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LINAC TO BAR/RCS TRANSFER LINE DESIGN FOR EIC ELECTRON INJECTION SYSTEM*

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Abstract

A transfer line has been designed for the Electron-Ion Collider (EIC) [1] to transport electron bunches from the linac to the Rapid Cycling Synchrotron (RCS). In its initial operational stage, the line accommodates 1 nC electron bunches directly from the linac. To support a future upgrade involving a Beam Accumulator Ring (BAR), which will stack individual bunches to form high-charge 28 nC bunches, the design incorporates two switching dipoles enabling injection into and extraction from the BAR. In addition, a beam dump has been included for operational flexibility and safety. The final segment of the line interfaces with the RCS through a modified Penner bend, preserving beam quality while satisfying geometric constraints. This layout ensures compatibility with both current and future operational modes of the EIC injection system.

INTRODUCTION

The Electron Injector is a pulsed accelerator chain designed to generate, accumulate, and accelerate polarized electron bunches for injection into the Electron Storage Ring (ESR). It supports both initial ring filling and periodic single-bunch replacements during collisions, a key feature for maintaining average polarization and luminosity throughout EIC operation. The system is optimized for high-repetition rate performance, minimal beam loss, and precise control of polarization preservation at each stage. A schematic of the machine layout with the new electron injector complex is shown in Fig. 1.

To achieve these goals, the injector complex consists of two sequential accelerators, a storage ring for bunch accumulation, and a network of connecting transfer lines. The front end, referred to as the Preinjector, includes a polarized electron source followed by a normal conducting S-band linear accelerator that delivers bunches at 750 MeV. Downstream of the linac, the Beam Accumulator Ring (BAR) enables the stacking of multiple low-charge pulses to produce high-intensity bunches, while also allowing for phase space damping and emittance equilibrium. These high-charge bunches are then transferred to the Rapid Cycling Synchrotron (RCS), which ramps the beam to GeV scale energies suitable for ESR injection, operating at a nominal repetition rate of 1 Hz.

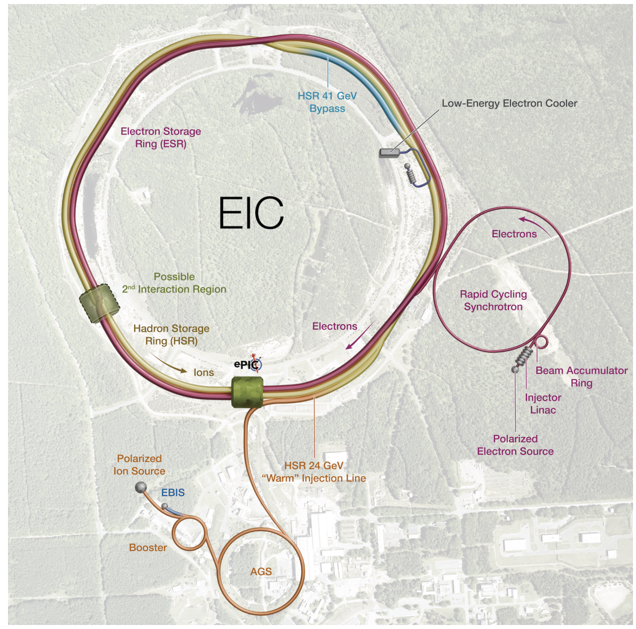

Figure 1: Layout of the EIC complex indicating the hadron storage ring (HSR), electron storage ring (ESR) and electron injector (RCS). The new electron injector complex is shown in purple, placed in the middle right side of the RHIC tunnel.

The synchrotron lattice is specifically designed to preserve polarization throughout the acceleration cycle.

This paper focuses on the design of the transport line connecting the preinjector Linac To the RCS (LTR). In the baseline configuration, electron bunches with a charge of approximately 1.1 nC are transported directly from the linac to the RCS, where they are accelerated to 5 , 10 , or 18 GeV before injection into the ESR at 4 o-clock region. A future upgrade will enable longitudinal stacking in the BAR to achieve bunch charges of up to 28 nC. To support this, the transfer line includes a branching section that allows beam transport into and out of the BAR using two switching dipoles. This adaptable configuration supports two operational modes: direct transport of low-charge bunches from the linac to the RCS, used during commissioning and reduced intensity operation and high-charge accumulation via the BAR for full intensity injection. Table 1 shows the incoming beam parameters from the linac.

DESIGN

The upstream portion of the Linac to RCS (LTR) transport line focuses on eliminating the horizontal dispersion coming from the linac prior to the first switching dipole (D1). A

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Table 1: Linac-To-Ring Interface Bunch Parameters

Parameter	Value	Units
Beam energy	750	MeV
$\beta_{x,y}$	15.34, 15.46	m
$\alpha_{x,y}$	-1.41, -2.04	-
$\eta x, y$	-0.13, 0.004	m
$\eta' x, y$	-0.02, 0.0	-
RMS $\sigma_{x,y}$	540, 435	µm
RMS $\epsilon_{x,y}$	19, 12	nm
RMS bunch length	0.7	mm
RMS momentum spread	0.19	%

20 meter long bypass section follows D1, providing a direct route to the second switching dipole (D2). This segment allows low-charge bunches to be sent directly from the linac to the RCS without accumulation in the BAR. Right after the D2 dipole, a vertical dipole is added to divert the beam toward an in-ground beam dump, which is positioned before a shield wall to provide radiation safety during RCS maintenance. Downstream of the beam dump, a quadrupole section is used to match the dispersion-free Twiss parameters of beams emerging from either the BAR or the bypass to the RCS injection point. Figure 2 shows a schematic of the LTR.

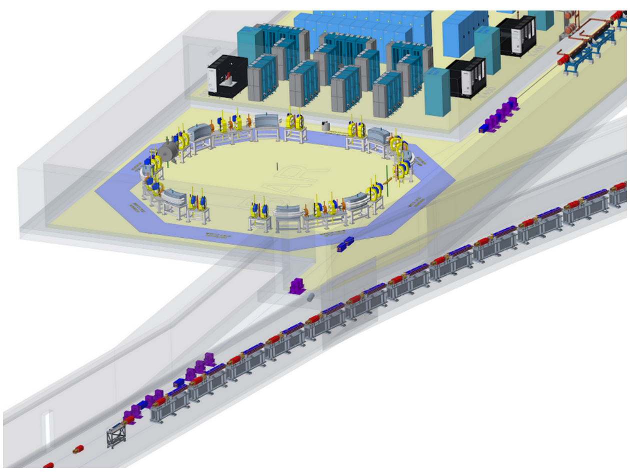

Figure 2: Layout of the the LTR coming from the injector linac in the top right corner and injecting into a straight section of the RCS. The beam accumulator ring is placed on the side within the bypass region that will eventually get added to the infrastructure.

RCS Injection

Infrastructure dictated that the linac makes a 9 degree angle with respect to the RCS straight, and it was desirable from a beam dynamics standpoint for dispersion and dispersion prime to be zero entering the injection chicane and at the exit of the injection kicker in the RCS. To fulfill these requirements, inspiration was taken from the Penner bend merger of the Jefferson Lab Free Electron Laser (JLab FEL) [2] and the merger of the Cornell-BNL ERL Test Accelerator (CBETA) [3] for a modified Penner bend, seen in Fig. 3. The injection chicane consists of two dipoles followed by a septum magnet, all with a bending angle of 8.7 degrees. The four quadrupoles are included to allow for some control over the Twiss parameters needed to match into the RCS optics and for the dispersion closure to be at the exit of the kicker, instead of the exit of the septum.

The orbit of the injected beam, once it exited the septum magnet, is always considered relative to the center of the RCS beam pipe. Exiting the septum, the offset is 26.2 mm, largely determined by the nominal beam pipe inner radius of 18.16 mm and the size of the injected beam at that location. Another constraint was that the orbit offset be 13 mm or less entering the downstream RCS quadrupole, in order for the beam envelope to not scrape on the quadrupole aperture. The kicker is downstream of the relevant quadrupole, with a length of 0.8 m and a kick angle of 7 mrad at 750 MeV.

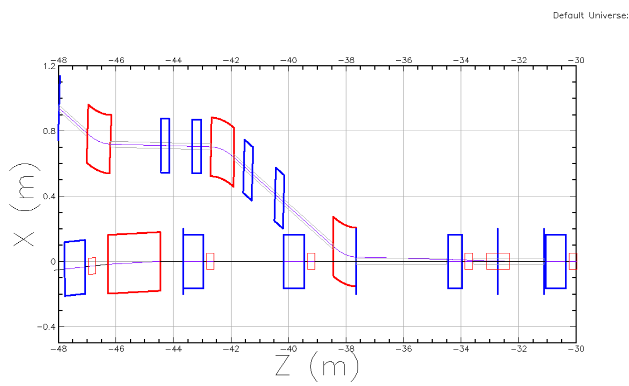

Figure 3: The layout of the injection chicane (top left) and the nearby RCS beamline (bottom). Both stored and injected bunches move left to right, with the trajectory of the injected bunch given by the purple line. The septum magnet is located near Z=−38 m and the kicker is located near Z=−33 m.

Optics

LTR matches the incoming optics from the linac to the injection point of the RCS. Due to the injector dipole and solenoids, the incoming bunches have dispersion in both planes. A horizontal dogleg was placed to fix the corresponding dispersion while the vertical is not fixed because it is negligibly small. Beam tracking in the RCS shows that the vertical dispersion remains small throughout the cycle, so a explicit compensation scheme is not necessary. Except the dipole magnets, the design reuses the existing BATES quadrupoles from MIT [4]. Figure 4 shows the twiss functions, dispersions and orbits of the LTR beamline for vertical and horizontal planes.

DIAGNOSTICS AND MEASUREMENTS

One of the most common techniques for measuring the transverse emittance of an electron beam is the *three-screen method*. In this approach, the beam's rms size (σ) is measured at three different locations along a drift section. As-

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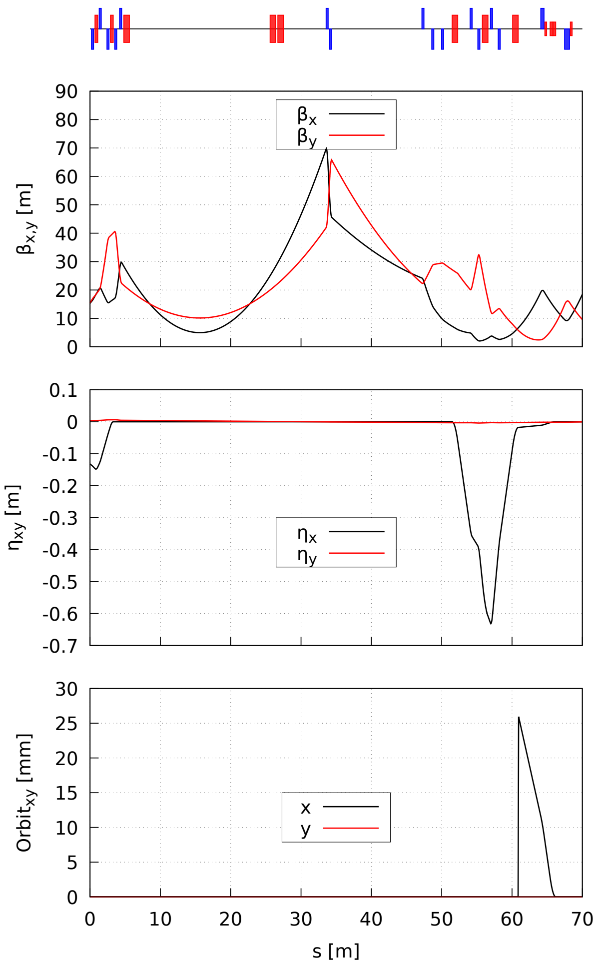

Figure 4: Twiss parameters along the LTR beamline: the top plot shows the horizontal and vertical beta functions (β_x, β_y), the middle plot shows the horizontal and vertical dispersion functions, and the bottom plot displays the orbits in both planes.

suming linear, space-charge-free conditions, these measurements are sufficient to reconstruct the Twiss parameters (α, β) and the geometric emittance (ε) using standard envelope equations. A key advantage of this diagnostic is that no magnets (quadrupoles) need to be changed, and the beam trajectory remains unchanged after the measurement is complete.

In low-energy or high-current regimes where space-charge effects are significant, the standard three-screen method can produce inaccurate results. A modified three-screen technique addresses this by fitting beam size data to models that include both emittance and generalized perveance K [5]. Tools like `TRACE 3-D` are commonly used for this purpose. The method remains effective for moderate space-charge levels (e.g., $R \lesssim$ 10–20, where $R = K\sigma^2/(4\varepsilon^2)$), where traditional assumptions begin to fail.

In beam dynamics, the *mismatch parameter* M [6] serves as a quantitative measure of how well the beam's actual phase-space ellipse matches the design (or "matched") optics. This parameter compares the measured Twiss parameters $(\alpha_m, \beta_m, \gamma_m)$ to their ideal counterparts $(\alpha_0, \beta_0, \gamma_0)$ and is defined as:

$$M = \frac{1}{2}\left(\gamma_0\beta_m + \beta_0\gamma_m - 2\,\alpha_0\alpha_m\right). \qquad (1)$$

A perfectly matched beam yields $M = 1$, indicating that the beam envelope conforms exactly to the designed optics. Values of $M > 1$ indicate mismatch, meaning the beam envelope either oscillates or deviates from the intended shape. Such mismatch can result in envelope oscillations, increased sensitivity to nonlinearities, and potential emittance growth due to phase-space filamentation. In experimental contexts, maintaining $M \lesssim 1.05$ is generally considered acceptable for ensuring reliable emittance measurements without introducing significant systematic error [6].

SUMMARY

This paper presents the design of the Linac to RCS (LTR) transfer line for the Electron Injector complex. The LTR transports polarized electron bunches from a 750 MeV linac to the Rapid Cycling Synchrotron (RCS), supporting both low-charge (1 nC) direct injection and high-charge (28 nC) injection via the Beam Accumulator Ring (BAR). The line includes sections for horizontal dispersion correction, a bypass region with two switching dipoles for BAR operation and a dedicated dump line. A three-screen emittance measurement setup is integrated into the bypass path to measure beam quality during low-intensity operation. The injection section uses a modified Penner bend to inject into the RCS with matched Twiss parameters. The design maintains beam polarization and emittance, enabling reliable operation at 1 Hz repetition rate.

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