions can reach.

An alternative explanation involves the formation of sharp surface on the cathode in a high-gradient environment as follows: 1) Fine crystal cathodes exhibit nanoscale roughness or contain transfer-induced particulates; 2) Low electron affinity results in a significantly reduced field emission threshold; 3) High-gradient operation enables field emission or dark current; 4) Field emission further sharpens tips and enhances field intensity; 5) High-power laser-induced localized temperature elevation amplifies field emission; 6) Field emission experiences exponential increase upon surpassing the field enhancement threshold. This mechanism elucidates damage spot occurrence away from the cathode center and increases trip probability at higher current levels. Employing smoother cathodes on atomically smooth substrates can mitigate these effects. Substrate particulate removal through high-pressure rinsing and clean room cathode installation further minimizes potential complications. Both ways will be incorporated into our program.

Despite numerous mitigation attempts, the HVDC gun encounters challenges in achieving 100 mA operation. We propose an additional mechanism wherein electron beam loss on the anode interacts with the monolayer, potentially degassing the anode and generating ions. These ions halt at the cathode, initiating secondary electron emission in a self-

reinforcing cycle similar as the multipacting in RF cavities, ultimately potentially tripping the HVPS.

At 100 mA, even a minimal beam loss of  $10^{-5}$  generates 1  $\mu$ A beam loss. With 550 kV applied, the beam power loss of 0.55 W can induce outgassing or X-ray generation. To reduce the X-ray generation, we utilize titanium ( $Z=22$ ) as a low-Z anode material at 550 kV DC gap voltage yields approximately 2 mW of X-ray power from lost electrons.

Cathode growth masks constrain cathode size, but growth material vapor diffusion extends beyond the designated area. Laser halo or scattered light can generate electrons from unexpected regions, which, under strong focusing, are prone to anode tube or aperture loss.

Within the DC gun, the initial aperture encountered by the beam is the anode, where electrons can generate hydrogen (H) or hydrogen gas molecules  $H_2$ . These ions, commonly trapped in materials or present as a monolayer coating on metal surfaces, are accelerated by the DC electric field, reaching the cathode surface and initiating the generation of secondary electrons. Another mechanism involves X-rays generated from the anode, which can also produce photo electrons. Cathode materials containing alkali metals exhibit a notably high photo yield or high secondary electron yield, often exceeding 100. Consequently, cathode-originating secondary electrons outnumber incident ions and are susceptible to anode loss, further ion generation.

The anode-cathode configuration enables electron-ion oscillation across an expanded area. When secondary yield exceeds unity, multiple iterations cause instantaneous peak current surges, increasing outgassing and ion backbombardment. Ionized gas movement toward the electrode frequently precipitates power supply failure.

Potential mitigation strategies include: 1) Anodizing cathode substrate to limit metal substrate exposure; 2) Employing low secondary yield materials like BN or SiC for cathode substrates or coatings; 3) Optimizing anode geometry to disrupt ion trajectories toward the cathode electrode. The R&D employ the method 2 and 3. And will leave the 1 as the risk mitigation.

## CONCLUSION

In this report, we briefly overview the proposed ERL-based high-energy coolers and low-energy coolers for the EIC. All these hadron coolers require a high-average-current, high-brightness electron source. As part of the EIC R&D efforts, we are developing an HVDC gun with a resistor network housed in a pancake container to fully eliminate stored energy.

The gun is designed as a 550 kV inverted structure utilizing a feedthrough with a novel cathode cooling mechanism. Furthermore, a single or large crystalline multialkali photocathode is being implemented. All these efforts are to address the main challenges in high current operation as laser overheating the cathode, as well as minimize high-voltage power supply (HVPS) trips. The project is currently in the construction phase, with high-voltage conditioning



planned for mid-2025 and beam commissioning scheduled to begin in 2026.

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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

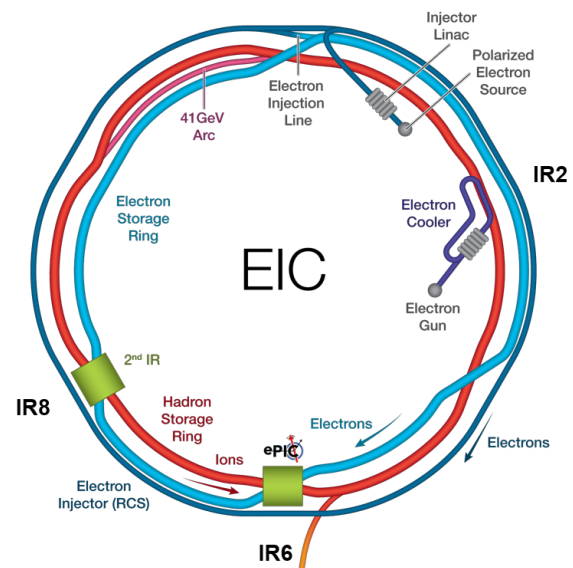


Figure 1: The current layout of a portion of the Electron-Ion Collider (EIC). The Hadron Storage Ring (HSR), Electron Storage Ring (ESR), and the Rapid Cycling Synchrotron (RCS) labels are color-coded to their respective rings; the current and proposed IRs are shown at IR6 and IR8, with the electron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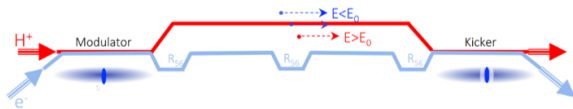


Figure 2: A representative layout of microbunched electron cooling. The protons and electrons co-propagate in the modulator section, separate into different lines, where the electron beam goes through a series of chicanes and drifts, before the electrons and protons once again co-propagate in the kicker section.

One type of coherent electron cooling is microbunched electron cooling (MBEC), the proposed mechanism for the Strong Hadron Cooler Energy Recovery Linac (SHC-ERL) to cool EIC protons during collisions. A representative diagram of this process is shown in Fig. 2. An electron bunch with the same relativistic gamma as the protons co-propagates with the proton bunch in the modulator, where the protons imprint on the electrons. Once separated, the electron bunch is sent through the amplifier, a series of chicanes and drifts which amplifies the energy modulation of the electron bunch that was induced by the protons; this energy modulation is converted into a density modulation. The protons and electrons co-propagate afterwards in the kicker, where the density modulation of the electrons provides a corrective kick to cool the protons. The necessary parameters for the electron beam and cooling section are shown in Table 1; further details of this cooling mechanism and these parameters can be found at [4].

## STRONG HADRON COOLER ERL

Given the significant beam power called for in Table 1, 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.

A representative layout of the SHC-ERL is shown in Fig. 3. 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 – after which, the beam begins energy recovery. Alternatively, the beam can be steered through the merger into the diagnostic line.

The injector consists of a photocathode DC gun and a cryomodule containing three superconducting radiofrequency (SRF) cavities – two 197 MHz quarter-wave resonators (QWRs) and a 591 MHz single-cell cavity. The beam is accelerated to roughly 6 MeV and the accelerating cavities are run off-crest so that the bunch is chirped; the single cell cavity is at the third harmonic of the 197 MHz frequency and is used to linearize the longitudinal phase space.

The booster consists of two cryomodules, oriented so that the cavity order is two 197 MHz QWRs, two 591 MHz, and

Table 1: The parameters of the electron beam (top) and the cooling section geometry and optics (bottom) for the two proton beam energies of the EIC. The electron beam longitudinal distribution is assumed to be a supergaussian of order  $\sim 4$ .

| Proton Energy                       | 100 GeV   | 275 GeV   |
|-------------------------------------|-----------|-----------|
| Gamma                               | 107.6     | 294       |
| Energy (MeV)                        | 55        | 150       |
| Bunch charge (nC)                   | 1         |           |
| Rep. rate (MHz)                     | 98.5      |           |
| Avg. current (mA)                   | 98.5      |           |
| $rms$ bunch length (mm)             | 9         | 7         |
| Peak current (A)                    | 10        | 13        |
| Slice energy spread $dp/p(10^{-4})$ | 0.6–1.5   | 0.4–0.8   |
| Norm. trans. emit. (mm-mrad)        | 2.8       |           |
| Modulator/Kicker Length (m)         | 33        |           |
| Number of Amplifier Drifts          | 2         |           |
| Amplifier Drift Length (m)          | 49        |           |
| $\beta_x/\beta_y$ in Modulator (m)  | 20.0/20.0 | 21.4/21.4 |
| $\beta_x/\beta_y$ in Kicker (m)     | 29.7/4.09 | 7.89/7.89 |
| $\beta_x/\beta_y$ in Amplifier (m)  | 12.0/12.0 | 4.89/4.89 |
| $R_{56}$ in First Chicane (mm)      | 23.3      | 12.0      |
| $R_{56}$ in Second Chicane (mm)     | -16.7     | -6.66     |
| $R_{56}$ in Third Chicane (mm)      | -18.2     | -6.85     |

two 197 MHz QWRs. The beam energy is roughly 13 MeV, the bunch is significantly chirped, and the single cell cavities are again used to linearize the longitudinal phase space; however, the longitudinal phase space is evaluated after the bunch compressor in the following section.

Next, the beam enters the PX section, which consists of the P1, P2, and P3 lines. Each line is energy-specific and during the acceleration of both configurations, the 13 MeV beam goes down the P1 line, which compresses the bunch; bunch compression is tunable due to the quadrupole magnets included in the compressor.

Following the PX section is the main linac, consisting of eight 591 MHz five-cell SRF cavities and four 1773 MHz five-cell SRF cavities, with the 1773 MHz cavities placed in the center and four 591 MHz cavities on either side. The beam is accelerated to the top energy of either 150 or 55 MeV and is no longer chirped. Similar to the injector and booster, the longitudinal phase space is linearized with the 1773 MHz cavities.

The dump chicane and the laser heater chicane follow the main linac, after which the beam is transported to the cooling section, which consists of the modulator, amplifier, and kicker. After the cooling section, the beam separates from the HSR before entering a Bates bend and going down the return line.

At the end of the return line is a 591 MHz five-cell SRF cavity, which is run at the zero crossing and chirps the beam,

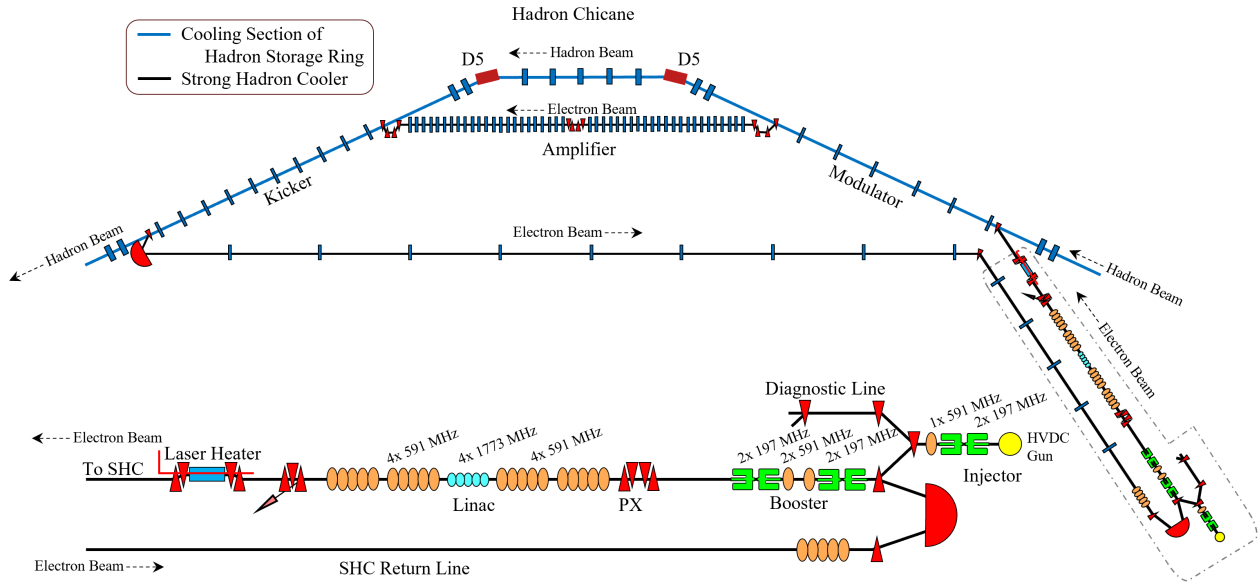


Figure 3: (Top) A representative layout of the cooling complex in IR2. The electron beam of the SHC-ERL begins at the HVDC gun, represented by a yellow circle in the bottom right. This beam is brought up to full energy before the electron beamline merges with the HSR in the cooling section, which consists of the modulator, amplifier, and kicker. At the end of the cooling section, the electron beam separates from the HSR, returns to energy recover, and is steered into the dump line. (Bottom) This is an enlarged view of the dashed gray box enclosing part of the SHC-ERL. Represented is the injector, followed by the merger, going to either the diagnostic line or the booster, the bunch compressor and high energy bypass lines (PX), the main linac (Linac), the dump chicane, the laser heater, the transport to the cooling section, and the return line from the cooler.

minimizing the energy spread of the beam at the dump. Without this chirp cavity, the only way to minimize the energy spread is to have the beam energy at the dump to be significantly different than the 6 MeV injection energy.

After the return line is a second Bates bend – following this, the high energy line merges with the injection line, and the chirped beam begins deceleration and energy recovery. The beam is decelerated during the second pass through the booster, then enters the PX section. For the second pass through PX, the beam enters either the P2 or P3 beamline, corresponding to the 55 and 150 MeV modes, respectively. During the second pass through the linac, the beam decelerates to the injection energy and is transported to the beam dump. Closed optics exist for both operational modes, shown in Figs. 4 and 5.

## LASER HEATER

Microbunched electron cooling is highly sensitive to the slice energy spread of the electron beam – for the EIC, this parameter needs to fall within the specified range, not just below a maximum value. While significant effort has been put into the design of the injector and booster to achieve a small slice energy spread, it is possible that the resulting value of this parameter will be too small at the exit of the linac and must be increased to fall within the target range before entering the cooling section. To increase the slice energy

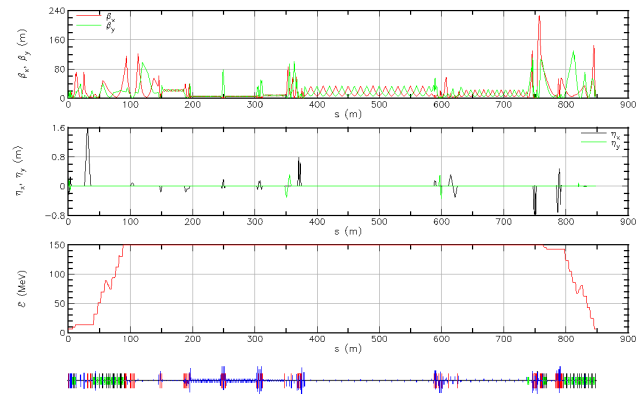


Figure 4: The closed design optics for the 150 MeV mode of the SHC-ERL. Shown are the beta functions in meters (top), dispersion in meters (middle), and the beam energy in MeV, all as a function of  $s$  in meters. Below the three plots is the component layout.

spread and provide an adjustable knob for this parameter downstream of the linac, a laser heater is located between the linac and the cooler [3]. The layout of the laser heater involves co-propagating a laser with the electron beam inside an undulator at the center of a chicane; a representative layout is shown in Fig. 6. The laser heater increases the slice energy spread by first applying a momentum modulation on the electron beam from the interaction with the laser within

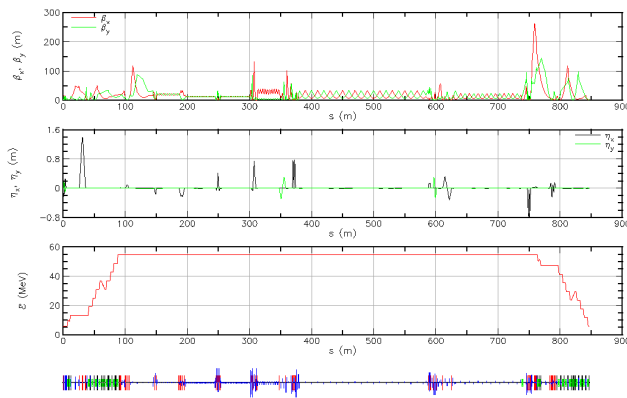


Figure 5: The closed design optics for the 55 MeV mode of the SHC-ERL. Shown are the beta functions in meters (top), dispersion in meters (middle), and the beam energy in MeV, all as a function of  $s$  in meters. Below the three plots is the component layout.

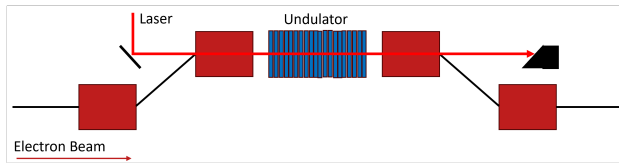


Figure 6: A representative layout of a laser heater, which involves co-propagating a laser with the electron beam inside an undulator at the center of a chicane.

the undulator. This modulation is smeared out in the second half of the chicane [5].

## INJECTION COOLER ERL

The injection cooling of the EIC protons is the first cooling stage, occurring after the protons are injected into the HSR but before they are ramped to the collision energy. The cooling mechanism used in this stage is non-magnetized bunch beam cooling, which is also used for Low Energy RHIC electron Cooling (LEReC) [6, 7].

One design option is for the injection cooler to be an ERL and have common components with the SHC-ERL; a representative layout of such a scheme is shown in Fig. 7 and select beam parameters are shown in Table 2 [9].

For this concept of an injection cooler ERL, the electron beam begins as it does in the SHC-ERL, though it is extracted in the PX section from the P1 line into a separate line that transports the low energy electron beam to the cooling section while bypassing the linac.

As the bunched beam cooling requires minimal residual fields during cooling, the quadrupole magnets in the modulator and kicker sections used during MBEC would need to be air-core Panofsky quadrupoles to meet this requirement. Additionally, a bypass line for the injection cooler to bypass the amplifier section would be necessary.

After the cooling section, the electron beam would be transported by the same return line that the 150 and 55 MeV electrons use, before decelerating in the booster and being

Table 2: The electron beam parameters for the proton beam energy at injection. The electron beam longitudinal distribution is assumed to be a supergaussian of order  $\sim 4$ . Three electron bunches, each of bunch charge 1.33 nC, overlap a single proton bunch during cooling.

| Proton Energy                        | 23 GeV          |
|--------------------------------------|-----------------|
| Gamma                                | 25.4            |
| Energy (MeV)                         | 13              |
| Bunch charge (nC)                    | $3 \times 1.33$ |
| <i>rms</i> bunch length (mm)         | 40              |
| Slice energy spread $dp/p(10^{-4})$  | 5               |
| Norm. transverse emittance (mm-mrad) | 2               |

transported to a beam dump located after the booster cryomodules.

At present, no cooling solution exists for the 41 GeV protons; using this injection cooler ERL allows the option to add additional cryomodules, increase the electron beam energy to roughly 22 MeV, and use bunched beam cooling [8, 9].

## CONCLUSION

An initial design exists for both energy modes of the SHC-ERL, which is capable of providing cooling of high energy protons during collisions at the EIC. One critical success of this design is that the magnet layout is unchanged between configurations, so no vault access is required between switching energies. This design allows for the option of incorporating bunched beam cooling at the proton injection energy and during collision of the 41 GeV proton beam. Though more complex than many ERLs, no show stoppers have been found. As collective effects and design alternatives are evaluated, we anticipate that a mature, robust design for an ERL-driven high energy cooler can be completed.

## ACKNOWLEDGMENTS

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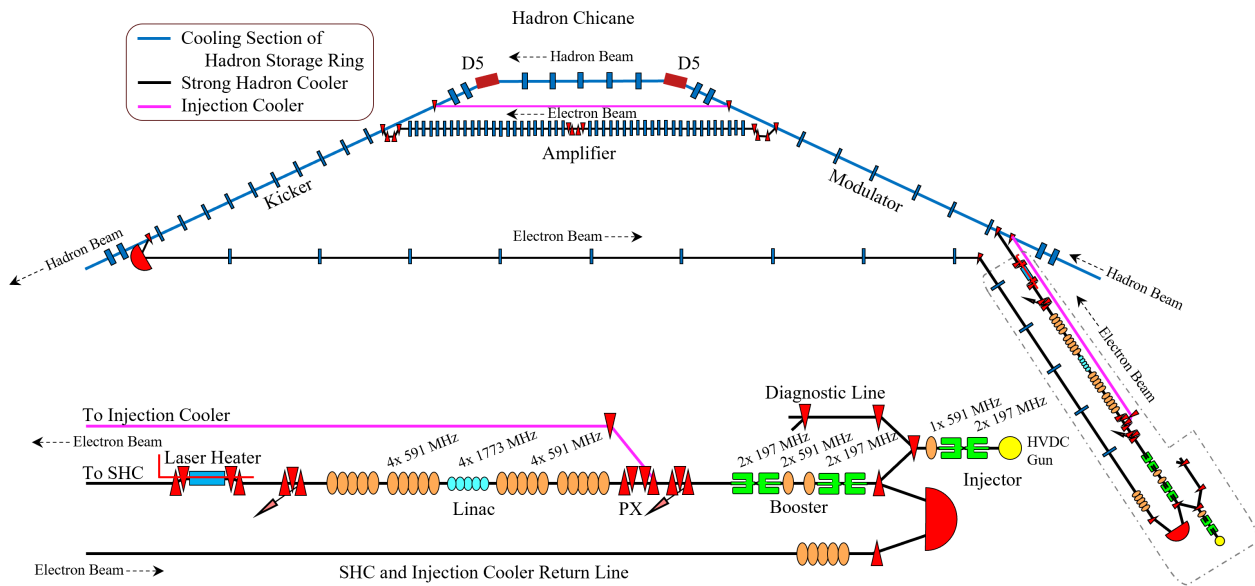


Figure 7: (Top) A representative layout of the cooling complex in IR2, with the injection cooler ERL sharing components with the SHC-ERL. The electron beam of the injection cooler ERL begins at the HVDC gun, represented by a yellow circle in the bottom right. This beam is brought up to full energy by the booster before being extracted from the SHC-ERL beamline in PX and transported to the HSR cooling section, which consists of drifts, including a drift beamline to bypass the amplifier section of the SHC-ERL. At the end of the cooling section, the electron beam separates from the HSR, returns to energy recover, and is steered into the dump line after the booster. (Bottom) This is an enlarged view of the dashed gray box enclosing part of the SHC-ERL and injection cooler ERL. Represented is the injector, followed by the merger, going to either the diagnostic line or the booster, the bunch compressor, high energy bypass lines, and extraction to the injection cooler transport line (PX), the main linac (Linac), the dump chicane, the laser heater, the transport to the cooling section, and the return line from the cooler.

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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.

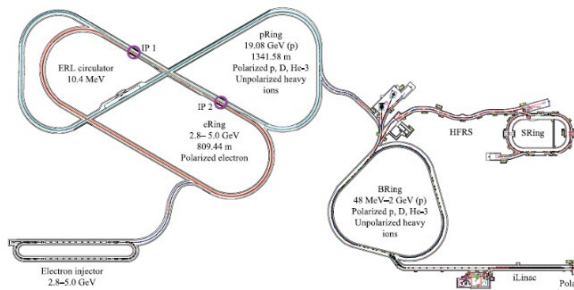


Figure 1: The layout of the EicC accelerator facility [1].

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

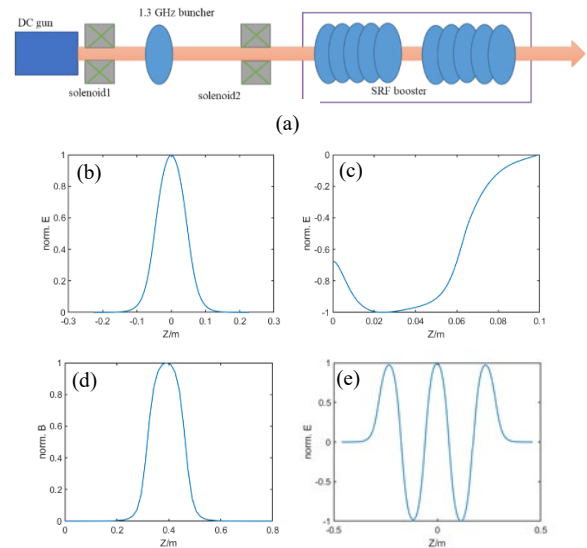


Figure 2: The polarized electron injector layout based on the DC gun structure (a) and the field maps(b-e).

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on the DC gun structure is shown in Fig. 2(a). The gun gradient is  $-4.96$  MV/m, correspond to 300 kV between anode and cathode and the electric field distribution along the  $z$  is shown in Fig. 2(b). The buncher cavity is the same with the KEK buncher cavity [5] and the simulated field map is shown in Fig. 2(c). The solenoid field map is shown in Fig. 2(d) and Fig. 2(e) is the five cell TESLA-type SRF cavity field map. All the field maps are simulated with POISSON SUPERFISH code [6]. The five cell TESLA-type SRF cavity is from normal nine cell TESLA cavity [7] except the middle four cells.

Table 1: The Polarized Electron Injector Parameters and the Corresponding Layout Shown in Fig. 1(a)

| Parameters                        | values          |
|-----------------------------------|-----------------|
| Gun field gradient (300 kV)       | $-4.96$ MV/m    |
| Laser transverse size             | $x_{rms}=1$ mm  |
| Laser longitudinal length         | flat top, 20 ps |
| Bunch charge                      | 100 pC          |
| Buncher position (peak)           | 1.0 m           |
| Buncher field gradient            | 1.4 MV/m        |
| Buncher phase                     | 248.6 degrees   |
| Solenoid1 position (peak)         | 0.23 m          |
| Solenoid1 field                   | $-0.030$ T      |
| Solenoid2 position (peak)         | 1.6 m           |
| Solenoid2 field                   | $-0.0224$ T     |
| Booster cavity 1 position (start) | 2.0 m           |
| Booster cavity 1 gradient         | 20 MV/m         |
| Booster cavity 1 phase            | 187.1 degrees   |
| Booster cavity 2 position (start) | 2.9 m           |
| Booster cavity 2 gradient         | 18 MV/m         |
| Booster cavity 2 phase            | 130.0 degrees   |

The polarized electron injector beam dynamics is studied by ASTRA code [8]. The multi-parameters of the injectors are optimized to achieve the required beam emittance. The optimized parameters are shown in Table 1 and achieved the optimized parameters from ASTRA at  $z = 5.5$  m from the cathode are following: transverse normalized emittance is 1.5 mm mrad; the longitudinal emittance is 252 mm keV/c and the rms energy spread is about 0.6%. The simulated results are shown in Fig. 3: (a) the normalized beam emittance and rms beam size along the beam line from cathode to  $z = 5.5$  m; (b) the beam average energy and rms energy spread along the beam line; (c) the beam transverse distribution (d) the beam  $x$  trace space distribution and (e) the beam longitudinal phase space at  $z = 5.5$  m.

## HIGH BUNCH CHARGE ELECTRON INJECTOR DESIGN FOR e-COOLING ERL

The injector for the e-cooling ERL requires high bunch charge, high repetition rate and high-quality CW operation mode specially. For electron cooling ERL injector, the QWR SRF photocathode gun is considered especially for high bunch charge. Currently, for example BNL 112 MHz quarter wave resonator (QWR) SRF gun, the bunch charge can be as high as 10.7 nC [9-10]. The “green” cathode is most promising for high average current electron source

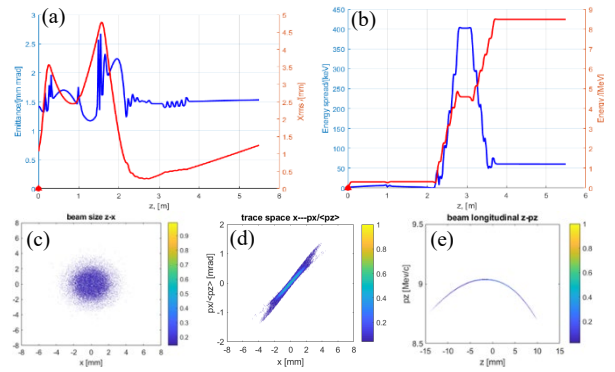


Figure 3: The beam dynamics simulated results of the polarized electron injector with the Table 1 parameters and Fig. 1(a) layout.

due to the high QE and high efficiency laser technology [11]. However, the SRF gun technology is still under development. To achieve the required beam parameters, one promising method is to enhance the field gradient at the cathode. For BNL QWR SRF cavity, the max field gradient in the gun cavity is about 20 MV/m. From simulation studies, if the max field gradient can reach 30 MV/m, which will make the injector easy to satisfy the beam requirements, which is also pursued from LCLS-HE injector [12, 13]. Other critical parameters are the low emittance and small energy spread, which should be cared from beginning of the beam dynamics design.

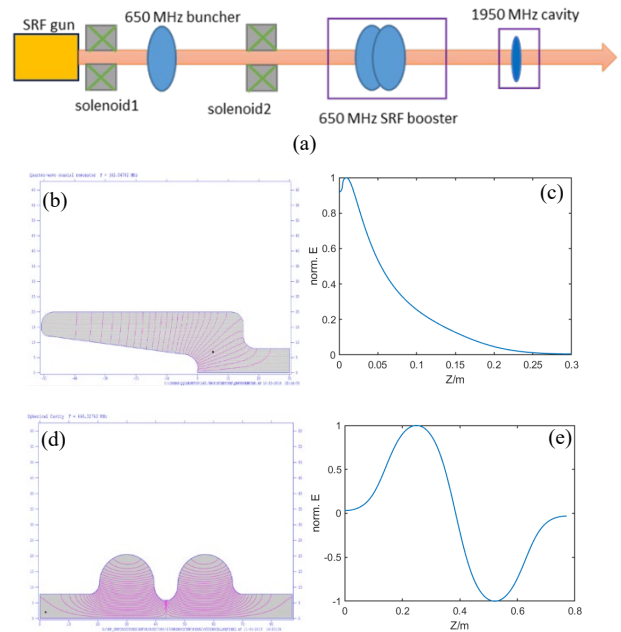


Figure 4: The high bunch charge electron injector based on the QWR SRF photocathode gun. (a) the injector layout, (b-c) the QWR SRF gun and field map and (d-e) the two-cell 650 MHz SRF cavity and field map.

The high bunch charge electron injector based on the QWR SRF photocathode gun is shown in Fig. 4: (a) the injector layout; (b-c) the QWR SRF 162.5 MHz cavity field map and (d-e) the two-cell 650 MHz SRF cavity field map which are simulated with POISSON SUPERFISH. The two cell 650 MHz SRF cavity design is the same with the reference [14], which is suitable for high average current acceleration and long bunch length, which is required from e-cooling purpose. A third harmonic cavity 1950 MHz cavity is used for flattening the RF accelerating voltage and make the energy spread lower. The solenoids fields are same with the one shown in Fig. 2(d).

Table 2: The QWR SRF Gun-based Injector Parameters and the Corresponding Layout Shown in Fig. 4(a)

| Parameters                      | Values          |
|---------------------------------|-----------------|
| Gun field gradient              | -30.0 MV/m      |
| Gun cavity frequency            | 162.5 MHz       |
| QWR Gun phase                   | 75.04 degrees   |
| Laser transverse size           | xrms = 0.78 mm  |
| Laser longitudinal length       | flat top, 60 ps |
| Bunch charge                    | 4000 pC         |
| Solenoid1 position (peak)       | 0.1 m           |
| Solenoid1 field                 | -7.82E-02 T     |
| Solenoid2 position (peak)       | 1.3 m           |
| Solenoid2 field                 | -4.00E-03 T     |
| Buncher position (peak)         | 0.6 m           |
| Buncher field gradient          | -8 MV/m         |
| Buncher phase                   | 350 degrees     |
| Booster cavity position (start) | 2.2 m           |
| Booster cavity gradient         | 8.0 MV/m        |
| Buncher/Booster frequency       | 650 MHz         |
| Booster cavity phase            | 230 degrees     |
| 3rd harmonic cavity gradient    | -15.0 MV/m      |
| 3rd harmonic cavity frequency   | 1950 MHz        |
| 3rd harmonic cavity phase       | 108.2 degrees   |

The beam dynamics of the QWR SRF gun-based injector, which is shown in Fig. 4(a), is studied with the code ASTRA. The multi parameters are optimized to achieve low emittance and energy spread for the high bunch charge. The optimized parameters and the results are shown in Table 2 and Fig. 5. With these parameters, the achieved transverse normalized emittance is 2.1  $\mu\text{m}$ , the longitudinal emittance is 124.94 keV/c mm and the rms energy spread can be reached 12 keV/c (0.3%).

## CONCLUSIONS AND DISCUSSIONS

The preliminary considerations and designs of polarized electron injectors for EicC and high bunch charge electron injector for the ERL e-cooling with beam dynamics simulation studies are presented in this paper. All the technology related to the designs are well within reality except the 30 MV/m in the QWR SRF cavity out of the state of art, which still needs more cavity design and experimental studies. More detailed simulation and experimental pre-research of the both injectors will be taken in the near future.

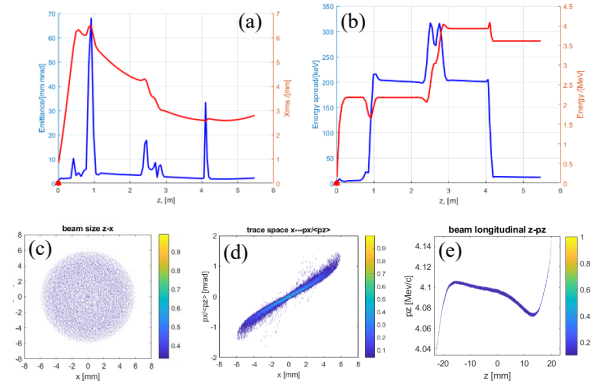


Figure 5: The simulated results for the ERL high bunch charge injector based QWR SRF gun. (a) the rms x emittance and beam size and (b) the average beam energy and rms energy spread along the beam line; (c) beam transverse distribution, (d) beam x trace space distribution and (e) beam longitudinal phase space distribution at  $z = 5.5$  m.

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# DESIGN OF A CONDUCTION-COOLED 2.856 GHz Nb<sub>3</sub>Sn SRF CAVITY AND COMPACT CRYOMODULE FOR ELECTRON ACCELERATOR\*

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## Abstract

This paper introduces the design of a conduction-cooled Nb<sub>3</sub>Sn 2.856 GHz cavity and compact cryomodule. The cryomodule incorporates a single-cell Nb<sub>3</sub>Sn 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. Nb<sub>3</sub>Sn 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 Nb<sub>3</sub>Sn (niobium-tin) conduction-cooled cavities represents a significant advancement over pure niobium, offering several advantages in terms of operational temperature, thermal stability, and efficiency.

Nb<sub>3</sub>Sn 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 Nb<sub>3</sub>Sn 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 Nb<sub>3</sub>Sn cavity. A beam acceleration test of a Nb<sub>3</sub>Sn 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  $\sim 1.0$  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

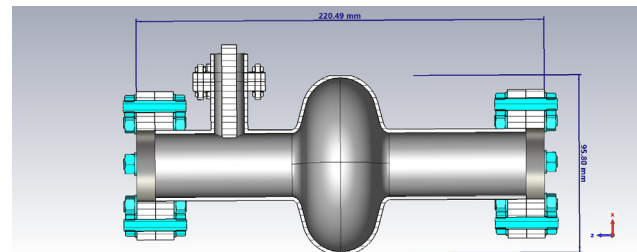


Figure 1: Schematic design of 2.856 GHz cavity.

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, TM<sub>010</sub>.

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Table 1: Cavity RF Parameters for  $E_{\text{acc}} = 20 \text{ MV/m}$ 

| Parameter                      | Unit         | Value              |
|--------------------------------|--------------|--------------------|
| Frequency                      | [GHz]        | 2.856              |
| Voltage                        | [MV]         | 1.050              |
| $E_{\text{acc}}$               | [MV/m]       | 20.000             |
| $Q_0$                          |              | $1 \times 10^{10}$ |
| R/Q                            | [ $\Omega$ ] | 109.600            |
| $E_{\text{pk}}$                | [MV/m]       | 35.788             |
| $B_{\text{pk}}$                | [mT]         | 84.454             |
| $E_{\text{pk}}/E_{\text{acc}}$ |              | 1.789              |
| $B_{\text{pk}}/E_{\text{acc}}$ | [mT/MV/m]    | 4.223              |

### 2.856 GHz Cavity Fields Profiles

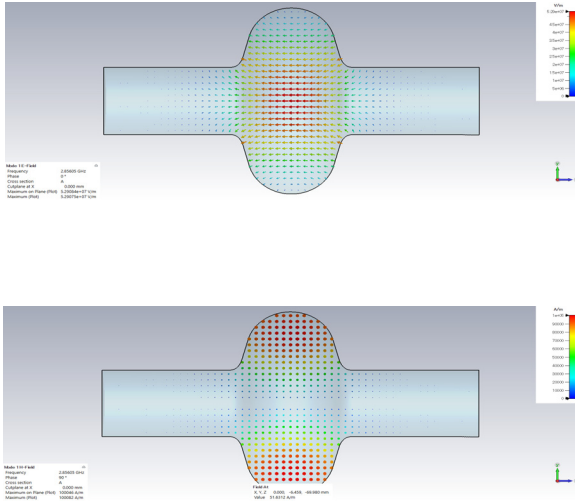


Figure 2: Electromagnetic fields of the 2.856 GHz cavity in the  $\text{TM}_{010}$  mode: the top shows the electric field distribution, while the bottom displays the magnetic field distribution.

Figure 3 shows the electric field distribution along the z-axis of the 2.856 GHz cavity at an accelerating gradient of 20 MV/m. Furthermore, the surface magnetic and electric fields across the cavity, from end to end, are calculated and presented in Fig. 4.

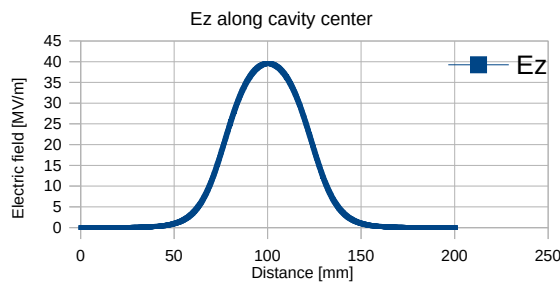


Figure 3: The electric field distribution along the z-axis of the 2.856 GHz cavity at an accelerating gradient of 20 MV/m.

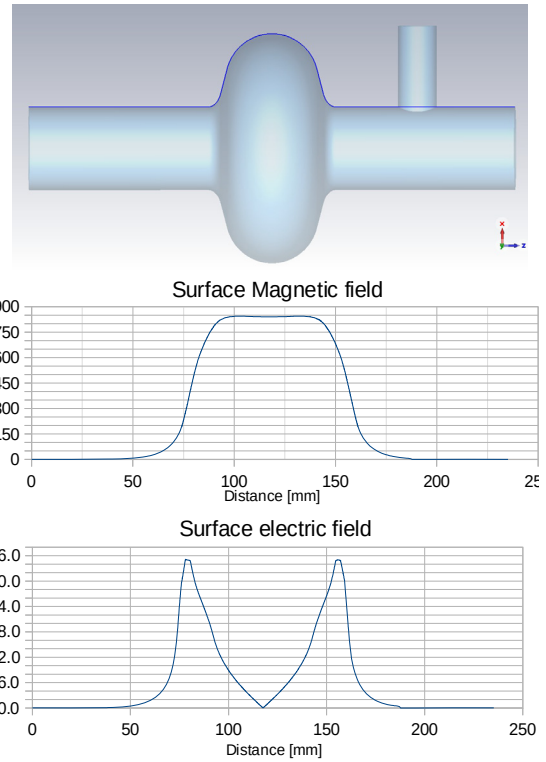


Figure 4: Top is the blue line along which the surface fields were calculated. middle is the surface magnetic field distribution and the bottom is the surface electric field distribution.

### 2.856 GHz CAVITY'S CRYOMODULE DESIGN

The cryomodule is composed of several critical components designed for high performance. The 2.856 GHz cavity is surrounded at its equator by a dual-function ring that functions as both a conduction cooling system and a frequency tuner. Cooling is achieved through a cryocooler with a capacity of approximately 1.8 W at 4.2 K. A magnetic shield minimizes external magnetic interference by reducing the ambient magnetic field to below 0.5 mG, while a thermal shield connected to the cryocooler's first stage ensures effective temperature regulation. Figure 5 shows a cross-sectional view of the cryomodule, and Fig. 6 provides a detailed depiction of the beamline components, including the conduction cooling/tuning system and cavity-end bellows, demonstrating their integration and functional arrangement. The cryomodule has an overall length of approximately 600 mm.

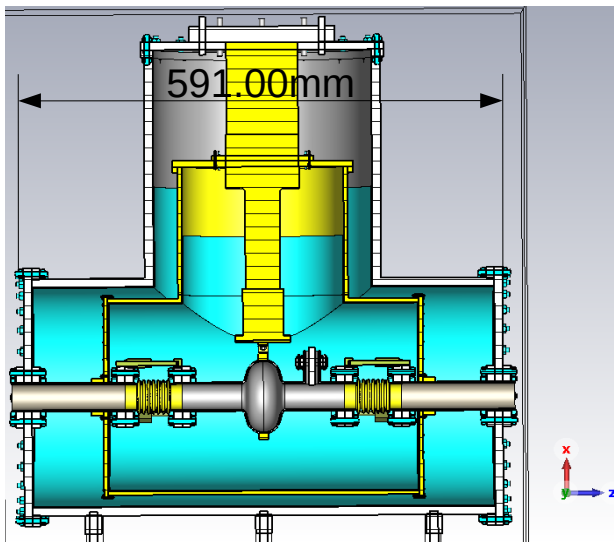


Figure 5: Cross-sectional view of the cryomodule.

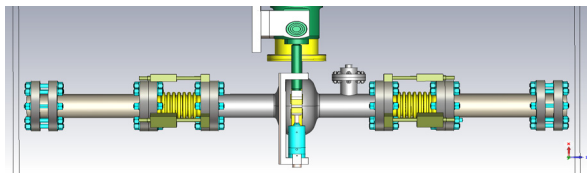


Figure 6: Beam-line of 2.856 GHz cavity cryomodule.

### THERMAL STUDY FOR THE CONDUCTION COOLING SYSTEM OF THE CAVITY

The conduction cooling system utilizes a ring surrounding the cavity equator shown in Fig. 7, which is thermally connected to the second stage of the cryocooler head. Copper with a Residual Resistivity Ratio (RRR) of 300 was used in the thermal simulations conducted in ANSYS [5] to evaluate system performance. A heat load of 1.5 W applied to the cavity equator resulted in a temperature rise of  $\Delta T = 1.6$  K, demonstrating effective thermal management and conduction efficiency. The temperature distribution under 1.5 W heat load is illustrated in Fig. 8.

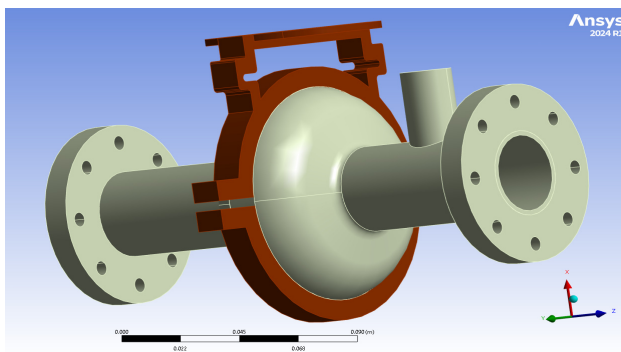


Figure 7: The conduction cooling system utilizes a ring surrounding the cavity equator.

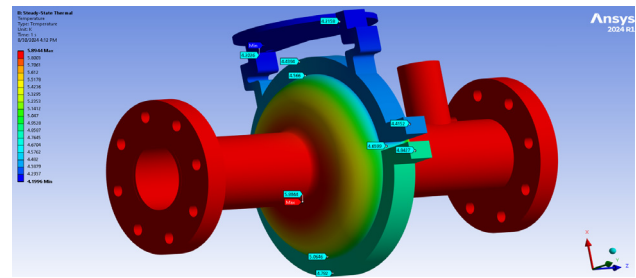


Figure 8: The temperature distribution under 1.5 W heat load.

### VACUUM VESSEL FOR 2.856 GHz CAVITY

SS400 vacuum vessel with a thickness of 11 mm can reduce the external magnetic field (earth magnetic field roughly equal to 0.5 G) to less than 65 mG. SS400 material has a relative magnetic permeability of approximately 1000.

After the vessel fabrication, demagnetization process maybe needed to minimize residual fields in vessel.

### MAGNETIC SHIELDING FOR 2.856 GHz CRYOMODULE

The magnetic shielding system is designed to significantly reduce the external magnetic field, initially around 65 mG, to less than 0.6 mG as shown in Fig. 9. This is achieved through a double shielding approach. Local magnetic shielding consists of a multi-layer shield with a thickness of 1 mm, applied inside the thermal shield, which can reduce the external field to approximately 3 mG. Global magnetic shielding involves covering the interior of the vacuum vessel with a similar 1 mm multi-layer shield to further reduce magnetic field at cavity region from 3 mG to less than 0.6 mG. The simulated earth magnetic field is assumed that its strength is 0.5 G, pointing from north west to south east. The magnetic shield material used in the simulations is a standard high-permeability material with a maximum relative permeability of 90,000, ensuring effective suppression of magnetic interference.



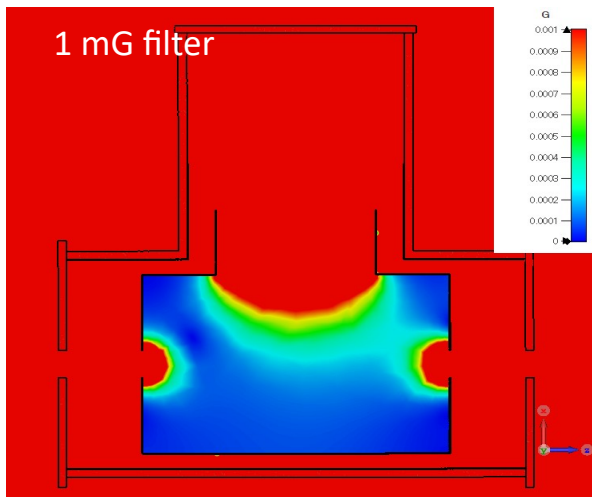


Figure 9: The magnetic shielding effectiveness for an external magnetic field of 0.5 G, with a 1 mG filter applied.

## TUNING SYSTEM FOR 2.856 GHz CAVITY

The tuning mechanism works by compressing the cavity equator with the conduction cooling ring, allowing for precise adjustment of the cavity's frequency. The tuning system integrates both slow and fast tuning mechanisms for precise control. A stepper motor is employed for slow tuning adjustments, while a piezoelectric actuator handles rapid tuning changes. These components are supported by a G-10 C-shaped clamp, which securely holds the motor and piezoelectric actuator in place. Additionally, a G-10 slider frame facilitates vertical movement of the motor as illustrated in Fig. 10.

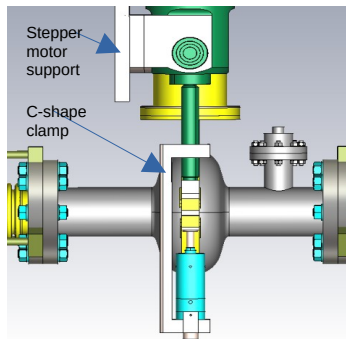


Figure 10: Frequency tuner system of the cavity.

## PRELIMINARY MEASUREMENT RESULT OF TUNING SYSTEM

As the 2.856 GHz cavity has not yet been fabricated, a 1.3 GHz cavity was used to evaluate the performance of the proposed tuning method as shown in Fig. 11. Preliminary results revealed that reducing the cavity's circumference by 1 mm led to an increase in cavity frequency of approximately 100 kHz. Additionally, the relationship between the tuning range and frequency change was found to be nearly linear, indicating predictable and precise tuning behaviour as shown in Fig. 12.

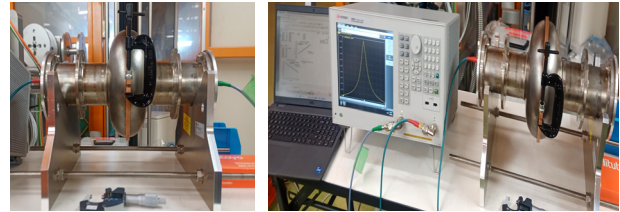


Figure 11: A 1.3 GHz cavity surrounded with a tuner copper ring and room temperature frequency measurement setup.

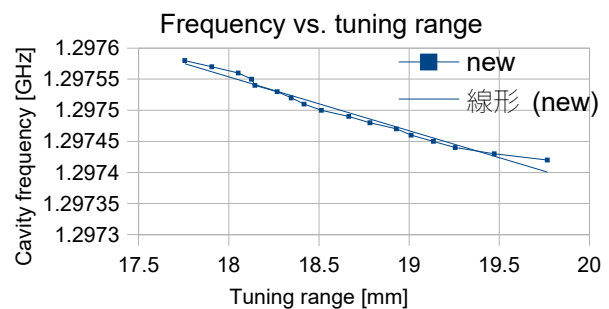


Figure 12: Preliminary measurement result of tuning test applied for a 1.3 GHz cavity.

## CONCLUSION AND PATH-FORWARD

2.856 GHz cavity design has been finalized and fabrication process is ongoing. Cryomodule design has been completed. Conduction cooling system is capable of cooling down cavity to 4.2 K. Combination of local and global magnetic shielding scheme shows that it's very promising to minimize external magnetic field to lower than 0.5 mG. Tuner system will be tested to validate the performance reliability and robustness. The vibration of the cryocooler head is a major concern. Microphonics will be assessed and addressed if necessary. Thermoelectric currents are also a significant issue, and they will be investigated, minimized, and mitigated as required.

## ACKNOWLEDGMENTS

The authors express their gratitude for the support provided by the Grant-in-Aid and extend their thanks to the staff of the Superconducting Linac Test Facility (STF) for their cooperation during the cavity tuning test.

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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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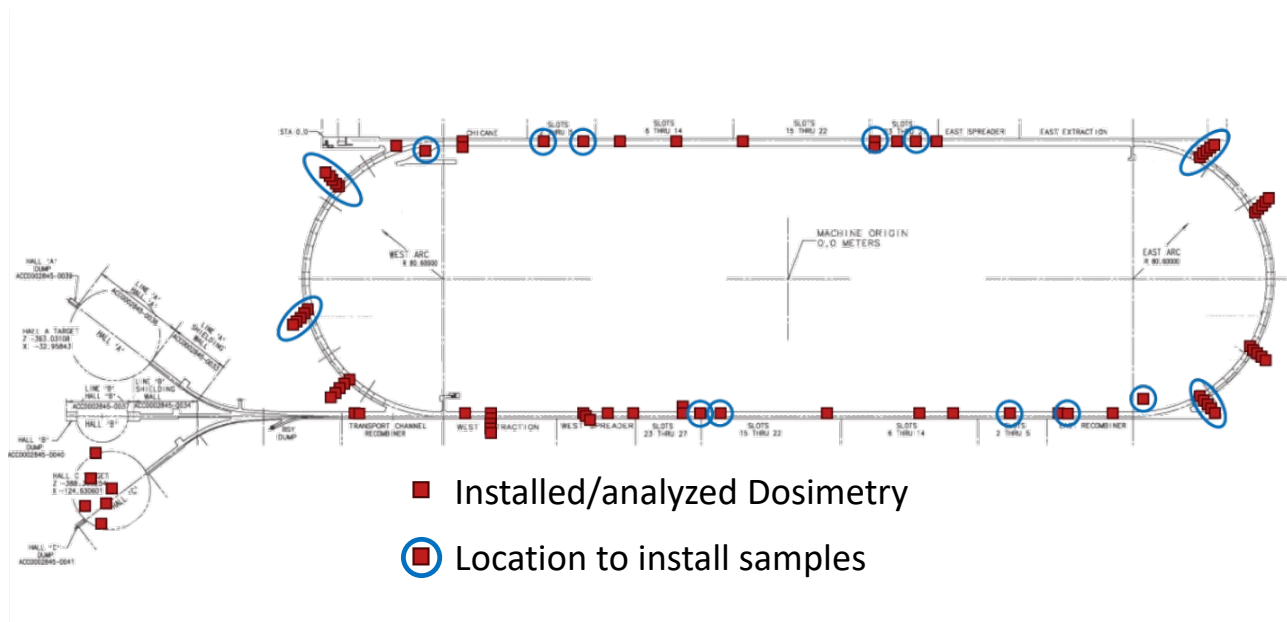


Figure 1: Sites around the CEBAF facility where dosimetry was tested (red squares), and where samples will be installed (circled squares).

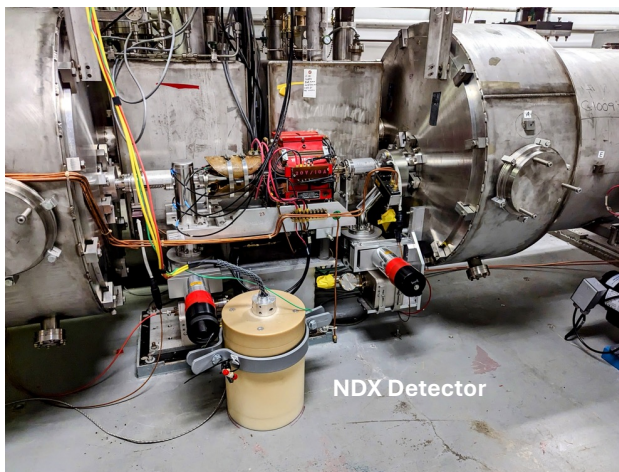


Figure 2: An NDX detector located in the warm region between two cryomodules in the CEBAF tunnel enclosure.

vide real-time and archived data on neutron and gamma radiation levels in specific locations.

### Magnet Selection and Preparation

When choosing which permanent magnet (PM) materials and grades to use, we needed to consider which would be likely candidates for use in the FFA@CEBAF arcs. We also wanted to find at least one grade which was used in similar studies, to see if there is a level of repeatability in the results. As such, the study prioritizes NdFeB grade N42EH, followed by SmCo33H, as the primary magnet materials, based on the initial prototyping designs by S.J. Brooks [4]. NdFeB N52SH and SmCo35 are included for comparative analysis as well.

We chose two sample sizes (shown in Fig. 3) to use for this study.

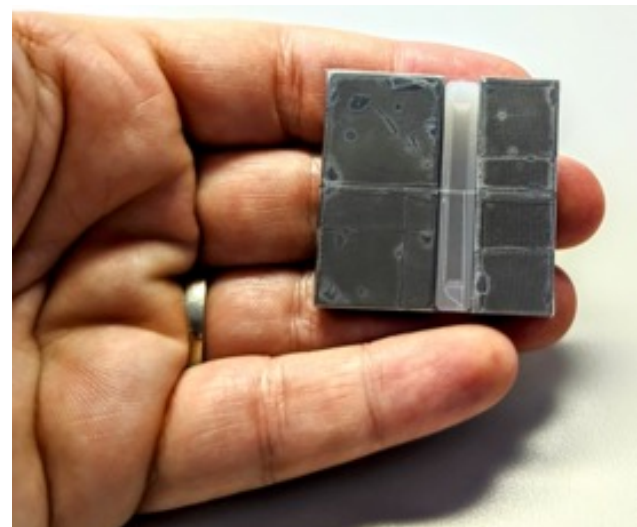


Figure 3: The two magnet sizes used for these studies, separated with a plastic spacer, and taped for safety.

- For single-sample tests: 1.5 in  $\times$  0.75 in  $\times$  0.25 in (38.1 mm  $\times$  19.05 mm  $\times$  6.35 mm)
- For pair assembly tests: 1.5 in  $\times$  0.5 in  $\times$  0.25 in (38.1 mm  $\times$  12.7 mm  $\times$  6.35 mm)

Upon arrival, quality control tests and standardized measurement protocols were established.

### Reverse-Flux Demagnetization Studies

An important factor which affects the demagnetization of permanent magnets in Halbach magnet assemblies is how the fields from the magnet wedges interact with each other [4, 5]. The sensitivity to demagnetization is related to the strength of the reverse H-field, running antiparallel



to the magnetization direction. Figure 4 shows a color map of sensitivity to demagnetization (due to radiation or heat) for one of the Halbach designs produced by S.J. Brooks at BNL [4]. Brooks' work shows that the sensitivity to demagnetization in a Halbach magnet is given by a field antiparallel to the direction of magnetization,  $-\mu_0 H \cdot M/|M|$ . In Fig. 4 the black regions indicate fields of 0 T to 0.5 T, green represents up to  $\leq 1$  T, yellow up to  $\leq 1.5$  T and red is  $> 1.5$  T. Magenta indicates parallel field. In this map, the orange/red and yellow areas are most sensitive to demagnetization, the black is slightly sensitive, and the magenta is not sensitive to demagnetization.

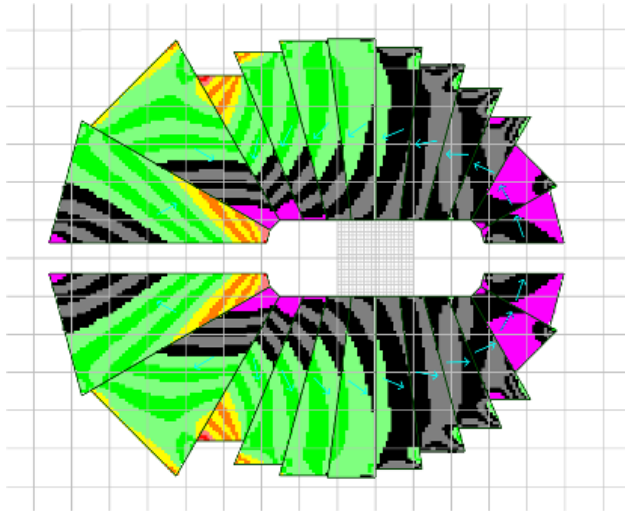


Figure 4: Demagnetization sensitivity map [4].

To approximate these regions in our study, we built pair assemblies. A diagram describing the assemblies is shown in Fig. 5. In this figure, the topmost image is a single magnet sample. The next image down consists of two magnet samples arranged so that the total field points in the same direction as it did in each sample. To approximate the parallel field regions, two of these pair assemblies are arranged so that the fields are parallel. To approximate the intermediate regions of sensitivity, one set of pairs is aligned so that the total field is perpendicular with respect to the original direction. Finally, to approximate the antiparallel fields, two pairs are aligned so that the fields are antiparallel.

### Measurement Techniques

This study aims to look at the overall field degradation from permanent magnets. Given that some magnets are expected to experience almost no degradation in the lower-radiation environments, precise measurements are required. To better accomplish this, we will be performing point measurements at several locations on each sample, pair, or assembly, as well as integrated measurements for the magnet samples, pairs, and assemblies.

To take accurate and repeatable measurements, as well as minimize human error and decrease the required time for measurements, we plan to use the following equipment and setups.

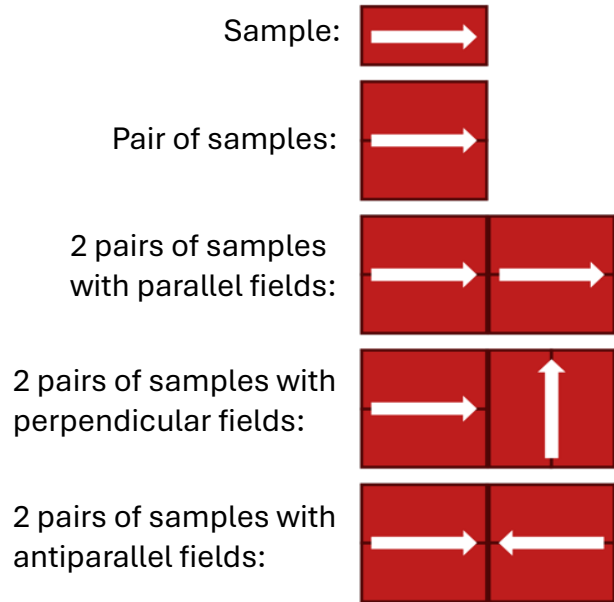


Figure 5: Design of the pair assemblies used to approximate the various regions shown in Fig. 4.

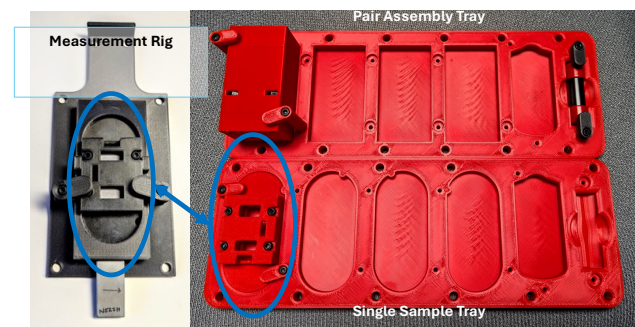


Figure 6: 3D printed mounts and measurement rigs. Each site will have one single sample tray and two pair assembly trays.

- A high-precision Teslameter (Senis 3MH6 with a C-type, three component Hall Probe [6]) with 0.005 % digital accuracy is employed for point measurements at several locations for each sample, pair, or pair assembly.
- A precision Helmholtz coil (Magnetic Instrumentation Model HCP w/Rotator and Model 2130 Digital Fluxmeter [7]) is utilized to measure the integrated magnetic field.
- A mobile measurement setup has been developed to facilitate in-situ measurements during accelerator down times, minimizing the need to transport potentially activated materials. This consists of two non-magnetic carts to carry our devices, a data acquisition laptop, an uninterruptible power supply, and a bar code/QR code scanner to quickly read and record sample and dosimetry identification.
- 3D printed mounting systems were designed for both magnets and the Teslameter probe to ensure accurate

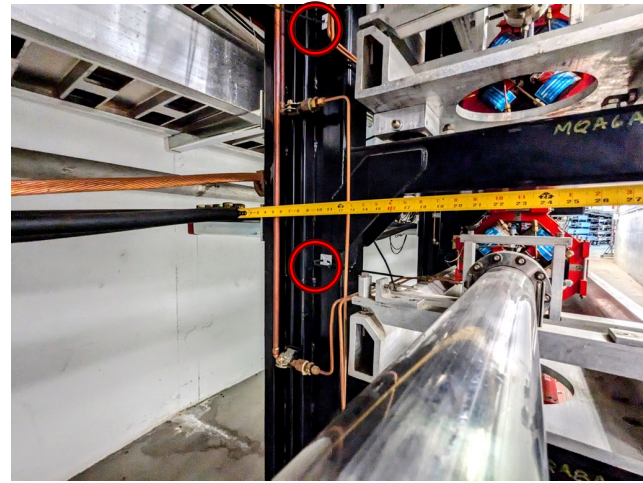
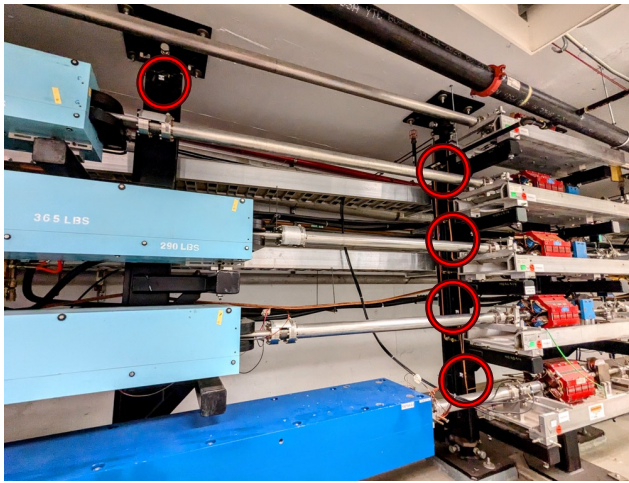


Figure 7: Example of planned sample placement locations in a recirculating arc. The circled areas are where dosimetry was placed to test for dose.

and repeatable measurements and minimize human error [8]. Examples of these assemblies are shown in Fig. 6. The trays are used to mount the samples and sample assemblies, as well as dosimetry. The measurement rigs contain slots, where the Hall probe can be inserted to measure the same place on the sample each time.

### Data Collection Strategy

Data will be collected during accelerator maintenance and down times. The standard plan at CEBAF is to have a scheduled maintenance day every two weeks. Not all of these will allow for Restricted Access (where personnel can access the tunnel and use the lifts for equipment), but most at least allow for Controlled Access (where personnel can access the tunnel, but the lifts cannot be used). Sometimes, only half of the machine is in Restricted while the other half is in Controlled. During Restricted Access, we plan to take in-situ measurements of the magnets, as well as swap out dosimetry. During Controlled Access, we will only swap out dosimetry.

If there is an unscheduled down time, and the machine access is changed to Restricted, measurements may also be taken during these times, assuming adequate time and personnel availability.

There are currently 30 planned locations for installation of samples. Twenty of these are in the recirculating arcs, with one set of three plates at each energy arc in two places. An example of the placement location of these is shown in Fig. 7. Aluminum arms will be placed into the upright struts and held approximately parallel to the beamline. These are usually 45 cm to 50 cm away from the beamline, though the value can change slightly.

Another ten sites will be located on tripods around the rest of the tunnel enclosure. Most will be located in close proximity to the cryomodules near NDX detectors. Some will be in the entry labyrinths to get very low dose data.

The sites are also distributed so that we can access an equal number of them on each half of the CEBAF enclosure.

This is done so that at least fifteen sites can be accessed if either half of the machine is in Restricted Access.

It is expected that measurements will need to be staggered, as despite all attempts to speed up the process, careful measurements still require several minutes per plate. Depending on how long the Restricted Access lasts, we may not be able to read all of the plates at each access. Careful documentation will help us to be sure that we are reading all of the samples adequately by the end of the next physics run cycle.

### Simulation Studies using BDSIM

To extrapolate the magnet degradation over time and higher-doses, we must understand the magnets' expected doses in our current machine, as well as the operating conditions (temperature, beam energy, deposition of secondaries, etc...). To do this, we will simulate the magnets in a variety of energies, positions, situations, and assemblies.

BDSIM (Beam Delivery Simulation) [9] is a program which uses GEANT4 [10] to simulate both the transport of particles in an accelerator, as well as the interaction of the particles with the accelerator materials. It is well-suited for the purposes of this project, allowing for importing beam-lines directly, as well as detailed custom shapes and materials. This will allow us to compare the data we gather to the simulations, and use this to extrapolate the overall degradation for the samples, the assemblies, and for our FFA@CEBAF magnets.

Our study is currently focusing on translating our current CEBAF beamlines from elegant [11] to BDSIM. As they are translated, results will be compared to doses that are read from dosimetry and other diagnostics in the machine. For more details on this work, please see B.R. Gamage's work [12].

After the appropriate sections of the current CEBAF machine are simulated, detailed studies of dose rates on our samples will begin, including the geometries and materials of the samples, placement in the enclosure, and contributions from secondaries produced by the beam.

The upgraded design sections of FFA@CEBAF will also be translated into BDSIM from Bmad [13]. This will allow investigation into radiation dosages expected at equivalent locations, and will be used in our extrapolation models.

## CONCLUSION

This LDRD project is mostly on-schedule to install all of the magnet samples and assemblies by the end of the long scheduled accelerator maintenance period, or shortly thereafter. Our protocols have been tested and refined, and data taking is expected to commence in early 2025.

## ACKNOWLEDGMENTS

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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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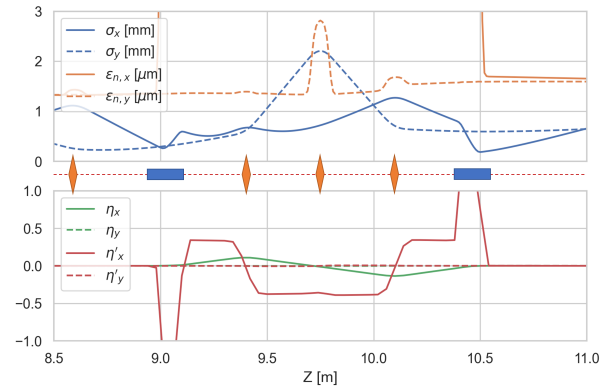


Figure 1: Merge dogleg, simulated with ASTRA [14] for BriXSinO [15, 16] after optimization with GIOTTO [3].

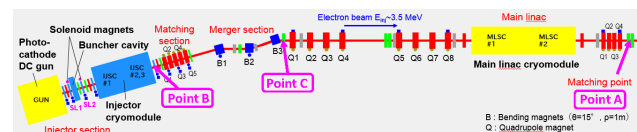


Figure 2: cERL injection line through just downstream of the main linac. Labeled points show where performance criteria were evaluated during the optimization process [8].

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.



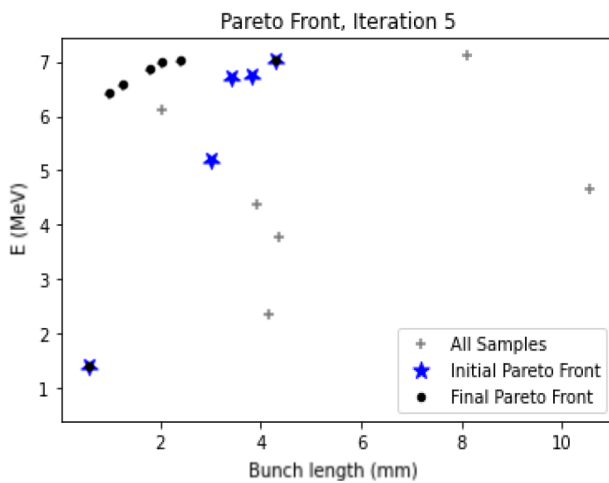


Figure 3: Results of optimization of the SEALab SRF gun for energy and bunch length [4]. Results are shown for early and late cycles in the optimization process.

Tanaka and collaborators applied multi objective genetic optimization to the cERL [7] injector line. cERL has operated in a number of different modes: a single-pass FEL, a recirculation mode, and a CW mode, with beam parameters and requirements different for each mode. Optimizations, using GPT [17] as the underlying tracking code, were performed for each configuration to find the desired beam settings for each [8]. Simultaneous optimization of all variables and all criteria turned out to be ineffective, so a sequence of optimizations was performed, each using criteria at a different point in the machine (Fig. 2): first just after the injector cryomodule, then just after the merge, and finally downstream of the main linac. Including the latter point in the optimization process differentiated this study from most others. They compared measurements with the GPT simulations, after using model-based tuning, with mixed results. Further research to better understand discrepancies is an important direction for future work.

Brookes discussed modeling and optimization of the SEALab SRF gun [18], comparing results from an analytic model to results from a simulation with ASTRA [14]. SEALab has a number of different operating modes, each requiring specific beam properties. She applied a multi-objective Bayesian optimization process to optimize for energy and bunch length (Fig. 3) [4]. Brookes also highlighted how a surrogate model could allow for estimation of observables for a range of input parameters that would be far more rapid than multi-particle simulations while still being more accurate than analytic models [19]. This approach enables real time machine optimization during operations. A surrogate model for the gun is currently being trained.

Monaghan presented the application of multi-objective genetic optimization techniques to the PERLE injector [5,6,20]. Various laser profile options were examined in this optimization (Fig. 4) [5]. The optimization process is improved by allowing required constraints to be violated in early gen-

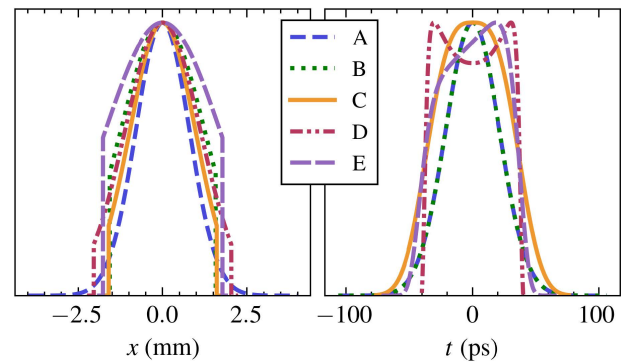


Figure 4: Some transverse and longitudinal laser profile distributions used for the optimization of the PERLE injector [5, 20, 21].

erations of the optimization, with the amount of allowed violation reduced in later stages, eventually to zero [6].

### Machine Operation

Optimization techniques were also applied in machine operation. Bayesian optimization was applied to cERL when operating with undulator vacuum chambers [22], allowing the machine to reach 600  $\mu$ A CW current [11]. The machine was optimized both for high current and low losses. Since this was done during operation, it was important to avoid beam loss that would lead to interlock, so a safe parameter space was first determined, then the optimization was performed within that parameter space. The optimization was performed by monitoring losses at multiple locations in the ring (Fig. 5), with the optimization process simulating the process that would be performed when tuning by hand.

For cavity phase and amplitude calibration of the main linac cavities in CBETA [23], a more traditional least-squares optimization was used [13]. One cavity in the linac was powered at a time, its phase was scanned over a full 360°, and arrival time was measured at the end of the linac. The measurements for all cavities were simultaneously fit to a model based on a field map for the cavities to determine the cavity amplitude calibration factors, phase offsets, and the injection energy. The data fit well to the model and provided accurate calibrations (Fig. 6), though errors were dominated by systematic uncertainties. Derivatives of the model were computed to improve the speed and reliability of the algorithm.

## MACHINE DESIGNS AND BEAM DYNAMICS STUDIES

There were presentations on the designs and simulation of two proposed ERLs. For the Electron-Ion Collider [24], an ERL is used for the electron beam that is needed for strong hadron cooling of the hadron beam. Figure 7 shows the layout of the ERL and the hadron beam line. The electron beam energy will vary between 55 and 150 MeV, depending on the hadron beam energy being cooled. An ERL is needed to handle the high electron beam power and to minimize

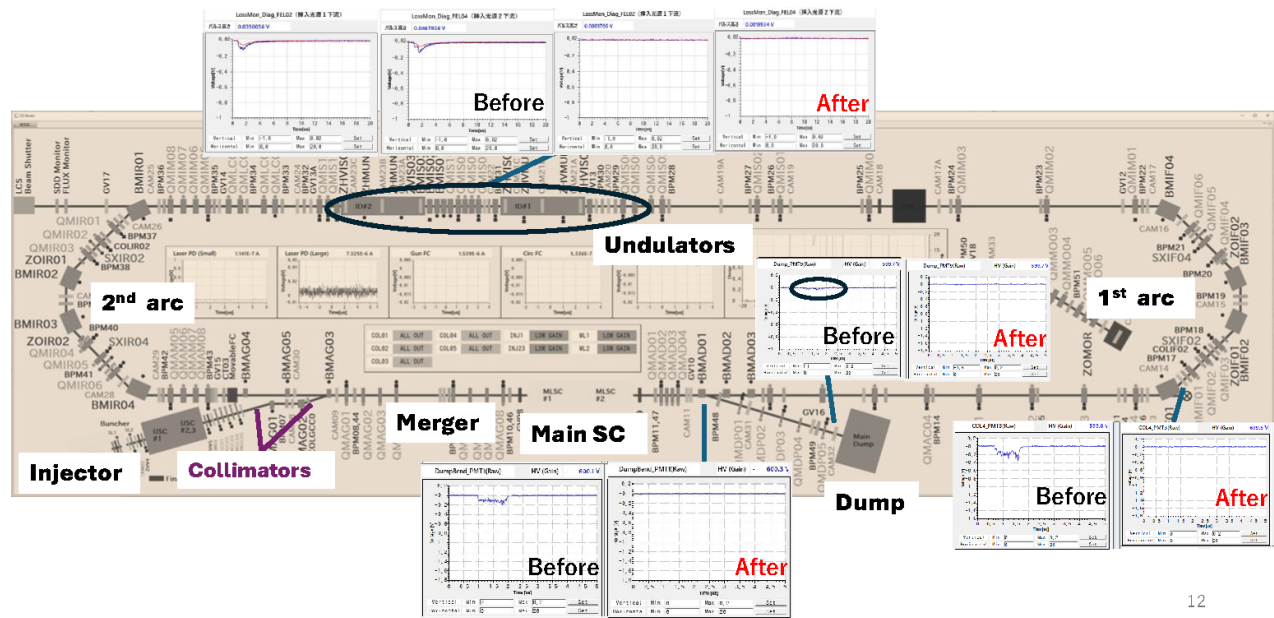


Figure 5: cERL layout, showing loss monitor readings at several locations before and after optimization [11].

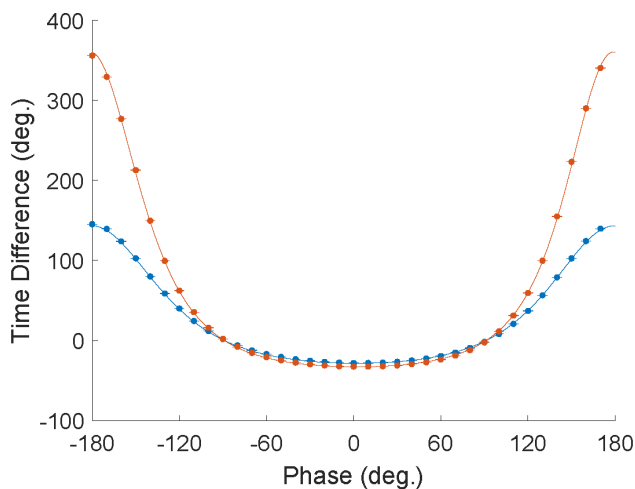


Figure 6: Time of flight measured at the end of the main linac in CBETA when only the first cavity is powered, and scanned in phase at two different voltages [13]. Curves show the fit of the model to the data taken when scanning all 6 cavity phases.

radiation. The design of that ERL was described [1]. A section is incorporated containing three separate beamlines allowing them to control time of flight for different beam energies without changing the layout; Bates bends are incorporated in the return loop to further manage time of flight, in particular because there are two separate accelerating sections in the return loop (Fig. 7). Simulations of the beam breakup instability were performed, and those simulation results are informing choices for the cavities to be used in the linac. The individual linac cavities had a slight energy imbalance; this is not necessarily a problem, but future work may try to improve this.

The PERLE [25] lattice design update was presented for several commissioning stages [2]. The lattice was reconfigured to improve behavior for the Fabry-Perot cavity, creating more physical space and improving the beam properties at that location. The merger was reconfigured and tuned to better control  $M_{56}$  and beam size.  $M_{56}$  control through changes in arc focusing was studied. The impact of instability in RF power amplitude and phase was examined, demonstrating a tolerance of  $2.5^\circ$  in phase and 0.5 % in amplitude [26] (Fig. 8). The tradeoffs were described for choosing bunch length to balance the emittance increasing effects of RF curvature and coherent synchrotron radiation [25]. Field errors and injector laser offset were studied to determine their impact on beam losses.

A study of the impact of bunch filling patterns on the beam breakup instability (BBU) in ERLs was presented [10, 27]. BBU simulations were performed using an in-house tracking code that uses transfer matrices between cavities then excites higher order modes (HOMs) and kicks the beam with them. Studies were presented for PERLE [25], demonstrating a strong dependence of threshold current on the filling pattern (Fig. 9). The impact of the filling pattern on the BBU current threshold depends on the HOM being driven, though it was found that two modes appeared to be dominant. For certain filling patterns, coherent BBU excitation between cavities occur more easily.

Multi-particle tracking is usually used for low energy space charge simulations in the injector of an ERL, but one presentation [9] demonstrated that accurate results could be obtained with moment-based methods. The moment-based code TRANSOPTR [28] was compared with the multi-particle tracking code GPT [17], and nearly identical results were obtained for the beam envelopes (Fig. 10) for the early portion of the ARIEL e-LINAC [29]. Good agreement was

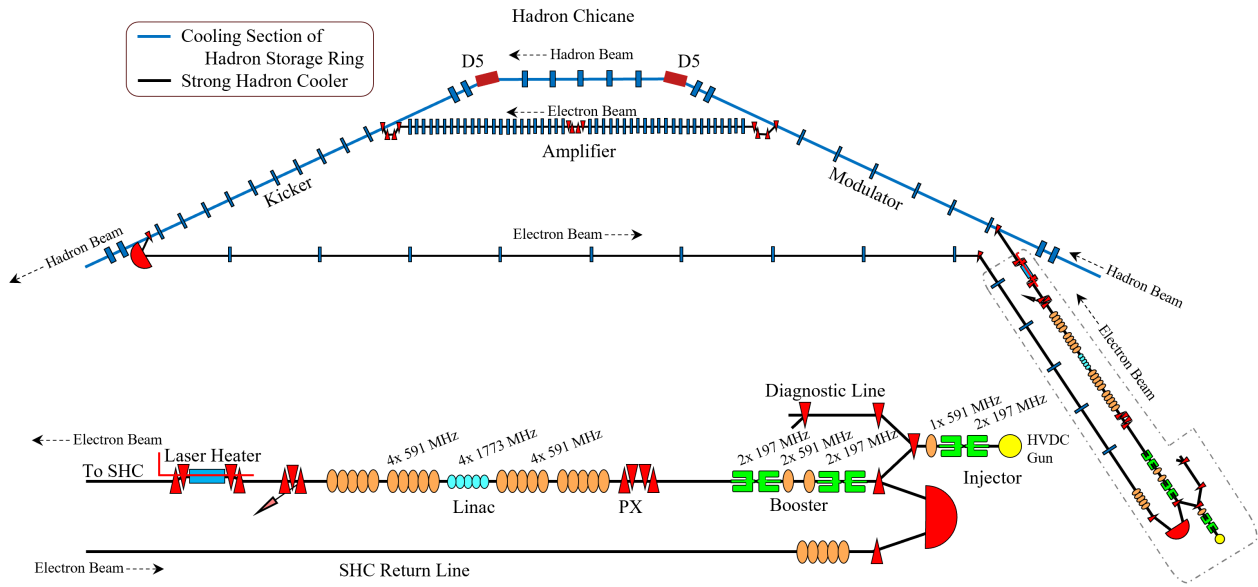


Figure 7: The layout of IR2 of the Electron-Ion Collider [24], showing the hadron line (topmost line in the figure), the electron line, with a detail of the primary ERL components at the bottom [1].

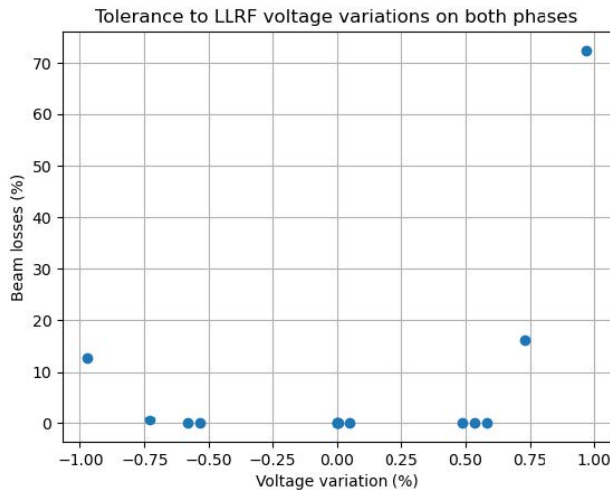


Figure 8: Beam loss as a function of RF gradient variation in the PERLE [25] 250 MeV configuration [26].

also found for the first 6 m of the cERL injector. The simulation was compared with measurements, and there was agreement within about 20 %.

## INSTRUMENTATION

While instrumentation was relevant in several talks, one talk directly discussed instrumentation for multi-turn ERL operation [30] at S-DALINAC [31]. Their goal was to non-destructively and simultaneously measure the accelerated and decelerated beams in an ERL return loop. One device was a 6 GHz  $TM_{110}$  cavity (twice the fundamental frequency), which they successfully used to measure an accelerated beam. The second was a wire scanner mea-

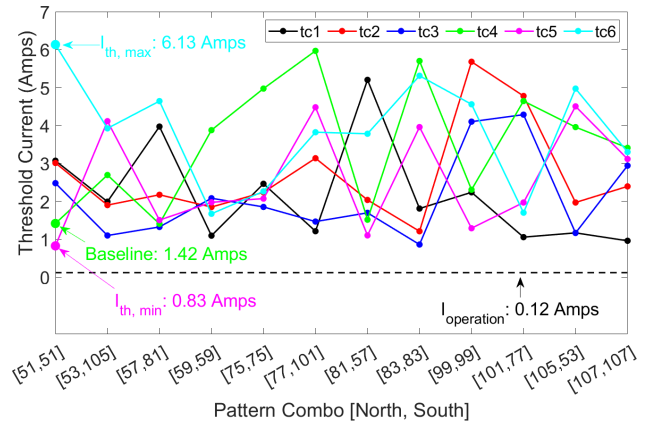


Figure 9: BBU threshold current for different PERLE filling patterns [10].

surement, where they measured beam profiles of both the accelerated and decelerated beams (Fig. 11).

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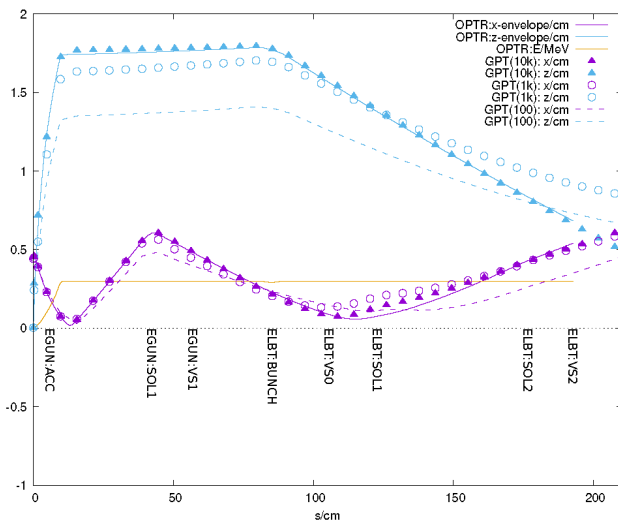


Figure 10: Comparison between envelope tracking with TRANSOPTR [28] and GPT [17] for the low energy portion of the ARIEL e-LINAC [29].

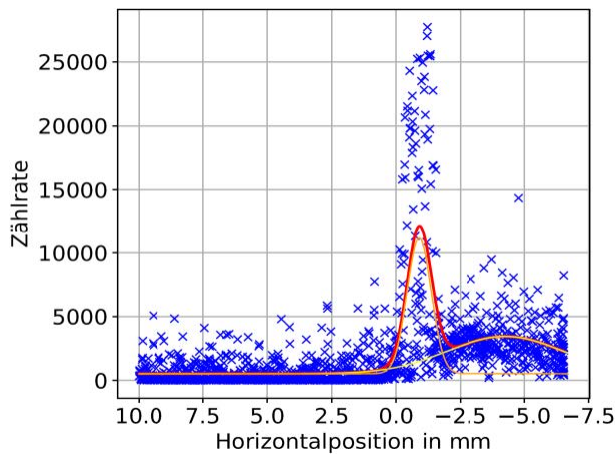


Figure 11: Wire scan measurement of horizontal beam profiles of accelerated and decelerated beams [12] at S-DALINAC [31].

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## 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.

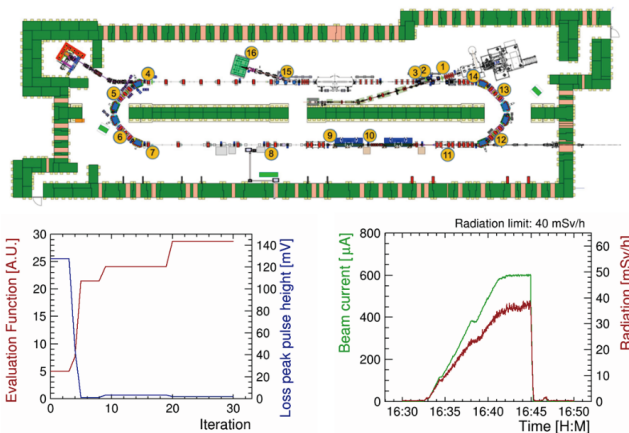


Figure 1: Top: Location of the loss monitor with high sensitivity for low current beam tuning. Bottom left: Trend of the evaluation function and the loss monitor response during the Bayesian optimization. Bottom right: Average beam current and the area monitor during the high current operation.

#### 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

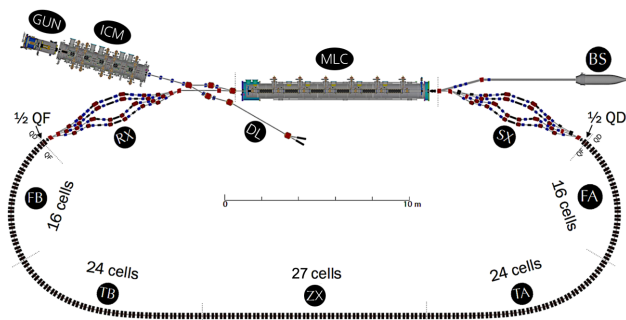


Figure 2: CBETA layout

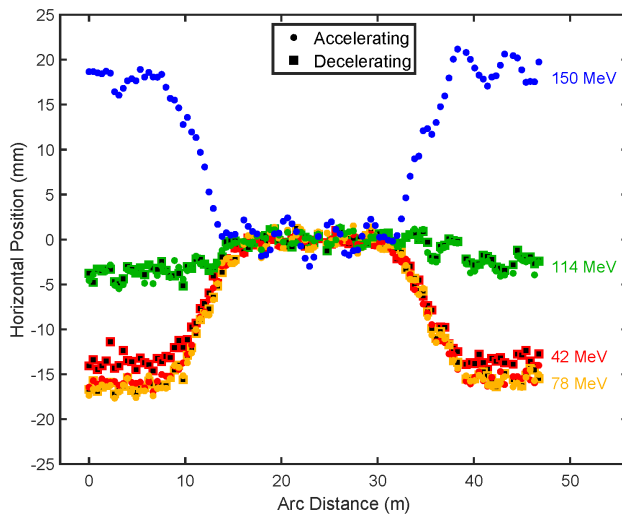


Figure 3: Orbits in the CBETA FFA return arc during 4-pass operation.

energies. The FFA return loop was constructed from permanent magnets [6]. Individual splitter lines were needed to connect the linac to the FFA return arc for time of flight and  $R_{56}$  control as well as lattice function matching. CBETA ended operations in 2020, but is still intact and could resume operation if funding were to become available. Potential applications of interest would be studies related to cooling for an electron-ion collider and/or a CEBAF energy upgrade which shares design similarities with CBETA, or construction of a bypass line for generating radiation through inverse Compton scattering.

CBETA was operated in 1-pass mode with currents as high as  $70 \mu\text{A}$ . Excellent energy recovery efficiency was measured in the individual cavities [7]. It was then reconfigured to operate in 4-pass mode. Beam was accelerated in 4 linac passes to 150 MeV, then decelerated and delivered back down to the 6 MeV injection energy and into the beam stop [8]. The machine behavior was in many ways as predicted in our modeling: the linac phases needed for energy recovery agreed well with predictions, and the phase advances in the FFA return arc cells agreed with calculations. The individual orbits could be simultaneously corrected for all passes in the return arc (Fig. 3).

The machine faced numerous challenges, some of which were overcome and some which will need to be addressed in future operations. Phase and amplitude jitter in the main linac created early difficulties, but were significantly improved during operations [9]. However, a slow drift in RF amplitude continued to present difficulties. Compact splitter lines had issues with crosstalk between lines, hysteresis, beam alignment, and motion of sliding joints for time of flight control. In 4-pass operation, about half of the beam was lost in one of these lines. Microbunching at high bunch charges and beam halo in the injector were observed.

## S-DALINAC

The superconducting Darmstadt linear accelerator S-DALINAC is in full operation since 1991 at the *Institut für Kernphysik* at *Technische Universität Darmstadt* [10]. 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 ERL since 2016 besides the conventional acceleration scheme serving various nuclear-physics experiments, see Fig. 4 and Table 1 for details on the parameters. The S-DALINAC achieved one-turn [11] and two-turn energy recovery [12]. There are also upcoming ERL-related projects at TU Darmstadt: The next step would be a three-turn ERL mode. A study on this scheme was done and shows a promising, first longitudinal solution [13]. As overall goal, an ERL should serve as a sustainable driver for an experiment. Especially collider applications can benefit a lot from an ERL. At the S-DALINAC, a laser beam will be collided with the electron beam. A setup for laser Compton backscattering is under commissioning [14]. The contribution TUO03 of this conference [15] gives an overview of the facility with a focus on the ERL activities.

## ERLS UNDER CONSTRUCTION

### bERLinPro

In end of 2020 the ERL facility bERLinPro [16] accomplished the project phase by finalizing the building, setup of all technical infrastructure and installation of all major components of the warm machine. In summer 2021 also the final part of the beamline vacuum system with the recirculator was closed and assembled under ISO5 cleanroom conditions (see Fig. 5), as all of the machine to allow to preserve the high level particulate free environment for proper operation of the SRF cavity systems of photo-injector, booster module of the injector line and any future linac installation [17] in the main recirculator. In 2024, the cryo-plant underwent a first complete test cooldown and in the following, the installed SRF photo-injector was also successfully cooled down, followed by an RF test in May this year. The field level reached will allow so far an energy of the beam up to 2.1 MeV, whereas the modified TTF-III couplers will limit the average beam current to about 10 mA. However, pulsed operation might also allow to study the 1.3 GHz beam repetition rate regime

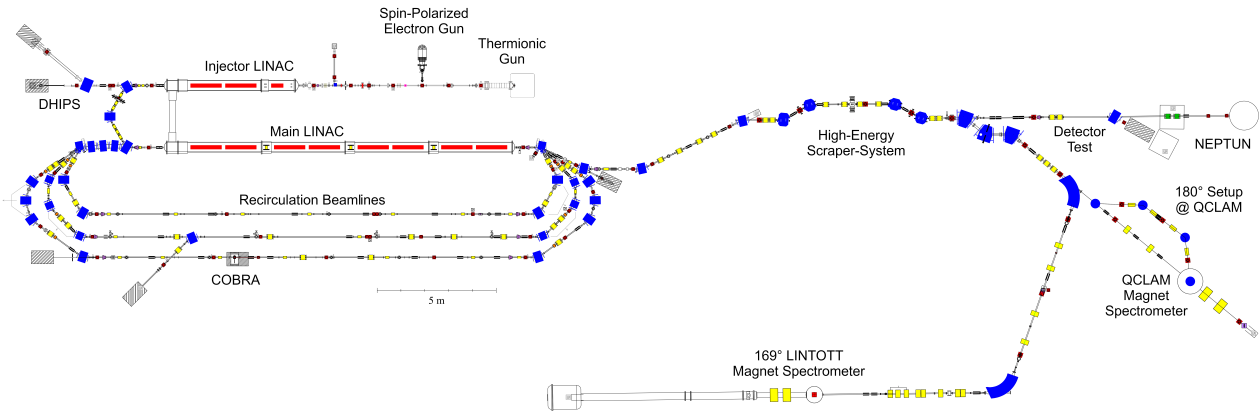


Figure 4: Layout of the facility S-DALINAC.

Table 1: Parameter list of the S-DALINAC. The values achieved during the one- and two-turn ERL run are given.

| Parameter                               | Value                           |
|-----------------------------------------|---------------------------------|
| Design energy                           | 130 MeV                         |
| Beam current at 130 MeV                 | 20 $\mu$ A                      |
| Frequency                               | 2.9972 GHz                      |
| Duty cycle                              | cw                              |
| Particles                               | Unpolarized/polarized electrons |
| Operating temperature                   | 2 K                             |
| One-turn ERL                            |                                 |
| Energy gain injector                    | 2.5 MeV                         |
| Energy gain main linac                  | 20.0 MeV                        |
| Beam current (initial)                  | 1.2 $\mu$ A                     |
| Energy-recovery first main linac cavity | (90 $\pm$ 0.3)%                 |
| Two-turn ERL                            |                                 |
| Momentum injector                       | 5 MeV/c                         |
| Max. momentum 2xERL beam                | 41.61 MeV/c                     |
| Beam current range                      | up to above 7 $\mu$ A           |
| Energy-recovery full main linac         | up to 87%                       |

Table 2: bERLinPro/SEALab Parameters in Planned ERL Mode and for the Injector Studies

| Parameter                          | ERL     | Injector/UED |
|------------------------------------|---------|--------------|
| Beam energy (MeV)                  | 50      | 6.5-10/2     |
| $I_{\text{avg}}$ (mA)              | 100     | 6-10/0.0025  |
| Laser freq. (MHz)                  | 1300    | 50, 1300     |
| RF freq. (MHz)                     | 1300    | 1300         |
| $\epsilon_{\text{norm}}$ (mm mrad) | 1 (0.6) | 0.6/0.03     |
| $\sigma_t$ (ps)                    | 2 (0.1) | 0.02-2       |
| Bunch charge (pC)                  | 77      | 0.05-400     |

with the high power laser system. Table 2 gives an overview of the originally planned beam parameters in the column *ERL* and the range, which can be studied with the current setup making use of the flexibility of the laser and SRF systems. Growing of high quantum-efficiency photo-cathodes and research for improved recipes is being continued and first results were presented here [18]. It was chosen, to start beam commissioning with a newly developed NaKSb cathode, as it behaves more robust with respect to lifetime and the handling steps prior to the transfer into the SRF gun. In fall to winter 2024, the beam commissioning program with the injector will start exploring the full parameter space of the SRF gun cavity to study beam properties from the UED [19] towards high power ERL regime. It is planned to install the Booster module towards the end of 2025 to thus allow full injector operation. As a Linac is currently not funded, we are

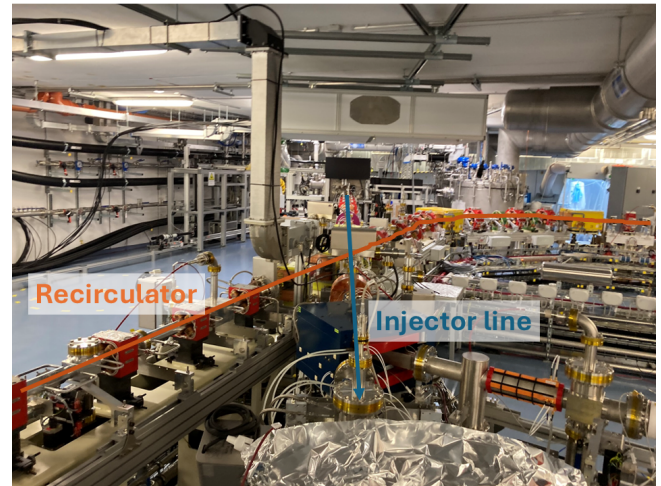


Figure 5: Currently installed bERLinPro injector line viewed from the local beam dump and part of the recirculator. The beam merger is in the center, where injector and recirculator cross paths.

focussing on developing more sustainable SRF technologies within the EU Horizon funded iSAS [20] program, as e.g. ferro-electric fast reactive tuner and coated cavities to secure funding for future prototyping for bERLinPro.



## MESA

The Mainz Energy-recovering Superconducting Accelerator (MESA) is an electron accelerator currently under construction at the Institute of Nuclear Physics at Johannes Gutenberg University Mainz, Germany [21]. MESA is designed as a superconducting multi-turn energy recovery linac (ERL), capable of delivering high-intensity, low-energy electron beams for precision electron scattering experiments, pushing the limits of the Standard Model of particle physics [22].

The accelerator system includes a polarized electron gun and a high-current unpolarized gun, a normal-conducting pre-accelerator that boosts particles up to 5 MeV, and a superconducting recirculating main accelerator. The core of the main accelerator consists of two ELBE/Rossendorf-type cryomodules, each housing two XFEL/TESLA cavities, capable of providing an energy gain of 25 MeV per cryomodule [23]. The overall layout of MESA is illustrated in Fig. 6.

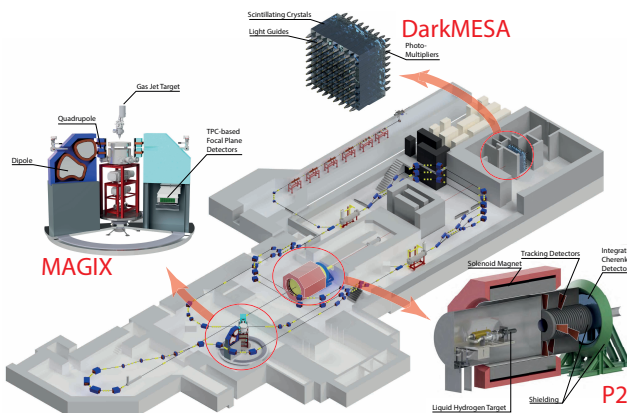


Figure 6: MESA layout, currently under construction at the Institute for nuclear physics of the Johannes Gutenberg Universität Mainz. Three main experiments, MAGIX, P2 and DarkMESA are shown.

MESA offers two operational modes the external beam mode and the energy recovery mode. The beam parameter can be found in Table 3.

In the external beam mode (non-energy recovery), a 155 MeV polarized electron beam with a beam current of up to 150  $\mu\text{A}$  CW will serve the P2 experiment [24]. The P2 experiment aims to perform a highly precise measurement of the electroweak mixing angle and has the potential to detect new physics beyond the Standard Model. The beam will be dumped after the experiment.

The energy recovery linac (ERL) mode features a twice-recirculated electron beam reaching 105 MeV with a beam current of 1 mA CW. After interaction with the internal target of the MAGIX experiment, the beam will be decelerated twice to recover its energy [25]. The MAGIX experiment, featuring a versatile spectrometer, will support a wide range of research, from nuclear astrophysics and precision proton radius measurements to searches for dark matter.

Table 3: MESA Main Parameters

| Parameter                     | Value                                                       |
|-------------------------------|-------------------------------------------------------------|
| <b>General</b>                |                                                             |
| Time structure                | CW                                                          |
| Operating frequency           | 1300 MHz                                                    |
| Norm. emittance               | $\leq 1 \mu\text{m}$                                        |
| <b>Injector</b>               |                                                             |
| Source, energy                | DC, 100 keV                                                 |
| RF-cavities                   | Normal conducting                                           |
| Operating temperature         | $\approx 300 \text{ K}$                                     |
| Output Energy                 | 5 MeV                                                       |
| <b>Main accelerator</b>       |                                                             |
| RF-cavities                   | superconducting                                             |
| Operating temperature         | 1.8 K                                                       |
| Cryomodules                   | 2                                                           |
| Energy gain per CM passage    | 50 MeV                                                      |
| Accelerating Field            | 12.5 MeV/m                                                  |
| Cavity quality factor         | $1.25 \times 10^{10}$                                       |
| cavity passages EB/ER-mode    | 3/2+2                                                       |
| Max. dipole field in Acc.     | $< 0.7 \text{ T}$                                           |
| Max. quadrupole field in Acc. | $< 10 \text{ T/m}$                                          |
| <b>EB-mode</b>                |                                                             |
| Beam current                  | 150 $\mu\text{A}$                                           |
| Beam energy                   | 155 MeV                                                     |
| Beam power                    | 23.25 kW                                                    |
| Spin polarization             | $> 0.85$                                                    |
| Luminosity                    | $\approx 2.3 \times 10^{39} \text{ s}^{-1} \text{ cm}^{-2}$ |
| <b>ER-mode</b>                |                                                             |
| Beam current                  | 1000 $\mu\text{A}$                                          |
| Spin polarization             | -                                                           |
| Beam energy                   | 105 MeV                                                     |
| Beam power                    | 105 kW                                                      |
| Luminosity                    | $> 1 \times 10^{35} \text{ s}^{-1} \text{ cm}^{-2}$         |

Currently the accelerator is under construction, with the main components already on site and within installation. The electron source achieved a first 100 keV beam in April 2024. First beam on target is expected within the Q4 2025.

## PERLE

Recently, several notable facts highly impacted the PERLE project progress and its future plans.

First, the acquisition in January 2024 of the PERLE electron source within a collaboration agreement with Research Instruments (RI-GmbH) company. An all-equipped load-lock DC gun, with its HV systems and a connected Photocathode Preparation Facility (PPF). Starting the installation (cf. Fig. 7) of this first important system in the site allocated to PERLE is a significant step in the project progress. Some related systems (laser, vacuum) are already acquired, others (command & control, diagnostics...) are under development or purchase. The aim is to have the first electrons by end 2025.

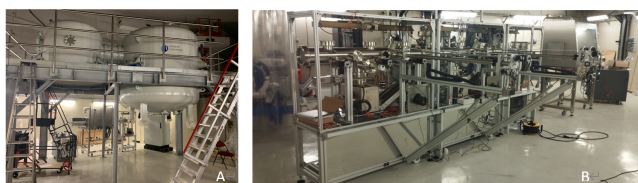


Figure 7: Installation of the DC gun HV system (A), and the Photocathode Preparation Facility- PPF (B) in the site allocated to PERLE (the IGLOO) at IJCLab.

The European iSAS project kick-off (April 2024), in which, the PERLE cryomodule (CM) will be manufactured and tested over the next 4 years. The CM and related equipment designs (cavities, HOM couplers, power couplers, beam line absorbers, magnetic shielding ...) will be fully optimized to maximize its efficiency. Several collaborators (CERN, ESS, INFN-Milan, CEA) are involved in these developments. The design effort for SRF systems is progressing very well: The dressed cavity design is now completed, the damping scheme defined and the call for tender for the 4 SRF cavities will be launched beginning of November. Further studies are ongoing to optimize the magnetic shielding, the cryogenic distribution, the power coupler adaptation and assembly, the integration of beam line absorbers... Vacuum vessel, space frame and thermal shielding of the CM are already available.

Afterward, in June 2024, there was the approval of the "ERL4ALL" project within the CNRS call "Projet à Risque et Impact- RI2". Funds were allocated to finance the PERLE injection line in the next 4 years. A first demonstration phase started in October (t0) for 15 months with a Go/No Go milestone: Production of the first electrons with the electron source. A second development phase: will be dedicated to finalization of the injection line + diagnostics line.

Discussions between IJCLab and Helmholtz Zentrum Berlin (HZB) are ongoing in order to recuperate the cryoplant of BESSY VSR by end 2026. The studies shown that this equipment is well dimensioned for PERLE (250 MeV version) needs.

With all these acquisitions, an additional effort still to be done to complete the funding of the 1-turn ERL phase of PERLE, an important milestone toward the realisation of the 250 MeV version of PERLE (3-turn ERL with one Cryomodule). The optic design of PERLE 1-turn is thought in a way to allow a relatively easy upgrade to the following phases.

## FUTURE PROJECTS

### *TRIUMF e-Linac*

In addition to the 520 MeV cyclotron, the TRIUMF e-Linac is a new primary beam driver of the Advanced Rare Isotope Laboratory (ARIEL) project to generate rare isotope beams (RIB). Prior to the full ARIEL implementation, the e-Linac supported several scientific programs, including FLASH [26] and terahertz (THz) light production, among

others. To improve overall stability and reliability, various hardware upgrades have been implemented as shown in Fig. 8 [27]. Furthermore, the sub-millimeter longitudinal beam size has demonstrated significant potential for using the e-Linac as a source of THz radiation. Instrumentation has been set up downstream of the accelerator module to detect THz light emissions. Additionally, a study is underway to incorporate a magnetic compressor and an SRF photogun to generate more intense THz light, opening the door to broader future applications.

### *BriXSino*

BriXSino, an ERL demonstrator being developed at INFN will operate in the energy range of 20–45 MeV with average current of 5 mA, 225 kW. It is the first ERL to adopt the original recirculation scheme proposed by Maury Tigner, also known as the "dog-bone" configuration. In this two-pass, two-way operation mode, the main linac accelerates the beam in one direction, recirculates it via an arc, and decelerates it in the opposite direction, recovering energy. For BriXSino injector we employed a non-cutting-edge 250–350 kV DC gun coupled to an innovative setup of dual sub-harmonic bunchers [28]. This innovative design enables precise control over space charge effects and non-linearities, crucial for optimizing 6D beam brightness and preserving emittance, considering the very low injector energy of 4.5 MeV with relevant bunch charge up to 200 pC. The machine will be capable of driving Inverse Compton Scattering (ICS) and THz Free Electron Laser (FEL) experimental stations in the recirculation ring. The injector has been funded in 2023 and the preliminary tests at INFN-LASA will be carried out at the end of 2025. The next scenario will be to proceed with the request of the fundings to complete the machine.

## ACKNOWLEDGEMENTS

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## CONCLUSION

We briefly summarize 8 facilities report. First we show three ERL facilities, such as cERL (KEK), CBETA (Cornell University), and S-DALINAC (Technical University of Darmstadt) in operation. Second, three ERL facilities, such as BerlinPro (HZB), MESA (Mainz University) and PERLE (IJCLab) under construction are shown. Finally, TRIUMF e-linac (TRIUMF) and BriXSino (INFN) are presented for future ERL projects. We hope that ERL technologies will be more improved in these facilities.

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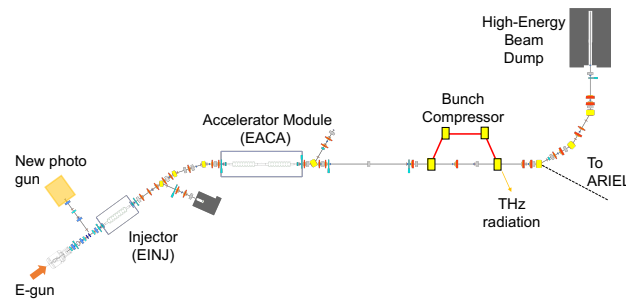


Figure 8: TRIUMF e-Linac layout and future plan for installation of a new bunch compressor and a new photo-gun for THz light production.

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