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SPACE CHARGE STUDIES ON STRONG HADRON COOLER ENERGY RECOVERY LINAC*

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Abstract

An Energy Recovery Linac (ERL) based cooler, using Coherent electron Cooling (CeC) is being designed for cooling hadron beams of the Electron-Ion Collider (EIC). The ERL design utilizes high current, high-brightness electron beams with low emittance and a uniform longitudinal distribution for efficient hadron cooling. In order to cool 275 GeV and 100 GeV protons, this is designed to operate with 150 MeV and 55 MeV electrons, in both cases with an average current of 100 mA and 1 nC bunch charge. With these parameters, the space charge effects become significant in this ERL design due to the low beam energy and high beam current. In this paper, we discuss strategies for including space charge effects in the optics design and implementation of an interface for space charge dominated and non-dominated regions of this ERL lattice.

INTRODUCTION

The U. S. Electron-Ion Collider (EIC) is planned to be build at the Brookhaven National Laboratory (BNL) in New York. Higher luminosity achievement is challenging for the EIC as maintaining a lower beam emittance throughout the long beam storage times. Intra-beam scattering, collective effects and beam-beam effects tend to increase hadron beam emittance, hence a proper cooling mechanism is required to achieve low emittance hadron beams, to achieve design luminosity requirement in the order of 10^{34} cm^{-2}s^{-1} [1]. A coherent electron cooling based energy recovery linac is being designed to serve as the strong hadron cooling source for the EIC complex.

This Strong Hadron Cooling (SHC)-ERL design incorporates a high voltage DC photocathode gun at the injector and is capable of delivering electron beam with a charge of 1 nC. The ERL design intends to cool hadrons beams at two different energies; 100 GeV and 275 GeV. To support this, design allows operating in two distinct modes; mode A and mode B, with corresponding electron beam energies of 55 MeV and 150 MeV, respectively [2, 3]. A detailed schematic of the SHC-ERL complex is given in Fig. 1.

The electron injector consists with two 197 MHz quarter wave resonator (QWR) cavities and one 591 MHz cavity. Solenoids integrated into the injector and dog-leg merger are used to control the beam size in this low energy regime. The electron beam exits the injector at 6 MeV, and is further accelerated up to 13 MeV within the booster, which includes four 197 MHz cavities and two 591 MHz cavities. Electron beam then goes through the PX bunch compressor and proceeds to the main linac, where it is accelerated to the energy corresponding to its operating mode. The main linac consist of eight 5-cell 591 MHz cavities and four 5-cell 1773 MHz cavities. Third harmonic cavities are used to linearize the longitudinal phase space of the electron beam [4].

PARTICLE TRACKING WITH SPACE CHARGE

Electron beam energy is relatively low until the main linac, hence the space charge fields play a dominant role affecting the quality of this high current electron beam. Preserving low beam emittance and low energy spread is crucial for effective hadron cooling. Therefore, careful measures must be taken throughout this low-energy regime to mitigate space charge effects and maintain electron beam quality.

Particle tracking including space charge fields was performed using the Bmad toolkit. Bmad's Integrated Green's Function (IGF) algorithm was employed to accurately model the electron beam dynamics under the influence of space charge fields [5, 6]. A sensitivity analysis was carried out on mesh size and particle count to ensure the robustness and accuracy of the tracking simulation [7]. In a prior study, beam shaping at the cathode was investigated as a strategy to mitigate strong space charge effects at the electron gun. The resulting optimized beam profile is used to suppress emittance growth and minimize beam energy spread within the downstream beamline where space charge effects dominate [8]. An interface point is defined in the ERL lattice to achieve a Twiss match between space-charge-dominated and non-space-charge regimes. Matching Twiss parameters at this transition is essential for maintaining electron beam quality and enabling effective transport through the following sections of the lattice.

Injector and Merger Optimization

The initial electron distribution at the cathode is radially Gaussian, truncated at 2.33 mm with a σ_r = 1.98 mm. Longitudinally, this distribution follows a 10^{th} order super-Gaussian profile, σ_t = 82.87 ps. The beam has a mean thermal energy of 130 meV and a bunch charge of 1 nC [7]. Beamline optimization utilized Xopt, with the continuous NSGA-II algorithm [9, 10]. The primary objective of injector and merger optimization is to minimize beam emittance

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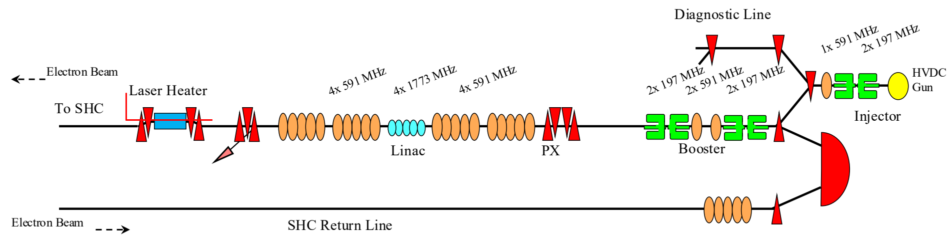

Figure 1: Conceptual design layout of the SHC-ERL, the main components of the ERL lattice; injector, booster, main linac and return line.

and energy spread at the merger exit. However, it was observed that despite using an optimal solution, significant emittance growth still occurs within the booster and PX chicane. This increase is largely due to chromatic effects induced by the intrinsic energy spread within the long electron bunch. Variation in particle energy cause differences in focusing strengths, causing their phase space ellipses to be misaligned. This eventually results incomplete emittance compensation and increasing projected emittance.

To address this, an additional objective was introduced to mitigate chromatic errors downstream by further reducing slice energy spread. An additional objective focusing on achieving uniform slice beta variation is added along with the objectives used in laser shaping [7, 8, 11]. These objectives ultimately contributed to achieving a solution that preserves low emittance throughout the entire accelerating beamline.

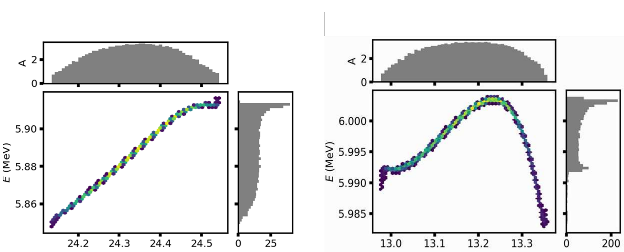

Figure 2: Longitudinal phase space at the injector exit before (left) and after (right) optimization.

The injector is optimized to minimize emittance and energy spread, while the merger solenoids are tuned to minimize emittance and achieve zero dispersion. An approximate 40% reduction in beam emittance is achieved, decreasing from an initial design value of 0.36 µm to a final value of $\epsilon_{x/y}$ = 0.22 µm. Longitudinal phase space of the beam at the injector exit before and after optimization of RF parameters is compared in Fig. 2. The energy chirp of this long bunch is compensated by the third harmonic cavity while maintaining the correct beam energy. The optimized settings enhance beam transport through the downstream sections, yielding a distribution that exhibits strong tolerance to chromatic effects in the PX chicane [7, 8].

Emittance Control in PX Chicane

The electron bunch length from the injector until the booster is approximately 28.8 mm, and compresses within PX to provide bunch lengths required for proper cooling in both modes. For mode A, bunch length is 7 mm, and 9 mm for mode B, hence different R_{56} values for two modes. Space charge tracking in Bmad resulted larger emittance peaks within the PX chicane, that cannot be attributed to numerical errors. The emittance at the exit of PX chicane gets larger as well. For mode A, the bunch distribution gets skewed, increasing the peak bunch current for 20 A as shown in Fig. 3, where the design peak current for this mode is 13 A. No significant change in mode B peak current is observed from the design value of 10 A.

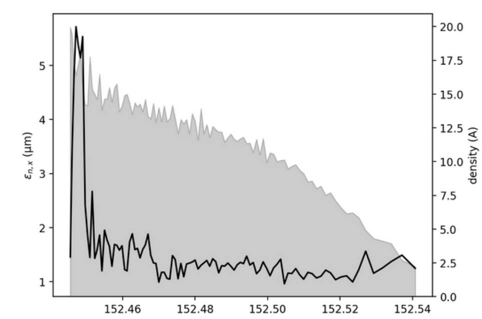

Figure 3: Slice current (black line) and slice ϵ_{nx} (gray) of the beam at the end of the PX chicane, for mode A. As shown, beam distribution is skewed, deviates from its initial beer-can distribution.

Even though the R_{56} value is determined by the bunch compression factor, neglecting higher order terms, T_{566} values are non-zero for both modes A and B. Compensating this T_{566} with adding a set of sextupoles is feasible, however, these sextupoles then may excite unwanted non-linear effects. A non invasive solution was found to mitigate these non-linear effects in PX chicane, by tuning RF parameters in the booster [12]. Figure 4 illustrates the distributions at the end of PX chicane. For mode A, tuning booster RF parameters is necessary to reform the distribution symmetry, but for mode B, design RF parameters are used.

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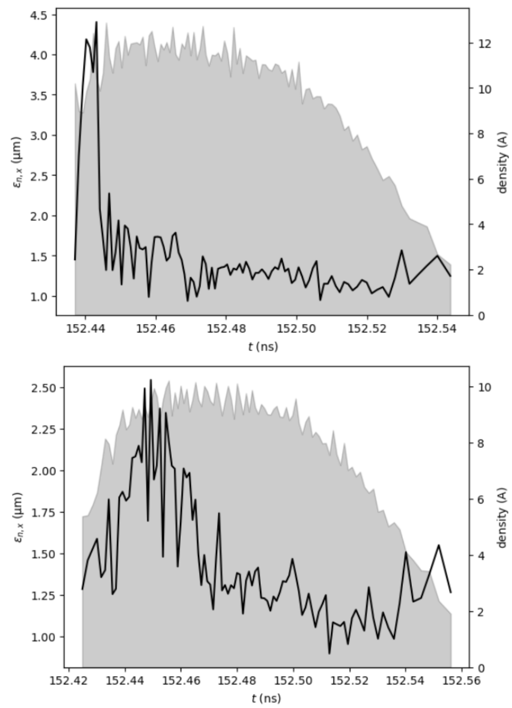

Figure 4: Slice current (black line) and slice ϵ_{nx} (gray) of the beam at the end of the PX chicane. Mode A (top) with peak bunch current 13 A and Mode B (bottom) with peak bunch current 10 A.

TWISS MATCH AT SPACE CHARGE- NON SPACE CHARGE INTERFACE

Achieving a proper Twiss match between the space charge dominated regime and relativistic regime is important to maintain electron beam parameters for proper hadron cooling. To facilitate this, an interface point has been defined, initially set at the end of the PX chicane. However, due to significant non-linear effects in the PX section, obtaining a proper Twiss match is difficult at this location. Optimizing beam tracking with space charge involved achieving this Twiss match while suppressing the beam emiitances at the end of the main linac (i.e. at the entrance to the cooling section). Quadrupoles triplets in the booster section and quadrupoles downstream of the PX dipoles are used to obtain the Twiss match at the interface point, which is now at the end of the first cryomodule of the main linac. The interface point is same for both modes, even though the energies are different. Figures 5 and 6 illustrate the beam sizes, beta functions, and normalized emittances (see Table 1) for the space-charge-dominated regime in modes A and B, respectively. Larger beam sizes and emittance peaks are observed within the PX chicane, as expected. However the exiting parameters are below the design requirements. Even though the vacuum pipe aperture for this ERL is considered to be 73 mm, a beam pipe with a larger aperture is required for this PX chicane to contain the beam.

The optimized lattice parameters for the space charge–dominated regime are used to refine the optics and

Table 1: Normalized emittance values at the space charge-non space charge interface point for modes A & B

	ϵ_{nx}	ϵ_{ny}
Mode A	2.726 $\times 10^{-6}$ m	2.902 $\times 10^{-6}$ m
Mode B	2.857 $\times 10^{-6}$ m	2.820 $\times 10^{-6}$ m

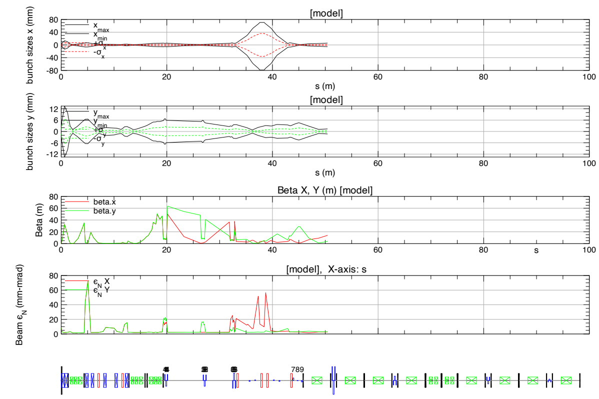

Figure 5: Beam parameter variation along the space charge dominated region for operating mode A.

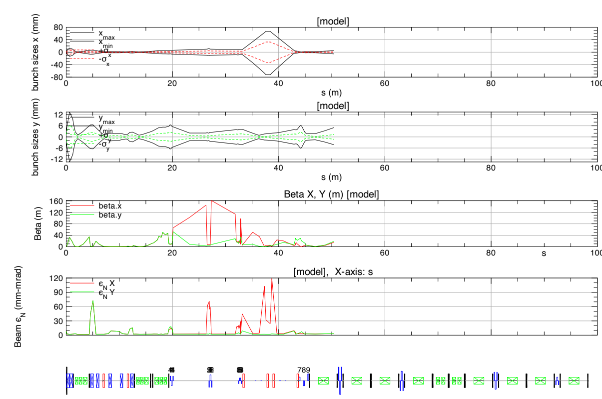

Figure 6: Beam parameter variation along the space charge dominated region for operating mode B.

guide the design of the SHC-ERL; the updated design is detailed in Ref. [13].

CONCLUSION

The SHC-ERL design utilizes a high-current electron beam with a relatively long bunch length, which is compressed in the PX bunch compressor. Strong space charge effects, longer bunch length excites non-linear chromatic effects and cause emittance blow up, with distorting the symmetry of the distribution. With proper magnet and RF settings, starting from the injector, this emittance blow up is controlled, while matching the lattice parameters within the space charge dominated regime to the non space charge dominated regime. Since the design energies at the matching interface point is different for two operating modes, two distinct solutions are obtained, and they are used for further design refinement.

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