Preliminary Physical Design and Simulation Study of ERL for EicC Electron Cooling

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Abstract

To meet the requirements of the electron cooling system for the Electron-Ion Collider in China (EicC) regarding high bunch charge, high repetition rate, long pulse duration, low emittance, and low energy spread of the electron beam source, a front-end physics design scheme based on an Energy Recovery Linac (ERL) is proposed. Beam dynamics simulations and optimization studies are conducted focusing on two core issues: strong space charge effects and high-order nonlinear coupling.

The injector adopts a collaborative configuration consisting of a 162.5 MHz quarter-wave superconducting radio-frequency (SRF) photocathode electron gun, a 650 MHz bunching cavity, a single-cavity booster section, and a 1.95 GHz third-harmonic cavity. Global optimization of parameters such as laser spot size, pulse length, cavity phases and gradients, and solenoid magnetic fields is performed using a genetic algorithm. For the merger section, four typical structures are comparatively evaluated, revealing the physical mechanism where the synergy between the second-order path length coefficient and the longitudinal charge density gradient leads to emittance growth within the merger.

The main acceleration section utilizes a three-cavity modular design, with each cavity containing two acceleration units. In the return beamline, the 180° arc employs a symmetric multi-magnet configuration to suppress high-order aberrations, while the path length adjustment section is used solely for phase matching. The results show that at the injector exit, the beam energy is 3.5 MeV, the normalized emittance is 1.4 mm · mrad, and the relative energy spread is 0.46‰. In the merger section, the multi-magnet small-deflection-angle configuration exhibits the minimum emittance growth. At the exit of the main acceleration section, the energy is 10.4 MeV, the emittance is 2.5 mm · mrad, and the energy spread is 0.47‰. Return phase adjustment achieves a theoretical energy

recovery efficiency of nearly 100%.

Global simulations demonstrate that the beam parameters at the cooling section entrance meet the design objectives. This study verifies the feasibility of the ERL physics design under high bunch charge and long bunch parameters, providing a reference for the future EicC electron cooling ERL.

Full Text

Preamble

Preliminary Physical Design and Optimization of an ERL for EicC Electron Cooling

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Abstract

The Electron-Ion Collider in China (EicC) is a proposed high-luminosity facility designed to explore the internal structure of nucleons. To achieve the required high luminosity, high-energy electron cooling is essential to counteract the emittance growth caused by intra-beam scattering (IBS). An Energy Recovery Linac (ERL) is the most promising candidate for providing the high-intensity, high-quality electron beams necessary for this cooling process. This paper presents a preliminary physical design and lattice optimization for an ERL-based electron cooler tailored for the EicC. We discuss the beam dynamics, including the compensation of the space charge effect and the optimization of the recovery efficiency.

1. Introduction

The Electron-Ion Collider in China (EicC) aims to provide a platform for studying the fundamental properties of nuclear matter, such as the spin structure of the proton and the 3D tomography of nucleons. To reach a luminosity of 1×10^{33} cm^{-2}s^{-1}, the ion beam must maintain high brightness and low emittance over long periods. However, intra-beam scattering (IBS) significantly limits the beam lifetime and increases emittance at the required energies. High-energy electron cooling is therefore a critical technology for the EicC project.

Traditional DC electron cooling is limited by the maximum voltage achievable in electrostatic accelerators. For the EicC, which requires electron energies in the tens of MeV range, an Energy Recovery Linac (ERL) is the preferred solution. An ERL combines the advantages of linear accelerators (high beam quality) with those of storage rings (high average current and efficiency) by recovering the energy of the used electron beam in superconducting RF (SRF) cavities.

2. ERL Layout and Parameters

The proposed ERL for EicC electron cooling consists of

摘要

To meet the requirements of the electron cooling system for the Electron-Ion Collider in China (EicC)—specifically regarding large bunch charge, high repetition rate,

long pulse duration, low emittance, and low energy spread—this paper proposes a front-end physical design based on an Energy Recovery Linac (ERL). Beam dynamics simulations and optimization studies were conducted, focusing on the two core challenges of strong space-charge effects and high-order nonlinear coupling.

The injector utilizes a collaborative configuration consisting of a 162.5 MHz quarter-wave superconducting radio-frequency (SRF) photocathode electron gun, a 650 MHz buncher cavity, a single-cavity booster section, and a 1.95 GHz third-harmonic cavity. Global optimization of parameters, including laser spot size, pulse length, cavity phases and gradients, and solenoid magnetic fields, was performed using a genetic algorithm. For the merger section, four typical structures were comparatively evaluated, revealing the physical mechanism by which the synergy between the second-order path length correlation and the longitudinal charge density gradient leads to emittance growth. The main acceleration section adopts a three-cavity modular design, with each cavity containing two accelerating cells. In the return beamline, the 180° bending section employs a symmetric multi-magnet configuration to suppress high-order aberrations, while the path-length adjustment section is used exclusively for phase matching. Results indicate that at the injector exit, the beam energy is 3.5 MeV, the normalized emittance is 1.4 mm · mrad, and the relative energy spread is 0.46‰. Among the merger options, the multi-magnet small-deflection-angle configuration exhibited the minimum emittance growth. At the exit of the main acceleration section, the energy reaches 10.4 MeV with an emittance of 2.5 mm · mrad and an energy spread of 0.47‰. Return phase adjustment achieves a theoretical energy recovery efficiency of nearly 100%. Global simulations demonstrate that the beam parameters at the entrance of the cooling section meet all design objectives. This study validates the feasibility of the ERL physical design under large-charge, long-bunch parameters, providing a critical reference for the future EicC electron cooling ERL.

关键词

Electron-Ion Collider in China (EicC); Energy Recovery Linac (ERL); Electron Cooling; Superconducting Radio Frequency (SRF) Photoinjector; Beam Dynamics

CLC number: TL53; Document code: A

To satisfy the urgent demand for high-luminosity and high-energy ion beam cooling in the Electron-Ion Collider in China (EicC) [?], the development of high-efficiency, low-emittance electron beam sources has become a core research priority. Electron cooling technology, characterized by its ability to provide cooling across the entire phase space, offers irreplaceable advantages in high-energy heavy-ion storage rings [?]. Internationally, electrostatic accelerator-based electron cooling devices, such as the 4.3 MeV system at Fermilab and the 2.0 MeV system at COSY, have been successfully operated [?, ?]. However, their limited energy scalability and challenges in controlling space charge effects make it difficult for them to meet the operational goals of EicC in higher luminosity and energy regimes. In recent years, schemes combining Energy Recovery Linacs (ERL) with electron cooling have gained significant international attention. These schemes offer the potential for high beam current, low emittance, and low power consumption, providing a novel path for the next generation of collider electron cooling [?].

However, the electron cooling beam required for EicC demands high energy (10.4 MeV), high bunch charge (4 nC), and long pulse duration (~150 ps).

These requirements pose significant challenges for ERL physical design, particularly regarding strong space charge effects and high-order nonlinear coupling. Although existing research has accumulated extensive experience in integrated machines and key technologies, the primary applications have been directed toward light sources and free-electron lasers. Systematic beam dynamics design for a fully superconducting ERL architecture—specifically one targeting nC-level high bunch charges and hundred-picosecond long bunches—remains a gap in the field. To address this, the present study focuses on the ERL required for EicC electron cooling. We conducted systematic beam dynamics simulations and optimizations centered on key issues such as the synergistic control of injector emittance and energy spread, the suppression of nonlinear-space charge coupling in the merger section, and the precise matching of the return phase. Starting from a high-brightness photocathode superconducting electron gun, this research evaluates the emittance evolution mechanisms of four merger configurations, identifying the advantages of a multi-magnet small-deflection-angle scheme. Building on this, optical matching for the main acceleration module and the return beamline was completed. Finally, start-to-end simulations verified that the beam parameters at the cooling section entrance meet the design requirements. This work provides a physical design reference for the development of the future EicC electron cooling ERL facility in China.

1 EicC-ERL 电子冷却系统总体设计

EicC Electron Cooling Scheme and Electron Beam Parameters. Electron cooling is a key technology that utilizes a cold electron beam, matched to the velocity of the ion beam, to reduce the ion beam emittance through Coulomb interactions.

The core physical mechanisms of this process are described by the electron cooling force $\vec{F}$ and the characteristic electron cooling time τ. The electron cooling force acting on an individual ion serves as the microscopic origin of the cooling process, inducing deceleration in both the transverse and longitudinal motions of the ions. In contrast, the characteristic electron cooling time describes the rate of emittance decay for the entire beam, representing the macroscopic manifestation of the cooling effect [**?**]. Together, these two parameters determine the overall performance of the cooling system and can be expressed by equations (**??**) and (**??**) as:

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$$2 \qquad 2 \ 8\sqrt{2} \quad 2$$

In this context, Z represents the ion charge number, ϵ_0 is the vacuum permittivity, n_e denotes the electron density, v is the velocity of the ions relative to the electron beam, and L_c is the Coulomb logarithm used to correct the truncation of the collision integral. Furthermore, k is the Boltzmann constant, while T_e and T_i represent the transverse temperatures of the electron beam and the

ion beam, respectively, which characterize the beam quality. Theoretical analysis indicates that the electron cooling force $\vec{F}$ and the characteristic cooling time τ are closely related to the key parameters of the electron beam. These relationships dictate that the design of an electron cooling system must produce a high-density,

high-quality electron beam and precisely align it with the ion beam to achieve efficient cooling results.

To improve cooling efficiency, the EicC adopts a multi-stage cooling scheme, as illustrated in Figure 1 [FIGURE:1] [**?**]. In the first stage, initial cooling is performed on the lower-energy proton beam within the booster ring (BRing). The most critical second stage takes place in the ion collider ring (pRing), where final cooling and steady-state maintenance are conducted for the 19.08 GeV proton beam. This stage utilizes advanced bunched beam cooling technology based on an Energy Recovery Linac (ERL), requiring a matched electron beam energy of 10.4 MeV. ERL technology can simultaneously satisfy the demanding requirements for high charge, low emittance, and energy recovery. It serves as the core technical guarantee for providing the strong cooling force required by the EicC to achieve its high-luminosity goals. Some design parameters for the electron beam in this stage are summarized in Table 1 below.

Requirements for selected parameters of the electron beam for EicC electron cooling

Beam parameters

Value

Beam energy

10.4 MeV

Bunch charge

Rms bunch length

150 ps

Transverse RMS normalized emittance

2.5 mm · mrad

RMS energy spread

< 5$×$10-4

Pulse Repetition Frequency

6.25 MHz

Overall Layout and Working Principle of the ERL Facility

The facility consists of core subsystems including the energy recovery loop (comprising the ARC bending sections and the chicane path-length regulator) and the electron cooling section. Its workflow follows a typical energy recovery operation mode as follows: First, an electron bunch with a large charge at the nC level and a duration of hundreds of picoseconds is generated at the photocathode of the injector. This bunch is pre-accelerated to

approximately 3.5 MeV using a superconducting radio-frequency (SRF) electron gun and SRF accelerating cavities, while the emittance and energy spread of the bunch are strictly controlled. Subsequently, the beam is deflected through the merger section and injected into the main acceleration stage, where it is further accelerated to the target energy of 10.4 MeV. The accelerated beam sequentially passes through ARC1 to complete a 180° turn and enters the electron cooling section to perform its cooling function. Afterward, the beam undergoes fine path-length adjustment in the chicane section and is deflected another 180° by ARC2. Finally, it is re-injected into the main acceleration stage with an RF phase that is 180° out of phase with the acceleration phase. During this second pass through the main acceleration stage, the beam is effectively decelerated, and its kinetic energy is efficiently converted back into the RF field, thereby achieving energy recovery. This process significantly reduces the net power consumption of the system and ensures the economical operation of the facility under high beam currents. In this scheme, the chicane is positioned between the electron cooling section and ARC2; its function is limited to adjusting the loop

timing to satisfy the phase-matching conditions for energy recovery. This maximizes the preservation of the electron beam quality entering the cooling section, meeting the high requirements for beam stability for EicC cooling.

Introduction to Core Physical Issues

To obtain the high-intensity electron beam required for EicC electron cooling, this ERL facility operates in a mode characterized by large nC-level bunch charges and long bunches of several hundred

picoseconds to increase the average beam current. In this mode, the key physical issues and technical implementations during beam generation and transport become the core factors determining the ultimate performance limits of the device.

(1) Synergistic control of emittance and energy spread for high-charge beams: In the low-energy section of the injector, nC-level charges introduce significant space-charge effects. These effects not only drive transverse electrostatic repulsion, leading to rapid emittance growth, but also cause substantial longitudinal energy broadening [**?**]. To obtain high-quality beams with both ultra-low emittance and ultra-low energy spread from the source, multi-dimensional active compensation and suppression of space-charge forces are required. This necessitates that the physical design of the high-brightness photocathode electron gun be synergistically optimized with the longitudinal phase-space manipulation in the injection section. Specifically, building upon the optimization of the electron gun’ s electric field and focusing magnetic fields to control transverse emittance, a third-harmonic cavity must be introduced in the injector. The nonlinear RF field generated by this cavity compensates for the longitudinal nonlinearity induced by the main accelerating cavities, thereby effectively suppressing the growth of energy spread and achieving simultaneous optimization of both transverse and longitudinal beam quality.

(2) Coupling between high-order nonlinearities and space-charge effects in the transport section: In the low-to-medium energy beam transport and merger regions, the inherent high-order optical nonlinearities of the magnet structures used to guide and deflect the beam undergo complex coupling with the beam’ s own space-charge field. For long bunches of several hundred picoseconds, the longitudinal charge density gradient is relatively gentle, resulting in a lower intrinsic growth rate of space-charge effects. However, this also makes the beam phase space extremely sensitive to nonlinear perturbations introduced by the structure. Theoretical analysis indicates that specific high-order dispersion terms of the structure (such as the second-order path length coefficient) map the momentum spread of the bunch into longitudinal displacements, causing particles to move to positions of different charge densities within the bunch [**?**]. Consequently, the transverse space-charge force experienced by a particle becomes a nonlinear function of its momentum. This nonlinear coupling disrupts the linear correlation of the beam phase space, leading to significant irreversible emittance growth. Therefore, suppressing the coupling between high-order nonlinear effects and space-charge effects

to achieve low-perturbation transport of high-brightness beams is one of the core physical tasks in the design of the transport section.

To address these issues, the subsequent chapters of this paper will conduct in-depth research: Sections 2 and 3 focus on the synergistic design of the large-bunch-charge photocathode electron gun and the injection section, emphasizing optimization methods for emittance control and energy spread suppression via the third-harmonic cavity. Sections 4 and 5 are dedicated to the structural design of the ERL loop transport section, elucidating the physics of the coupling between high-order nonlinearities and space-charge effects and proposing optimized design criteria accordingly.

2 Physical Design and Optimization of the High-Charge Long-Bunch Photocathode Electron Gun

As the beam source of the ERL, the core task of the injector is to generate electron beams with both high brightness and low energy spread. Its output beam quality directly determines the performance ceiling of the entire system. To achieve the large single-bunch charge (~4 nC) and bunch length (~150 ps) required for EicC electron cooling, and to overcome the influence of strong space-charge effects in the low-energy section, the technical selection of the electron gun is of primary importance. Photocathode electron guns are mainly categorized by their accelerating structures into three types: Direct Current (DC), normal-conducting Radio Frequency (RF), and Superconducting Radio Frequency (SRF) [**?**]. Traditional DC photocathode guns are limited by the cathode surface field strength (typically < 10 MV/m), and the bunch charge they can stably emit is generally below 1 nC, which fails to meet the design requirements [**?**]. While normal-conducting RF guns can achieve higher accelerating gradients, their ohmic losses under high duty-cycle operation are extremely severe, leading to difficulties in thermal load management, low efficiency, and challenges in operational stability. Therefore, the SRF photocathode electron gun has emerged as the only feasible solution to meet all the extreme performance requirements of this design [**?**]. It combines the nearly lossless operation of superconducting cavities at high gradients with the high quantum efficiency of photocathodes. Despite the higher complexity in cryogenic engineering, multi-physics coupling, and cathode integration, this scheme can stably produce electron beams with large charges, high repetition rates, and extremely low initial emittance. Notably, the BNL laboratory has successfully obtained high-quality electron beams of 5-10 nC using a 112 MHz, 1/4-wavelength resonator [**?**].

Based on the above discussion, the overall layout of the injector in this study is shown in FIGURE:3. Its core components include: a $\lambda/4$ coaxial resonator-type SRF photocathode electron gun operating at 162.5 MHz, with the electric field distribution shown in FIGURE:3, used for the

direct generation of large-bunch-charge electron beams; a 650 MHz buncher cavity for preliminary longitudinal compression of the extracted bunch; a booster section consisting of two 650 MHz SRF accelerating cavities in series, with the electric field distribution shown in FIGURE:3, used to rapidly increase the beam energy to the MeV level to suppress space-charge effects [?]; a third-harmonic cavity containing two accelerating units operating at 1.95 GHz (the third harmonic) with the electric field distribution shown in FIGURE:3, used to compensate for longitudinal phase-space nonlinearity; and a magnetic lens system composed of multiple

solenoids, used to compensate for the emittance growth induced by space-charge effects.

To verify the design and obtain optimal parameters, beam dynamics tracking simulations were performed using the General Particle Tracer (GPT) program [?]. The optimization process targeted the minimization of both the normalized transverse emittance and the rms relative energy spread at the exit as dual objectives. Simultaneously, the beam energy, energy spread, and rms bunch size at the exit were controlled. A genetic algorithm was utilized to automatically search for the optimal values of the key parameters listed in .

Optimizable parameters of the injector and their values

Parameters

Value

RMS laser spot size

0.78 mm

Laser pulse length

110 ps

SRF gun phase

SRF gun accelerating gradient

30 MV/m

Buncher phase

-30.8°

Buncher gradient

30 MV/m

Booster phase

-25.5°

Booster accelerating gradient

Figure 4

Figure 1: Figure 4

8 MV/m

3rd harmonic cavity phase

127.9°

3rd harmonic cavity accelerating gradient

7.8 MV/m

Solenoid 1 magnetic field

0.053 T

Solenoid 1 position

1.21 m

Solenoid 2 magnetic field

0.007 T

Solenoid 2 position

3.13 m

Table Note: All phases in the table are expressed as differences relative to the maximum phase.

The optimized beam evolution results are shown in

. Simulations demonstrate that at the injector exit, the beam energy reaches 3.5 MeV, with a normalized RMS emittance of 1.4 mm • mrad and an RMS relative energy spread of 0.46‰. At the exit, the transverse beam⋯

The transverse phase space distribution and the longitudinal phase space distribution, both with and without the harmonic cavity, are shown in [FIGURE:5]. Here, B_x represents the normalized velocity in the x direction (v_x/c).

[FIGURE:5]

As illustrated in [FIGURE:5], the introduction of the harmonic cavity significantly alters the longitudinal phase space distribution of the electron beam. Specifically, the harmonic cavity effectively linearizes the longitudinal phase space, leading to a more uniform distribution of particles along the bunch length. This modification is crucial for suppressing instabilities and optimizing the beam lifetime. In the transverse plane, the distribution remains relatively stable, ensuring that the overall beam quality and emittance are preserved while achieving the desired longitudinal profiles.

In the following discussion, B_y represents the normalized velocity in the y-direction (v_z), and G denotes the Lorentz factor γ. This convention applies to all phase space distribution plots presented hereafter. Under the influence of the third-harmonic cavity, the longitudinal phase space exhibits highly linearized characteristics, thereby validating the effectiveness of the harmonic compensation strategy.

These results demonstrate that through the integration and systematic optimization of the SRF gun, emittance compensation, and harmonic linearization techniques, the collaborative control of transverse and longitudinal beam quality has been successfully achieved under strong space-charge effects. This provides a robust foundation for the subsequent systems.

A qualified beam source.

3 并束段结构的高阶非线性效应与束流传输物理分析

As a critical transition unit connecting the injector and the main accelerator, the merger section serves to guide and deflect the beam. Its core physical objective is to achieve geometric beam merging while minimizing the irreversible growth of transverse emittance. For the high bunch charge (~4 nC) and long pulse (~hundreds of picoseconds) electron bunches targeted in this design, the primary mechanism for emittance growth stems from the complex coupling between the inherent high-order optical nonlinearities of the magnetic structure and the space charge effects of the bunch itself.

By combining analytical theory with numerical simulations, we conducted an in-depth analysis of the different merger configurations shown in [FIGURE:6] and the underlying physical causes affecting beam quality to identify an optimal solution.

To achieve high-quality beam transport, the merger section must decouple transverse and longitudinal motion. In the ideal case where space charge forces are absent or "frozen," decoupling can be achieved through traditional achromatic conditions, which require the dispersion function and its derivative to be zero at the exit of the merger: $\eta(s_f) = 0$ and $\eta'(s_f) = 0$. However, for low-energy beams dominated by space charge, the energy of the particles changes significantly as they pass through the merger due to Coulomb interactions, such that $\delta'(s) \neq 0$. In this scenario, satisfying only the traditional achromatic conditions is insufficient. Theoretical analysis indicates that to achieve complete decoupling, a set of high-order integral conditions regarding the energy variation patterns must also be satisfied. These conditions require the structure not only to be achromatic for constant-energy particles but also to cancel the additional transverse-longitudinal coupling introduced by energy variations along the path.

This ensures the compensation of coupling effects arising from energy changes along the trajectory.

To analyze the impact of different structures on beam quality, a systematic analysis was performed using the high-charge, long-pulse bunches generated by the injector designed in Section 2. The simulations used the injector output as initial conditions for beam tracking, and the resulting transverse emittance evolution curves are shown in [FIGURE:7]. The results demonstrate significant performance differences among the four structures: the chicane-type structure performed best, with the normalized emittance at the exit increasing from 1.4 mm · mrad at the entrance to only 2.1 mm · mrad. The three-dipole structure followed, with emittance growing to 2.6 mm · mrad. The zigzag structure led to a significant increase in emittance to 7.0 mm · mrad, while the dogleg structure performed the worst, with emittance deteriorating sharply to 7.3 mm · mrad.

Based on the comparative analysis, different structures exert varying influences on transverse emittance. For electron bunches with high charge, long pulse duration, and low-to-medium energy, the emittance growth within the merger section follows a chain reaction path triggered by structural nonlinearities.

First, in low-to-medium energy scenarios, even a long pulse duration cannot smooth out the longitudinal space charge force gradients caused by a high charge (4 nC). The bunch exists in a state of “fragile equilibrium” regarding its phase-space coherence and possesses an inherent energy spread δ.

Subsequently, as the bunch passes through the merger section, particles with different momenta traverse different paths due to the presence of bending magnets. At this stage, the longitudinal displacement of particles relative to the reference particle is nonlinearly mapped by the energy spread:

$$\Delta z \approx R_{56}\delta + T_{566}\delta^2 + ...$$

In this expression, the first-order effect is described by R_{56}, while the second-order effect is described by T_{566}. The longitudinal displacement caused by $T_{566}\delta^2$ moves particles to positions within the bunch with different longitudinal charge densities. Consequently, the transverse space charge force experienced by the particles becomes a nonlinear function of their momentum in the form of a defocusing force:

$$\Delta F_\perp(\delta) \propto$$

( )   (2 566)

This δ-dependent nonlinear transverse force applies a kick to the transverse phase space (x, x'), disrupting the linear correlation of the phase space ellipse.

This results in an irreversible increase in the phase space area and leads to nonlinear coupling between the transverse and longitudinal planes. The emittance growth can be scaled as $\Delta\epsilon_n \propto$

566 2 eff)

This formula indicates that nonlinear transverse emittance growth is highly sensitive to the longitudinal space charge force gradient, structural nonlinearities, and energy spread. Based on this physical framework, the performance of different structures can be explained: Chicane and three-dipole structures are composed of multiple magnets with small bending angles. Their intrinsic T_{566} values are small and their trajectories are smooth; consequently, the nonlinear perturbations introduced by the structure itself are relatively weak.

This allows these structures to more easily harmonize with the energy variation patterns of the beam, even without complex intermediate matching, thereby coming closer to satisfying the aforementioned high-order decoupling conditions. In contrast, the Dogleg structure features a single large-angle bend that results in an extremely large intrinsic T_{566}, acting as a strong source of nonlinearity. Even if matching quadrupoles are placed within the structure to optimize first-order optics, it remains difficult to compensate for this inherent nonlinear coupling. Furthermore, the strong focusing required to satisfy first-order achromatic conditions may disrupt the laminar flow of the beam, further exacerbating emittance growth. The performance of the Zigzag structure lies between these two extremes, suggesting that its symmetrical design may fail to effectively suppress critical high-order aberrations if not precisely optimized.

In summary, the design of merger sections for high-brightness ERLs should follow these core principles: First, priority should be given to configurations with weak intrinsic nonlinearity and smooth trajectories (such as multi-magnet, small-bending-angle schemes), as these provide the foundation for low-perturbation transport. Second, while satisfying geometric constraints, structural symmetry can be utilized as a tool to simplify the design and automatically cancel certain aberrations; however, it must be noted that symmetry itself is not a guarantee, and the ultimate goal must be to satisfy the complete transverse-longitudinal decoupling conditions. Finally, the design must be validated through beam dynamics simulations that include space charge effects to ensure that beam quality is effectively maintained in a realistic, strong space charge environment. By clarifying the physical mechanisms of emittance growth in merger sections, this study provides a physical basis and optimization direction for the design of this critical component in the future EicC and other high-brightness ERL facilities.

4 主加速段的物理设计与模拟

In an Energy Recovery Linac (ERL), the main accelerating section performs a dual function. First, it accelerates the low-energy beam from the injector to the target energy required for downstream applications. Second, it decelerates the high-energy beam—which returns at a precise anti-phase relative to the RF field —thereby coupling its energy back into the RF cavities. This process ultimately reduces the beam energy to a level near that of the initial injection, achieving highly efficient energy recovery.

The successful implementation of this "acceleration-deceleration" process strictly depends on the precise control of the bunch return timing by the return beamline. This ensures that the radio-frequency (RF) phase, upon the bunch' s arrival at the entrance of the main acceleration section, is exactly 180° out of phase with the initial acceleration phase.

To achieve the requirements of stable accelerating gradients and high energy recovery efficiency under the high average current operation of EicC, while also ensuring engineering reliability, this design adopts an architecture characterized by multi-cavity modularization and consistent frequency across the entire system. As shown in [FIGURE:8], the main acceleration section consists of three ...

Superconducting accelerating cavities, sharing the same structure as the booster, are integrated into a single module, with two units forming an individual accelerating cavity assembly. This design distributes the RF power load during high-current operation across multiple cavities, significantly reducing the burden on individual cavities and their respective power sources. Consequently, this enhances the system' s robustness against beam loading effects and improves long-term operational stability. Furthermore, this configuration provides additional adjustable parameters, simplifying the longitudinal phase synchronization and control across the entire link.

To further optimize beam quality, a third-harmonic cavity is configured in synchronization following the main acceleration module. This cavity is utilized to compensate for longitudinal nonlinearities generated during the main acceleration process, thereby ensuring low energy spread characteristics of the output bunches while achieving high acceleration efficiency. Physically, this design guarantees the precision and efficiency of the energy recovery process; from an engineering perspective, it provides a foundation for high-power, high-stability operation.

Qualitative operation has laid a critical foundation.

The beam energy is 100 MeV, with normalized rms emittances in the x and y directions of 2.5 mm · mrad and 2.3 mm · mrad, respectively. The RMS relative energy spread is 0.47‰. All performance indicators satisfy the design requirements. Beam instabilities induced by higher-order modes (HOMs) in the superconducting cavities represent a critical challenge for the operation of high-average-current Energy Recovery Linacs (ERLs). A detailed evaluation of these effects requires an integrated analysis of specific cavity geometries, coupler layouts, threshold current scanning, and multi-bunch simulations. Consequently, a comprehensive discussion of HOM effects is beyond the scope of this paper and will be addressed in subsequent specialized studies. This paper focuses on the overall physical design and beam dynamics optimization of the ERL facility; calculations regarding HOM effects and associated threshold currents are reserved for future research stages.

5 返航束线的物理设计与模拟

The return beamline primarily consists of two 180° bending ARC sections and a chicane section used for path length adjustment. There are two main structural configurations for the ARC sections, as shown in [FIGURE:10]. Consistent with the physical principles applied in the previous beam combining section, this paper adopts the structure shown in FIGURE:10. Although this configuration requires a larger number of quadrupole magnets and occupies more space, it is more conducive to achieving low-perturbation transport.

In general ERL facilities, the magnetic compression section (chicane) plays a critical role. It is used in conjunction with the accelerating cavities to precisely shape the longitudinal phase space of the beam output from ARC1, thereby providing high-quality electron beams for downstream experimental applications. As a system that introduces significant dispersion, the ARC section inevitably introduces momentum-dependent effects (such as energy spread and longitudinal phase space distortion) while guiding the beam for energy recovery. The chicane acts as a precision "optical corrector." By adjusting the momentum compaction factor (R_{56}) inherent in its symmetric four-magnet configuration, it can actively and flexibly compensate for or reconstruct the bunch length.

This configuration can either counteract the disadvantageous bunch stretching caused by the arc regions or further compress the bunch to achieve the ultra-high peak currents and ultra-short pulses required for applications such as Free Electron Lasers (FEL) or Compton light sources [**?**]. However, in the present design, bunch length compression is not required; the chicane section is used solely for path length adjustment, the principle of which is illustrated in [FIGURE:11]. To avoid emittance growth introduced by the chicane, this structure is positioned between the electron cooling section and ARC2 to ensure that the higher-quality beam is utilized.

The path length adjustment function is realized by changing the bending angle (via the dipole magnet current intensity), which subsequently adjusts the phase of the return beam as it re-injects into the main acceleration section. The relevant formula is as follows:

$$\Delta L = 4l_{eff}\left(\frac{\alpha}{\sin\alpha} - 1\right) + 2d \cdot \left(\frac{1}{\cos\alpha} - 1\right)$$

where l_{eff} is the effective length of the dipole magnet, α is the bending angle of the dipole, and d is the spacing between the magnets. A fundamental prerequisite for efficient energy recovery is achieving precise phase matching between the accelerating bunch and the decelerating bunch, requiring a phase difference of $(360 \times n + 180)^\circ$, where n is an integer. Once the relative RF phase for acceleration in the main linac is determined, the phase of the re-injected bunch is determined by its transit time T_r in the return beamline, which in turn depends on the total path length L_r:

To satisfy the phase condition of $(n+0.5)$ RF cycles, the following must be met:

The equivalent path length is:

$$L_r = \left(n + \frac{1}{2}\right)\lambda_{RF}$$

For the electron bunch operating frequency of 650 MHz discussed in this paper, the corresponding wavelength is $\lambda_{RF} = 0.4612$ m. presents the variations in path length, the re-injection phase of the return beamline, and the ideal energy recovery efficiency as a function of the bending angle.

Bend angle (°)

(cm)

(°)

Energy Recovery Efficiency (%)

At the exit of ARC1 (which serves as the entrance to the electron cooling section), the electron bunch achieves normalized emittances of 2.8 mm · mrad and 2.7 mm · mrad in the x and y directions, respectively. The bunch length is approximately 110 ps, the energy is 10.4 MeV, and the energy spread is 0.52‰. These performance indicators are very close to the target parameters, fundamentally satisfying the design requirements.

Due to the inherent characteristics of the system, beam size parameters within the continuous deflection structures (ARC, Chicane, and Dump) no longer provide meaningful reference values; consequently, these regions are marked with gray blocks in the figures, with beam sizes retained only at the entry and exit points for analysis. The results demonstrate that through rational physical design and layout, space charge effects and high-order nonlinear effects have been effectively suppressed, allowing the transverse emittance to maintain a high quality upon reaching the electron cooling section. Furthermore, during the optimization process, the transverse dimensions of the beam spot were effectively controlled by finely adjusting the strengths and positions of the quadrupole magnets along the return beamline. However, because three quadrupole magnets are shared between the merger section and the main acceleration section, the return beam still exhibits significant envelope growth ($4\sigma \approx 20$ mm) upon re-entering the main acceleration stage. This effect necessitates that sufficient physical aperture margin be reserved in subsequent cavity designs to ensure the stable operation of the facility.

6 结论

To meet the stringent requirements of the Electron-Ion Collider in China (EicC) electron cooling system for an electron source characterized by high bunch charge, long pulse duration, and low emittance, this paper proposes a physical design for a compact Energy Recovery Linac (ERL). Systematic beam dynamics simulations and optimizations were conducted, focusing on strong space-charge effects and high-order nonlinear coupling. The injector design employs a collaborative configuration consisting of a 162.5 MHz quarter-wave superconducting radio-frequency (SRF) photocathode gun, a 650 MHz buncher, a single-cavity booster section, and a 1.95 GHz third-harmonic cavity. By utilizing genetic algorithms for global optimization of key parameters, a high-quality beam output was successfully achieved at an energy of 3.5 MeV, featuring a normalized transverse emittance of 1.4 mm · mrad and a relative energy spread of 0.46‰.

These results validate the effectiveness of the third-harmonic cavity in compensating for nonlinearities in the longitudinal phase space. Furthermore, they demonstrate that the applicability of emittance compensation techniques can be extended to the nC-level bunch charge regime.

In the study of the merger section, comparative simulations of four typical configurations (chicane, three-dipole, zigzag, and dogleg) revealed significant differences in emittance growth. The chicane-type configuration exhibited the minimum growth (from 1.4 to 2.1 mm · mrad), while the dogleg-type showed the most severe degradation (from 1.4 to 7.3 mm · mrad). This phenomenon prompted a deep investigation into the underlying physical mechanisms. Theoretical analysis indicates that the primary cause of emittance growth is the intrinsic second-order path length coefficient (T_{566}) of the structure, which nonlinearly maps the beam momentum spread into longitudinal displacements. This causes particles to shift to positions with non-zero charge density gradients, where they experience momentum-dependent transverse space-charge forces. This process ultimately disrupts the linear correlation of the phase space and triggers irreversible emittance growth.

The establishment of this physical model extends the design criteria for merger sections from traditional first-order achromatism to a priority on intrinsic nonlinearity suppression and trajectory smoothing. It clearly identifies the significant advantages of multi-magnet, small-deflection-angle schemes under the influence of strong space-charge effects.

The main acceleration section adopts a three-cavity modular architecture with frequencies synchronized to the injector, thereby simplifying longitudinal synchronization control. Combined with subsequent compensation from the third-harmonic cavity, the beam energy spread is maintained at 0.47‰ at the target energy of 10.4 MeV, while the transverse emittance satisfies the design specification of 2.5 mm · mrad. The ARC section in the return beamline utilizes a symmetric multi-magnet configuration to suppress high-order aberrations, while the chicane section is used exclusively for path length adjustment to avoid introducing additional perturbations to the beam quality in the cooling section. Precise matching between the return phase and the main acceleration RF field is achieved through deflection angle scanning, yielding a theoretical energy recovery efficiency of 100%. Start-to-end global simulations based on GPT software indicate that key parameters at the entrance of the electron cooling section—including beam energy, emittance, energy spread, and bunch length—fundamentally meet the physical design objectives required for EicC. This preliminarily verifies the theoretical feasibility of the scheme and the rationality of the parameter selection.

Simultaneously, this study reveals several physical issues requiring further investigation. The slight emittance growth in the ARC section, caused by residual coupling of the dispersion function, suggests the necessity of introducing a sextupole magnet system for chromaticity correction. Furthermore, beam instabilities induced by high-order modes (HOMs) and beam-cavity interactions must be addressed in subsequent design stages through multi-bunch collaborative analysis, incorporating specific cavity structures and coupler layouts. Additionally, as a compact scheme oriented toward physical validation, this design requires further scaling and structural optimization based on the actual tunnel conditions of the EicC and the physical requirements of the cooling section.

In summary, this paper provides a comprehensive physical framework, key parametric evidence, and simulation support for the ERL design of the EicC electron cooling system. A low-emittance ERL scheme tailored for high bunch charge, long bunches, and high repetition rates has been proposed and its feasibility verified through simulation. Future research will focus on the detailed design of the electron cooling system, with emphasis on the active correction of high-order aberrations in continuous deflection structures (such as the merger, ARC, and chicane sections), multi-physics collaborative analysis of full-ring beam stability, and the engineering integration and experimental validation of the entire system. These efforts will lay a solid foundation for achieving the high-luminosity collision goals of the EicC.

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Abstract

To meet the requirements of the electron cooling system for the China Electron-Ion Collider regarding high bunch charge, high repetition rate, long pulse length, low emittance, and low energy spread in the electron beam source, this paper proposes a front-end physics design scheme based on an energy recovery linac. Beam dynamics simulations and optimization studies are conducted, focusing on two core challenges: strong space

charge effects and high-order nonlinear coupling. The injector employs a synergistic configuration comprising a 162.5 MHz quarter-wave superconducting RF photocathode electron gun, a 650 MHz buncher cavity, a two-cell 650MHz booster cavity, and a two-cell 1.95 GHz third harmonic cavity. A genetic algorithm is applied for global optimization of parameters such as laser spot size, pulse length, cavity phase and gradient, and solenoid magnetic field. Four typical merger section configurations are evaluated comparatively, revealing the physical mechanism by which the synergy between second-order path length coefficient and longitudinal charge density gradient leads to emittance growth in the merger section. The main accelerator section adopts a three-cavity module design. The 180°bending section in the return beamline utilizes a symmetric multi-magnet configuration to suppress highorder aberrations, while the path length adjustment section is used solely for phase matching. Results indicate that at the injector exit, the beam energy reaches 3.5 MeV, with a normalized emittance of 1.4 mm · mrad and a relative energy spread of 0.46‰. Among the merger configurations, the multi-magnet small-angle bending scheme exhibits the minimal emittance growth. At the main accelerator exit, the beam energy is 10.4 MeV, with an emittance of 2.5 mm · mrad and an energy spread of 0.47‰. Phase adjustment in the return beamline yields a theoretical energy recovery efficiency approaching 100%. Global simulations demonstrate that the beam parameters at the cooling section entrance meet the design objectives. This study demonstrates the feasibility of the physical design of an ERL under high-charge, long-bunch parameters, providing critical insights for the development of the ERL-based electron cooler for the future Electron-ion Collider in China.

Keywords

EicC; ERL; electron cooling; superconducting radio-frequency electron gun; merger section.

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